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Final report

Climate and environmental impact of nuclear power

by:
Christoph Pistner, Matthias Englert, Carl-Otto Gensch, Ralph Harthan, Anke Herold, Anna Kopp, Ran Liu, Charlotte Loreck, Roman Mendelevitch, Martin Möller, Lothar Rausch, Jürgen Sutter
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Abstract: Climate and environmental impact of nuclear power

Against the background of the global objective of achieving net zero greenhouse gas emissions by 2050, the necessary phase-out of fossil fuels, and the transformation of the energy sector, this study assesses the role of nuclear energy in this transformation process from several perspectives.

To this end, we first examine the role of nuclear energy for achieving climate targets in five different integrated assessment models and compare them with a comprehensive bottom-up analysis of countries' plans and programs for nuclear power until 2050. Next is a comprehensive life cycle assessment of nuclear power with a focus on the greenhouse gas emmissions. Different life-cycle chains are covering different countries and regions for the baseline year 2020 and a projection year 2030. The sudy adds a brief discussion of environmental impacts due to severe accidents in nuclear power plants and the proliferation risks inherent in the nuclear fuel cycle. Finally, we provide an assessment of the life cycle costs of electricity from new nuclear power plants and resulting greenhouse gas abatement costs with respect to hard coal, comparing them with those of renewable energies.

The results show that the development of renewable energies is the key to achieving the net-zero targets. Nuclear energy, on the other hand, is not necessary for achieving the climate targets and its significance for electricity generation in 2050 is very limited in any case. Despite the greenhouse gas emissions of nuclear energy, which are at a comparably low level to those of renewable energies, it is not a quick or cost-effective option for significantly reducing the energy system's greenhouse gas emissions due to long construction times and high costs.

Kurzbeschreibung: Klima- und Umweltwirkungen der Kernenergie

Vor dem Hintergrund des globalen Ziels, bis 2050 netto null Treibhausgasemissionen zu erreichen, des notwendigen Ausstiegs aus fossilen Brennstoffen und der Transformation des Energiesektors wird in dieser Studie die Rolle der Kernenergie in diesem Transformationsprozess aus mehreren Perspektiven bewertet.

Zu diesem Zweck untersuchen wir zunächst die Rolle der Kernenergie für die Erreichung der Klimaziele in fünf verschiedenen integrierten Bewertungsmodellen und vergleichen sie mit einer umfassenden Bottom-up-Analyse der Pläne und Programme der Länder für die Kernenergie bis 2050. Es folgt eine umfassende Lebenszyklusanalyse der Kernenergie mit einem Fokus auf die Treibhausgasemissionen. Verschiedene Lebenszyklusketten werden für verschiedene Länder und Regionen für das Basisjahr 2020 und ein Projektionsjahr 2030 berechnet. Die Studie enthält auch eine Erörterung der Umweltauswirkungen schwerer Unfälle in Kernkraftwerken und der mit dem Kernbrennstoffkreislauf verbundenen Proliferationsrisiken. Schließlich werden die Lebenszykluskosten von Strom aus neuen Kernkraftwerken und die Kosten für die Vermeidung von Treibhausgasen im Verlgeich zu Steinkohle berechnet und mit denen von erneuerbaren Energien verglichen.

Die Ergebnisse zeigen, dass die Entwicklung erneuerbarer Energien der Schlüssel zur Erreichung der Netto-Null-Ziele ist. Kernenergie ist dagegen für das Erreichen der Klimaziele nicht erforderlich und ihre Bedeutung für die Stromerzeugung im Jahr 2050 ist in jedem Fall sehr begrenzt. Trotz Treibhausgasemmissionen der Kernenergie, die auf einem vergleichbar niedrigen Niveau wie diejenigen von Erneuerbaren Energien liegen, stellt sie aufgrund langer Errichtungszeiten und hoher Kosten keine schnelle oder kostengünstige Option für eine signifikante Verringerung der Treibhausgasemmissionen des Energiesystems dar.

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List of abbreviations

Abbreviation	Explanation
AP	Announced pledges
ATF	Accident tolerant fuel
BOA	Business Opportunity Analyser
BWR	Boiling water reactor
CAPEX	Capital expenditure
CAREM	Central Argentina de Elementos Modulares
CCGT	Combined cycle gas turbine
CCS	Carbon Capture and Storage
CF	Capacity Factor
CFF	Containment Failure Frequency
CDF	Core Damage Frequency
CET	Core exit temperature
CNEC	China Nuclear Engineering & Construction Corp
CNNC	China National Nuclear Corporation
CO_2	Carbon dioxide
COP	Conference of the Parties
D	Deutschland
DEEP	Desalination Economic Evaluation Program
DOE	U.S. Departement of Energy
DRB	Dispute Review Board
DSM	Demand side management
EAF	Energy Availability Factor
EC	European Commission
EDI	Electrodeionisation
EIA	Environmental Impact Assessment
EIO-LCA	economic input output LCA
EPC	Engineering, Procurement and Construction
EPR	European Pressurised Reactor
EPRI	Electric Power Research Institute
ESA	Euratom Supply Agency
EU	European Union

Abbreviation	Explanation
EU-ETS	EU Emissions Trading Scheme
F-gases	Fluorinated greenhouse gases
FANC	Federal Agency for Nuclear Control
FBR	Fast breeder reactor
FID	Final investment decision
FOAK	first-of-a-kind
FTIP	Federal Transport Infrastructure Plan
GCR	Gas cooled graphite moderated reactor
GEMIS	Global Emissions Model of Integrated Systems
GHG	Greenhouse gas
GJ	Gigajoule (measuring units for energy)
GW	Gigawatt
GWd	Gigawatt day (measuring units for energy)
HAEA	Hungarian Atomic Energy Authority
HALEU	High-Assay Low-Enriched Uranium
HEU	Highly enriched uranium
HGV	Heavy goods vehicle
HLW	High-level waste
HTGR	High temperature gas cooled reactor
HWR	Heavy water moderated reactor
IAEA	International Atomic Energy Agency
ICAO	International Civil Aviation Organization
ICE	Internal combustion engine
ILW	Intermediate-level waste
ILLW	Low- and intermediate-level waste
ISL	In-situ leaching
KNDE 2035	Klimaneutrales Stromsystem 2035 (für Deutschland)
KSBV	UBA-study Klimaschutzbeitrag des Verkehrs bis 2050 [UBA, 2016a]
kWh	Kilowatt hour
LCA	Life cycle assessment
LCC	Life cycle costing

Abbreviation	Explanation
LCOE	Levelized cost of Electricity
LCOH	Levelized costs of hydrogen
LDR	Low-temperature District Heating Reactor
LEU	Low-enriched uranium
LF	Load factor
LFS	Langfristszenarien
LHV	Lower heating value
LLW	Low-level waste
LTO	Long-term operation
LWR	Light water reactor
MED	Multi-effect distillation
MMS	Mit-Maßnahmen-Szenario
MNF	Mitsubishi Nuclear Fuel Ltd.
MoU	Memorandum of understanding
MOX	Mixed-oxide
MSF	Multi-stage flash distillation
MW	Megawatt
MWh	Megawatt hour (measuring units for energy)
MWMS	Mit-weiteren-Maßnahmen-Szenario
N_2O	Nitrous oxide (laughing gas)
NC2I	Nuclear Cogeneration Industrial Initiative
NDC	Nationally Determined Contributions (in Paris-Agreement)
NEA	Nuclear Energy Agency of the OECD
NEDC	New European Driving Cycle
NG	Natural gas
NGFS	Network for Greening the Financial System
NHR	Nuclear heating reactor
NOAK	n^{th}-of-a-kind
NPP	Nuclear power plant
NPV	Net Present Value
NRC	Nuclear Regulatory Commission
OC	Overnight costs

Abbreviation	Explanation
OCC	Overnight construction costs
OCGT	Open-cycle gas turbine
OECD	Organisation for Economic Co-operation and Development
OEF	Organization Environmental Footprint
OPEX	Operational expenditure
PB	Projektionsbericht
PEM	Proton exchange membrane
PJ	Petajoule (energy measuring unit)
PtG	Power-to-Gas (any power-based gaseous fuels)
PtL	Power-to-Liquid (any power-based liquid fuels)
PUREX	Plutonium Uranium REdoX
PV	Photovoltaics
PWR	Pressurized water reactor
RAR	Reasonably assured resources
RDE	Real Driving Emissions
RepU	Reprocessed Uranium
RES-E	Renewable energy sources - electricity
Rf	Retrofitting factor
SAF	Synthetic aviation fuels
SFR	Sodium cooled fast reactor
SMART	System-integrated modular advanced reactor
SMR	Small modular reactor
SNETP	Sustainable Nuclear Energy Technology Platform
SOEC	Solid oxide electrolyzer cell
SSC	Systems, structures and components
SWU	Separative work unit
TWh	Terawatt hours (measuring units for energy)
TWR	Traveling wave reactor
UCF	Unit Capability Factor
UCL	Unplanned Capability Loss Factor
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change

Abbreviation	Explanation
VHTR	Very high temperature reactor
VRE	Variable renewable energy
WACC	Weighted average cost of capital
WLTP	Worldwide Harmonized Light-Duty Vehicles Test Procedure
WNA	World Nuclear Association

Summary

Against the background of the global objective of achieving net zero greenhouse gas emissions by 2050, the necessary phase-out of fossil fuels, and the transformation of the energy sector, this report assesses the role of nuclear energy in this transformation process to GHG emission neutrality from several perspectives:

- The report evaluates the role of nuclear energy in global transformation scenarios modelling a future with net zero greenhouse gas emissions by 2050. This analysis is complemented by an evaluation of future plans and programmes of all countries with nuclear power plants until 2050, as well as the plans of newcomer countries that intend to operate nuclear reactors in the future. We compare top-down global net zero scenarios with bottom-up country-specific information on the role of nuclear energy and renewable energies in a climate-neutral future. This includes comparing scientific net zero scenarios and the analysis of country's plans with the pledge of 30 countries at the UN climate conferences COP 28 and COP 29 to triple nuclear capacity by 2050.
- The report analyses the requirements for future power systems with a high proportion of renewable energies. Renewable energy sources – mainly wind and solar – produce electricity intermittently, depending on weather conditions and the time of day. Flexibility is therefore required to ensure that load demands are always met. The report assesses the potential role of nuclear power in providing such flexibility in a power system dominated by renewable energy.
- In the future, the reliability of electricity production from nuclear power plants will increasingly be affected by climate change impacts such as extreme weather hazards, rising temperatures, sea level rise and changes in precipitation. The report analyses the impact of climate change on nuclear electricity generation and its likely effect on the role of nuclear energy in future energy scenarios.
- By applying harmonized environmental footprint methods, the report clarifies how nuclear energy compares to other energy technologies in terms of environmental impacts under realistic boundary conditions. To this end, the report re-evalutes the assumptions and parameters for all the key elements of the nuclear lifecycle analysis with regard to both greenhouse gas emissions and other environmental impacts. This analysis provides an updated overview and aggregation of the impacts of nuclear power plants on greenhouse gas emissions compared to other energy technologies.
- Lifecycle costs and greenhouse gas abatement costs of nuclear energy are analysed for selected regions and compared with those of renewable energies, providing an up-to-date, transparent analysis of the current costs of electricity generation from newbuilt nuclear power plants of different capacities.

Through these multiple perspectives our aim is to provide an empirically grounded, methodologically consistent, and policy-relevant assessment of the environmental and economic performance of nuclear power compared to other clean energy options.

Nuclear energy in global scenarios

Today the global situation of nuclear energy can be characterized by the following numbers: By mid-2024, 32 countries operated nuclear power plants. Global nuclear operating capacity has remained at a relatively constant level of around 370 GW over the past 25 years. In 2024, 9% of the world's electricity was generated by nuclear power This share has fallen steadily since

peaking at 17% in 1996 while total electricity generation more than doubled over the same period. By contrast, renewable energies supplied one third of global electricity in 2024, and their share continues to rise strongly across all regions in the world.

In order to achieve the climate objectives under the Paris Agreement, it is necessary to reach net-zero greenhouse gas emissions by 2050 at global level. This will require transformation of the global energy system, moving away from fossil fuels. Global energy scenarios developed by different scientific groups and international organisations project the future mix of energy generation technologies that meet the net-zero targets until the middle of this century.

This report analyses climate scenarios from five different integrated assessment models (two different climate scenarios from each model and even three scenarios from the IEA's World Energy Outlook). All scenarios in all models project a decline in the share of nuclear energy in electricity generation until 2050 compared to the present day. In the IEA's World Energy Outlook, the decline is small, in the MESSAGEix-GLOBIOM scenarios, GCAM "Net Zero by 2050" scenario and the Remind-MAgPIE scenarios the share of nuclear energy drops from the current 9% to 3-4% by 2050. In these same scenarios, renewable energies increase to between 88 and 97% by 2050. Only IEA's World Energy Outlook projects lower shares ranging from 70% to 85% depending on the scenario. Thus, in all models and scenarios, the development of renewable energies is key for achieving net-zero targets, while the role of nuclear energy remains rather limited.

Due to the projected global increase in energy consumption, constant shares of nuclear energy in electricity generation can still be underpinned by rising nuclear energy production. The analysed model results show significant variation in the projected development of total primary energy from nuclear power plants by 2050, ranging from a decline of 38% (MESSAGEix-Globiom Below 2°C scenario) to a 280% increase (IEA World Energy Outlook Net Zero by 2050 scenario) compared to today.

Modelling results also differ with regard to the development of installed nuclear capacities until 2050. While the MESSAGEix-GLOBIOM modellers project a decrease in capacities of 29-44%, the REMIND-MAgPIE modellers foresee a rather limited increase of 8-27% and GCAM modellers between 11-53%. The IEA World Energy Outlook is the exception with a very strong nuclear capacity increase by a factor of 2.7 for the "Net Zero by 2050" scenario, in contract to a growth factor of only 1.7 in the "Stated Policies" scenario which models the actual country policies.

To analyse how realistic the assumptions of these global scenarios are, a comprehensive bottom-up analysis was performed to assess countries' plans and programs regarding the decommissioning, lifetime extensions and new construction of nuclear power plants until 2050. This results in a baseline scenario and an ambitious scenario, the latter of which includes relatively optimistic plans by governments that may not be fully implemented.

According to the baseline development, nuclear capacities will increase by 9% by 2030 and by 10% by 2040, though they will decline to a level close to the current situation by 2050. In the ambitious scenario, capacities peak around 2040/2045, increasing by 38% compared to the current level. By 2050, capacities would be 24% higher than today. Therefore, even the ambitious scenario only shows a rather limited growth in nuclear capacities and will not lead to a "renaissance" of nuclear energy in global energy production.

These results contrast sharply with the 'Declaration to Triple Nuclear Energy by 2050' announced at COP 28 in Dubai by French President Emmanuel Macron and US Special Envoy for Climate John Kerry. This pledge projects a global installed nuclear capacity of 1,160 GW by 2050 and 700 GW by 2040. The declaration was signed by 30 countries, 12 of which currently do not

operate nuclear power stations. For some of these countries, such a prospect seems rather unrealistic (e.g. Jamaica, Ghana, Kosovo or Moldova). The capacity development path envisaged by this pledge far exceeds the ambitious scenario of our bottom-up analysis of country programmes worldwide, as well as the projected capacity increases in all the recent global climate scenarios analysed in this report.

Over the past ten years, between 3.4 and 10.3 GW of new net electrical nuclear capacity has become operational each year. Prior to this period, 1990 was the last year that more than 10 GW of net electrical capacity come online in a single year. The overall historic maximum was in the year 1985 with 31 GW of net electrical capacity connected to the grid.

Tripling today's nuclear capacity would require 1.160 GW of net electrical capacity to be operational by 2050 as projected by the Nuclear Energy Agency in 2023. Assuming a very high lifetime of sixty years for all nuclear reactors in operation and a linear increase in the rate of new construction up to 2050, in 2050 almost 70 GW of new nuclear capacity would need to be connected to the grid to meet the target of tripling nuclear capacity. This would be more than twice the maximum historical capacity ever connected to the grid in a single year. On average, more new capacity would need to be added every year for 25 years, as was the case at the historical maximum in 1985. Based on this comparison, it is evident, that a tripling of nuclear capacity by2050 is not realistic. Disaggregated results for key countries and regions confirm that the tripling of nuclear capacities by2050 is not in line with the real trends and is highly unlikely.

Global climate scenarios show that developing renewable energies is key to achieving the climate targets set out in the Paris Agreement, whereas nuclear energy is not essential for this objective. Even with high levels of nuclear energy production, scenarios with low shares of renewable energy miss the climate targets. Therefore, building up renewable energy is the crucial and primary driver to achieve climate targets.

There are several reasons why nuclear energy is unlikely to account for a significantly higher share of electricity production than at present despite policy shifts towards pro-nuclear parties in a number of governments:

- Levelised costs of electricity for new nuclear plants show that nuclear power is the most expensive electricity source. The significant cost advantages of wind and solar generation lead to much higher investments in renewables. According to IEA data on world energy investment in 2024, investment in renewables in China was 20 times larger than in nuclear energy; in the U.S., investment in renewables was 9 times larger than in nuclear energy and in Europe investment in renewables 7 times higher.

- In competitive electricity markets with several competing energy utilities, nuclear reactors are too expensive in relation to the total investment portfolios of the electricity companies. Construction costs for new nuclear reactors in recent years in Europe and the U.S. were between US$ 12 to 30 billion per reactor[1]. New nuclear reactors would consume large portions of the investment portfolio for a single project with high risks. Therefore, new nuclear constructions are mostly implemented by state-owned companies, as is the case in France, Russia, the United Arab Emirates, South Korea and China. In these cases, governments pay for the higher costs and take financial responsibility for the significant financial risks. However, in competitive electricity markets, companies avoid these risks.

[1] Vogtle in the U.S. US$ 37 billion for two reactors, Olkiluoto in Finland US$ 12 billion, Flamanville in France 14.6 billion, Hinkley Point C in UK is currently at 59 billion for two reactors.

- For small countries, the transaction costs and framework conditions required to build and manage nuclear plants and deal with nuclear waste are very high and difficult to provide. They need to have the legal framework in place, establish regulatory and safety authorities, have electricity grids that can integrate single large sources and ensure that trained staff with the relevant expertise are available, which mostly means relying on foreign expertise. Downtimes of nuclear plants for maintenance or due to accidents would directly impact the security of the electricity supply if a single nuclear plant would supply a large share of the electricity in the country. Small modular reactors require most of these framework conditions, but for rather small generation capacities. If countries do not yet have nuclear reactors, their governments would face much higher costs than just the nuclear plant itself.
- Most recent nuclear projects outside China have experienced cost overruns and significant delays in construction (which also increases the capital costs). Construction times for renewable energies are much shorter and costs are more predictable.
- Few countries or companies build nuclear power plants in other countries. Russia's Rosatom is the biggest nuclear supplier, with 26 units currently under construction globally. Besides Rosatom, only France's EDF and South Korea are building nuclear power stations abroad. China has only exported one nuclear plant so far, to Pakistan. U.S. and Canadian companies have not recently built reactors abroad Thus, the number of suppliers of the technology for large nuclear power plants is rather limited, and countries must choose between dependency on Russia and the high uncertainties surrounding the costs and final construction period with Western suppliers.
- Nuclear power creates strong dependencies in the supply chains because uranium mining, conversion, enrichment and fuel fabrication capacities are owned by a few major producers. An overview of countries with uranium mining does not reflect the fact that these mines may be located in Africa but are owned by French, Russian or Chinese companies.
- The security of the electricity supply from nuclear plants can decrease significantly due to safety or environmental reasons, which has affected France particularly in 2022, but also in other years. Climate change impacts, further threaten the security of supply, in particular the lack of water in summer months for cooling of nuclear reactors at rivers.

Climate change impacts on nuclear energy

Climate change itself constitutes a further limiting factor. Existing and planned nuclear installations are increasingly exposed to hydrological and thermal stress. Inland reactors located at rivers face growing risks from lack of water for cooling in summer periods, periods of reduced cooling efficiency, and regulatory discharge limits during heatwaves. This reduces the power generation and economic potential as well as reliability of supply of inland nuclear plants. Coastal sites are vulnerable to sea-level rise, extreme storm surges, coastal flooding and coastal erosion. Severe coastal flooding can lead to inundation of critical infrastructure and disruption of operations. The greatest impact of sea level rise occurs in combination with extreme storm surges, which can cause severe damage to nuclear plants, similar to the tsunami events at the Fukushima nuclear plant in Japan in 2011.

Higher water temperatures increase the risk of biofouling, accelerated growth of plants (jellyfish or clams) and algae and other microorganisms can colonize cooling water inlets and outlets and lead to clogging of water intakes.

These effects are not hypothetical. Reactor output reductions and temporary shutdowns linked to climate-induced conditions have already occurred in multiple European countries. The

operational stability of nuclear power cannot be assumed independent of climate impacts; indeed, these effects directly undermine the reliability nuclear systems claim to offer.

Climate Change impacts will influence nuclear generation in the following ways:

- The power generation potential of the existing and future reactor fleet will be reduced.
- Climate change will limit the number of suitable sites for nuclear power plants. Constructing more reactors at existing sites if often seen as the fastest option, but many of these sites will no longer be suitable because of their vulnerabilities to climate impacts.
- Adaptation measures will increase construction and operation costs of nuclear power plants. Retrofitting of older plants may become too costly if climate change risks at specific sites require significant additional protective measures against climate-related threats.

Technological and economic characteristics of nuclear power generation and requirements of a future energy system

Technological requirements of an electricity system dominated by variable renewables further constrain nuclear power's future role. The shift from base- and peak-load focussed paradigms to systems focusing on residual load and flexibility alters the valuation of dispatchable assets. Given the large unit size, long lead times, and limited technical flexibility such as start-up time or ramping capability of conventional nuclear power plants, they are structurally misaligned with demand for highly flexible units that balance load that remains after integration of intermittent RES-E generation (residual load). Even if modern reactors are able to support load-following mode, their large unit sizes and minimum load requirements make the technology a bad fit for RES-E dominated electricity systems. There is also an economic mismatch: high flexibility comes with low capacity utilization rates. Scenarios for Germany show capacity factors of 3-26% for 2035 and beyond for dispatchable units. Technologies with low capital intensity like gas turbines are best suited for such low utilization rates, while capital-intensive nuclear power generation depends on high utilization rates to recover investments. Already high levelized costs of electricity for nuclear power plants based on capacity factors of 75 % and more as assumed in this study would further significantly increase if utilization rates drop to these levels.

Role of nuclear in future energy systems

Proposed alternative use cases such as hydrogen production, district heating, and desalination do not alter this general assessment. While these applications may improve load factor economics in specific cases, they remain peripheral in scale and in some cases speculative in maturity. Especially nuclear hydrogen is consistently less cost-competitive than renewable-based electrolysis under plausible 2030 assumptions. District heating from nuclear sources is geographically constrained and socially contested. Nuclear desalination, though technically demonstrated, lacks comparative efficiency relative to advanced reverse osmosis. None of these applications supports the conclusion that nuclear can regain structural centrality within decarbonisation pathways.

The current interest in Small Modular Reactors (SMRs) is often framed as a response to the constraints of conventional large size reactor designs. SMRs promise reduced capital risk, shorter construction timelines, and improved safety profiles. However, as of 2025, no SMR design has reached commercial maturity. Cost estimates by SMR developers remain speculative and rely on volume assumptions that have not yet materialized. While SMRs may lower entry thresholds for nuclear adoption in niche contexts, they do not resolve the core constraints identified above: incompatibility in a renewable-dominated energy system and financial risks

due to decreasing capacity factors, and policy volatility. Their contribution to global mitigation efforts before 2040 is therefore likely to be negligible.

Overall nuclear energy will, at best, remain a supplementary feature in global decarbonisation efforts. Its contribution is real but bounded. The empirical data do not support the hypothesis of a global nuclear renaissance. Expansion remains regionally limited, economically constrained, and temporally misaligned with urgent mitigation timelines. The gap between modelled ambition and infrastructural reality is not closing. Any serious integration of nuclear into climate policy must account for this asymmetry—not as an argument against nuclear per se, but as a condition for realistic planning. If mitigation goals are to be met within the required timeframes, they must be pursued through deployment strategies and energy technologies that are both materially available and politically executable. Nuclear power, as currently constituted, struggles to meet either criterion.

A further finding concerns the temporal dimension of nuclear investment. With planning and construction phases exceeding a decade, and operational lifetimes of 40 to 60 years, nuclear plants commit infrastructure to environmental baselines that no longer exist. By contrast, modular and distributed renewable technologies can adapt more quickly to shifting environmental conditions, both in terms of siting and system integration.

Life cycle assessment of nuclear power

One of the central parts of this report is a comprehensive life cycle assessment (LCA) of nuclear electricity systems. The assessment covers the full structure of the nuclear fuel cycle. This approach enables a differentiated view: one that recognizes the relatively low direct emissions of nuclear operation while taking upstream and downstream burdens into account, that accumulate across mining, enrichment, reactor construction, and backend processes. The LCA is grounded in harmonized European data frameworks and operational assumptions aligned with present-day technology and regulation. It targets a pressurized water reactor (PWR)—typical for both the current worldwide nuclear fleet and units under construction.

The assessment employs the Product Environmental Footprint (PEF) method, incorporating 11 indicators across impact categories such as global warming potential, ionizing radiation, cumulative energy demand, water consumption, land use, and abiotic depletion potential. The system boundary is cradle-to-grave, covering uranium mining and milling, conversion and enrichment, fuel fabrication, plant construction, operation and maintenance, and backend activities—interim storage, reprocessing (where relevant), final conditioning, and geological disposal. No exclusion is made for infrastructure or auxiliary systems, and all impacts are allocated to the same functional unit.

The life cycle greenhouse gas emissions associated with this reference system are calculated at a range of 5 to 15 g CO_2eq/kWh for the baseline year 2020 and only marginally decline to 4.8-14.2 g CO_2eq/kWh for the projection year 2030, depending on variations in uranium sourcing, enrichment pathways and further regional impacts. This places nuclear electricity within the spectrum of low-emission technologies, on par with wind energy and significantly below natural gas or coal-fired generation.

The analysis emphasizes the embedded assumptions on which the lower end result rests: high-grade uranium ores, access to energy-efficient centrifuge enrichment, extended reactor lifetime without significant retrofitting, and the availability of a functioning backend infrastructure for interim storage and geological disposal. These parameters are not invariant. They are politically contingent, geologically finite, and in many regions, institutionally uncertain. Should ore quality decline or enrichment rely on carbon-intensive electricity the emission balance shifts

considerably. The life cycle result is thus not a feature of nuclear technology per se, but of specific infrastructural configurations under regional framework conditions.

To reflect real-world variability and system diversity, the study explicitly analyses forty distinct nuclear fuel cycle chains, each representing a different combination of supply chain parameters. These include variations in uranium origin (e.g., high-grade ores from Canada vs. low-grade sources in Africa or Kazakhstan), enrichment facilities, differences in the electricity mix used for enrichment, fuel fabrication practices, reactor performance parameters and backend strategies (e.g., with or without reprocessing). Each chain is modelled consistently using the same LCA boundary conditions, allowing for comparative analysis across the dataset.

The total GWP is typically dominated by the impact of uranium mining of up to 10.7 g CO_2eq/kWh as well as transportation in connection with uranium mining, followed by the impact of NPP infrastructure and operation with up to 5.1 g CO_2eq/kWh, enrichment with up to 3.2 g CO_2eq/kWh and conversion with up to 1.3 g CO_2eq/kWh. The other process steps contribute less than 1 g CO_2eq/kWh to the total GWP.

The resulting impact profiles exhibit considerable variation—especially in GHG emissions—underscoring that the environmental burden of nuclear power is not monolithic. Chains relying on low-grade ores and enrichment with high electricity intensity show the highest total impacts; those based on high-grade ores, enrichment with low electricity intensity and direct disposal strategies tend toward the lower end of the spectrum. These variations do not merely reflect technical diversity, but structural dependencies on global resource logistics and regional electricity intensities.

This regionalization is further operationalized through parameter sensitivity and localization exercises. The report includes explicit regional adaptations of key process steps, especially uranium mining and enrichment. Mining conditions are modelled for locations such as Australia, Canada, Niger, Kazakhstan, and Namibia, reflecting differences in ore concentration, energy inputs, and transport distances. Enrichment processes are modelled under different national grid conditions—e.g., low-carbon (France), coal-intensive (China), and mixed intensity (Russia)—to reflect actual global deployment conditions.

Within the different regions covered by the life cycle chains, the corresponding values of total GWP show a large spread compared to a standard chain. Within the European chains, total GWP may be 63-311% of a standard EU chain with 6.9 g CO_2eq/kWh. For Russia, the corresponding chains show values of 69-199% of a standard chain with 8.9 g CO_2eq/kWh, for North America 32-98% of a standard chain with 15.1 g CO_2eq/kWh, for China 62-126% of a standard chain with 11.7 g CO_2eq/kWh and for the rest of the world 58-149% compared to the Chinese standard chain.

These regional distinctions matter, they show that the environmental footprint of nuclear electricity generated in Europe or Japan may differ significantly from that of nuclear electricity in China or India, even when assuming similar reactor technology. This undermines the notion of a globally stable emissions profile for nuclear power and reinforces the need for localized assessments when comparing it to other low-carbon options.

A key structural insight of the analysis lies in the distribution and scaling of environmental impacts. While direct emissions during reactor operation are low, upstream processes—especially uranium mining and enrichment—dominate climate warming potential. Mining emissions vary strongly with ore grade: high-grade ores result in lower emissions per kWh, while the transition to lower-grade resources—likely under large-scale deployment—can significantly increase emissions. Similarly, the enrichment process may contribute heavily to the

overall impact. When based on centrifuge technology and powered by low-carbon electricity, its share in GHG emissions is modest. However, if enrichment is conducted via fossil-intensive grids, it becomes an important contributor to total CO_2 emissions in the nuclear life cycle. This reinforces the conclusion that nuclear climate performance is not autonomous—it is structurally entangled with the carbon intensity of the broader energy system.

Backend processes are also taken into account. Conditioning, storage, and disposal require long-term energy and material inputs, but their contribution to GWP is nevertheless minor. Final disposal of high-level waste in geological repositories requires a multigenerational technical infrastructure and the ongoing institutional maintenance of memory, monitoring, and security. These requirements are not merely technical but deeply political, contingent on long-term governance continuity and public trust. No comparable burdens exist in wind, solar, or other renewable systems. The LCA does not factor institutional fragility into its emissions results, but it must be noted that the backend constitutes an irreversible systems commitment.

In addition to life cycle emissions, the study discusses environmental impacts of severe accidents. These are not included in the quantitative LCA due to methodological incompatibility. While improvements in reactor design and operational procedures have lowered the likelihood of severe core damage, the systemic consequences of a major accident remain profound. The assessment shows, that the (environmental) impact of accidents in nuclear power plants do have significant impact on the overall (environmental) impact of nuclear power. An exemplary discussion shows that hundreds of thousands of people may have to be evacuated and relocated after severe accidents in nuclear power plants, the land loss due to radiologic contamination after a severe accident may increase the land loss by normal operation of nuclear power plants by a factor of 2-10 and a very large amount of low-level waste arises. The long-term contamination, social dislocation, and economic disruption following events like Chernobyl and Fukushima underline that statistical improbability does not equate to acceptable risk. Moreover, the capacity to respond to complex emergencies is not solely technical—it depends on institutional readiness and social trust. These dimensions are difficult to capture in formal risk metrics but are essential to any full-spectrum sustainability assessment.

Finally, the analysis also covers briefly the proliferation risks inherent in the nuclear fuel cycle. While civilian reactors themselves are not proliferation-prone, the supporting infrastructure—particularly enrichment and reprocessing—represents a latent dual-use risk. The diffusion of such technologies, especially in politically unstable regions or under weak safeguards, increases the difficulty of maintaining a credible and enforceable global non-proliferation regime. The report does not treat proliferation as a deterministic outcome, but rather as a structural liability that grows in proportion to the global expansion of nuclear energy systems. It must therefore be considered when evaluating the sustainability and governance costs of nuclear electricity in a global context.

Life cycle costing

Another key element of this report is the assessment of the economic costs associated with nuclear electricity generation. The methodological approach in this respect is based on the Life Cycle Costing (LCC) methodology, which calculates all monetizable costs incurred over the entire lifespan of a nuclear power system—cradle to grave—including capital investment, operational expenditure, fuel procurement as well as post-operation, decommissioning, and final disposal.

The functional unit is 1 kWh of net electrical output, consistent with the LCA approach. The aim is not to establish average or idealized cost levels, but to map the structural cost components and their variation across scenarios and boundary assumptions. We avoid industry-provided data and focus instead on publicly accessible and empirically grounded sources of recently

completed as well as ongoing construction projects, particularly from Western Europe and North America. While the recently completed construction projects form the data basis for the reference year 2020, cost estimates for the projection year 2030 are derived from the analysed ongoing construction projects. With regard to its key modelling parameters, the analysis assumes a technical lifetime of 60 years, a discount rate of 7% (used for both the interest on loans and discounting of future costs), 37% efficiency and a load factor of 75-93%.

Under these parameters, the levelized costs of electricity (LCOE) of nuclear power in 2020 range between 15.0 and 19.2 €ct/kWh for Europe and between 15.6 and 16.3 €ct for North America.

The LCC analysis reveals that the main drivers for the LCOE results are primarily the high initial investments combined with extremely long construction times, usually 10-18 years for recently completed construction projects in Europe and North America. It needs to be noted that the capital costs not only include reactor construction, but also licensing, financing, site preparation, grid integration, and insurance. The share of capital costs ranges from 80% to 85%, depending on the considered geographic region.

The costs for post-operation, decommissioning and disposal can reach considerable absolute sums and represent important factors to the total costs of nuclear energy. Before discounting, they range from 1.2 to 2.1 €ct/kWh. Nevertheless, their direct share of the LCOE is relatively low because they are incurred at a late stage in the life cycle of the plants, and discounting is applied to future costs. Within this context, however, it has to be stressed that there are significant uncertainties in estimating the end-of-life costs, and the actual expenses can vary greatly depending on the reactor type, location and regulatory framework. Furthermore, the uncertainty over future cost escalation in waste conditioning and disposal needs to be acknowledged, and the potential for cost externalization—particularly in institutional settings with weak cost recovery mechanisms—has to be highlighted as a structural problem.

The analysis contrasts nuclear LCOE with that of other technologies. The comparison clearly shows that electricity from nuclear power plants is significantly more expensive than electricity from renewable energy sources such as solar and wind energy, which usually have significantly lower LCOE values. In particular, the costs for onshore wind energy (2.4-7.7 €ct/kWh) and photovoltaics (4.6-14.8 €ct/kWh) in 2020 are in most cases significantly lower than those for nuclear power. As a result, the average value for electricity from new nuclear power plants in Europe (17 €ct/kWh) in 2020 is more than four times as high as the average value for onshore wind energy in Europe (approx. 4.2 €ct/kWh).

Looking ahead, no cost reductions are to be expected for nuclear power, as shown by the ongoing construction projects for conventional reactors in the UK. For the projection year 2030, the LCOE is expected to be between 26.1 and 36.2 €ct/kWh. Within this context, rising construction material prices (especially for concrete and steel) are important. The future prospects for SMRs are similar: if they are available at all by 2030, we expect the first plants to be built at a cost of between 19.3 and 43.9 €ct/kWh. In this respect, our analysis references the ongoing construction projects as evidence that nuclear capital costs tend to further escalate over time, not decline, especially under safety-related regulatory revisions and project-specific uncertainties. Even under stable political frameworks, the construction phase introduces systematic risks of cost overrun and delay, which translate into higher effective costs per kWh produced. In contrast, costs for renewable electricity production have already further declined compared to the baseline year 2020. Thus, for the projection year 2030 we assess global weighted average values for onshore wind energy of 2.8 €ct/kWh and 3.5 €ct/kWh for photovoltaics.

Greenhouse gas abatement costs

The GHG abatement costs in the baseline year 2020 range between 102 €/t CO_2eq and 158 €/t CO_2eq for nuclear power in Europe as well as 111 €/t CO_2eq and 121 €/t CO_2eq for North America. For wind onshore and offshore, abatement costs range between -66 and -50 €/t CO_2eq as well as -16 and 6 €/t CO_2eq, respectively, based on 5th percentile and weighted average LCOE. They are negative for both cases, which is due to the fact that in this case LCOE are lower than for the reference technology hard coal. For photovoltaics, the range of GHG abatement costs is between -38 €/t CO2eq and -29 €/t CO2eq, again based on 5th percentile and weighted average LCOE. The fact that weighted average values are close to 5th percentile values indicates that the majority of realized capacities is in the lower cost range.

For the projection year 2030, GHG abatement costs for nuclear power range between 285 €/t CO_2e and 420 €/t CO_2eq for conventional nuclear power plants in Europe as well as 196 €/t CO_2eq and 527 €/t CO_2eq for SMR in America. These high abatement costs are primarily the result of significant cost differences, given that nuclear power is generally considered to be much more expensive than coal. In comparison, the GHG abatement costs for renewables are much lower: For wind onshore and offshore, they range between -37 and -26 €/t CO_2eq as well as -13 and 18 €/t CO_2eq, respectively; photovoltaics has a range between -29 €/t CO2eq and -16 €/t CO2eq. Again, weighted average values are close to 5th percentile values meaning that new projects are very likely to be constructed in the low cost range rather than with the high costs of 95th percentile LCOE:

Therefore, it can be concluded that renewable electricity provides a cost-effective way of reducing greenhouse gas emissions already in the baseline year of 2020, especially under favourable (5th percentile) or average conditions). The same is applicable for most options in 2030. By contrast, nuclear power remains an expensive abatement option for 2020 and 2030 at both ends of the cost range. Moreover, the cost situation for nuclear power is expected to become even more unfavourable by 2030, whereas further cost reductions can be expected for renewables.

Against this background, we come to the conclusion that newly-built nuclear reactors do not exhibit economic competitiveness and hence cannot be considered a cost-effective pillar of a future-oriented, decentralised and decarbonised energy system. In particular, due to the relatively high LCOE in combination with the long construction times, new reactor projects brought online will be too expensive and too late to achieve significant and cost-effective greenhouse gas savings that could contribute to the existing climate targets. Unlike renewable energy, which benefits from short lead times and perspective cost reductions, nuclear energy remains a capital-intensive technology involving high financial risks throughout its entire lifecycle.

Zusammenfassung

Vor dem Hintergrund des weltweiten Ziels, bis 2050 Netto-Null-Treibhausgasemissionen zu erreichen, des dazu notwendigen Ausstiegs aus fossilen Brennstoffen und der Transformation des Energiesektors untersucht dieser Bericht die Rolle der Kernenergie in diesem Transformationsprozess hin zur Treibhausgasneutralität aus mehreren Perspektiven:

- Der Bericht bewertet die Rolle der Kernenergie in globalen Energieszenarien, die eine Zukunft mit Netto-Null-Treibhausgasemissionen bis 2050 modellieren. Ergänzt wird diese Analyse durch eine Bewertung der Zukunftspläne und -programme aller Länder mit Kernkraftwerken sowie der Pläne von Staaten, die in Zukunft Kernreaktoren betreiben wollen. Wir vergleichen diesen Top-Down-Ansatz der globalen Netto-Null-Szenarien mit dem Bottom-Up-Ansatz durch die länderspezifische Informationen über die geplante Rolle der Kernenergie in einer klimaneutralen Zukunft. Dies umfasst einen Vergleich wissenschaftlicher Netto-Null-Szenarien mit einer Analyse der Pläne der mehr als 30 Länder, die auf den UN-Klimakonferenzen COP 28 und COP 29 eine Zusage machten, die Kernkraftkapazität bis 2050 zu verdreifachen.
- Der Bericht analysiert die Anforderungen an zukünftige Stromsysteme mit einem hohen Anteil an erneuerbaren Energien. Erneuerbare Energiequellen – hauptsächlich Wind und Sonne – produzieren Strom intermittierend, abhängig von den Wetterbedingungen und der Tageszeit. Daher ist Flexibilität erforderlich, um sicherzustellen, dass der Lastbedarf stets gedeckt ist. Der Bericht bewertet die potenzielle Rolle der Kernenergie bei der Bereitstellung dieser Flexibilität in einem von erneuerbaren Energien dominierten Stromsystem.
- In Zukunft wird die Zuverlässigkeit der Stromerzeugung aus Kernkraftwerken zunehmend durch Auswirkungen des Klimawandels wie extreme Wetterereignisse, steigende Temperaturen, Anstieg des Meeresspiegels und Veränderungen von Niederschlägen beeinträchtigt werden. Der Bericht analysiert die Auswirkungen auf die Stromerzeugung aus Kernkraftwerken und deren voraussichtliche Auswirkungen auf die Rolle der Kernenergie in zukünftigen Energieszenarien.
- Durch die Anwendung harmonisierter Methoden zur Ermittlung des ökologischen Fußabdrucks verdeutlicht der Bericht, wie die Kernenergie im Vergleich zu anderen Energietechnologien unter realistischen Randbedingungen in Bezug auf verschiedene Umweltauswirkungen abschneidet. Zu diesem Zweck werden die Annahmen und Parameter für alle Elemente des Kernenergie-Lebenszyklus sowohl hinsichtlich der Treibhausgasemissionen als auch anderer Umweltauswirkungen neu bewertet. Die Untersuchung bietet einen aktuellen Überblick und eine Zusammenfassung der Auswirkungen der Kernenergie auf die Treibhausgasemissionen im Vergleich zu anderen Energietechnologien.
- Die Lebenszykluskosten der Kernenergie und die Kosten für die Reduzierung von Treibhausgasen werden für ausgewählte Regionen analysiert und mit denen erneuerbarer Energien verglichen, wodurch eine aktuelle, transparente Analyse der Kosten der Stromerzeugung aus neu gebauten Kernkraftwerken unterschiedlicher Leistung bereitgestellt wird.

Durch diese vielfältigen Perspektiven liefern wir eine empirisch fundierte, methodisch konsistente und politikrelevante Bewertung der ökologischen und wirtschaftlichen Leistung der Kernenergie im Vergleich zu anderen sauberen Energieoptionen.

Kernenergie in globalen Szenarien

Die globale Situation der Kernenergie wird durch die folgenden Zahlen beschrieben: Bis Mitte 2024 betrieben 32 Länder Kernkraftwerke. Die weltweite Kernkraftwerkskapazität blieb in den letzten 25 Jahren mit rund 370 GW relativ konstant. Im Jahr 2024 wurden 9% der weltweiten Elektrizität durch Kernenergie erzeugt. Dieser Anteil ist seit seinem Höchststand von 17% im Jahr 1996 stetig zurückgegangen, während sich die gesamte Stromerzeugung im gleichen Zeitraum mehr als verdoppelt hat. Im Gegensatz dazu lieferten erneuerbare Energien im Jahr 2024 ein Drittel der weltweiten Elektrizität, und ihr Anteil steigt in allen Regionen der Welt weiterhin stark an.

Um die Klimaziele des Pariser Abkommens zu erreichen, müssen die Treibhausgasemissionen bis 2050 weltweit auf netto null gesenkt werden. Dies erfordert eine Transformation des globalen Energiesystems und die Abkehr von fossilen Brennstoffen. Von verschiedenen wissenschaftlichen Gruppen und internationalen Organisationen entwickelte globale Energieszenarien prognostizieren den zukünftigen Mix an Energieerzeugungstechnologien, mit denen die Netto-Null-Ziele bis zur Mitte dieses Jahrhunderts erreicht werden können.

Dieser Bericht analysiert Szenarien aus fünf verschiedenen integrierten Bewertungsmodellen (zwei verschiedene Szenarien aus jedem Modell und drei Szenarien aus dem World Energy Outlook der IEA). Alle Szenarien in allen Modellen prognostizieren bis 2050 einen Rückgang des Anteils der Kernenergie an der Stromerzeugung im Vergleich zum heutigen Stand. Im World Energy Outlook der IEA ist der Rückgang gering, in den MESSAGEix-GLOBIOM-Szenarien, dem GCAM-Szenario „Net Zero by 2050" und den Remind-MAgPIE-Szenarien sinkt der Anteil der Kernenergie von derzeit 9% bis 2050 auf 3-4%. In denselben Szenarien steigt der Anteil erneuerbarer Energien bis 2050 auf 88 bis 97%. Nur der World Energy Outlook der IEA prognostiziert je nach Szenario geringere Anteile zwischen 70% und 85%. Somit ist in allen Modellen und Szenarien die Entwicklung erneuerbarer Energien entscheidend für die Erreichung der Netto-Null-Ziele, während die Rolle der Kernenergie eher begrenzt bleibt.

Aufgrund des prognostizierten weltweiten Anstiegs des Energieverbrauchs entsprechen konstante Anteile der Kernenergie an der Stromerzeugung einer steigenden Kernenergieproduktion. Die analysierten Szenarien zeigen erhebliche Unterschiede hinsichtlich der prognostizierten Entwicklung der Primärenergie aus Kernkraftwerken bis 2050, die von einem Rückgang um 38% (MESSAGEix-Globiom-Szenario „Below 2°C") bis zu einem Anstieg um 280% (IEA World Energy Outlook-Szenario „Net Zero by 2050") im Vergleich zu heute reichen.

Die Szenarien unterscheiden sich auch hinsichtlich der Entwicklung der installierten Kernkraftkapazitäten bis 2050. Während MESSAGEix-GLOBIOM einen Rückgang der Kapazitäten um 29-44% prognostiziert, ergibt sich bei REMIND-MAgPIE ein eher begrenzter Anstieg von 8-27% und bei GCAM ein Anstieg zwischen 11-53%. Der IEA World Energy Outlook bildet mit einem sehr starken Anstieg der Kernkraftkapazitäten um den Faktor 2,7 für das Szenario „Netto-Null bis 2050" eine Ausnahme, auch im Gegensatz zu einem Anstieg um einen Faktor von 1,7 im Szenario „Stated Policies", das die tatsächlichen Länderpolitiken modelliert.

Um zu analysieren, wie realistisch die Annahmen dieser globalen Szenarien sind, wurde eine umfassende Bottom-up-Analyse der Pläne und Programme der Länder hinsichtlich der Stilllegung, der Verlängerung der Laufzeiten und des Neubaus von Kernkraftwerken bis 2050 durchgeführt. Daraus ergeben sich ein Basisszenario und ein ambitioniertes Szenario, wobei letzteres relativ optimistische Pläne von Regierungen enthält, die möglicherweise nicht vollständig umgesetzt werden.

Im Basiszenario werden die Kernkraftkapazitäten bis 2030 um 9% und bis 2040 um 10% steigen, bis 2050 jedoch auf ein Niveau zurückgehen, das etwa den heutigen Werten entspricht.

Im ambitionierten Szenario erreichen die Kapazitäten um 2040/2045 ihren Höchststand von 38% über dem aktuellen Niveau. In 2050 würden die Kapazitäten 24% höher liegen als heute. Daher zeigt selbst das ambitionierte Szenario nur ein eher begrenztes Wachstum der Kernkraftkapazitäten und führt nicht zu einer „Renaissance" der Kernenergie in der globalen Energieerzeugung.

Diese Ergebnisse stehen in starkem Kontrast zum Ziel einer Verdreifachung der Kernenergie bis 2050, das der französische Präsident Emmanuel Macron und der US-Sonderbeauftragte für Klimafragen John Kerry auf der COP 28 in Dubai erklärt haben. Diese Erklärung sieht eine weltweit installierte Kernenergiekapazität von 700 GW bis 2040 und 1.160 GW bis 2050 vor. Die Erklärung wurde von mehr als 30 Ländern unterzeichnet, von denen allerdings 12 derzeit keine Kernkraftwerke betreiben. Für einige dieser Länder erscheint eine solche Perspektive eher unrealistisch (z. B. Jamaika, Ghana, Kosovo oder Moldawien). Der in dieser Zusage vorgesehene Weg zum Kapazitätsaufbau geht weit über das ambitionierte Szenario unserer Bottom-up-Analyse sowie über die prognostizierten Kapazitätssteigerungen in den analysierten globalen Senarien hinaus.

In den letzten zehn Jahren wurden jedes Jahr zwischen 3,4 und 10,3 GW Netto-Stromkapazitäten aus Kernenergie in Betrieb genommen. Vor diesem Zeitraum war 1990 das letzte Jahr, in dem mehr als 10 GW Netto-Stromkapazitäten in einem einzigen Jahr ans Netz gingen. Das historische Maximum von neu ans Netz angeschlossenen Kernkraftkapazitäten wurde im Jahr 1985 mit 31 GW Netto-Stromkapazitäten erreicht.

Eine Verdreifachung der heutigen Kernkraftkapazität würde laut Prognose der NEA aus dem Jahr 2023 in 2050 eine Netto-Stromkapazität von 1.160 GW erfordern. Unter der Annahme einer sehr hohen Lebensdauer von 60 Jahren für alle in Betrieb befindlichen Kernkraftwerke und einer linearen Zunahme der Neubautätigkeit bis 2050 müssten im Jahr 2050 dazu fast 70 GW neue Kapazität an das Netz angeschlossen werden. Dies wäre mehr als doppelt so viel wie bis heute maximal in einem einzigen Jahr an das Netz angeschlossen wurde. Im Durchschnitt müssten 25 Jahre lang jedes Jahr neue Kapazitäten hinzukommen, wie es beim historischen Maximum im Jahr 1985 der Fall war. Aus diesem Vergleich geht hervor, dass eine Verdreifachung der Kernkraftkapazität bis 2050 nicht realistisch ist. Die Analyse für wichtige Länder und Regionen bestätigt, dass die Verdreifachung der Kernkraftkapazitäten bis 2050 nicht den tatsächlichen Trends entspricht und höchst unwahrscheinlich ist.

Globale Klimaszenarien zeigen, dass die Entwicklung erneuerbarer Energien der Schlüssel zur Erreichung der im Pariser Abkommen festgelegten Klimaziele ist, während Kernenergie für dieses Ziel nicht wesentlich ist. Selbst bei einem hohen Anteil an Kernenergie verfehlen Szenarien mit einem geringen Anteil an erneuerbaren Energien die Klimaziele. Daher ist der Ausbau erneuerbarer Energien der entscheidende und wichtigste Faktor für die Erreichung der Klimaziele.

Es gibt mehrere Gründe, warum es unwahrscheinlich ist, dass die Kernenergie trotz der politischen Verschiebung hin zu kernkraftfreundlichen Parteien in einer Reihe von Regierungen einen deutlich höheren Anteil an der Stromerzeugung haben wird als derzeit:

- Die Stromgestehungskosten für neue Kernkraftwerke zeigen, dass Kernenergie die teuerste Stromquelle ist. Die erheblichen Kostenvorteile der Wind- und Solarenergie führen zu viel höheren Investitionen in erneuerbare Energien. Nach Angaben der IEA zu den weltweiten Energieinvestitionen im Jahr 2024 waren die Investitionen in erneuerbare Energien in China 20-mal höher als in Kernenergie, in den USA 9-mal höher und in Europa 7-mal höher.

- In wettbewerbsorientierten Strommärkten mit mehreren konkurrierenden Energieversorgern sind Kernreaktoren im Verhältnis zum gesamten Investitionsportfolio der Stromunternehmen zu teuer. Die Baukosten für neue Kernreaktoren lagen in den letzten Jahren in Europa und den USA zwischen 12 und 30 Milliarden US-Dollar pro Reaktor. Neue Kernreaktoren würden einen großen Teil des Investitionsportfolios eines Unternehmens für ein einzelnes Projekt mit hohen Risiken beanspruchen. Daher werden neue Kernkraftwerke meist von staatlichen Unternehmen gebaut, wie dies in Frankreich, Russland, den Vereinigten Arabischen Emiraten, Südkorea und China der Fall ist. In diesen Fällen übernehmen die Regierungen die höheren Kosten und die finanzielle Verantwortung für die erheblichen finanziellen Risiken. In wettbewerbsorientierten Strommärkten vermeiden Unternehmen jedoch diese Risiken.

- Für kleine Länder sind die Transaktionskosten und Rahmenbedingungen, die für den Bau und Betrieb von Kernkraftwerken sowie die Entsorgung von radioaktiven Abfällen erforderlich sind, sehr hoch und schwer zu erfüllen. Sie müssen über die entsprechenden rechtlichen Rahmenbedingungen verfügen, Aufsichts- und Sicherheitsbehörden einrichten und sicherstellen, dass geschultes Personal mit dem entsprechenden Fachwissen zur Verfügung steht, was meist bedeutet, dass sie auf ausländisches Fachwissen angewiesen sind. Auch müssen die Stromnetze einzelne große Reaktorkapazitäten integrieren können. Ausfallzeiten von Kernkraftwerken aufgrund von Wartungsarbeiten oder Unfällen würden sich direkt auf die Sicherheit der Stromversorgung auswirken, wenn ein einzelnes Kernkraftwerk einen großen Teil des Stroms im Land liefern würde. Auch für kleine, modulare Reaktoren müssen die meisten dieser Rahmenbedingungen erfüllt sein, jedoch für relativ geringe Erzeugungskapazitäten. Wenn Länder noch keine Kernreaktoren haben, würden ihre Regierungen mit viel höheren Kosten konfrontiert sein als nur denen für das Kernkraftwerk selbst.

- Die meisten aktuellen Kernkraftprojekte außerhalb Chinas haben Kostenüberschreitungen und erhebliche Verzögerungen beim Bau erfahren (was auch die Kapitalkosten erhöht). Die Bauzeiten für erneuerbare Energien sind viel kürzer und die Kosten besser vorhersehbar.

- Nur wenige Länder oder Unternehmen bauen Kernkraftwerke in anderen Ländern. Russlands Rosatom ist mit derzeit 26 im Bau befindlichen Blöcken weltweit der größte Kernkraftwerkslieferant. Neben Rosatom bauen nur die französische EDF und Südkorea Kernkraftwerke im Ausland. China hat bisher nur ein Kernkraftwerk exportiert, und zwar nach Pakistan. US-amerikanische und kanadische Unternehmen haben in letzter Zeit keine Reaktoren im Ausland gebaut. Daher ist die Zahl der Anbieter von Kernkraftwerke eher begrenzt, und die Länder müssen sich zwischen der Abhängigkeit von Russland und den hohen Unsicherheiten hinsichtlich der Kosten und der endgültigen Bauzeit bei westlichen Anbietern entscheiden.

- Die Kernenergie führt zu starken Abhängigkeiten in den Lieferketten, da die Kapazitäten für den Uranabbau, die Umwandlung, die Anreicherung und die Brennstoffherstellung sich im Besitz einiger weniger großer Produzenten befinden. Ein Überblick über die Länder mit Uranabbau spiegelt nicht die Tatsache wider, dass Minen bspw. in Afrika liegen, aber französischen, russischen oder chinesischen Unternehmen gehören.

- Die Sicherheit der Stromversorgung aus Kernkraftwerken kann aus Sicherheits- oder Umweltgründen erheblich beeinträchtigt werden, was bspw. insbesondere im Jahr 2022, aber auch in anderen Jahren Auswirkungen auf Frankreich hatte. Die Auswirkungen des

Klimawandels gefährden die Versorgungssicherheit zusätzlich, insbesondere durch den Wassermangel in den Sommermonaten für die Kühlung von Kernreaktoren an Flüssen.

Auswirkungen des Klimawandels auf die Kernenergie

Der Klimawandel selbst stellt einen weiteren begrenzenden Faktor dar. Bestehende und geplante Kernkraftwerke sind zunehmend hydrologischen und thermischen Belastungen ausgesetzt. Reaktoren im Landesinneren, die an Flüssen liegen, sind zunehmenden Risiken durch Wassermangel für die Kühlung in Sommerperioden, Perioden mit verminderter Kühlleistung und Leistungsbegrenzungen durch behördliche Auflagen während Hitzewellen ausgesetzt. Dies verringert die Stromerzeugung und das wirtschaftliche Potenzial sowie die Versorgungssicherheit. Küstenstandorte sind anfällig für den Anstieg des Meeresspiegels, extreme Sturmfluten, Küstenüberschwemmungen und Küstenerosion. Schwere Küstenüberschwemmungen können zur Überflutung wichtiger Infrastrukturen und zu Betriebsstörungen führen. Die größten Auswirkungen des Meeresspiegelanstiegs treten in Kombination mit extremen Sturmfluten auf, die schwere Schäden an Kernkraftwerken verursachen können, ähnlich wie bei den Tsunami-Ereignissen im Kernkraftwerk Fukushima in Japan im Jahr 2011.

Höhere Wassertemperaturen erhöhen das Risiko von Biofouling, beschleunigtem Wachstum von Pflanzen (Quallen oder Muscheln) und Algen sowie anderen Mikroorganismen, die sich in den Kühlwasserzuläufen und -ausläufen ansiedeln und zu einer Verstopfung der Wasserzuläufe führen können. In mehreren europäischen Ländern kam es bereits zu klimabedingten Leistungsreduzierungen und vorübergehenden Abschaltungen von Reaktoren. Die Betriebsstabilität der Kernenergie kann nicht unabhängig von den Auswirkungen des Klimawandels betrachtet werden, denn diese Auswirkungen untergraben direkt die Zuverlässigkeit, die Kernkraftwerke angeblich bieten.

Die Auswirkungen des Klimawandels werden die Kernenergieerzeugung auf folgende Weise beeinflussen:

- Das Auslastung der bestehenden und zukünftigen Reaktorflotte wird reduziert.
- Der Klimawandel wird die Anzahl geeigneter Standorte für Kernkraftwerke einschränken. Der Bau weiterer Reaktoren an bestehenden Standorten wird oft als die schnellste Option angesehen, aber viele dieser Standorte können aufgrund ihrer Anfälligkeit für Klimafolgen nicht mehr geeignet sein.
- Anpassungsmaßnahmen werden die Bau- und Betriebskosten von Kernkraftwerken erhöhen. Die Nachrüstung älterer Anlagen kann zu kostspielig werden, wenn die Risiken des Klimawandels an bestimmten Standorten erhebliche zusätzliche Schutzmaßnahmen gegen klimabedingte Gefahren erfordern.

Technologische und wirtschaftliche Merkmale der Kernenergieerzeugung und Anforderungen an ein zukünftiges Energiesystem

Die technologischen Anforderungen eines Stromsystems, das von variablen erneuerbaren Energien dominiert wird, schränken die zukünftige Rolle der Kernenergie weiter ein. Der Wandel von Paradigmen, die sich auf Grund- und Spitzenlast konzentrieren, hin zu Systemen, die sich auf Residuallast und Flexibilität konzentrieren, verändert die Bewertung von regelbaren Anlagen. Angesichts der großen Leistung, der langen Vorlaufzeiten und der begrenzten technischen Flexibilität, wie z. B. der Anlaufzeit oder der Rampenfähigkeit konventioneller Kernkraftwerke, sind diese strukturell nicht auf die Nachfrage nach hochflexiblen Anlagen abgestimmt, die die nach der Integration der intermittierenden erneuerbaren Stromerzeugung

(RES-E) verbleibende Last (Residuallast) ausgleichen. Selbst wenn moderne Reaktoren in der Lage sind, den Lastfolgebetrieb zu unterstützen, sind Kernkraftwerke aufgrund ihrer großen Leistung und Mindestlastanforderungen für RES-E-dominierte Stromsysteme ungeeignet. Hinzu kommt eine wirtschaftliche Diskrepanz: Hohe Flexibilität geht mit einer niedrigen Auslastung einher. Szenarien für Deutschland zeigen für regelbare Anlagen Auslastungen von 3 bis 26% für 2035 und darüber hinaus. Technologien mit geringer Kapitalintensität wie Gasturbinen eignen sich am besten für solche niedrigen Auslastungen, während die kapitalintensive Kernenergieerzeugung auf hohe Auslastungen angewiesen ist, um Investitionen zu amortisieren. Die bereits hohen Stromgestehungskosten für Kernkraftwerke, die typisch auf Kapazitätsfaktoren von 75% und mehr basieren, würden sich weiter deutlich erhöhen, wenn die Auslastungsraten auf dieses Niveau sinken würden.

Die Rolle der Kernenergie in zukünftigen Energiesystemen

Vorgeschlagene alternative Anwendungsfälle wie Wasserstoffproduktion, Fernwärme und Entsalzung ändern nichts an dieser allgemeinen Einschätzung. Diese Anwendungen können zwar in bestimmten Fällen die Wirtschaftlichkeit durch höhere Auslastung verbessern, bleiben jedoch in ihrem Umfang nebensächlich und sind in einigen Fällen hinsichtlich ihrer technischen Reife spekulativ. Insbesondere nuklearer Wasserstoff ist unter plausiblen Annahmen für 2030 durchweg weniger kostengünstig als die Elektrolyse auf Basis erneuerbarer Energien. Fernwärme aus nuklearen Quellen ist geografisch begrenzt und gesellschaftlich umstritten. Die nukleare Entsalzung ist zwar technisch erprobt, aber im Vergleich zur fortschrittlichen Umkehrosmose nicht effizient genug. Keine dieser Anwendungen stützt die Schlussfolgerung, dass die Kernenergie innerhalb der Dekarbonisierungsstrategien wieder eine zentrale Rolle erlangen kann.

Das derzeitige Interesse an kleinen modularen Reaktoren (SMR) wird oft als Reaktion auf die Einschränkungen herkömmlicher großer Reaktoren dargestellt. SMR versprechen ein geringeres Kapitalrisiko, kürzere Bauzeiten und erhöhte Sicherheit. Bis 2025 hat jedoch noch kein SMR-Konzept die kommerzielle Reife erreicht. Die Kostenschätzungen der SMR-Entwickler sind nach wie vor spekulativ und basieren auf Stückzahlen, die sich noch nirgends realisiert haben. SMRs mögen zwar die Einstiegshürden für die Einführung der Kernenergie in Nischenmärkten senken, aber sie lösen nicht die oben genannten zentralen Einschränkungen: Inkompatibilität in einem von erneuerbaren Energien dominierten Energiesystem und finanzielle Risiken aufgrund sinkender Auslastung und politischer Volatilität. Ihr Beitrag zu den globalen Klimaschutzbemühungen vor 2040 dürfte daher vernachlässigbar sein.

Insgesamt wird die Kernenergie bestenfalls eine ergänzende Rolle bei den weltweiten Bemühungen zur Dekarbonisierung spielen. Ihr Beitrag ist real, aber begrenzt. Die empirischen Daten stützen die Hypothese einer globalen Renaissance der Kernenergie nicht. Der Ausbau bleibt regional begrenzt, wirtschaftlich eingeschränkt und zeitlich nicht auf die dringenden Klimaschutzziele abgestimmt. Die Kluft zwischen Modellannahmen und Realität schließt sich nicht. Jede ernsthafte Integration der Kernenergie in die Klimapolitik muss dieser Asymmetrie Rechnung tragen – nicht als Argument gegen die Kernenergie an sich, sondern als Voraussetzung für eine realistische Planung. Wenn die Klimaschutzziele innerhalb der erforderlichen Zeiträume erreicht werden sollen, müssen sie durch Einsatzstrategien und Energietechnologien verfolgt werden, die sowohl materiell verfügbar als auch politisch umsetzbar sind. Die Kernenergie in ihrer derzeitigen Form hat Schwierigkeiten, diese Kriterien zu erfüllen.

Eine weitere Erkenntnis betrifft die zeitliche Dimension von Investitionen in die Kernenergie. Mit Planungs- und Bauphasen von mehr als einem Jahrzehnt und einer Betriebsdauer von 40 bis 60 Jahren binden Kernkraftwerke Infrastruktur an Umweltbedingungen, die es nicht mehr gibt.

Im Gegensatz dazu können sich modulare und dezentrale Technologien für erneuerbare Energien sowohl hinsichtlich der Standortwahl als auch der Systemintegration schneller an veränderte Umweltbedingungen anpassen.

Lebenszyklusanalyse der Kernenergie

Einer der zentralen Teile dieses Berichts ist eine umfassende Lebenszyklusanalyse (LCA) der Kernenergie. Die Bewertung umfasst den gesamten Kernbrennstoffkreislauf. Dieser Ansatz ermöglicht eine differenzierte Sichtweise: die relativ geringen direkten Emissionen des Kernkraftwerksbetriebs werden deutlich und gleichzeitig werden die vor- und nachgelagerten Belastungen berücksichtigt, die sich durch den Uranabbau, die Anreicherung, den Reaktorbau und die Entsorgungsprozesse ergeben. Die Ökobilanz basiert auf harmonisierten europäischen Datenrahmenwerken und Betriebsannahmen, die auf den aktuellen Stand der Technik und die geltenden Vorschriften abgestimmt sind. Sie bezieht sich auf einen Druckwasserreaktor (DWR), der sowohl für den aktuellen weltweiten Kernkraftwerkspark als auch für im Bau befindliche Anlagen typisch ist.

Die Bewertung erfolgt nach der Methode des Umweltfußabdruck von Produkten (PEF) unter Einbeziehung von 11 Indikatoren aus verschiedenen Wirkungskategorien wie Treibhausgaspotential, ionisierende Strahlung, kumulativer Energiebedarf, Wasserverbrauch und Landnutzung. Die Systemgrenze umfasst den gesamten Lebenszyklus, einschließlich Uranabbau und -aufbereitung, Umwandlung und Anreicherung, Brennstoffherstellung, Anlagenbau, Betrieb und Wartung sowie nachgelagerte Aktivitäten wie Zwischenlagerung, Wiederaufbereitung (sofern relevant), Konditionierung und geologische Endlagerung. Alle Auswirkungen werden derselben Funktionseinheit zugeordnet.

Die mit dem Referenzsystem verbundenen Treibhausgasemissionen werden für das Basisjahr 2020 mit 5 bis 15 g CO_2eq/kWh berechnet und sinken bis zum Prognosejahr 2030 nur geringfügig auf 4,8 bis 14,2 g CO_2eq/kWh, abhängig von Unterschieden in der der Uranbeschaffung, den Anreicherungswegen und weiteren regionalen Randbedingungen. Damit liegt die Kernenergie im Spektrum der emissionsarmen Technologien, gleichauf mit Windenergie und deutlich unter Erdgas- oder Kohlekraftwerken.

Die Analyse macht die zugrunde liegenden Randbedingungen deutlich, auf denen das niedrigere Endergebnis beruht: hochwertige Uranerze, Zugang zu energieeffizienter Zentrifugenanreicherung, verlängerte Reaktorlebensdauer ohne umfassende Nachrüstungen und die Verfügbarkeit einer funktionierenden Infrastruktur für die Zwischenlagerung und geologische Endlagerung. Diese Parameter sind nicht unveränderlich. Sie sind politisch abhängig, geologisch begrenzt und in vielen Regionen institutionell unsicher. Sollte die Erzqualität sinken oder die Anreicherung auf kohlenstoffintensivem Strom beruhen, verschiebt sich die Emissionsbilanz erheblich. Das konkrete Lebenszyklusergebnis ist somit kein Merkmal der Kerntechnik an sich, sondern spezifischer Infrastrukturkonfigurationen unter regionalen Rahmenbedingungen.

Um die Variabilität in der Praxis widerzugeben, analysiert die Studie vierzig verschiedene Lebenszyklusketten, die jeweils eine unterschiedliche Kombination von Lieferkettenparametern wiedergeben. Dazu gehören Variationen hinsichtlich der Herkunft des Urans (z. B. hochgradige Erze aus Kanada gegenüber Quellen in Afrika oder Kasachstan mit geringen Erzgehalten), Unterschiede im für die Anreicherung verwendeten Strommix, Parameter des Reaktorbetriebs und Strategien für die Endlagerung (z. B. mit oder ohne Wiederaufbereitung). Jede Kette wird unter Verwendung derselben methodischen Randbedingungen modelliert, was eine vergleichende Analyse ermöglicht.

Die gesamten Treibhausgasemissionen werden in der Regel durch die Auswirkungen des Uranabbaus mit bis zu 10,7 g CO_2eq/kWh sowie den Transport im Zusammenhang mit dem Uranabbau dominiert, gefolgt von den Auswirkungen der Infrastruktur und des Betriebs von Kernkraftwerken mit bis zu 5,1 g CO_2eq/kWh, der Anreicherung mit bis zu 3,2 g CO_2eq/kWh und der Umwandlung mit bis zu 1,3 g CO_2eq/kWh. Die anderen Prozessschritte tragen weniger als 1 g CO_2eq/kWh zu den gesamten Treibhausgasemissionen bei.

Die sich daraus ergebenden Ketten weisen erhebliche Unterschiede auf – insbesondere bei den Treibhausgasemissionen –, was unterstreicht, dass die Umweltbelastung durch Kernenergie nicht einheitlich ist. Ketten, die auf minderwertigen Erzen und einer Anreicherung mit hohem Stromverbrauch basieren, weisen die höchsten Gesamtbelastungen auf; diejenigen, die auf hochwertigen Erzen, einer Anreicherung mit geringem Stromverbrauch und direkten Entsorgungsstrategien basieren, tendieren zum unteren Ende des Spektrums. Diese Unterschiede spiegeln nicht nur die technische Vielfalt wider, sondern auch strukturelle Abhängigkeiten von der globalen Ressourcenlogistik und regionalen Treibhausgasintensitäten der Stromerzeugung.

Die Regionalisierung wird durch Parameteranpassungen und Sensitivitätsanalysen weiter operationalisiert. Der Bericht enthält explizite regionale Anpassungen wichtiger Prozessschritte, insbesondere des Uranabbaus und der Urananreicherung. Die Abbaubedingungen werden für Standorte wie Australien, Kanada, Niger, Kasachstan und Namibia modelliert, wobei Unterschiede in der Erzkonzentration, dem Energieaufwand und den Transportentfernungen berücksichtigt werden. Die Anreicherungsprozesse werden unter verschiedenen nationalen Bedingungen modelliert – z. B. kohlenstoffarm (Frankreich), kohleintensiv (China) und gemischte Intensität (Russland) –, um die tatsächlichen globalen Einsatzbedingungen widerzuspiegeln.

Innerhalb der verschiedenen Regionen, die von den Lebenszyklusketten abgedeckt werden, weisen die Werte der Treibhausgasemissionen verschiedener Ketten im Vergleich zu einer Standardkette eine große Streuung auf. Innerhalb der europäischen Ketten können die Treibhausgasemissionen 63–311% einer Standard-EU-Kette mit 6,9 g CO_2eq/kWh betragen. Für Russland zeigen die entsprechenden Ketten Werte von 69–199% einer Standardkette mit 8,9 g CO_2eq/kWh, für Nordamerika 32 bis 98% einer Standardkette mit 15,1 g CO_2 eq/kWh, für China 62 bis 126% einer Standardkette mit 11,7 g CO_2 eq/kWh und für den Rest der Welt 58 bis 149 % im Vergleich zur chinesischen Standardkette.

Diese regionalen Unterschiede sind von Bedeutung, da sie zeigen, dass sich die Umweltbilanz der Kernenergie in Europa oder Japan erheblich von derjenigen in China oder Indien unterscheiden kann, selbst wenn man von einer ähnlichen Reaktortechnologie ausgeht. Dies unterstreicht die Notwendigkeit lokaler Bewertungen beim Vergleich mit anderen kohlenstoffarmen Optionen.

Eine wichtige strukturelle Erkenntnis der Analyse liegt in der Verteilung und Skalierung der Umweltauswirkungen. Während die direkten Emissionen während des Reaktorbetriebs gering sind, dominieren vorgelagerte Prozesse – insbesondere der Uranabbau und die Urananreicherung – die Treibhausgasemissionen. Die Emissionen aus dem Bergbau variieren stark je nach Erzgehalt: Hochgradige Erze führen zu geringeren Emissionen pro kWh, während der Übergang zu minderwertigeren Ressourcen – wahrscheinlich bei großflächigem Einsatz – die Emissionen erheblich erhöhen kann. In ähnlicher Weise kann der Anreicherungsprozess erheblich zu den Gesamtauswirkungen beitragen. Basierend auf Zentrifugentechnologie und mit kohlenstoffarmem Strom betrieben, ist ihr Anteil an den Treibhausgasemissionen gering. Wenn die Anreicherung jedoch über Strom mit einem hohen Anteil fossiler Brennstoffe erfolgt, wird

sie zu einem wichtigen Faktor für die gesamten Treibhausgasemissionen im Lebenszyklus der Kernenergie. Dies untermauert die Schlussfolgerung, dass die Klimabilanz der Kernenergie strukturell mit der Kohlenstoffintensität des gesamten Energiesystems verflochten ist.

Auch nachgelagerte Prozesse werden berücksichtigt. Die Konditionierung, Lagerung und Entsorgung erfordern langfristige Energie- und Materialeinsätze, ihr absoluter Beitrag den Treibhausgasemissionen ist jedoch gering. Die Endlagerung hochradioaktiver Abfälle in geologischen Endlagern erfordert eine generationenübergreifende technische Infrastruktur und die kontinuierliche institutionelle Aufrechterhaltung von Erinnerung, Überwachung und Sicherheit. Diese Anforderungen sind nicht nur technischer, sondern auch zutiefst politischer Natur und hängen von einer langfristigen staatlichen Kontinuität und dem Vertrauen der Öffentlichkeit ab. Bei Wind-, Solar- oder anderen erneuerbaren Systemen gibt es keine vergleichbaren Belastungen. Die Ökobilanz berücksichtigt die institutionellen Unsicherheiten nicht, aber es muss beachtet werden, dass aus dem Anfall radioaktiver Abfälle eine langfristige und irreversible Systembindung entsteht.

Zusätzlich zu den Lebenszyklusemissionen diskutiert die Studie die Umweltauswirkungen schwerer Unfälle. Diese sind aufgrund methodischer Inkompatibilität nicht in der quantitativen LCA enthalten. Obwohl stetige Verbesserungen von Reaktorkonzepten und Betriebsweisen die grundlegende Wahrscheinlichkeit schwerer Unfälle verringert haben, bleiben die systemischen Folgen eines schweren Unfalls gravierend. Die Bewertung zeigt, dass die (Umwelt-)Auswirkungen von Unfällen in Kernkraftwerken einen erheblichen Einfluss auf die gesamten (Umwelt-)Auswirkungen der Kernenergie haben. Eine beispielhafte Diskussion zeigt, dass nach schweren Unfällen möglicherweise Hunderttausende Menschen evakuiert und umgesiedelt werden müssen, dass der Landverlust aufgrund radioaktiver Kontamination den Landverlust durch den normalen Betrieb von Kernkraftwerken um einen Faktor 2 bis 10 erhöhen kann und dass sehr große Mengen an schwach radioaktiven Abfällen anfällt. Die langfristige Kontamination, die sozialen Verwerfungen und die wirtschaftlichen Störungen nach Ereignissen wie Tschernobyl und Fukushima unterstreichen, dass statistische Unwahrscheinlichkeit nicht gleichbedeutend mit einem akzeptablen Risiko ist. Darüber hinaus ist die Fähigkeit, auf komplexe Notfälle zu reagieren, nicht nur eine technische Frage, sondern hängt auch von der institutionellen Bereitschaft und dem sozialen Vertrauen ab. Diese Dimensionen lassen sich nur schwer in formalen Risikokennzahlen erfassen, sind jedoch für eine umfassende Nachhaltigkeitsbewertung unerlässlich.

Schließlich befasst sich die Analyse auch kurz mit den Proliferationsrisiken des Kernbrennstoffkreislaufs. Während zivile Reaktoren selbst nicht proliferationsanfällig sind, stellt die unterstützende Infrastruktur – insbesondere die Anreicherung und Wiederaufbereitung – ein latentes Risiko für die nukleare Nichtverbreitung dar. Die Verbreitung solcher Technologien, insbesondere in politisch instabilen Regionen oder unter schwachen Sicherheitsvorkehrungen, erschwert die Aufrechterhaltung eines glaubwürdigen und durchsetzbaren globalen Nichtverbreitungsregimes. Der Bericht behandelt die Proliferation nicht als deterministisches Ergebnis, sondern als strukturelles Risiko, das sich proportional zur globalen Nutzung der Kernenergie verhält. Es muss daher bei der Bewertung der Nachhaltigkeit der Kernenergie im globalen Kontext berücksichtigt werden.

Lebenszykluskosten

Ein weiteres Schlüsselelement dieses Berichts ist die Bewertung der mit der Kernenergie verbundenen wirtschaftlichen Kosten. Der methodische Ansatz basiert dabei auf der Lebenszykluskostenrechnung (LCC), die alle monetarisierbaren Kosten berechnet, die über die gesamte Lebensdauer eines Kernkraftwerks entstehen – vom Bau bis zur Stilllegung –,

einschließlich Kapitalinvestitionen, Betriebsausgaben, Brennstoffbeschaffung sowie Nachbetrieb, Stilllegung und Endlagerung.

Die Funktionseinheit ist 1 kWh Netto-Stromleistung, entsprechend den LCA-Analysen. Das Ziel besteht nicht darin, durchschnittliche oder idealisierte Kosten zu ermitteln, sondern die strukturellen Kostenkomponenten und ihre Variation über verschiedene Szenarien und Randbedingungen hinweg abzubilden. Wir vermeiden von der Industrie bereitgestellte Daten und konzentrieren uns stattdessen auf öffentlich zugängliche und empirisch fundierte Quellen zu kürzlich abgeschlossenen sowie laufenden Bauprojekten, insbesondere aus Westeuropa und Nordamerika. Während die kürzlich abgeschlossenen Bauprojekte die Datenbasis für das Referenzjahr 2020 bilden, werden die Kostenschätzungen für das Prognosejahr 2030 aus den analysierten laufenden Bauprojekten abgeleitet. Hinsichtlich der wichtigsten Modellierungsparameter geht die Analyse von einer technischen Lebensdauer von 60 Jahren, einem Diskontsatz von 7% (sowohl für die Zinsen auf Darlehen als auch für die Diskontierung zukünftiger Kosten), einem Kraftwerks-Wirkungsgrad von 37% und einer Auslastung von 75-93% aus.

Mit diesen Parametern liegen die Stromgestehungskosten (LCOE) der Kernenergie im Jahr 2020 zwischen 15,0 und 19,2 €ct/kWh für Europa und zwischen 15,6 und 16,3 €ct für Nordamerika.

Die Analyse zeigt, dass die Hauptfaktoren für die LCOE in erster Linie die hohen Anfangsinvestitionen in Verbindung mit extrem langen Bauzeiten sind, die in der Regel 10 bis 18 Jahre für kürzlich fertiggestellte Bauprojekte in Europa und Nordamerika betragen. Es ist zu beachten, dass die Kapitalkosten nicht nur den Bau des Reaktors, sondern auch die Genehmigung, Finanzierung, Standortvorbereitung, Netzintegration und Versicherung umfassen. Der Anteil der Kapitalkosten an den LCOE liegt je nach betrachteter geografischer Region zwischen 80% und 85%.

Die Kosten für den Nachbetrieb, die Stilllegung und die Entsorgung können beträchtliche absolute Summen erreichen und stellen wichtige Faktoren für die Gesamtkosten der Kernenergie dar. Vor der Diskontierung liegen sie zwischen 1,2 und 2,1 €ct/kWh. Dennoch ist ihr direkter Anteil an den LCOE relativ gering, da sie in einer späten Phase des Lebenszyklus der Anlagen anfallen und eine Diskontierung auf zukünftige Kosten angewendet wird. In diesem Zusammenhang muss jedoch betont werden, dass die Schätzung der Kosten am Ende der Lebensdauer mit erheblichen Unsicherheiten behaftet ist und die tatsächlichen Ausgaben je nach Reaktortyp, Standort und regulatorischem Rahmen stark variieren können. Darüber hinaus muss die Unsicherheit hinsichtlich künftiger Kostensteigerungen bei der Abfallkonditionierung und -entsorgung anerkannt und die Gefahr einer Externalisierung der Kosten – insbesondere in institutionellen Umgebungen mit schwachen Kostendeckungsmechanismen – als strukturelles Problem hervorgehoben werden.

Die Analyse vergleicht die Stromgestehungskosten der Kernenergie mit derjenigen anderer Technologien. Der Vergleich zeigt deutlich, dass Strom aus Kernkraftwerken deutlich teurer ist als Strom aus erneuerbaren Energiequellen wie Solar- und Windenergie, die in der Regel deutlich niedrigere LCOE-Werte aufweisen. Insbesondere die Kosten für Onshore-Windenergie (2,4-7,7 €ct/kWh) und Photovoltaik (4,6-14,8 €ct/kWh) im Jahr 2020 sind in den meisten Fällen deutlich niedriger als die für Kernenergie. Der Durchschnittswert für Strom aus neuen Kernkraftwerken in Europa (17 €ct/kWh) im Jahr 2020 mehr als viermal so hoch wie der Durchschnittswert für Onshore-Windenergie in Europa (ca. 4,2 €ct/kWh).

Mit Blick auf die Zukunft sind keine Kostensenkungen für die Kernenergie zu erwarten, wie laufenden Bauprojekte im Vereinigten Königreich zeigen. Für das Prognosejahr 2030 wird ein LCOE zwischen 26,1 und 36,2 €ct/kWh erwartet. In diesem Zusammenhang sind steigende

Preise für Baumaterialien (insbesondere für Beton und Stahl) von Bedeutung. Die Zukunftsaussichten für SMRs sind ähnlich: Wenn sie bis 2030 überhaupt verfügbar sind, erwarten wir, dass die ersten Anlagen zu Kosten zwischen 19,3 und 43,9 €ct/kWh gebaut werden. In diesem Zusammenhang verweist unsere Analyse auf die laufenden Bauprojekte als Beleg dafür, dass die Kapitalkosten für Kernkraftwerke im Laufe der Zeit tendenziell weiter steigen und nicht sinken, insbesondere angesichts potenziell weiter steigender Sicherheitsanforderungen und projektspezifischer Unsicherheiten. Selbst unter stabilen politischen Rahmenbedingungen birgt die Bauphase systematische Risiken von Kostenüberschreitungen und Verzögerungen, die sich in höheren effektiven Kosten pro erzeugter kWh niederschlagen. Im Gegensatz dazu sind die Kosten für die Stromerzeugung aus erneuerbaren Energien im Vergleich zum Basisjahr 2020 bereits weiter gesunken. Für das Prognosejahr 2030 schätzen wir daher die globalen gewichteten Durchschnittswerte für Onshore-Windenergie auf 2,8 €ct/kWh und für Photovoltaik auf 3,5 €ct/kWh.

Kosten für die Reduzierung von Treibhausgasen

Die Vermeidungskosten für Treibhausgase im Basisjahr 2020 liegen für Kernkraft in Europa zwischen 102 €/t CO_2eq und 158 €/t CO_2eq sowie für Nordamerika zwischen 111 €/t CO_2eq und 121 €/t CO_2eq. Für Onshore- und Offshore-Windenergie liegen die Vermeidungskosten zwischen -66 und -50 €/t CO_2eq bzw. zwischen -16 und 6 €/t CO_2eq, basierend auf dem 5ten Perzentil und den gewichteten durchschnittlichen LCOE. In beiden Fällen sind sie überwiegend negativ, was darauf zurückzuführen ist, dass die LCOE in diesem Fall niedriger sind als für die Referenztechnologie Steinkohle. Für Photovoltaik liegen die Kosten für die Reduzierung von Treibhausgasen zwischen -38 €/t CO_2eq und -29 €/t CO_2eq, wiederum basierend auf dem 5ten Perzentil und den gewichteten durchschnittlichen LCOE. Die Tatsache, dass die gewichteten Durchschnittswerte nahe am 5ten Perzentil liegen, deutet darauf hin, dass der Großteil der realisierten Kapazitäten im unteren Kostenbereich liegt.

Für das Prognosejahr 2030 liegen die Vermeidungskosten bei der Kernenergie zwischen 285 €/t CO_2eq und 420 €/t CO_2eq für konventionelle Kernkraftwerke in Europa sowie zwischen 196 €/t CO_2eq und 527 €/t CO_2eq für SMR in Amerika. Im Vergleich dazu sind die Vermeidungskosten bei erneuerbaren Energien wesentlich geringer: Für Onshore- und Offshore-Windenergie liegen sie zwischen -37 und -26 €/t CO_2eq bzw. zwischen -13 und 18 €/t CO_2eq; für Photovoltaik liegen sie zwischen -29 €/t CO_2eq und -16 €/t CO_2eq. Auch hier liegen die gewichteten Durchschnittswerte nahe den Werten des 5ten Perzentils, was bedeutet, dass neue Projekte sehr wahrscheinlich im niedrigen Kostenbereich und nicht mit den hohen Kosten des 95ten Perzentils der Stromgestehungskosten gebaut werden:

Daraus lässt sich schließen, dass erneuerbare Energien bereits im Basisjahr 2020 eine kostengünstige Möglichkeit zur Reduzierung der Treibhausgasemissionen darstellen, insbesondere unter günstigen (5. Perzentil) oder durchschnittlichen Bedingungen. Das Gleiche gilt für die meisten Optionen im Jahr 2030. Im Gegensatz dazu bleibt die Kernenergie sowohl für 2020 als auch für 2030 an beiden Enden der Kostenskala eine teure Vermeidungsoption. Darüber hinaus wird sich die Kostensituation für die Kernenergie bis 2030 voraussichtlich noch weiter verschlechtern, während für erneuerbare Energien weitere Kostensenkungen zu erwarten sind.

Vor diesem Hintergrund kommen wir zu dem Schluss, dass neu gebaute Kernreaktoren keine wirtschaftliche Wettbewerbsfähigkeit aufweisen und daher nicht als kosteneffiziente Säule eines zukunftsorientierten, dezentralen und dekarbonisierten Energiesystems angesehen werden können. Insbesondere aufgrund der relativ hohen Stromgestehungskosten in Verbindung mit den langen Bauzeiten werden neue Reaktorprojekte zu teuer sein und zu spät bereitstehen, um

signifikante und kosteneffiziente Treibhausgaseinsparungen zu erzielen, die zu den bestehenden Klimazielen beitragen könnten. Im Gegensatz zu erneuerbaren Energien, die von kurzen Vorlaufzeiten und perspektivischen Kostensenkungen profitieren, bleibt die Kernenergie eine kapitalintensive Technologie, die während ihres gesamten Lebenszyklus mit hohen finanziellen Risiken verbunden ist.

1 Introduction

Against the background of the global objective of achieving net zero greenhouse gas emissions by 2050, the necessary phase-out of fossil fuels, and the transformation of the energy sector, this report assesses the role of nuclear energy in this transformation process to GHG emission neutrality from several perspectives.

To this end, we will first discuss the future role of nuclear energy as it results from global energy scenarios that represent the wide range of assumptions about the development of nuclear energy that can be observed in the current literature, see chapter 2. The outcome of global energy scenarios will be compared with a bottom-up analysis of the existing fleet of nuclear power plants (NPPs) and national programs for the future development of nuclear power up to the year 2050, which results in a baseline scenario and an ambitious scenario, the latter of which includes relatively optimistic plans by governments that may not be fully implemented. Results are put into perspective by comparing the expected future use of nuclear power with that of renewable electricity production and the claims made by some states to triple nuclear power production. For the long-term use of nuclear power plants, climate impact has to be taken into account, compare section 2.8. Finally, the possible role of nuclear power in future energy systems from a system perspective is discussed in section 2.9, addressing the technical flexibility of nuclear power plants to meet future needs for intermittent residual electricity demand, options to at least partly decouple it from intermittent residual electricity demand and constraints given by relatively high realization times of nuclear power compared to other energy technologies.

To evaluate the role of nuclear power with respect to combating climate change, we perform a detailed analysis of the environmental impact of nuclear power from a life cycle perspective, see chapter 3. The assessment employs the Product Environmental Footprint (PEF) method, incorporating 11 indicators across different impact categories such as global warming potential. The system boundary is cradle-to-grave, covering uranium mining and milling, conversion and enrichment, fuel fabrication, plant construction, operation and maintenance, and backend activities. After a short description of the nuclear life cycle and the methodology used in this study, we describe in detail the different steps in the nuclear life cycle chain starting from mining up to final disposal of wastes. Overall results of this life cycle analysis (LCA) are discussed in section 3.12 with a clear focus on the global warming potential (GWP) of nuclear power. As there are aspects related to the life cycle of nuclear power that are not sufficiently covered by current LCA methodology, we discuss such aspects exemplarily on a qualitative as well as partially quantitave basis in section 3.13 for severe accidents in nuclear power plants and in section 3.14 for proliferation aspects related to the nuclear fuel cycle on a qualitative basis. Full details on the results of our LCA are given in Appendix B and C.

As is commonly accepted and can be confirmed by the results of our study, the GWP of nuclear power(5 to 15 g CO_2eq/kWh for the baseline year 2020) is low compared with the use of fossil fuels for electricity production and has a similar GWP as renewable electricity production technologies (approx. 10 g CO_2eq/kWh for wind and 50 g CO_2eq/kWh for photovoltaics). Besides the actual GWP of nuclear power, it is therefore of particular importance, whether the use of nuclear power is a cost-effective means to replace current fossil fuelled technologies. In chapter 4 we will therefore analyse the cost of producing electricity with nuclear power by means of a life cycle costing (LCC) approach. After discussing basic principles and key parameters and data used in our analysis, results of our analysis are presented in section 4.3. Based on the levelized cost of electricity (LCOE) calculated, in a second step in section 4.4 we estimate greenhouse gas abatements costs that would result from replacing current fossil

fuelled production by nuclear power based on the results of our estimation of GWP and compare these numbers with renewable technologies. Overall results are discussed in section 4.5.

2 Analysis of scenarios on the future role of nuclear energy

2.1 Introduction

This section analyses the role of nuclear energy in a future global energy system that is consistent with the international climate objective under the Paris Agreement to limit global warming to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C. For this purpose, it is necessary to reach net-zero greenhouse gas emissions by 2050 at global level. Several scientific groups and international organisations developed integrated assessment models that can project the future mix of energy generation technologies that enable the achievement of such GHG emission reduction until the middle of this century.

Such global energy scenarios vary significantly in terms of the future role of nuclear energy, with some scenarios projecting a (varying degree of) increase of the share of nuclear electricity generation while others depict a constant nuclear share or even a phase out of nuclear energy in the future.

The major task in this work package is to analyse the role of nuclear energy in global scenarios on the one hand and compare them on the other hand to nuclear energy in plans and programs of governments around the world. While global energy models might calculate an expansion of nuclear energy in a top down approach based on the numerical parameters of the model, a government's plan will take other factors into account, such as the real world economic and political conditions for nuclear energy in the country in question.

The purpose of this analysis is to assess how realistic the global scenarios regarding nuclear power are, and what role nuclear energy plays in achieving the climate targets in the scenarios analysed. The role of nuclear energy is also being compared to the role of renewable energy sources in global scenarios.

The original analysis was conducted in 2023/2024 based on scenarios released at the end of 2022. This analysis was complemented by an assessment of updated scenarios published in autumn 2024 which is presented in section 2.2.3.

2.2 Comparison of global energy scenarios

2.2.1 Scenario selection

In this work package global energy scenarios, that picture a global energy system with low greenhouse gas emissions by the middle of the century, are analysed based on current studies and publications. A particular focus here is on the role of nuclear energy. The role of renewable energies in the scenarios is also discussed.

The scenarios considered must represent the wide range of assumptions about the development of nuclear energy that can be observed in the current literature and fulfil certain criteria in order to fit within the scope of this analysis and ensure comparability across scenarios:

1. time range until 2050;
2. data are published in tabular form or can be provided by the organisation in tabular form;
3. data on primary energy use (total, nuclear energy, renewables by individual technologies) and final energy consumption must be available;
4. data on electricity generation (total, nuclear energy, renewables by individual technologies) and the development of electricity consumption available;

5. capacity development (nuclear energy, renewables by individual technologies) available;
6. regional disaggregation of the data and disaggregation for important countries and regions (e.g. USA, Russia, China, Europe, India) available;
7. key assumptions such as population development, economic growth and energy prices published;
8. assumed costs of generation technologies and their differentiation over time available;
9. timeliness (publication date) of the scenarios and last base year of real values;
10. free access to the reports.

Scenarios that represent a suitable selection for this task are the various scenarios published by the "Network for Greening the Financial System (NGFS)" in September 2022 (Network for Greening the Financial System [NGFS], 2022) which have been repeatedly updated, most recently in 2024 (Richterss et al., 2024). These scenarios were developed for central banks and financial supervisory institutions in a modelling alliance between Potsdam Institute for Climate Impact Research (PIK) (using the REMIND-MAgPIE), the International Institute for Applied Systems Analysis (IIASA) (using the MESSAGEix-GLOBIOM model), the Joint Global Change Research Institute (JGCRI), USA (using the GCAM model), Climate Analytics and the National Institute of Economic and Social Research (NIESR). The three different models used in these projections are scientific integrated assessment models which are also regularly used in the IPCC Assessment Reports.

The three models use nuclear energy to very different extents. Out of the six storylines in this project, which were each modelled using these three different models, this analysis focuses on the “Net Zero” and the “Divergent Net Zero” storylines, both of which achieve the 1.5°C target. The present analysis also includes two additional scenarios with a phase-out of nuclear energy by 2050 (Teske, 2019), one achieving the 1.5°C target and the other achieving a 2°C global mean temperature rise.

As an important international reference, three scenarios from the IEA’s World Energy Outlook (International Energy Agency [IEA], 2022) are also included: one that achieves the 1.5°C target ("Net Zero by 2050") and two scenarios ("Stated Policies" and "Announced Pledges") that fall short of the 1.5°C target to varying degrees. The most recent update of the World Energy Outlook (IEA, 2024) is also taken into account.

Although the detailed analysis in this work package was conducted on the basis of the scenarios presented in (NGFS, 2022), (IEA, 2022)and (Teske, 2019), sections 2.2.3, 2.6 and 2.7 also review and discuss the results in the context of the more recent 2024 scenarios (Richterss et al., 2024), (IEA, 2024).

Other scenarios in the literature feature high shares of nuclear energy but fall short of achieving the climate targets, like the three scenarios of the World Energy Council (World Energy Council [WEC], 2019) or the developments presented by the U.S. Energy Information Administration in their “International Energy Outlooks” (U.S. Energy Information Administration [eia], 2021).

2.2.2 Comparison of global parameters between scenarios

In 2023, 9% of the world's electricity was generated by nuclear energy. This share has fallen steadily since peaking at 17% in 1996 (Energy Institute, 2024). In comparison, renewable energies already supplied one third of global electricity in 2023, and their share continues to rise. By mid-2024, 32 countries operated nuclear power plants, in the EU 12 out of 27 Member States have nuclear reactors. Nuclear operating capacity has remained at a relatively constant level of around 370 GW in the past 25 years with a drop of capacity after the Fukushima accident in 2011. From this starting point we analyse the future projections until 2050.

Figure 1 shows the development of global CO_2 emissions in the scenarios analysed. All scenarios, besides the IEA's World Energy Outlook "Stated Policies", decrease CO_2 emissions by 2050 significantly and reach a climate target compatible with the Paris Agreement to varying degrees as this was the intent of the scenario development.

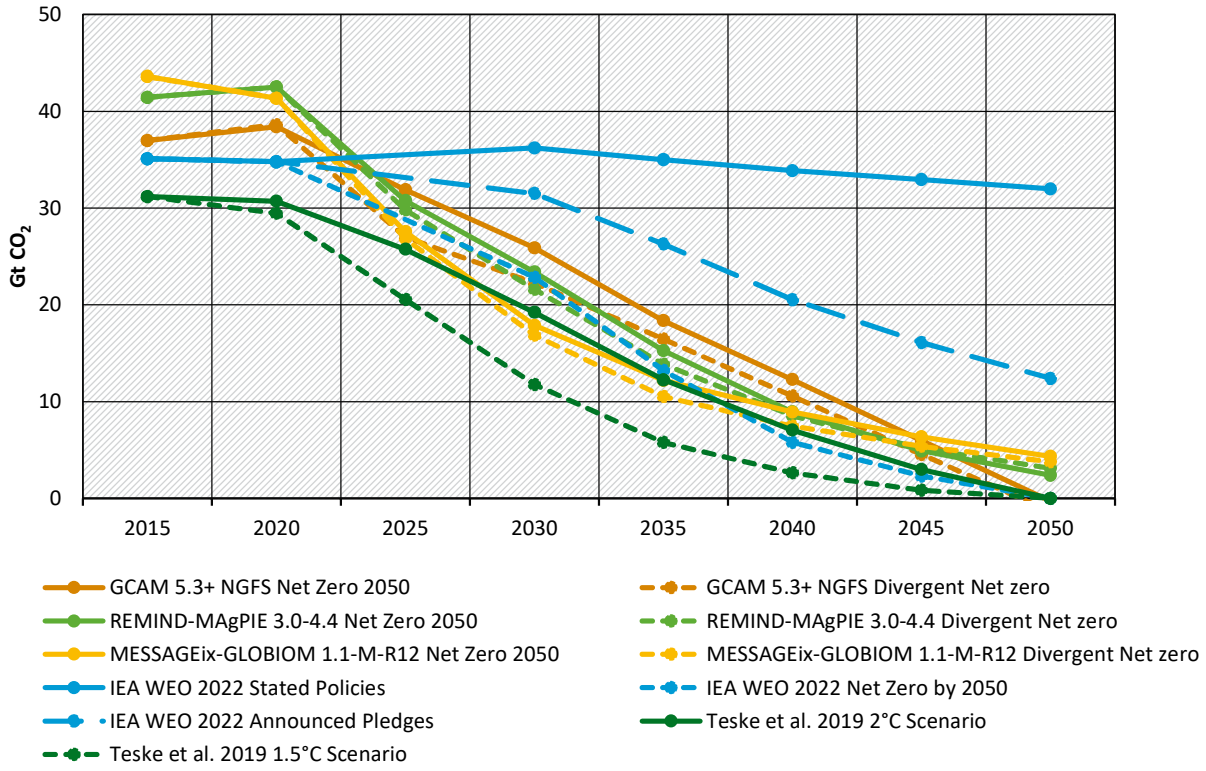
The Net Zero 2050 and the Divergent Net Zero storylines of the six scientific scenarios (NGFS, 2022) both limit global warming to 1.5°C and reach net zero emissions around 2050. The Net Zero 2050 storyline envisages stringent climate policies and innovation and represents a more "orderly" development of the world while the Divergent Net Zero (more "disorderly") storyline comes with higher costs due to divergent policies introduced across sectors leading to a quicker phase out of oil use.

The two scenarios of (Teske, 2019) achieve the 1.5°C and 2°C target respectively. Both scenarios are normatively limited with emission budgets that can't be exceeded. According to the authors they are described like this: "The 2.0°C Scenario represents a far more likely pathway than the 1.5°C Scenario, because the 2.0°C case takes into account unavoidable delays due to political, economic, and societal processes and stakeholders. (…) The 1.5°C Scenario requires immediate action to realize all available options. It is a technical pathway, not a political prognosis. It refers to technically possible measures and options without taking into account societal risks or barriers. Efficiency and renewable potentials must be deployed even more quickly than in the 2.0°C Scenario. Furthermore, avoiding inefficient technologies and behaviours are essential strategies for developing regions in this time period."

The IEA's "Net Zero by 2050" scenario, as outlined in the World Energy Outlook, also limits the increase in global temperature to 1.5°C. It is described as "based on the deployment of a wide portfolio of clean energy technologies, with decisions about deployment driven by costs, technology maturity, market conditions and policy preferences. The pathway reflects the particular circumstances of various countries in terms of resource and infrastructure endowments, development pathways and policy preferences." (IEA, 2022).

The IEA's "Announced Pledges" scenario would result in a projected global median temperature rise in 2100 of around 1.7°C. The "Stated Policies" scenario fails to reach the climate targets: It would result in a global median temperature rise of 2.5°C in 2100.

Figure 1: CO_2 emissions (world) in the scenarios analysed



Different starting points stem presumably from different data sources used for global CO_2 emissions and different points in time when the data sources for global emissions were consulted.
Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022); own illustration, Öko-Institut e.V.

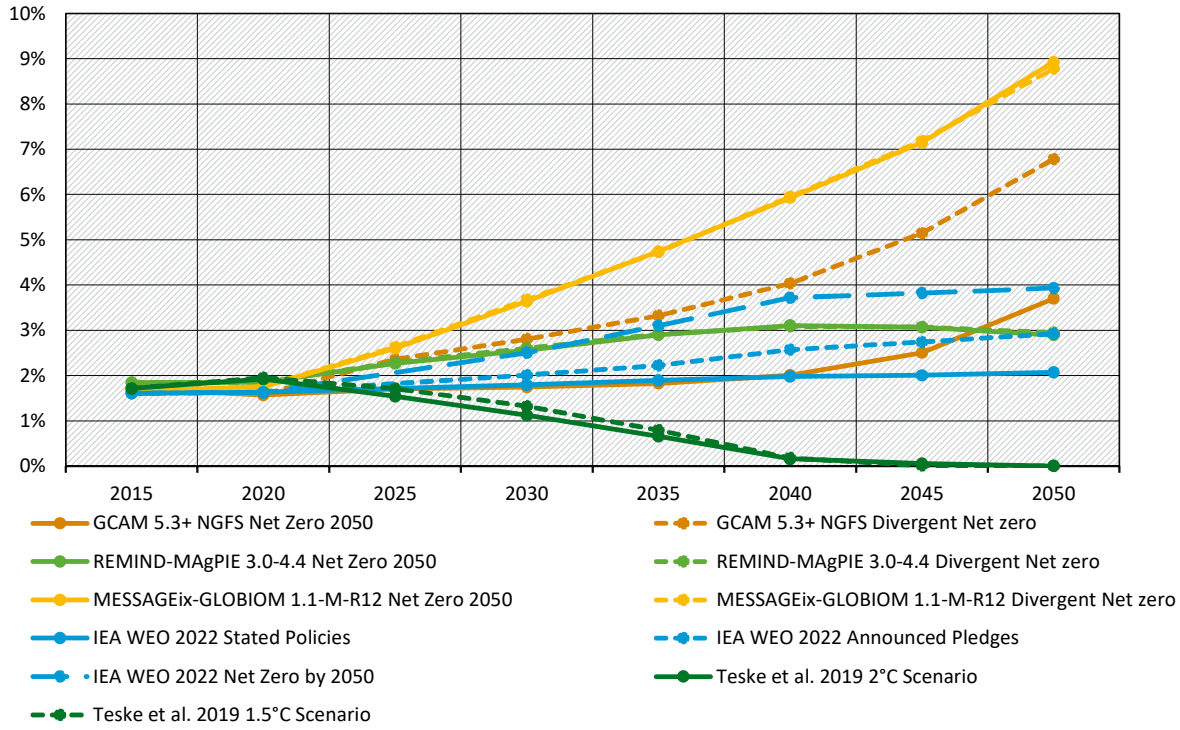
A first look at the role of nuclear in the scenarios analysed is presented by the comparison of the **share of nuclear energy in global primary energy** as presented in Figure 2. While nuclear energy currently accounts for less than 2% of primary energy, projections for 2050 range from 0% (Teske, 2019) to 9% (in both scenarios calculated with the MESSAGEix-GLOBIOM model, (NGFS, 2022). The REMIND-MAgPIE scenarios both show a 3% nuclear energy share, while the IEA scenarios show a share of nuclear energy ranging from 2% to 4% in 2050. The GCAM model is the only one that shows significant differences between the "orderly" and "disorderly" scenarios with a nuclear share of almost 4% in the "Net Zero 2050" scenario, increasing to almost 7% in the "Divergent Net Zero 2050" storyline in 2050.

A first key finding from these figures is that with only 9% of primary energy even in the maximum case of the scenarios analysed and values between 2% and 4% in most of the scenarios in the selection, the role of nuclear energy for the global energy system is limited. This is especially evident when compared with the numbers for renewable energies, as shown below.

Figure 3 and Figure 4 show the absolute numbers for primary energy (Figure 3Figure 3:) and nuclear primary energy (Figure 4) in the scenarios analysed. The development of primary energy is dependent on the underlying assumptions such as population, economic growth and efficiency. Compared to today the scenarios vary between a development towards more (IEA scenarios "Stated policies" and "Announced Pledges"), about constant (GCAM Net Zero 2050) and less primary energy consumption (with the Teske 1.5°C scenario showing the strongest decrease).

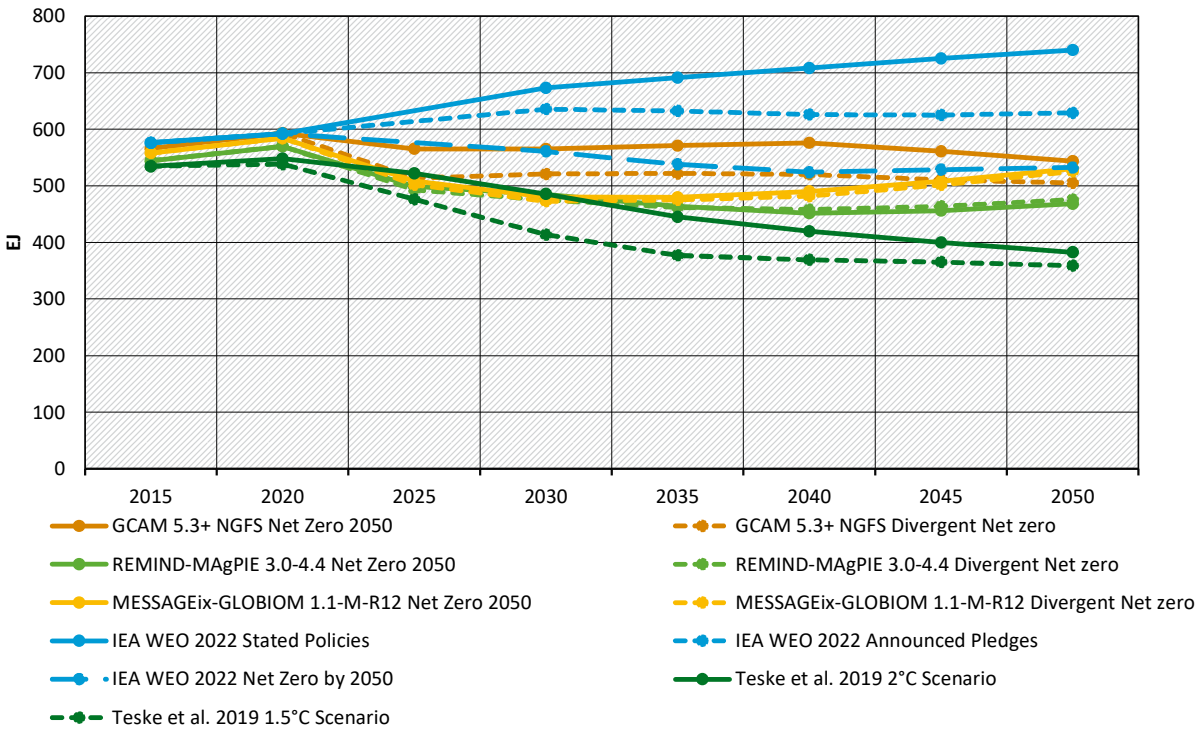
The MESSAGEix-GLOBIOM scenarios, which show the highest proportion of nuclear energy, is in the middle of the range of developments in global primary energy use with a slight downward trend in primary energy compared to today.

Figure 2: Share of nuclear energy in primary energy (world) in the scenarios analysed



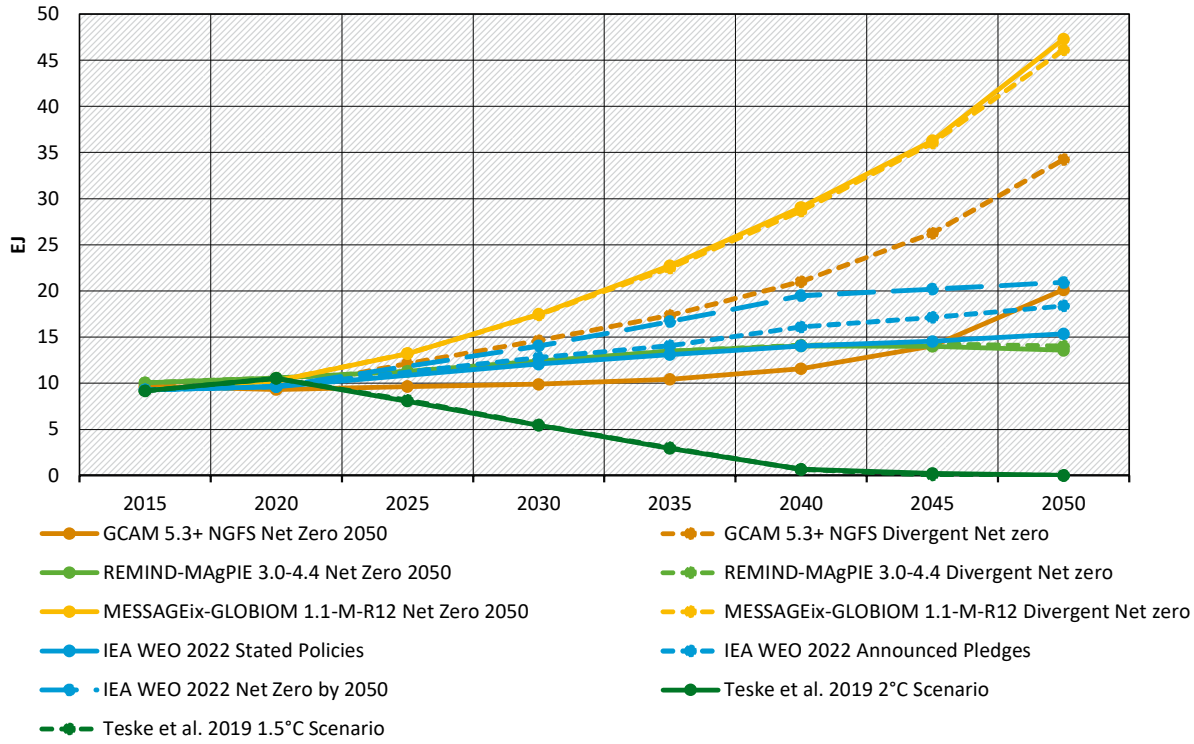
Both REMIND-MAgPIE scenarios run parallel resulting in barely visible differences.
Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022); own calculation, own illustration, Öko-Institut e.V.

Figure 3: Primary energy (world) in the scenarios analysed



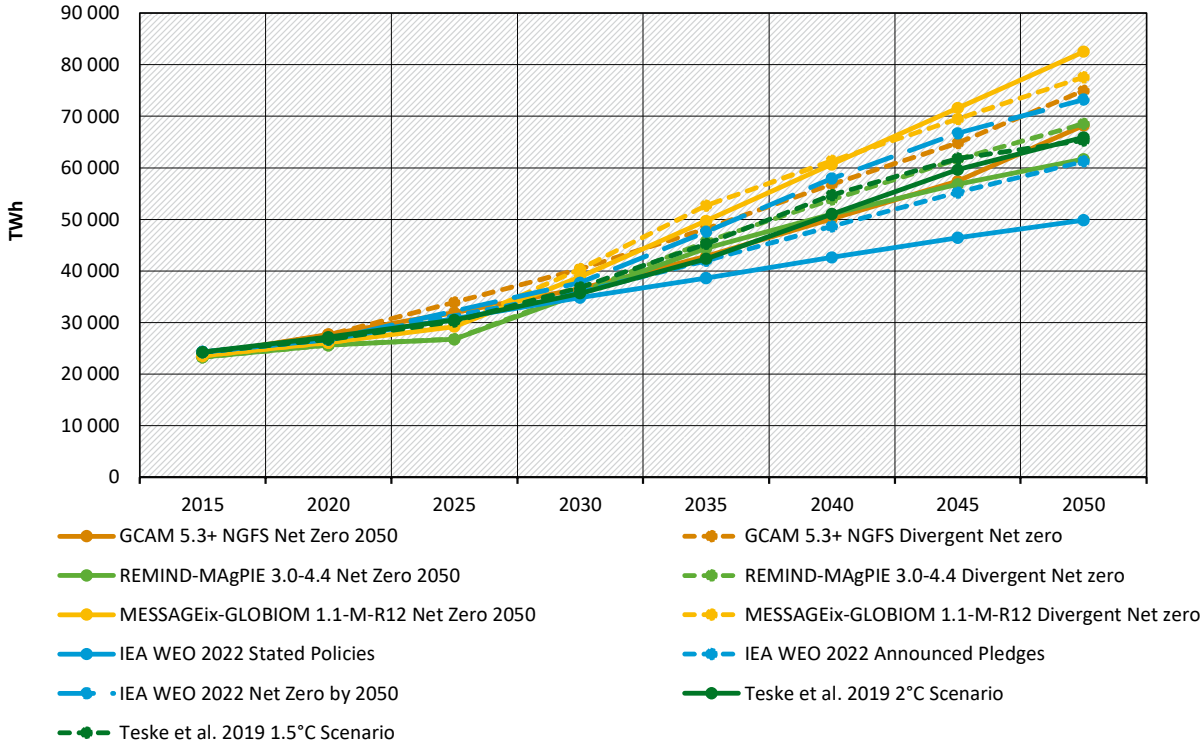
Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022); own illustration, Öko-Institut e.V.

Figure 4: Nuclear primary energy (world) in the scenarios analysed



Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022); own illustration, Öko-Institut e.V.

Figure 5: Electricity generation (world) in the scenarios analysed



Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022); own illustration, Öko-Institut e.V.

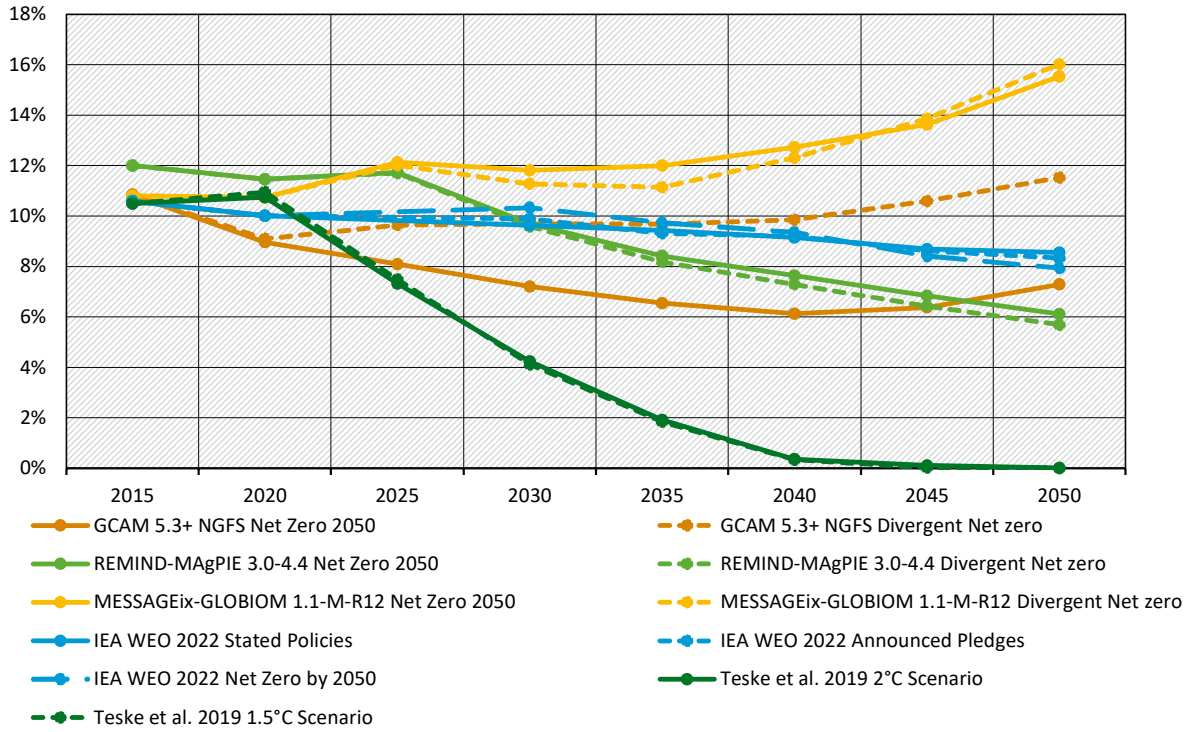
In absolute terms, the MESSAGEix GLOBIOM scenarios envisage an increase in nuclear primary energy from around 10 EJ today to more than 45 EJ in 2050 (Figure 4). This would mean an increase in nuclear energy by a factor of more than 4.5 within the next (approximately) 25 years. In second place, the GCAM "Divergent Net Zero 2050" scenario shows a more than threefold increase of nuclear until 2050. Other scenarios vary between an increase by a factor of 1.5 to 2, with the exception of the Teske scenarios, which envisage the phasing out of nuclear energy.

In contrast to primary energy, electricity generation increases over time in all scenarios compared to today as can be seen in Figure 5. The minimal increase in global electricity generation corresponds to a doubling in the (not climate target compatible) IEA "Stated Policies" scenario. All other scenarios range between an increase in electricity generation by a factor of 2.5 to 3.5 between today and 2050, because the electrification of other sectors is an essential strategy for decarbonisation.

Figure 6 shows the share of nuclear energy in global electricity generation in the scenarios analysed. Today, the share of nuclear energy in global electricity generation is around 10%. Due to the increase in total electricity generation (also as a result of the decarbonisation of other sectors), most scenarios show constant or lower shares of nuclear energy in the electricity mix in 2050 compared to today, even if electricity generation from nuclear energy increases in absolute terms, as shown above (compare Figure 4).

Most of the selected scenarios show a share of nuclear electricity of between 6% and 9% in 2050, with only the MESSAGEix GLOBIOM scenario rising to around 16% and the GCAM "Divergent Net Zero" to 12% and the Teske scenarios decreasing to 0%.

Figure 6: Share of nuclear energy in electricity generation (world) in the scenarios analysed



Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022); own illustration, Öko-Institut e.V.

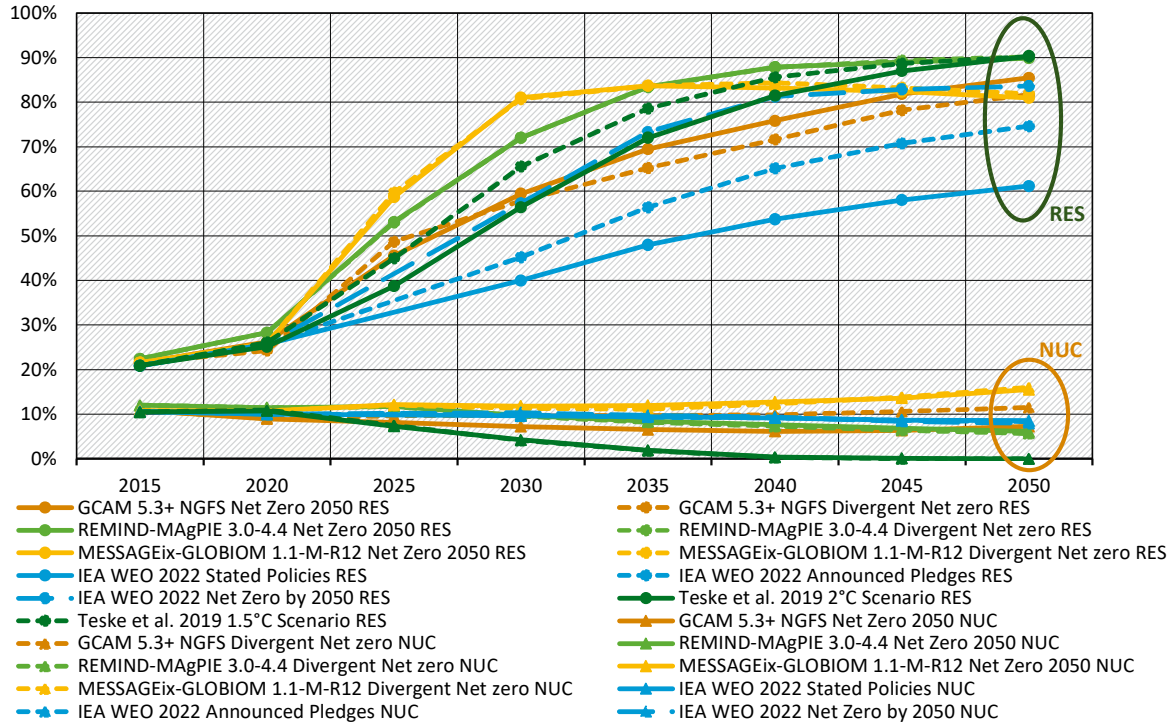
Despite these differences in all the scenarios analysed, the role of nuclear energy is comparatively small compared to the development of renewable energies, as is presented in Figure 7. Already today, electricity generation from non-biomass renewable energy sources is

around twice as high as electricity generation from nuclear energy. In 2050 all scenarios show shares of non-biomass renewable electricity generation between 80% and 90% except the IEA's "Announced Pledges" (75%) and the non-target "Stated Policies" scenario that falls short of renewable electricity with a comparatively low share of 61%.

Figure 8 shows the global electricity generation in 2050 in absolute terms for all scenarios as well as the contribution of nuclear and (non-biomass) renewable sources.

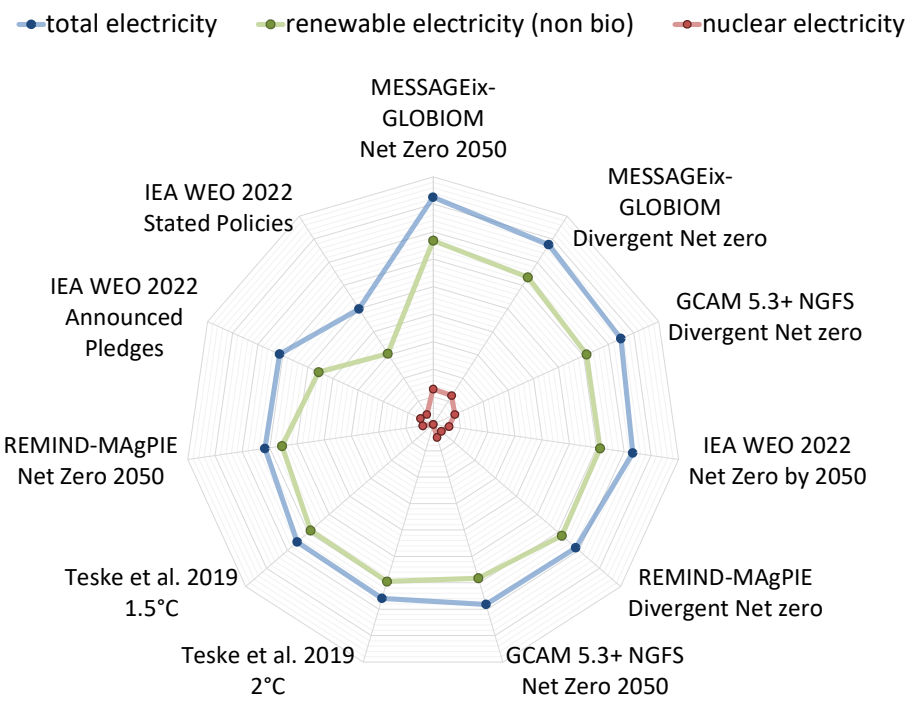
The MESSAGEix-GLOBIOM scenarios are not only the ones with the highest nuclear energy generation but also the ones with the highest total electricity generation and the highest renewable electricity generation in absolute terms.

Figure 7: Share of non-biomass renewable (RES) and nuclear (NUC) electricity generation (world) in the scenarios analysed



Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022); own illustration, Öko-Institut e.V.

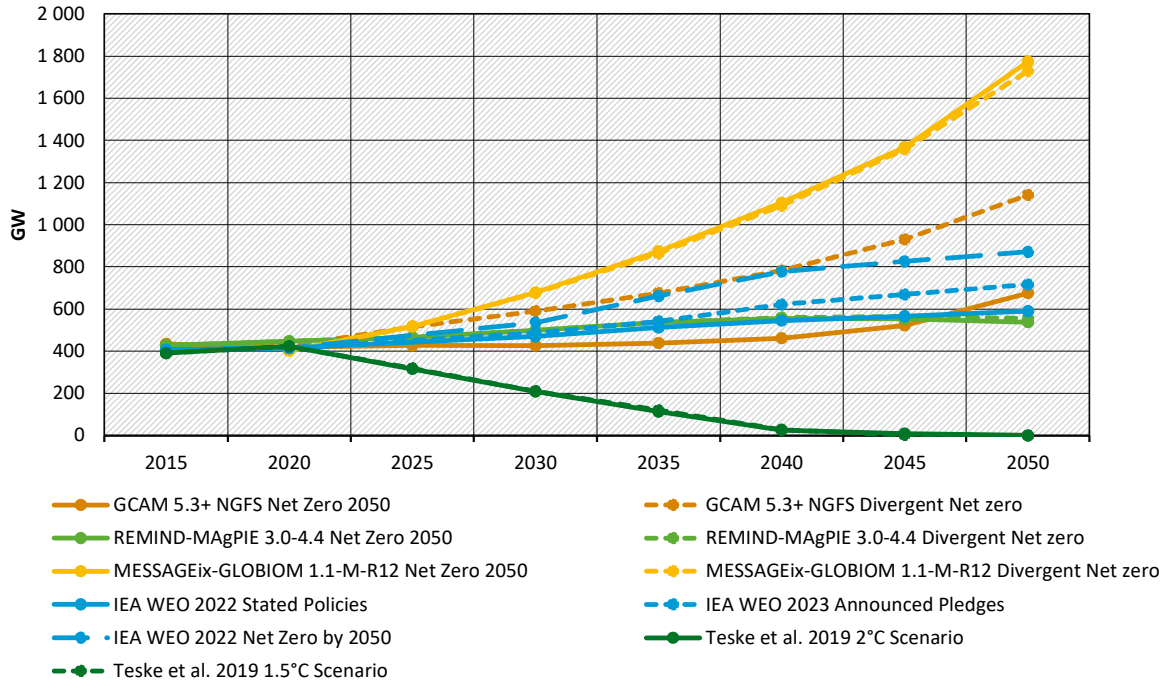
Figure 8: World nuclear electricity and renewable electricity in 2050 in comparison with total electricity in the scenarios analysed



Scale from 0 to 900.000 TWh in units of 100.000

Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022); own illustration, Öko-Institut e.V.

Figure 9: Installed capacity of nuclear reactors (world) in the scenarios analysed



Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022); own illustration, Öko-Institut e.V.

Corresponding with the development of nuclear electricity generation in the scenarios is the installed capacity. The development of the installed capacity of nuclear reactors worldwide is shown in Figure 9. It shows a wide range of installed nuclear capacity from 0 GW (Teske, 2019) to almost 1800 GW (MESSAGEix-GLOBIOM) in 2050 and installed capacities between 540 GW and around 1140 GW for the other scenarios as compared to approximately 370 GW today.[2]

The development of nuclear reactors in the scenarios analysed results from the assumptions on which the respective modelling work is based, such as assumptions about cost developments of various technologies and fuels or the representation of political framework conditions for the world regions included in the model.

To assess how realistic such developments are, it is helpful to analyse today's nuclear power plant fleet as a starting point and to contrast the global scenarios with a bottom-up analysis of countries' nuclear plans which is undertaken in section 2.3.

2.2.3 Update of global scenarios in 2024

The initial analysis of the NGFS scenarios for this report was conducted in 2023, meanwhile the NGFS scenarios have been updated, most recently in November 2024 ("Phase 5"). The NGFS long-term scenarios have been updated with the most recent economic and climate data, improved model versions, and current policy pledges, incorporating national commitments to achieve net-zero emissions announced up to March 2024. They also account for the latest developments in renewable energy technologies (such as solar and wind), key mitigation solutions, and the energy market impacts of the war in Ukraine (NGFS, 2024). Therefore an update of the analysis was implemented which also took into account the updated the latest 2024 edition of the IEA's World Energy Outlook (IEA, 2024).This version has updated GDP and population data, assumptions related to Carbon Capture and Storage (CCS) and more realistic current policy representations for different regions.

A comparison of the updated 2024 scenarios with the 2022 scenarios, which were analysed in detail in this report, underpins the key results described above, that nuclear energy will only make a rather limited contribution to reducing global greenhouse gas emissions. Generally, the role of nuclear energy in the updated scenarios is lower than in the previous versions, in particular in scenarios from models that had the highest growth in nuclear energy.

Figure 10 and Figure 11are showing the share of nuclear energy in global primary for the 2022 and the 2024 version of the scenarios. Instead of the "Divergent Net Zero" scenario, which was not updated, the "Below 2°C" scenario[3] is included as a second target scenario into the graph of the 2024 scenarios.

In the 2022 version, the MESSAGEix GLOBIOM model had the highest share of nuclear energy in primary energy in the year 2050 in the "Net Zero 2050" scenario with 9%. This changed drastically in the 2024 version, where the share of nuclear energy in primary energy dropped to less than 2% in the MESSAGEix GLOBIOM scenario and is now lower than the other models.

The two other NGFS models, REMIND and GCAM, show similar shares of nuclear energy in primary energy, in the updated "Net Zero 2050" scenarios as in the 2022 versions, both at a very low level of below 4% (GCAM) and below 3% (REMIND) in 2050.

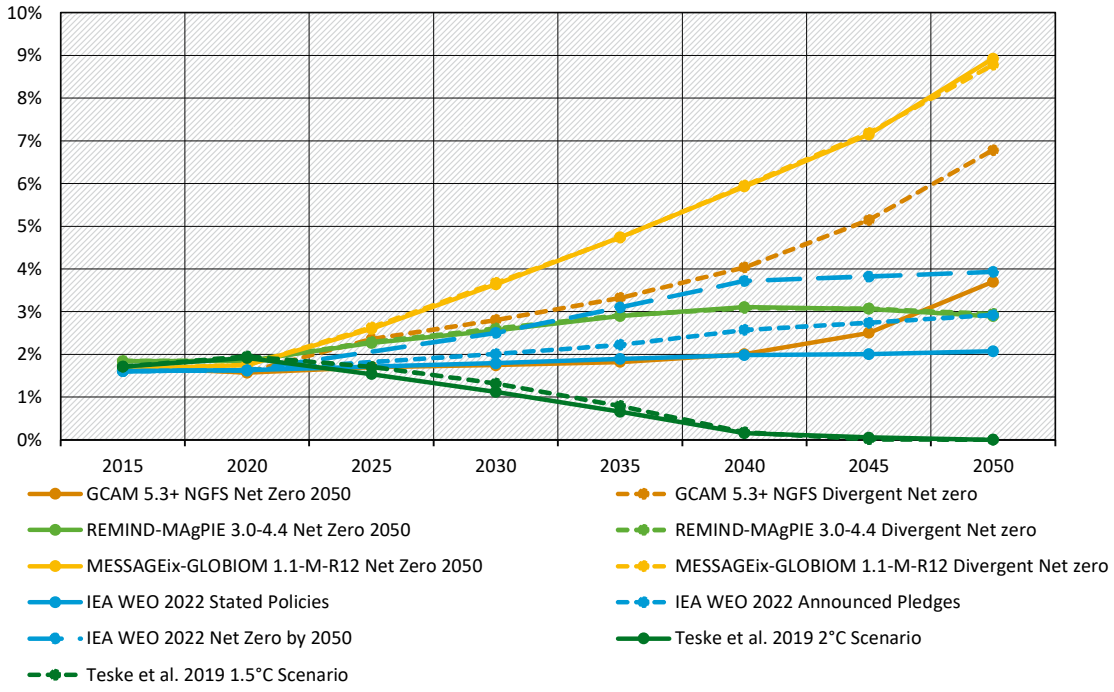
[2] According to the IAEA's PRIS database International Atomic Energy Agency (IAEA) (2025) 370.99 GW of net electrical capacity was installed worldwide at the end of 2022. Numbers of installed capacity may include reactors in long-term outage, that are formally declared operational but have not produced electricity for an extended period of time.

[3] While the Net Zero 2050 scenario limits global warming to below 1.5° C with a chance of 50%, the Below 2°C scenario limits global warming to below 2°C with a chance of 67% and is a little less ambitious than the Net Zero 2050 scenario.

In the latest World Energy Outlook (2024), the share of nuclear energy in primary energy hardly changed in the Stated Policies Scenario (approx. 2% in 2050) compared to the 2022 edition, but does change slightly in the Announced Pledges Scenario (3.6% instead of the previous 2.9%) and in the Net Zero 2050 Scenario (now 4.6% instead of the previous 3.9%).

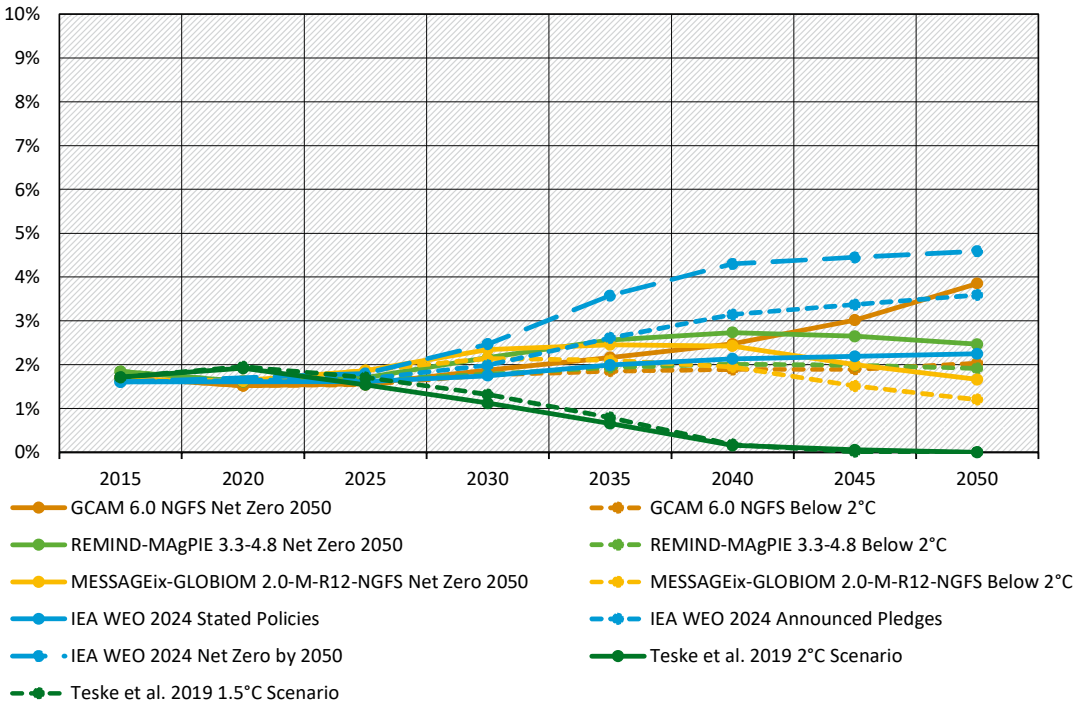
This makes the World Energy Outlook (2024) "Net zero by 2050" with 4.6% to the scenario with the highest share of nuclear energy in primary energy among the 2024 scenarios.

Figure 10: Share of nuclear energy in primary energy (worldwide) in the analysed scenarios



Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022); own illustration, Öko-Institut e.V.

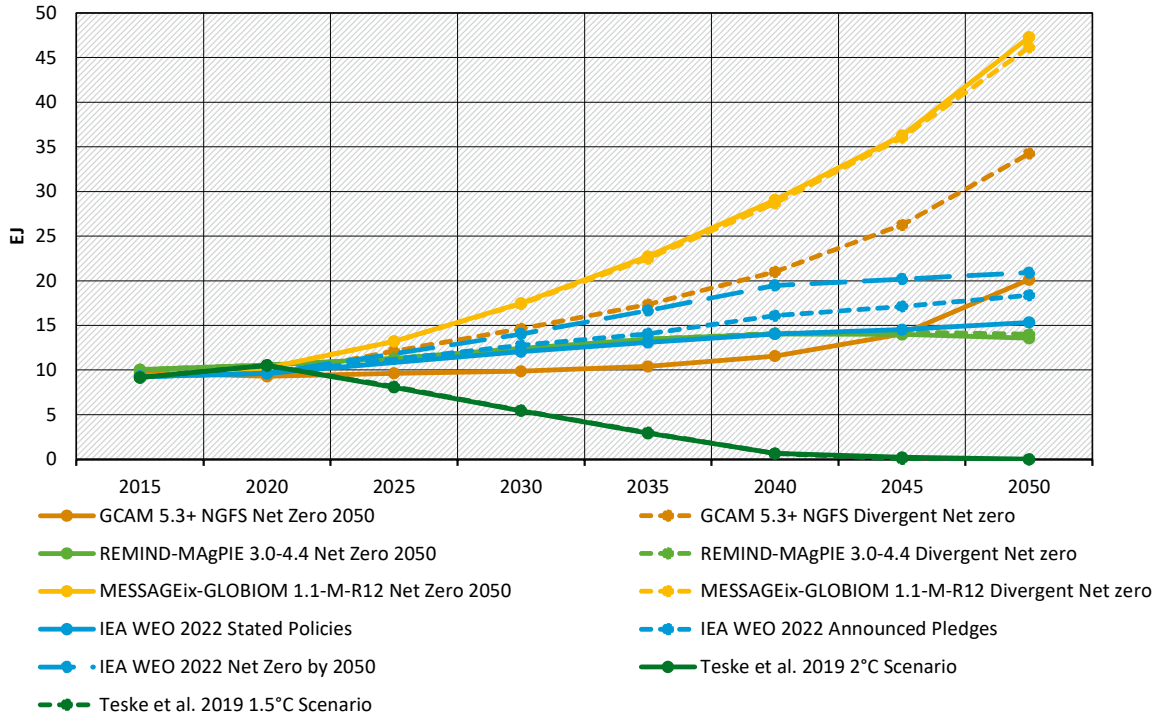
Figure 11: Share of nuclear energy in primary energy (worldwide) in the updated scenarios



Source: (Richterss et al., 2024), (Teske, 2019), (IEA, 2024); own illustration, Öko-Institut e.V.

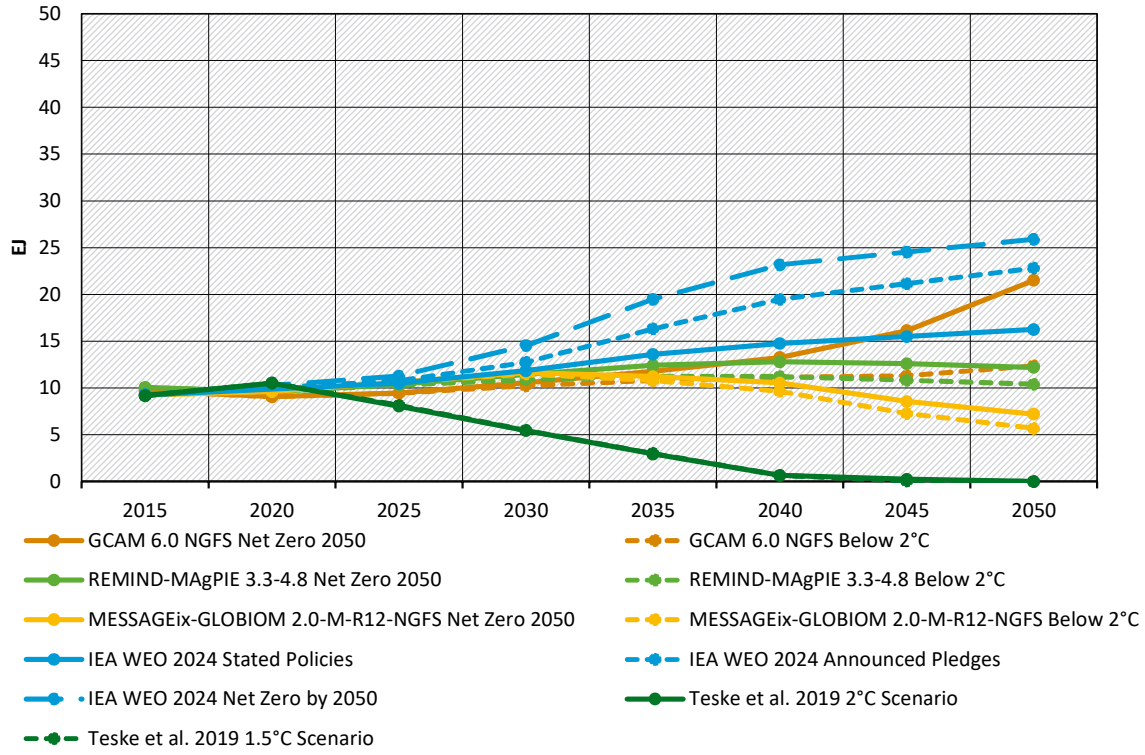
Figure 12 and Figure 13 are showing the absolute nuclear primary energy production in the previous and updated version of the scenarios. The biggest change is visible for the MESSAGEix-GLOBIOM scenarios results in which nuclear energy production dropped from 47 EJ to 5 to 7 EJ in 2050. The GCAM Net zero 2050 scenario remained very similar, while the REMIND-MagPIE scenario is slightly lower in the updated version (12 EJ nuclear primary energy instead of 14 EJ). In the World Energy Outlook scenario, the values for nuclear primary energy remained very similar as in 2023, but now the WEO scenario "Net Zero by 2050" has the highest value of 26 EJ nuclear primary energy in 2050 of all scenarios.

Figure 12: Nuclear primary energy (world) in the scenarios analysed



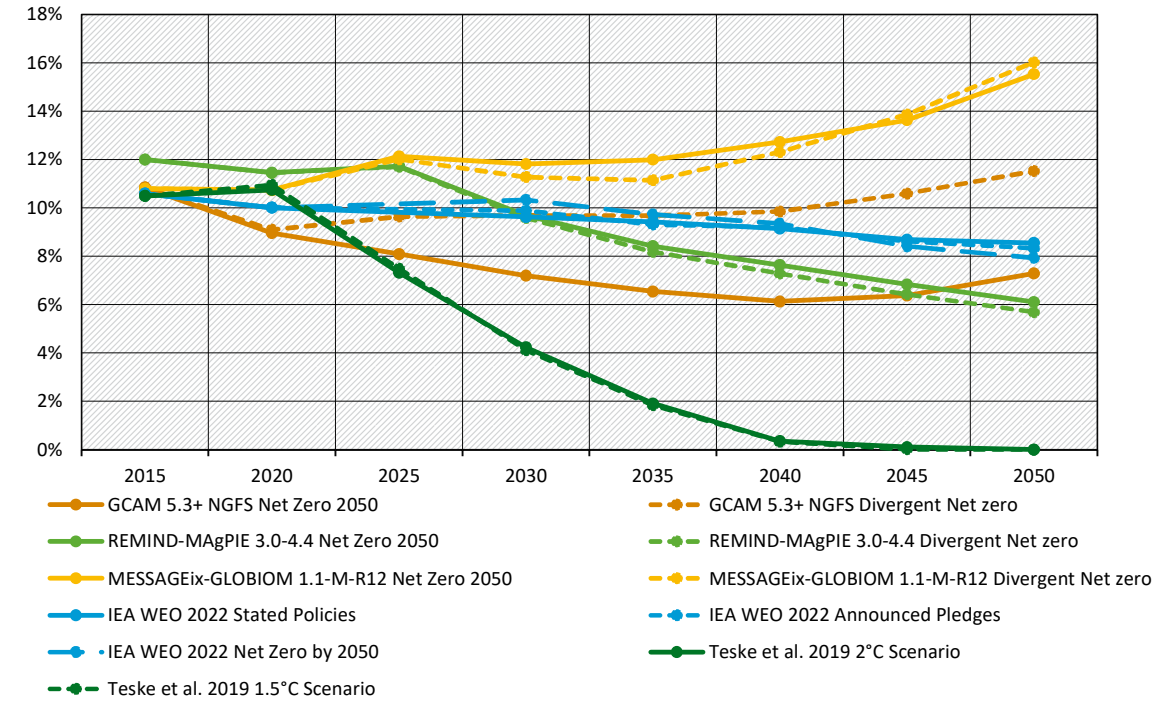
Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022); own illustration, Öko-Institut e.V.

Figure 13: Nuclear primary energy (world) in the updated scenarios



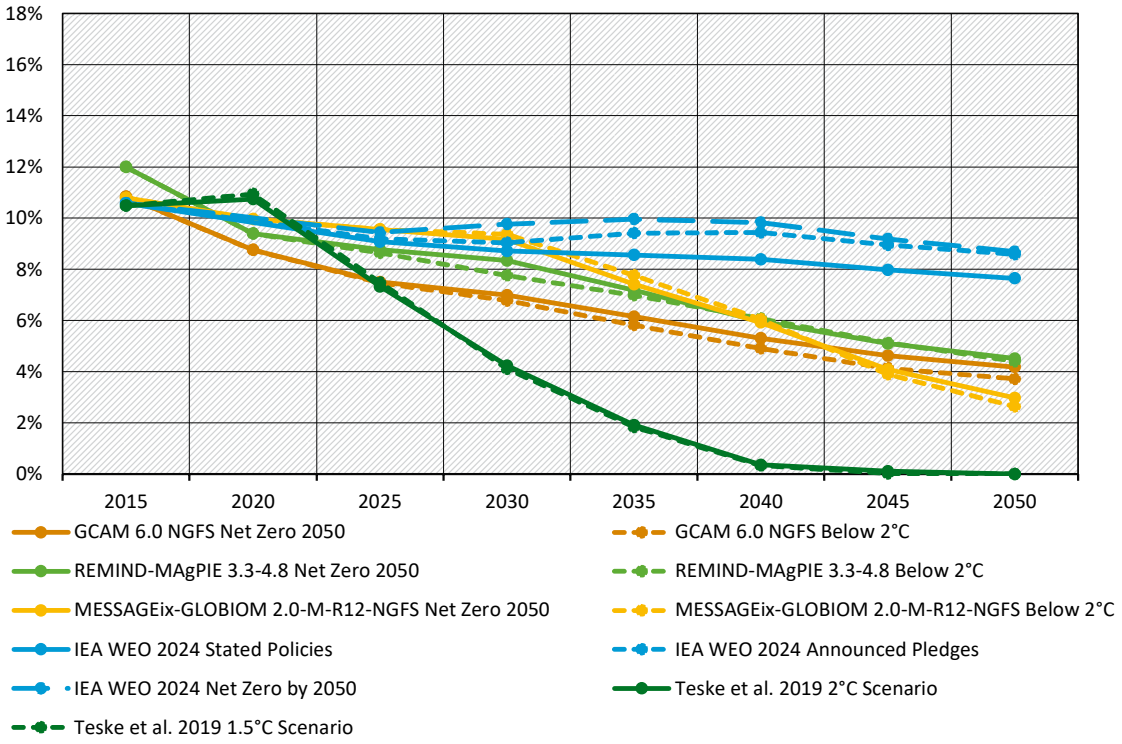
Source: (Richterss et al., 2024), (Teske, 2019), (IEA, 2024); own illustration, Öko-Institut e.V.

Figure 14: Share of nuclear energy in electricity generation (world) in the scenarios analysed



Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022); own illustration, Öko-Institut e.V.

Figure 15: Share of nuclear energy in electricity generation (world) in the updated scenarios



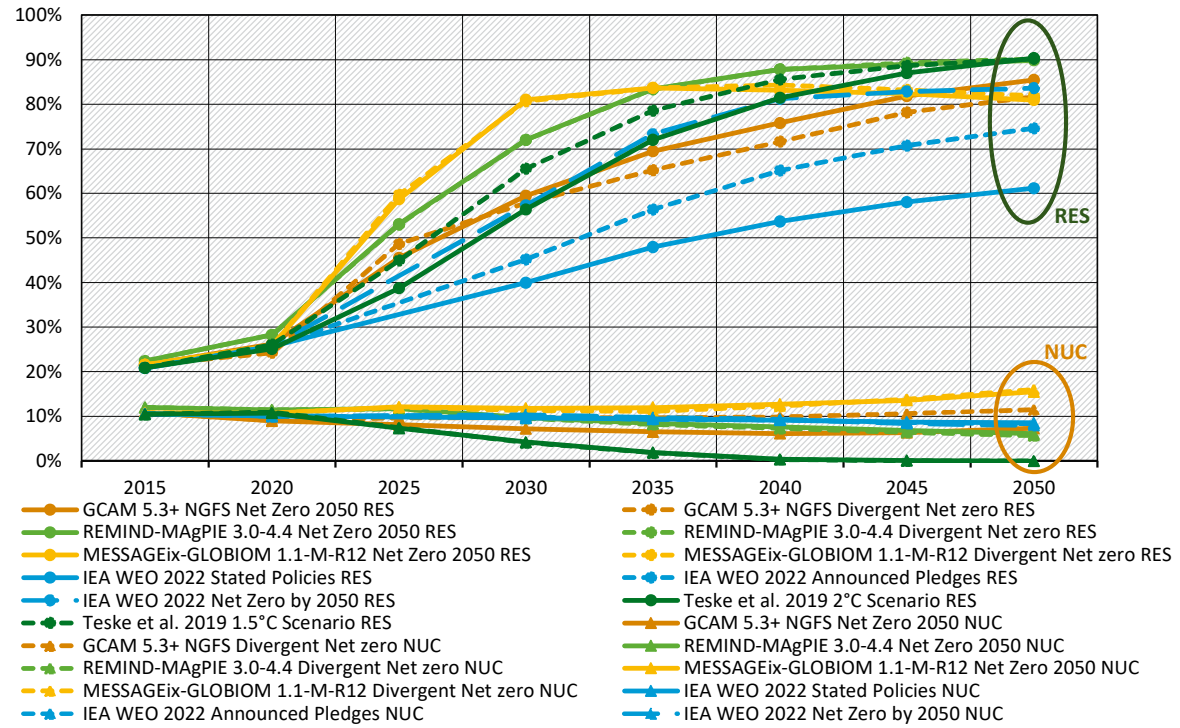
Source: (Richterss et al., 2024), (Teske, 2019), (IEA, 2024); own illustration, Öko-Institut e.V.

Figure 14 and Figure 15 are presenting the share of nuclear energy in electricity generation for the previous and the updated scenarios. The message of the updated versions is very consistent: all models foresee a decline in the share of nuclear in electricity generation until 2050 compared to today. The lowest decrease is predicted in the World Energy Outlook scenarios from currently 10 to 9% in 2050. In the MESSAGEix-GLOBIOM scenarios, the share of nuclear in electricity generation in 2050 drops from 10% to 3-4%. GCAM NET Zero by 2050 scenario had foreseen a share of nuclear in electricity generation of 7% which now is only 4%. Remind-MAgPIE also decreases from 6% to approximately 4%.

While the contribution of nuclear energy decreases in the updated NGFS scenarios compared to the 2022 edition, the share of non-biomass renewable electricity generation increases in all updated scenarios, as is shown in Figure 16 and Figure 17. Of the 2022 scenarios, Teske's were the most ambitious, with a renewable electricity share of 90%. In the 2024 versions, most NGFS scenarios exceed this figure, with shares of non-biomass renewable electricity of up to 97%.

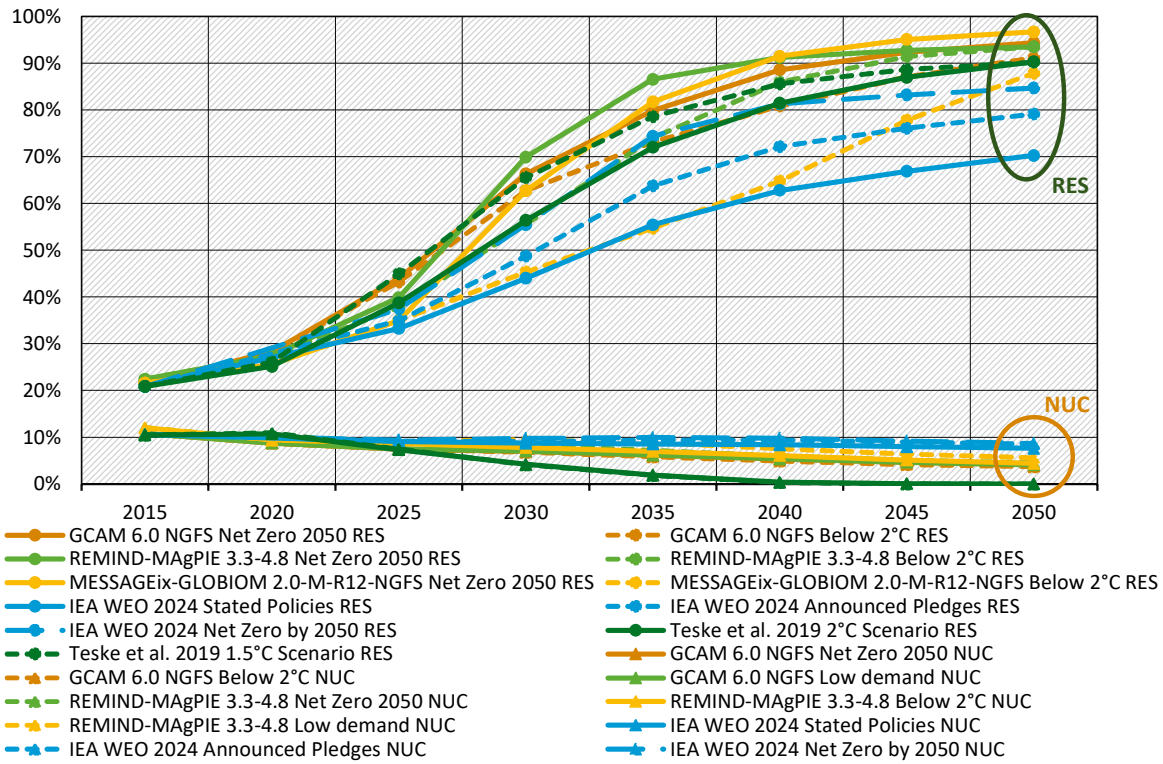
The major role of renewable energies – compared to the rather limited contribution of nuclear energy - is also evident inFigure 18, It shows the generation of nuclear and renewable electricity compared to total electricity generation in the 2022 and 2024 scenarios for 2050.

Figure 16: Share of non-biomass renewable (RES) and nuclear (NUC) electricity generation (world) in the scenarios analysed



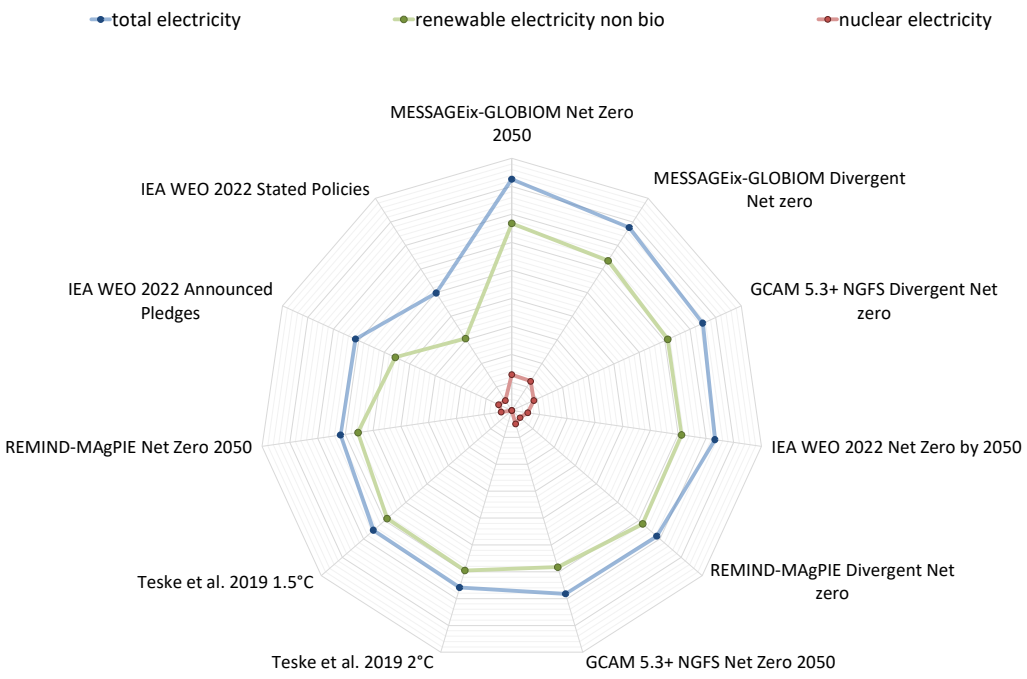
Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022); own illustration, Öko-Institut e.V.

Figure 17: Share of non-biomass renewable (RES) and nuclear (NUC) electricity generation (world) in the updated scenarios



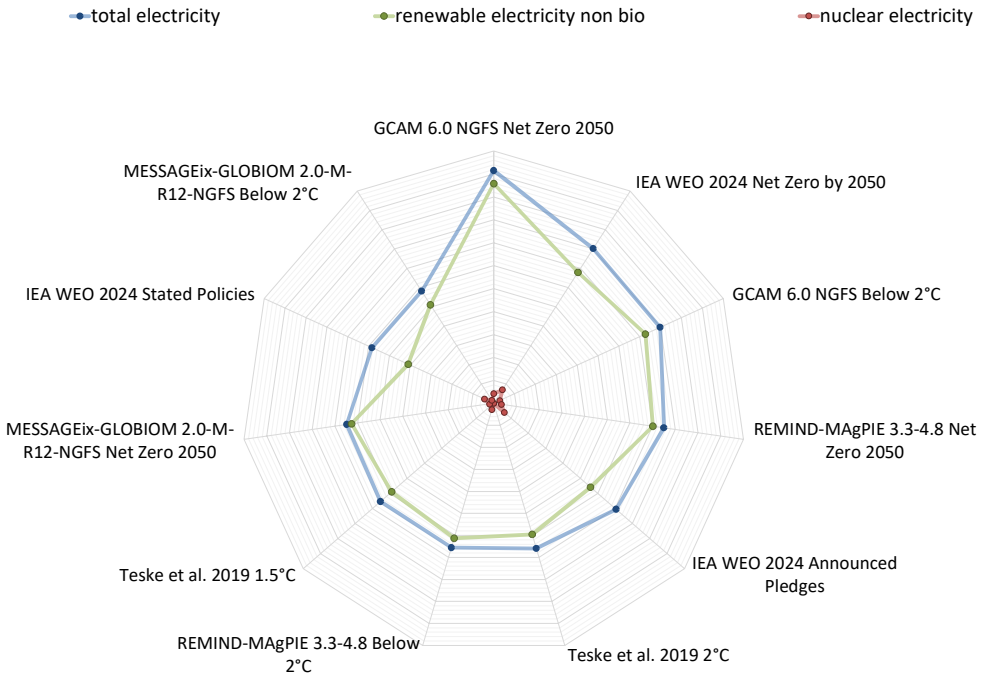
Source: (Richterss et al., 2024), (Teske, 2019), (IEA, 2024); own illustration, Öko-Institut e.V.

Figure 18: World nuclear electricity and renewable electricity in 2050 in comparison with total electricity in the scenarios analysed



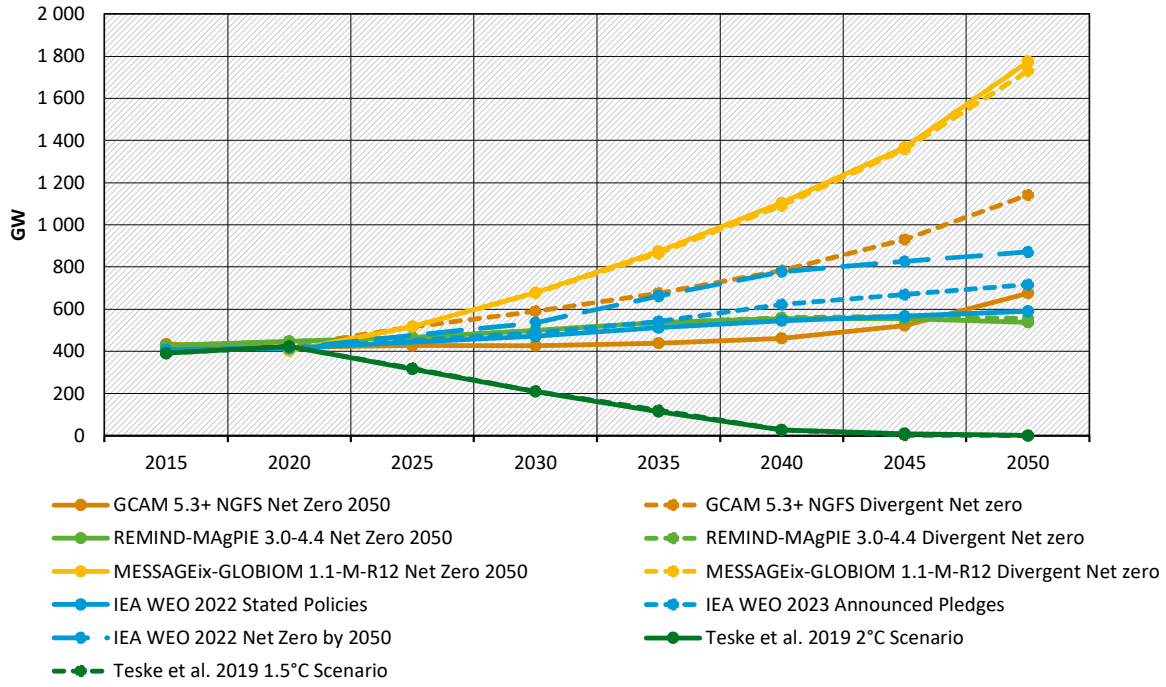
Scale from 0 to 110 000 TWh in units of 10 000 TWh
Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022); own illustration, Öko-Institut e.V.

Figure 19: World nuclear electricity and renewable electricity in 2050 in comparison with total electricity in the updated scenarios



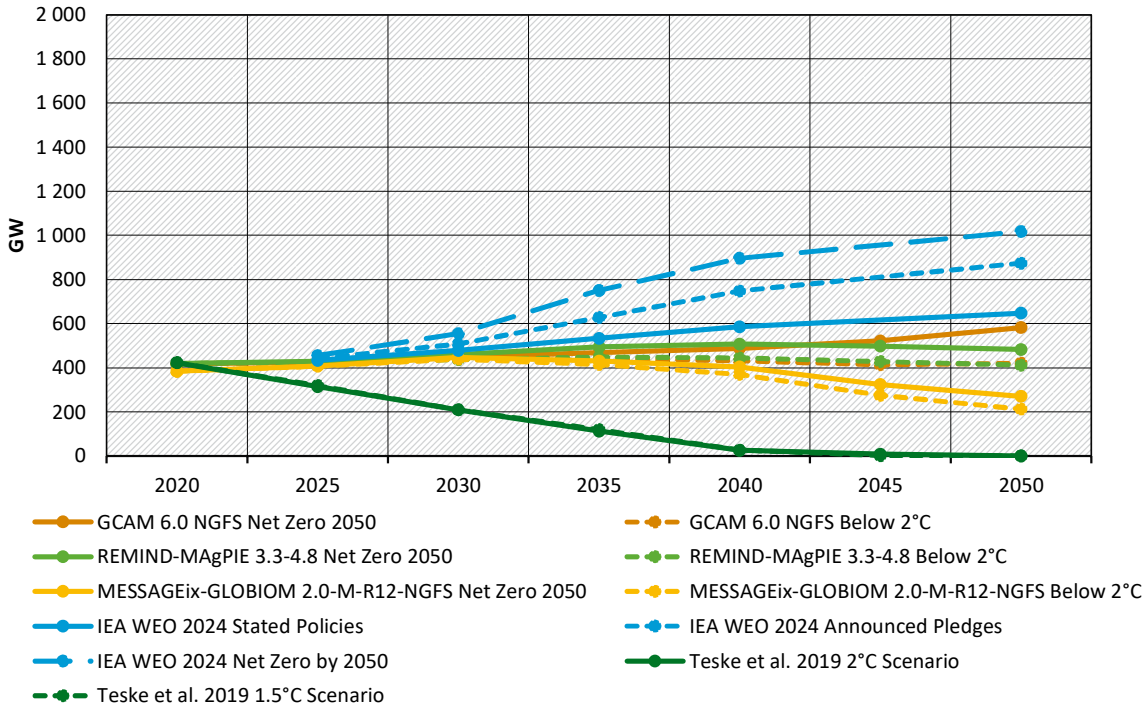
Scale from 0 to 110 000 TWh in units of 10 000 TWh
Source: (Richterss et al., 2024), (Teske, 2019), (IEA, 2024); own illustration, Öko-Institut e.V.

Figure 20: Installed capacity of nuclear reactors (world) in the scenarios



Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022); own illustration, Öko-Institut e.V.

Figure 21: Installed capacity of nuclear reactors (world) in the updated scenarios



Source: (Richterss et al., 2024), (Teske, 2019), (IEA, 2024); own illustration, Öko-Institut e.V.

The decline in the share of nuclear in electricity generation in all modelling results is linked to a much lower nuclear capacity development in the updated scenario compared to the previous ones (Figure 20 and Figure 21). In the 2023 version, MESSAGEix-GLOBIUM envisaged 1700 GW

of nuclear capacities in 2050, which is now reduced to values between 213 and 271 GW depending on the individual scenario. This presents a drastic change in the modelling results. The GCAM scenario results for nuclear capacities are also much lower than in the previous version and dropped from 676 GW to 583 GW in the recent update of the "Net Zero by 2050" scenario. The IEA World Energy Outlook scenario "Net zero by 2050" stands out with the highest nuclear capacities among the modelling organisations in the comparison with 1017 GW in 2050 – which is almost the doubled capacity compared to the closest scientific scenario from the GCAM team. Compared to today's global nuclear capacity of 380 GW, for the year 2050 IEA WEO projects an increase by a factor of 1.7 (Stated Policies Scneario) 2.3 (Announced Pledges scenario) and 2.7 (Net zero by 2050 scenario), GCAM modellers project s smaller increase in capacities by 53% (Net zero by 2050 scenario) and 11% (Below 2°C scenario), capacities grow to small extend until 2O50 in the REMIND-MAgPIE results with 27% (Net Zero 2050) and 8% (Below 2°C) and they decrease in MESSAGEix-GLOBIOM by 29% (Net zero by 2050) and 44% (Below 2 °C). Most models use a starting point of 420-430 GW for 2024 which is higher than the actual 380 GW. They do not yet consider the recent downward revision of nuclear capacities in the global IAEA PRIS database.

2.3 Country plans and programmes

As of November 2023, 31 countries operate a total of 412 nuclear reactors (International Atomic Energy Agency [IAEA], 2025).[4] By far the most nuclear reactors are located in the USA, followed by France, China, Russia and South Korea, as is shown inFigure 22. Only nine countries operate more than 10 nuclear reactors.

The age structure of the existing fleet is a major factor for the future development of the installed nuclear capacity. According to (M. Schneider et al., 2023) the mean age of all nuclear reactors in operation as of October 2023 is 31.7 years. The average age of nuclear reactors that have been shut down until July 1st 2022 was 27.7 years according to (M. Schneider et al., 2022).

Whether nuclear reactors are shut down at the end of their design lifetime depends on various factors. Some countries have legislation in place that limit operating lifetime for all reactors or part of the fleet and closure is mainly triggered by legislation. The old plants need to undergo additional safety checks to determine whether extended operation would still be considered safe. These checks can result in the need for additional safety measures which can be costly. Some countries extended permits beyond the operating lifetime, but operators nevertheless decided to close the plant because the continued operation would require additional investments and operation would no longer be economic. Such early closures happened for example in the U.S.

As a first step, a short analysis of the existing global nuclear capacities (installed and under construction) is conducted. By varying the lifetime of all nuclear reactors with the same value (40 years, 50 years, 60 years) it is possible to get a first, if simplified, impression of the magnitude of global nuclear capacities in the future, that would result from today's fleet taking into account only new nuclear reactors already under construction. The resulting capacity developments are presented in Figure 23.

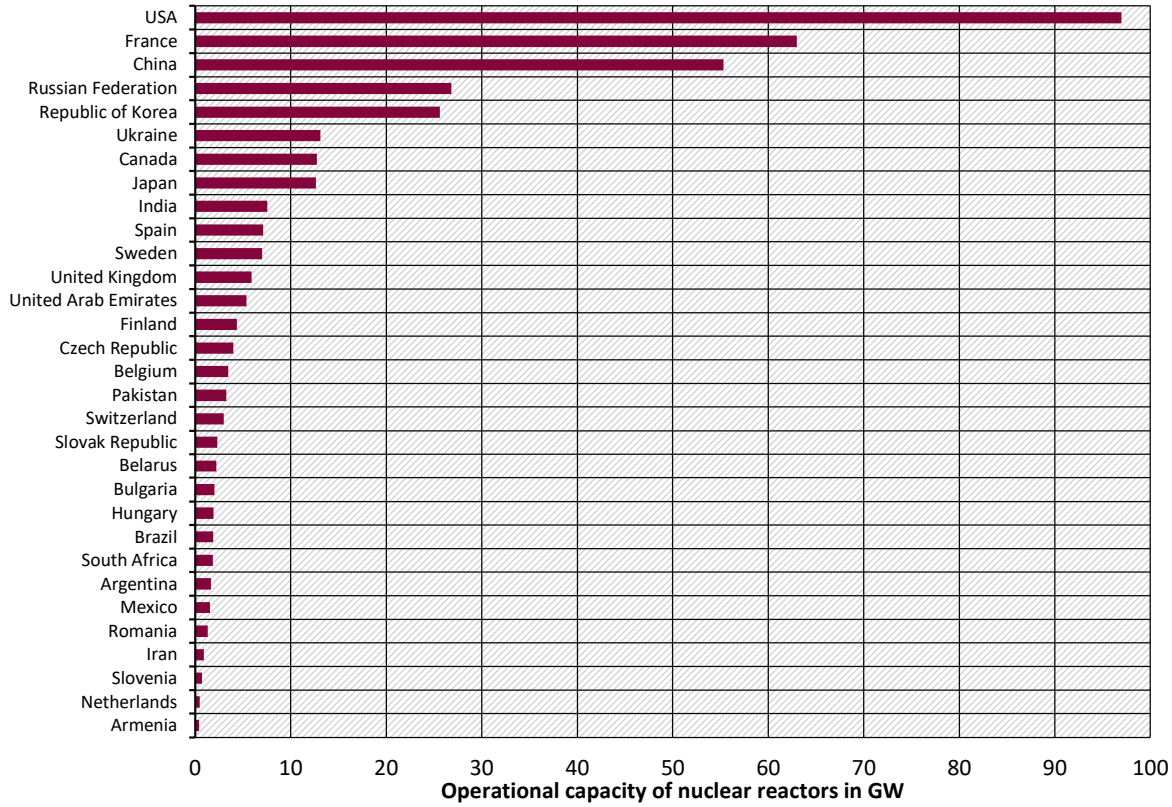
Due to the age structure of the existing fleet, an assumed lifetime of 40 years would result in a strong decline of installed nuclear capacity already by 2030, while a lifetime of 60 years on the other hand would postpone this decline until 2040-2050.

[4] In the IAEA PRIS data Taiwan is included in the numbers for China.

While the different lifetime assumptions would make a significant difference in the years 2030 to 2040, the differences between the three paths presented decrease by 2050, with installed capacities in 2050 between 134 GW (for 40 years lifetime), 160 GW (50 years) and 212 GW (60 years). Even considering a 60 years lifetime would leave a considerable gap to the analysed scenarios (with the exception of the Teske scenarios with a phase-out of nuclear energy), which show installed capacities between 540 GW and almost 1800 GW in 2050 as mentioned above. This means that such scenarios must assume high levels of new nuclear power plant construction.

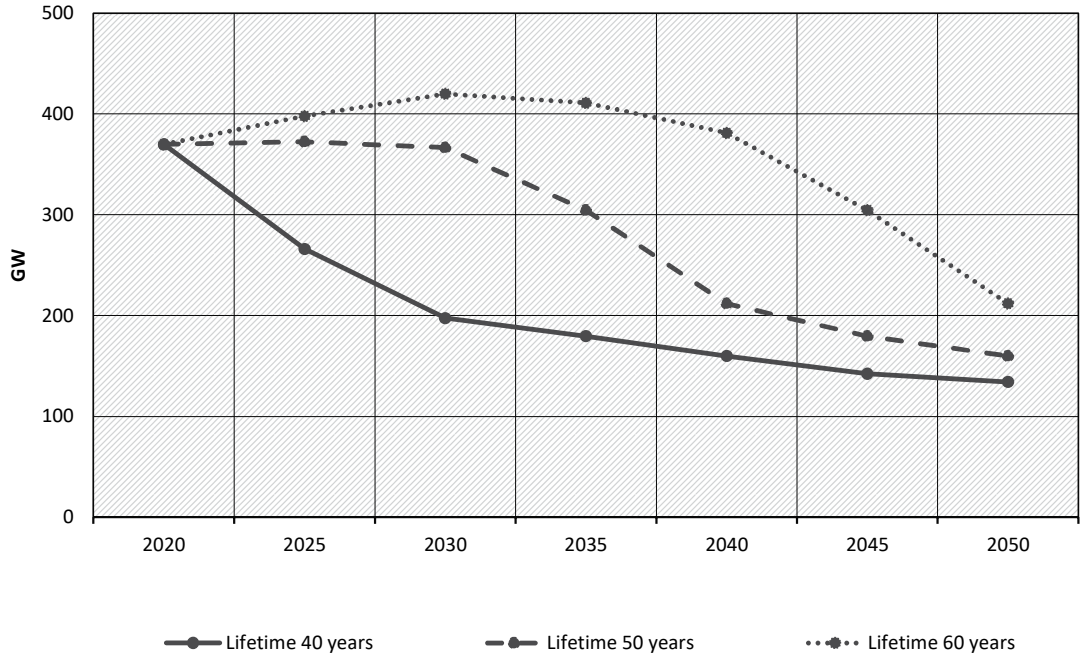
In order to compare such assumptions with the real world, it is necessary to examine the plans and programmes of governments worldwide for the expansion (or phase-out) of nuclear energy.

Figure 22: Installed capacity of nuclear reactors (world)



Source: data: (IAEA, 2025); own illustration, Öko-Institut e.V.

Figure 23: Development of global nuclear capacity (installed and under construction) depending on different lifetime assumptions



Source: data: (IAEA, 2025); own illustration, Öko-Institut e.V.

2.4 Bottom-up analysis of existing nuclear power plants

2.4.1 Introduction and methodological approach

An alternative way to analyse the future development of nuclear energy is to assess countries' plans and programs regarding decommissioning, lifetime extensions and new construction of nuclear power plants. Therefore, in addition to the energy scenarios presented in the previous section, the plans and programmes of the countries with nuclear plants or those with plans for installation have been researched.

The starting point of the assessment of each country is the country information provided in the IAEA Power Reactor Information System (PRIS) (IAEA, 2025) related to the operating nuclear plants, the plants under construction and the decommissioned plants. According to the IAEA PRIS database, on September 5, 2025, there were 416 nuclear power plants in operation with a net capacity of 376 GW(el). 62 reactors with a capacity of 65 GW(el) were under construction. The detailed assessment with official country sources showed that indeed, PRIS data include nuclear plants as "operational" that have not been operating for many years and plants "under construction" where it is very unlikely that the respective nuclear plants will finally be constructed. We also used PLATTs database of global power plants – a commercial source of power plant data – as a second source of information and compared all entries for each country. While for some nuclear plants PLATTS included updated information about the operational status, in other cases PRIS database was better. Thus, at the end we checked all power plants included in the PRIS database with current information from countries nuclear authorities with regard to the number, capacities and status of the nuclear plants.

The information is based on an extensive literature research for each country. For this purpose, documents and studies were researched and evaluated that specifically deal with the planned lifetime expansions, decommissioning and investments in nuclear energy for the individual

countries. The preferred sources used at country level were documents provided by legal authorities such as energy ministries, nuclear safety authorities or nuclear plant operators. Sometimes, these sources had to be complemented by scientific reports or news articles. These sources are certainly less reliable, but sometimes they showed that the official information was not fully updated. From the sources found, there is substantial information to forecast the country's plants until 2030. But it was difficult to find reliable sources with specific plans for the period 2040 to 2050. Therefore, we used simplified assumptions to project the capacities until in 2050, mostly a continued trend based on the trend in the period 2020-2030. This introduces significant uncertainty for the period 2040 to 2050. The specific assumptions are documented in the individual country sections. We frequently used a high and a low assumption and presented two scenarios to capture the range in future developments.

For countries with a significant number of existing nuclear plants, the assumptions for the lifetime and planned lifetime extensions are very relevant. In some countries operators provide such information for each nuclear plant, in other countries it was more difficult to collect such information. The PRIS database often uses a standard lifetime for nuclear power plants (but this is not always the case) which is not sufficiently reliable for the projections at country level. If specific official information for individual nuclear plants was not available, we used assumptions based on information communicated by the governments, in particular decisions already taken or announced related to lifetime extensions. The individual sources and assumptions are presented in the country sections.

The capacity developments at country level were developed for five-year periods in order to be able to compare them with data of global scenarios.

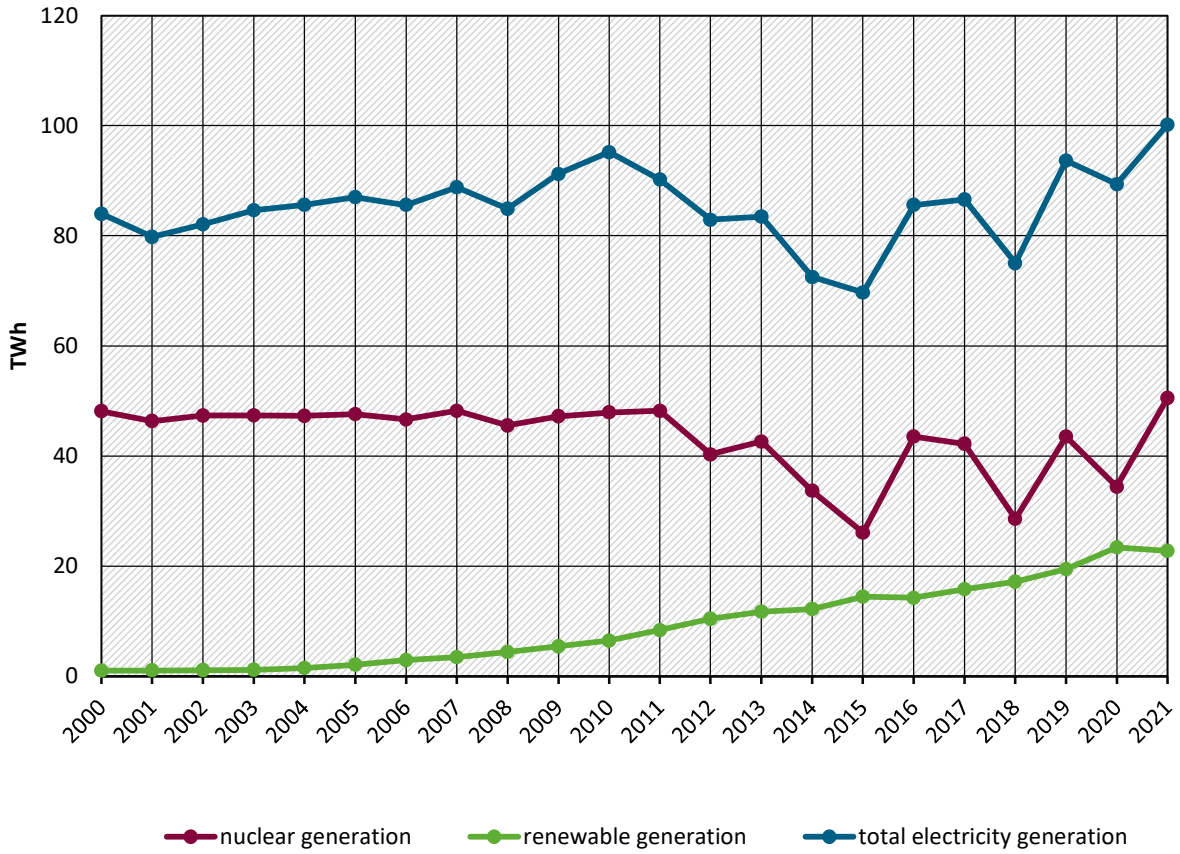
2.4.2 Europe

2.4.2.1 Belgium

According to IAEA Power Reactor Information System (PRIS), Belgium has 4 nuclear reactors in operation with a total net capacity of 3.5 GWe and 4 reactors have been permanently closed. There are no reactors under construction.

The share of nuclear in electricity production was 35% in 2021. In the past 10 years, nuclear power production stayed relatively constant, but since 2013 in a number of years nuclear generation dropped significantly due to problems and maintenance at the rather old nuclear plants (Figure 24). The share of renewable energy in electricity production is 22%. The growth rate for renewables without hydro power was 10.6 per year in the decade 2011-2021.

Figure 24: Electricity generation in Belgium (TWh)



Source: BP Statistical Review of World Energy 2022, Renewables include hydro, wind, geothermal, solar, biomass and waste

The average age of the four remaining reactors is 45 year, thus Belgium operates the third oldest fleet in the world after the Netherlands and Switzerland (M. Schneider & Froggatt, 2024). According to its first National Climate and Energy Plan (Groupe de Concertation État-Régions pour l'Energie [CONCERE] & Commission nationale du climat [CNC], 2019), Belgium's energy mix will radically change due to the planned gradual phase-out of nuclear power by 2025, with 5.918 GW of decommissioned nuclear capacity having to be replaced (partly this decommissioning already occurred since the NECP was published). The Federal Government confirmed this commitment – which was enshrined in legislation in 2003 – on 30 March 2018 as part of the Interfederal Energy Pact (CONCERE & CNC, 2019). In March 2022, the Belgian Federal Government decided against the phase-out of the two newest nuclear plants Doel 4 and Tihange 3 and to extent the lifetimes of these reactors by 10 years until 2035(with a closure date at the latest on 31 December 2037) due to concerns about security of electricity supply in the context of the energy crisis after the war of Russia against Ukraine. A legally binding agreement for the lifetime extension was signed in March 2025 between Engie and the Belgian government[5]. In February 2025, the European Commission approved state aid measures to finance the considerable costs for the life-time extension of these two reactors. Engie will pay €15 billion for the future costs of nuclear waste management in 2025. With this payment all nuclear waste liabilities are transferred to the Belgian government, ENGIE will no longer be responsible for future costs related to the treatment of waste. Doel 4 and Tihange 3 will be equally owned by the Belgian State and ENGIE, with a contract for difference mechanism. The

[5] https://en.newsroom.engie.com/assets/engie-group-pr-closing-belgium-20250314-pdf-64ff8-314df.html, last accessed on 01.10.2025

Federal Agency for Nuclear Control (FANC) approved the continued operation for Tihange 3 in July 2025 and the approval for Doel 4 is expected for November 2025.[6]

After the start of the new Belgian Federal government in the beginning of 2025, plans further changed and it adopted plans extending the lifetime of Doel 4 and Tihange 3 by additional 10 years. The new government also proposed to extend the lifetimes of the old reactors Doel 1, Doel 2 and Tihange 1 which are already in the process of being decommissioned (M. Schneider & Froggatt, 2024). Doel 1 was shut down after 50 years operation time in February 2025, Tihange 1 and Doel 2 and will follow in October and December 2025. No preparations have been taken place to prepare these reactors technically (technical safety analysis) or organisationally (legal permitting or staff availability) for further operation, in contract preparations for the decommissioning are ongoint.[7] The new government announced an overall target of 4 GW of nuclear power in the Belgian energy mix (Belga News Agency, 2025). Vincent Verbeke, the CEO of ENGIE Belgium - the operator of Belgian nuclear plants - strongly opposes these plans and stated to the press that he considers it "unthinkable" to extent Doel 4 and Tihange 3 beyond 2035 and wants to continue decommissioning the already shut-down plants. In his view the additional lifetime extension is too expensive and not in Engie's strategic interest (The Brussels Time, 2025; vrtnws, 2025). The FANC emphasized in its statement related to the current 10 year lifetime extension, that it requests that clarity be provided on a possible extension of the operation of Doel 4 and Tihange 3 beyond 2035 during the current legislative term in order to start the necessary safety analyses and preparations in good time. In May 2025 FANC and the nuclear research centre SCK CEN announced that they started preliminary talks on a SMR that uses lead-cooled technology related to the potential licence application which however do not prejudge the outcome of a licence application.[8]

The bottom-up projections for Belgium takes into account the current lifetime extension until 2035 in the low scenario. The high scenario reflects the new government plans from 2025 with increasing capacities. However, it is currently very unclear whether these plans can be implemented and how these plans will be financed.

Table 1: Nuclear capacities in Belgium in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Belgium low scenario (current lifetime extension)	3.46	2.06	2.06	0.0	0.0	0.0
Belgium high scenario (new government plans 02/2025)	3.46	3.46	3.46	2.02	2.02	0.50

Source: (CONCERE & CNC, 2019)

2.4.2.2 Bulgaria

According to IAEA Power Reactor Information System (PRIS), Bulgaria has 2 nuclear reactors in operation with a total net capacity of 2 GWe and 4 reactors have been permanently closed. There are no reactors under construction.

The share of nuclear in electricity production was 40.6% in 2023. In the past 10 years, nuclear power production remained relatively constant (Figure 25). The share of renewable energy

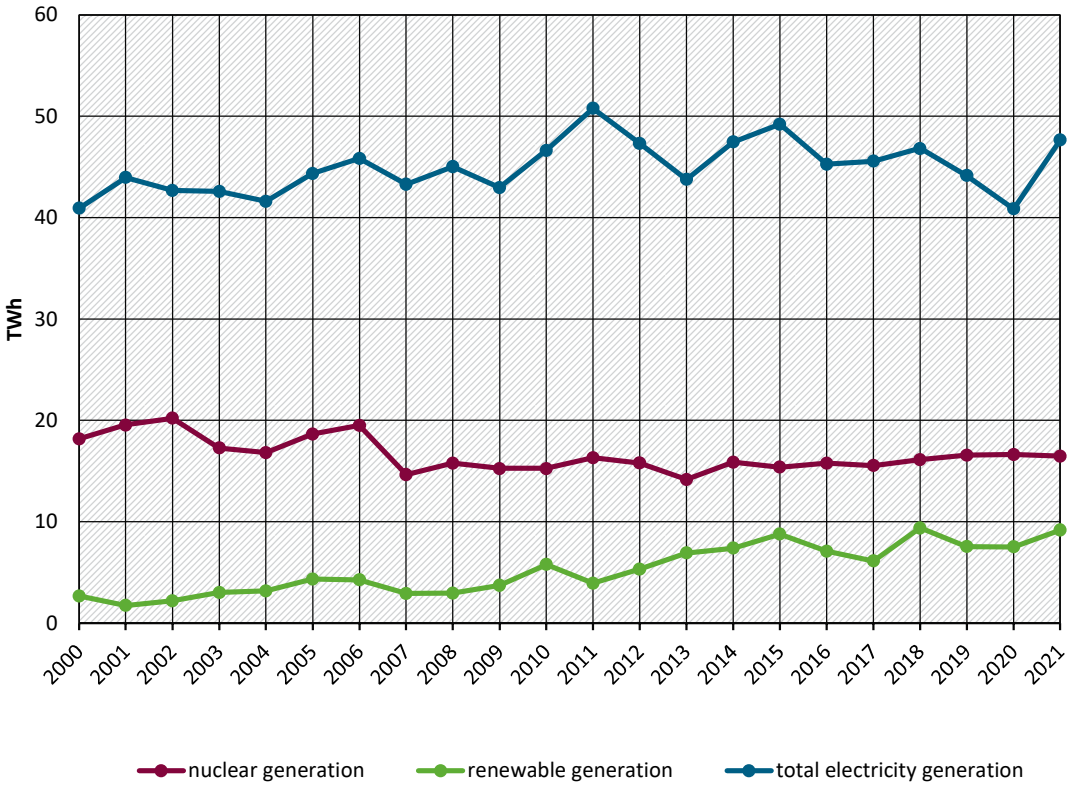
[6] https://afcn.fgov.be/fr/actualites/lafcn-approuve-le-redemarrage-et-la-poursuite-de-lexploitation-de-tihange-3, last accessed on 01.10.2025

[7] https://fank.fgov.be/de/dossiers/kernkraftwerke-belgien/einstellung-der-aktivitaeten-und-rueckbau-der-belgischen, last accessed on 01.10.2025

[8] https://fank.fgov.be/de/news/fank-und-sck-cen-starten-explorativen-prozess-rund-um-kleinen-modularen-reaktor-smr, last accessed on 01.10.2025

without hydro power in electricity production is at only 17.2%, with hydro energy it is 25%. The growth rate for renewables without hydro power was 4% per year in the decade 2013-2023.

Figure 25: Electricity generation in Bulgaria (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

Bulgaria has recently extended the lifetime of Kozloduy 5 and 6 reactors by 10 years, and we assumed an extension until 60 years for both operating reactors. In its National Climate and Energy Plan (Republic of Bulgaria, Ministry of Energy, Ministry of the Environment and Water, 2019) Bulgaria announced the intention to build 2 GW of new nuclear capacities. According to WNA, in January 2021, the Bulgarian government approved plans for a new unit at Kozloduy (World Nuclear Association [WNA], 2023) and in January 2023, Bulgaria's National Assembly voted in favour of a draft decision asking ministers to negotiate with the US government for the new AP1000 unit at Kozloduy (unit 7) and urged action by 1 March to speed up the process for approval and construction of the unit as well as initiating a licensing and environmental impact assessment procedure for another reactor, which would be unit 8 at Kozloduy (M. Schneider & Froggatt, 2024). In March 2023, a MoU with the U.S: manufacturing Westinghouse was signed to begin the planning of the two new units and a final investment decision is expected for 2025. In July 2025 U.S. Citi Bank and Bulgaria's Ministry of Energy have agreed on a partnership to secure funding for the construction of the two new units.[9] Therefore, we took into account two new units of 1000 MW each, as this is consistent with the information provided in the NECP as well as with the information provided by WNA. We assumed that one new unit would be operating by 2035 and the second by 2045. The start date of 2035 is in line with the current plans of the Bulgarian government, the second unit is planned to start in 2037 or 2038. The later assumption

[9] https://www.world-nuclear-news.org/articles/bulgaria-says-citi-to-help-financing-of-new-kozloduy-units, last accessed on 01.10.2025

reflects the frequent delays in nuclear constructions in Europe. The available capacities until 2050 are shown in Table 2.

Table 2: Nuclear capacities in Bulgaria in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Bulgaria scenario (based on NECP)	2.01	2.01	2.96	2.96	3.96	3.00

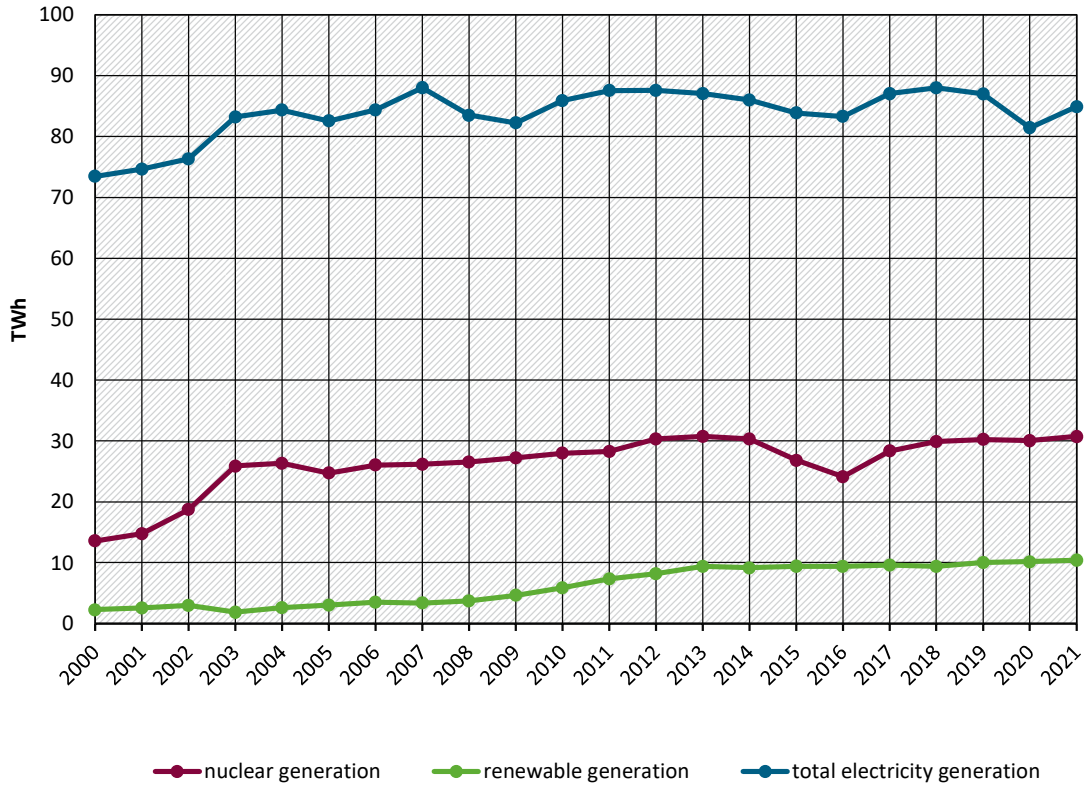
Source: Öko-Institut

2.4.2.3 Czech Republic

According to IAEA Power Reactor Information System (PRIS), the Czech Republic has 6 nuclear reactors in operation with a total net capacity of 3.9 GWe. There are no reactors under construction.

The share of nuclear in electricity production was 36% in 2021. In the past 10 years, nuclear power production remained relatively constant. The share of renewable energy in electricity production is only 9%, renewable electricity production including hydro power is 12% (Figure 26). The growth rate for renewables without hydro power was 4.4% per year in the decade 2011-2021.

Figure 26: Electricity generation in the Czech Republic (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

A total of 6 nuclear power units in the Temelín power plant and the Dukovany power plant are currently in operation in the Czech Republic. The Czech National Climate and Energy Plan (Czech Government, 2019) foresees the maintenance of the current share of nuclear energy in the energy mix. The updated National Climate and Energy Plan envisages increasing the share of

nuclear energy in gross electricity production to 46–58% by 2040 (from the current level of about 36%) (Czech Government, 2023). The large range reflects the uncertainty related to the total level of future electricity production and the uncertainty in the development of different energy sources. In terms of nuclear capacity, the plan assumes a nuclear capacity of 5.2 GW in 2040 (ibid), an increase by 1.3 GW. Following the approval of the State Energy Policy in the Czech Republic in May 2015, the National Action Plan for the Development of Nuclear Energy in the Czech Republic was approved in June 2015, which specifically elaborates on the requirement of the State Energy Policy of the Czech Republic to strengthen the role of nuclear energy. The strategic assignment is to ensure the continuity of operation of the Dukovany Nuclear Power Plant, which will have been in operation for 50 years in 2035. The Dukovany 1-4 reactors have received licenses for lifetime extensions and are expected to operate until 2037, potentially even until 2047 (M. Schneider & Froggatt, 2024).

According to the Czech NECP and (M. Schneider et al., 2022), Czech Republic is aiming at building new nuclear reactors at the Dukovany and the Temelin site. The plans for Dukovany-5 reactor are most advanced. According to World Nuclear Association, in March 2022, the Czech energy company ČEZ launched a tender for the construction of a new nuclear power plant in Dukovany (WNA, 2024n). At the end of November 2022 ČEZ announced that it had received initial bids from EDF, Westinghouse and Korea Hydro and Nuclear Power (KHNP). In 2024, KHNP was selected to build a minimum of two reactors of up to 1.2 GW, contract finalisation was expected to 2025 and grid connection is planned for 2036 for the first unit and two years later for the second unit (M. Schneider & Froggatt, 2024). The construction time of around 10 years is met by KHNP for reactors in Korea. However Europe's nuclear safety regulations are stricter and KHNP has not yet built a reactor with a double containment design (M. Schneider & Froggatt, 2024). The Dukovany site is located inland and requires cooling towers while Korean reactors are located at the coast, thus for KHNP this is a new design feature. So far also the financing plan is only limited to one reactor in Dukovany (ibid). Thus, it seems not unlikely that these challenges will lead to future delays. The Czech government also announced plans for two additional reactors at the Temelín site, but they still lack specific plans for construction and financing.

We have considered two scenarios, in the lower scenario, the minimum new constructions of 2 new nuclear reactors are implemented and existing Dukovany reactors run until 2037. The higher scenario assumed the construction of 4 new reactors (the maximum amount in the Czech NECP) and a lifetime of the Dukovany reactors until 2047. The results are shown in Table 3.

Table 3: Nuclear capacities in Czech Republic in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Czech Republic low scenario	3.96	3.96	3.96	3.96	4.45	4.45
Czech Republic high scenario	3.96	3.96	3.96	4.93	6.13	6.85

Source: Öko-Institut

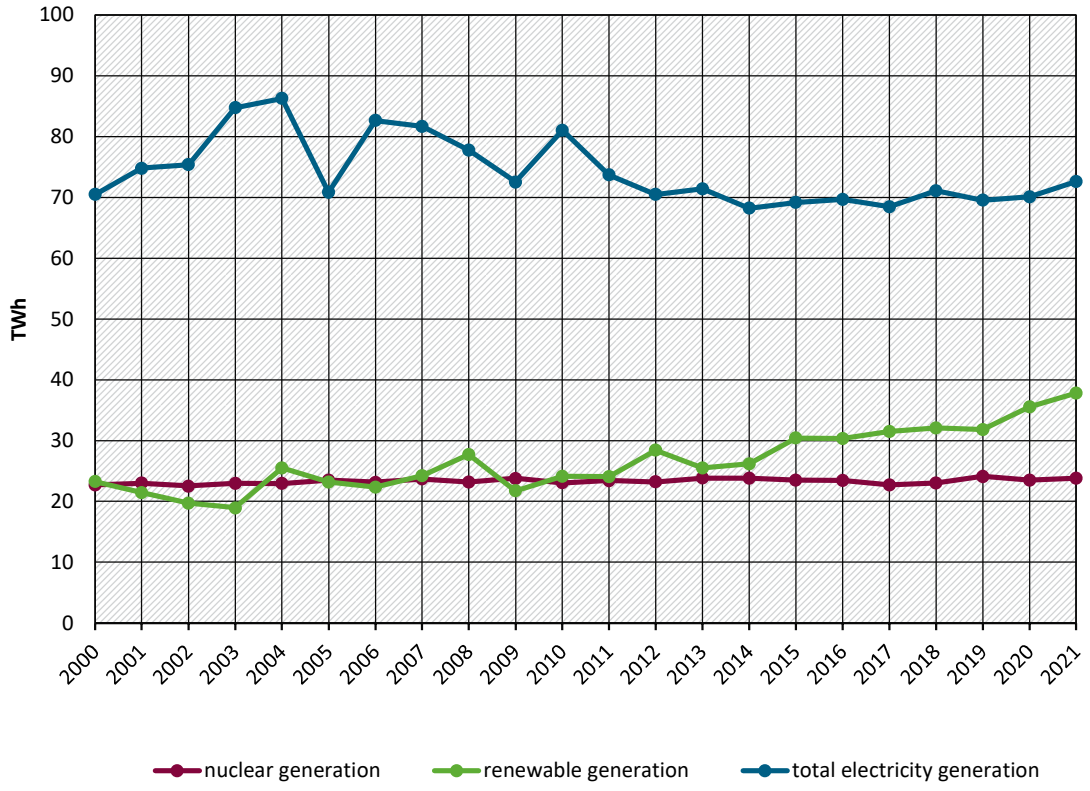
2.4.2.4 Finland

According to IAEA Power Reactor Information System (PRIS), Finland has 5 nuclear reactors in operation with a total net capacity of 4.4 GWe. There are no reactors under construction.

The share of nuclear in electricity production was 33% in 2021. In the past 10 years, nuclear power production was relatively constant, but will increase with the Olkiluoto-3 plant that started operation in 2023. The share of renewable energy in electricity production is 30%

without hydro energy and 52% with hydro power in 2021 (Figure 27). The growth rate for renewables without hydro power was 12% per year in the decade 2011-2021.

Figure 27: Electricity generation in Finland (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

The construction of Finland's fifth reactor, the 1.6 GW reactor at Olkiluoto-3 started in August 2005 and was originally scheduled to begin operations in 2009. Olkiluoto-3 was finally connected to the grid in 2022 and started regular operation in 2023 with a delay of 13 years.

In the Finnish National Climate and Energy Plan (Ministry of Economic Affairs and Employment, 2019), a second new reactor is planned to start operation at the end of the 2020s. In 2007, the group Fennovoima was set up as a non-profit cooperative of power companies and industry. In March 2014, Russian state nuclear operator Rosatom, through subsidiary company RAOS Voima Oy, completed the purchase of 34 percent of the Finnish company Fennovoima for an undisclosed price and then in April 2014 a "binding decision to construct" Hanhikivi-1, a 1,200 MW Russian-designed VVER pressurised water reactor, was announced (M. Schneider et al., 2022). The original plan was to start construction in 2023 and begin commercial operation in 2029. But the Russian attack on Ukraine considerably changes the Finnish plans. On 2 May 2022, Fennovoima announced that the contract with Rosatom to build the Hanhikivi-1 reactor was terminated "with immediate effect" (M. Schneider et al., 2022). In December 2022, the Dispute Review Board (DRB) confirmed that Fennovoima had unlawfully terminated the contract for the construction of Hanhikivi-1 nuclear power plant, which gives Rosatom the right to claim damages from Fennovoima. Damages will be determined in additional proceedings. The mechanism of referring to the DRB is provided for in the contract between Fennovoima Oy and RAOS Project Oy. Thus, the legal proceedings between both Parties about the financial compensation will continue. The Finnish revised integrated National Energy and Climate Plan

submitted in 2024 to the European Commission reports that a total of 10 to 20 SMRs are currently being investigated for the production of electricity and heat with a total thermal output of 1 to 3 GW (Autorité de Sûreté Nucléaire [ASN] et al., 2023; Ministry of Economic Affairs and Employment, 2024). The Finnish government supports research on SMR projects. As these considerations are still in the research phase, they have not been included in the scenario for Finland described below.

In the projection for Finland, we assumed that the current applications for lifetime extensions for the reactors Loviisa 1 and 2 will be granted, then these plants will continue operation almost until 2050. Licenses for lifetime extension was already given to reactors Olkiluoto 1 and 2 until 2038 and the updated NECP reports about plans to extend lifetimes to 2048 or 2058. The Hanhikivi-1 reactor has been stopped, and the updated NECP does not include new nuclear constructions (Ministry of Economic Affairs and Employment, 2024). The resulting capacities, taking into account the lifetime extensions are depicted in Table 4.

Table 4: Nuclear capacities in Finland in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Finland scenario, based on NECP	4.37	4.37	4.37	4.37	4.37	3.89

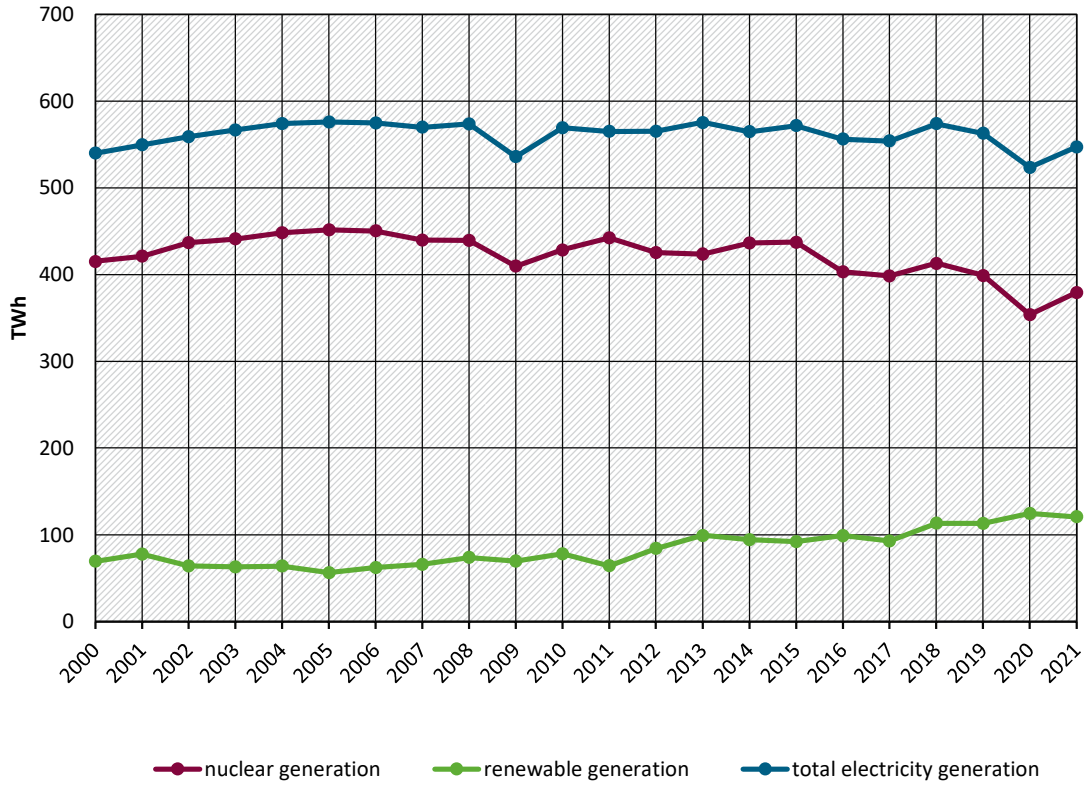
Source: Öko-Institut

2.4.2.5 France

According to IAEA Power Reactor Information System (PRIS), France has 57 nuclear reactors in operation with a total net capacity of 63 GWe. Flamanville-3 with a capacity of 1.62 GWe became operational in September 2024, the first new new reactor since Civaux-2 in 1999.

The share of nuclear in electricity production was 69% in 2021. In the past 10 years, nuclear power production decreased by 14.2% from 442.4 TWh in 2011 to 379.4 TWh in 2021, as shown in Figure 28 (BP, 2022). The share of renewable energy in electricity production was 27% in 2023 and renewables (without hydro electricity) increased by 11% per year in the past decade (Energy Institute, 2024).

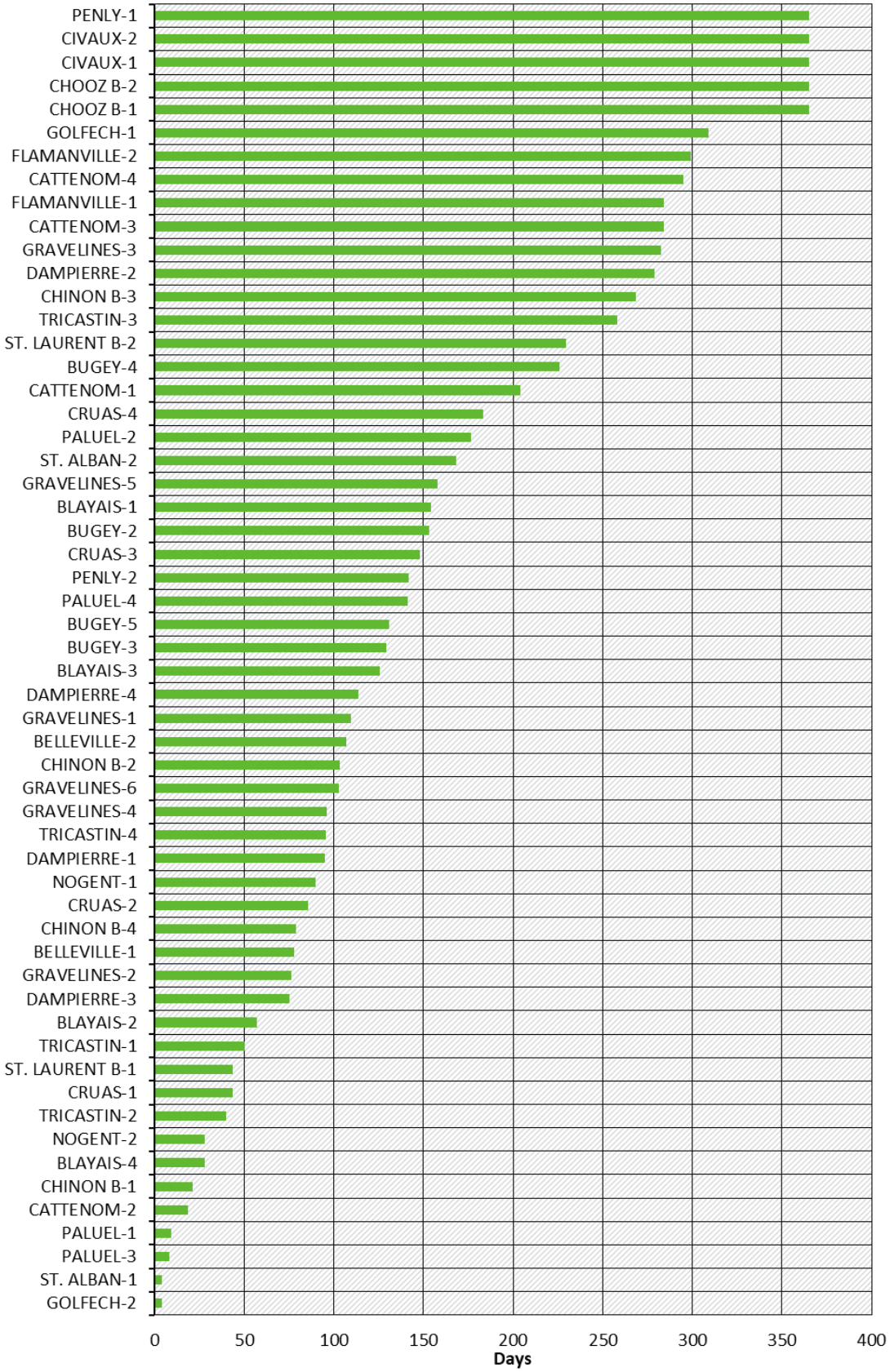
Figure 28: Electricity generation in France (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

In 2022 more than half of the nuclear power plants in France were shut down for long periods and nuclear electricity generation dropped to a historic low of 295 TWh, 30% below the level of 2018. In August, out of a total of 61 GW of existing nuclear power plant capacity in France, 33 GW were switched off. The average unavailability across all reactors was 118 days in France in 2022 (Figure 29). In 2018, this was an average of 86 days per reactor, meaning that the long outage of many nuclear power plants has been a problem in France for years.

Figure 29: Outage of French nuclear power plants in 2022 in days



Source: (IAEA, 2025), evaluation Öko-Institut

In 2022, 12 of the newest and largest reactors in France were shut down due to stress corrosion cracks, which occurred in three reactors. Nine other reactors of the same type were then shut down to investigate whether they were also affected by the cracks. Twenty reactors were shut down for maintenance, seven of which were not operating due to a ten-year safety review throughout the year. In the summer, the production of the nuclear power plants also had to be curtailed cooling water of the nuclear power plants would have heated up the rivers too much. Here, the French government had granted an exemption so that discharges were also permitted at higher river water temperatures, but even these exceptions were no longer sufficient.

Due to the reactor outages in France, electricity production from nuclear power decreased by 22% or 81 terawatt hours compared to the previous year. This significant production gap had to be replaced in the European electricity network by neighbouring countries. In 2023, nuclear production increased by 15% compared to the historic low in 2022, but was still 20% lower with 338 TWh at the level of the year 1992, when the six most recent units had not yet started operation (M. Schneider & Froggatt, 2024).

Despite these substantial problems, France will continue to rely on nuclear energy. The first final French Integrated National Energy and Climate Plan (European Commission [EC], 2020) from 2020, expects a nuclear electricity production of 371 to 382 TWh in 2028. This is about the level of nuclear electricity production in 2021. The updated French National Energy Climate Plan from 2024 increased the target to 400 TWh in 2030 but includes a conservative assumption of 360 TWh if further problems with the reactor fleet occur (Gouvernement de la France, 2024).

The French president announced on 10 February 2022 a “French nuclear renaissance”. In his speech, the French president announced to extend the lifetime of existing nuclear plants beyond 50 years, and that he “wishes that six EPR2 be built and that we launch the studies for the construction of eight additional EPR2”. And at the moment, the EPR2 reactors do not even exist in form of a clear technical design concept. The government administration estimated in October 2021 in an internal note that 19 million engineering hours still had to be deployed to get from “basic design” to the “detailed design” stage and that, if everything goes well, the first EPR2 could start up by 2039–2040 (ibid). In case unexpected industrial difficulties occur—as they have in the past and do currently—it could take until 2043 to commission the first EPR2, the project review states (French Government, 2021). France also faces problems in financing the new nuclear reactors and finance for the 6 new reactors is not yet secured. Current legislation however stipulates the closure of a dozen reactors until 2035 and the reduction of the nuclear share in the power mix to 50 percent (M. Schneider et al., 2022).

Until 2035, we therefore assume the same level of nuclear capacities as in current years. In the high scenario, we took into account that by 2040, the 9. GWe from additional EPR2 reactors will be operating and by 2050 the potential planned 13 GWe of additional constructions. In the low scenario, we considered further delays in the construction of the 6 EPR2 reactors leading to a start of operation only by 2045 and a delay of additional new constructions to the period after 2050.

By mid-2024, the average age of the 56 nuclear power reactors will surpass 39 years (M. Schneider & Froggatt, 2024). 50 operating units are already older than 31 years and 18 units older than 41 years. Extending their operation beyond 40 years requires major upgrades. Extending their operation beyond 40 years requires major upgrades (M. Schneider et al., 2022). The upgrading to longer lifetimes will need substantial investments which have not yet been secured. According to EDF figures, extension of reactor lifetimes from 40 to 50 years would cost more than €35/MWh (ibid). The nuclear generation costs will therefore increase in the future years. The Energy Regulatory Commission calculated the electricity costs for the French nuclear

fleet in the period 2026 – 2030 between €$_{2022}$ 53.8 and 60.7/MWh. (ibid). In addition, the required upgrades will result in extended reactor outages, thus the availability of the nuclear fleet will decrease for many years. ASN, the French nuclear authority, has accepted extended timescales of refurbishments and upgrades in the past, e.g. measures it requested in 2012 were still not fully implemented in 2022, and some sources anticipate that the programme may only be completed by 2039 (Lauf et al., 2021; M. Schneider et al., 2022; M. Schneider et al., 2023).

The projection until 2050 strongly depends on the assumptions related the lifetimes of existing reactors in France. We assumed 50 years in the low scenario scenario and 60 years in the high scenario.

Table 5: Nuclear capacities in France in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
France low scenario, lifetime 50 years	63.0	59.9	38.3	15.3	17.3	17.3
France high scenario, lifetime 60 years	63.0	62.6	62.7	68.9	49.1	35.5

Source: Öko-Institut

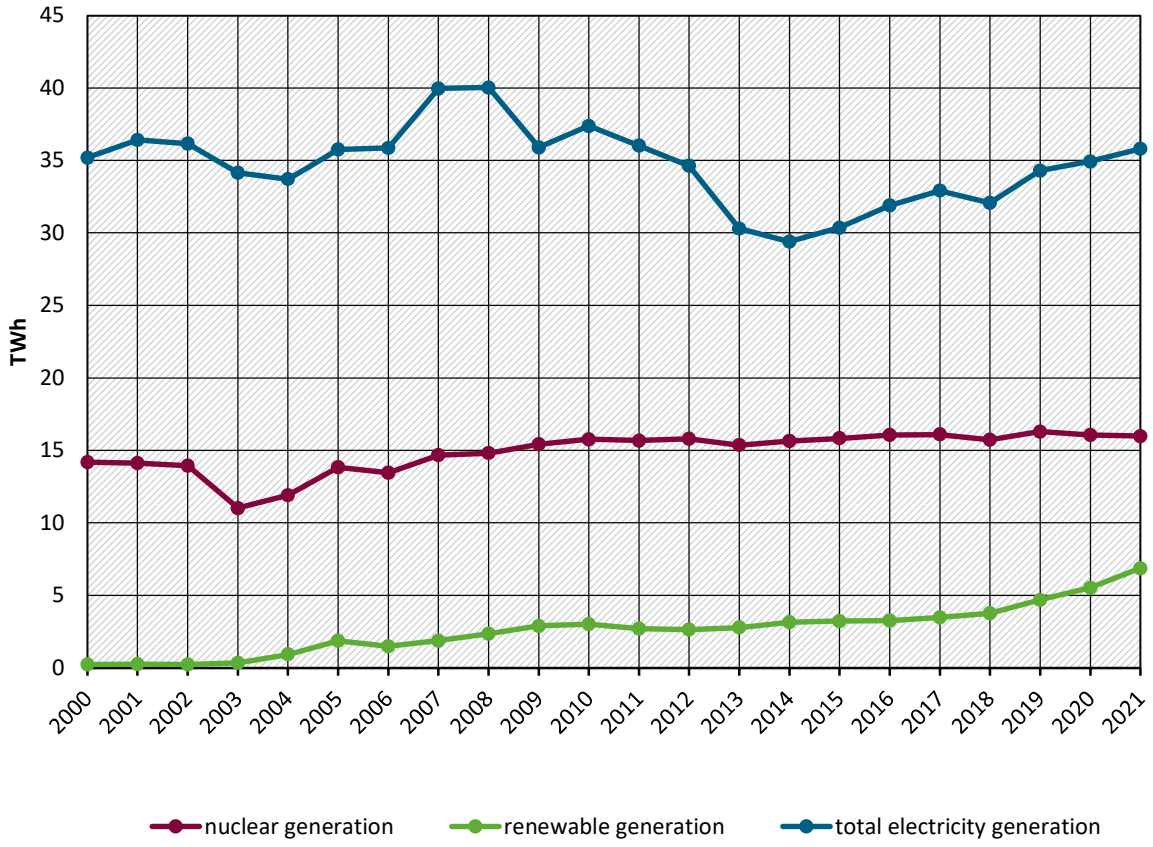
Table 5 shows that a lifetime extension from 40 to 50 years will lead to a strong decline of the French nuclear capacity after 2030, because the planned new reactors cannot replace the capacities that will be decommissioned. But also a lifetime extension of 60 years will lead to a declining nuclear fleet with more than 10 GWe of installed capacity less in 2045 than in 2023, because the planned nuclear reactors will not fully replace the capacity that will be shut down. It has to be taken into account that the electricity production will decline stronger than the capacities because it is unlikely that the very old reactors will operate at full capacity all the time taking into account the current problems leading to low availabilities.

2.4.2.6 Hungary

According to IAEA Power Reactor Information System (PRIS), Hungary has 4 nuclear reactors in operation with a total net capacity of 1.9 GWe. There are no reactors under construction.

The share of nuclear in electricity production was 45% in 2021. In the past 10 years, nuclear power production was relatively constant (Figure 30). The share of renewable energy in electricity production has increased to 31%. The growth rate for renewables without hydro power was 14.8% per year in the decade 2014-2024 (Energy Institute, 2025).

Figure 30: Electricity generation in Hungary (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

The Hungarian Atomic Energy Authority (HAEA or OAH) has approved the operating lifetime extension of all four existing reactors until mid to end 2030s. In December 2022 The Hungarian parliament approved plans to further extend the lifespan of the four units at Paks site (WNA, 2024h).

Since more than a decade, plans have been developed to build two new reactors at the Paks site – referred to as Paks II, but the construction still did not start. In March 2009, the Hungarian Parliament gave preliminary approval to this plan (WNA, 2023). Rather than proceeding with an open tender, in January 2014 the government signed an agreement with Rosatom to build two reactors at Paks with a capacity of 2.4 GWe. The units were originally scheduled to start operating in 2025/2026.

A €10 billion financing deal from Russia was agreed in February to cover 80% of the anticipated project cost, with Hungary to repay the loan over 21 years of operation, starting in 2026 (ibid). The interest rate would be set below 4% for 11 years then 4.5% then 4.95%. The loan agreement was adjusted in May 2019 such that Hungary would start repaying only once the two reactors are connected to the grid (ibid). Earlier in February 2017 the Russian President said that Russia was prepared to finance 100% of the plant if necessary. In May 2021 Hungary's finance ministry stated that it had agreed with the Russian government that the loan repayments would commence in 2031 (ibid). Despite of the general EU sanctions against Russia, the financing scheme and construction continues. Hungary achieved that Paks II is excluded from future EU sanctions. This was the concession to Hungary as part of the agreement of the 14th EU sanction package against Russia.

Fuel is to be supplied solely by Rosatom for the first 10 years of operation. This aspect of the deal was challenged by the EU's Euratom Supply Agency (ESA), backed by the European Commission (EC), on the basis of there being no alternative supplier for the particular fuel design in the event of a supply disruption. The contract was later approved by the ESA.

Since its approval, there have been increasing concerns over the impact of hotter summers on the cooling water availability due to higher water temperatures from the Danube River, especially if both Paks I and II are in operation. Within the Environmental Impact Assessment (EIA) process the solution to this problem was to reduce output from the plants when cooling water availability was limited, which would affect the economics of the project and the demand-supply grid balance (M. Schneider et al., 2022). In August 2022 the HAEA issued the construction licence for the two VVER-1200 PWRs at Paks II, to be built by Rosatom (WNA, 2023).

In our projection we assumed that the Paks II units will only become operational after 2035, taking into account the current delays. In addition, we assumed a lifetime extension of the existing Paks reactors to a maximum of 60 years. The result in capacity development is shown in Table 6.

Table 6: Nuclear capacities in Hungary in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Hungary planned capacity expansion	1.92	1.91	1.92	4.04	3.22	2.40

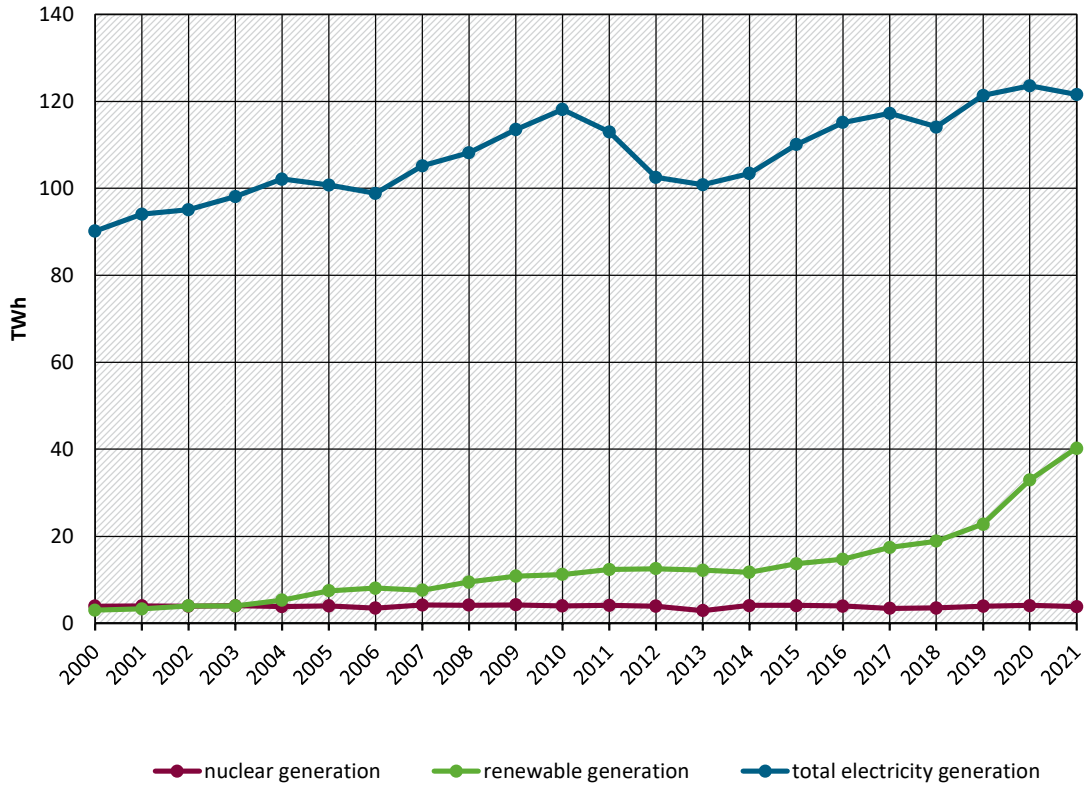
Source: Öko-Institut

2.4.2.7 Netherlands

According to IAEA Power Reactor Information System (PRIS), the Netherlands have 1 nuclear reactors in operation with a total net capacity of 0.482 GWe and 1 reactors has been permanently closed. The Dutch nuclear plant Borssele started operation in 1973 and with 52 years of operation time it is the oldest nuclear plant in the EU. There are no reactors under construction.

The share of nuclear in electricity production was 3.3% in 2021. In the past 10 years, nuclear power production decreased by 34% from 69 TWh in 2011 to 46 TWh in 2021 (Figure 31). The share of renewable energy in electricity production is 38%. The growth rate for renewables without hydro power was 15% per year in the decade 2011-2021.

Figure 31: Electricity generation in the Netherlands (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

The closure of the only nuclear power plant in the Netherlands, Borssele, was planned for 2033. The first Dutch NECP stated: "*As the government indicated in its letter dated 6 November 2018, nuclear power is one of the options for the future energy mix. A number of studies reveal that for 2050, nuclear power could be a cost-effective option and that a positive business case could be one of the long-term options. Given the lead times, additional nuclear power for 2030 does not seem likely in the Netherlands*" (Ministry of Economic Affairs and Climate Policy, 2019) Until 2023, there were no concrete plans for new nuclear plants, but nuclear power was not entirely ruled out.

This situation changed with the new right-wing government in 2024 of the parties PVV (Partij voor de Vreijheid), VVD (Volkspartij voor Vrijheid en Democratie), NSC (Nieuw Sociaal Contract) and BB (BoerBurgerBeweging). The new updated National Climate and Energy Plan includes a further unlimited lifetime extension of the Borssele nuclear plant and steps for the construction of two new nuclear plants (Ministry of Economic Affairs and Climate Policy, 2024). The updated NECP states that additional nuclear generation does not seem likely for 2030 but considers such plants available by 2035. The document also mentions the development of SMRs without a timeline. The climate fund has allocated fund for studies related to the lifetime extension and new nuclear constructions. According to M. Schneider and Froggatt (2024), the favoured option are two reactors of around 1.5 GW capacity each with a construction duration of 8 years. This is rather unlikely given the recent European experiences and was also questioned by the Dutch "Expert team Energy System 2050" that considered a period by 2040 more likely (M. Schneider & Froggatt, 2024). Meanwhile a technical feasibility study on the construction of two reactors at Borssele have been commissioned (ibid).

Taking into account that Borssele plant was constructed for a lifetime of 40 years and already runs 52 years, our projection includes operation until 2033 which is a lifetime of 60 years. In our high scenario, we consider two new nuclear plants for the Netherlands operating after 2040. The low scenario does not include new nuclear plants in the Netherlands because a government change could suspend the current plans and because financing for the construction or the construction entity for the two plants has not yet been secured and high investment cost needs could still change the future decisions.

Table 7: Nuclear capacities in the Netherlands in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Netherlands, low scenario	0.48	0.48	0,48	0.0	0.0	0.0
Netherlands high scenario	0.48	0.48	0.0	3.0	3.0	3.0

Source: Öko-Institut

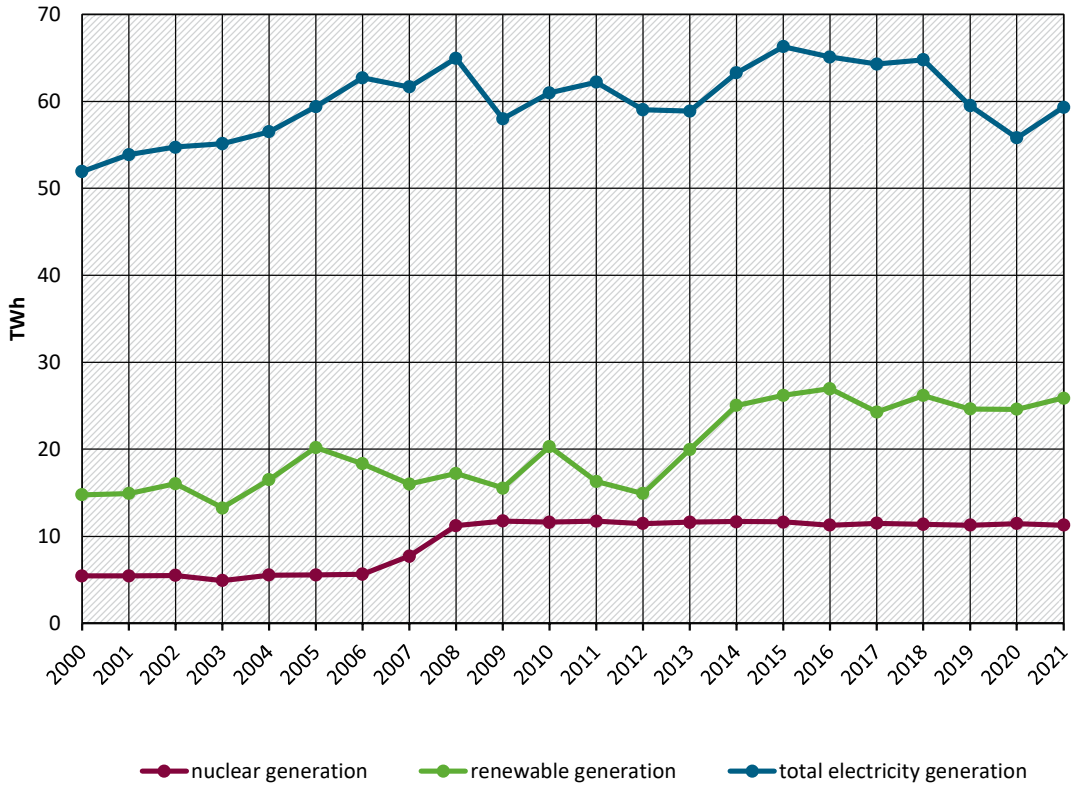
2.4.2.8 Romania

According to IAEA Power Reactor Information System (PRIS), Romania has 2 nuclear reactors in operation with a total net capacity of 1.3 GWe. The reactors are the only CANDU reactors (Canadian design)[10] operating in Europe. There are no reactors under construction.

The share of nuclear in electricity production was 19% in 2021. In the past 10 years, nuclear power production remained at a constant level. The share of renewable energy in electricity production is 15% and 44% when hydro power is included in renewables. The growth rate for renewables without hydro power was 19% per year in the decade 2011-2021.

[10] The CANDU (CANada Deuterium Uranium) is a Canadian pressurized heavy-water reactor design. The heavy water allows CANDU reactors to run on unenriched natural uranium, or uranium mixed with a wide variety of other materials such as plutonium and thorium.

Figure 32: Electricity generation in Romania (TWh)



Source (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

The Romanian updated National Climate and Energy Plan includes the construction of two new reactors at the Cernavoda site where the current reactors are located. Cernavoda 3 and 4 units have a total net capacity of 3.3 GW from 2035 onwards. Romania had signed an agreement with CGN (China Nuclear Power Engineering Co) to build the new reactors. In 2020, the Romanian prime minister announced that the country would no longer partner with CGN for the project. In October it was announced that the USA would finance the construction of Cernavoda 3&4, as well as the refurbishment programme of unit 1 (WNA, 2024e). Nuclearelectrica announced construction start for 2024 and start of operation in 2031. Given the recent timelines of completion of nuclear plants, this schedule seems highly optimistic. In addition, in November 2021, SNN signed an agreement" with U.S. small modular reactor (SMR) vendor NuScale to build a 462 MW facility at a former coal plant in Romania. In May 2023 the USA, along with multinational public-private partners from Japan, South Korea and the United Arab Emirates, announced funding of up to $275 million for the deployment of the SMR in Romania.

For the projection for Romania, the construction of the 2 new reactors at Cernavoda and the SMR reactor were taken into account.

Table 8: Planned nuclear capacities in Romania in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Romania projection	1.30	1.30	4.30	4.76	4.76	4.11

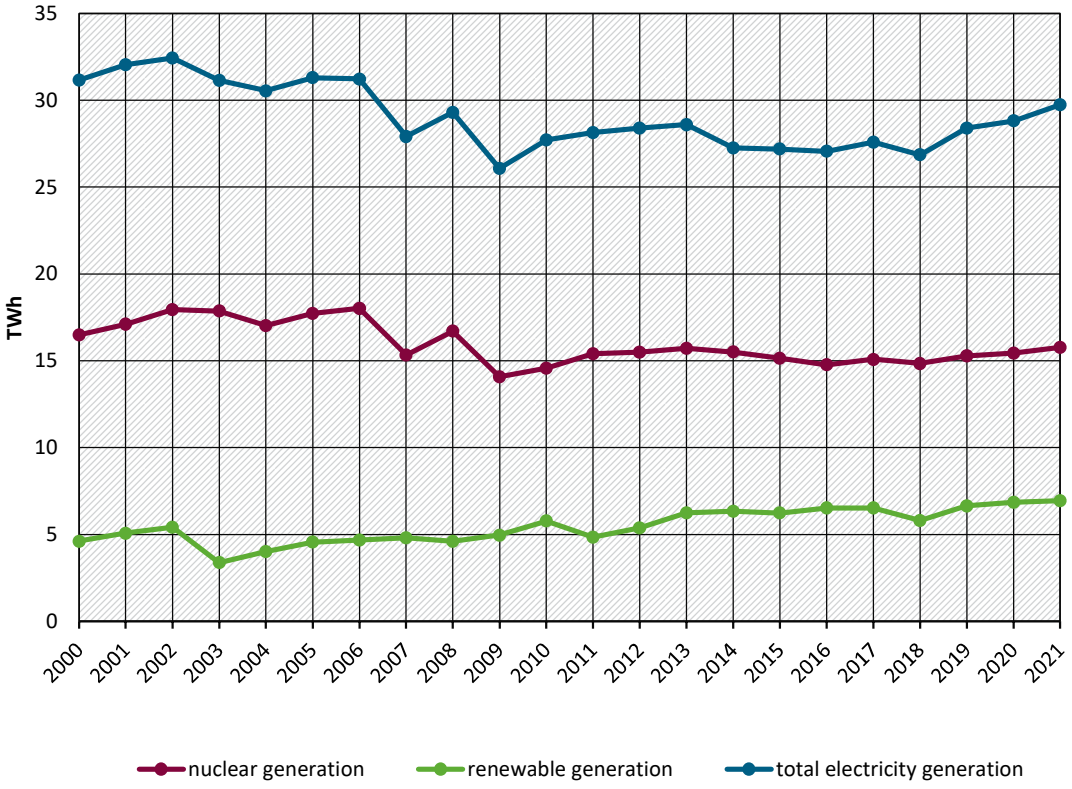
Source: Öko-Institut

2.4.2.9 Slovakia

According to IAEA Power Reactor Information System (PRIS), Slovakia has 5 nuclear reactors in operation with a total net capacity of 2.3 GWe and 3 reactors have been permanently closed. There is one reactorof 0.44 GWe under construction.

The share of nuclear in electricity production was 53% in 2021. In the past 10 years, nuclear power production remained at a rather constant level. The share of renewable energy in electricity production is 9% and 23% if hydro power is included in renewables. The growth rate for renewables without hydro power was 8% per year in the decade 2011-2021.

Figure 33: Electricity generation in Slovakia (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

According to M. Schneider and Froggatt (2024), Slovakia plans to operate Bohunice-3 and -4 until 2044 and 2045 respectively and Mochovce-1 and -2 until 2058 and 2060.

Mochovce unit 4 started in 1986, stopped in the 90s and restarted in 2008 and is still under construction. It was expected to start operation in 2023, delayed from earlier plans for 2018 and 2019, but operation will be further delayed and is now expected to become operational in 2025 (ibid). The Mochovce project faced delays due to the post-Fukushima requirement for enhanced safety standards, complications for obtaining operational permits, and challenges with outdated regulations and design specifications. It was also discovered that some materials used, did not meet the specified criteria.

In our projection we took into account the additional Mochovce unit 4. Slovakia expects to become a net electricity exporter after finalisation of this plant. In addition, in 2024, the Slovak government approved plans to develop a new unit at Bohunice with a capacity of around 1,200 MW and a target operational date of 2040.

Table 9: Planned nuclear capacities in Slovakia in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Slovakia projection	2.30	2.30	2.30	2.30	2.30	1.70

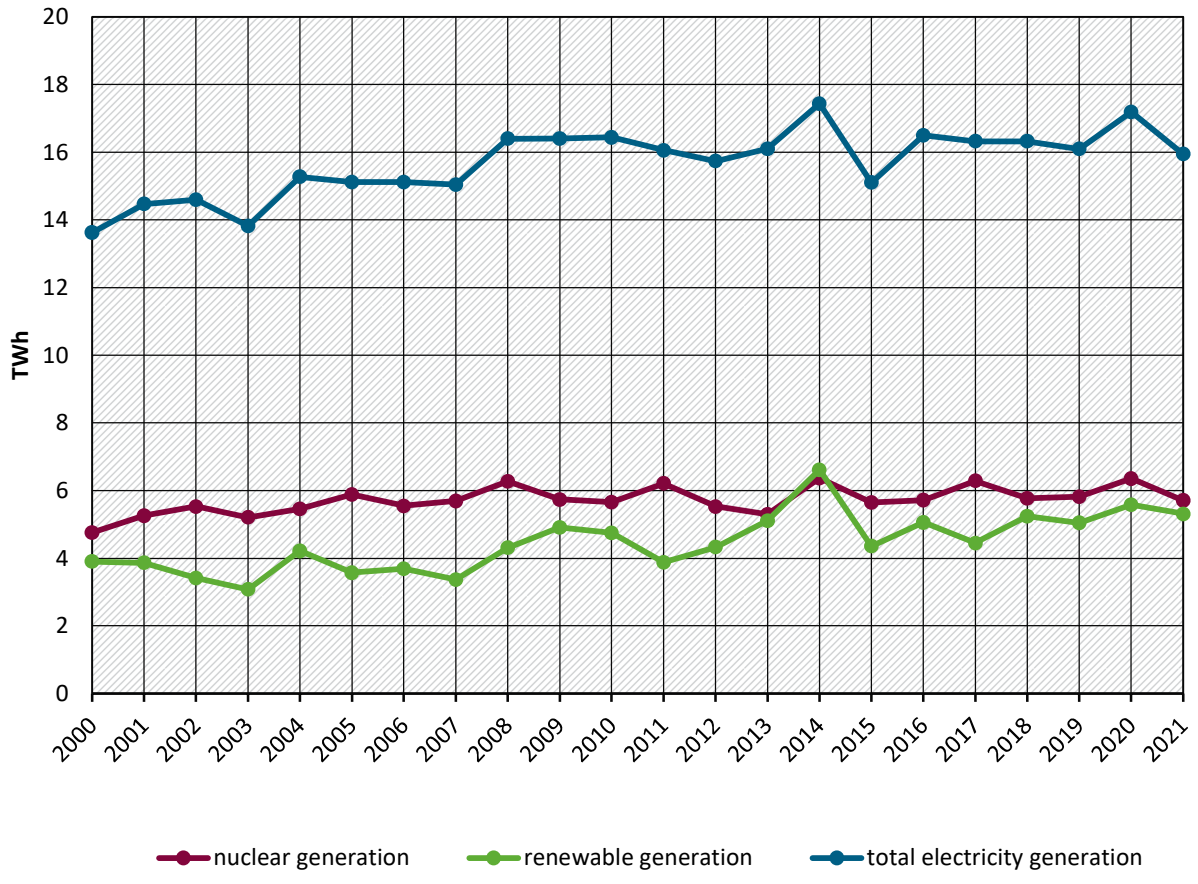
Source: Öko-Institut

2.4.2.10 Slovenia

According to IAEA Power Reactor Information System (PRIS), Slovenia has 1 nuclear reactor in operation with a total net capacity of 0.696 GWe. There is no reactor under construction.

The share of nuclear in electricity production was 36% in 2021. In the past 10 years, nuclear power production remained at a rather constant level. The share of renewable energy in electricity production is 40% if hydro power is included. The growth rate for renewables without hydro power was 10% per year in the decade 2013-2023.

Figure 34: Electricity generation in Slovenia (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

According to the National Energy and Climate Plan (Government of the Republic of Slovenia, 2024), the Slovenian governments wants to extend the lifetime of the existing reactor until 2043. By 2028 a decision should be taken whether a new nuclear unit will be built or not. The NECP assumed a capacity of 1.1 GW for the new nuclear plant. We used a low and high scenario reflecting the situation with and without a new reactor in Slovenia in Table 10.

Table 10: Planned nuclear capacities in Slovenia in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Slovenia low scenario (no new construction)	0.69	0.69	0.69	0.69	0.0	0.0
Slovenia Republic high scenario (new construction)	0.69	0.69	0.69	0.69	1.10	1.10

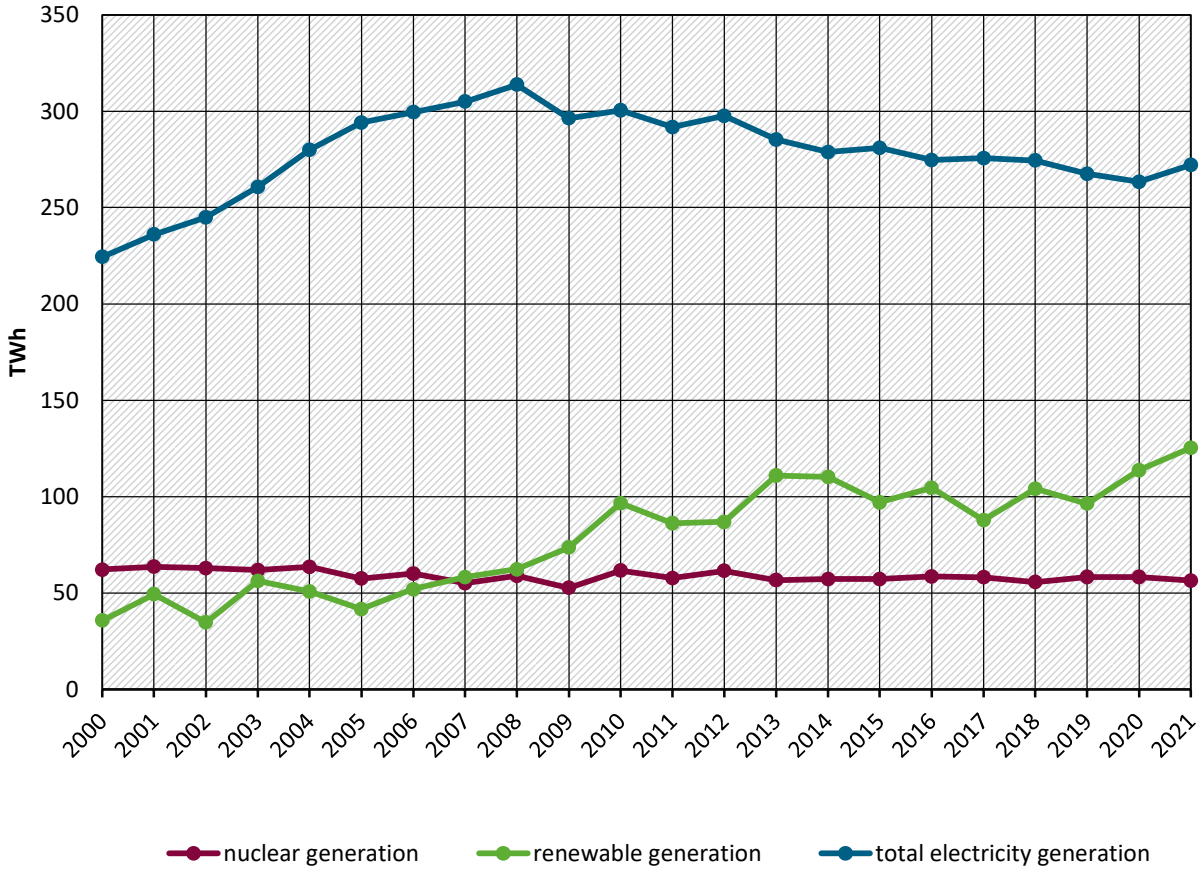
Source: Öko-Institut

2.4.2.11 Spain

According to IAEA Power Reactor Information System (PRIS), Spain has 7 nuclear reactors in operation with a total net capacity of 7.1 GWe and 3 reactors have been permanently closed. There are no reactors under construction. The average age of the Spanish reactors is 40 years (M. Schneider & Froggatt, 2024).

The share of nuclear in electricity production was 21% in 2021. In the past 10 years, nuclear power production decreased slightly by 0.2% per year. The share of renewable energy in electricity production is 35%, if hydro is included in renewables, the share of renewables is 46%. The growth rate for renewables without hydro power was 5.6 per year in the decade 2011-2021.

Figure 35: Electricity generation in Spain (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

Spain decided a phase-out of nuclear energy. According to the Spanish National Climate and Energy Plan (EC, 2020) four of the existing seven reactors (4 GW) will be closed by 2030.. This decrease is part of an "*organised, phased and flexible closure plan for the existing nuclear reactors,*

which foresees the closure of another three reactors in the period between 2031 and 2035" (Government of Spain, 2020). Thus, the nuclear phase-out is expected to be completed by 2035. The phase-out plans are not supported by the opposition Party Partido Popular (PP), but Prime Minister Sánchez confirmed the phase-out plans.

For the year 2030, the Spanish National Climate and Energy Plan foresees a total installed capacity in the electricity sector of 161 GW, 50 GW of which will be wind energy; 39 GW solar photovoltaic; 27 GW combined gas cycles3; 16 GW hydroelectric energy; 9.5 GW pumping; 7 GW solar thermal electric; and 3 GW nuclear (EC, 2020). The reduction of the nuclear capacity is offset by the significant penetration of renewable electricity generation technologies, in particular solar and wind technologies.

The projection for Spain reflects the National Climate and Energy Plan in which nuclear plants will close after their lifetime ceased by 2035.

Table 11: Nuclear capacities in Spain in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Spain (based on NECP)	7.12	3.18	0.0	0.0	0.0	0.0

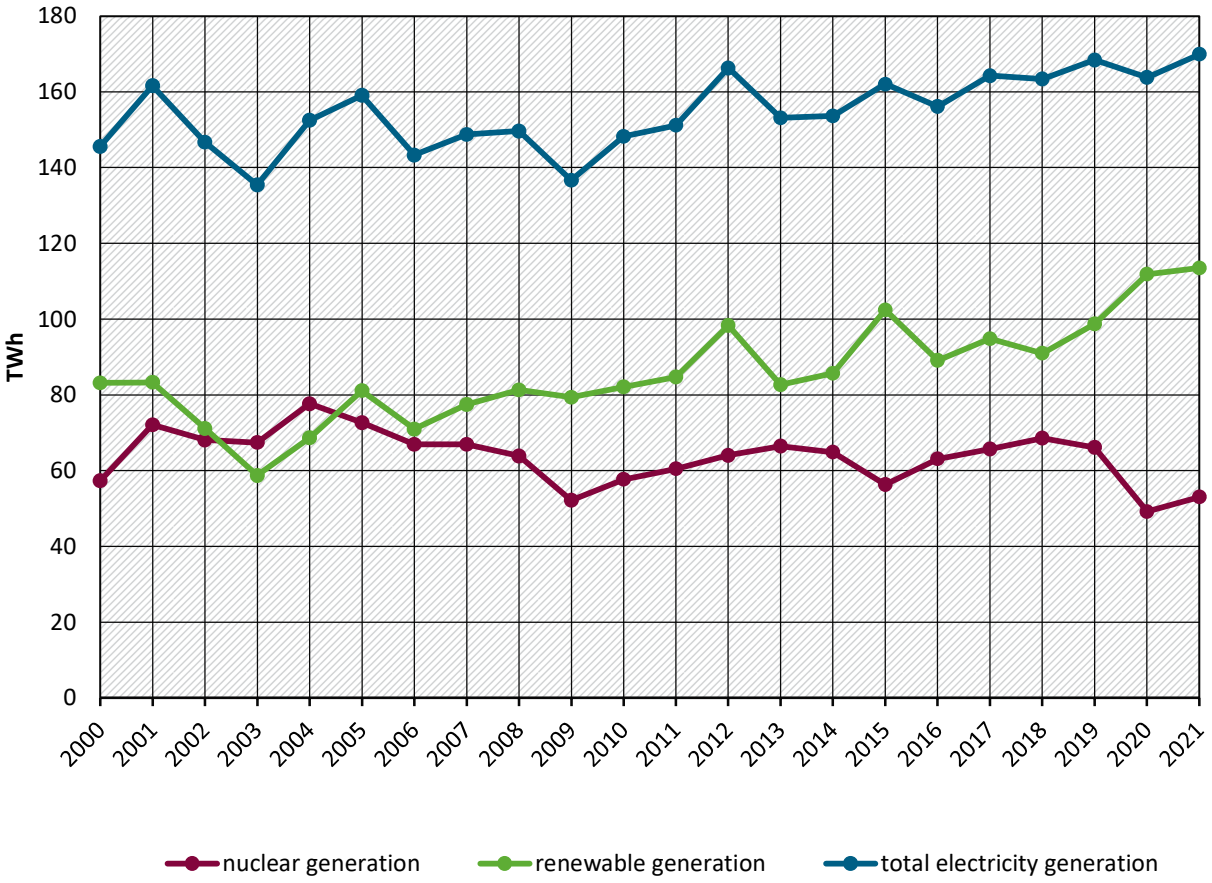
Source: Öko-Institut

2.4.2.12 Sweden

According to IAEA Power Reactor Information System (PRIS), Sweden has 6 nuclear reactors in operation with a total net capacity of 7GWe and 7 reactors have been permanently closed. There are no reactors under construction.

The share of nuclear in electricity production was 31% in 2021. In the past 10 years, nuclear power production decreased by 1.3% per year. Between 2018 – the most recent peak and 2021, nuclear production sank from 68.5 TWh to 53.1 TWh, a decline of 22%. The share of renewable energy in electricity production is 25%, if hydro is included in renewables, the share of renewables in 67%. The growth rate for renewables without hydro power was 9% per year in the decade 2011-2021.

Figure 36: Electricity generation in Sweden (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

The initial Swedish National Climate and Energy Plan from 2020 (EC, 2020) described a scenario that expands renewable electricity production and a phasing-out of existing nuclear power. The scenario was based on the closure of reactors 1 and 2 of the Ringhals nuclear power plant in 2020 and 2019, respectively, as per the owners' announcement. The remaining six reactors will be phased-out after 60 years of operation, based on information provided by the owners. The existing nuclear power plants will continue to operate for as long as they are profitable and safety requirements are met, which may be either shorter or longer than the expected 60 years. It is expected that approx. 60% of nuclear power will have been phased-out by around 2040, with 25 TWh remaining in the electricity system.

The new government elected in 2022 changed the nuclear policy and in the updated National Energy and Climate Plan from 2024, "*nuclear expansion is the single most important measure to reduce our emissions nationally*" (Swedens Ministry of Climate and Enterprise, 2024). In 2023, the Swedish government presented a roadmap to build two new nuclear plants of a total capacity of 2.5 GW by 2035 and up to ten large reactors by 2045. The capacities and location of these additional reactors has not been included in the NECP and the report also lacks targets for future nuclear capacities. The Swedish energy supplier Vattenfall currently plans a project with five SMRs from GE Vernova or three Rolls-Royce SMR reactors on the Värö Peninsula with a total output of approximately 1.5 GW and is also exploring the possibility of, in a next step, building an additional 1 GW on the site where Ringhals 1 and 2 are located. Final investment decisions will be made later in the process.[11] It is also unclear whether five SMRs will really be less

[11] https://group.vattenfall.com/press-and-media/newsroom/2025/vattenfall-selects-suppliers-on-the-journey-towards-new-nuclear-power, last accessed on 01.10.2025

expensive than one large nuclear reactor. These specific plans are far lower in additional capacity than the announcements of the Swedish government in 2023. The Swedish state may be involved in form of a direct ownership in the project.[12]

These plans were taken into account in the projection of nuclear capacities for Sweden.

In the low scenario, we assumed that after 2040 Forsmark-1 and -2 as well as Ringhals-3 and -4 reactors would be shut down and in 2045 only the newest reactors Forsmark-3 and Oskarshamn-3 would still operate. Their lifetime will also exceed 60 years before 2050 and they would stop operation between 2045 and 2050. Only one new nuclear plant of 1.5 GW is assumed to be built in the low scenario. This results in a decrease of nuclear capacities after 2040 (Table 12).

In the high scenario, all current nuclear plants are assumed to operate until 2045. Two new nuclear reactors of 2.5 GW would be built before 2040 and two additional ones after 2045 (Table 12). Due to the new reactors, nuclear capacities would increase after 2035.

Table 12: Nuclear capacities in Sweden in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Sweden low scenario	7.00	7.00	7.00	8.50	4.07	1.50
Sweden high scenario	7.00	7.00	7.00	9.50	9.50	5.00

Source: Öko-Institut

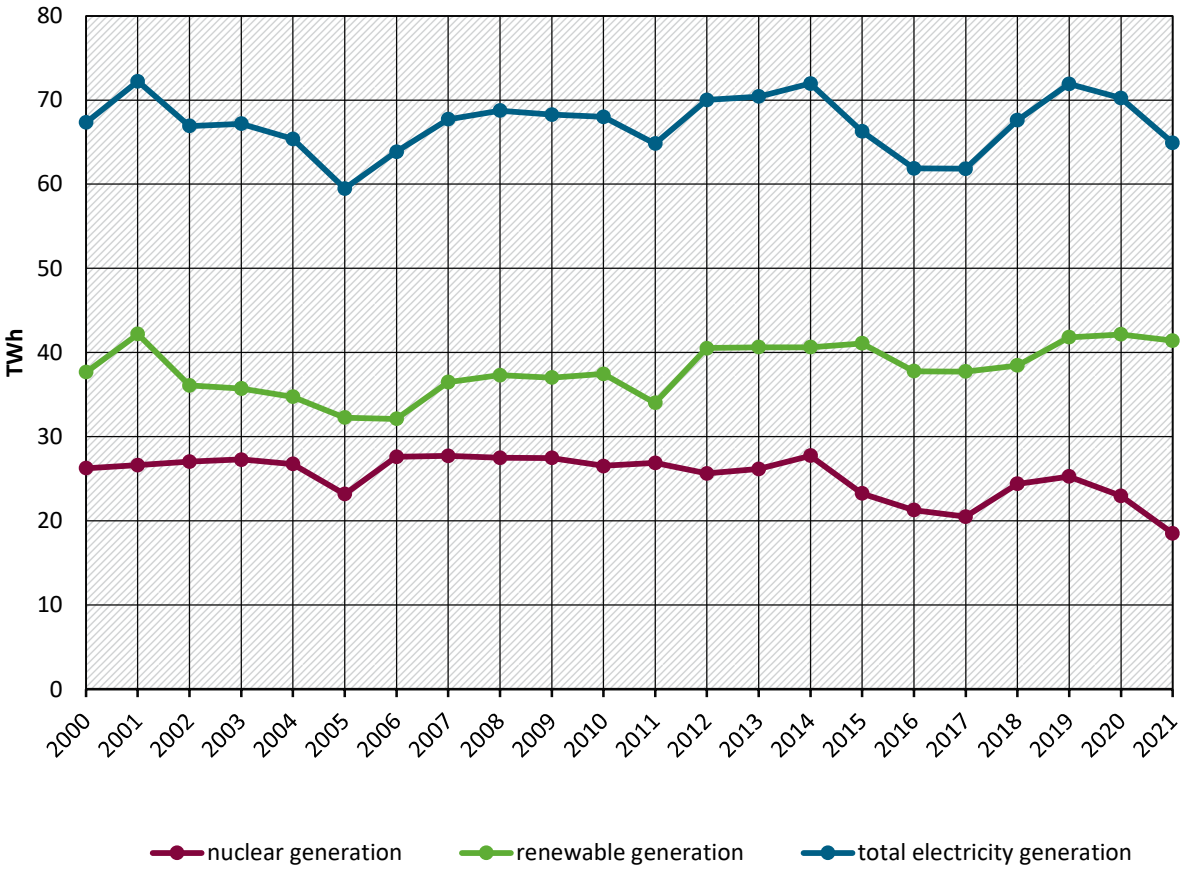
2.4.2.13 Switzerland

According to IAEA Power Reactor Information System (PRIS), Switzerland has 4 nuclear reactors in operation with a total net capacity of 2.97 GWe. There are no reactors under construction.

The share of nuclear in electricity production was 29% in 2021. In the past 10 years, nuclear power production decreased by 3.7% per year from 30 TWh in 2011 to 18.5 TWh in 2021. The share of renewable energy in electricity production (including hydro energy) is 64%. The growth rate for renewables without hydro power was 12% per year in the decade 2011-2021.

[12] https://montelnews.com/news/3c230cef-b228-4027-9496-24b1378481c8/sweden-to-support-vattenfall-nuclear-plan-by-taking-direct-stake, last accessed on 01.10.2025

Figure 37: Electricity generation in Switzerland (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

With an average age of 48.3 years, Switzerland operates the second oldest nuclear fleet (M. Schneider & Froggatt, 2024) (M. Schneider et al., 2022). The Beznau-1 plant with an age of 55 is the oldest commercially operating reactor in the world. Beznau-2 plant is almost 53 years old. The Swiss government envisages lifetime extensions to 60 years for the four remaining plants. There are no plans to build new nuclear plants. In line with the Swiss Energy Act following the 2017 referendum, the Swiss Energy Strategy 2050 does not fix any closure dates for the operating nuclear power plants, but prohibits the construction of new nuclear power plants. In the projection for Switzerland we assumed lifetimes of 60 years for the remaining reactors and a phase-out of nuclear afterwards.

Table 13: Planned nuclear capacities in Switzerland in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Switzerland	2.97	2.23	1.88	0.96	0.0	0.0

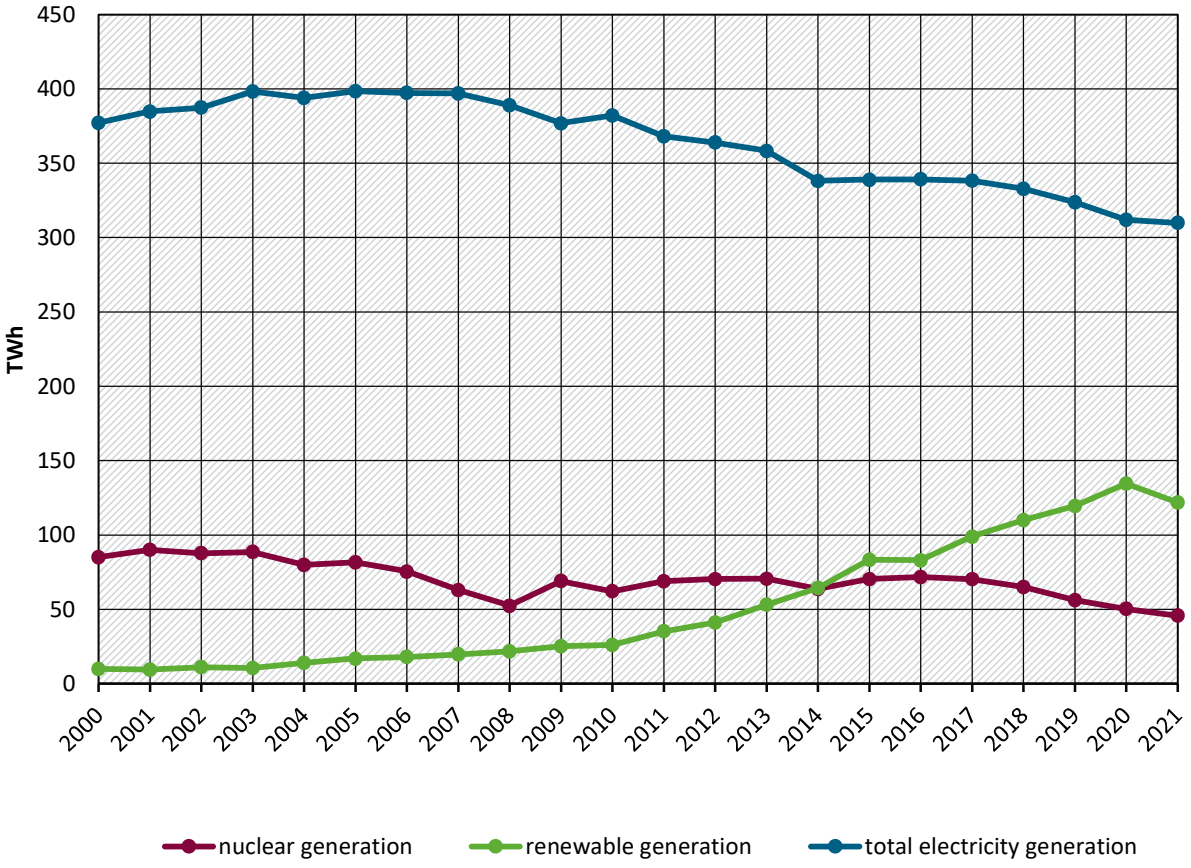
Source: Öko-Institut

2.4.2.14 United Kingdom

According to IAEA Power Reactor Information System (PRIS), the UK has 9 nuclear reactors in operation with a total net capacity of 5.88 GWe and 36 reactors have been permanently closed. There are two reactors under construction.

The share of nuclear in electricity production was 15% in 2021. In the past 10 years, nuclear power production decreased by 34% in the past 10 years from 69 TWh in 2011 to 46 TWh in 2021, the annual decline was 4% in the past decade. The share of renewable energy in electricity production is 47% in 2023. The growth rate for renewables without hydro power was 15% per year in the decade 2011-2021.

Figure 38: Electricity generation in the United Kingdom (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

In April 2022, the UK government has released a new British Energy Security Strategy (HM Government, 2022).

- The main details of the plan are:
- To increase the deployment of nuclear power of up to 24 GW of capacity by 2050 which would amount to 25% of the electricity demand.
- This would be equivalent to eight additional reactors until 2050.
- By 2024 one project should be taken to the final investment decision (Sizewell C), which has already been announced.
- Two further projects, including SMRs, should be decided in the period 2025–2029.
- Four nuclear projects should be built in total by 2030.

However, the strategy also underlines that "any projects would be subject to a value for money assessment, all relevant approvals and future spending reviews". And the Future Nuclear

Enabling Fund with £120 million launched together with the strategy did not provide additional funding to what had been announced earlier.

The objective of 24 GW nuclear capacity stated in the Energy Security Strategy for 2050 was taken into account in the bottom-up projection. The current construction of two reactors at the Hinkley Point site are delayed and are at the moment expected to become operational between 2029-2031. The old Advanced-gas cooled reactors that dominate the existing fleet will however be shut-down earlier and we took into account the closure dates provided by (M. Schneider & Froggatt, 2024) (M. Schneider et al., 2022) which will lead to a decrease in capacity after 2025 because four reactors will be closed in March 2026 before the new Hinkley Point plants will become operational. The objective of 24 GW in 2050 seems very ambitious given the financing and construction problems that the current construction projects are facing. It is neither clear where the necessary investment will come from, nor how UK will manage to build these new reactors much faster than the current projects.

The current new construction of two reactors at Hinkley Point C of 1.63 GW each faced extreme cost increases and delays (M. Schneider & Froggatt, 2024). This is similar compared to other EPR projects, e.g. in France and Finland. Planning permission was granted in 2013 with planned operation in 2025. This is now postponed to 2029-2032. Planned costs initially were calculated at US$$_{2015}$ 30 billion rose to US$ 52-59 billion for the two units.

The UK government and EDF and CGN (China General Nuclear Power Group) had planned for another two EPR reactors of 1.6 GW at the Sizewell Site (Sizewell C) in 2020. This project is still lacking a final investment decision (FID). The British government already invested US$ 3.2 billion for infrastructure development work, but investment from a third party is still needed.

In a low scenario we assume that Hinkley Pont C starts operating in 2030, that two SMRs are build in 2040, but Sizewell C will not be built. In the high scenario, Sizewell C becomes operational after 2040 and but no SMRs are built.

Table 14: Nuclear capacities in the UK in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
United Kingdom, low scenario	5.88	4.45	4.45	5.39	5.39	5.39
United Kingdom, high scenario	5.88	4.45	4.45	8.15	8.15	8.15

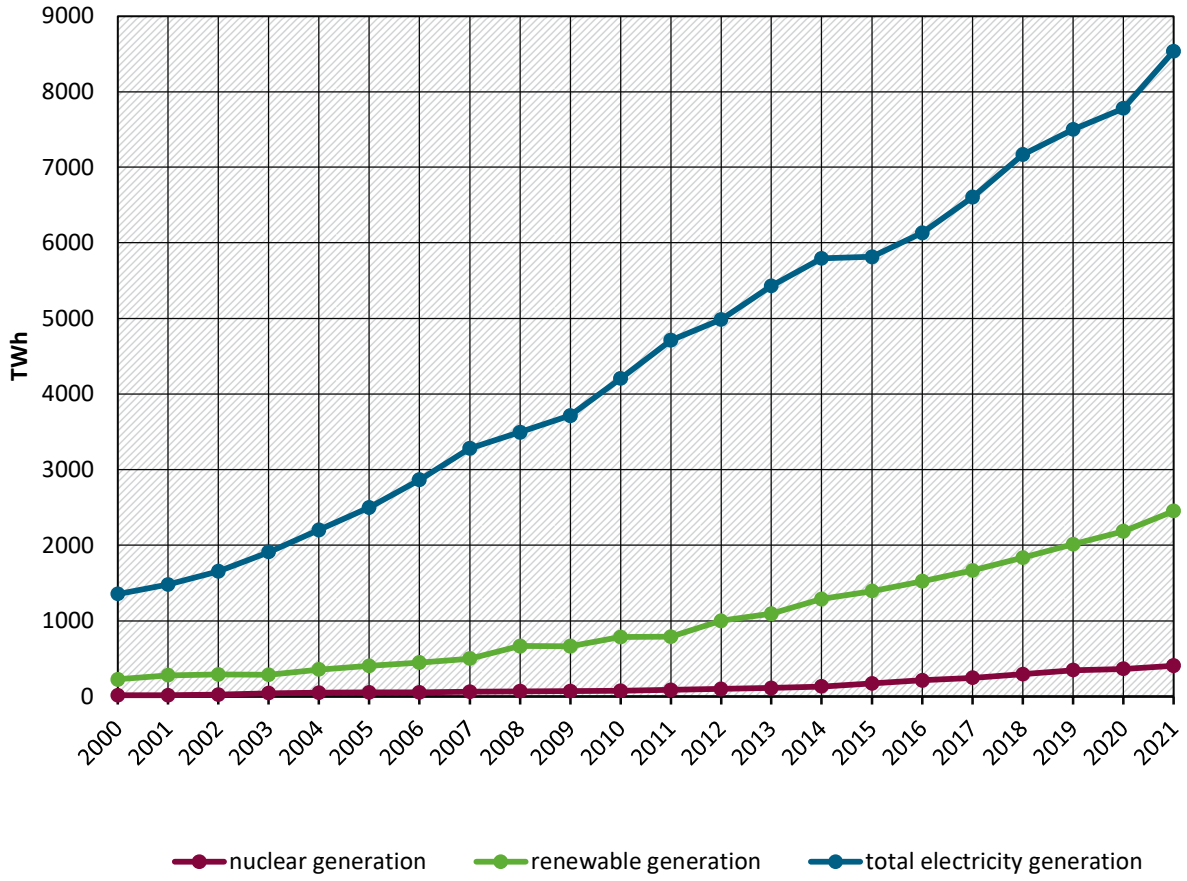
Source: Öko-Institut

2.4.3 Asia

2.4.3.1 China

According to IAEA Power Reactor Information System (PRIS), China has 57 nuclear reactors in operation with a total net capacity of 55 GWe. 28 reactors of a capacity of 28.5 GWe are under construction. This is the highest number of new constructions globally. The share of nuclear in electricity production was 5% in 2023 with total production of 435 TWh. In the past 10 years, nuclear power production grew by 14.6% per year (Energy Institute, 2024). The share of renewable energy in electricity production was 31% with a total generation of 2,894 TWh and renewables increased by 10.2% per year in the past decade.

Figure 39: Electricity generation in China (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

China's Energy Development Strategic Action Plan for the period 2014-2020 established the objective to expand nuclear power capacity to reach 58 GWe by 2020 and to build additional 30 GWe or more after 2020. The 14th Five-year Plan for Modern Energy System established a target of 70 GWe of nuclear capacity for 2025 (The State Council, the People's Republic of China, 2022). In the 13th Five-Year Plan from 2016, six to eight nuclear reactors were to be approved each year, increasing to 10 units each year after 2020. The target for 2020 has only been achieved by 92% in 2022. Only one of the reactors under construction is expected to become operational before 2025, thus the target of 70 GWe is likely not achieved in 2025, but it will take until around 2030 to reach this goal. Thus, there is likely to be a delay of about 5 years. China is the only country where the duration of the construction of nuclear reactors mostly remains below 10 year and has taken only 6 years for many reactors according to PRIS database. The construction of the 10 newest nuclear plants in China that started operation since 2019 took 7 years on average with a range of 5 to 9 years, which was significantly faster than in Western European countries. This is possible through state support in financing, supply chains and streamlined permitting and regulatory approval. The construction time is also shortened through standardized design, single module production, and mass production (Ezell, 2024).

The World Nuclear Association reports on plans to install 500 GWe by 2050. But the source quoted is not a plan of the Chinese government or a government target, but a scientific publication from 2018 using with a rather theoretical method for the identification of a maximum number of sites for nuclear plants in China. If the current real operational reactors and reactors under construction are used as a starting point, this would imply that China would

need to install an additional nuclear capacity of 430 GWe in 20 years, or 22 GWe per year, which is about 10 times the current construction rate.

The annual average nuclear capacity addition in China between 2000 to 2010 has been 0.8 GWe/year, between 2011 and 2020 3.6 GWe/yr and from 2021 to 2030 it will be about 2 GWe/yr. In our scenarios, the capacity growth until 2035 is based on the reactors under construction and under planned construction in the PRIS database.

In 2023, the Chinese Energy Research Institute of the Chinese Academy of Macroeconomic Research published the "China Energy Transformation Outlook" (China Energy Transformation Program [CET], 2023). The report is a cooperation between the Chinese Energy Research Institute (ERI) and the Danish Energy Agency. This report projects a continued strong increase of nuclear capacities to 110 GW in 2035, but a slower increase thereafter by only 1 GW additional capacity per year reaching 120 GW in 2045. The share of nuclear energy in the total electricity generation is expected to be at the level of 5-6% in 2025 – thus the share of nuclear will remain rather constant, while the share of renewables will increase to 94%.

The period after 2035 is based on this report is used for the low nuclear scenario for China. The high nuclear scenario reflects a higher growth rate after 2035 of 20 GW per decade, the double of the scenarios published by the Chinese Energy Research Institute (Table 15).

Table 15: Nuclear capacities in China in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
China, low scenario	55.3	72.3	100.0	115.0	120.0	125.0
China, high scenario	55.3	73.3	110.0	120.0	130.0	140.0

Source: Öko-Institut

2.4.3.2 India

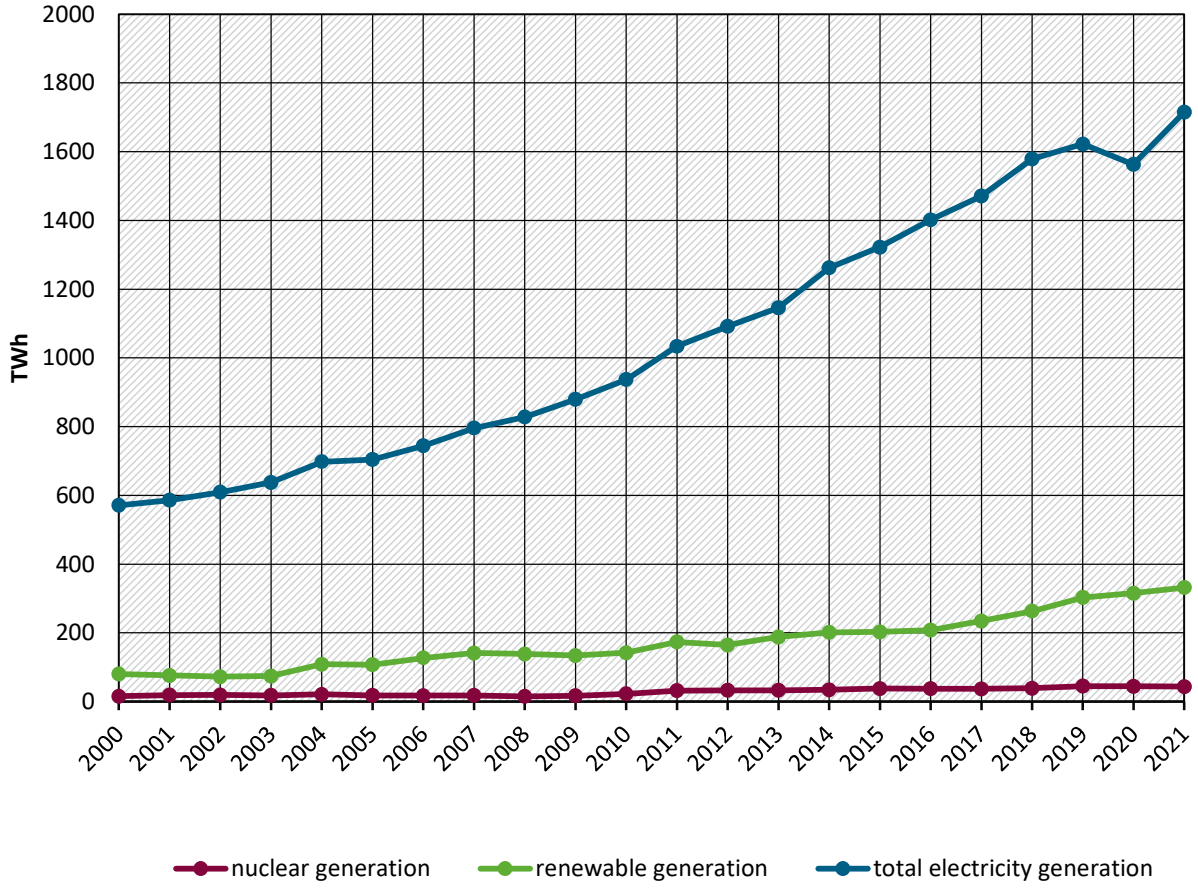
India operates a fleet of 21 nuclear reactors at seven sites with a total capacity of 5.9 GWe. The reactors Tarapur 1, 2 and Madras have not produced electricity in the past 2-3 years and are therefore not included in this capacity estimate, therefore it is slightly lower than the current capacity provided in the IAEA Power Reactor Information System (PRIS) (Nuclear Power Corporation of India Limited [NPCIL], 2023a, 2023b).[13] There are six nuclear reactors under construction with a total capacity of 4.8 GWe. The Rajasthan-7 reactor started operation in 2025.

In 2021 nuclear power contributed with 2.6% to India's electricity generation, whereas renewable energy[14] had a share of 10.0% (Figure 40). The contribution increased after 2015 when two new reactors with 1000 MW at Kudankulam started operation (Figure 41). Many of India's reactors have low load factors: Only 6 reactors have load factors higher than 80%, 7 have load factors between >70% and ≤ 80%, 4 reactors have load factors between > 60% and ≤ 70% and 4 reactors show load factors < 60% (PRIS database, 2023). The oldest nuclear plant in operation was built in 1981, most reactors were constructed between 1990 and 2010 (seeTable 16)

[13] Status as of June 2023

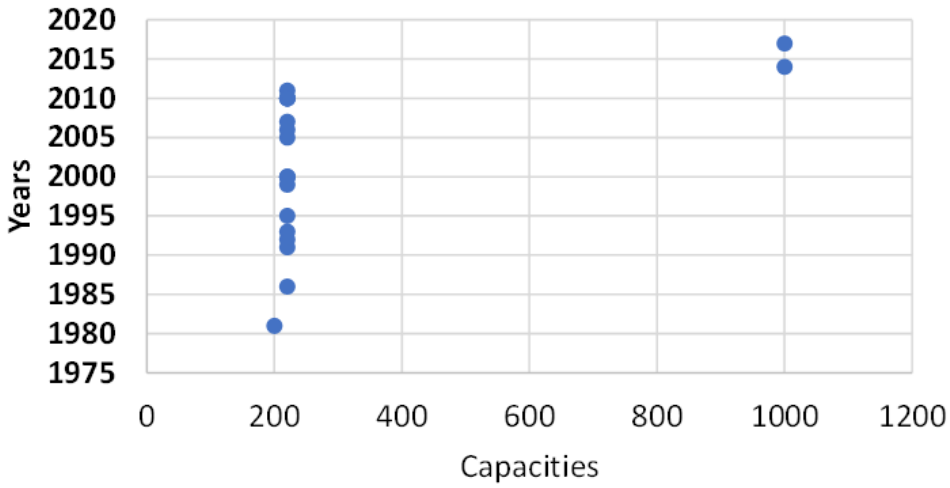
[14] Renewable power is based on gross generation from renewable sources including wind, geothermal, solar, biomass and waste

Figure 40: Electricity generation in India (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

Figure 41: Capacity additions in India



Source: (NPCIL, 2023a, 2023b)

The stagnation of the nuclear construction observed in India can be attributed to various factors. One primary reason are the delays encountered in implementing the second phase of the nuclear program. The commissioning of nuclear reactors has faced technological challenges, leading to significant time and cost overruns that have contributed to the delays. Additionally, the emergence of renewable energy technologies has caused significant changes in the energy

system planning. The commercialization and increased utilization of renewable energy technologies have considerably reduced the cost per unit of electricity generated from renewables. Currently, the cost of solar power in India is Rs 2.62 per unit, which is nearly half the cost per unit of electricity generated by the recently operational Kudankulam nuclear power plant (Rs 4.10 per unit) (Tagotra, 2020). Another obstacle arises from India's nuclear liability law, which makes equipment suppliers liable for accidents (Bundhun, 2022). This has led to substantial decline in companies offering to construct nuclear plants in India.

In its Long-Term Low-Carbon Development Strategy, India reported a target of 22.48 GWe nuclear capacity in the year 2031 (Department of Atomic Energy, 2021). (NPCIL, 2025) reports planned construction mostly in 2031 of 22.1 GWe. According to M. Schneider and Froggatt (2024) these plans have been announced by the Indian government for many years and have been continuously been postponed further in the future and no concrete progress seems to be implemented.

Together the existing capacities and the ones under construction amount to 12.74 GWe. The capacities under planned construction will not be operational by 2031, therefore the objective of 22.48 GWe in 2031 will very likely not be achieved. When all the plants in preparation towards construction are in operation, the total capacities would amount to 22.34 GWe, which is very close to the 2031 objective. However, this level of nuclear capacities will only be achieved after 2040, because construction of nuclear plants in India takes more than 10 years per plant (based on recent historic experience).

In the low scenario for India, we took into account the plants under construction, but assumed that the planned constructions that have not yet been started until 2030 will not be built. After 2030 we considered limited planned construction of 2 GW (2 reactors) in each 10-year period. However, based on the existing information, realistic assumptions are difficult. This uncertainty results from institutional delays and lack of financing commitments which are difficult to predict until 2050. In the high scenario, we assumed that the large number of planned reactors until 2030 with a capacity of around 10 GWe will be built, but it seems impossible to implement these plans until 2030. Therefore, we extended the period for these new constructions to 2035. After 2035 we added 4 GW additional construction in 2045 in the high scenario. Given the strong development of cheap renewable energy in India, it is unlikely that finance schemes will be available to build a significantly bigger nuclear fleet.

Some of India's nuclear reactors will be decommissioned until 2050, we assumed 50 years lifetimes for the older reactors, however the future capacities are not very sensitive related to these assumptions, because India's nuclear fleet is relatively young. Table 16 shows the resulting trends of nuclear power capacities in India based on the considerations above.

Table 16: Nuclear capacities in India assumed in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
India, low scenario	7.6	12.3	14.1	13.9	15.4	14.3
India, high scenario	7.6	12.7	22.6	22.4	26.0	24.9

Source: Öko-Institut

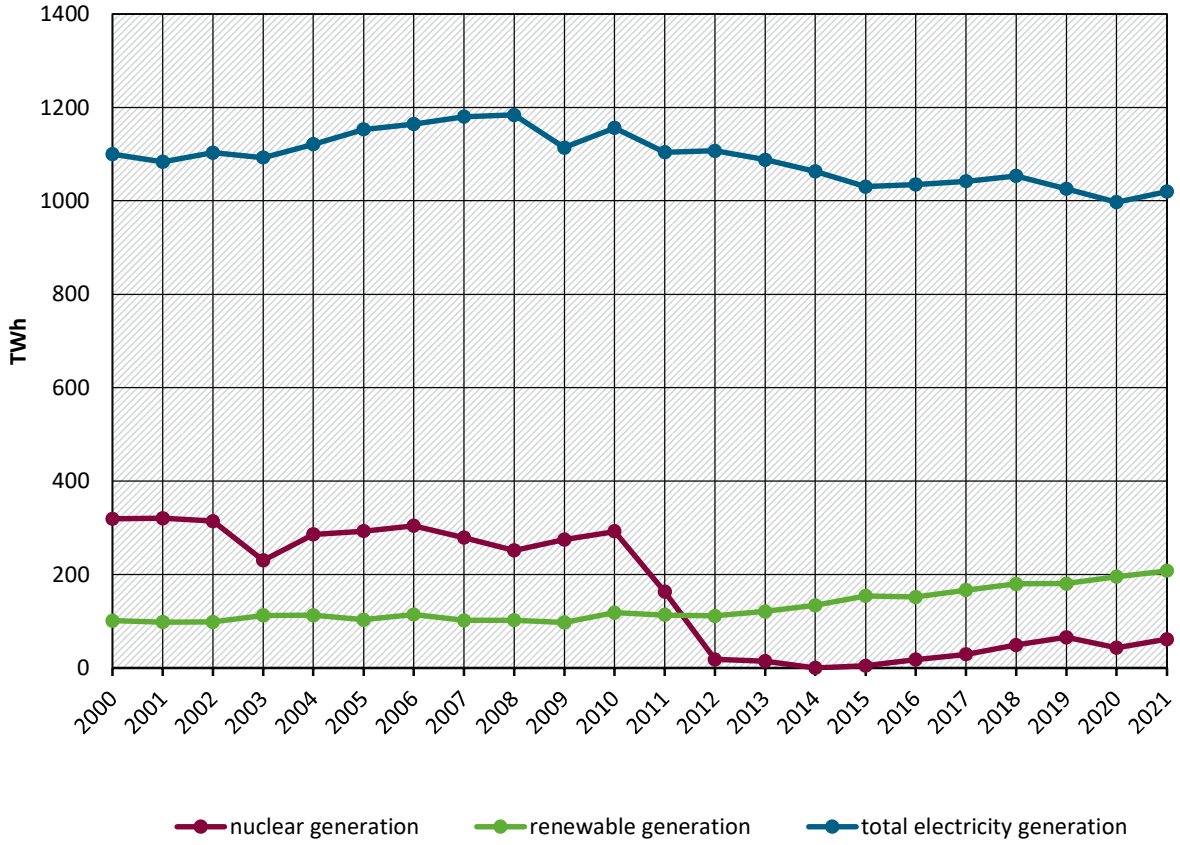
2.4.3.3 Japan

According to IAEA Power Reactor Information System (PRIS), Japan has 14 nuclear reactors in operation with a total net capacity of 12.6 GWe, 19 reactors with 19.2 GWe are in suspended

operation after the Fukushima accident. There were two reactors under construction with 2.65 GWe, but their construction was also suspended after the Fukushima accident in 2011.

The share of nuclear in electricity production was 8% in 2023. Before the accident in the Fukushima plant, the share of nuclear energy was around 30% or 163 TWh in 2011. From this level it dropped to zero in 2014 after the nuclear disaster and then slowly increased to 77 TWh in 2023. The share of renewable energy in electricity production is 13%, if hydro is included in renewables, the share of renewables in 20%. The growth rate for renewables without hydro power was 15.4% per year in the decade 2011-2021.

Figure 42: Electricity generation in Japan (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

In Japan's strategic energy plan from 2025, nuclear power is expected to grow from a share of current 8.5% to 20% in electricity production in 2040, mainly by restarting existing reactors and by extending the lifetime of operating reactors (Agency of Natural Resources and Energy, 2025) (Ministry of Economy, Trade and Industry [METI], 2021). The total electricity generation in 2040 in the strategic energy plan is expected to be 1100 TWh. Thus around 220 TWh would be produced from nuclear energy in 2040. Assuming the current load factors for the operating plants in Japan, this would mean that all suspended nuclear plants and the two plants under construction would become operational by 2030. Beyond 2030 Japan's Long-Term Strategy under the Paris Agreement has a strong focus on the development of renewable energy, but less on nuclear energy and there is no explicit mentioning of building new nuclear plants:

"Japan will address maximum introduction of renewable energy as major power sources on the top priority; societal implementation of hydrogen and CCUS will be promoted; and necessary amount of nuclear power will be continuously utilized on the major premise of ensuring safety and public trust."

According to (M. Schneider et al., 2022) the Russian attacks against civilian nuclear facilities in Ukraine, including Chernobyl and Zaporizhzhia nuclear power plants, raised serious safety and security concerns related to nuclear facilities in Japan. This threat may also influence the long-term energy strategy after 2030.

The projection for Japan is based on the 6th strategic energy plan until 2030 and assumed current operational reactors will continue to produce as well as all currently suspended plants and the two plants under construction. For the period from 2030 to 2050, we assumed in one scenario that the 2030 production will continue.

As of mid-2022, the Japanese nuclear fleet had reached a mean age of 31.4 years. Four reactors are older than 41 years, 13 units are between 31 and 40 years, 12 between 21 and 30 years and only 4 reactor are younger than 20 years (M. Schneider et al., 2022). In a second scenario we assumed that some of the old plants will be decommissioned after they achieve a lifetime of 60 years. This will lead to a decreasing reactor fleet after 2040 if no replacements will be built.

Table 17 present both projections in terms of nuclear capacities.

Table 17: Nuclear capacities in Japan in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Japan, low scenario (trategic energy plan until 2030, decommissioning of old plants afterwards)	12.6	30.4	31.8	31.8	28.6	23.2
Japan high scenario (strategic energy plan until 2030, new constrcution afterwards)	12.6	30.4	31.8	31.8	31.8	31.8

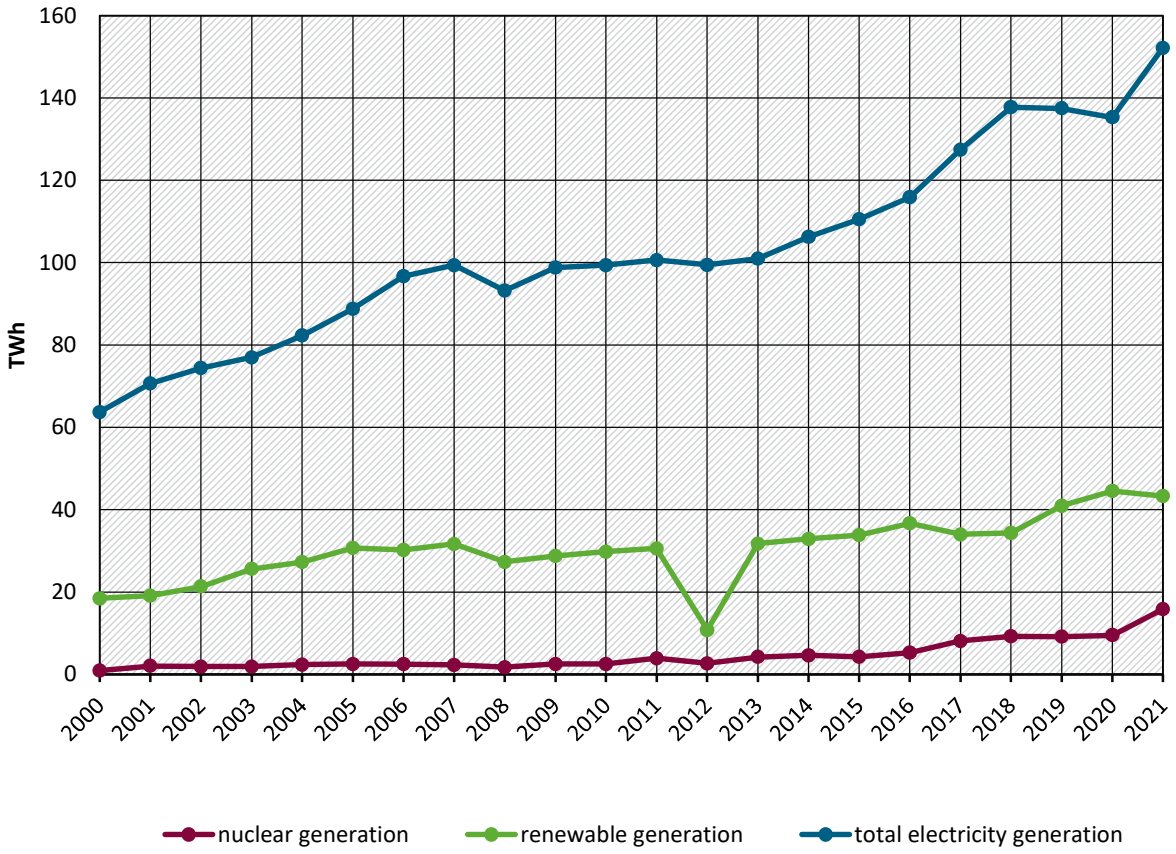
Source: Öko-Institut

2.4.3.4 Pakistan

According to IAEA Power Reactor Information System (PRIS), Pakistan has 6 nuclear reactors in operation with a total net capacity of 3.3 GWe, one reactor is shut down. One reactor is under construction. The share of nuclear in electricity production was 10% in 2021. The share of renewable energy in electricity production was 4% and 28% including hydro energy. The growth rate for renewables without hydro power was 71% per year in the decade 2011-2021. All operating reactors were constructed by China National Nuclear Corporation (CNNC). In February 2023 PAEC announced that it signed the final contracts for the construction of a new Hualong One at Chashma. CNNC would build the reactor and provide 85% of the estimated US$4.8 billion required for the construction.[15]

[15] https://www.world-nuclear-news.org/articles/agreement-reached-for-chashma-unit-5, last accessed on 01.10.2025

Figure 43: Electricity generation in Pakistan (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

In Pakistan's "Nuclear Energy Vision", the country has envisaged a nuclear power generation capacity of 40 GW until 2050 with a total of 32 nuclear power plants to meet one-fourth of the country's energy needs. However, it is very unlikely that a poor county like Pakistan will be able to finance the construction of 26 reactors in the next 26 years. IAEA reports about a planned extension to 8.8 GW in the next decade. These plans included four further Chinese reactors of 300 MWe each and seven of 1000 MWe, all PWR, but also these plans seem not very realistic given the large amounts of investment credits needed from third countries and the current high ratio of debt-to-GDP which raised concerns about the country's ability to meet its debt obligations.

Because Pakistan is outside the Nuclear Non-Proliferation Treaty, due to its weapons programme, it is largely excluded from trade in nuclear plant or materials. However, China nevertheless cooperates with Pakistan, and a 2018 International Atomic Energy Agency programme further supports civil nuclear power in Pakistan (WNA, 2024i).

In our projection for Pakistan we assumed that one additional reactor of 1 GW will be built for which planning seems to be already rather specific.

Table 18: Planned nuclear capacities in Pakistan in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Pakistan scenario	3.26	3.26	4.28	4.28	4.28	4.28

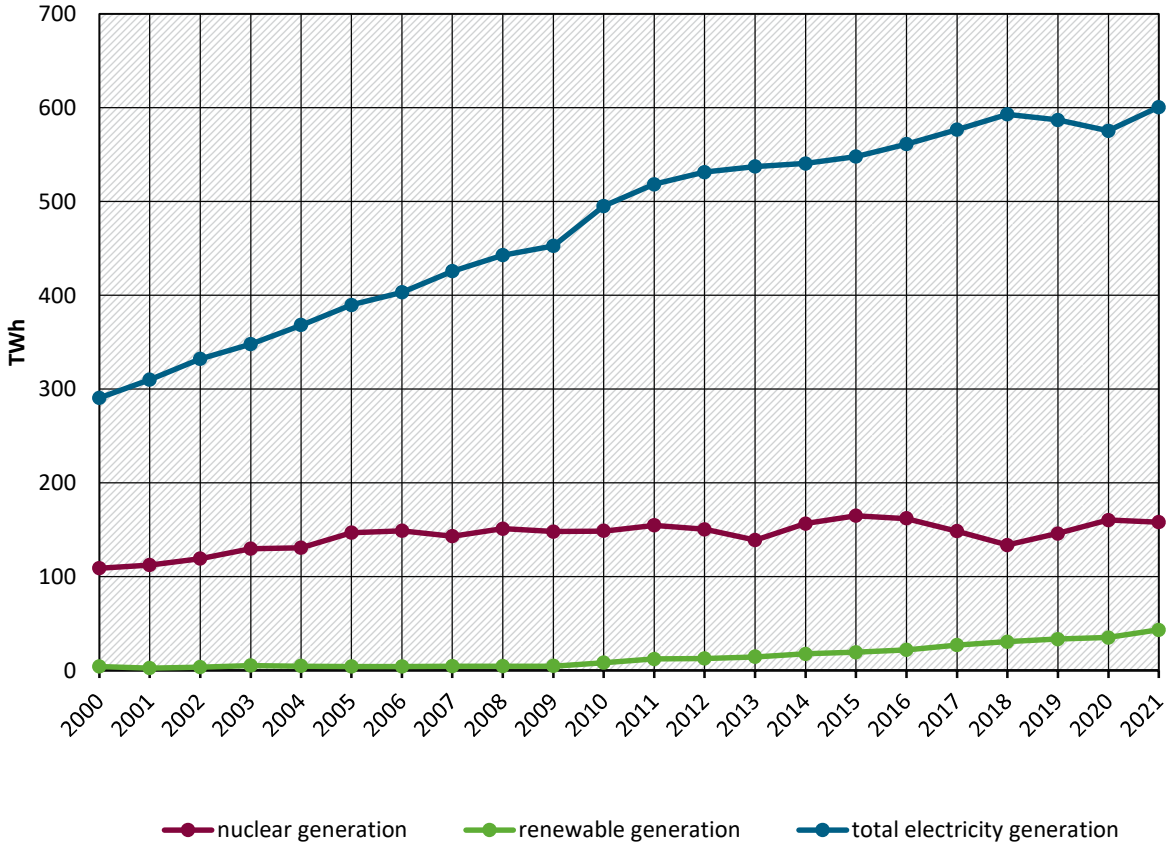
Source: Öko-Institut

2.4.3.5 Republic of Korea

According to IAEA Power Reactor Information System (PRIS), South Korea has 26 nuclear reactors in operation with a total net capacity of 25.6 GWe and 2 reactors have been permanently closed. Two reactors with a capacity of 2.68 GWe are currently under construction.

The share of nuclear in electricity production was 26% in 2021. In the past 10 years, nuclear power production increased by 0.2% per year from 155 TWh in 2011 to 158 TWh in 2021. With an additional unit becoming operational, nuclear generation increased to 181 TWh in 2023. The share of renewable energy in electricity production is only 6.7%, but the growth rate is high and was 30% in 2021 and 18.1% per year in the decade 2011-2021.

Figure 44: Electricity generation in the Republic of Korea (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

At the end of 2022 Korea's Ministry for Trade, Industry and Energy (MOTIE) published its 10th Basic Plan for Long-Term Electricity Supply and Demand. The plan increases the target of a nuclear share in electricity decreases to 32% in 2030 and 25% in 2036. The previous government had planned to phase out nuclear, thus the new government triggered a key change in nuclear energy policy. Although South Korea has the lowest renewables share in the electricity mix amongst OECD member countries, the Yoon administration reduced the previous renewables goal from a share of 30% to only 22% in 2030 and with over 40% of electricity still being produced from fossil fuels. This is a key difference to most other global governments that try to benefit from low prices for renewable energies and drastically increase renewable generation to meet climate targets.

In this plan nuclear generating capacity is expected to increase from 24.7 GW in 2022 to 28.9 GW in 2030 and to 31.7 GW in 2036. This increase assumes the commissioning of six new

reactors between now and 2033 (Shin Hanul units 1-4 and Shin Kori units 5 and 6) and the continued operation of 12 existing reactors (WNN World Nuclear News, 2023b), the Yoon administration intends to still lower the ambitions on renewables and increase the share of nuclear with over 40 percent of electricity still coming from fossil fuels in 2030.

South Korea has only four nuclear station sites, but each site locates four or more units, and three sites have more reactors planned. Thus, Korea has very concentrated nuclear reactors. If the construction was completed prior to the closure of the first reactors, the Shin-Hanul site would become the world's largest and densest nuclear power plant, with 10 reactors and 11,5 GW capacity at one site. For comparison, the total installed capacity of Europe's largest nuclear power plant, Zaporizhzhia in Ukraine, is 5,700 MW with six reactors (M. Schneider et al., 2022).This concentration poses an even greater risk for South Korea than currently for the Ukraine in Zaporizhzhia in case of a military conflict with North Korea.

In the projection for Korea we used the new energy plan announced in 2022 and the capacity targets included. In addition, we took into account that a number of nuclear plants will be decommissioned until 2050. For the decommissioning date we used the end of lifetime as indicated in the IAEA PRIS database. We did not find information about any nuclear plans after 2035. In the low scenario, no further capacities will be added after 2035. In the high scenario we assume that the growth rate until 2035 continues until 2050.

Table 19: Nuclear capacities in the Republic of Korea in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Republic of Korea, low scenario	25.6	27.9	33.9	28.3	28.3	23.4
Republic of Korea, high scenario	25.6	27.9	33.9	35.0	41.7	43.5

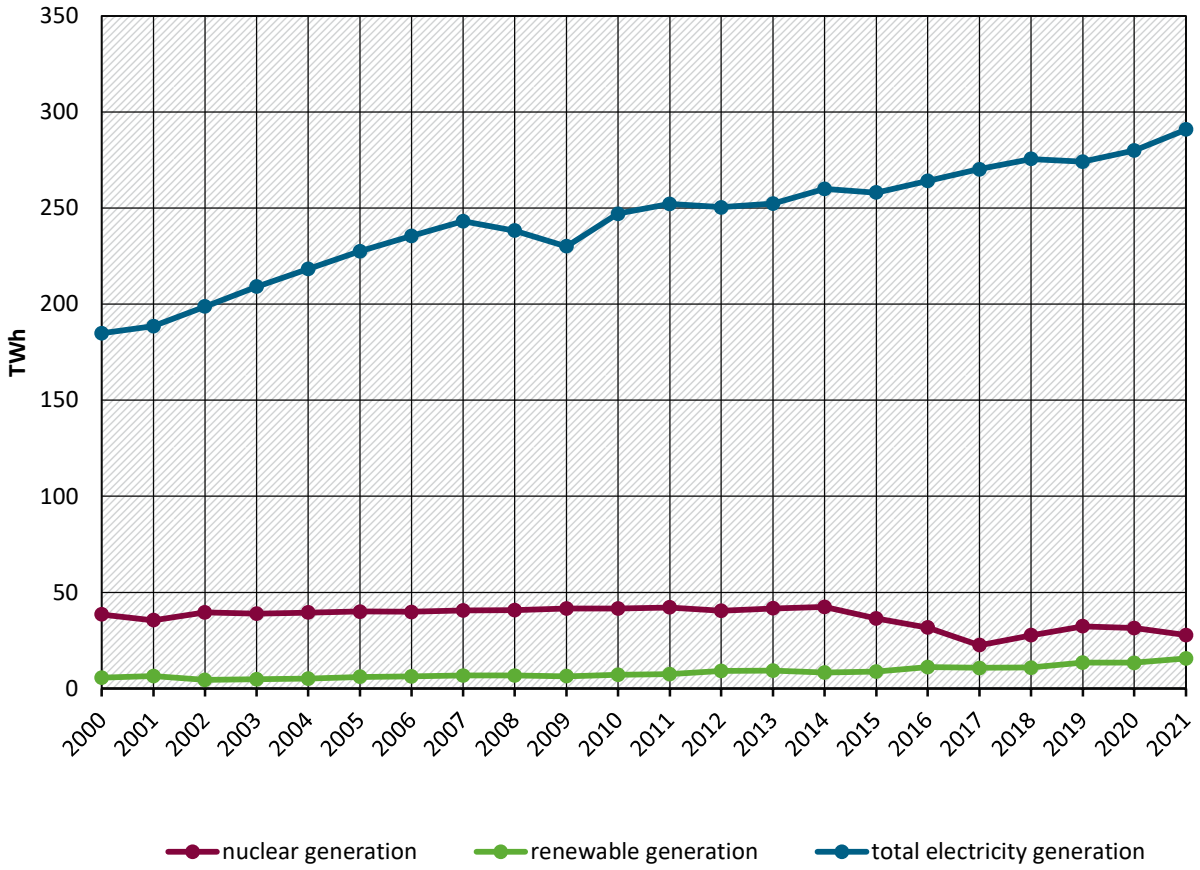
Source: Öko-Institut

2.4.3.6 Taiwan

According to IAEA Power Reactor Information System (PRIS), Taiwan has 2 nuclear reactors in operation with a total net capacity of 1.9 GWe. The plants are included in the PRIS database, but cannot be searched under the country's name which may be a concession to China on behalf of IAEA. There are no reactors under construction.

The share of nuclear in electricity production was 10% in 2021. In the past 10 years, nuclear power production decreased by 4.1% per year from 42 TWh in 2011 to 28 TWh in 2021. Nuclear generation reached its maximum share of 41 percent in 1988. The share of renewable energy in electricity production is only 4%. The growth rate for renewables without hydro power was 14% per year in the decade 2011-2021.

Figure 45: Electricity generation in Taiwan (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

Taiwan plans a nuclear phaseout by 2025 and has already closed four reactors. A referendum in December 2021 rejected a proposal to resume construction of two reactors at the Lungmen Nuclear Power Plant (M. Schneider et al., 2022). This phase-out plan has been used as a basis for our projection for Taiwan. Another referendum was held in August 2025 which considered the reopening of the Maanshan 2 nuclear reactor which was closed in May 2025. The referendum was backed by the opposition parties Kuomintang (KTM) and Taiwan's people party. The referendum failed and did not achieve the necessary quorum of 25% if the eligible electorate.

Table 20: Planned nuclear capacities in Taiwan in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Taiwan scenario	1.85	1.85	0.0	0.0	0.0	0.0

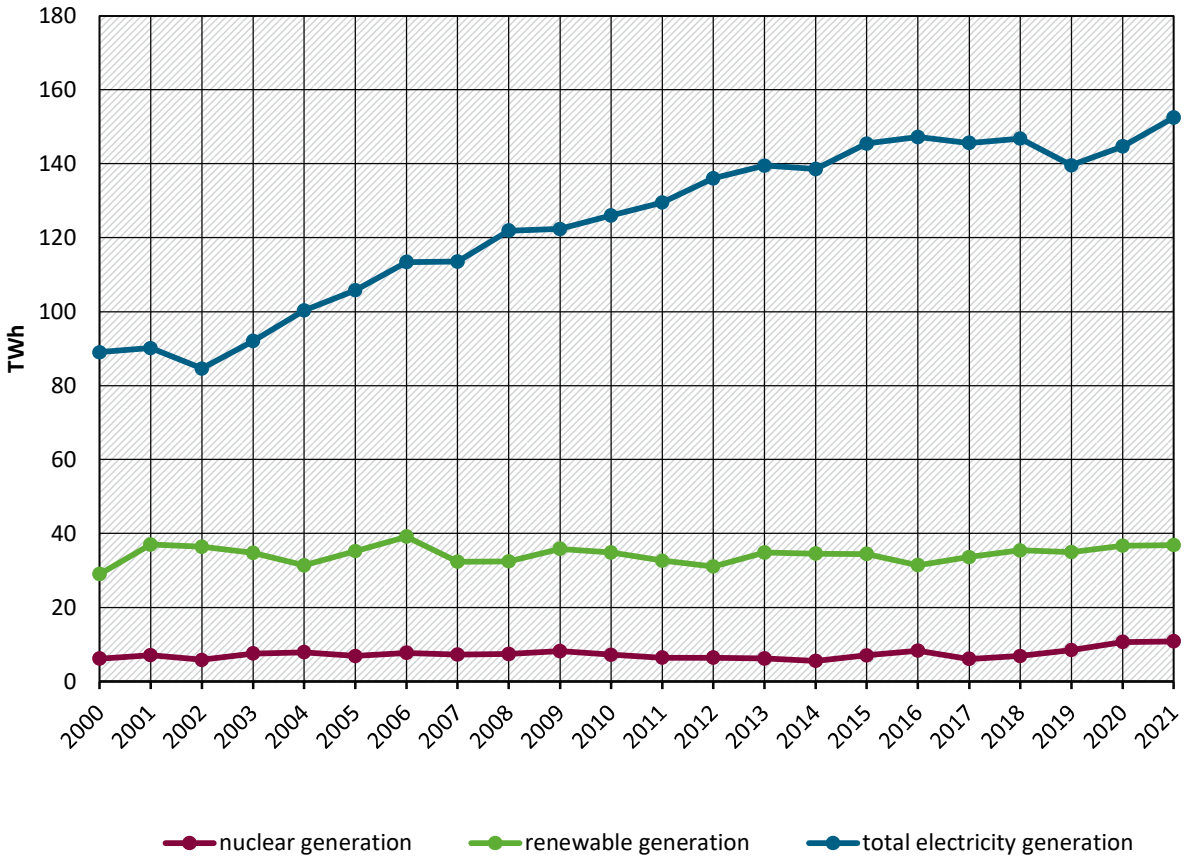
Source: Öko-Institut

2.4.4 America

2.4.4.1 Argentina

According to IAEA Power Reactor Information System (PRIS), Argentina has 3 nuclear reactor in operation with a total net capacity of 1.6 GWe. The share of nuclear in electricity production was 7% in 2021. The share of renewable energy in electricity production was 11% and 24% including hydro energy. The growth rate for renewables without hydro power was 28% per year in the decade 2011-2021.

Figure 46: Electricity generation in Argentina (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

In April 2018, a lifetime extension license for the Atucha-1 reactor, originally started up in 1974, until 2024 was provided and in 2022 lifetime was extended for an additional 20 years of operation with refurbishment to take two years and cost US$ 463 million (M. Schneider et al., 2022).

Atucha-2 entered in commercial operation in 2016 and has recently had weak performance with very low load factors, according to IAEA-PRIS, of respectively 29 percent (2019), 40 percent (2020), and 58 percent (2021). Embalse, the third reactors started operating in 1983, was overhauled in 2015 and the operating license was extended to 2029 (M. Schneider et al., 2022).

Argentina started the construction of a prototype SMR 25-MWe PWR, CAREM-25 (Central Argentina de Elementos Modulares—a pressurized-water SMR) reactor near the Atucha site in February 2014 (M. Schneider et al., 2022). It is still not completed and operating and currently operation is scheduled for 2027. Even with the current the lower cost estimate of US$520 million, the per unit cost of the project is around US$17,000/kW, roughly twice the cost estimate of the most expensive Generation-III reactors (M. Schneider et al., 2022).

There are plans to build another Atucha-3 reactor of 1.2 GW in a cooperation with China National Nuclear Corporation (CNNC) since 2015. So far the plans have not been realised. In 2022 a contract has been signed, but without a financial agreement and the current high inflation rate in Argentina of more than 70% will make financing of such size very difficult. Nevertheless, we assumed a new construction in our projection for Argentina.

Table 21: Planned nuclear capacities in Argentina in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Argentina scenario	1.64	1.64	2.24	2.24	1.92	1.92

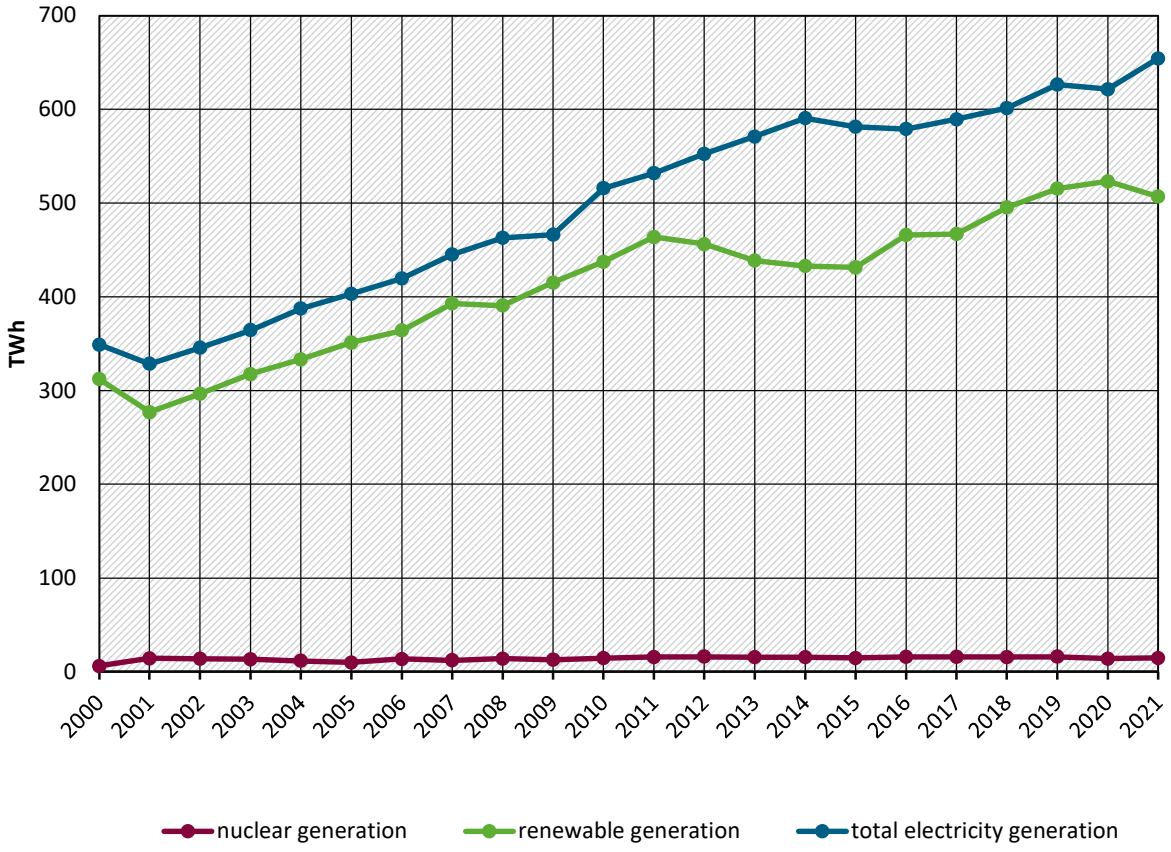
Source: Öko-Institut

2.4.4.2 Brazil

According to IAEA Power Reactor Information System (PRIS), Brazil has 2 nuclear reactors in operation with a total net capacity of 1.9 GWe.

The share of nuclear in electricity production was 2% in 2021. The share of renewable energy in electricity production was 22% and 77% including hydro energy. The growth rate for renewables without hydro power was 15% per year in the decade 2011-2021.

Figure 47: Electricity generation in Brazil (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

The construction of a third reactor was suspended in late 2015 due to a large corruption investigation, and it is unclear whether work will resume (M. Schneider et al., 2022).

The Brasilian National Energy Plan 2050 (Danilow, 2020) includes two long-term scenarios, in the lower scenario foresees an increase of nuclear capacity of 8 GW and the higher scenario of 10 GW until 2050 which would bring nuclear to a share of about 10% in electricity generation. The plan assumes an increase of energy demand by a factor of 3.3 until 2050.

Brazil's "Ten-Year Energy Expansion Plan" or PDE 2031 provides more detail on the short-term planning (Ministerio der Minas e Energía, 2022). The plan envisages lifetime extensions for the Angra 1 and 2 plants until 2044, the finalisation of Angra 3 and the construction of an additional nuclear plants. The background of the Brazilian strategy are large uranium resources in the country and apart from mining Brazil also intends to start enrichment and the production of fuel rods. The plan foresees to commission a new 1 GW unit by 2031. The projection for Brazil takes into account these plans in a lower and higher scenario.

Table 22: Planned nuclear capacities in Brazil in the bottom-up projection until 2050 [GWe] (Ministerio der Minas e Energía, 2022)

GWe (net)	2025	2030	2035	2040	2045	2050
Brazil, low scenario	1.85	1.85	1.85	1.85	1.25	1.25
Brazil, high scenario	1.85	1.85	1.85	3.19	4.19	4.19

Source: Öko-Institut

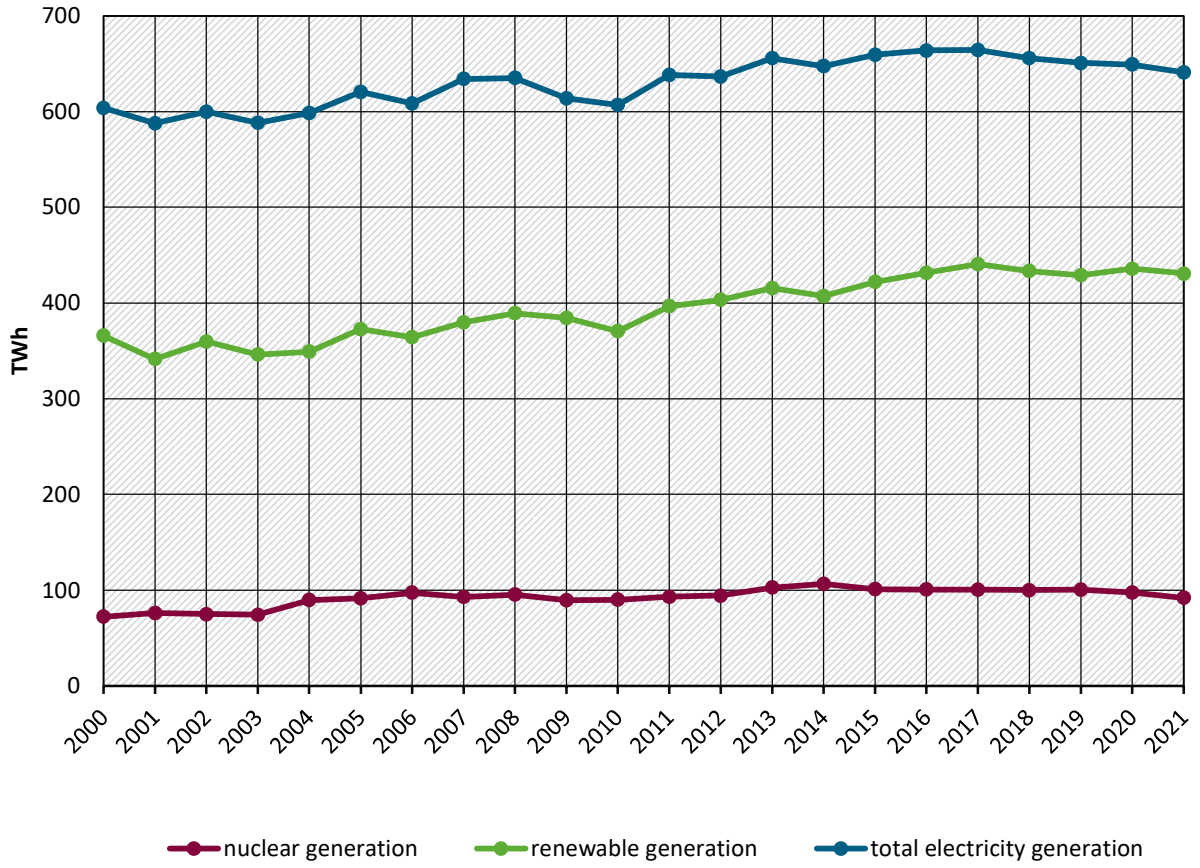
2.4.4.3 Canada

According to IAEA Power Reactor Information System (PRIS), Canada has 17 nuclear reactors in operation with a total net capacity of 12.7 GWe and 8 reactors have been permanently closed. There are no reactors under construction.

The share of nuclear in electricity production was 14% in 2021. In the past 10 years, nuclear power production decreased by 0.1% per year. Between 2014 – the most recent peak and 2021, nuclear production sank from 106 TWh to 92 TWh, a decline of 14%. All but one reactor are located in the province of Ontario. The share of renewable energy in electricity production is 16%, if hydro is included in renewables, the share of renewables in 67%.[16] The growth rate for renewables without hydro power was 9% per year in the decade 2011-2021.

[16] BP World energy statistics review treats hydro energy separately.

Figure 48: Electricity generation in Canada (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

The Canada Energy Regulator regularly publishes projections of the future energy production capacities and energy production. The latest version available in June was "Canada's Energy Future 2021". The projection separates between a current policy and an evolving policy scenario, for nuclear capacities however, both scenarios are the same. For Canada, we used the projected nuclear capacities until 2050 based on the publication "Canada's Energy Future 2021".

Table 23: Nuclear capacities in Canada in the bottom-up projection until 2050 [GWe]

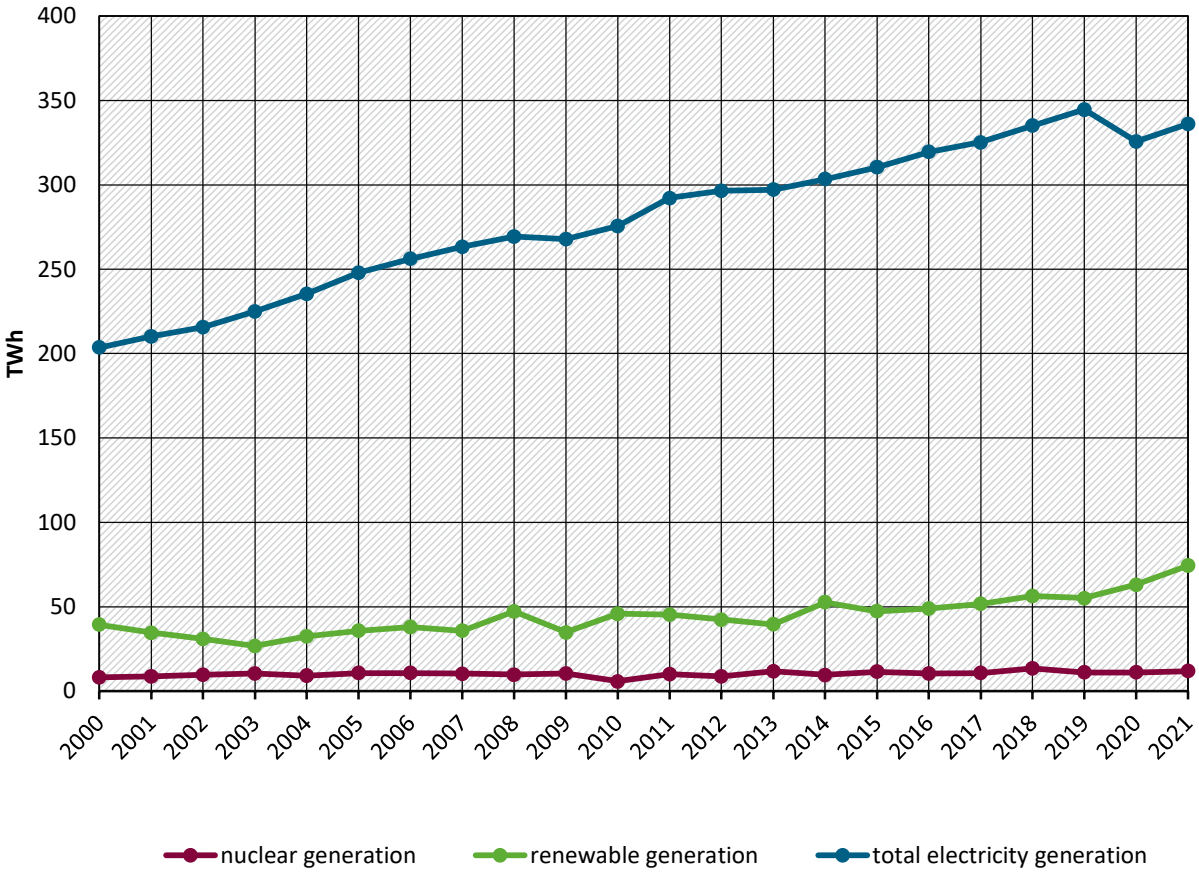
GWe (net)	2025	2030	2035	2040	2045	2050
Canada	12.7	10.3	11.1	11.2	11.2	11.6

Source: (Canada Energy Regulator, 2021)

2.4.4.4 Mexico

According to IAEA Power Reactor Information System (PRIS), Mexico has 2 nuclear reactors in operation with a total net capacity of 1.6 GWe. The share of nuclear in electricity production was 4% in 2021. The share of renewable energy in electricity production was 12% and 22% including hydro energy. The growth rate for renewables without hydro power was 16% per year in the decade 2011-2021.

Figure 49: Electricity generation in Mexico (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

On 31 May 2022, the Government published its "Program for the Development of the National Electricity System 2022–2036", which forecasts an addition of 2.5 GW. However, there are no specific agreements or contracts in place for these additional capacities, therefore we did not take them into account in the scenario for Mexico.

Table 24: Planned nuclear capacities in Mexico in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Mexico	1.55	1.55	1.55	1.55	1.55	1.55

Source: Öko-Institut

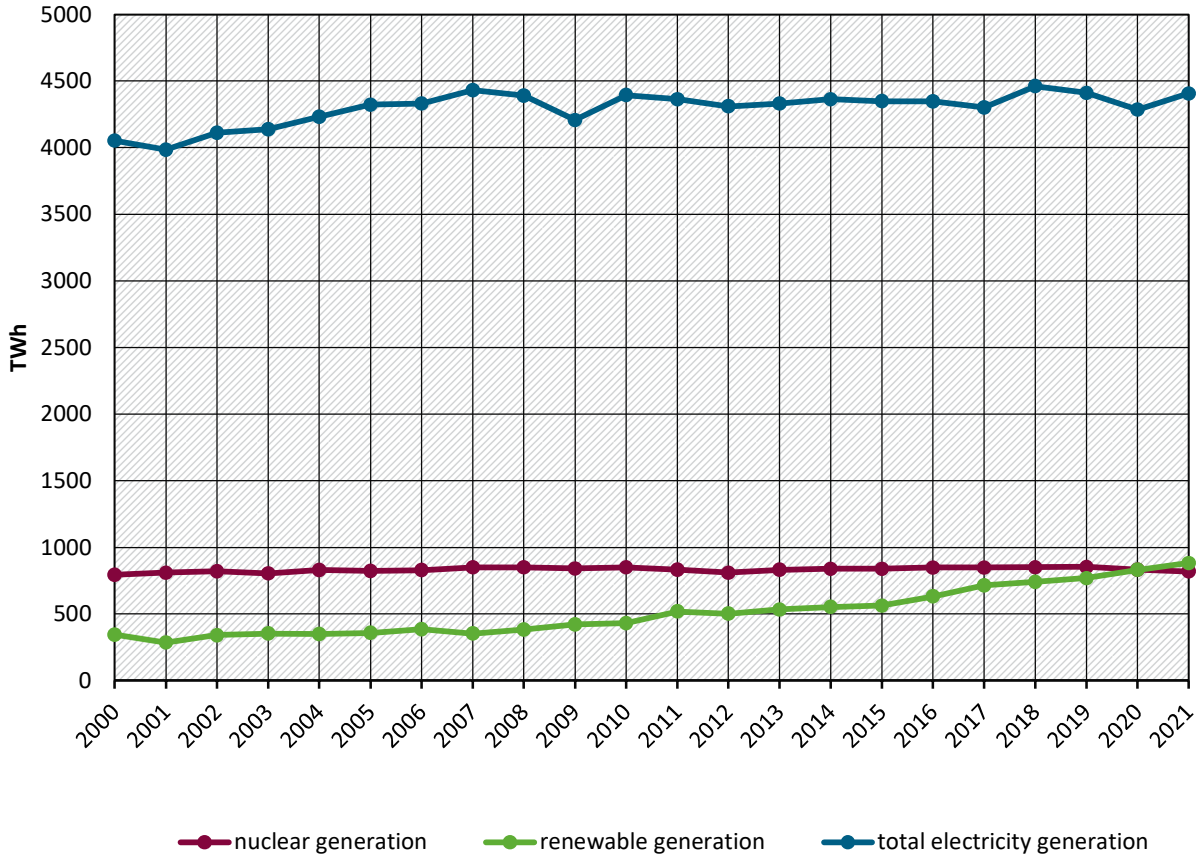
2.4.4.5 USA

According to IAEA Power Reactor Information System (PRIS), the USA has 94 nuclear reactors in operation in 2024 with a total net capacity of 96.9 GWe. 41 reactors have been permanently closed. One nuclear plant, the twin AP-1000s at Plant Vogtle Units 3 and 4 with 1.1 GWe started operation in 2023 and 2024 after the finalisation of the plant had been postponed many times.

The USA is the country with the largest nuclear reactor fleet in the world. The share of nuclear in electricity production was 18.1% in 2023 with a total electricity generation of 812 TWh. In the past 10 years, nuclear power production declined by 2% per year (Energy Institute, 2024). The share of renewable energy in electricity production was 21.6% with a total generation of 974 TWh and renewables increased by 6.2% per year in the past decade. Thus, also in the country

with the largest nuclear capacity, renewable energies reached a higher share in electricity generation and is increasing while nuclear energy declines.

Figure 50: Electricity generation in the USA (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

The average age of the US nuclear fleet is 42.1 years (M. Schneider et al., 2023), which is one of the oldest fleets in the world. Only four reactors are younger than 30 years, about 40 reactors are 31-40 years and 41-50 years. 10 plants operate since more than 50 years. The future nuclear capacities in the USA until 2050 are therefore strongly influenced by the point in time of decommissioning of around 90 old reactors in this period.

In 2022, the Infrastructure Investment and Jobs Act (IIJA) and the Inflation Reduction Act (IRA) have been adopted. IIJA includes a US$6 billion Civil Nuclear Credits program to support uneconomic reactors at imminent risk of closure, as well as US$3.2 billion to support new reactor demonstration projects. IRA includes five measures that provide subsidies and financing for existing and new reactors:

- Production tax credits for existing reactors;
- Clean energy production and investment tax credits for new energy sources, including new reactors;
- US$40 billion in loan guarantees for new clean energy projects, including new reactors;
- US$250 billion in loan guarantees for existing energy infrastructure (Energy Infrastructure Reinvestment Financing), for which existing reactors are likely to be eligible; and

- US$700 million for High-Assay Low-Enriched Uranium (HALEU).

The total amount of spending for nuclear energy under these measures is not yet clear. But the programme is the largest direct federal investment in commercial nuclear energy in decades. Congress's Joint Committee on Taxation's (JTC) latest estimate of the bill's budget impacts projects the production tax credits for existing reactors to cost US$30 billion over the nine years of the program (from 2024 through 2032).

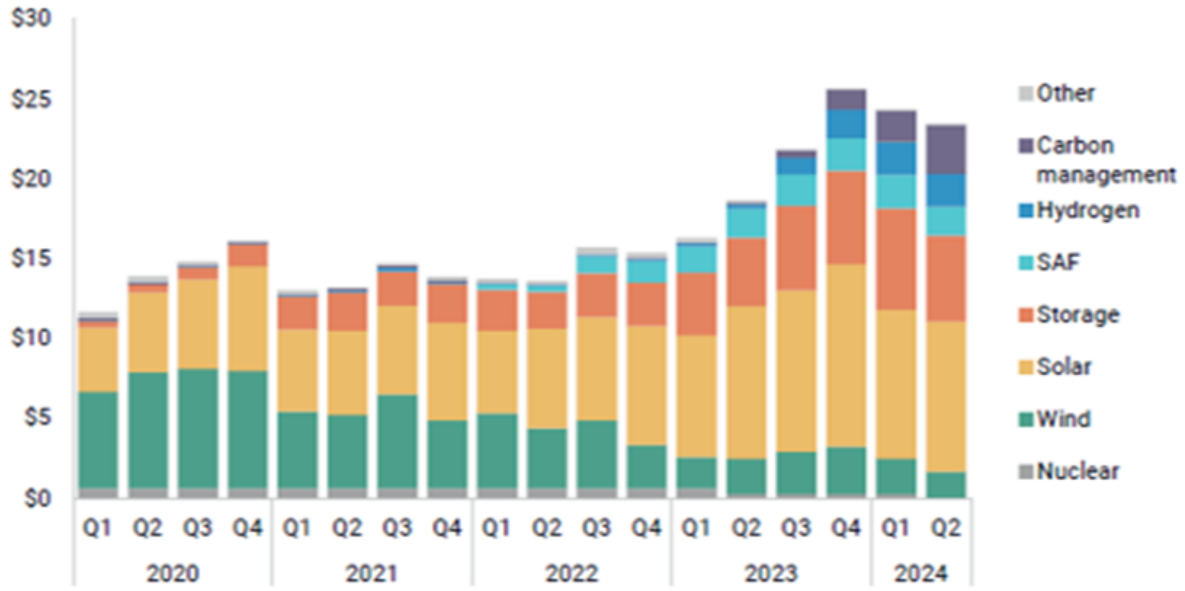
The production tax credit under the Inflation Reduction Act will help preserve the existing fleet of nuclear plants. The zero-emission nuclear power production credit provides up to $15 per megawatt-hour for the electricity produced by the plants assuming that labor and wage requirements are met. This is available for facilities in service in 2024 and would last through 2032, keeping existing reactors competitive with other power generators (Office for Nuclear Energy, 2022). Therefore, we assumed that no reactors would be decommissioned before 2032. The Unites States Nuclear Regulatory Commission (NRC) has already renewed licences for most of the old reactors in the US. Currently, there are only nine reactors whose licence expire before 2030. We assumed that the additional subsidies provided to old nuclear plants will lead to renewal of licenses for the seven reactors for which the license has not yet been renewed (Clinton 1, Diablo Canyon 1 and 2, Dresden 2, Grand Gulf 1, Limerick 1 and 2).

Rhodium Group projects that the nuclear provisions in the Inflation Reduction Act are likely to "prevent 10-20 GW from retiring through 2030 (Rhodium Group, 2022).

Other studies believe that the IRA subsidies are not sufficient to change the economics of nuclear power. Before the IRA, nuclear construction costs were too high for nuclear to be competitive with natural gas or coal. Even with the IRA subsidies and even if nuclear construction costs were 65 percent less than the current costs of the Vogtle plant in Georgia, gas plants would still be cheaper unless natural gas prices remain historically high for decades (D. Kemp & van Doren, 2022).

Recent monitoring reports analysing the clean investments triggered by the IRA since 2020 document an increase in investments in solar energy, energy storage, synthetic aviation fuels (SAF), hydrogen production and carbon management while investments in nuclear energy remain very low and further declined in 2023 and 2024.

Figure 51: Investments by technology since the enactment of the Inflation Reduction Act in the USA [Billion 2023 USD]



Source: (Rhodium Group, 2024)

Due to the large uncertainties and a wide range of estimates of the IRA's impact from different sources, it is difficult to provide a reliable projection of the development of nuclear capacities in the US.

As the production tax credit under the IRA will support the existing nuclear fleet and prevent decommissioning, we assumed that no reactors would be decommissioned before 2032. The Unites States Nuclear Regulatory Commission (NRC) has already renewed licences for most of the old reactors in the US. In 2019, the US Nuclear Regulatory Commission (NRC) has approved a license extension for operation for up to 80 years for Turkey Point units 3 and 4 (WNN World Nuclear News, 2019b). It was the first time that the regulator extended a license beyond 60 years. Most of the USA's operating nuclear reactors have already renewed their licences for up to 60 years of operation. The NRC is currently reviewing applications for subsequent licence renewals for Surry 1 and 2 and for Peach Bottom 2 and 3 and the operator has announced to apply for a subsequent licence renewal for North Anna 1 and 2 (WNN World Nuclear News, 2019b). According to the US Department of Energy, some 20 reactors are planning or intending to operate up to 80 years (ibit).

We assumed that the additional subsidies provided to old nuclear plants will lead to renewal of licenses for the seventeen reactors for which the license would expire until 2032 as for which the license has not yet been renewed. For the estimation we used the data on license expiration dates available from US Nuclear Regulatory Commission.[17]

The recently completed Vogtle 3- and 4 units have accumulated costs of more than US$ 35 billion (M. Schneider et al., 2023). The IRA includes US$ 40 billion in loan guarantees for new clean energy projects, including new reactors. Given the huge costs of the most recent project, we assumed that these loan guarantees will not be sufficient to spur many new constructions. In 2024 the US senate adopted the Advanced Nuclear for Clean Energy Act (U.S. Congress, 2023).

[17] https://www.nrc.gov/info-finder/reactors/index.html#listAlpha, last accessed on 01.10.2025, license end dates available in the information for specific reactors.

This bill sets forth provisions to develop and deploy advanced nuclear fuel for the United States and provides incentives for developing and deploying new nuclear technologies such as small modular reactors and requires the Nuclear Regulatory Commission (NRC) to develop a streamlined licensing process for advanced nuclear technologies.

In an executive order in May 2024, president Trump accounted the plan to expand the U.S. nuclear capacity to 400 GW by 2050 and to start 10 large reactors by 2030. This would mean around 180 reactors of 1 GW per decade. If the Vogtle costs are assumed, these plans would cost around US$ 6.000 billion. The "One Big Beautiful Bill Act" adopted in 2025, preserves the support for nuclear, including access to tax credits, established under the IRA. It also adds US$ 125 million for "the acceleration of development of small, portable modular nuclear reactors for military use". Thus, the subsidies for nuclear adopted by the Biden administration remain unchanged, but no additional support was granted that would provide financial support for 400 new reactors. The "One Big Beautiful Bill Act" introduces restrictions related to the eligibility to the support for companies with ties to specified foreign countries. Westinghouse, the only large U.S. company that builds large-scale nuclear reactors, has expressed the vision to build 10 large reactors by 2030.[18] However, the construction of ten reactors in less than five years seems not very likely and would have no recent global precedent. It is unclear which U.S. companies would be able to build such large capacities and who would provide the necessary finance. There are more U.S. companies planning the construction of SMRs (e.g. Kairos Power, TerraPower or BWXT), but with SMRs it is difficult to achieve the planned large capacity additions.

Only ten federal states have initiated planning processes to promote nuclear energy since 2023 (M. Schneider & Froggatt, 2024). But support activities include very few specific new construction projects.

Table 25: Nuclear capacities in the USA in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
USA, low scenario	97.0	97.0	90.6	86.3	74.2	45.8
USA, high scenario	97.0	97.0	98.1	93.8	89.2	60.8

Source: Öko-Institut

Table 25 shows the capacity development in the USA if all reactors whose licences have been extended by the Nuclear Regulatory Commission (NRC) or who applied for extended licences would operate for the full licenced lifetime. This is a very optimistic scenario, because recently closed reactors in the US were closed earlier than their licenced lifetime for economic reasons and because the financial support under the IRA is only foreseen until 2032. For new capacities, the development is difficult to predict. Given the delays, high overruns and lawsuits around the Vogtle construction and the considerable amount of criminal investigations of nuclear power corporations (M. Schneider et al., 2022), we did not assume a large number of new constructions. In the low projection, we assumed that 2.5 GWe will be built in the periods 2030-3040 and 2040-2050. The high projections is based on the assumption of 10 GWe new construction in both periods. In both cases, nuclear capacities in the US will decline after 2030, because it is unlikely that it is possible and economically viable to extent the very old reactors in the US even further. At the same time it is unlikely that a similar amount of new construction as in the 80s and 90s will happen, given the much lower costs of renewable energies. Whether

[18] https://info.westinghousenuclear.com/news/enec-and-westinghouse-sign-agreement-to-accelerate-nuclear-energy-deployment-in-the-u.s, last accessed on 01.10.2025

SMRs can play a big role is unclear, given the cancellation of the flagship SMR project by NuScale in 2023. To achieve the announced capacity increase, a large number of SMRs would be needed.

2.4.5 Eastern Europe (without Eastern European EU Member States)

2.4.5.1 Armenia

According to IAEA Power Reactor Information System (PRIS), Armenia has 1 nuclear reactor in operation with a total net capacity of 0.42 GWe. One reactor is permanently closed. The share of nuclear in electricity production was 25% in 2021, the maximum nuclear share was 45 percent in 2009.

The reactor started generating in January 1980 and is a first-generation, Soviet-designed reactor, a VVER-440 v270 (M. Schneider et al., 2022). In December 1988 after a major earthquake Armenia closed its two reactors in March 1989. The territorial dispute between Armenia and Azerbaijan resulted in an energy blockade that resulted in power shortages which led to the Government's decision in 1993 to re-open Unit 2. Since 2003, the plant is operated by InterRAO, a subsidiary of Russian Rosatom.

In October 2012, the Armenia Government extended the operating license until 2021. In February 2020, the Government announced the country's 2040 energy strategy which plans to further extending the life of the reactor until 2036 along with measures to increase its output by 12-15 percent (M. Schneider et al., 2022). Armenia has been negotiating for many years with Russia for the construction of a new 1000 MW unit and also the US and Armenian Governments signed an MoU on civil nuclear power in 2022, but it seems not very likely that the construction will go ahead while the war between Armenia and Azerbaijan continues.

The power plant remains a high risk for the region due to potential earthquakes in the area and due to the armed conflict with Azerbaijan. In July 2020 a senior Azerbaijani official threatened a missile strike against the Metsamor nuclear plant on the Armenia-Azerbaijan border (M. Schneider et al., 2022). In our projection we assumed that the current nuclear plant will run until 2036, but that it will not be replaced by a new plant within the projection horizon of this study.

Table 26: Planned nuclear capacities in Armenia in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Armenia scenario	0.42	0.42	0.42	0.0	0.0	0.0

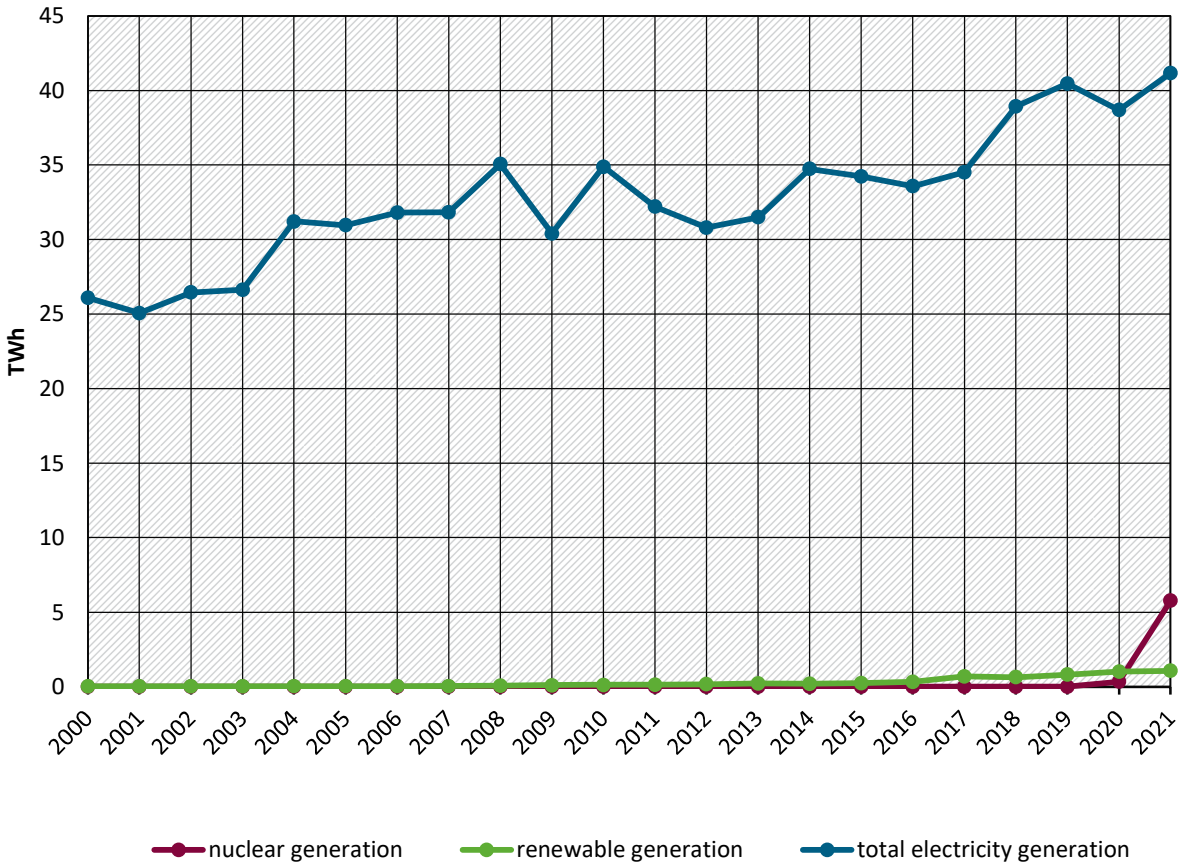
Source: Öko-Institut

2.4.5.2 Belarus

According to IAEA Power Reactor Information System (PRIS), Belarus has 2 nuclear reactors in operation with a total net capacity of 2.2 GWe which only started operation in 2020.

The share of nuclear in electricity production was 28% in 2023. The share of renewable energy in electricity production is only 3%.

Figure 52: Electricity generation in Belarus (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

Construction started in November 2013 at Belarus's first nuclear reactor at Ostrovets power plant, also called Belarusian-1. Construction of a second 1200 MWe AES-2006 reactor started at the same site in June 2014. The first unit was completed and connected to the grid on 3 November 2020 and reached full power in January 2021. The second unit was connected in May 2023. The plant will cover about 40% of Belarus' domestic electricity needs. No further plants are under construction. In our projection we assumed that the two new reactors will continue operating until 2050. Further plants would likely require electricity exports, but neighbouring Baltic countries, Poland and Ukraine oppose electricity imports from Belarus, thus it would not make much economic sense to plan further reactors.

Table 27: Planned nuclear capacities in Belarus in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Belarus scenario	2.22	2.22	2.22	2.22	2.22	2.22

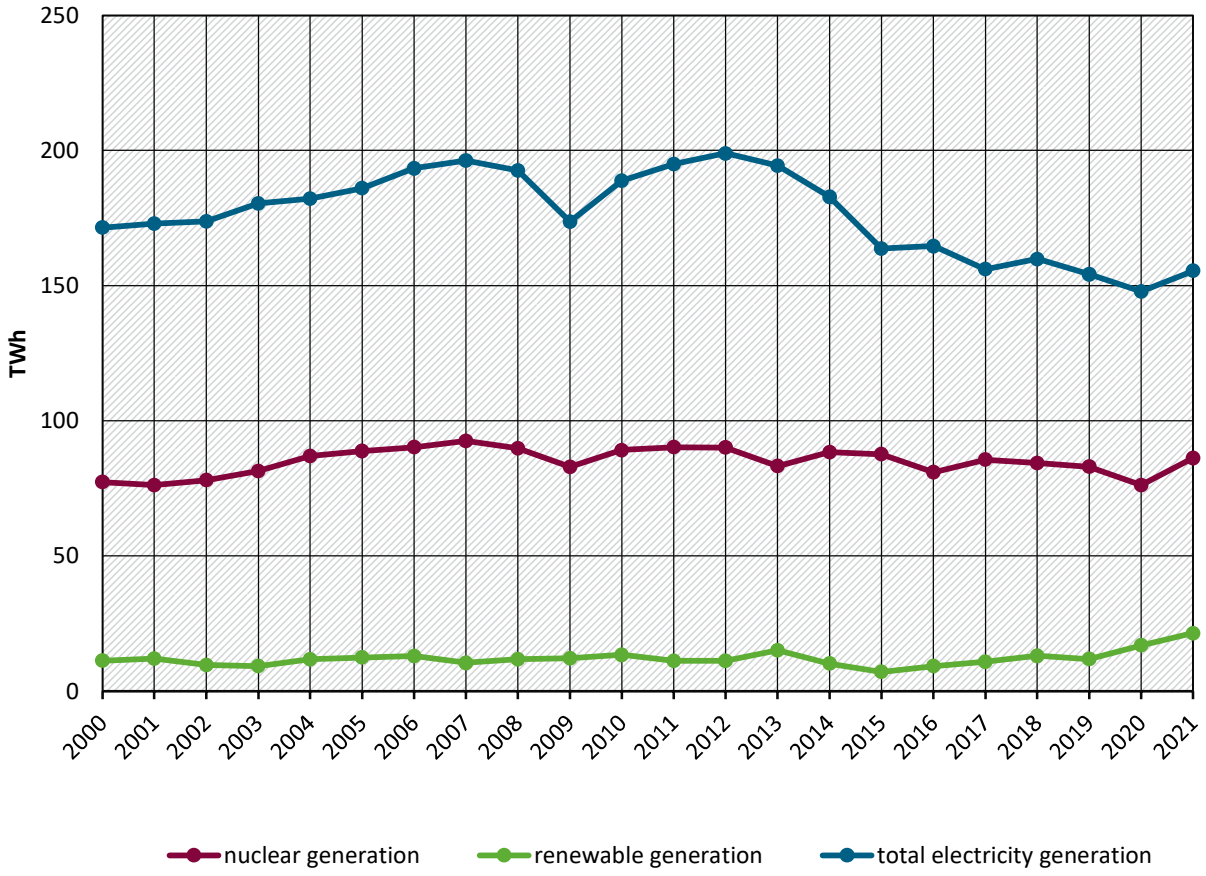
Source: Öko-Institut

2.4.5.3 Ukraine

According to IAEA Power Reactor Information System (PRIS), Ukraine has 15 nuclear reactors in operation with a total net capacity of 13.1 GWe. These are located at four sites. **The six reactors at the Zaporozhye site are currently not operating** due to the war attacks, the critical situation with only one power line supplying the units and the potential difficulties to get sufficient cooling water after the disaster of the Kakhovka reservoir. The 4 reactors in Chernobyl

are permanently closed. There were two reactors under construction, Khmelnitsky-3 and -4, but WNISR removed them from the construction list as no active work has been reported in many years (M. Schneider et al., 2022). In Ukraine nuclear power had a very high share of 55% in electricity production in 2021.

Figure 53: Electricity generation in Ukraine (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

Due to the ongoing war of the Russian Federation against Ukraine, the future of nuclear energy is difficult to predict. The Ukrainian government has been planning to expand nuclear energy before the war, but it is unlikely that after the war sufficient investment capital will be available to build new nuclear plants, given the large needs of reconstruction in many parts of the country. The destruction of many industrial sites will also decrease the electricity demand. We therefore assumed that no additional reactors will be build. The current reactors are mostly built in the 80s. The Rovno plants have already been refurbished and lifetime was extended by 20 years, whereas South Ukraine plants and Zaporozhye were only extended by 10 years (M. Schneider et al., 2022). In the low scenario, we assumed that the current reactors run until the current will licenses expire. The high projection assumes that all reactors will be granted a license for 60 years and will only be shut down after this period. Such extension will bring a big change in nuclear capacity in the period from 2035 to 2045. But also with 60 years lifetimes, capacities will drop considerably in 2050, if no new nuclear plants will be built in Ukraine. Given the ongoing war in Ukraine, there is a high uncertainty related to the future nuclear development and the lifetime extensions.

Table 28: Nuclear capacities in Ukraine in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Ukraine, low scenario	13.1	13.1	4.8	1.9	1.9	1.9
Ukraine, high scenario	13.1	13.1	13.1	13.1	11.4	2.85

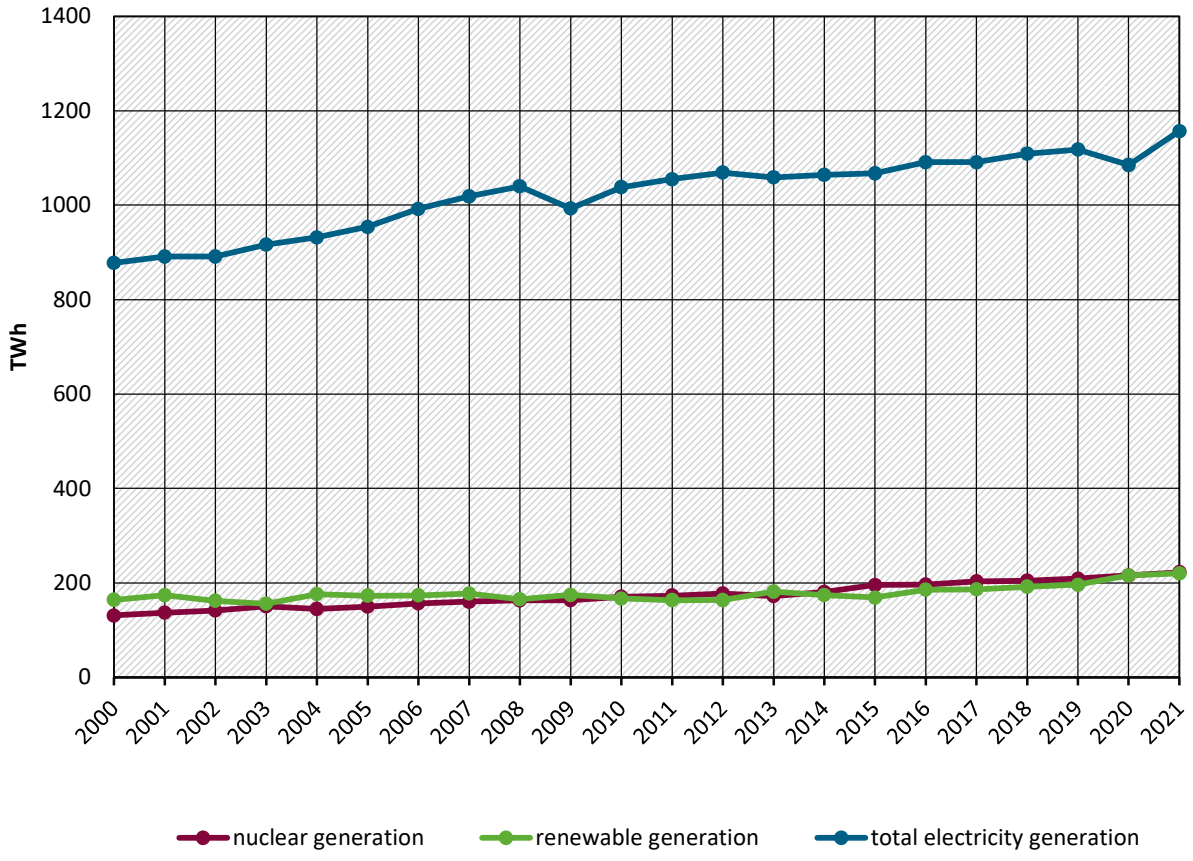
Source: Öko-Institut

2.4.5.4 Russian Federation

According to IAEA Power Reactor Information System (PRIS), the Russian Federation has 36 nuclear reactors in operation with a total net capacity of 26.8 GWe and 11 reactors have been permanently closed. Four reactors with a capacity of 3.85 GWe are currently under construction.

The share of nuclear in electricity production was 19% in 2021. In the past 10 years, nuclear power production increased by 2.5% per year from 172.9 TWh in 2011 to 222.4 TWh in 2021 (BP, 2022). The share of renewable energy in electricity production was 18%.

Figure 54: Electricity generation in the Russian Federation (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

The average age of the Russian reactor fleet is now 28.9 years, with 12 reactors between 41-50 years, 11 reactors between 31-40 years and 2 between 21-30 years (M. Schneider et al., 2022). Therefore, for the projected capacities in Russia it is important for how long the old units will be upgraded and kept in production. The VVER-440 and RBMK types have been designed for an operational lifetime of 30 years, but lifetime extension has been granted for 45 years. VVER-1000 are expected to work for 50 years, but some plants of this type (Leningrad 1 and 2) have already been shut down permanently. WNA provides a detailed plant-specific overview about

the current lifetime extensions of Russian nuclear plants, which has been used for the bottom-up projection (WNA, 2024f).

According to recent information from Rosatom's Director General Alexei Likhachev , it will have to build 17 new nuclear units by 2035 and decommission about 10 power units over the coming 10 years (traceyhonney, 2023). In March 2021, in its strategic review, Rosatom said that by 2045 nuclear should provide 25 percent of the country's electricity. According to Rosatom CEO Alexei Likhachev, require the commissioning of 24 units, including at new sites and in new regions (thonney, 2021). In 2017 Rosatom considered postponing commissioning new nuclear plants due to rising prices for new nuclear capacities and pressure from competitors. Given the reduced demand for energy in Russia, Rosenergoatom has already curtailed the investment programme, and some nuclear projects have been postponed or frozen including construction of a commercial unit with a fast neutron BN-1200 reactor at Beloyarsk (Peachey, 2017). In early 2017, the CEO of Rosatom said that the Government would end state support for the construction of new nuclear units in 2020, and therefore any new reactors would have to be financed primarily via commercial nuclear energy projects on the international market (M. Schneider et al., 2022). In 2019 a S&P Global Ratings report stated that "*We expect domestic nuclear capacity to increase only moderately because electricity demand in Russia is stagnating, given only modest GDP growth, a significant potential for energy savings, and the government's intention to avoid raising electricity prices through additional increases in capacity payments*" (WNN World Nuclear News, 2019a).

In our projection for Russia we used lifetimes of existing nuclear plants as provided by WNA (WNA, 2024f). WNA also provides a list of specific planned nuclear reactors in Russia. In the low scenario, we assumed the construction of 17 new nuclear units until 2035 and chose the reactors from this list with the highest likelihood to be build based on WNA's description[19]. In the past, the government plans frequently were only partly implemented. In 2009 and 2015 the plans for new nuclear reactors were substantially scaled back due to reduced electricity demand growth and financial constraints (WNA, 2024f). For example, the 2015 energy roadmap included a target of additional 30.5 GWe nuclear capacity with an average of one reactor per year commissioned until 2025. But net additions in this period were only 6 GWe (ibid). In the domestic Russian energy market, nuclear energy is competing with cheap oil, gas and coal resources while only about half of uranium production originates from domestic mines[20]. Due to a lack of information after 2035, no further construction of nuclear capacities was assumed. In the high scenario we assumed additional construction after 2035 based on the list of planned reactors from WNA and that all these reactors will be built by 2050 (total of 21 reactors). Table 29 shows the result of this projection.

Table 29: Nuclear capacities in the Russian Federation in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Russian Federation, low scenario	26.8	31.4	35.2	35.4	34.4	28.7
Russian Federation, high scenario	26.8	31.4	35.2	37.6	38.9	35.4

Source: Öko-Institut

[19] Criteria used were in particular the specific information available related to the planning stage of the reactors in the list, for some planned reactors information was very scarce. Priority was also given to new reactors that replace old reactors at the same site that are expected to stop operation.

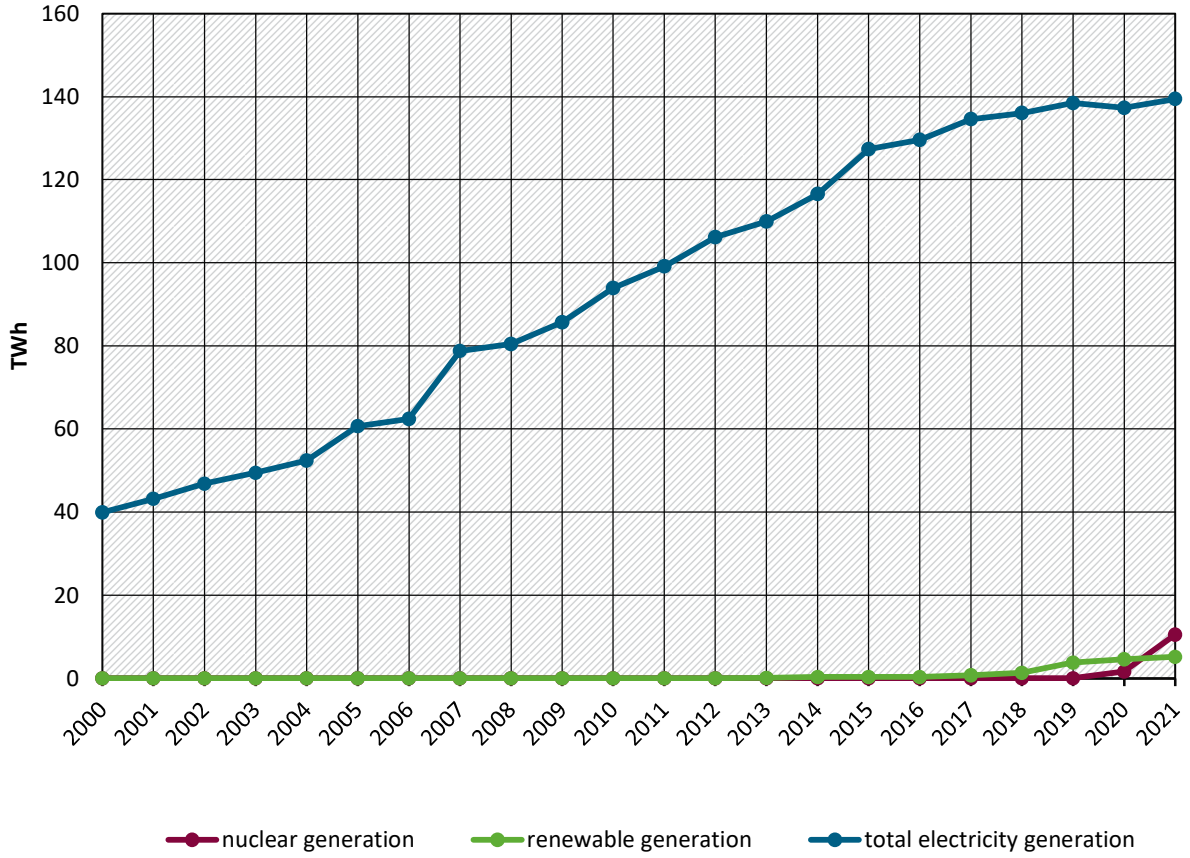
[20] https://world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-fuel-cycle, last accessed on 01.10.2025

2.4.6 Middle East

2.4.6.1 United Arab Emirates

According to IAEA Power Reactor Information System (PRIS), United Arab Emirates (UAE) have 4 nuclear reactors in operation with a total net capacity of 5.3 GWe. The share of nuclear in electricity production was 20% with the new plants in 2023 (IAEA PRIS).

Figure 55: Electricity generation in the United Arab Emirates (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

In UAE's first and second National Determined Contribution (NDC) under the UNFCCC, the National Energy Strategy 2050 is quoted with the objective of 50% share of clean energy (renewables and nuclear) in the installed power capacity mix by 2050. The updated NDCs states that "The abundance of solar radiation in the UAE coupled with a conducive regulatory framework and innovative business models has led to the development of both photovoltaic and concentrated solar power projects with record-breaking low electricity prices. The UAE is also investing in nuclear energy with the development of the four-reactor Barakah nuclear power plant. Installed clean power capacity, including solar and nuclear, is on track to reach 14 gigawatts (GW) by 2030, from just above 100 megawatts (MW) in 2015 and 2.4 GW in 2020." No plans for adding further nuclear capacities are mentioned. In the projection for UAE we therefore assumed that the new Barakah nuclear reactors will continue operation until 2050, but no further capacities will be added.

Table 30: Planned nuclear capacities in United Arab Emirates in the bottom-up projection until 2050 [GWe]

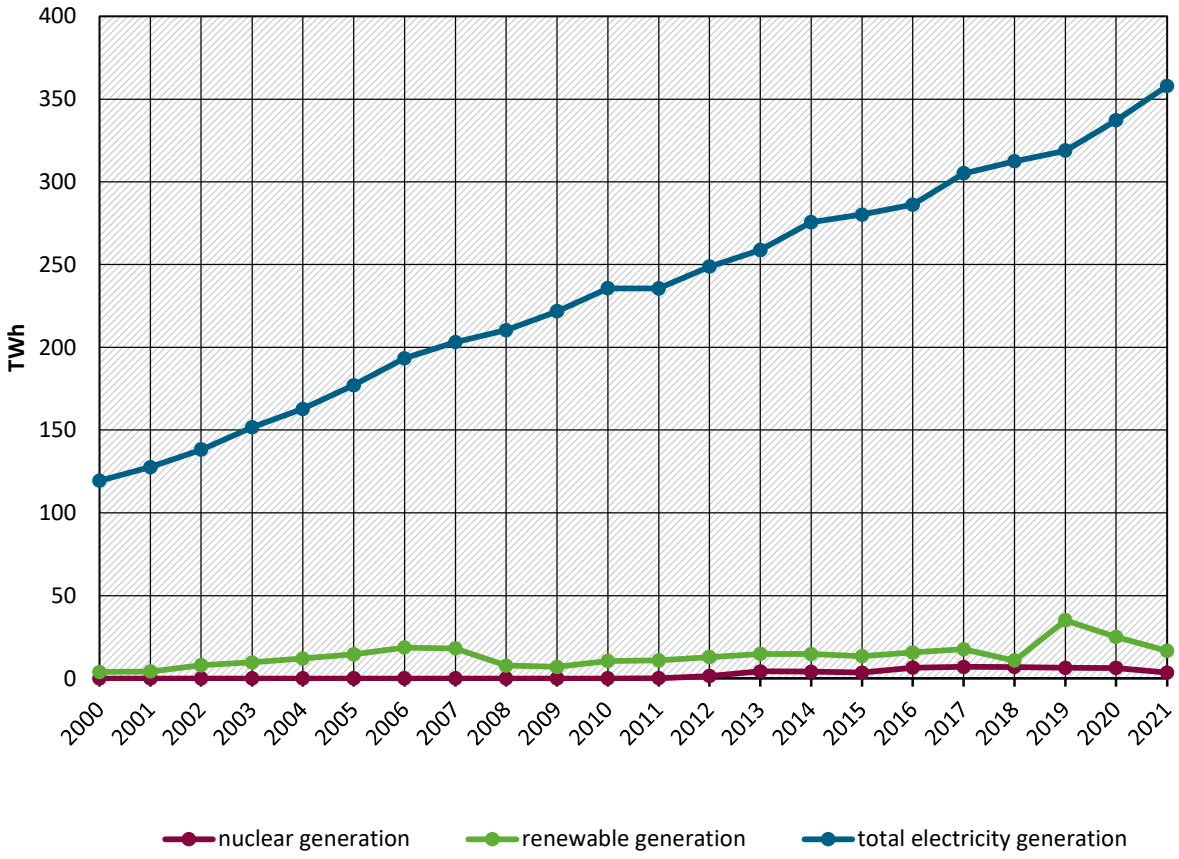
GWe (net)	2025	2030	2035	2040	2045	2050
United Arab Emirates	5.35	5.35	5.35	5.35	5.35	5.35

Source: Öko-Institut

2.4.6.2 Iran

According to IAEA Power Reactor Information System (PRIS), Iran has 1 nuclear reactor in operation with a total net capacity of 0.9 GWe and another reactor with 0.97 GWe under construction and a third unit is planned (Bushar-3 with 1057 MW) (WNA, 2024l). The share of nuclear in electricity production was 1% in 2021. Iran has stated that it intends to build further nuclear capacities, but most of these plans are older and have not been realised. In our projection we assumed the finalisation of these three units, but no further additions of capacities.

Figure 56: Electricity generation in Iran (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

Table 31: Planned nuclear capacities in Iran in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Iran	0.92	0.92	1.97	1.97	1.97	1.97

Source: Öko-Institut

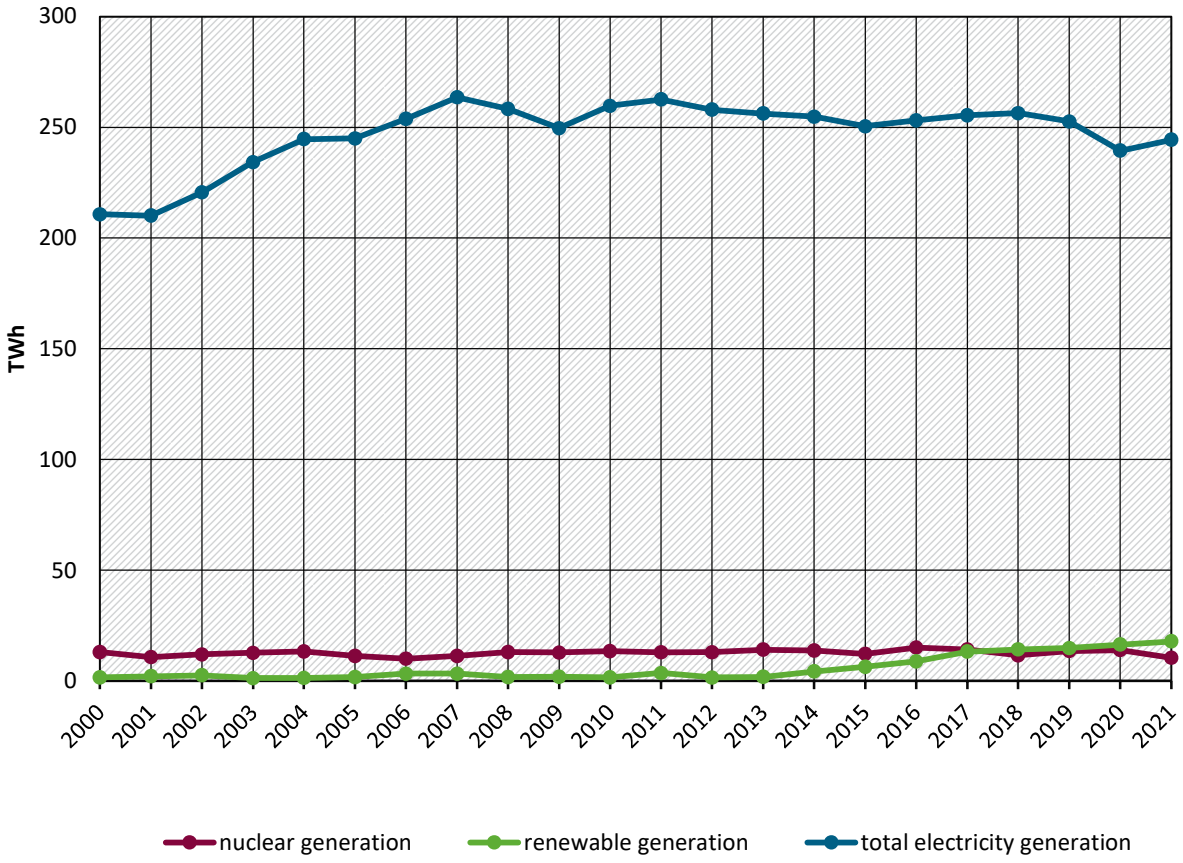
2.4.7 Africa

2.4.7.1 South Africa

According to IAEA Power Reactor Information System (PRIS), South Africa has 2 nuclear reactor in operation with a total net capacity of 1.9 GWe. There are no reactors under construction.

The share of nuclear in electricity production was 4% in 2021. The share of renewable energy in electricity production was 7%. The growth rate for renewables without hydro power was 41% per year in the decade 2011-2021, thus renewables grew very strongly and produced 16.5 TWh in 2021 whereas the nuclear plants only produced 10.4 TWh.

Figure 57: Electricity generation in South Africa (TWh)



Source: (BP, 2022), Renewables include hydro, wind, geothermal, solar, biomass and waste

The reactors started operation in the mid-1980s. In 2010 the decision to replace the six steam generators in the existing plants was taken and Areva was awarded with the contract in 2014. After corruption allegations and many delays, the first three steam generators were replaced at Koeberg 1 in March 2023 and the steam generators of unit 2 are also planned to be replaced in the later part of 2023. Due to the outage of Koeberg 1 unit, along with the extended outage of three units at the Kusile coal-fired power station, South Africa's power system was severely constrained in mid-2023. However, the replacement of the steam generators in unit 1 has still not happened (WNA, 2024j). The country's Integrated Resources Plan (IRP) 2018 states that the 1.8 GWe of capacity at Koeberg is expected to operate until 2045-2047 (ibid).

For more than a decade, South Africa has planned to build additional nuclear capacities until mid-2020s, but the plans were not implemented. In 2017, the Western Cape division of South Africa’s High Court ruled in favour of two NGOs, the Southern African Faith Communities

Environment Institute (SAFCEI) and Earthlife Africa, in their cases against the Government. This stopped a government decision to procure 9.6 GW of new nuclear capacity. The court concluded that the lack of public consultation on the decisions "rendered its decision procedurally unfair" and breached its statute (M. Schneider et al., 2022).

The IRP 2019 proposed to "commence preparations for a nuclear build programme to the extent of 2,500 MW at a pace and scale the country can afford." The "National Infrastructure Plan 2050" from March 2022 states that the IRP 2019 document "*will need revision and updating to adequately account for the pace of global innovation and cost reductions realised in the renewable energy sector in determining the least-cost electricity plan for the country*" (M. Schneider et al., 2022). The power company Eskom has large debt and is short in finance for new investments. From this perspective, it is difficult to imagine how South Africa will finance new nuclear power plants. In November 2021, the European Commission and the German government announced the "Just Energy Transition Partnership" with South Africa pledging US$ 8.5 billion in funding to help finance South Africa's transition away from coal which is focused on renewable energies.

Based on this background, we assumed a scenario without additional nuclear reactor constructions for South Africa.

Table 32: Planned nuclear capacities in South Africa in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
South Africa	1.85	1.85	1.85	1.85	1.85	0.0

Source: Öko-Institut

2.4.8 Potential newcomer countries

World Nuclear Association quotes about 30 countries "*considering, planning or starting nuclear power programmes, and a further 20 or so countries have at some point expressed an interest. Despite the large number of these emerging countries, they are not expected to contribute very much to the expansion of nuclear capacity in the foreseeable future – the main growth will come in countries where the technology is already well established*" (WNA, 2024g).

WNA classified the emerging countries according to how far their nuclear power programmes or plans have progressed:

- Power reactors under construction (= first concrete have been poured): Bangladesh, Egypt, Turkey.
- Power reactors proposed (=Specific programme or site proposals; timing very uncertain): Jordan, Kazakhstan, Lithuania, Poland, Saudi Arabia, Uzbekistan.
- Provisional plans, commitment pending or deferred: Algeria, Azerbaijan, Estonia, Ethiopia, Ghana, Kenya, Laos, Morocco, Nigeria, Philippines, Rwanda, Sri Lanka, Sudan, Thailand, Indonesia, Saudi Arabia, Vietnam (deferred).

The increasing interest rates at global level and higher inflation in many countries is currently decreasing the prospects of additional newcomer countries, in particular of relatively poor countries. In addition, the decreasing prices for renewable energies add to their attractiveness apart from their environmental advantages. Newcomer countries would also need to establish a government and regulatory infrastructure for nuclear safety, licensing, nuclear waste storage

etc. which is extremely costly for the government compared to renewable energy if only few nuclear plants would be built in smaller countries.

For this study we took into account the countries with nuclear reactors under construction (Bangladesh, Egypt and Turkey) and some countries where power reactors are proposed (Poland, Saudi Arabia) that are also considered as emerging countries in the World Nuclear Industry Status Report. Lithuania mentioned in WNA's list does not report on plans to build nuclear reactors in its NECP and tries to ensure that no electricity is imported from unsave nuclear reactors in Belarus into the European grid, which is mentioned as a specific measure in the Lithuanian NECP. In addition, Lithuania is still working on the decommissioning of the closed Ignalina nuclear plant. Thus, we do not think that there is evidence for new nuclear reactors in Lithuania. Other countries' activities seem still rather uncertain and will not add large capacities to the global nuclear fleet.

2.4.8.1 Egypt

In 2022, Russian state company Rosatom secured a construction permit for the first nuclear power reactor in Egypt, and on 20 July 2022, construction was officially launched. The El-Dabaa Nuclear Power Plant is the first nuclear power plant in Egypt. It will be constructed in the city of El-Dabaa, Matrouh Governorate, on the Mediterranean coast, roughly 300 km north-west of Cairo. The El-Dabaa Nuclear Power Plant will consist of 4 units with a total net generating capacity of 4.4 GWe using generation III+ VVER-1200 reactors (pressurized water reactors).

Apart from Russia, nuclear cooperation agreements are in place with China (2006) and South Korea (2013) (WNA, 2023). In May 2015 China National Nuclear Corporation (CNNC) signed an agreement with the NPPA to enhance nuclear cooperation and to "become an official partner" in the country's nuclear project.

PRIS database indicates the start date of the first unit with 2032, but ten years in a country where no nuclear reactors have been built seems very optimistic. In our projection we therefore assume a somewhat later and staged start of the four units.

Table 33: Planned nuclear capacities in Egypt in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Egypt	0.0	0.0	0.0	1.1	3.3	4.4

Source: Öko-Institut

2.4.8.2 Estonia

In its National Energy and Climate Plan, Estonia explains that nuclear energy can be one potential option for meeting Estonia's electricity demand after 2030 (EC, 2020). However, Estonia also highlights that considerably preparations are necessary for this. "*the making of thorough political preparations at the State level, the recruitment of people with relevant training and the creation of a legal basis. The commissioning of nuclear energy requires legislation to be drawn up which would establish the terms, conditions and process of building a nuclear power plant in Estonia and, if necessary, the creation of the necessary structures. Currently Estonia does not have the necessary legal framework, competent authorities or thematic experts to build nuclear stations.*" Further analysis is planned to be carried out to identify roadmaps towards climate neutral electricity generation in Estonia and the country will also analyse the socio-economic impacts of different roadmaps. The Russian attacks on nuclear plants in Ukraine may also influence Estonia's decision to build nuclear plants which would present a new military target and a very high risk.

2.4.8.3 Bangladesh

Bangladesh is in the process of building its first nuclear power plant at Rooppur with with two Russian VVER-1200 reactors of the total 2400 MW capacity.

Construction at Rooppur, which began in November 2017 and July 2018, respectively. As of October 2021, fuel loading of the first reactor was scheduled in the fourth quarter of 2023; Unit 1 is scheduled for grid connection the same year, and Unit 2 for 2024 (M. Schneider et al., 2022). The dates for commencement of commercial operations were 2024 and 2025 respectively (WNA, 2024k). By mid-2025 none of the reactors has started commercial operation which is now scheduled for 2025 for Rooppur 1 performed several tests in 2025 while unit 2 is still in the construction phase. Even before the first two reactor units have been fully constructed, and the full costs ascertained, Bangladesh's Prime Minister, Sheik Hasina, has called for building a second nuclear power plant (M. Schneider et al., 2022). China's Dongfang Electric Corporation (DEC) has expressed interest in building the second power plant, with China Nuclear Engineering & Construction Corp (CNEC), but it is currently unclear whether this plan will be really implemented. We assumed a low scenario, in which only the current nuclear plants are build and a high scenario where Bangladesh continues with the plans for a second nuclear plant.

Table 34: Planned nuclear capacities in Bangladesh in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Bangladesh, low scenario	2.2	2.2	2.2	2.2	2.2	2.2
Bangladesh, high scenario	2.2	2.2	2.2	4.2	4.2	4.2

Source: Öko-Institut

2.4.8.4 Poland

Poland currently has no nuclear reactors, but the government announced plans to build new reactors. In its NECP Poland announced that it plans to use nuclear power by 2033 (Polish Ministry of Climate, 2024). According to the Polish NECP the first unit (with a capacity of ca. 1-1.5 GW) of the first nuclear power plant is expected to be commissioned in the period 2030-2035, with another five units to be launched every 2-3 years with a total capacity of 7.4 until 2040 and 9.4 GW in the long term. The plans are further detailed in the "Polish Nuclear Power Programme" which was adopted by the Polish government in 2020 (Government of Poland, Ministry of Climate, 2020). The programme foresees the construction of six reactors at two sites, of which one should be at the Polish coast.

At the end of October 2022 prime minister Mateusz Morawiecki announced that Westinghouse had been chosen to build the country's first nuclear plant in the Pomerania province, with the exact location near the Baltic Sea to be confirmed (WNA, 2024m). Also at the end of October 2022, energy company ZE PAK announced it had signed a letter of intent with PGE and Korea Hydro & Nuclear Power (KHNP) to build a nuclear plant based on APR1400 technology at the Pątnów site in central Poland (WNA, 2023). In November 2022 KHNP commenced a site assessment at Pątnów. The following month, four eastern German states – Mecklenburg-Western Pomerania, Brandenburg and Saxony, which border Poland, as well as Berlin – formally expressed opposition to the Polish government's plans to develop the country's first nuclear power station (ibid). In April 2023 ZE PAK and PGE announced the establishment of a joint venture known as PGE PAK Energia Jądrowa to manage the development of a nuclear plant in Pątnów (ibid).

The new Polish government under Donald Tusk is still in favour of nuclear energy, but also considers previous timelines as not achievable. Industry minister Czarnecka considers 2035 as the earliest date for a first reactor and 2039 to 2040 for the plant in Pomerania. A second new nuclear construction project is planned in the Lodz region with 6-9 GW nuclear capacity and SMRs are also considered.

A number of sites have been assessed and are mentioned in the document, but no specific decisions have been taken, In the Nuclear Power Programme, the sites Lubiatowo-Kopalino and Żarnowiec at the Baltic coast are described at those for which the work on environmental and siting studies is most advanced (Polish Ministry of Climate, 2020). The advantages of these sites are described as a significant electricity demand and the lack of large, dispatchable generation sources in the area, access to cooling water, the possibility of transporting large-size loads by sea. However, both sites are very close to Kaliningrad Russian territory and it may be unlikely that after the Russian attacks on the Zaporizhzhia power plant in Ukraine, Poland will build its reactors in the direct vicinity of armed Russian territory.

Our bottom-up projections reflect the planned construction in Poland in accordance with the Polish Nuclear Power Programme and the updated National Energy and Climate Plan from 2024 (Polish Ministry of Climate, 2024). Given the substantial delays of all recent nuclear construction projects in Europe, it is however unlikely that the timeline will be kept as depicted in Table 35. It is also unclear whether the enormous risk shown with the Russian attacks on nuclear plants in Ukraine will change the plans of the Polish government, given the fact that the new reactors would present a military target of a new dimension for Poland.

Table 35: Planned nuclear capacities in Poland in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Poland	0.0	0.0	1.5	1.5	7.4	9.4

Source: Öko-Institut

2.4.8.5 Türkiye

Türkiye is in the process of building its first nuclear power plant at Akkuyu. Russia's Rosatom is building four VVER-1200 reactors with a total capacity of 4,8 GW. The first unit is expected to start operation in 2023, but there are doubts whether this schedule will be kept (M. Schneider et al., 2022). IAEA PRIS database provides a start date of 2028 which we used in our projection.

Table 36: Planned nuclear capacities in Turkey in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Türkiye	0.0	4.5	4.5	4.5	4.5	4.5

Source: Öko-Institut

2.4.8.6 Saudi Arabia

In 2010 Saudi Arabia established the "King Abdullah City for Atomic and Renewable Energy (KA-CARE)", a research entity headed by the Minister of Energy, Industry and Mineral Resources. There have been plans to build nuclear plants since then, but no construction has started yet. In May 2022, KA-CARE invited bids from China, France, Russia, and South Korea to construct two 1,400 MW nuclear reactors (M. Schneider et al., 2022). Saudi Arabia also established the Nuclear Holding Company, which will act as the country's nuclear developer (WNA, 2023).

It is unclear how these plans will continue, but in our projection for Saudi Arabia we included the two nuclear reactors for Saudi Arabia. The country was included in the projection due to its high capacity to finance a nuclear plant and the concrete start of the bidding process for its first plant. It is also assumed that Saudi Arabia has a strong military interest in a domestic nuclear programme. But it will at least take a decade before the reactors will start operating.

Table 37: Planned nuclear capacities in Saudi Arabia in the bottom-up projection until 2050 [GWe]

GWe (net)	2025	2030	2035	2040	2045	2050
Saudi Arabia	0.0	0.0	2.8	2.8	2.8	2.8

Source: Öko-Institut

2.4.8.7 Other countries

At COP 28 in Dubai French president Emmanuel Macron and US Special Envoy for Climate John Kerry announced that more than 20 countries launched the 'Declaration to Triple Nuclear Energy by 2050' (see section 2.7). The renewed pledge was signed by eleven countries that neither run nuclear reactors, nor have started building nuclear plants (Croatia, Ghana, Jamaica, Kazakhstan, Kenya, Kosovo, Moldova, Mongolia, Morocco, Nigeria, Poland).

Russia has established nuclear agreements (MoU) with about 20 African States (Algeria, Burkina Faso, Burundi, Republic of Congo, Ethiopia, Ghana, Kenya, Mali, Morocco, Namibia, Rwanda, Sudan, Tanzania, Uganda, Zambia, Zimbabwe). China has entered agreements with Kenya and Sudan, but not specific construction plans (M. Schneider & Froggatt, 2024). Many of these agreements are dating back to years before 2020, but have never moved forward. For the smaller countries such as Burkina Faso, Burundi, Mali, Namibia or Rwanda, a typical capacity of a nuclear power plant would exceed the current total installed capacity of the country. The IAEA stipulates as a general rule that a single power plant should represent no more than 10 percent of the total capacity of a country (M. Schneider & Froggatt, 2024). From this perspective, only Algeria, Libya, Morocco and Nigeria would have sufficiently large electricity production to qualify for nuclear plants.

From this perspective of the size and total electricity capacity of the country, some of the countries part of the declaration to triple nuclear (Jamaica with about 1 GW electricity production, Kosovo with about 1 GW, Moldova with less than 1 GW or Croatia with 5.5 GW) also seem far too small to build a regular nuclear power plant.

2.5 Summary of scenarios for countries based on plans and programmes

Table 38 presents an overview of the results of the individual countries discussed in the previous section and the following analysis is linked to this table.

Table 38: Overview of nuclear capacity development until 2050 in bottom-up baseline and ambitious scenarios [Net GWe]

		Baseline scenario capacities (Net GW)						Ambitious scenario capacities (Net GW)					
		2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
EU27		*97.6*	*89.1*	*69.4*	*54.3*	*51.9*	*47.8*	*97.6*	*93.3*	*95.1*	*114.9*	*96.8*	*76.4*
	Belgium	3.5	2.1	2.1	0.0	0.0	0.0	3.5	3.5	3.5	2.0	2.0	0.5
	Bulgaria	2.0	2.0	3.0	3.0	4.0	3.0	2.0	2.0	3.0	3.0	4.0	3.0
	Czech Republic	4.0	4.0	4.0	4.0	4.5	4.5	4.0	4.0	4.0	4.9	6.1	6.9
	Finland	4.4	4.4	4.4	4.4	4.4	3.9	4.4	4.4	4.4	4.4	4.4	3.9
	France	63.0	59.9	38.3	15.3	17.3	17.3	63.0	62.6	62.7	68.9	49.1	35.5
	Hungary	1.9	1.9	1.9	4.0	3.2	2.4	1.9	1.9	1.9	4.0	3.2	2.4
	Netherlands	0.5	0.5	0.0	0.0	0.0	0.0	0.5	0.5	0.0	3.0	3.0	3.0
	Poland	0.0	0.0	1.5	7.4	7.4	9.4	0.0	0.0	1.5	7.4	7.4	9.4
	Romania	1.3	1.3	4.3	4.8	4.8	4.1	1.3	1.3	4.3	4.8	4.8	4.1
	Slowakia	2.3	2.3	2.3	2.3	2.3	1.7	2.3	2.3	2.3	2.3	2.3	1.7
	Slovenia	0.7	0.7	0.7	0.7	0.0	0.0	0.7	0.7	0.7	0.7	1.1	1.1
	Spain	7.1	3.2	0.0	0.0	0.0	0.0	7.1	3.2	0.0	0.0	0.0	0.0
	Sweden	7.0	7.0	7.0	8.5	4.1	1.5	7.0	7.0	7.0	9.5	9.5	5.0
Other Europe		*22,0*	*24.2*	*15.5*	*12.7*	*11.7*	*11.7*	*22.0*	*24.2*	*23.9*	*26.7*	*24.0*	*15.5*
	Switzerland	3.0	2.2	1.9	1.0	0.0	0.0	3.0	2.2	1.9	1.0	0.0	0.0

		Baseline scenario capacities (Net GW)						Ambitious scenario capacities (Net GW)					
	Turkey	0.0	4.5	4.5	4.5	4.5	4.5	0.0	4.5	4.5	4.5	4.5	4.5
	Ukraine	13.1	13.1	4.8	1.9	1.9	1.9	13.1	13.1	13.1	13.1	11.4	2.9
	United Kingdom	5.9	4.4	4.4	5.4	5.4	5.4	5.9	4.4	4.4	8.1	8.1	8.1
North America		*111,2*	*108.8*	*103.3*	*99.0*	*87.0*	*59.0*	*111.2*	*108.8*	*110.8*	*106.5*	*102.0*	*74.0*
	Canada	12.7	10.2	11.1	11.1	11.2	11.6	12.7	10.2	11.1	11.1	11.2	11.6
	Mexico	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
	USA	97.0	97.0	90.6	86.3	74.2	45.8	97.0	97.0	98.1	93.8	89.2	60.8
South America		*3,5*	*3.5*	*4.1*	*4.1*	*3.2*	*3.2*	*3.5*	*3.5*	*4.1*	*5.4*	*6.1*	*6.1*
	Argentina	1.6	1.6	2.2	2.2	1.9	1.9	1.6	1.6	2.2	2.2	1.9	1.9
	Brazil	1.9	1.9	1.9	1.9	1.2	1.2	1.9	1.9	1.9	3.2	4.2	4.2
Eastern Europe		*29,4*	*34.0*	*37.8*	*37.6*	*36.7*	*30.9*	*29.4*	*34.0*	*37.8*	*39.9*	*41.1*	*37.6*
	Belarus	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
	Russian Federation	26.8	31.4	35.2	35.4	34.4	28.7	26.8	31.4	35.2	37.6	38.9	35.4
	Armenia	0.4	0.4	0.4	0.0	0.0	0.0	0.4	0.4	0.4	0.0	0.0	0.0
Middle East		*6,3*	*6.3*	*11.2*	*13.4*	*14.5*	*14.5*	*6.3*	*6.3*	*11.2*	*13.4*	*14.5*	*14.5*
	Egypt	0.0	0.0	1.1	3.3	4.4	4.4	0.0	0.0	1.1	3.3	4.4	4.4
	Iran	0.9	0.9	2.0	2.0	2.0	2.0	0.9	0.9	2.0	2.0	2.0	2.0
	Saudia Arabia	0.0	0.0	2.8	2.8	2.8	2.8	0.0	0.0	2.8	2.8	2.8	2.8
	United Arab Emirates	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3

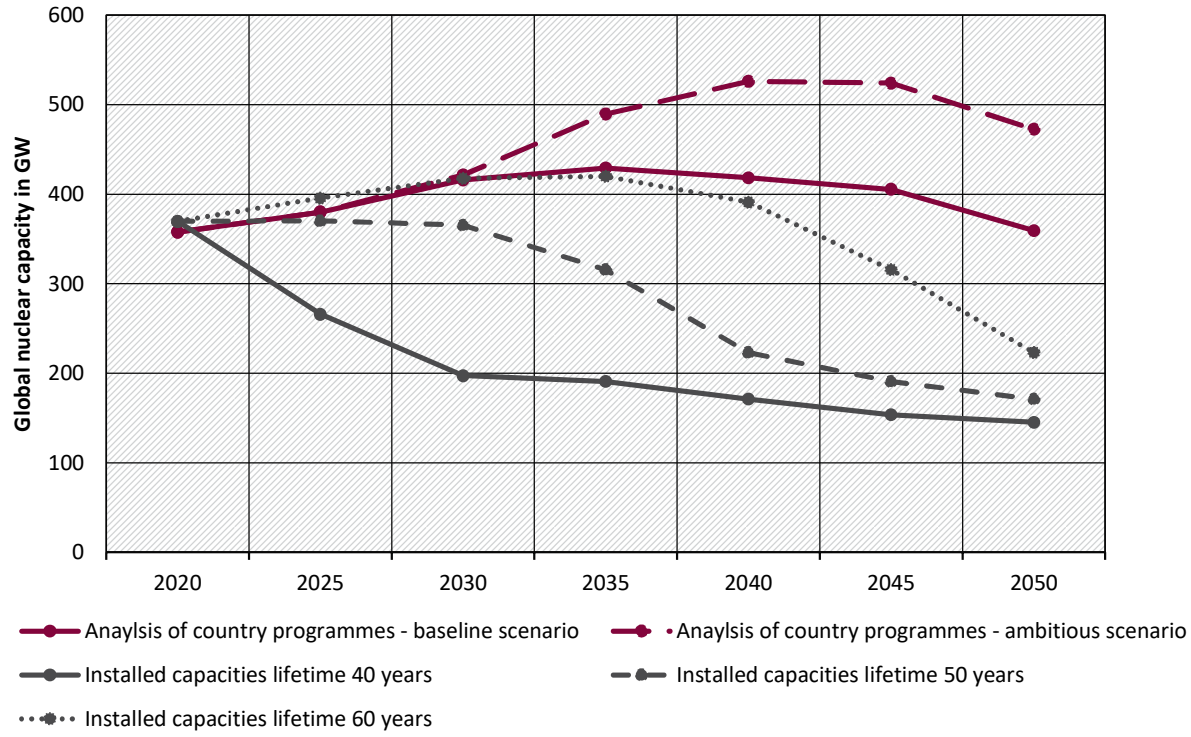
		Baseline scenario capacities (Net GW)						Ambitious scenario capacities (Net GW)					
Africa		*1.9*	*1.9*	*1.9*	*1.9*	*1.9*	*0.0*	*1.9*	*1.9*	*1.9*	*1.9*	*1.9*	*0.0*
	South Africa	1.9	1.9	1.9	1.9	1.9	0.0	1.9	1.9	1.9	1.9	1.9	0.0
Asia		*108.4*	*148.3*	*186.3*	*195.5*	*198.8*	*192.4*	*108.4*	*149.7*	*204.9*	*217.7*	*238.0*	*248.7*
	Bangladesh	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	4.2	4.2	4.2
	China	55.3	72.3	100.0	115.0	120.0	125.0	55.3	73.3	110.0	120.0	130.0	140.0
	India	7.6	12.3	14.1	13.9	15.4	14.3	7.6	12.7	22.6	22.4	26.0	24.9
	Pakistan	3.3	3.3	4.3	4.3	4.3	4.3	3.3	3.3	4.3	4.3	4.3	4.3
	Japan	12.6	30.4	31.8	31.8	28.6	23.2	12.6	30.4	31.8	31.8	31.8	31.8
	South Korea	25.6	27.9	33.9	28.3	28.3	23.4	25.6	27.9	33.9	35.0	41.7	43.5
	Taiwan	1.8	0.0	0.0	0.0	0.0	0.0	1.8	0.0	0.0	0.0	0.0	0.0
Total		*380.2*	*416.0*	*429.5*	*418.5*	*405.6*	*359.5*	*380.2*	*421.6*	*489.6*	*526.3*	*524.4*	*472.8*

Source: Öko-Institut

Figure 58 shows the baseline scenario and the ambitious scenario at global level compared with the development of nuclear power capacities installed today for various assumptions regarding lifetime (40, 50 and 60 years). In the baseline development, nuclear capacities increase by 9% by 2030 and by 10% by 2040, before declining to a level close to the current situation by 2050. In the ambitious scenario – in which government plans have been incorporated that are partly not very likely to receive funding – capacities peak around 2040/2045 with an increase of 38% compared to the current level. In 2050, capacities would be 24% (around 100 GW) higher than today.

Thus, while in the baseline scenario capacities decrease in the long-term, even the ambitious scenario only presents a rather limited growth in nuclear capacities and will not lead to a "renaissance" of nuclear energy in global energy production. Taking into account a strong expected global increase in electricity generation, the share of nuclear in electricity production is unlikely to be higher in 2050 than around the current 10%.

Figure 58: Development of global nuclear capacity according to an analysis of government programmes worldwide in comparison with the development of current capacity (including those under construction today)



Source: data: (IAEA, 2025), own calculation; own illustration, Öko-Institut e.V.

Figure 59 presents the regional distribution of nuclear capacities. In the ambitious scenario, capacities in Europe grow by 15% compared to current level in 2040, but decline to a level 24% lower than today by 2050. In the EU, the situation is dominated by France and to what extent France will replace its partly outdated nuclear fleet and whether state-own company EDF will be able to invest very large amounts in the lifetime extensions and new nuclear constructions at the same time. At the moment EDF's debt is at more than €60 billion[21], and it is therefore not very

[21] https://www.spiegel.de/wirtschaft/unternehmen/edf-franzoesischer-energiekonzern-macht-knapp-18-milliarden-euro-verlust-a-8c6ff5bb-d2cd-4ead-81df-8d8368670655, last accessed on 01.10.2025

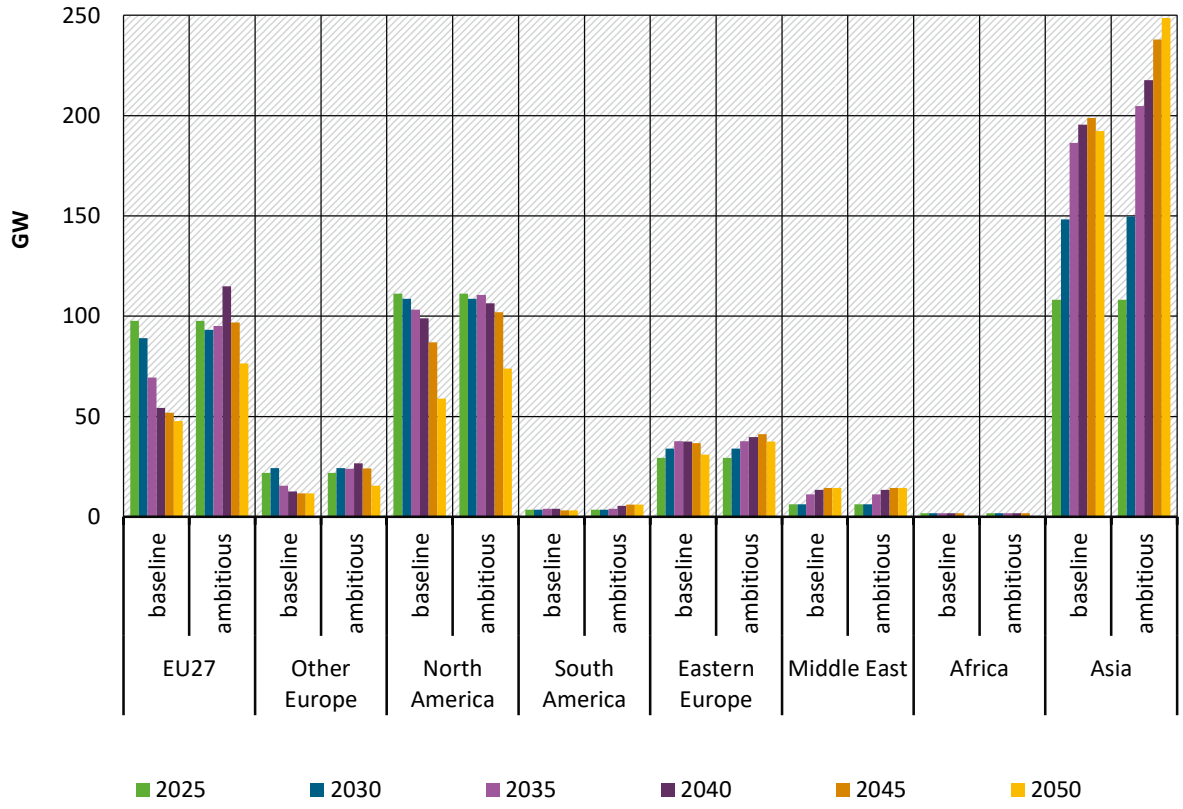
likely that the ambitious plans of the French government for new nuclear plants can be financed and implemented.

The situation in North America, in particular in the U.S. is very similar. In the current energy market and with current costs structures, it seems unlikely that all the very old reactors will be replaced. Therefore, even the ambitious scenario expects a slow decline in nuclear capacities until 2050 by 26%. If operators will decide to close existing plants earlier than the rather long lifetimes assumed in the scenarios, this decline could happen much faster. Whether this will happen, will depend on the performance of the nuclear plants with operating lifetimes of more than 40 or 50 years. In Belgium or France, stability of operation decreased significantly with the age of the reactors which makes operation expensive and can lead to earlier shutdown for economic reasons even when the permit may allow longer operation.

In Eastern Europe, in particular Russia, capacities will grow by 28% by 2040 and by 21% by 2050. The regions with strong growth trends are Asia where capacities are expected to grow by the factor of 2.5 by 2050 in the ambitious scenario and almost double in the baseline scenario. This trend is mostly driven by China, but also India, Japan and South Korea show growing nuclear capacities. The Middle East also shows a strongly growing trend, however the countries in this group start from a low level of 6 GW total nuclear capacities and have a limited energy need in relation to their size and population. Thus, the effect for the global capacities are small. In general, the replacement of old nuclear plants in the US and France and the future construction in China are the most important determining factors for the global development. Figure 59 also shows that while the current regions with high nuclear capacities will remain, Asia will likely be the region with highest nuclear capacities in the future.

Small modular reactors (SMRs) play an increasing role in the discussions and in future plans of governments for new nuclear constructions. Despite considerable public funding in research activities and start-ups for SMRs, there are not many realised projects or projects under construction. SMRs have capacities up to 300 MW, many designs are below or up to 100 MW. Thus, 10 SMRs would be necessary to replace one large nuclear plant. The plans for SMRs have been considered in the assessment at country level, but due to their smaller size, the current lack of cost advantages and the same or even longer construction times as large nuclear plants, they do not have a significant quantitative impact on the roles of nuclear electricity in the bottom-up scenarios.

Figure 59: Development of nuclear capacities in world regions in the baseline and ambitious bottom-up scenarios



Source: Öko-Institut

Despite the Russian role as biggest international investor and Rosatom the company with most international nuclear construction projects, the capacity addition in Russia will be limited and current plans do not point at a strong increase in nuclear capacities in the Russian Federation, but more at a stable capacity level. This is due to the fact that nuclear energy is more expensive compared to the fossil energy resources available in abundance in Russia.

While investments in the middle East are increasing, the countries and their electricity demand are relatively small, thus this development does not impact the global trend in a very significant way.

There are several reasons why nuclear energy is unlikely to gain significant higher shares in electricity production compared to current levels despite policy shifts in in a number of governments with towards pro-nuclear (and mostly right-wing) parties:

- Levelized costs of energy for newbuild nuclear show that nuclear is the most expensive energy source (see section 4.5). The significant cost advantages of wind and solar generation lead to much higher investments in renewables. According to IEA data on world energy investment in 2024, in China the investment in renewables was 20 times larger as in nuclear energy, in the U.S. the investment in renewables was 9 times larger than in nuclear energy and in Europe 7 times.
- In competitive electricity markets with several competing energy utilities, nuclear reactors are too expensive related to the total investment portfolios of the electricity companies. Construction costs for new nuclear reactors in recent years in Europe and the U.S: were

between US$ 7 to 15 billion per reactor[22]. German energy companies EnBW or Eon have investment portfolios of around EUR 40 billion for the period 2024 to 2028 (EnBW) and EUR 42 billion until 2028 (Eon), RWE's investment portfolio is EUR 55 billion for the period 2024 to 2030. New nuclear reactors would consume large parts of the investment portfolio for one single project with high risks. Therefore, new nuclear constructions are mostly implemented by state-owned companies such as in France, Russia, United Arab Emirates, South Korea or China. In these cases, the governments pay for the higher costs and take financial responsibility for the significant financial risks. But in competitive electricity markets, companies avoid these risks.

- For small countries, the transaction costs and framework conditions to build and manage nuclear plants and deal with nuclear waste are very high and difficult to provide. They need to have the legal framework in place, establish regulatory and safety authorities, have electricity grids that can integrate single large sources and ensure that trained staff is available with relevant competences which mostly means reliance on foreign expertise. Downtimes of nuclear plants for maintenance or due to accidents would directly impact the security of electricity supply if one nuclear plant would supply a large share of the electricity in the country. Small modular reactors require most of these framework conditions, but for rather small generation capacities. If countries do not yet have nuclear reactors, the governments face much higher costs than only the nuclear plant.
- Most recent nuclear projects outside China experience cost overruns and significant delays in construction (which also increases the capital costs for nuclear) while the construction times for renewable energies are much shorter and costs more predictable.
- Few countries or companies build nuclear power plants in other countries. The biggest nuclear supplier with currently 26 units under construction globally is Russia's Rosatom. Besides Rosatom, only France's EDF and South Korea are building nuclear plants abroad (two reactors in UK). China has so far only exported one nuclear plant to Pakistan. U.S. or Canadian companies have not built reactors abroad recently. Thus, the number of suppliers of the technology for large nuclear plants is rather limited.
- Nuclear power creates strong dependencies in the supply chains on few countries because uranium mining and capacities for conversion, enrichment and fuel rod fabrication are owned by few major producers. The overview of countries with uranium mining is frequently not reflecting the ownership of these mines that may be located in Africa, but in ownership of Western, Russian or Chinese companies.
- With increasing age, the security of electricity supply from nuclear plants can decrease significantly which has affected France significantly in 2022, but also other years. Climate change impacts, further threaten the security of supply, in particular the lack of water in summer months for cooling of nuclear reactors at rivers.

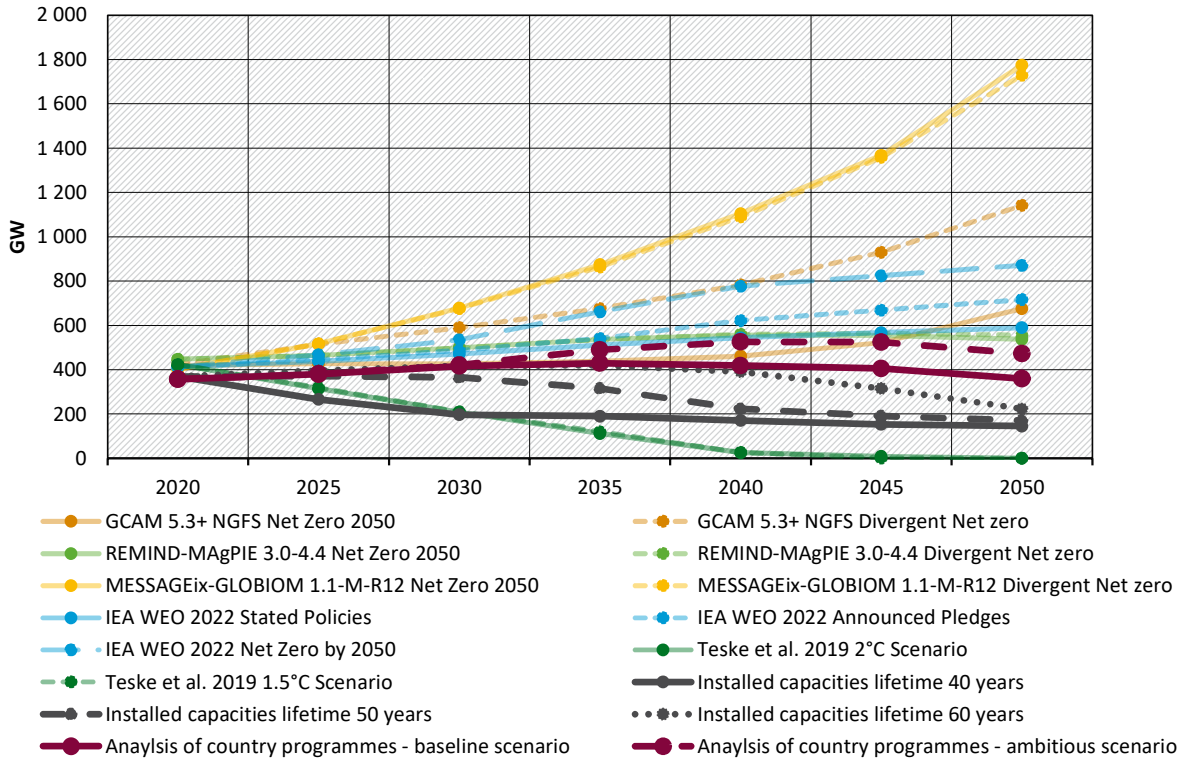
2.6 Comparison of global scenarios with bottom-up analysis

A comparison of the conducted analysis of the existing nuclear power plant fleet, the development paths based on bottom-up government plans worldwide and the model-based scenarios described in the chapters above is presented in Figure 60.

[22] Vogtle in the U.S. US$ 37 billion for two reactors, Finland US$ 12 billion, Flamanville in France 14.6 billion, Hinkley Point C in UK is currently at 59 billion for two reactors.

Even in the ambitious scenario, the analysis of government programmes results in a path that would envisage a maximum of 526 GW installed capacity in 2040 and 473 GW in 2050. These plans would still mean a considerable addition of new power plants as described in the previous section. Even the ambitious scenario based on the government programmes, shows a lower nuclear capacity2050 than all the scenarios analysed (with the exception of the Teske nuclear phase-out scenarios). The difference in capacities between the ambitious bottom-up scenario of country programmes to the highest MESSAGEix-GLOBIOM scenario is 1300 GW. The IEA WEO scenario "Net Zero by 2050" includes almost 400 GW more nuclear capacity compared to the ambitious bottom-up scenario. The differences to the global REMIND-MAgPIE scenarios are much smaller and these are higher by 65 GW and 83 GW.

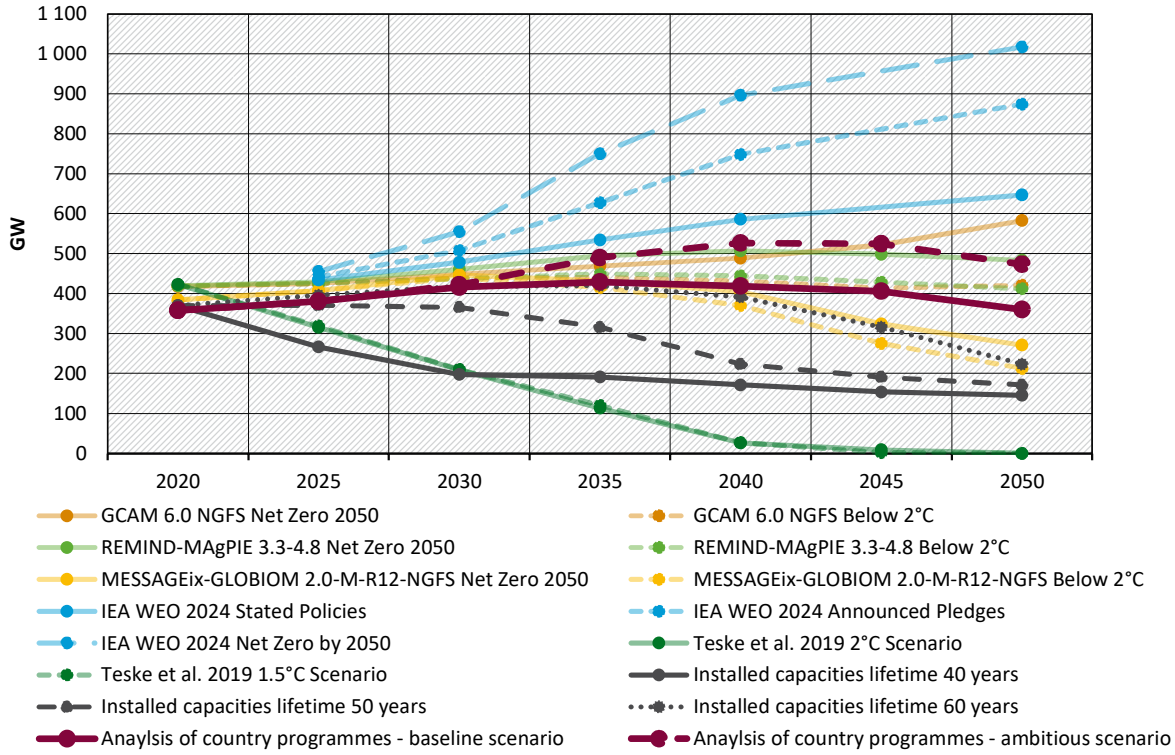
Figure 60: Installed capacity of nuclear reactors (world) in the scenarios analysed



Source: (NGFS, 2022), (Teske, 2019), (IEA, 2022), (IAEA, 2025); own calculation, own illustration, Öko-Institut e.V.

The comparison between the bottom-up scenarios and the top-down scenarios looks different when using the updated NGFS scenarios from 2024 and the 2024 World Energy Outlook as presented in Figure 61. The nuclear capacities in the 2024 World Energy Outlook "Net Zero by 2050" and "Announced Pledges" scenarios double those of the ambitious bottom-up scenario in 2050. The WEO "Stated Policy" scenario however is closer and about 40% higher than the ambitious bottom-up scenario. The MESSAGEix-GLOBIOM results are now significantly lower in 2050 than both bottom-up scenarios. The nuclear capacities projected for2050 by GCAM and REMIND-MAgPIE are in the range of the baseline and ambitious bottom-up scenarios. Thus, the scenario updated have resulted in an alignment with the bottom-up analysis.

Figure 61: Installed capacity of nuclear reactors (world) in UPDATED scenarios analysed



Source: (Richterss et al., 2024), (Teske, 2019), (IEA, 2024), (IAEA, 2025); own calculation, own illustration, Öko-Institut e.V.

As the model-based scenarios are disaggregated by region[23], it is possible to identify the regions that show the major differences between the model results and the real world government programmes.

Figure 62 illustrates this for the scenario with highest nuclear energy contribution of the scenarios analysed, the “Net Zero 2050 scenario” calculated with the MESSAGEix-GLOBIOM model (NGFS, 2022) for 2050.

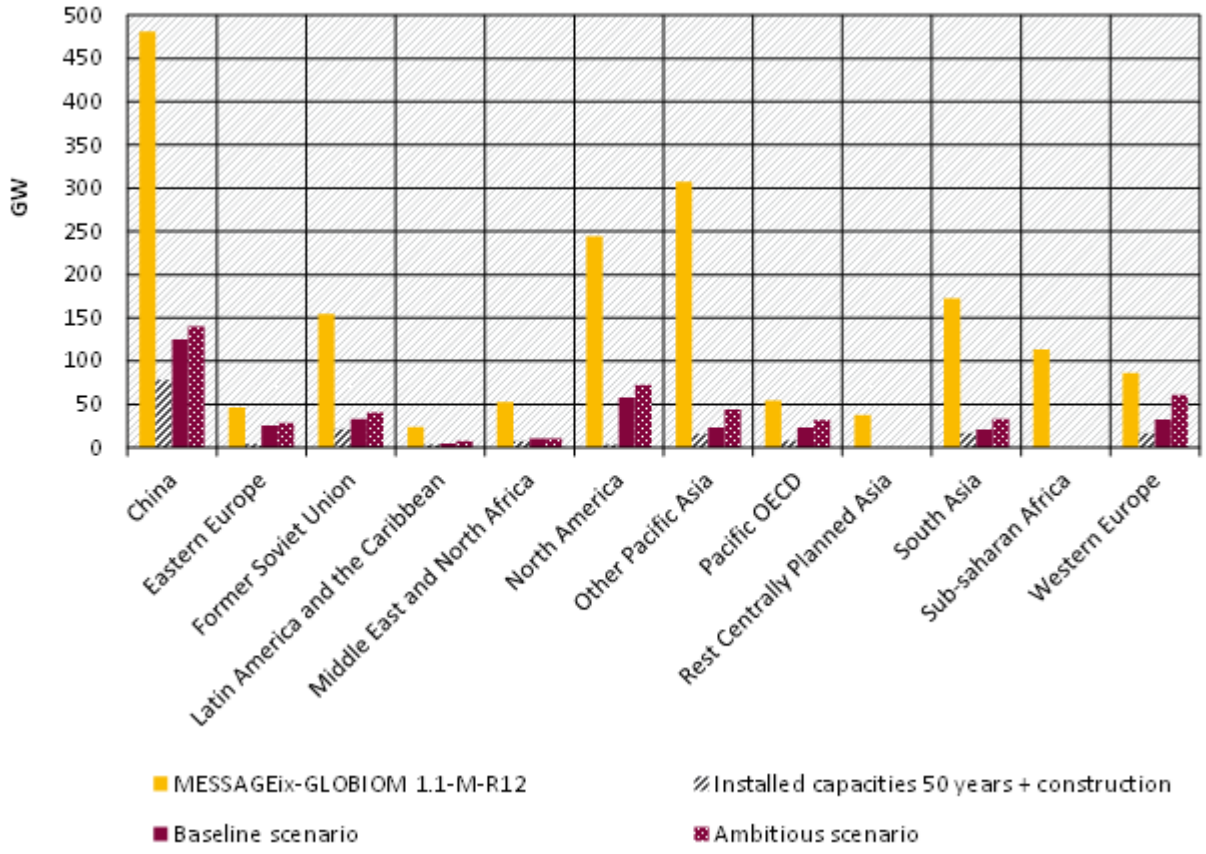
The model assumes a significantly higher nuclear power capacity in all regions of the world than the global bottom-up analysis of the government programmes. The largest absolute difference occurs in China, with 480 GW in the model compared to around 140 GW in the ambitious scenario. This assumes nuclear capacities of about 8.8 times the current Chinese capacity. China would need to build around 192 reactors of 1 GW per decade in this model scenario. Given the strong growth of renewable energies in China and the current government plans, such strong future increase is not very likely. The model region “Other Pacific Asia[24]” also has very high nuclear power capacities in the model in 2050 (more than 300 GW), while the government programmes only lead to more than 40 GW in the ambitious case. The model region with the third highest capacity is "North America" with slightly less than 250 GW compared to only around 60 GW in the ambitious scenario. It is also remarkable that the model envisages more than 100 GW in Sub-saharan Africa in 2050, which would necessarily involve many nuclear newcomer states. African countries without any nuclear plants lack technical expertise,

[23] The division of the world into regions is different in the various models, making a regional comparison between individual models difficult.

[24] “Other Pacific Asia” includes countries with ISO codes: IDN, KOR, ASM, BRN, CCK, COK, CXR, FJI, FSM, GUM, KHM, KIR, LAO, MHL, MMR, MNP, MYS, MYT, NCL, NFK, NIU, NRU, PCI, PCN, PHL, PLW, PNG, PRK, PYF, SGP, SLB, SYC, THA, TKL, TLS, TON, TUV, VNM, VUT, WSM, TWN

regulatory frameworks and authorities, infrastructure but particularly finance for such an string increase in capacities.

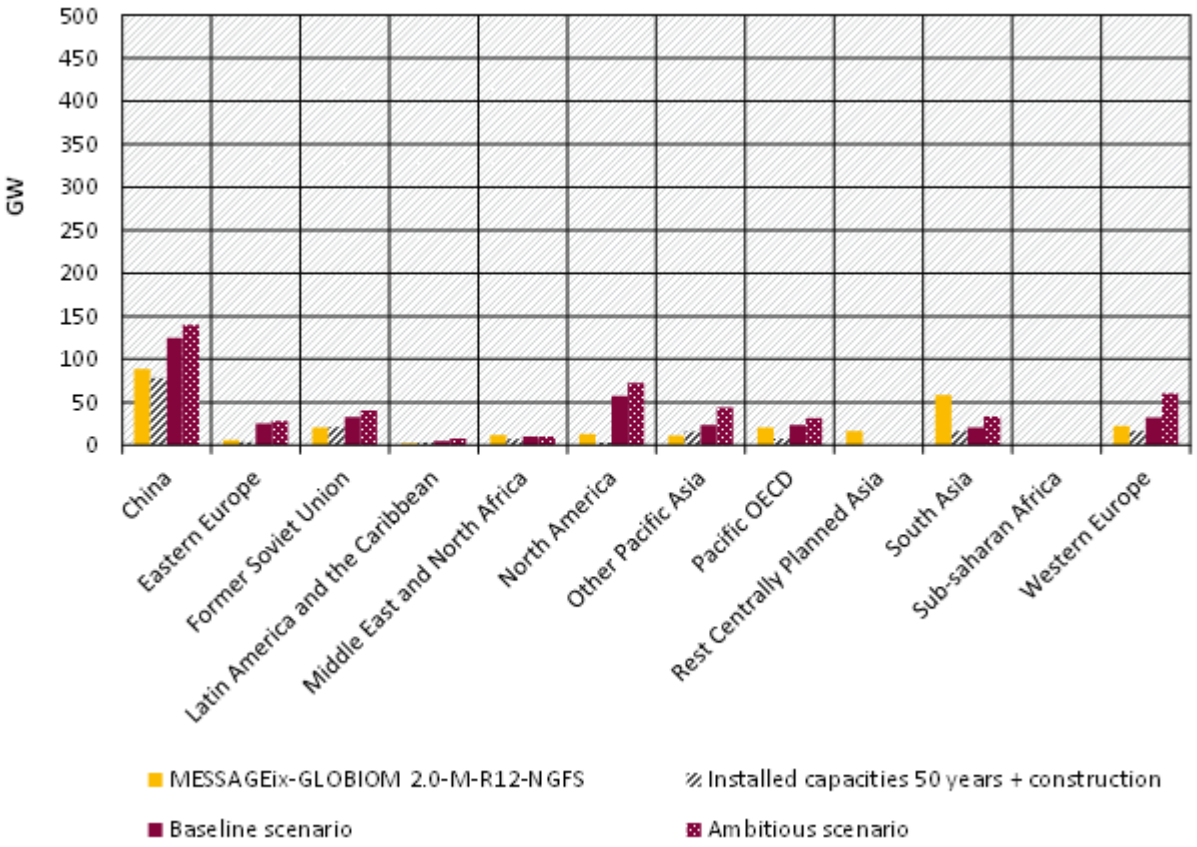
Figure 62: Regional comparison of MESSAGEix-GLOBIOM scenario "Net zero 2050" (2022) with installed capacities and analysis of government programmes for 2050



Source: (NGFS, 2022), (IAEA, 2025); own calculation, own illustration, Öko-Institut e.V.

Figure 63 compares the updated MESSAGEix-GLOBIOM scenarios for capacities in 2050 which are now mostly lower than the bottom-up scenarios apart from the region South Asia. In the updated MESSAGEix-GLOBIOM scenarios, nuclear capacities almost disappear in Europe and North America by 2050.

Figure 63: Regional comparison of MESSAGEix-GLOBIOM in the UPDATED scenario "Net zero 2050" (2024) with installed capacities and analysis of government programmes for 2050

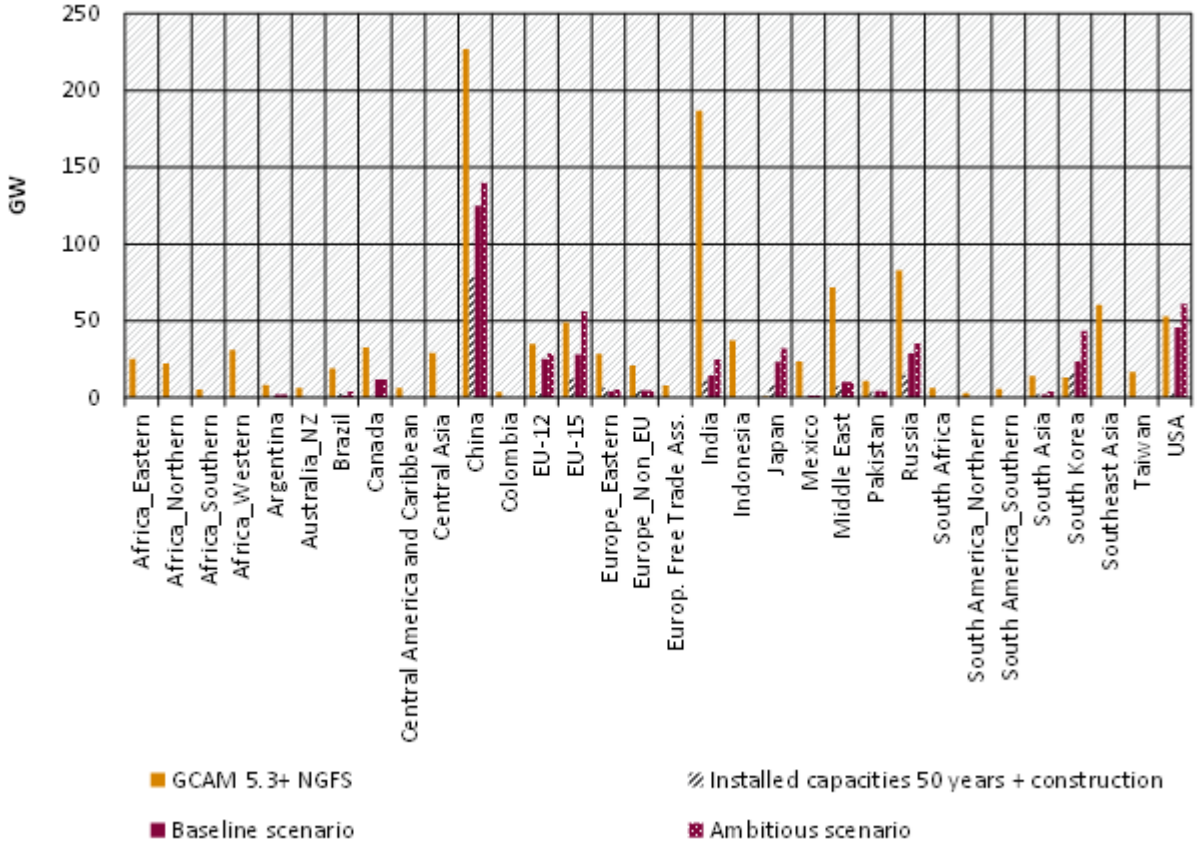


Source: : (Richterss et al., 2024), (IAEA, 2025); own calculation, own illustration, Öko-Institut e.V.

Figure 64 shows the regional comparison between the "Divergent net zero" scenario calculated with the GCAM model, which shows the second highest global nuclear capacity with the bottom-up government plans analysis for 2050. The GCAM model has a more disaggregated regional resolution than the MESSAGEix GLOBIOM model. Also in this model, China is the location of most nuclear power plants, but with around 230 GW, installed capacity in China in the GCAM "Divergent net zero" scenario is significantly lower than in the MESSAGEix GLOBIOM model discussed before. In the GCAM model resolution, India forms its own region and, with almost 190 GW, is the largest user of nuclear power after China. In comparison, the ambitious scenario based on the government's plans only leads to around 30 GW for India in 2050.

All other regions except Japan, South Korea and the EU-15, where the capacity in the model is lower than in the ambitious bottom-up scenario, have higher nuclear power capacities in the model than in the real-world analysis, although the differences are smaller in some regions than in others. In this modelling work, too, there are many newcomer countries in which the additional capacities are projected, in particular in Africa or Indonesia. Nuclear capacities in Taiwan are expected to grow despite a nuclear phase-out plan.

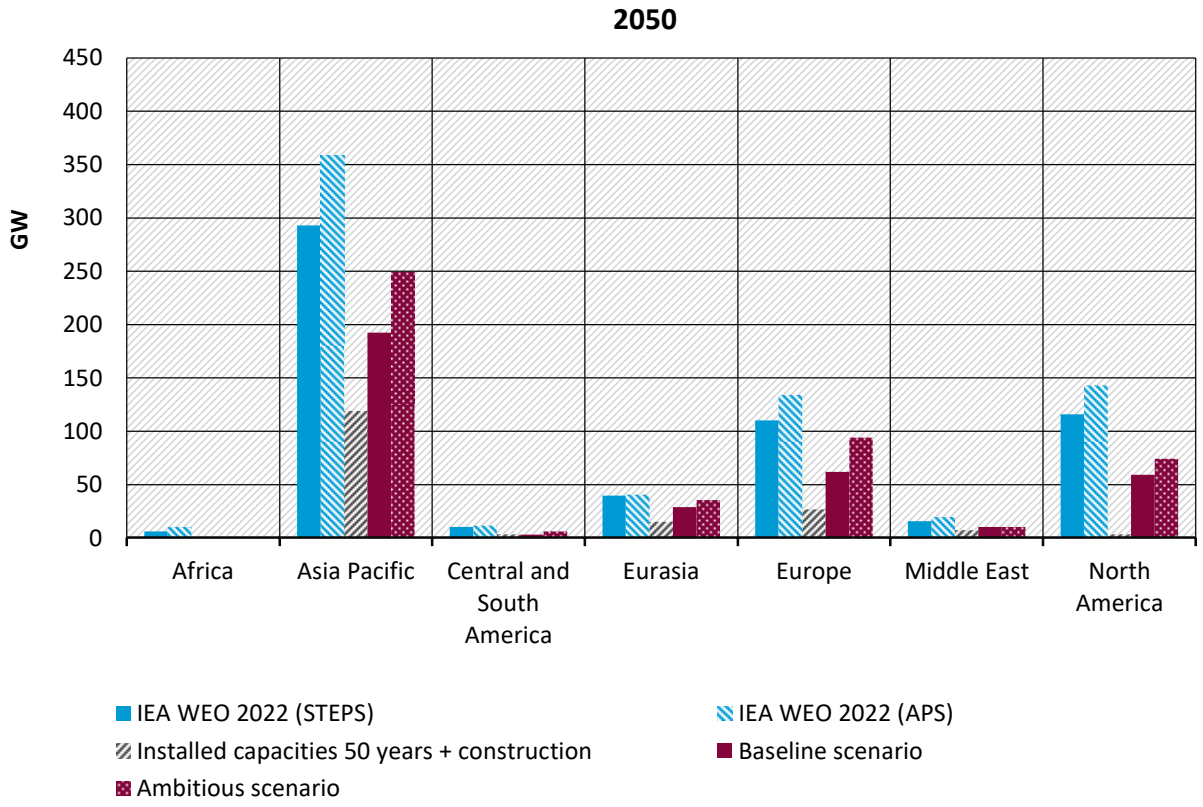
Figure 64: Regional comparison of GCAM scenario "Divergent net zero" with installed capacities and analysis of government programmes for 2050



Source: (NGFS, 2022), (IAEA, 2025); own calculation, own illustration, Öko-Institut e.V.

The "Stated Policies" scenario of the World Energy Outlook (IEA, 2022), on the other hand, shows comparatively similar nuclear power capacities for 2050 in the seven regions under consideration as the bottom-up analysis of the government programmes. Only for North America WEO projects significantly more nuclear power plants compared to the bottom-up scenarios (Figure 65).

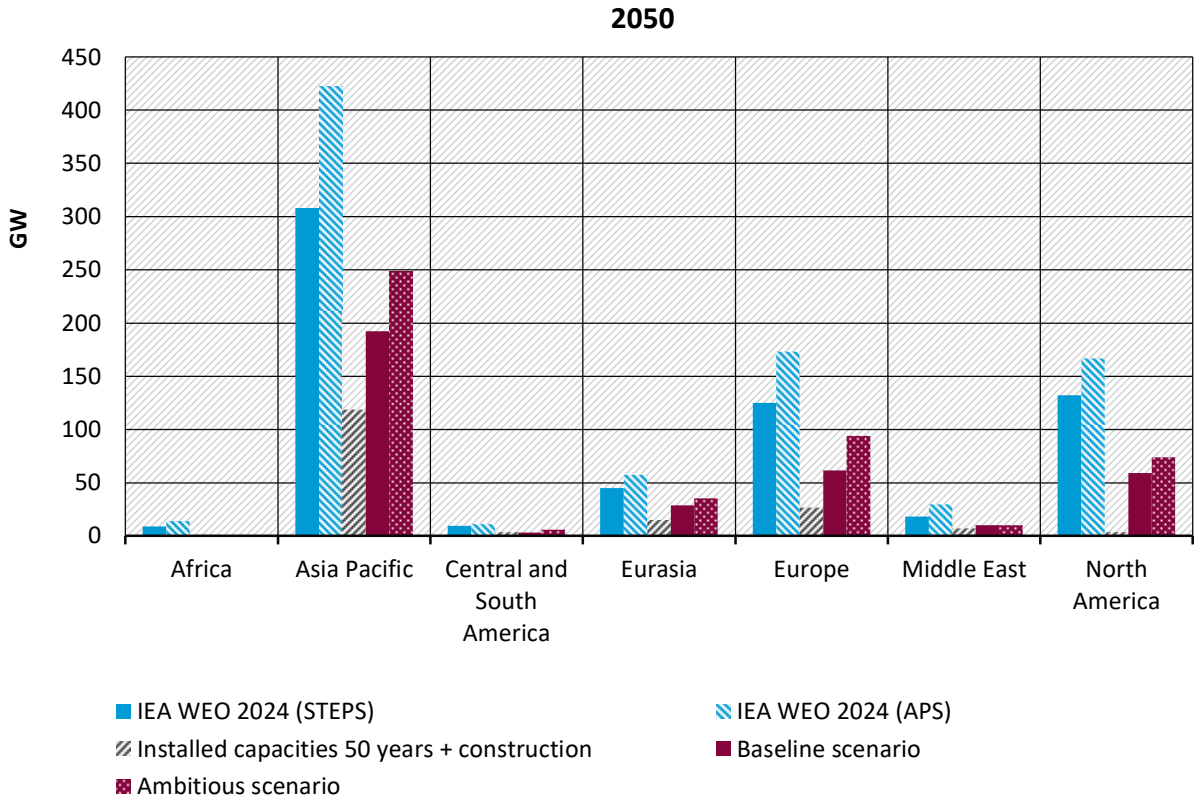
Figure 65: Regional comparison of IEA WEO scenarios (2022) with installed capacities and analysis of government programmes for 2050



Source: (IEA, 2022), (IAEA, 2025), own calculation, own illustration, Öko-Institut e.V.

Figure 66 presents the 2050 capacity projections of the updated World Energy Outlook (WEO) scenarios "Stated Policies (STEPS)" and "Announced Pledges (AP)"and compares them with the bottom-up analysis at regional level. The WEO scenarios assume a significant higher growth in the Asia Pacific which includes China and India, but also for Europe and North America. Newcomer countries in Africa or South America do not play a big role in the WEO scenarios.

Figure 66: Regional comparison of the UPDATED IEA WEO scenarios (2024) with installed capacities and analysis of government programmes for 2050

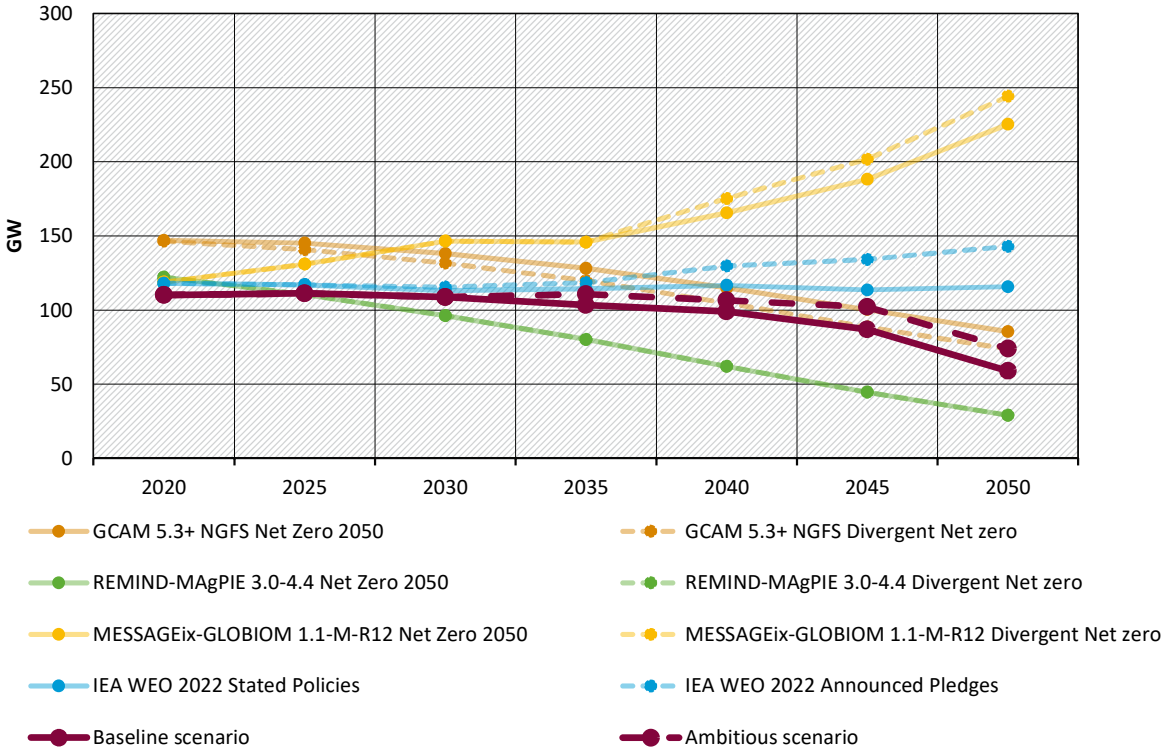


Source: (IEA, 2024), (IAEA, 2025); own calculation, own illustration, Öko-Institut e.V.

In the following sections we compared the different models results and country programmes for key regions and countries which currently have the largest nuclear capacities. For the NGFS scenarios we had to use the 2022 scenario publication for this purpose because the publication of the recent update does not include a disaggregation by country or region.

For North America, the MESSAGE-GLOBIOM results for the years from 2035 to 2050 project much higher nuclear capacities of 244 GW than all other scenarios and other analysis of country programmes (see Figure 67). Even if all current nuclear plants in the U.S. would continue operating for 80 years (which is highly unlikely), this would require the additional construction of 142 GW of nuclear capacities in 25 years of which none is currently backed with specific plans until 2030. Given the fact that construction time is around 10 years, the MESSAGE-GLOBIOM scenario would require the construction of about 14 nuclear plants per year in North America in the period 2030 to 2040 for the projected capacity addition until 2050. This seems quite unrealistic given the fact that it took more than 10 years and investment costs of more than US$ 35 billion for the two recently completed Vogtle reactors. With similar costs, such assumed addition would cost US$ 210 billion per year. Most other scenarios envisage a decline in nuclear capacities in the U.S. until 2050 given the old fleet and the lack of construction projects that could replace the large reactor fleet.

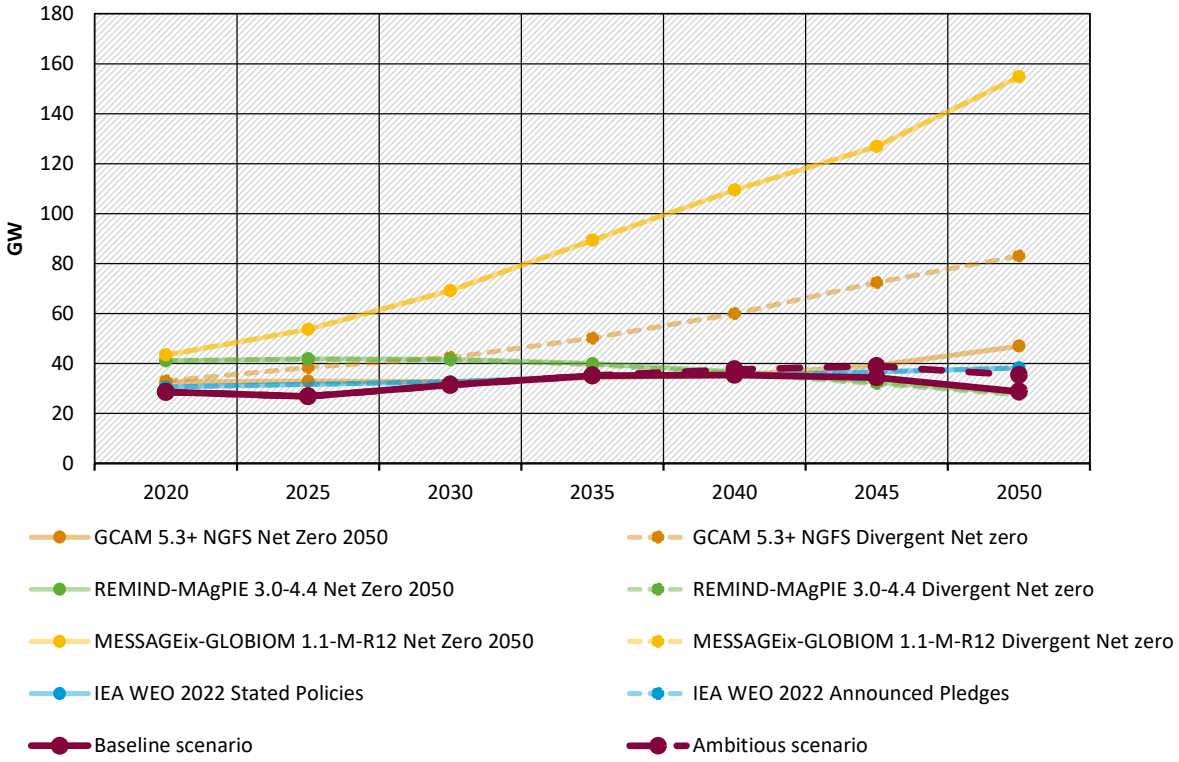
Figure 67: Projected capacity of global nuclear reactors in the selected climate scenarios of key global models and in our own analysis of country programmes for North America (USA and Canada)



Source: (NGFS, 2022), (IEA, 2022), (IAEA, 2025); own calculation, own illustration, Öko-Institut e.V.

For Russia, the different global scenarios show surprisingly similar results with relative constant nuclear capacities until 2050 apart from the MESSAGE/GLOBIOM Net Zero Scenario which projects a strong increase in nuclear capacities in Russia (see Figure 68). Given the abundance of fossil fuels in Russia, there is no indicator that supports such strong addition of nuclear capacities in Russia. Most of the scenarios also match well with the bottom-up projection of Russia's plans and programmes.

Figure 68: Projected capacity of global nuclear reactors in the selected climate scenarios of key global models and in our own analysis of country programmes for Russia

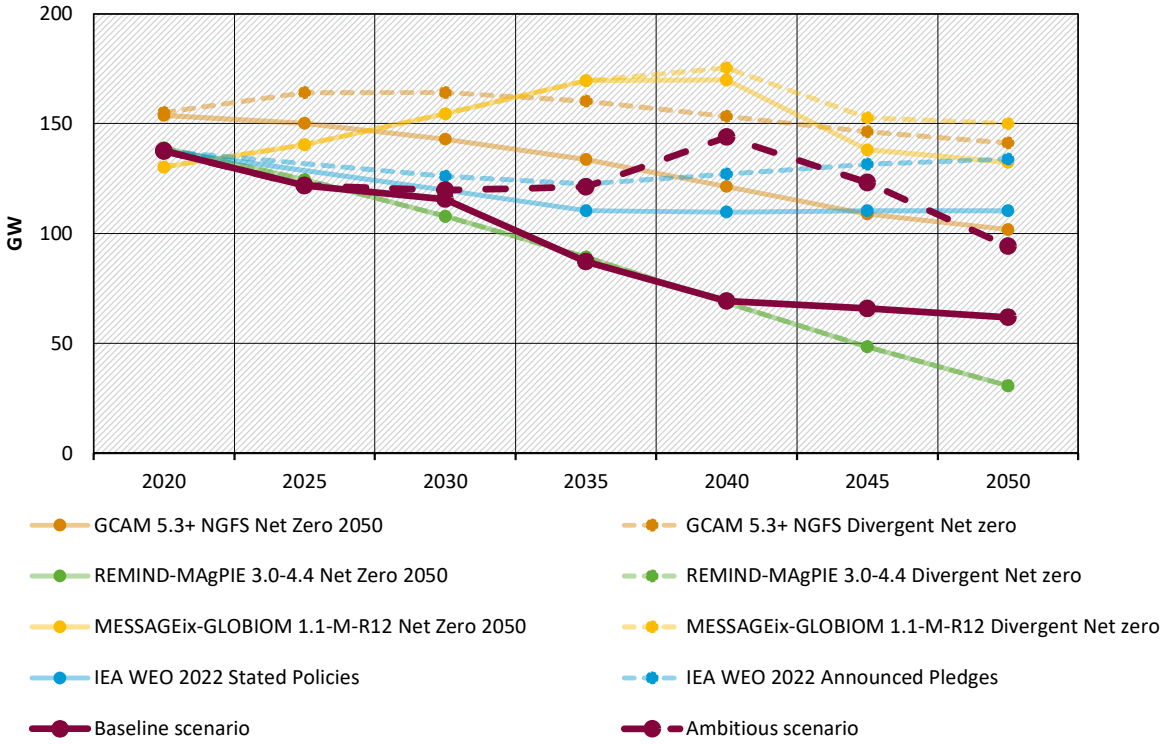


Source: (NGFS, 2022), (IEA, 2022), (IAEA, 2025); own calculation, own illustration, Öko-Institut e.V.

For Europe the different scenarios deviate less. They either foresee relative constant nuclear capacities in 2050 compared to the current situation (MESSAGE-GLOBIOM, IEA WEO Announced Pledges scenario) or a decline in nuclear capacities until 2050 (see Figure 69). Thus, Europe with a significant share of global nuclear capacities will not contribute to a global tripling of nuclear capacities. Similar to the previous regions, the MESSAGEix-GLOBIOM projection is the highest, but from 2045 onwards, the capacities are similar to the IEA WEO scenario results.

The projected results from countries' plans and programmes are lower than most of the net zero scenarios, except the results from REMIND-MAgPIE which project lowest nuclear capacities in Europe after 2040.

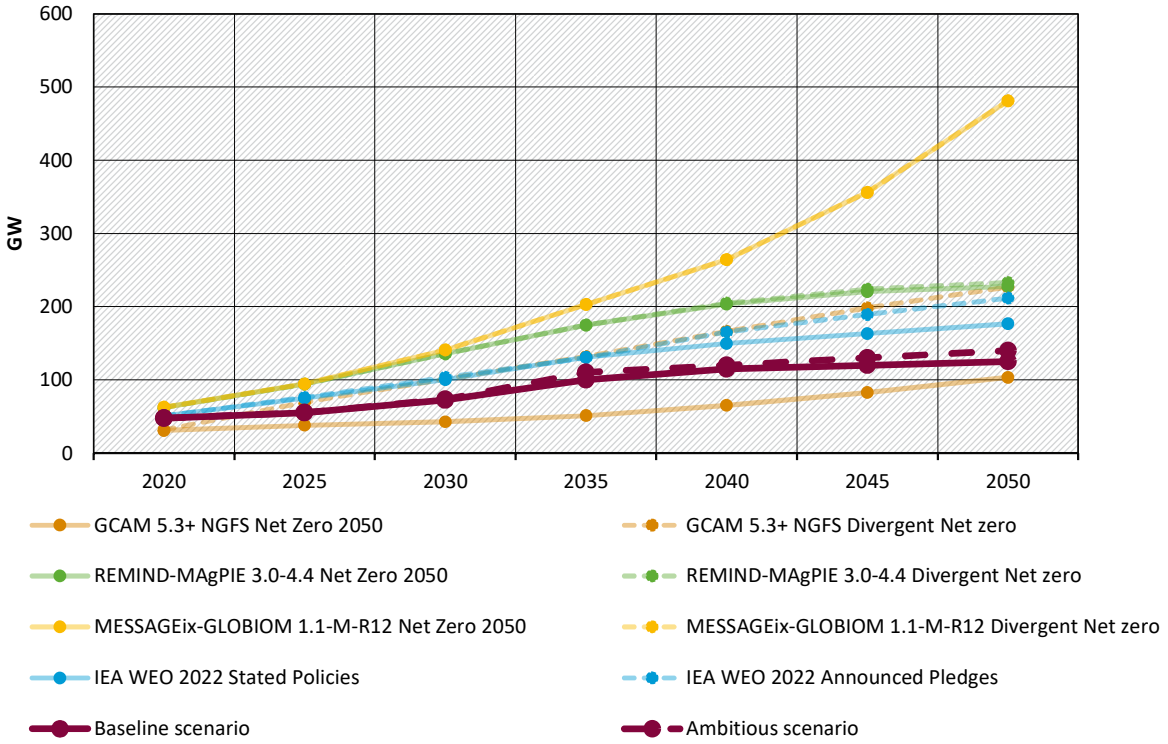
Figure 69: Projected capacity of global nuclear reactors in the selected climate scenarios of key global models and in our own analysis of country programmes for Europe



Source: (NGFS, 2022), (IEA, 2022), (IAEA, 2025); own calculation, own illustration, Öko-Institut e.V.

China built the largest number of new nuclear reactors in recent years. All scenarios assume a continued increase in nuclear capacities until 2050. But again, the projection of the MESSAGE/GLOBIOM net zero 2050 scenario is much higher than all the other projections (see Figure 70Figure 70:) and foresees that the nuclear capacities increase 10 times until 2050. Even with the large growth of nuclear capacities in recent years in China, it seems unlikely that capacities increase so strongly, given the large growth of renewable energies planned and implemented in China. Such large increase of nuclear capacities is also not consistent with China's recent published projections which were used as a basis for the high scenario of the analysis of country programmes.

Figure 70: Projected capacity of global nuclear reactors in the selected climate scenarios of key global models and in our own analysis of country programmes for China



Source: (NGFS, 2022), (IEA, 2022), (IAEA, 2025); own calculation, own illustration, Öko-Institut e.V.

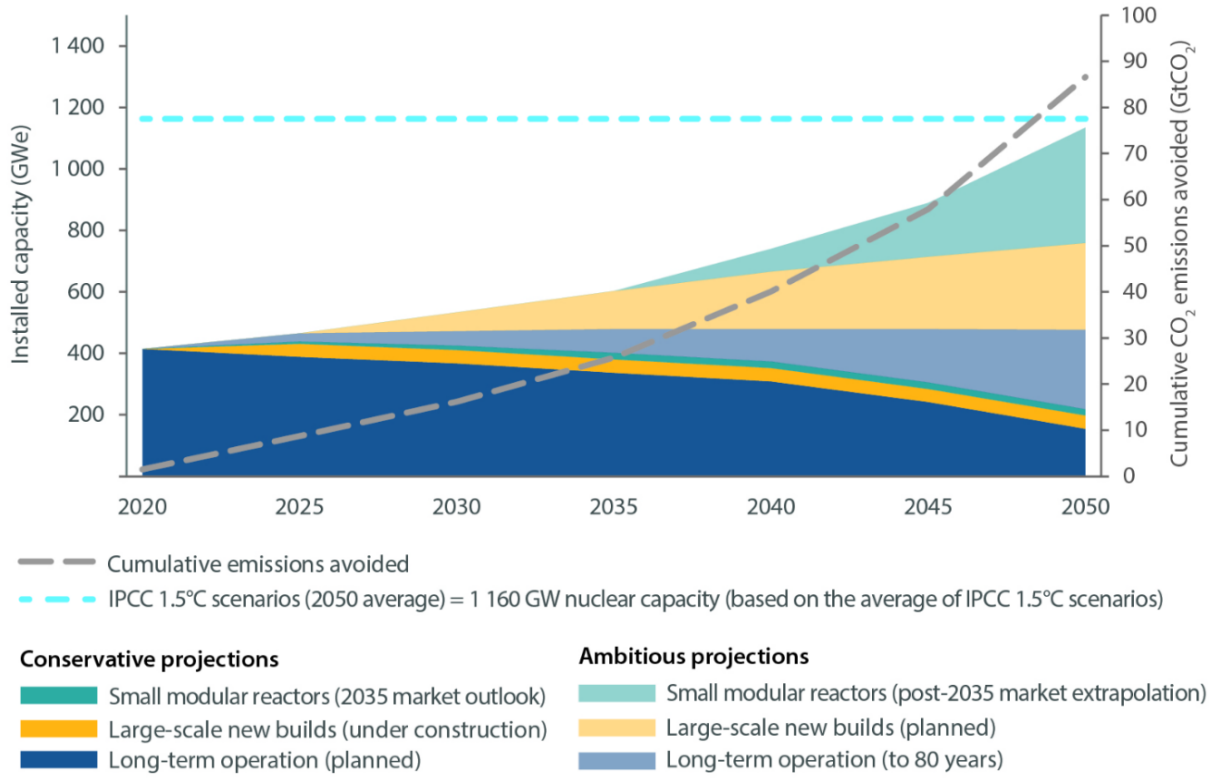
Thus, the regional and country analysis confirms the global assessment that the scenario results of the MESSAGE/GLOBIOM net zero 2050 scenario- which are consistent with the tripling pledge at global level – are significantly higher than all other scenarios for individual regions and countries and also seem unrealistic at a higher level of disaggregation.

2.7 Global Pledge to triple nuclear energy by 2050

As a separate output in form of a factsheet for COP 29, we assessed the pledge of more than 20 countries at COP 28 in 2023 to triple nuclear capacity until 2050 against the projected capacities in key global climate scenarios and against the country's future nuclear plans to understand whether this declaration is realistic and matched with current plans and programmes expressed in form of government strategies.

At COP 28 in Dubai French president Emmanuel Macron and US Special Envoy for Climate John Kerry announced that more than 20 countries launched the 'Declaration to Triple Nuclear Energy by 2050'. This declaration is related to an analysis of the Nuclear Energy Agency indicating a global installed capacity of 1,160 GW in 2050, a global nuclear capacity of about 600 GW in 2035, 700 GW in 2040 and 900 GW in 2045 (Figure 71)(OECD Nuclear Energy Agency [NEA], 2023; U.S. Department of Energy [DoE], 2023). The countries signing the declaration were United States, Armenia, Bulgaria, Canada, **Croatia**, Czech Republic, Finland, France, **Ghana**, Hungary, **Jamaica**, Japan, Republic of Korea, **Moldova, Mongolia, Morocco**, Netherlands, **Poland**, Romania, Slovakia, Slovenia, Sweden, Ukraine, United Arab Emirates, and United Kingdom. At COP 29 six additional countries **Kazakhstan, Kenya, Kosovo, Nigeria** and **Turkey** joined the declaration. The countries printed in bold currently do not have operating nuclear plants.

Figure 71: Nuclear capacities assumed in pledge to triple nuclear energy by 2050



Source: NEA (2023)

In order to assess how realistic the pledge to triple nuclear capacities until 2050 and the top-down climate scenarios are, we compiled the plans and programmes of governments for the maintenance, expansion (or phase out) of their respective nuclear power plant fleets until 2050.

As of May 2025, 31 countries[25] operate a total of 416 nuclear reactors with a net capacity of 360 GW[26]. By far the most nuclear reactors are located in the USA, followed by France, China, Russia and South Korea (IAEA, 2025). Only nine countries operate more than 10 nuclear reactors.

The 26 countries that pledged for global tripling nuclear capacities until 2050 at COP28 run 68% of the existing nuclear reactors equivalent to 246 GW net capacity. In these countries 10 new reactors are under construction which is only 12% of the global new construction. Eleven countries that joined the pledge neither run nuclear reactors, nor have started building nuclear plants (Croatia, Ghana, Jamaica, Kazakhstan, Kenya, Kosovo, Moldova, Mongolia, Morocco, Nigeria, Poland).

The age structure of the existing fleet is a major factor for the future development of the installed nuclear capacity. According to M. Schneider and Froggatt (2024) the mean age of all nuclear reactors in operation as of July 2024 is 32.1 years. The average age of nuclear reactors that have been shut down until July 1st 2023 was 28.2 years according to (M. Schneider & Froggatt, 2024). The oldest reactors in the world run since 55 or 56 years in the U.S. and in Switzerland. 24 of the currently operating reactors in the U.S. are older than 50 years. In 2023, the U.S. Nuclear Regulatory Commission (NRC) granted licenses to six reactors permitting

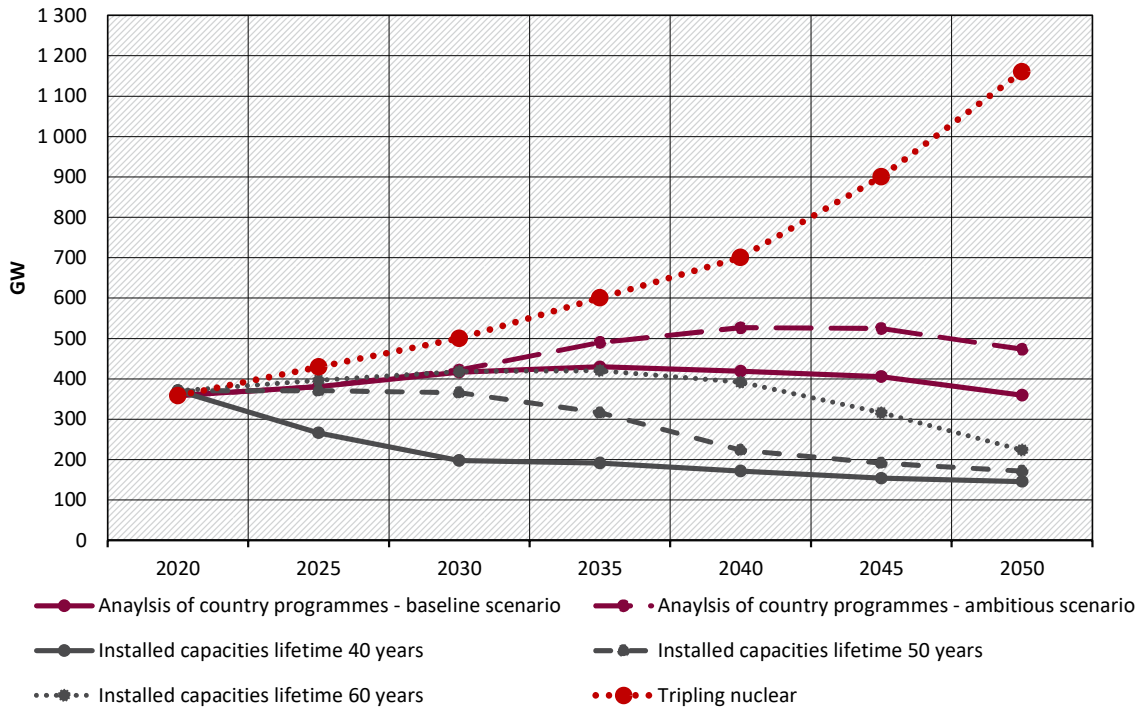
[25] In the IAEA PRIS data Taiwan is included in the numbers for China.

[26] According to the IAEA's PRIS database (International Atomic Energy Agency (IAEA) 2024) 373.7 GW of net electrical capacity was installed worldwide by September 5th, 2024. Numbers of installed capacity may include reactors in long-term outage, that are formally declared operational but have not produced electricity for an extended period of time.

operation from 60 to 80 years, however NRC has later suspended four of these licences. The average age of the seven reactors closed in the U.S. over the five-year period 2018–2022 was 47.1 years, while their licences would have allowed operation for 60 years. Frequently it is no longer economic to operate these old nuclear plants. They do not only require licences, but significant investments for maintenance and continued operation.

We compare our bottom-up analysis of nuclear capacities with the global net zero energy scenarios and the "pledge to triple nuclear capacities until 2050". Even if a lifetime of 60 years were assumed for all existing reactors, existing nuclear capacities would decrease significantly by 2050. Huge investments in new nuclear power plants would therefore be necessary to achieve the "tripling nuclear" pledge. The capacity development path envisaged by the governments of the countries behind the "tripling nuclear pledge" would also far exceed the ambitious scenario of our bottom-up analysis of country programmes worldwide (Figure 72).

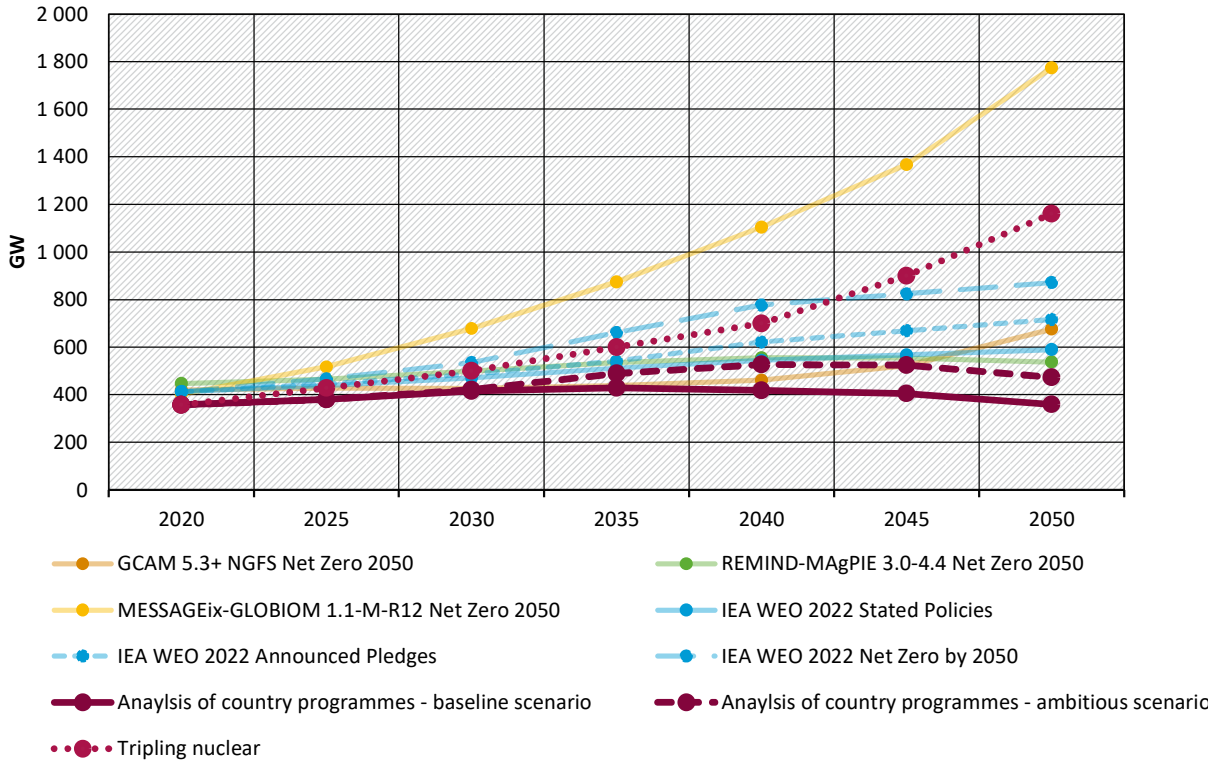
Figure 72: Projected capacity of global nuclear reactors in the "tripling pledge" compared to existing capacities with different lifetime assumptions and to our analysis of country programmes



Source: data: (IAEA, 2025); (NEA, 2023), own calculation; own illustration, Öko-Institut e.V.

Figure 73 shows the development of the installed capacity of nuclear reactors worldwide as projected in the tripling pledge, in net zero scenarios by three different models and in three scenarios of IEA's World Energy Outlook (2022 edition). In this comparison, the MESSAGE/ GLOBIOM "Net zero 2050" scenario for capacities is significantly higher than the tripling pledge. All other scenarios project lower capacities than the pledge. In particular the bottom-up scenarios of countries' policies and programmes are much lower. The REMIND-MAgPIE scenario forsees constant nuclear capacities until 2050 compared to today's level. The three scenarios of IEA's World Energy Outlook vary considerably: the "Net zero 2050" scenario projects an increase of nuclear capacities by a factor of 2.2 while nuclear capacities in the "stated policies" scenario only increase by 50%.

Figure 73: Projected capacity of global nuclear reactors in the "tripling pledge", selected climate scenarios of key global models and in our analysis of country programmes

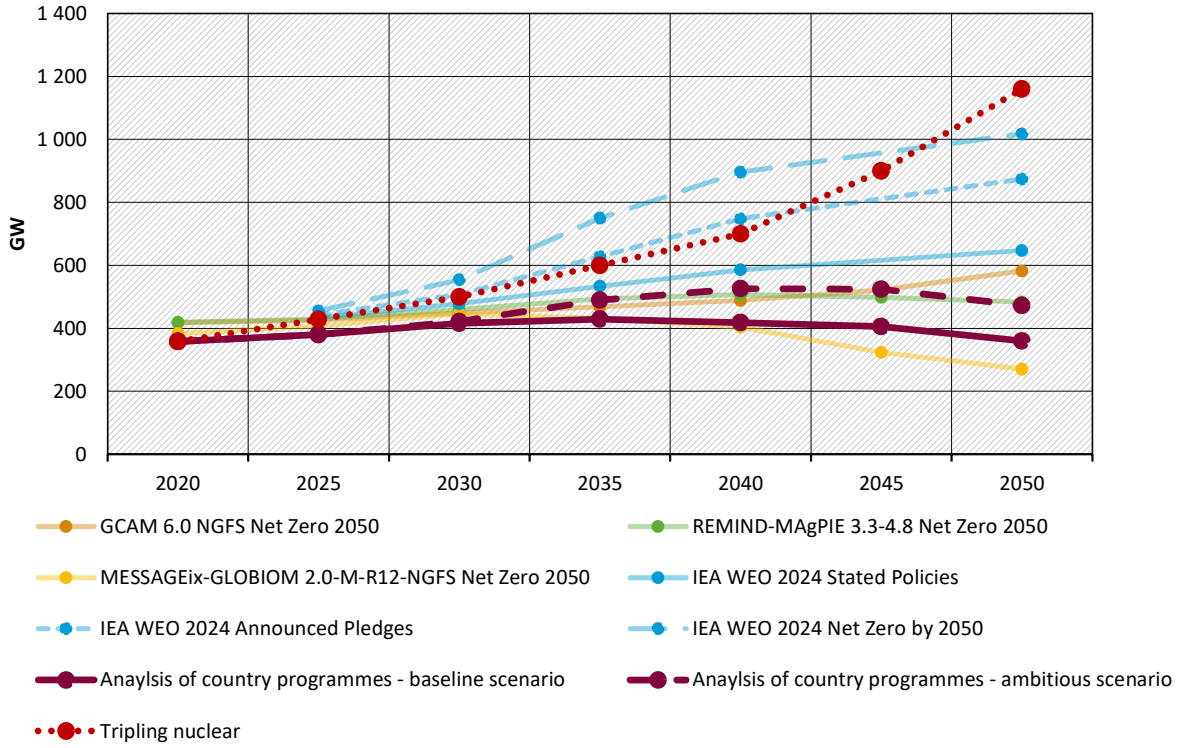


The WEO (World Energy Outlook) scenarios do not provide data for 2025 in the public dataset. Therefore, values are interpolated.

Source: data: (NGFS, 2022), (IEA, 2022), (NEA, 2023), (IAEA, 2025); own calculation own illustration, Öko-Institut e.V.

Figure 74 compares the "pledge to triple nuclear capacities until 2050" with the updated scenarios from 2024 and the bottom-up scenarios. In none of the updated scenarios, tripling of nuclear capacities is achieved. There is a large discrepancy between the "pledge to triple nuclear capacities until 2050", the results from MESSAGEix-GLOBIOM, REMIND-MAgPIE and GCAM. All three global scenarios from the IEA's World Energy Outlook 2024 show significantly higher installed capacities than even the ambitious scenario in our bottom-up analysis. The WEO scenario 'Net Zero by 2050' would require drastic changes and the construction of new nuclear power plants by 2035, for which there are no concrete plans yet. But even this scenario does not achieve the increase that would be necessary to triple nuclear energy by 2050.

Figure 74: Projected capacity of global nuclear reactors in the "tripling pledge", selected UPDATED climate scenarios of key global models and in our analysis of country programmes



The WEO (World Energy Outlook) 2024 scenarios do not provide data for 2025 and 2045 in the public dataset. Therefore, values are interpolated.
Source: data: (Richterss et al., 2024), (IEA, 2024), (NEA, 2023); own illustration, Öko-Institut e.V.

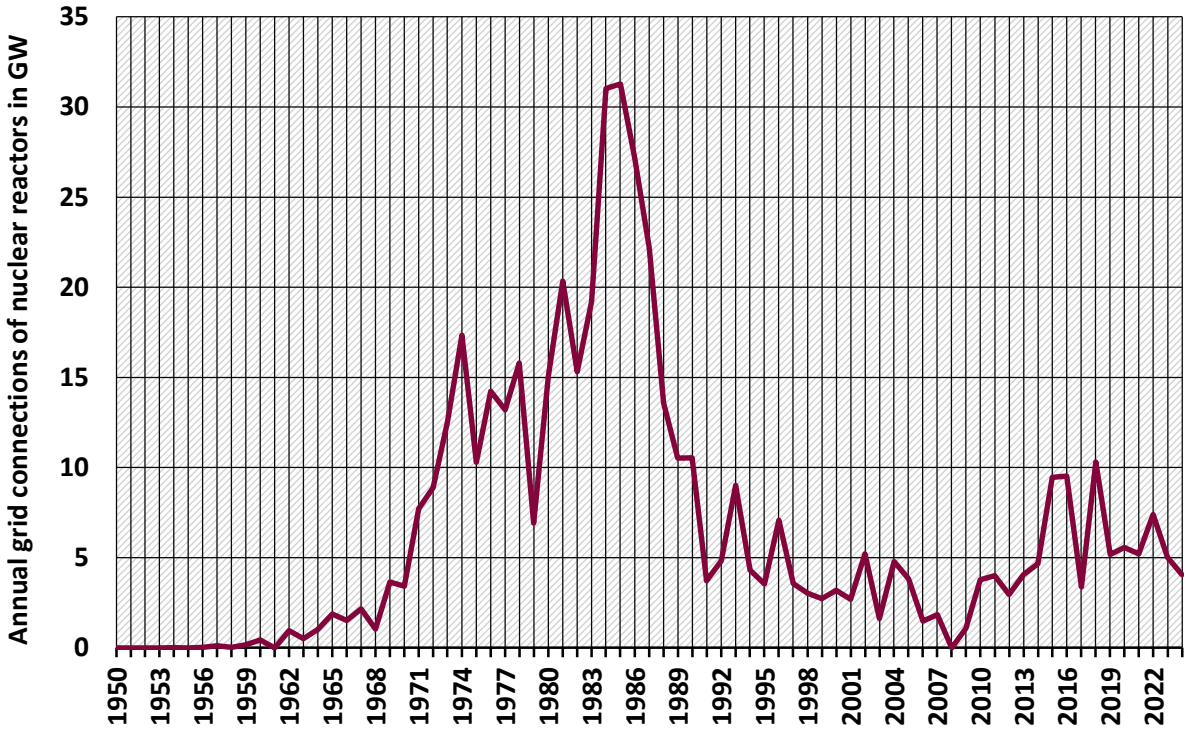
Figure 75 shows the historic annual grid connections of nuclear reactors worldwide. For the past ten years, between 3.4 and 10.3 GW net electrical capacity came online each year. Before that, 1990 was the last year that more than 10 GW net electrical capacity come online in a single year. The overall historic maximum was in the year 1985 with 31.3 GW net electrical capacity connected to the grid.

A tripling of today's nuclear capacity of 370 GW would require 1.160 GW net electrical capacity to be operational in 2050.

If we assume a very high lifetime of sixty years for all nuclear reactors in operation and under construction today, roughly 220 GW of the current nuclear fleet would still be online in 2050. Thus, a total of nearly 940 GW would have to be constructed additionally between September 2024 and end of 2050. Assuming a linear increase in the rate of new construction up to 2050, starting with the amount of new nuclear connected to the grid in 2023, in 2050 almost 70 GW would need to be connected to the grid to meet the tripling nuclear target, compareFigure 76. This would be more than twice the maximum historic capacity connected to the grid in a single year. On average, more new capacity would have to be added every year over 25 years as was the case at the historical maximum in 1985.

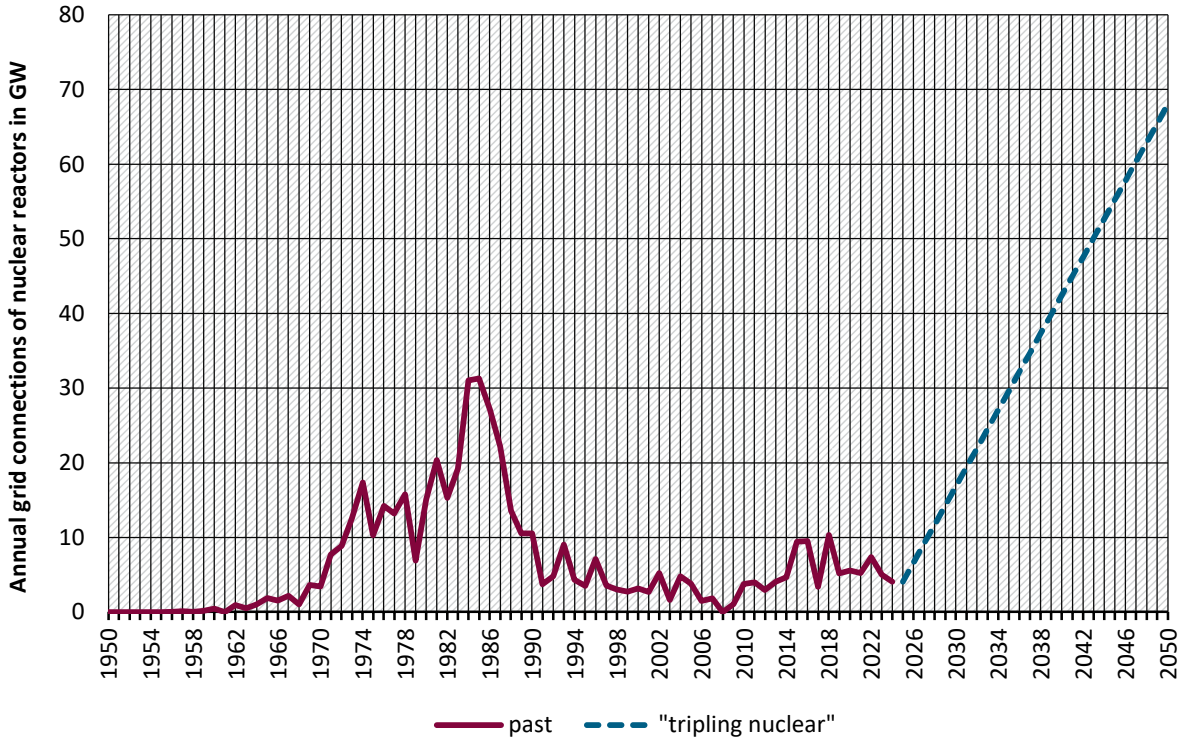
From these numbers, it is evident, that a tripling of nuclear capacity until 2050 is neither realistic nor is it needed to achieve climate targets according to the Paris agreement.

Figure 75: Annual grid connections of nuclear reactors worldwide 1950 – mid 2024



Source: data: (IAEA, 2025); own illustration, Öko-Institut e.V.

Figure 76: Future annual grid connections of nuclear reactors worldwide necessary for "tripling nuclear" in comparison with past annual additions



Source: data: (IAEA, 2025), own calculation; own illustration, Öko-Institut e.V.

Such an increase in nuclear energy as in the tripling pledge is not necessary to achieve the climate targets: Except for IEA's "Stated Policies" all other scenarios shown in Figure 76 achieve the Paris agreement targets, and they do it with less or even without the usage of nuclear energy in 2050.

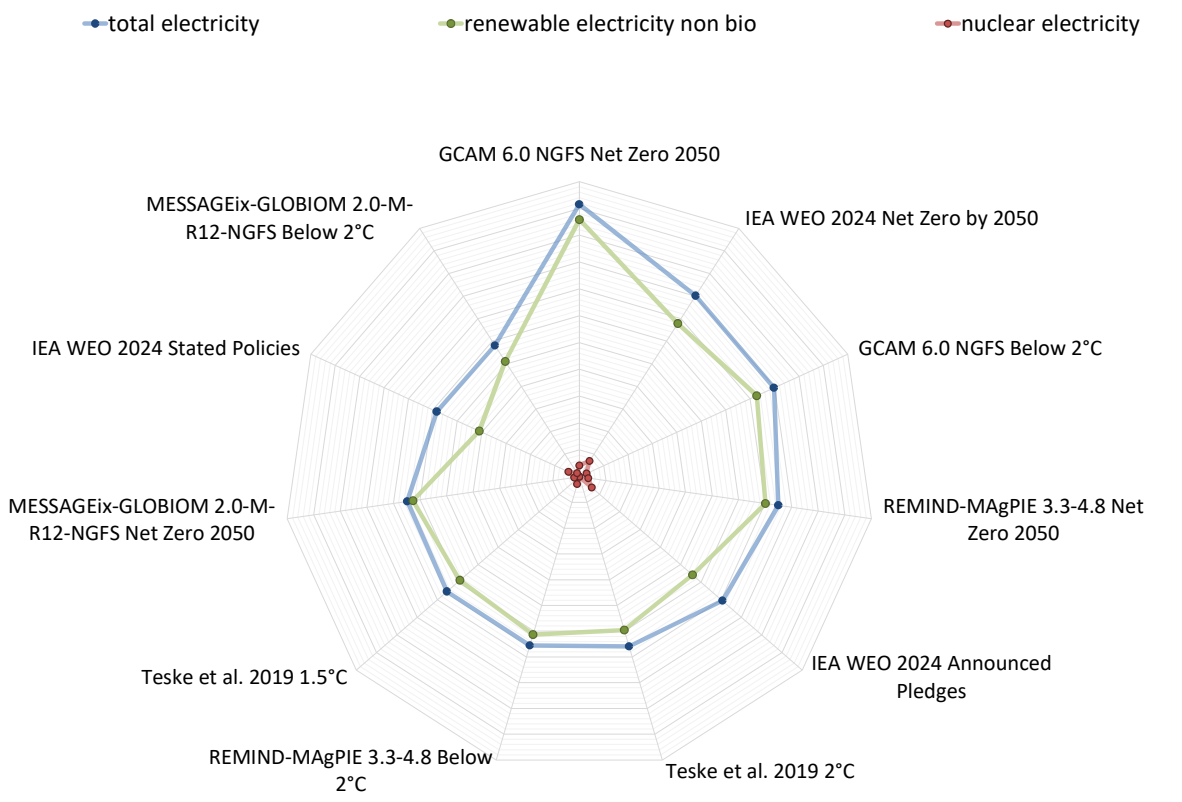
In order to achieve the climate targets, nuclear energy is in fact only a small part of the story:

Figure 77 shows the contribution of non-biomass renewable energy to the total electricity generation in the scenarios achieving climate targets compared to the electricity generation from nuclear power plants in 2050 in the (2024) scenarios analysed. The world electricity generation in 2050 varies between scenarios due to different results for the degree of electrification and overall energy demand. It also becomes clear that nuclear electricity generation plays a minor role in all scenarios compared to non-biomass renewable generation.

The share of non-biomass renewable energy in the scientific global target scenarios of the NGFS ranges between 88% (MESSAGEix- GLOBIOM "Below 2°C") to 97% (MESSAGEix- GLOBIOM "Net Zero 2050") as is evident in Figure 16(section 2.2.3)

In the non-target scenario ("Stated Policies") of (IEA, 2024), the expansion of renewable energies falls short with only 70% of global electricity generation. The comparison with the target scenarios implies: It is not the role of nuclear energy that determines compliance with the climate targets, but the sufficient expansion of renewable energies.

Figure 77: World nuclear electricity and renewable electricity in 2050 in comparison with total electricity in the scenarios analysed



Scale from 0 to 110 000 TWh in units of 10 000

Source: data: (Richterss et al., 2024), (Teske, 2019), (IEA, 2024), own illustration, Öko-Institut e.V.

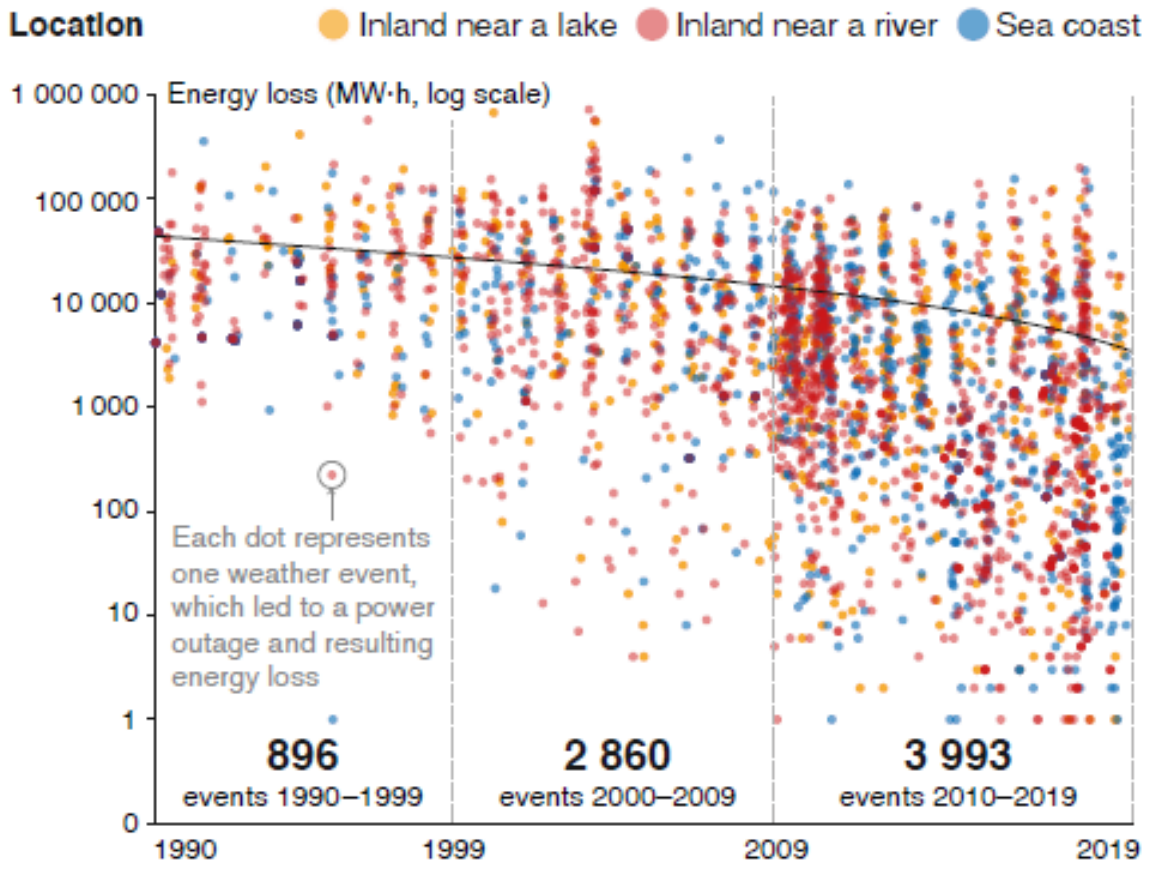
From thus analysis we derive the following key conclusions:

- All of the recent global climate target scenarios analysed in this report show a substantially lower future of nuclear energy in 2050 than the tripling pledge of 26 countries at COP28.
- Global climate scenarios show that the development of renewable energies is key to achieve climate targets according to the Paris agreement, while nuclear energy is not essential for this objective. Even with a high nuclear energy production, scenarios with low shares of renewable energy miss the climate targets. Thus, the build-up of renewable energy is the crucial and primary driver to achieve climate targets.
- An assessment of plans and programmes of all countries with current nuclear plants or with realistic plans to start construction of nuclear reactors shows that a considerable increase in nuclear capacities until 2050 is not to be expected.
- Disaggregated results for important countries and regions confirm that the tripling of nuclear capacities until 2050 is not in line with the real trends and presents a highly unlikely development. The tripling of global nuclear capacities until 2050 is neither realistic nor is it needed to achieve climate targets according to the Paris agreement.

2.8 Climate impacts and risks on existing and future nuclear power supply

In the future, stronger variability and unpredictability of extreme weather hazards, rising global temperatures, sea level rise and changes in precipitation due to global warming will increasingly affect the reliability of electricity production from nuclear power plants. Figure 78 shows that disruptions due to weather events already increased significantly from 1990 to 2019. Almost ¾ of the outages occurred at riverine sites. This graph does not include the recent period 2020 to 2024, when extreme climate events were more frequently and more damaging.

Figure 78: Reported nuclear power outages due to weather events, by plant location



Source: (IAEA, 2022a)

Some climate impacts will reduce the productivity of nuclear power plants and increase power outages. Coal or gas thermal power generation plants may be similarly affected. Other impacts may also enhanced the risk of nuclear accidents and require changes in the site selection and design of new nuclear power plants. Two-thirds of the global nuclear fleet has been in operation for more than 30 years and was built before climate change was on the agenda. Adaptation measures are therefore likely to be necessary, if the lifetime of these old plants are extended. This section analyses different types of climate impacts and risks on nuclear power production to assess the nature and significance of the impacts and how climate change may affect the global electricity generation scenarios.

2.8.1 Temperature increase

Higher ambient air temperatures negatively impact on the efficiency of nuclear power plants. Plant efficiency depends on the temperature difference between the steam inlet and the condenser, which is ultimately affected by the ambient air temperature. It is estimated that a 1°C increase in air temperature reduces power output by about 0.1% (European Commission, Directorate-General for Energy [DG ENER], 2011, March). (Vliet et al., 2016)analysed more than 1,400 thermoelectric power plants and showed a reduction in the usable capacity of 81-86% of the thermoelectric power plants worldwide in the period 2040-2069 due to climate change. This effect applies to all thermal power plants and the study doesn't distinguish between nuclear and fossil power plants.

2.8.2 Droughts and heat waves

Droughts are frequently combined with very high temperature events that increase the need for cooling of power plants and at the same time reduce water provision from reservoirs or rivers. When sufficient cooling water is unavailable, nuclear power station operators must reduce electricity generation to lower cooling demand. This measure is essential to ensure safe operation. In extreme situations nuclear power plants have to completely shut down production. A 'ramp down' may also be required to comply with regulations protecting aquatic ecosystems by limiting water withdrawals and establishing limits for water discharge temperatures.

(Ahmad, 2021) analysed nuclear power outages due to changing climate in the period 2010-2019. His analysis indicated that outages due to water shortages last longer than outages due to storms or hurricanes and are hence more important for the loss of electricity production. In addition, power outages during heat waves occur at a time of peak demand of electricity due to cooling demand and can affect more plants at the same time. Therefore, the risk for energy security is significant.

Nuclear sites with freshwater cooling at rivers will be particularly affected. As of 2022, these are 59% of the existing nuclear sites (IAEA, 2025). The IPCC's sixth assessment report quantifies possible reductions of production due to water constraints for freshwater thermoelectric plants in the northern Mediterranean by 6–33% under 2°C warming and by 20–60% beyond 3°C warming (Pörtner et al., 2022).

Other thermal power plants also need cooling water and experience similar problems, however, nuclear power plants mostly use open loop cooling and have significantly higher water abstraction than coal or gas power plants as shown in Table 39. This is due to the fact that nuclear plants operate at a lower temperature and lower thermal efficiency, and do not lose heat via smokestacks. Therefore, the impacts of draught and heat waves are considerably stronger for nuclear plants. In new nuclear plants in China, water use efficiency of nuclear plants was 0.22 m^3/kWh which is significantly lower than water use efficiency of Chinese coal plants (0.1 m^3/kWh) or gas plants (0.09 m^3/kWh) (Li et al., 2022). Nuclear power plants in China such as Dayawan use 0.92 billion m^3 of water per year which is equivalent to 60% of the total annual water supply in Shenzhen, a megacity of 20 million people (Li et al., 2022). These dimensions indicate the difficulties inland nuclear sites at rivers will face in the future close to large cities. (Li et al., 2022) concluded that nuclear power plants in China should be built on coastal areas with sufficient cooling water resources.

Often clusters of nuclear reactors are at the same sites –due to acceptance and costs. This will lead to substantial water abstraction from multiple plants and increase the risks of more frequently reduced operation. Due to the large production capacities of individual nuclear plants, the threat to energy supply security can be significant.

In Europe, the impacts will occur particularly in Central and South Europe where hot summers will lead to relatively small differences between inlet and outlet water temperature, resulting in lower thermal efficiency and potential outages (DG ENER, 2011, March). This challenge is often most acute during summer in Europe when electricity demand peaks, water demand is highest, and water resources are scarcest. In summer 2022, the production of nuclear power plants in France had to be significantly reduced because of a lack of cooling water in a draught and heat period. Although the French government had granted an exemption allowing discharges at higher river water temperatures, even these exceptions were no longer sufficient for continued operation of the nuclear plants. In 2019 a heatwave also strongly impacted French and German nuclear power stations and two plants in France and one in Germany had to shut down (United Nations Environment Programme [UNEP], 2024). (Kopytko & Perkins, 2011) analysed the

reduction of nuclear power supply in France in 2003, a year with an extreme heat wave in Europe's summer. The total nuclear power reduction in France was 5.3 TWh, an equivalent to a loss of more than 200 reactor days (Kopytko & Perkins, 2011). France could avoid blackouts but cut power exports to Italy by more than half which led to blackouts lasting several hours in many Italian cities. The increased mortality rate in Italy during the heat wave was 20,000 deaths, to which the blackouts may have contributed due to a lack of electricity for air conditioning.

For the UK, (Byers et al., 2014) showed in energy scenarios up to 2050 that high levels of nuclear generation and high level of carbon capture and storage, will lead to an increase of water abstraction and consumption to up to six times the current levels. These scenarios looked at nuclear plants located at coastal sites. In addition, (Byers et al., 2014) summarized that the evidence examined indicates a lack of suitable sites for wide scale nuclear power deployment in the UK if negative environmental impacts, in particular related to water shortage, are to be avoided (Byers et al., 2014).

An S&P Global analysis from 2020 indicated that 61% of nuclear plants in the US can face medium-high to extremely-high water stress by 2030 and that in total 48 GW of nuclear capacity in the US face elevated exposure to heat and water stress (S&P Global, 2020).

(Portugal-Pereira et al., 2024) report growing concerns that inland nuclear power plants may be constrained by water availability in the future in many countries and mention future water competition and scarcity as a potential disruptive production factor for nuclear plants recently built in the Middle East, North Africa and Southeast Asia. (IAEA, 2022a) also assesses that nuclear plants in South Asia will be particularly prone to heat and draught.

Hence, reduced water availability will need to be integrated in future risk assessments and water availability will also reduce suitable sites for nuclear power plants. A switch to available cooling options with lower water needs (e.g. dry cooling towers) is an option, but will increase the construction and operating costs for nuclear plants. Retrofitting existing reactors for other cooling systems will have high costs and will reduce power output of the plants (Kopytko & Perkins, 2011).

Table 39: Average water use factors for thermal power plants

	Nuclear plants		Coal plants (sub-critical)		Combined-cycle gas turnbine	
Litres/ kWh	Open loop	Closed loop	Open loop	Closed loop	Open loop	Closed loop
Water abstraction	164	3.88	118	2.11	47.6	0.93
Water consumption	1.24	2.66	0.78	1.77	0.38	0.72

Source: (Byers et al., 2014)

2.8.3 Flooding

The water capacity of the atmosphere grows by almost 7% per 1 degree Celsius of warming, resulting in an increase in the frequency and severity of heavy precipitation events. These can lead to unprecedented levels of river flooding, as seen in the Valencia region in Spain in 2024 or in the Ahrtal valley in Germany in 2021. As a result, nuclear power plant sites on rivers will be more frequently threatened by floods of historic proportions. During flooding events, debris and rubble can also damage the water intakes or power plant structures. A report for the European Commission identified flooding as "the most harmful climate change effect on the operation of nuclear facilities." (DG ENER, 2011, March).

In recent years, the threat of flooding has increased at many nuclear power plant sites. Flood events at nuclear power plants have shown that water levels – even below the theoretically available safety levels for flooding – have caused safety problems because the water resistance of doors had been exceeded or the sealing of cable penetrations had corroded. Flood events carry the risk that redundant safety systems become inoperable. This risk is greater for old plants due to the lower safety standards and the fact that climate hazards had not been taken into account at the time of construction. Floods can also cause significant damage to power infrastructure and prevent access to the nuclear power plant. High-intensity rainfall can also cause dams upstream of nuclear power plants to burst, flooding the plants.

In the past, a severe flooding event occurred at the Blayais nuclear power plant in France, demonstrating that such an event could jeopardize the safety of all units in a single plant (Gorbatchev et al., 2001). In the summer of 2020, Bangladesh was hit by extreme flooding. One of the affected regions was the Pabna district, where two nuclear power reactors are under construction at the Rooppur Nuclear Power Plant site (Caltabiano, 2020). The districts surrounding the nuclear power plant were among the most affected in Bangladesh in 2020. The site for the plant was selected in 1963, when climate change was not an issue. (UNEP, 2024) reports on an analysis by Moody's Investors Service showing that 37 gigawatts of the US' nuclear capacity is vulnerable to flooding.

2.8.4 Extreme storms and hurricanes/ tornados

Coastal nuclear power plants will be exposed to more severe storms with extreme water levels and stronger tidal waves. Extreme storms can impact the power plant construction and often affect the power grid, resulting in loss of on-site power for the nuclear power plant systems. Extreme storms can cause damage to nuclear plants, in particular when storms are combined with high-level rainfalls and severe flooding.

A combination of climate impact modelling and nuclear site locations showed that nuclear plant sites located on the east coast of the United States are most likely to be exposed to sea level rise and severe cyclones and heavy precipitation (IAEA, 2022a).

43% of new nuclear power plants have been built in East Asia, where tropical cyclones, floods and draughts have increased considerably (IAEA, 2022a) Super Typhoon Hinnamnor in South Korea in 2002 forced three nuclear reactors to reduce their capacity to 30% (Portugal-Pereira et al., 2024). Hurricane Sandy in the US in 2012 caused three nuclear plants to shut down due to high water levels (Portugal-Pereira et al., 2024).

(Kopytko & Perkins, 2011) analysed the impact of storms on several US nuclear power plants on the east coast. For the Turkey Point units in Florida, they found that Category III storms would already inundate the site and a Category V storm would cause complete flooding. The Turkey Point site already experienced multiple damage when it was hit by Hurricane Andrew, a Category V storm, in 1992 which showed that multiple failures occur simultaneously, such as loss of communications, loss of off-site power, obstruction of site access, loss of emergency sirens or the failure of protection equipment such as fire protection systems or water pumps. Multiple systems failure is a typical feature occurring of severe storms, which are more difficult to manage. Therefore, extreme storms can cause high risks for nuclear plants.

2.8.5 Sea level rise and storms

Coastal nuclear plants are threatened by rising sea levels which increase the risk of storm surges. Rising sea levels also increase coastal erosion and landslides. 41% of nuclear power plants are located at coasts and more than 100 reactors are only a few metres above sea level

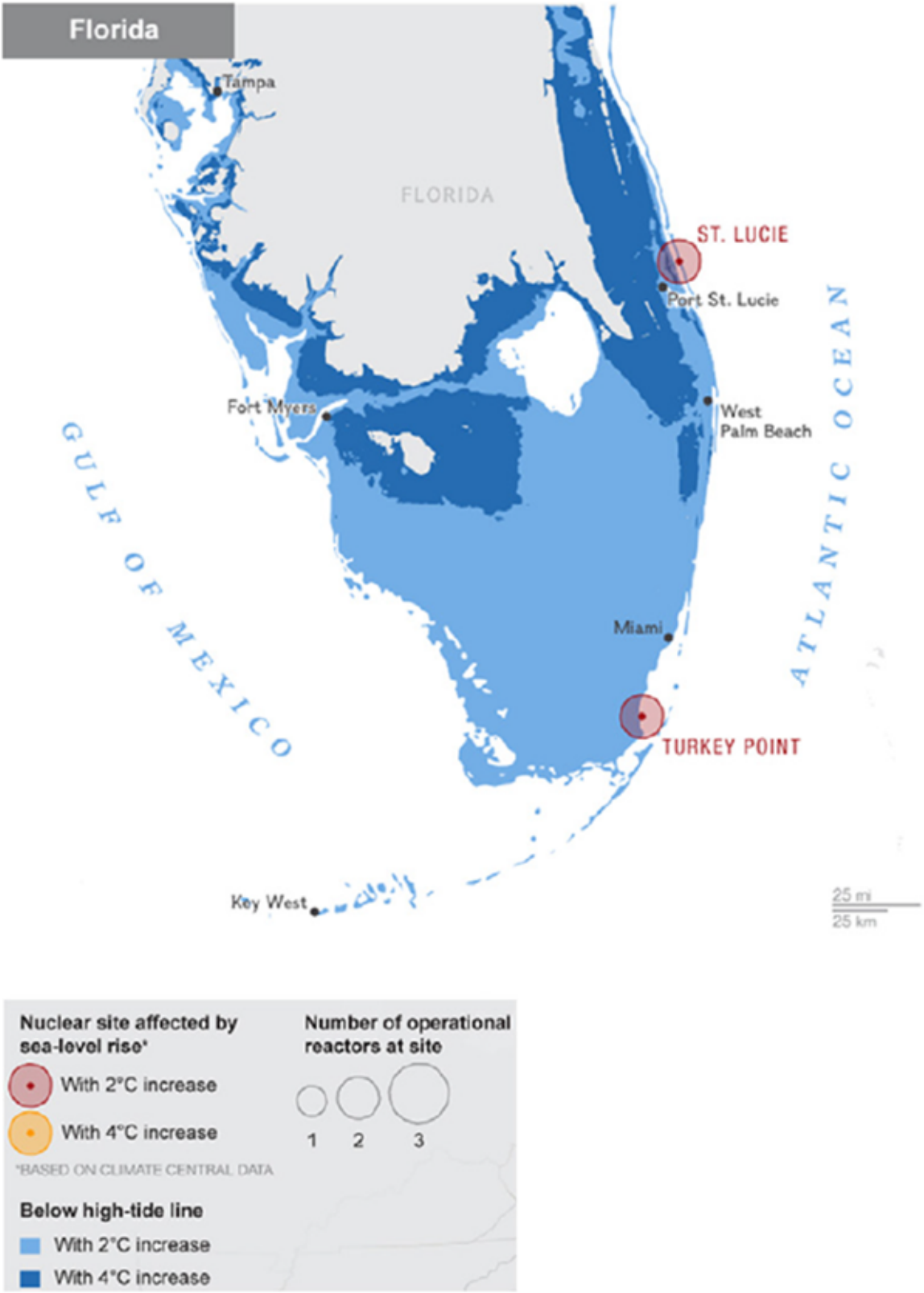
(IAEA, 2022a). Sea levels are expected to rise by 50 to 90 cm by the end of this century. According to (IAEA, 2022a), a total of 10% of the nuclear generation fleet is already exposed to severe coastal flooding. Severe coastal flooding can lead to inundation of critical infrastructure and disruption of operations. The greatest impact of sea level rise occurs in combination with extreme storm surges, which can cause severe damage to nuclear plants, similar to the tsunami events at the Fukushima nuclear plant in Japan in 2011. Additional threats arise from enhanced erosion and changes of the shorelines. According to (Kopytko & Perkins, 2011), coastal vulnerability is usually not considered in the risk analysis of nuclear power plants at coastal sites. The presence of well-protected nuclear plants at coasts increases the risk of erosion for adjacent coastal parts with natural habitats or infrastructures.

(Portugal-Pereira et al., 2024) identify hotspot regions for threats due to sea-level rise to nuclear plants in the Middle east, South Asia as well as some regions in the US, China and Europe.

Sea level rise is already having an impact on existing nuclear power plants. For example, in 2019, a 20-year lifetime extension of the Turkey Point plant in Florida was approved despite the failures the plant showed during previous storm events. Three years later, however, the decision was reversed due to the plant's high risk of frequent flooding associated with sea-level rise in the 2040s (UNEP, 2024).

Protecting existing coastal nuclear power plants against storms, floods and erosion will be costly. Uncertainties related to the severity and frequency of unprecedented events that are likely to happen in the future, make it difficult to determine the safety levels that need to be achieved. For new nuclear power plants, extreme storms and coastal erosion make the identification of adequate coastal sites more difficult. Moving coastal reactors further inland will be more costly, e.g. for extended piping. Achieving the desired level of safety with climate change impacts will be too expensive in many locations (Kopytko & Perkins, 2011).

Figure 79: Exposure to sea level rise of Turkey Point and St. Lucie nuclear plants in Florida



Source: (UNEP, 2024)

2.8.6 Other climate impacts

With a combination of snow and wind, there is a potential for a loss of offsite power and a simultaneous failure of diesel generators due to air intake blockage, and the possibility of formation of snow banks. In areas with a high winter precipitation, snowstorms and ice accumulation can also block the cooling water inlets and outlets of nuclear power plants, especially when the wind is blowing on the right side. Extreme cold waves occurred more frequently in recent years in the US and resulted in very cold temperatures. This can disrupt feedwater pumps as in 2021 when a reactor of the South Texas plant in the US had to stop due to frozen water pumps (Portugal-Pereira et al., 2024).

Drought (due to high air temperature) could be combined with strong winds and forest fires. A climate-induced increase in fire activity has been starkly visible in recent years. Record-setting forest fires are becoming the norm, with 2020, 2021 and 2023 marking the fourth, third and first worst years for global forest fires, respectively. (Jordaan et al., 2019) report that workers have been evacuated from a California nuclear power plant due to wildfires. But there is less evidence, that forest fires have already led to significant climate impacts on nuclear power plants.

Higher water temperatures increase the risk of biofouling, accelerated growth of plants (jellyfish or clams) and algae and other microorganisms can colonize cooling water inlets and outlets and lead to clogging of water intakes. One example is the shutdown of the nuclear plant Gravelines in the north of France in summer 2025 due to jellyfish clogging the filter drums of the cooling water pumping stations. The eutrophication of coastal waters has become more frequent due to global warming and the increase in ambient water temperature.

2.8.7 Climate change and governance stability

Whereas the impacts listed above are directly related to the operation of a nuclear plant, severe climate impacts can have the potential to destabilise regions and countries with nuclear plants creating indirect security risks. Some of the countries attempting to start nuclear energy programmes such as Nigeria, Malaysia or Bangladesh are also dealing with severe flooding, sea-level rise, extensive draughts, heat waves and at the same time experience terrorist threats, massive population displacements or loss of territories to subnational groups. When climate impacts will become more severe, the risks to countries' stability will grow significantly, in particular in countries that already face governance problems. This can strongly increase the risks of nuclear accidents. (Parthemore et al., 2018) highlights that the threats due to climate change and nuclear threats increase due to a general weakening of international norms, order and multilateral treaties.

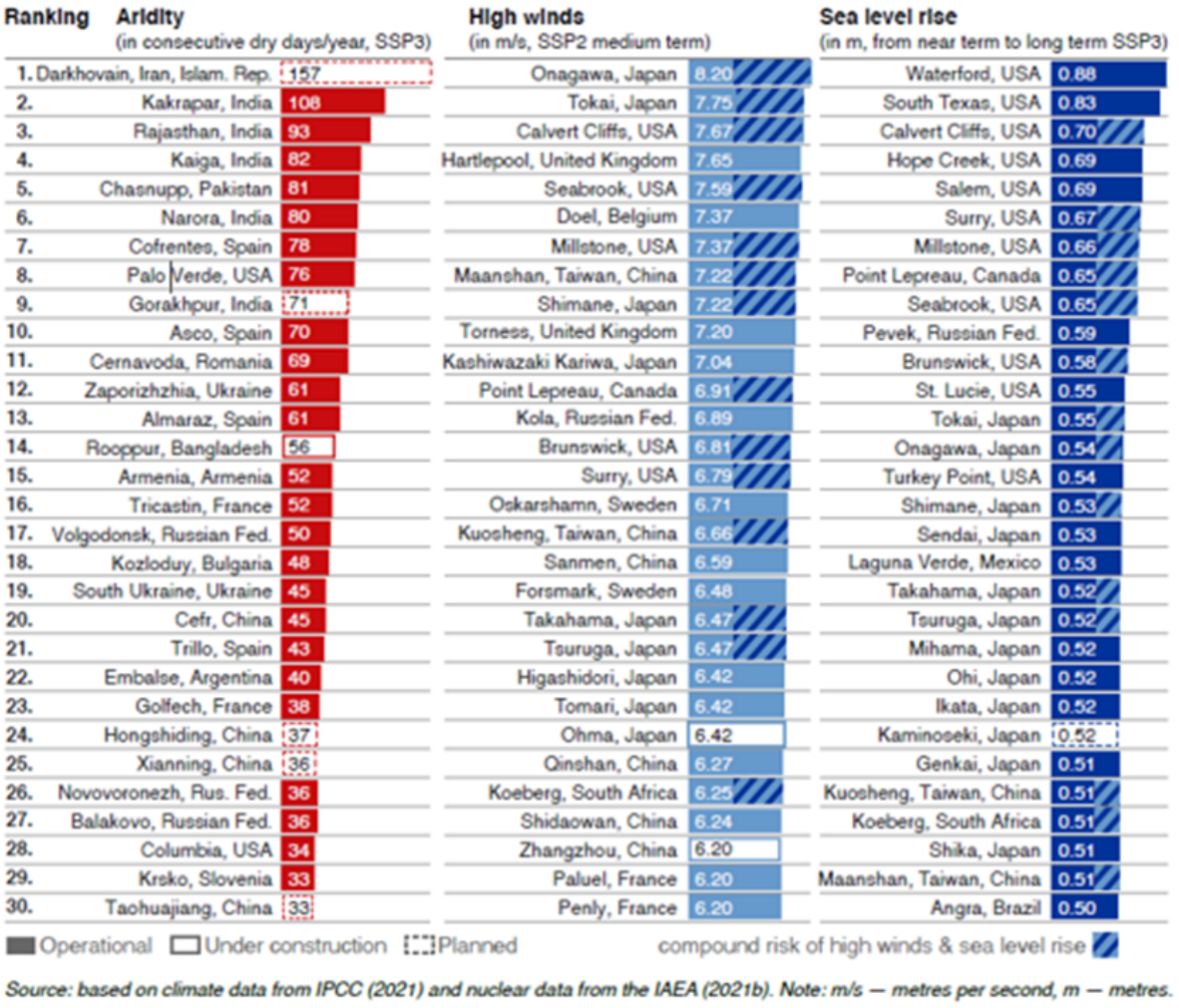
2.8.8 Climate change impacts on nuclear energy scenarios

It is challenging to develop quantitative estimated for current and future production losses due to climate impacts on nuclear power plants. (Linnerud et al., 2011) suggest that nuclear power supply may drop by over 2.3 percent per degree Celsius of warming in selected European countries (Linnerud et al., 2011). This analysis also assumes that the impacts of extreme weather events increases in a linear way with rising temperatures. However, this assumption incorrect and IPCC reports show disruptive and non-linear effects with increasing temperatures.

The discussion above has not yet explored compound risks when several weather or climate events — not necessarily extreme — occur either at the same time, in close succession or concurrently in different regions.

In a report in 2022, IAEA tried to assess compound climate risks for individual nuclear power plants and developed a ranking of plants most exposed to three main risks of aridity/ lack of cooling water, storms and sea level rise (see Figure 80).

Figure 80: Ranking of nuclear sites by climate risks



Source: based on climate data from IPCC (2021) and nuclear data from the IAEA (2021b). Note: m/s — metres per second, m — metres.

Source: (IAEA, 2022a)

(Portugal-Pereira et al., 2024) highlight that regions that are most vulnerable to climate change hazards are the regions that build most new nuclear plants. This on the one hand shows that climate impacts are not fully considered in the political decision-making on new nuclear constructions and on the other hand indicates that reduced production and outages are likely to increase further.

Climate change impacts will impact the future development of nuclear energy in three key ways:

- The power generation potential of the existing and future reactor fleet will be reduced.
- Climate change will limit the number of suitable sites for nuclear power plants. Constructing more reactors at existing sites is often seen as the fastest option, but many of these sites will no longer be suitable because of their vulnerabilities to climate impacts. Appropriate inland sites for nuclear power plants will be more limited in the future because of diminished water resources. The lack of suitable sites at inland locations cannot be addressed simply by

locating nuclear power plants along the coast due to restrictions on coastal development due to sea level rise and increased storm threats.

- Adaptation measures will increase construction and operation costs of nuclear power plants. Retrofitting of older plants may become too costly if climate change risks at specific sites require significant additional protective measures against climate-related threats.

These effects are not taken into account in the climate mitigation scenarios discussed above and the role if nuclear energy in the future. The analysis shows that climate impacts can significantly reduce the contribution of nuclear energy to global energy production. Table 40 provides an overview of the most important climate impacts on nuclear generation and the related effects on the future potential of nuclear energy to global energy production.

Table 40: Overview of key climate change impacts on nuclear power generation

Climate impact	Impacts on nuclear generation	Impacts on nuclear energy in future climate scenarios
Rising global temperatures	Reduced generation efficiency Higher cooling demand	Lower generation potential of existing and future nuclear fleet
Increased draught and heat waves	Lower generation potential More frequent outages	Significant fewer river sites with positive conditions for high productivity Riverine sites less attractive for nuclear power plants Lower generation potential of existing and future nuclear fleet Increased costs for adaptation measures
Flooding	Increased physical risks for accidents More frequent outages Operational disruptions	Lower generation potential of existing and future nuclear fleet Increased costs for adaptation measures
Sea level rise and storms	Increased physical risks for accidents More frequent outages Operational disruptions	Significant fewer coastal sites with positive conditions for high productivity Increased costs for adaptation measures

Source: Öko-Institut

2.9 System perspective of nuclear power

2.9.1 Introduction

In analyzing the system perspective of nuclear power, the basic premise is a power system primarily based on renewable electricity[27]. Renewable energy sources – mainly wind and solar – feature an intermittent production of electricity, depending on weather conditions (e.g., solar radiation and availability of wind) and time of day (especially solar radiation). For this reason, in decarbonized power systems with a high share of renewable, flexibility is required to always

[27] In this regard, system perspective refers to the energy system. On the one hand, this refers to the interaction of nuclear power with the electricity system. On the other hand, other energy uses such as for desalination, the production of hydrogen, or combined heat and power are discussed. Other aspects, such as infrastructure, water demand of nuclear power, or grid stability are not discussed here.

meet load demands. The research question is what role nuclear power can play to provide such flexibility.

To answer this question, the technical flexibility of nuclear power plants is assessed considering technical parameters such as ramping rates, minimum load or minimum downtime (section 2.9.2). Subsequently, observed past flexibility of nuclear power plants in the power system and the required future flexibility in a system primarily based on renewable electricity is analyzed (section 2.9.3). As a third part, the potential for decoupling of nuclear power plants from the power grid to meet specific demands (such as heat, hydrogen, or desalinated water) is studied (section 2.9.4). Lastly, section 2.9.5 elaborates on the realization time of different power technologies, which is a crucial parameter to meet greenhouse gas reduction targets.

2.9.2 Technical flexibility of nuclear power plants

The flexibility of a power plant is determined by its ability to operate in partial load and by parameters such as load change rate, minimum load, start-up time and minimum downtime. A good partial load capability, short start-up time and short minimum downtime increase the flexibility of the power plant and enable a rapid response to changes in the residual load.

Nuclear reactors are often portrayed as inflexible technology and most countries operate them exclusively as base-load power plants. However, modern reactors can be designed for a certain degree of operational flexibility (Agora Energiewende, 2015). They can contribute to frequency regulation and the provision of balancing energy and are able to adapt daily or weekly generation to cyclical fluctuations in demand (i.e., adapting to low demand at night, on Sundays and public holidays) in a sub-range of their total output.

German plants were upgraded so that they could make a greater contribution to load-following operation. The reactor control system, for example, was upgraded for this purpose. They can contribute to primary frequency control (activation and deactivation within 30 seconds for up to 15 minutes) with a variable band of ±94 MW at up to 200 MW/min, to secondary control between approx. 60% (875 MW) and 100% of full load with a gradient of up to 30 MW/min and to load-following operation between approx. 450 MW and 100% of full load with a gradient of approx. 30 MW/min. Load-following operation affects, for example, the feed of boric acid and deionized water into the primary cooling circuit, as well as the operating cycles of the control elements (to compensate for the resulting xenon poisoning). Furthermore, more heavily stressed components such as power contactors, for example, must be inspected or replaced more frequently as part of ageing management or maintenance (Ludwig et al., 2010; Müller, 2020). Other countries have different restrictions (IAEA, 2018b; Morilhat et al., 2019).

Agora Energiewende (2015) prepared an in-depth, model-based analysis of future scenarios for the European electricity system, which, however, focuses on the period 2030. The study found that the load-following capability of modern nuclear reactors can, in principle, help to compensate for a high feed-in of solar or wind energy. However, this flexibility is only limited to the range between minimum load and full load. A more complicated situation arises for nuclear power plants regarding falling below the minimum load and the shutdown and start-up processes. Nuclear reactors are subject to certain technical and safety restrictions and do therefore not offer the same flexibility characteristics as gas turbines, for example, and are more comparable to those of large coal-fired power plants (cp. Table 41). According to (IAEA, 2018b), only a few countries worldwide have explicit nuclear power plant designs and configurations to operate in a wide range of flexibility with load following and frequency response. Especially France and Germany have accumulated some experience with load following operation of their

reactors. In both countries, a minimum load of 20% of the design power must not be fallen short of.

The main reason for this is nuclear-physical reactions that occur when the reactor output changes. Strongly neutron-absorbing radionuclides are also produced from the decay of the fission products resulting from nuclear fission. If the reactor power deviates from full load for a longer period of time, these radionuclides can build up in the reactor core. This influences the controllability of the reactor and therefore places increased demands on the control rods and the boric acid or deionate feed. Accordingly, not all reactors worldwide are suitable for contributing to load-following operation to a relevant extent. Against this background, there is also an intensive discussion of the load-following capability of future reactor concepts (NEA, 2021a; Pistner et al., 2021).

Table 41: Technical flexibility of different power generation technologies

Technology	Specification	Start-up time [min or h]	Minimum load [% of nominal power]	Avg. ramp rate [% of nominal power/min]	Minimum up time [h]	Minimum down time [h]
Hard coal	Average plant	2-10 h	25-40%	1.5-4%	48 h	48 h
	Post flex.	80 min -6 h	10-20%	3-6%	8 h	8 h
Combined Cycle Gas Turbine (CCGT)	Average plant	1-4 h	40-50%	2-4%	4 h	2 h
	Post flex.	30 min -3 h	20-40%	8-11%	4 h	2 h
Open-Cycle Gas Turbine (OCGT)		5-11 min	40-50%	8-12%	10-30 min	30-60 min
		5-10 min	20-50%	8-15%	10-30 min	30-60 min
Internal combustion engine (ICE)	Average plant	5 min	20% (per unit)	> 100%	< 1 min	5 min
	Post flex./ advanced plant	2 min	10% (per unit)	> 100%	< 1 min	5 min
Nuclear	France	2-48 h	20%	3%	See text	See text
	Germany	2-48 h	20-30%	1-2%	See text	See text
	SMR	2-48 h	10-50%	2-10%	See text	See text

Source: International Renewable Energy Agency (2019), (NEA, 2011), (Pistner et al., 2021), (IAEA, 2018b)

Table 41 shows flexibility parameters for different fossil power plants (hard coal, combined cycle gas turbine (CCGT), open-cycle gas turbine (OCGT), internal combustion engine (ICE)) in comparison to nuclear power plants.

Start-up time of nuclear power plants (2-48 hours) is not comparable to open-cycle gas turbines or internal combustion engines (minutes). However, it is partially comparable to hard coal power plants and combined-cycle gas turbines (up to 10 hours, depending on the design).

Minimum load of nuclear power plants (down to 20% for conventional reactors, down to 10% for new small modular reactors) is comparable to existing fossil power generation technologies (depending on the design).

Ramp rates of nuclear power plants (1% to 10% depending on the design) is also comparable with many fossil power generators, with open-cycle gas turbines and internal combustion engines featuring the highest values.

Minimum up time and minimum down times for nuclear power plants may vary widely depending on operational and legal restrictions. For example, some nuclear power plants can be operated for a limited period of time in house load operation, where only a minimum load is produced to provide the plant with the electrical power needed to be independent of the external grid. Thus, the plant will not have to be shut down immediately to either hot or cold shutdown states (where the primary cooling system temperature is still at the operating temperature or temperature and pressure of the primary coolant system are reduced to low levels). In comparison, minimum up time and minimum down times are short for OCGT and ICE (minutes) and medium (hours) for CCGT and hard coal power plants. It can thus be concluded that nuclear power plants are not designed to shut on and off nuclear plants frequently as is the case for fossil power plants.

Based on these considerations it can be concluded that load-following operation of nuclear power plants is possible within limits. However, as pointed out above load-following operation of nuclear power plants engenders higher tear and wear and thus higher costs. This also induces increased downtime due to maintenance. Furthermore, in general terms, electric efficiency is reduced when a power plant is operated in part load for longer periods of time, which thus increases (upstream) emissions. Part load operation also generally reduces the load factor of power plants and thus leads to a poorer economic efficiency. Since nuclear power plants are the most capital-intensive power plants, see section 4.2.1, economic considerations are more important than for other power plants. It can thus be concluded that nuclear power plants are not suitable for balancing highly fluctuating renewable electricity feed-in in a system with a high share of renewable electricity.

2.9.3 Observed past and required future flexibility of the power system

The analysis of flexibility of nuclear power plants in the power system is based on several considerations. Firstly, the observed past flexibility and operation of nuclear power plants is assessed based on available data and literature (section 2.9.3.1). Secondly, it is discussed how load patterns are affected by the increasing share of renewables in the power system (section 2.9.3.2). Thirdly, the required future flexibility based on a further penetration of renewable electricity is evaluated (section 2.9.3.3).

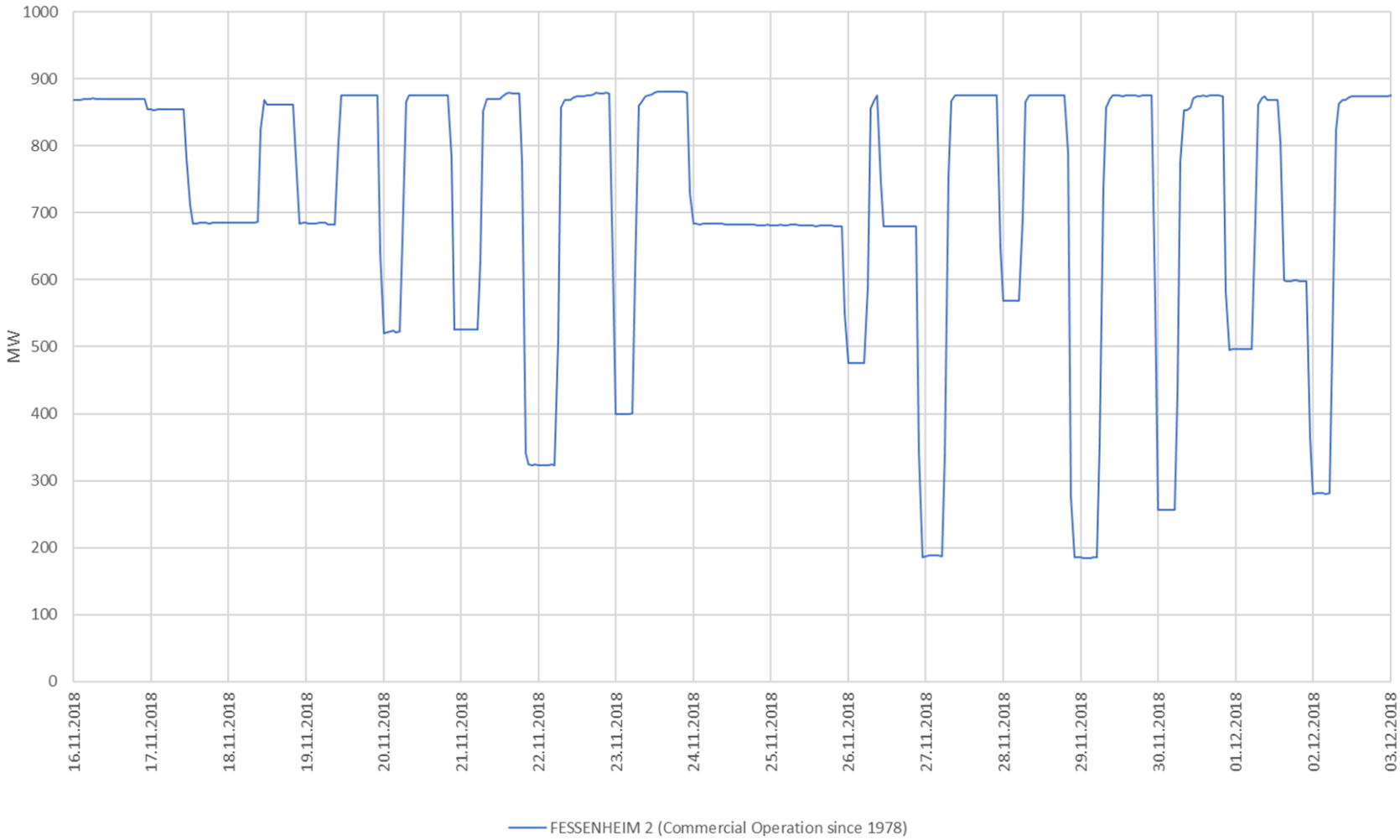
2.9.3.1 Observed past flexibility

In this section, past flexibility is assessed from two sides. Firstly, power plant operation of French nuclear power plants is evaluated. Secondly, operation of renewable energy plants is scrutinized.

In the following, data from three French nuclear power plants are used to discuss flexibility of power plant operation: Fessenheim 2, Bugey 2 and Chooz 2. Values stem from ENTSO-E Transparency Data (ENTSO-E, 2025).

Figure 81 shows operation of nuclear power plant Fessenheim 2 from 16 November 2018 to 3 December 2018. It shows that load is lowest during nighttime and highest during day times. Lowest load values are not linked to weekends, though. The graph also demonstrates that the power plant is never shut off during the period with lowest values reaching 200 MW.

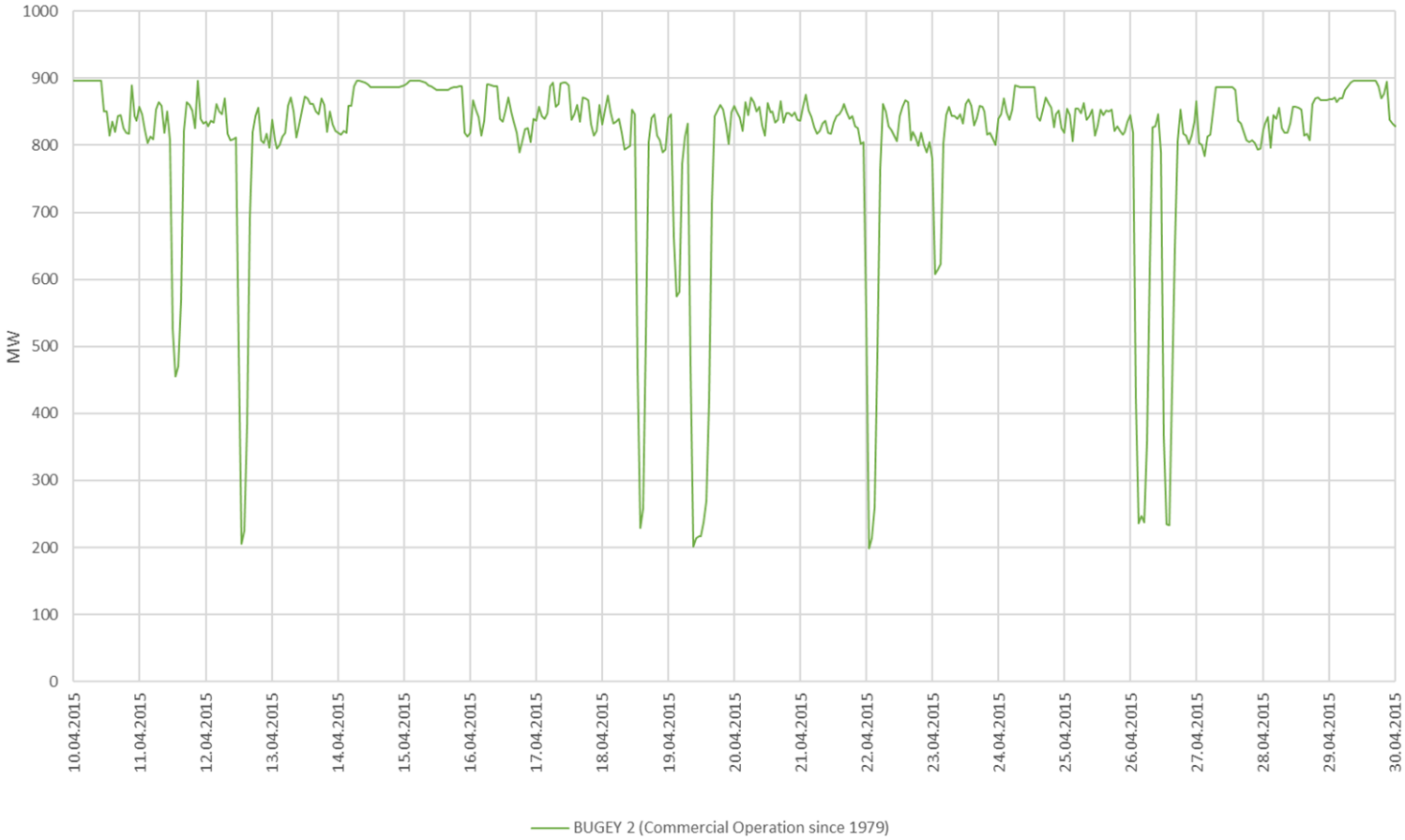
Figure 81: Operation of nuclear power plant Fessenheim 2, 2018



Source: ENTSO-E Transparency Data

Figure 82 shows operation of nuclear power plant Bugeye 2 from 10 April 2015 to 30 April 2015. Load is at maximum load during most of the time. Lowest values are reached during daytime on weekend days. The graph also demonstrates that the power plant is never shut off during the period with lowest values reaching 200 MW.

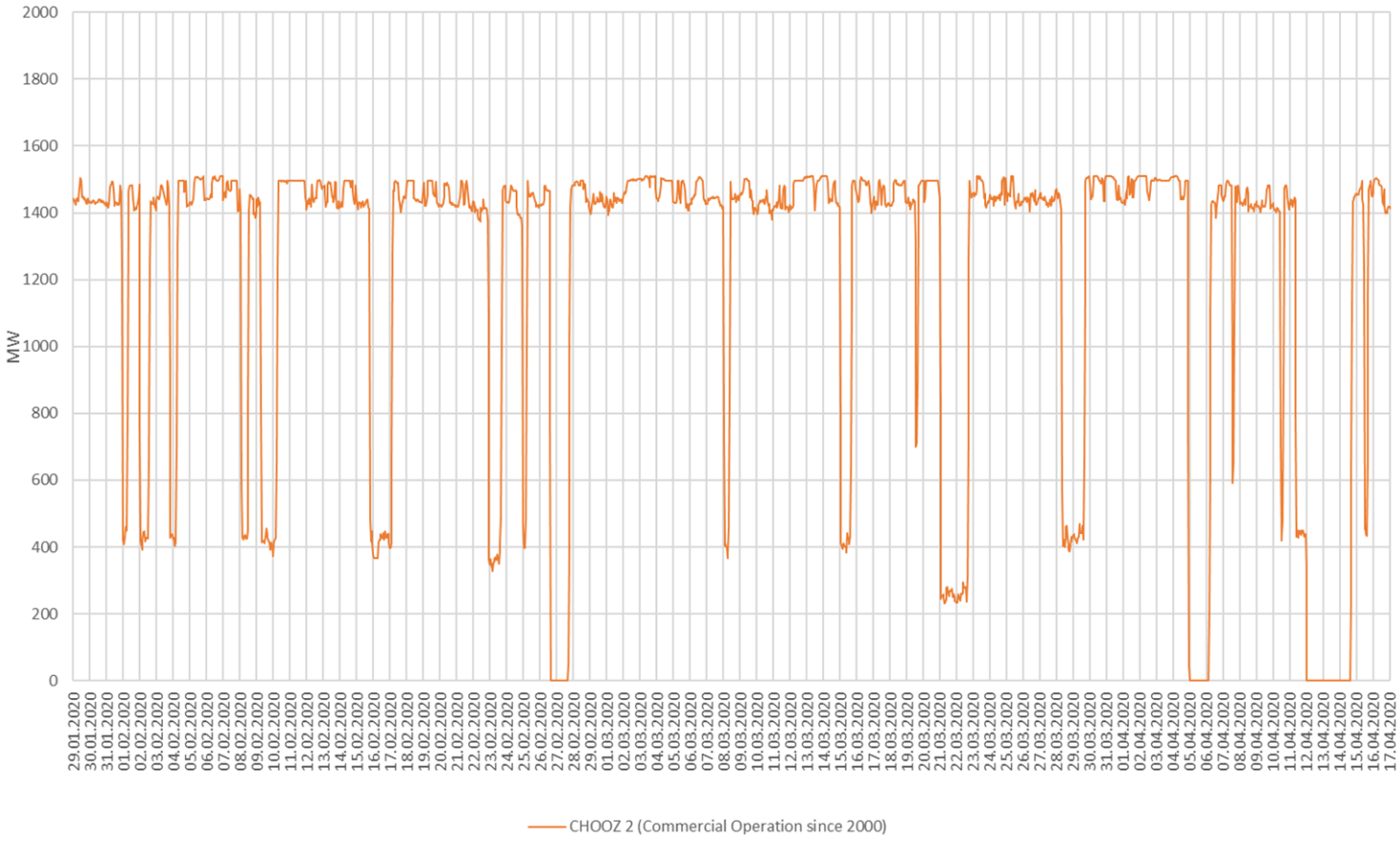
Figure 82: Operation of nuclear power plant Buguey 2, 2015



Source: ENTSO-E Transparency Data (ENTSO-E, 2025)

Figure 83 shows operation of nuclear power plant Chooz 2 from 29 January 2020 to 17 April 2020. Load is lowest on several weekend days. The graph also shows that the power plant is shut off on a few days (the reason is unknown, though). During most of the time, minimum load is about 300-400 MW.

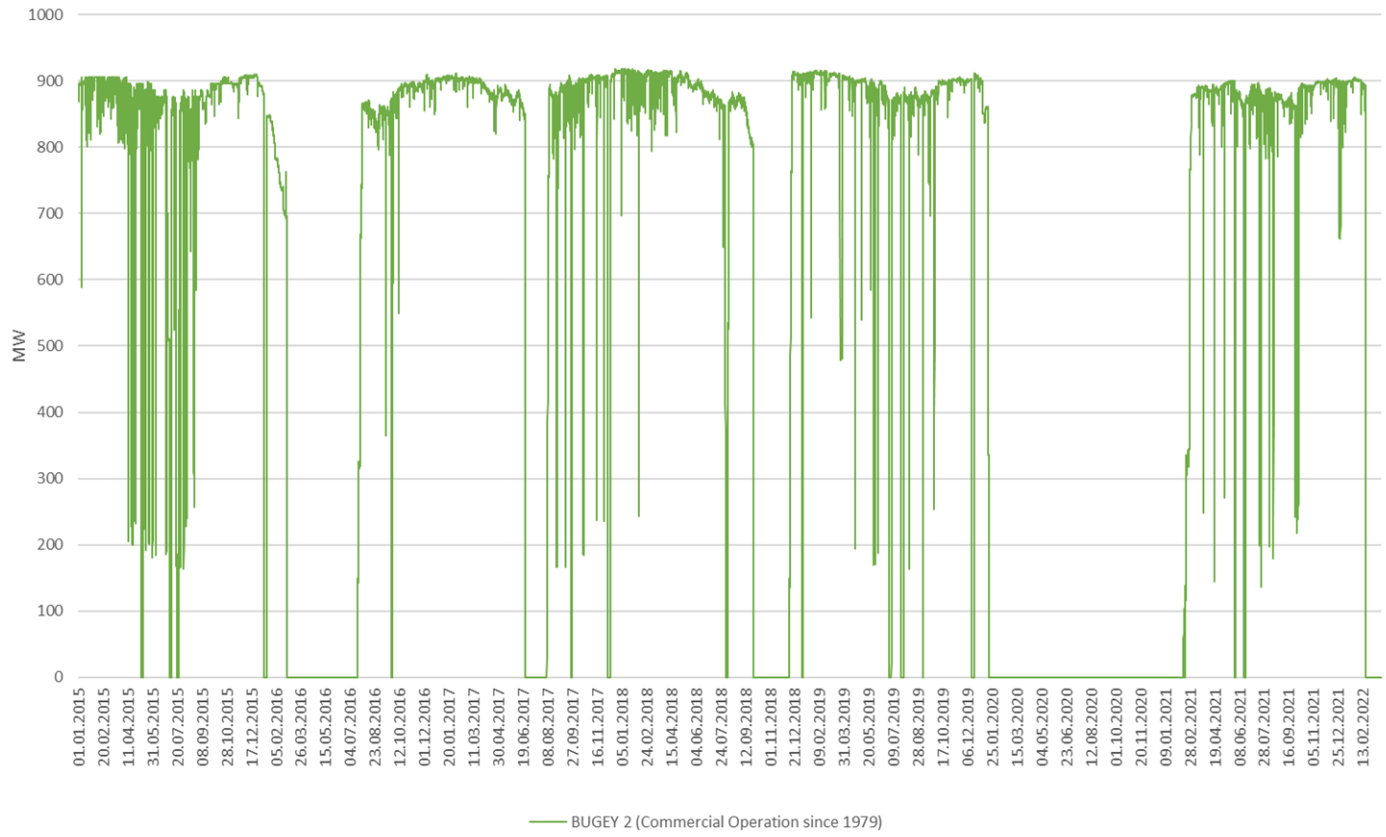
Figure 83: Operation of nuclear power plant Chooz 2, 2020



Source: ENTSO-E Transparency Data (ENTSO-E, 2025)

Figure 84 shows operation of nuclear power plant Buguey 2 from 1 January 2015 to 13 February 2022. It shows that the power plant is at maximum load during most of the time. Minimum load is about 200 MW during many days. During some days the power plant is shut off, including some longer periods (weeks to months). The longer periods indicate that the power plant may have been under maintenance during these periods.

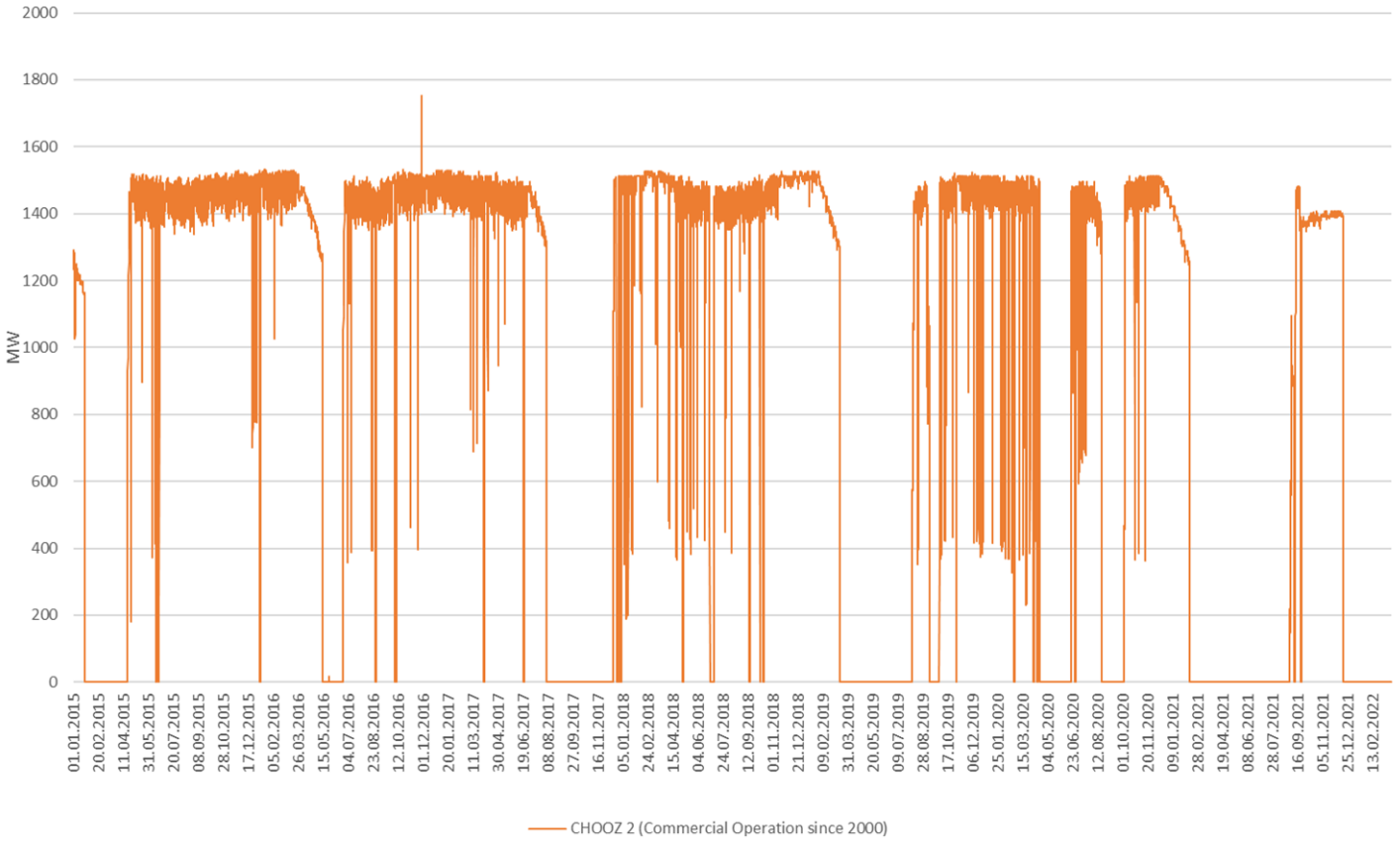
Figure 84: Operation of nuclear power plant Bugey 2, 2015-2022



Source: ENTSO-E Transparency Data (ENTSO-E, 2025)

Figure 85 shows operation of nuclear power plant Chooz 2 from 1 January 2015 to 13 February 2022. It shows that the power plant is at maximum load during longer periods of time, even over weekends and nighttime. Minimum load reaches mostly 400 MW, in some cases 200 MW. During some days the power plant is shut off, including some longer periods (weeks to months). The longer periods indicate that the power plant may have been under maintenance during these periods.

Figure 85: Operation of nuclear power plant Chooz 2, 2015-2022



Source: ENTSO-E Transparency Data (ENTSO-E, 2025)

From the graphs above it can be concluded that load-following operation is in fact possible for most of the nuclear power plants with the lower limit mostly being the minimum load. This confirms the discussion in section 2.9.2. Going below the minimum load, i.e., being shut off, occurs during longer periods of time in most occasions, which suggests that this occurs mostly due to maintenance. This therefore limits the flexibility required for the integration of renewable electricity in a system with a high share of renewables.

Regarding renewable electricity, there are two important interactions with nuclear power:

- On the one hand, nuclear power plants could operate flexibly so that the use of renewable electricity is maximized;
- On the other, nuclear power plants could operate independently of renewable electricity generation with consequences for any potential surplus electricity generation,
  - Renewable electricity generation is exported to neighboring countries to the extent possible,
  - Renewable electricity generation is curtailed, for instance wind turbines could be shut off even though wind is blowing.

In the case of Germany, nuclear electricity generation ended on 15 April 2023 for the three remaining reactors[28]. Prior to the final decommissioning, discussion was going on whether to further extend the nuclear generation.

In an analysis of a further lifetime extension, Bundesverband Erneuerbare Energie e.V. (2023) found that in previous years, nuclear power plants in Germany were operating between 7.000 and 8.200 hours per year. Accordingly, this rather rigid operation of nuclear power plants leads to market losses for renewable energies and may lead, in case of negative electricity prices, to a curtailment of renewables (ibid.). Furthermore, based on an analysis of electricity generation over past years, it was found that nuclear power plants were operated with a least one third of capacity even in times of negative electricity prices (ibid.).

According to Bundesnetzagentur and Bundeskartellamt (2023), about 6 TWh renewable electricity was curtailed annually in Germany between 2019 and 2021. In 2022, 8 TWh were curtailed. In 2023, more than 10 TWh were curtailed (Bundesnetzagentur, 2023). Furthermore, since 2008, there has been a net export in all years (Bundesnetzagentur & Bundeskartellamt, 2023). However, a direct link to nuclear electricity generation is not made. Grid restrictions are also shown.

Conversely, renewable electricity may reduce operating hours of nuclear power plants considerably. In 2024, French power plants were shut down for several days due a large availability of renewable electricity and since, in consequence, electricity prices had become negative (Cleanthinking.de, 2024). This indicates two aspects: on the one hand, the mentioned power plants did not operate flexibly in order to accommodate the large supply of renewables. On the other, due to the required shutdown for several days, operating hours were reduced significantly, which reduces profitability of nuclear power plants.

Präger et al. (2024) find that „ nuclear power plants are generally generating electricity in the baseload spectrum with must-run constraints and must be backed up for meeting peak load demands with flexible operating generation units“. Furthermore, they argue that “although

[28] Including cycle strechout for 3,5 months since the planned completion date for all nuclear power plants in Germany was end of December 2022. The German Government decided to use strechout operation for three remaining reactors due to the energy crisis in the aftermath of the Russian attack on Ukraine since February 2022.

newer reactor designs technically possess better capabilities for load-following operations, existing nuclear power fleets are typically operated as continuous baseload power plants due to economic, technical, and safety considerations". In case, nuclear power plants are to be operated flexibly, "the integration of thermal energy storage and three to four times the steam turbine capacity of a conventional baseload nuclear power plant" (ibid.) would be required, which would reduce "full load hours from 8,000 to 2,000 per year" (ibid.). This would result "in worsened economics for new nuclear power plants due to increased capital cost associated with thermal energy storage and higher steam turbine capacity" (ibid.).

2.9.3.2 Changing paradigms towards a renewables-based electricity system: from base- and peak load to residual load

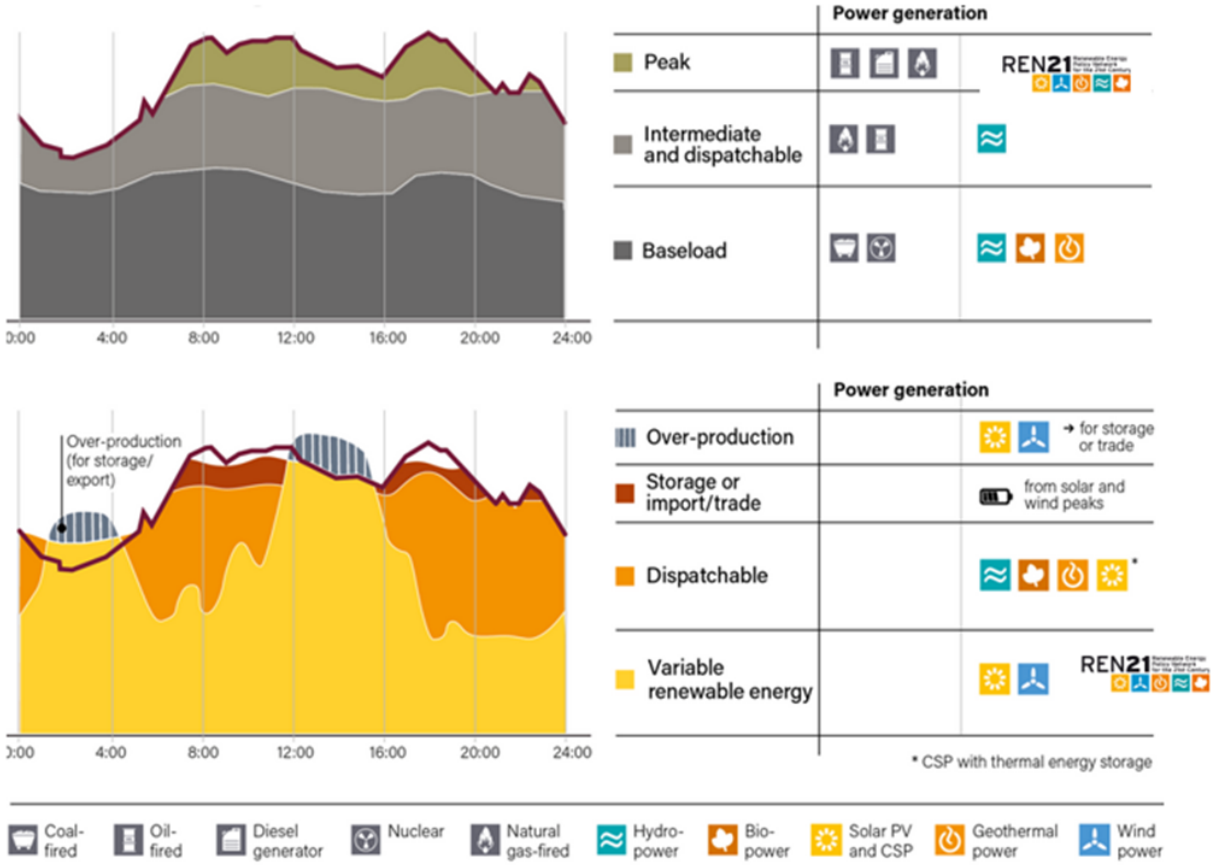
Traditional energy planning has usually focused on determining the number of baseload, intermediate, or peaking units required to meet future energy demands (see e.g., Milligan and Katz (2016)). However, with the increasing integration of variable renewable energy (VRE) sources like solar and wind, a new planning approach is necessary. This approach must account for the costs and benefits of solar and wind power, as well as the operational demands these sources place on system flexibility. Figure 86 illustrates the two different paradigms: in the base- and peak-load paradigm, load is segmented into three typical bands: baseload, peak load and mid- or intermediate load. Baseload generation is dispatched constantly, with no adaptation to the daily load variations. Peak load typically provides generation during morning and afternoon load peaks. Mid-load generation is somewhere in between. Nuclear power is a typical baseload generation technology. The choice of typical technologies to provide generation in the respective band, and their respective optimal size can be explained using the screening curves model as shown in Figure 88. Figure 88 (panel a, and b) shows typical screening curves: The first graph shows available dispatchable generation technologies, typically with different fuels and CAPEX to OPEX ratio. The lines represent annualized full costs (y-axis) to provide a certain amount of full load hours of electricity (x-axis). The axis section are the annualized fix costs (capital and operational exenditure, CAPEX and OPEX) and the slope marks the fuel and other variable costs. Directly below, there is a graph with the annual load curve, but the individual hours are sorted according to the realized load, with the highest load on the left, a so-call load-duration curve. To identify optimal technology choice and respective capacities, the two graphs are read from right to left: the technology that has the lowest annualized full costs, if running at least as many full load hours as indicated by the intersection with the next technology, is cost optimal to be installed with a capacity equal to the load at the respective point of the load duration curve. Moving left on the screening cost graph, the next technology is cost optimal to provide the next chunk of generation, and optimal installed capacity is equal to the difference between the first and the second intersection point (read from the right) on the screening curve projected on the load duration curve. And so on.

In the example in Figure 88 (panel a), optimal nuclear, baseload capacity is between 30-40 GW, optimal coal-fired mid-load capacity is about 20 GW, and optimal peak load capacity is about 25 GW.

Figure 88 (panel b) now shows the effect that occurs if the load duration curve is replaced by a residual load duration curve, where non-dispatchable RES-E-based generation is subtracted. With increasing shares of RES-E generation, the size of the residual load that needs to be supplied from non-RES-E sources in all hours of the year shrinks. At some point, with the respective size of the RES-E-based generation fleet, it becomes negative, indicating that in these hours there is surplus RES-E generation. With increasing RES-E shares, the optimal share of baseload generation capacity declines rapidly (see Figure 88,panel c). In the example, optimal

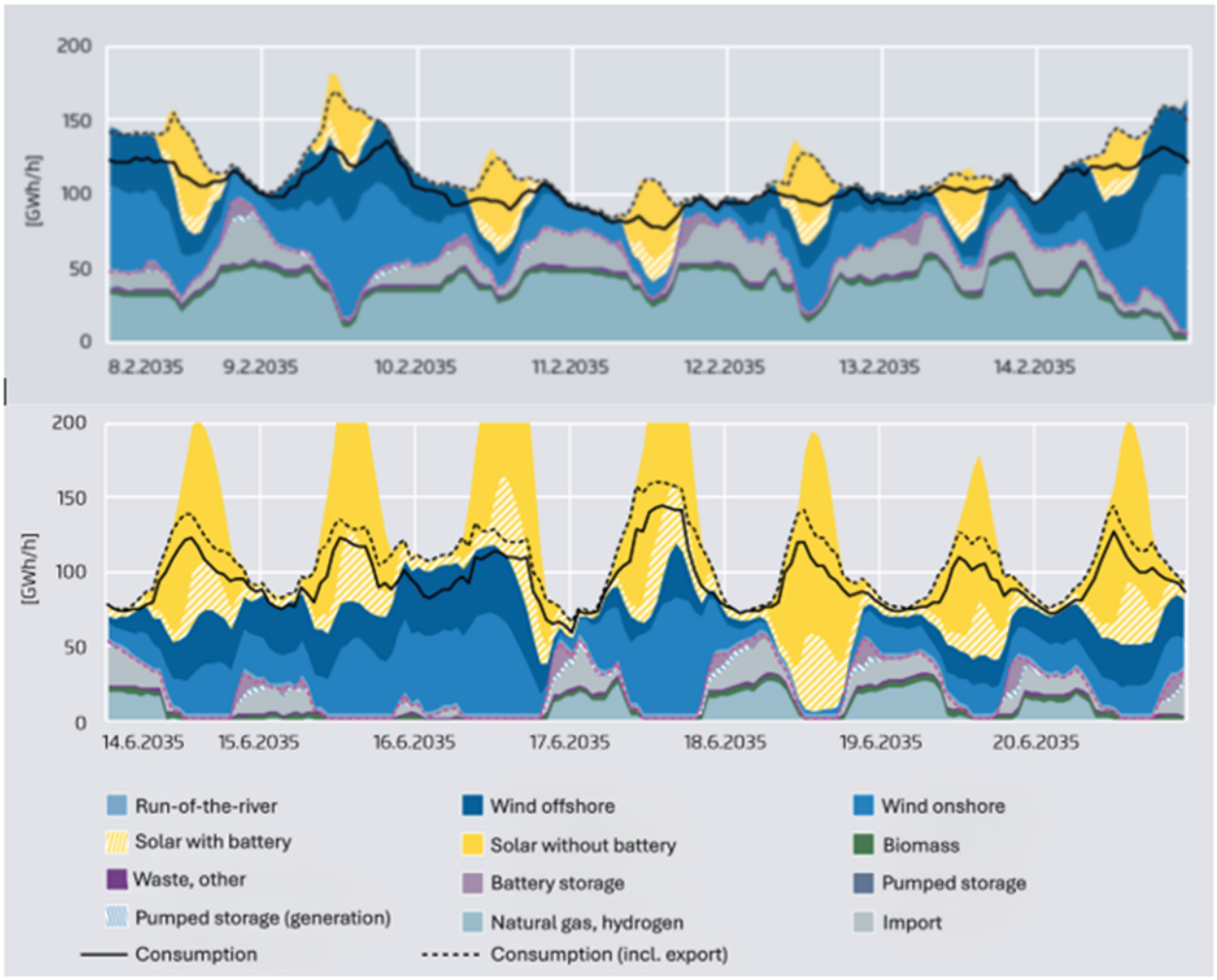
baseload capacity is above 70%, if RES-E shares are zero, but declines to 0% once RES-E shares get towards 50% and beyond.

Figure 86: Changing paradigms towards a renewables-based electricity system: from base- and peak load to residual load – part one



Source: REN21 (2017), Figures 59 a) and c).

Figure 87: Changing paradigms towards a renewables-based electricity system: from base- and peak load to residual load – part two

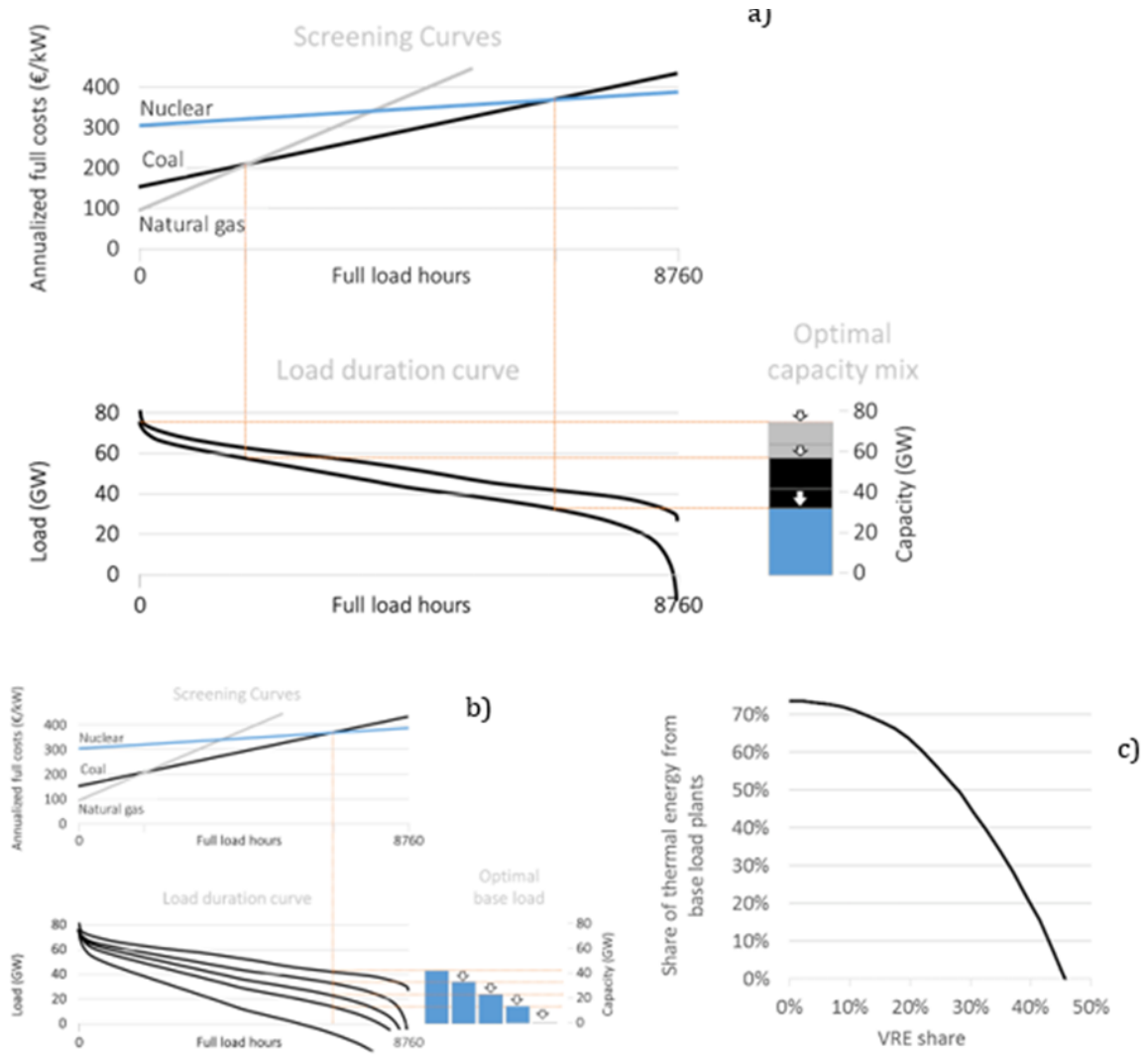


Source: Agora Energiewende et al. (2022), Figures, 17 and 19, CC BY 4.0, translated by Oeko-Institut.

This is also reflected in the technology choice in the residual load paradigm illustrated inFigure 87. Here, RES-E based generation serves the bulk of load during the day. In hours with lower availability, dispatchable RES-E generation, storage, imports, and DSM ensure that supply and demand meet.

While Figure 86 presents stylized generation patterns, Figure 87 shows generation in a "almost climate neutral electricity system" in Germany, for 2035 (Agora Energiewende et al., 2022). The upper part of Figure 87 shows generation patterns in a typical winter week, with low availability of PV, and in addition, days with low availability of wind. Residual load is supplied from natural gas or hydrogen-based units, and via imports. In a typical summer week as shown in the lower part of Figure 87, necessary dispatchable generation is substantially lower, and zero in many hours, while storage helps to shift some of the surplus generation towards other hours. In such an electricity system, there is no role for baseload nuclear capacities. In addition, due to the technical restrictions described above (cp. Table 41), nuclear power plants cannot provide the required technical flexibility to accommodate the maximum uptake of renewable electricity.

Figure 88: Screening curves: optimal baseload capacity with increasing RES-E generation shares

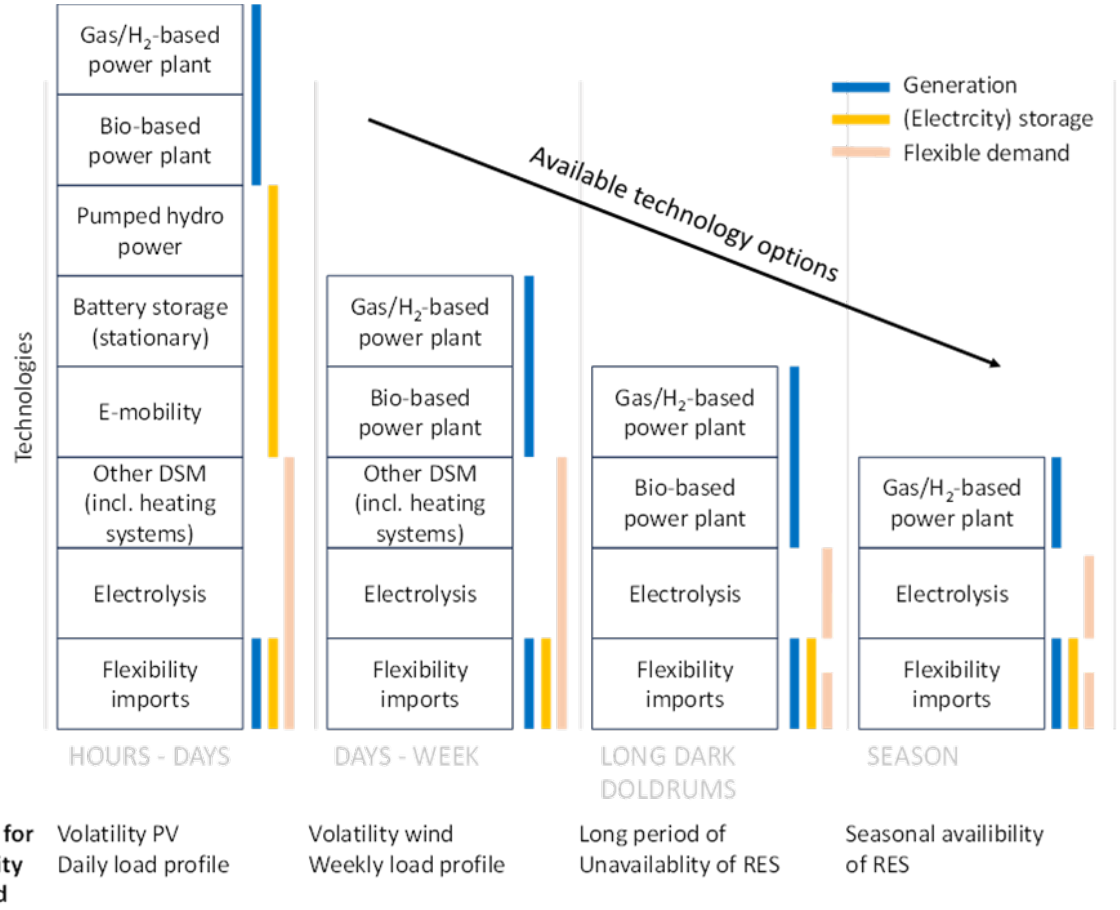


Source: (Hirth et al., 2015; Open Electricity Economics).

2.9.3.3 Required future flexibility

While there is no role for baseload nuclear capacities in a RES-E based electricity system (as detailed in section 2.9.3.2 above), flexibility is required over different time periods and for different tasks. Figure 89 illustrates which technologies can provide which type of flexibility. Available flexibility options to back up PV volatility and daily load profiles are broadly available and range from dispatchable gas/H_2-based power plants, over different types of short-term electricity storage, to DSM, electrolysis, and finally flexibility imports. However, the longer the time to bridge a lack of RES-E generation, the fewer technologies are available. In the case of long dark doldrums or seasonal variation backup options are reduced to dispatchable power plants, electrolysis or flexibility imports.

Figure 89: Flexibility requirements for different time periods and different tasks



Source: Bundesministerium für Wirtschaft und Klimaschutz (2023), slide 17 (Translation by Öko-Institut)

Given fewer technology options, there is a lack of and high willingness to pay for flexibility over weeks, for dark doldrums, and seasonal flexibility. Hence, if nuclear power is to play a significant role in a RES-E dominated electricity system, if would have to provide this type of flexibility.

Dispatchable units providing this type of flexibility typically exhibit high ramp rates (Table 41), and low full load hours. Therefore, as described in section 2.9.3.2, in a cost-optimal electricity system such capacities should have low CAPEX but may have high OPEX.

Resulting full load hours of such capacities are difficult to predict and depend on the system setup, weather conditions, and the market design. However, in the following, different studies of future RES-E based electricity systems are compared to develop an indication for future capacity factors. Table 42 provides a comparison of capacity factors for dispatchable units in RES-E-based electricity systems in Germany and Europe, for 2035 and 2040. On average, capacity factors are 14% in 2035, and about 11% in 2040. In the most conservative scenarios with high shares of RES-E generation but no achievement of the climate neutrality target for 2045, for Germany, capacity factors are at low 26% in 2035 and 17% in 2040.

Table 42: Comparison of capacity factors for dispatchable units in RES-E-based electricity systems for 2035 and 2040

Study	Scenario	Fuel	Capacity (GW)		Generation (TWh)		Capacity factor		Comments
			2035	2040	2035	2040	2035	2040	
KNDE 2035	Main scenario	Gases/H_2	61		86		16%		Almost climate-neutral electricity system in 2035
KNDE 2035	Sensitivity	Gases/H_2	61		106		20%		
PB 2024	MMS	NG	32	31	72	45	26%	17%	Not climate-neutral electricity system in 2035 (about 60 Mt CO_2e in 2035)
PB 2024	MWMS	NG	31	29	71	43	26%	17%	
LFS (D)	O45-Strom	NG	30	1	52	2	20%	23%	Not climate-neutral electricity system in 2035
LFS (D)	O45-Strom	H_2	26	63	12	44	5%	8%	
LFS (D)	O45-H2	NG	27	1	40	1	17%	11%	
LFS (D)	O45-H2	H_2	18	42	4	23	3%	6%	
LFS (EU)	O45-Strom	NG	172	102	202	66	13%	7%	
LFS (EU)	O45-Strom	H_2	74	131	48	88	7%	8%	
LFS (EU)	O45-H2	NG	169	102	184	63	12%	7%	
LFS (EU)	O45-H2	H_2	64	106	31	52	6%	6%	

Source: Own compilation based on data from Agora Energiewende et al. (2022), Harthan et al. (2024), Fraunhofer Institut für System und Innovationsforschung et al. (2024).

Germany is planning a support scheme to bring hydrogen-based capacities into the market which should provide flexibility in times of dark doldrums, and on weekly or seasonal basis (BMWK, 2024). Financial support is suggested to be paid for a maximum of 800 full load hours.[29]

As described in section 2.9.3.2, the share of optimal capacity of power plant with high CAPEX decreases rapidly with higher shares of RES-E in the system and is zero for RES-E dominated systems. However, low carbon electricity systems with a combination of nuclear power and RES-E generation are also feasible. However, the integration of nuclear generation in a RES-E-based system might be driven by the historical composition of the power plant fleet, or by political will. The EC Impact Assessment (EC, 2024) for a 2040 interim climate target on the way towards climate neutrality in 2050, for example, included nuclear power in a RES-E-based energy system.

[29] Accompanying this initiative there is a second instrument which targets "dispatchable capacities to contribute to security of supply" and aims to support gas-fired capacities. For this instrument the gas-fired units are expected to exhibit full load hours in the range of 1.000 h/a.

Also, the China Energy Transformation Outlook 2023 (CET, 2023), which aims to substantiate China's commitment to achieving carbon neutrality before 2060, analyses a RES-E-based energy system that includes nuclear power generation. In both energy systems, nuclear plays a minor role, with a contribution to total electricity generation of 10% for the EU27 and 5% for China, in 2040.[30] In both cases, average capacity factors are 80%. In a further analysis, Stöcker et al. (2024) find that "a secure energy supply is feasible without baseload power plants". In that case, a combination of solar and wind energy with storage, flexible electricity demand and residual load power plants is required. By expanding renewable electricity generation as well as the European electricity and hydrogen grids, electricity and the bulk of hydrogen demand in Europe can be met. Based on detailed modelling, Stöcker et al. (2024) also conclude that "baseload technologies can be incorporated in an energy system dominated by solar and wind energy". In such a configuration, "a flexible hydrogen system would be key to enable high capacity factors of power plants" (ibid.). Furthermore, the modelling demonstrates "that system costs for climate neutrality in 2045 could be" in a similar range as the reference scenario based on wind and solar energy (ibid.). However, as regards nuclear power plants as baseload power plants, Stöcker et al. (2024) conclude that due to "safety risks and ensuing problems due to radioactive waste", a use of this type of power plants "should only be considered in case of significant […] economic advantages".

2.9.4 Decoupling of nuclear power plants

In order to make nuclear electricity more compatible, one idea is that nuclear power generation is at least partly decoupled from intermittent residual electricity demand either

- By flexibly switching between electricity/heat supply to the grid and transforming electricity/heat into other storable energy forms of same or higher value: electricity in batteries, heat storage, hydrogen and derivatives; or products. The storage capacity needs to satisfy demand in all circumstances. If there is insufficient storage for the final products, the power plant needs to be designed in a load-following mode, which goes against the initial idea; or
- By supply predominately to dedicated consumers with high and constant demand. These could include industrial applications, hydrogen production, saltwater desalination, data centers, calcination, CO_2 capture, etc. Such a setup allows for de-facto decoupling from the grid;
- Cases where nuclear power generation is fully decoupled and used in island applications are a special case of the application described above.

A number of institutions push for the development and advertise the concepts. These include

- Nuclear Cogeneration Industrial Initiative (NC2I): The European Nuclear Cogeneration Industrial Initiative (NC2I) aims at demonstrating innovative and competitive energy solutions for the low-carbon cogeneration of heat and electricity, and hydrogen production based on nuclear energy.
- part of the Sustainable Nuclear Energy Technology Platform (SNETP)

[30] Values for EU-27 are calculated based data from European Commission (EC) (2024). Values for China are calculated based on China Energy Transformation Program (CET) (2023). According to CET (2023), installed capacity in 2040 is 115 GW (see p. 79), and the capacity factor is 80% (see Figure 3-19). Correspondingly, electricity generation is about 800 TWh, which is about 5% of total generation of about 17.500 TWh (see Figure 3-14).

The combination is also discussed in the literature. For example, the developers of the so-called "traveling wave reactor" (TWR) essentially see the baseload supply of large agglomerations as an application scenario (Gilleland et al., 2016). However, in view of the system costs, it is also being discussed whether the heat generated in the TWR should initially be transferred to heat storage units using commercially available molten salt from the solar thermal sector. The subsequent use as process heat in industry or for hydrogen production or for variable electricity generation in load-following operation would then be decoupled from nuclear heat generation. The developers also expect this to result in lower system costs (Hejzlar, 2021).

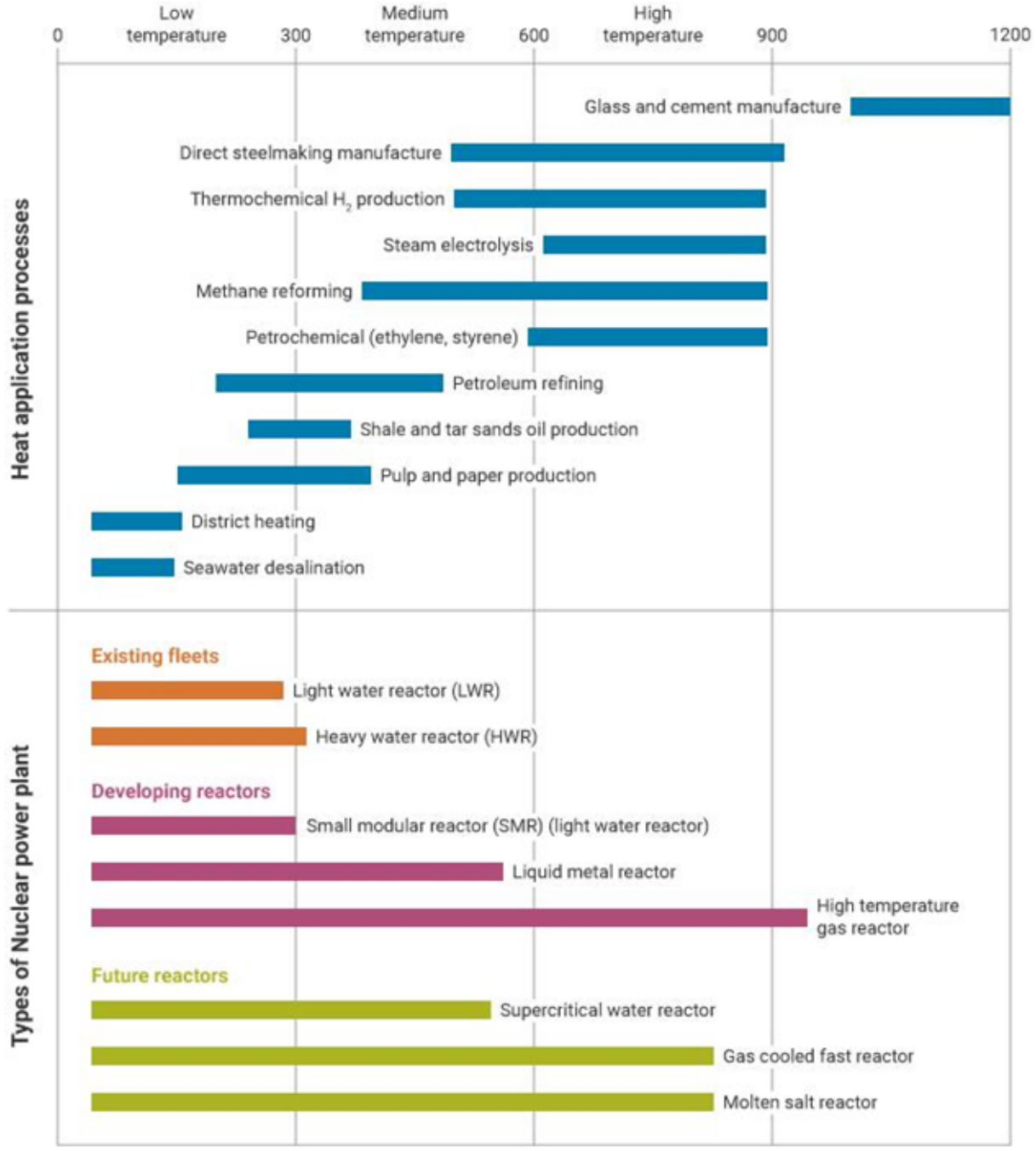
2.9.4.1 Combined heat and power

Figure 90 provides an overview of temperature levels of different heat application processes with significant heat demand, and temperature levels of potential heat output for different nuclear generation technologies. Nuclear power plant types available today (light water and heavy water reactors) have temperature levels of up to ~300°C in the primary circuit and even lower temperatures in the secondary circuit. SMRs that will be commercially available in the foreseeable future (by 2035) are also fundamentally based on the same concepts and therefore achieve the same temperature levels. This means that the possible area of application is limited to the provision of low temperature heat.

Possible areas of application:

- Seawater desalination see section 2.9.4.2
- District and residual heat supply for households and selected industries

Figure 90: Temperature levels of different heat application processes with significant heat demand, and temperature levels of potential heat output for different nuclear generation technologies



Source: WNA (2024c)https://world-nuclear.org/information-library/non-power-nuclear-applications/industry/nuclear-process-heat-for-industry based on IAEA (2017)

Technology description with current and future state of development

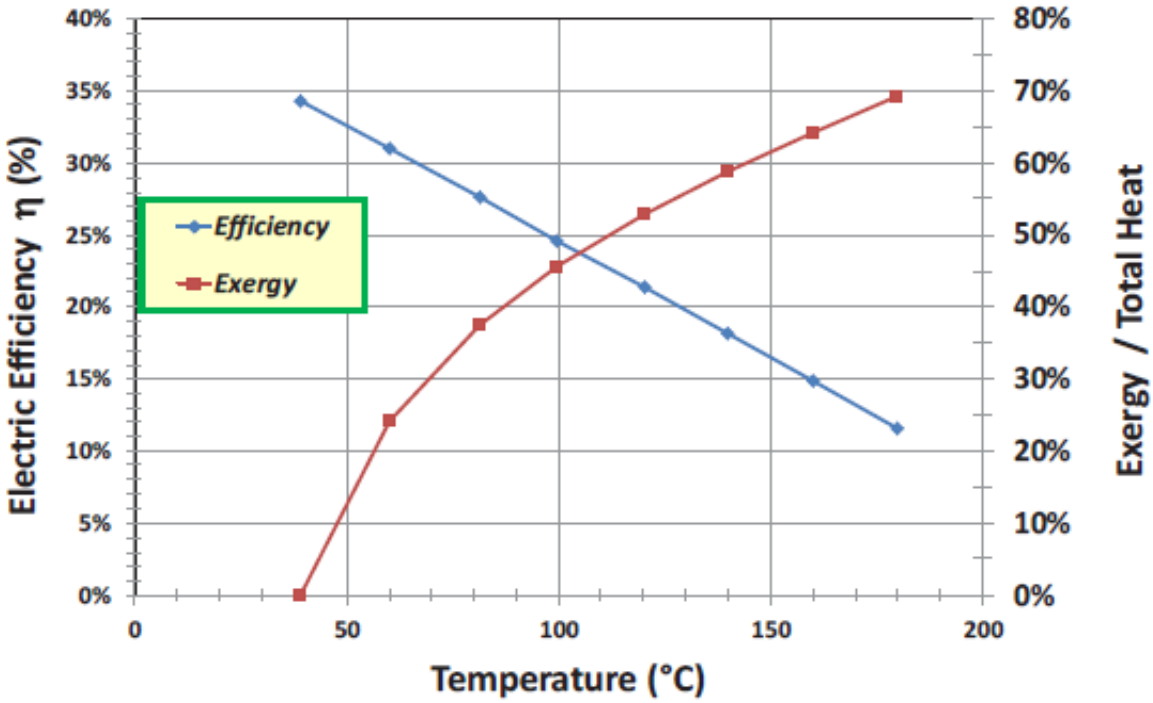
In nuclear-based cogeneration, some of the steam in the secondary loop is extracted from the lower pressure turbine and directed to a heat exchanger to heat the circulating water returning from the district heating or industrial network (IAEA, 2017). Additional safety measures[31] include several separate heat loops with the consumer being on the last loop, and keeping water

[31] To avoid contamination.

pressure of the main transport loop higher than the secondary steam so that no secondary steam can enter the loop in case of accidental leak in the water heating heat exchanger tubes (IAEA, 2017).

Figure 91 details the relationship of electric efficiency to extractable heat output for typical currently available nuclear reactors. The already low efficiency of nuclear power plants drops even further when heat is extracted. If heat is extracted at a temperature level of 100°C, efficiency drops from about 35% to 25%. Moreover, with high costs of transmission lines, which increase rapidly with distance and steam pressure, and the lack of an economic case for compressors in steam systems, transmission line length is typically kept as short as possible. With hot water, losses are less of an issue with 0.02%/km (IAEA, 2017).

Figure 91: Relationship of electric efficiency to extractable heat output for typical currently available nuclear reactors



Source: (IAEA, 2017).

Existing applications

In 2019, there were 79 nuclear reactors with a total of 750 reactor years of experience whose heat was used for desalination, district heating or process heat (WNA, 2024c).

Electric Power Research Institute (2022) provides a representative overview of 27 plants in 11 countries, which differ in terms of

- conditions of the heat transfer medium (phase, temperature, pressure, flow rate)
- distance from the NPP to the district heating network
- size and demand of the network
- fluctuations in network supply and demand due to plant outages and seasonal fluctuations.

All assessed plants were in areas with cold weather. Regular planned reactor shutdowns for refueling must be considered by reserve capacities. Hence, operation can only be guaranteed in a

setup with several units. Additional safety measures need to be complied with, including separate heat transfer loops (see above). Nuclear power is usually far away from large agglomerations; if hot water is transported over long distances, transmission losses are high. All units investigated were dependent on government subsidies.

For future applications, the use in cooling networks or for the provision of heat only is also proposed.

In Far East Russia (Pevek, Tschukotka), a nuclear reactor built on a vessel, the so-called Akademik Lomonosov is in operation since 2019 (Power Technology, 2021). The reactor has the following design features:

- Electrical capacity: 70 MW
- Thermal capacity: 300 MW
- Investment costs: 4.360 €/kW_{el}[32]
- Fuel cycle: 36 months
- Operation: since 2019[33]

According to Power Technology (2021), the nuclear reactor can also "be converted into a desalination plan with a capacity to produce 240,000 m_3 of freshwater a day".

According to Voice of America (2024), China is also advancing the development of floating nuclear reactors to "act as mobile 'power banks' at sea for stationary facilities and other ships". The website also notes that "Russia is the only country that currently has a floating nuclear power plant in operation".

Current plans for future application

As part of the "Finnish heating solution for the 2030's", a small modular district heating reactor is proposed (LDR, 2024) covering the following design features:

- Thermal power: 10-50 MWth
- Core exit temperature (CET): 130-155°C
- Fuel cycle: 24 months
- Potential application area: Finland
- Planned availability: demonstration by the end of the 2020ies, commercial application in the 2030ies
- Targeted investment costs: 1,500 €/kW

According to Finnish regulation, the requirement for a "5-kilometre exclusion zone around any nuclear plant" was lifted. Now, it needs to be demonstrated that "similar levels of safety with shorter distances [can be reached]" (WNN World Nuclear News, 2024).

[32] Based on estimated investment costs of 336 million $ (Power Technology (2021)) and an assumed exchange rate of 1,1 $/€.

[33] Foundations for the project were laid in April 2007. Full commissioning took place in May 2020 (Power Technology (2021)).

According to the manufacturer, operation conditions are less demanding since no external electricity supply or mechanical moving parts are required für ensuring the cooling. Therefore, simpler solutions are expected to be possible to comply with safety standards.

To put this solution into perspective with a renewable-based heat supply, investments costs for an electrode boiler in combination with an onshore wind power plant can be estimated at 650 €/kW and 1.000 €/kW, respectively, based on 2.000-3.000 full load hours.

Conclusion

Based on the presented examples, it can be concluded that based on current and potentially planned nuclear technologies, electricity and heat can be produced based on existing (district) heat and electricity networks.

However, nuclear power plants are usually located far away from big agglomerations; if hot water is transported over long distances transmission losses are therefore high. In turn, high temperatures of the extracted heat lead to a significant decrease of electrical efficiency. Small modular district heating solutions (LDR, 2024) are also expected to be able to provide heat on a smaller scale. However, existing safety zones had to be lifted.

It remains uncertain whether target investment costs will be reached. While the Finnish solution (LDR, 2024) aims at investment costs of 1,500 €/kW, already existing solutions (Akademik Lomonosov) exceed 4,000 €/kW. In contrast, investments costs for a renewable-based solution based on existing technologies, e.g., for an electrode boiler in combination with an onshore wind power plant can be estimated at 650 €/kW and 1.000 €/kW, respectively, based on 2.000-3.000 full load hours.

Furthermore, in case alternative heat sources are available, such as waste heat from other cogeneration plants, geothermal energy, waste incineration, and solar-thermal energy, these could affect the feasibility and profitability of a nuclear-based heat solution.

It also needs to be noted that all facilities in this review have some form of state support.

Eventually, realisation times for heating solutions may be long. While the Russian floating nuclear power plant took more than 10 years from foundations to final commissioning, the Finnish heating solution is expected to become commercially available only in the 2030ies.

2.9.4.2 Water desalination

In the literature (e.g. El-Emam et al. (2022)), different desalination technologies with different degrees of maturity are described, which in principle may be coupled with nuclear reactors

- Osmosis (Reverse/forward osmosis)
- Evaporation processes (e.g., multi-stage flash distillation (MSF), multi-effect distillation (MED), low temperature evaporation)
- Deionisation processes (e.g., electrodeionisation (EDI))

The coupling of desalination plants with nuclear reactors can be carried out in two ways:

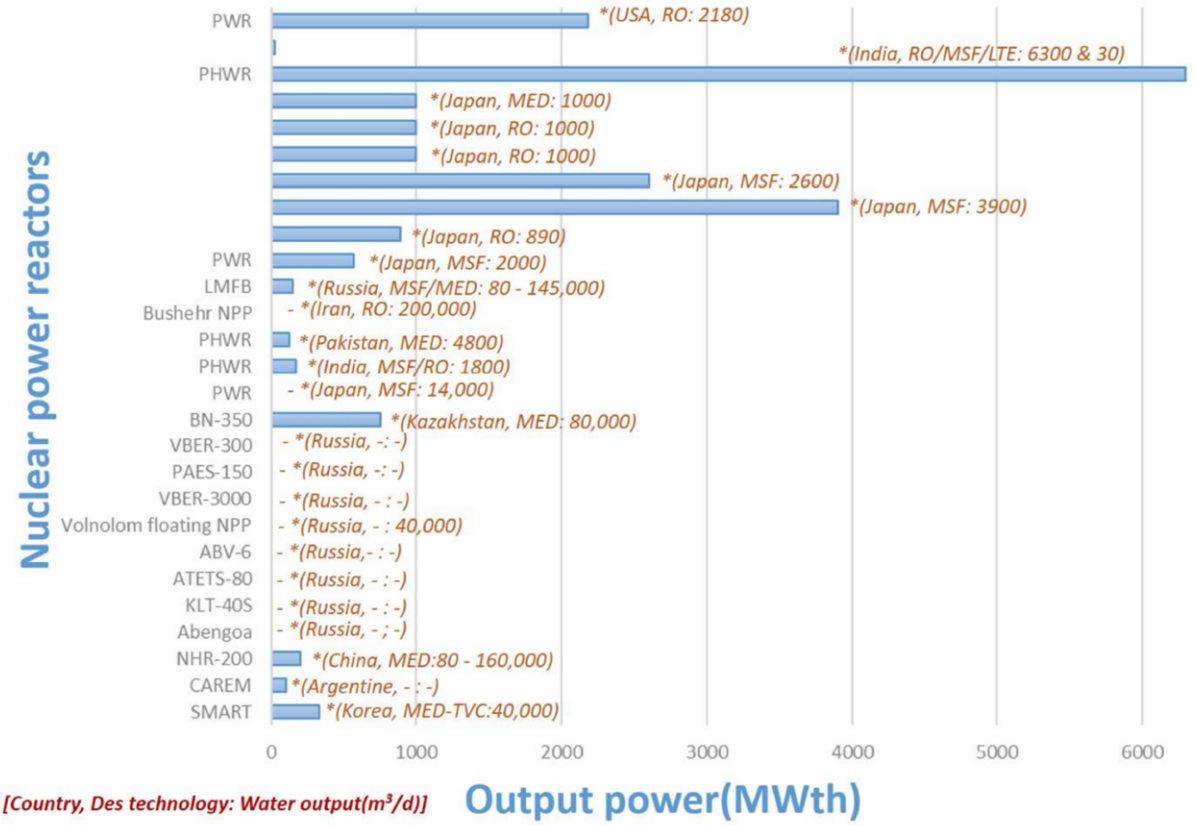
- Provision of pumping energy
- Thermal coupling (secondary steam cycle)

The International Atomic Energy Agency (IAEA) provides a software for conducting comparisons of different nuclear-based configurations with other energy carries – the so-called

DEEP (Desalination Economic Evaluation Program) software (IAEA, 2006). Several studies have been carried out so far based on the DEEP software.

According to IAEA, there are so far more than 200 reactor-years of operating experience with nuclear desalination, especially in Japan, India and Kazakhstan (IAEA). Khan and Orfi (2021) find that nuclear desalination projects encompass already 50 years in terms of concepts and implementation, „but could not receive wider applications“. Figure 92Figure 92: shows the status of nuclear desalination units including technology, water output and country. Largest output is provided by India, Japan, Kazakhstan, and the United States.

Figure 92: Status of nuclear desalination units, 2021



Source: Khan and Orfi (2021)

WNA (2024b) elaborates, inter alia, on new nuclear desalination projects in different countries. These include:

- South Korea (SMART): Coupling of electricity production and desalination
  - System-integrated modular advanced reactor (SMART)
  - Pressurized water reactor (PWR): 100 MW_{el}, 330 MW_{th}
  - Concept study (2011)
  - Study on economic feasibility of desalination using DEEP 5.1 (2015)
  - Basic design of the PWR finalized. However, further development was stopped due to missing orders. There is a memorandum of understanding with Canada for nuclear research partnership (WNN World Nuclear News, 2023a).

- Argentina (CAREM)
  - Pressurized water reactor (PWR)
  - Small modular reactor (SMR)
  - Demonstration project
  - 32 MW_{el}
  - Desalination is mentioned as one of the options for SMR
- China (Wang et al., 1994)
  - NHR-200-II (NHR: nuclear heating reactor)
  - 5 MW pilot plant
- Russia
  - Swimming and land-based nuclear power plants
  - E.g., based on reactors on ice breakers.
  - KLT-40S reactors (JSC, 2013)
    - Pressurized water reactor
    - 70 MW_{el}, 300 MW_{th}
    - Experience with water desalination in Aktau (Kazakhstan) (Panov et al.)
  - ABV-6 reactors
    - Theoretical simulation of a coupling with water desalination (Ud-Din Khan et al., 2015)
  - VBER-300 reactors
    - 325 MW_{el}
    - 917 MW_{th}

As concluded by Khan and Orfi (2021) above, nuclear desalination projects „ could not receive wider applications“ albeit their long history of experience. Furthermore, since desalination requires heat supply, concerns regarding investments costs, profitability and realisation times as discussed in section 2.9.4.1 also apply here.

In contrast, Prado de Nicolás et al. (2023) find that the operation of desalination plants on the basis of fluctuating renewable energy sources is possible. In case continuous desalination is required, a connection to the grid or the combination with batteries would be necessary. Prado de Nicolás et al. (2023) also conclude that different sizes of desalination plants are feasible depending on the plant design (renewable energies + desalination method). Eventually, desalination based on solar and wind is considered to be competitive with fossil fuels (Prado de Nicolás et al., 2023).

2.9.4.3 Production of hydrogen

2.9.4.3.1 Description of technologies and assessment of relevance

Many sources are available for the technology description of hydrogen based on nuclear power. The following is based on Matthes et al. (2020) and Pinsky et al. (2020).

Using electricity input from nuclear power generation

If electricity only is used as input from nuclear power generation, alkaline water electrolysis (AEL) and proton exchange membrane (PEM) electrolysis may be used. These are mature technologies in the commercialization and scaling phase. There are construction plans in many countries to realize the required hydrogen production and to satisfy the corresponding demand.

For this technology, electricity and water are required as inputs to produce hydrogen. PEM electrolysis has higher capital costs due to the use of rare metals. However, PEM can handle fluctuations more easily. In contrast, AEL is cheaper and more efficient. In most cases, this technology is chosen.

Using electricity and heat from nuclear power generation

In cases electricity and heat are used from nuclear power generation, the thermochemical technology solid oxide electrolyzer cell (SOEC) is used.

The technology is not yet mature and will not be available at large scale until the 2040ies. The technology requires high temperature heat which cannot be produced by currently available reactor types. This technology is therefore not assessed in the further analysis.

Interim conclusion

In general terms, nuclear power plants compete with renewable electricity for the provision of electricity for the electrolysis. The two types of electricity supply differ in terms of their supply profile: For a given electrolysis capacity, nuclear power plants can support a high utilization via a constant electricity supply. With RES-E supply is intermittent and capacity utilization is lower, compared to the same installed capacity of nuclear power. Capacity utilization of the electrolysis can be increased by increasing (oversizing) RES-E capacity and including electricity storage into the system. This trade-off is analysed in the following section.

2.9.4.3.2 Quantitative assessment of hydrogen production using nuclear power

To analyze the competitiveness of hydrogen production based on nuclear power generation we take the following steps:

- The analysis is based on an existing tool that allows to compare the delivery costs of hydrogen and other hydrogen molecules for different production countries and demand regions in the world.
    - The tool is based on country-specific data on RES-E generation profiles for PV, onshore and offshore wind that are derived from a geospatial analysis (see Mendelevitch et al. (2024) for an easily accessible description of the tool, and Heinemann, Mendelevitch, Haller, et al. (2024) for the tool itself, as well as Heinemann, Mendelevitch, Krieger, et al. (2024) for a detailed documentation of assumptions and methodology). Also, investment costs into RES-E technologies are country-specific, reflecting local experience, labor, and technology costs. Costs and parameters for other technologies in the hydrogen chain are generic for all countries.

- Based on the potential generation profiles, and on investment and variable costs of the different components, the tool calculates the optimal capacities to produce a MWh of final production. Transportation and reconversion are not part of the optimization.

- We extend this tool by adding additional production countries, namely, France, UK, and Finland.
- We introduce a new technology: nuclear; with respective investment costs, and further technology parameters, in line with the analysis performed in chapter 4.
- Profiles for nuclear power generation are generated to align with the average country-specific capacity factors reported in chapter 4.
- Given the long lead times in the construction of nuclear power plants, we deviate from overnight capital costs as the basis for investment costs, but account for the contingency required during the construction phase based on the same WACC that is applied for all other capacities in the respective county.

Table 43: Input parameters for comparison of hydrogen production based on nuclear power vs. renewable energy sources

Country	Unit	Finland	France	UK	USA	USA	Argentina
Reactor technology		Conv. reactor	Conv. reactor	Conv. reactor	Conv. reactor	SMR	SMR
Total CAPEX (overnight)	[$MEUR_{2023}$/MW_{el}]	7.1	8.3	15.1	14.5	18.6	29.2
Total CAPEX (incl. conting.)*	[$MEUR_{2023}$/MW_{el}]	10.7	14.9	21.0	18.1	19.5	145.4
WACC	[%]	5%	7%	5%	5%	5%	22%
Construction time	[years]	17.8	17.0	14.8	10.4	3.0	14.0
OPEX	[$MEUR_{2023}$/MW_{el}/a]	0.1	0.1	0.1	0.1	0.1	0.1
Load factor	[%]	93%	77%	75%	91%	91%	75%
Lifetime	[years]	60	60	60	60	60	40
Electric efficiency	[%]	37%	37%	37%	33%	29%	29%
Fuel costs	[EUR_{2023}/MWh_{el}]	7.4	7.4	7.4	8.3	9.5	9.5

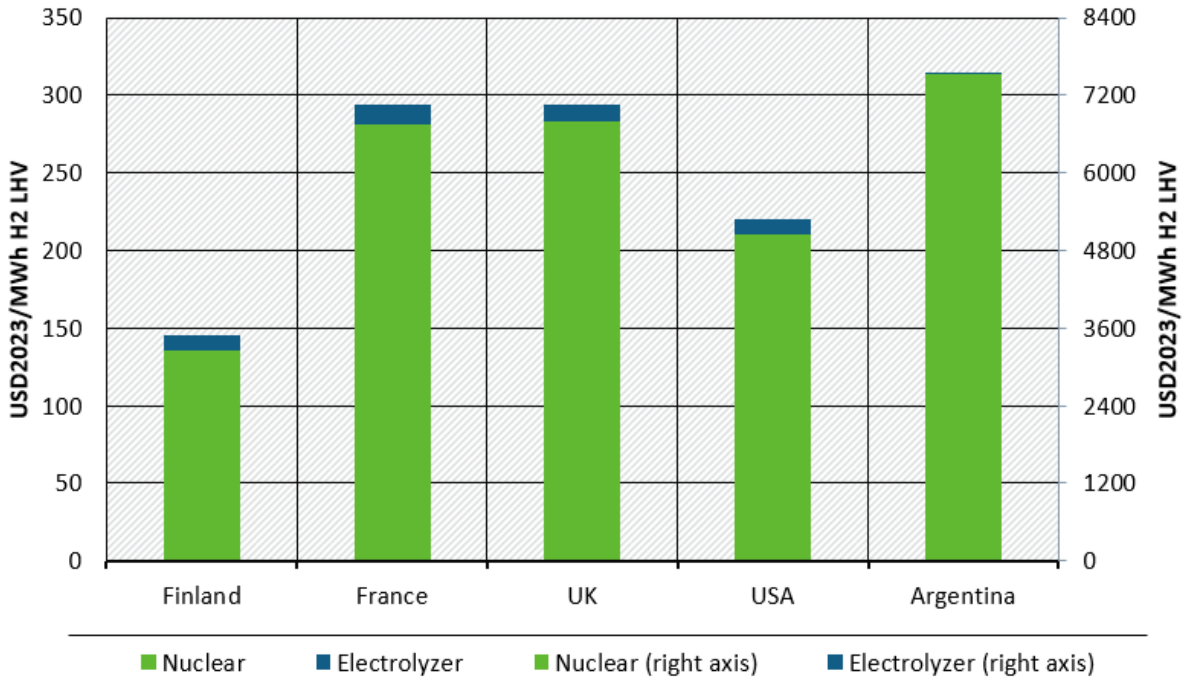
Note: * To calculate CAPEX including contingency, we assume that equal share of overnight CAPEX has to be borrowed during the construction time and imply lending costs according to the respective country WACC. Decommissioning and storage costs are not included.

Source: Own compilation, Öko-Institut.

Nuclear power generation-based hydrogen production vs. RES-E based production

Figure 93 shows results on levelized costs of hydrogen (LCOH) using power from a newly constructed nuclear power plant as electricity input. Respective country-specific input parameters for nuclear power generation are detailed in Table 43, and electrolyzer costs are detailed in Heinemann, Mendelevitch, Krieger, et al. (2024). In line with lowest CAPEX and lowest WACC, LCOH are lowest in Finland, at about 150 USD_{2023}/MWh H_2 LHV in 2040. USA has LCOH of about 220 USD_{2023}/MWh H_2 LHV, while UK and France are both at about 290 USD_{2023}/MWh H_2 LHV. Extremely high investment costs coupled with extra-ordinary WACC, yield LCOH at prohibitive 7.600 USD_{2023}/MWh H_2 LHV in Argentina. While there are many different forecasts for LCOH, these levels are clearly of the target zone. (Frieden & Leker, 2024) published a comprehensive review of forecasted LCOH. They find a global average of about 140 USD_{2023}/MWh H_2 LHV for 2030, and a decrease to 90 USD_{2023}/MWh H_2 LHV by 2050. Nuclear electricity-based electrolysis is clearly of this range in any of the assessed countries.

Figure 93: Levelized costs of hydrogen with nuclear power as input for electricity for Finland, France, UK, USA (left axis) and Argentina (right axis), in 2040

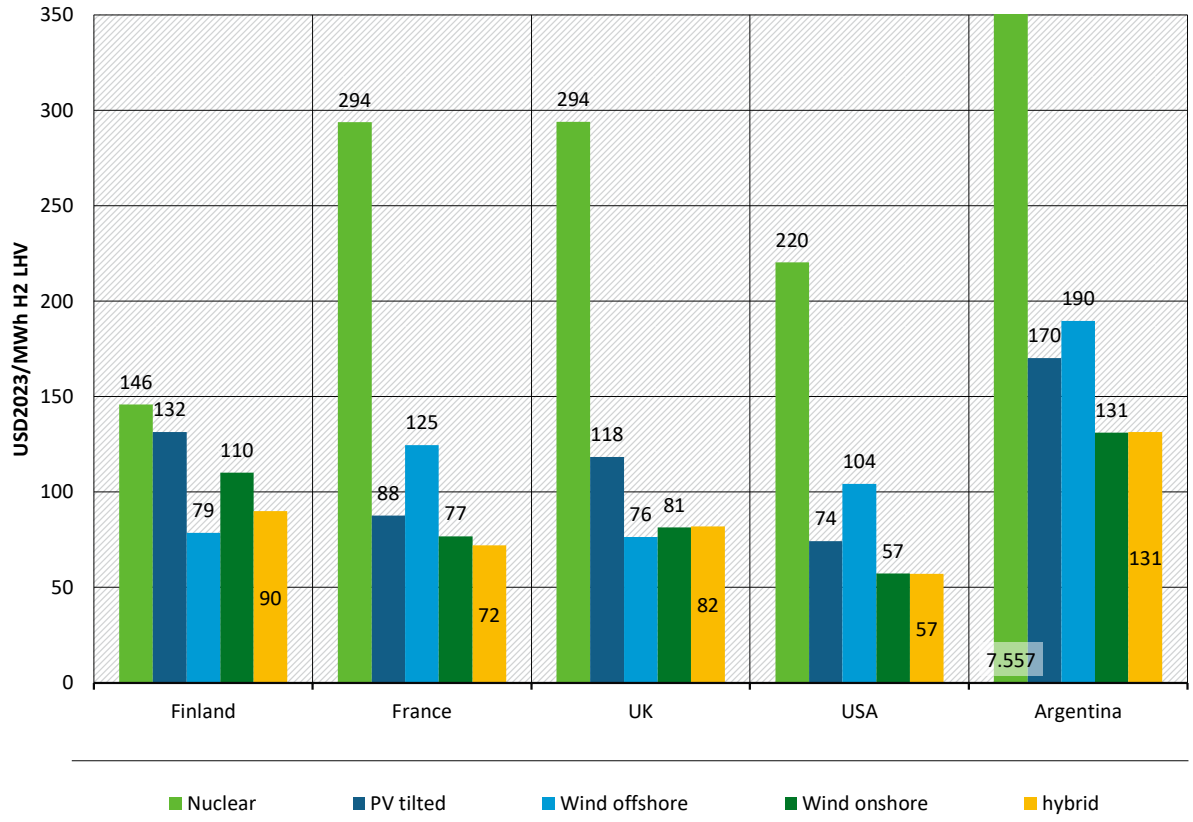


Note: Water costs are not included here, but according to calculation with PtX-BOA (Heinemann, Mendelevitch, Haller, et al., 2024), they are in the range of 0.1 USD_{2023}/MWh H_2 LHV, even if it water comes from a new saltwater desalination plant.
Source: Own calculation, Öko-Institut.

However, for none of these countries, nuclear-based hydrogen production is the cheapest option. Figure 94:Figure 94 shows results of the comparison of levelized costs of hydrogen using different RES-E sources and nuclear power as electricity input for Finland, France, UK, USA, and Argentina, in 2040. Nuclear power is the most expensive option to produce hydrogen in all five countries. In Finland, where nuclear electricity generation is cheapest compared to the other countries, this option is still almost twice as expensive as the cheapest option (wind offshore), and 60% more expensive than a hybrid of PV and wind onshore. For the other countries, the gap between the cheapest renewable option and nuclear electricity is even bigger, with LCOH four times higher, if nuclear is chosen as electricity source. Due to high WACC, LCOH are generally

higher in Argentina, compared to the other four countries, even if Argentina has much more favorable RES-E potentials.

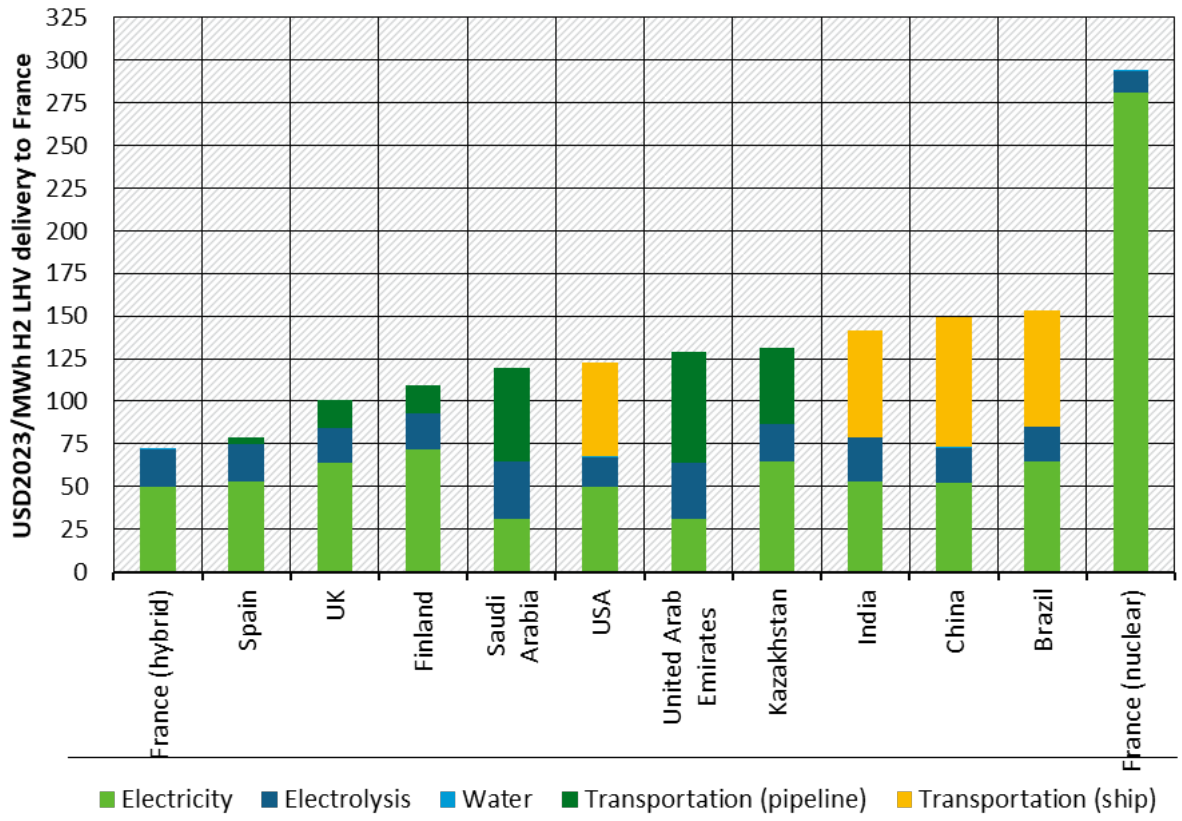
Figure 94: Comparison of levelized costs of hydrogen using different RES-E sources and nuclear power as electricity input for Finland, France, UK, USA, and Argentina, in 2040



Source: Own calculation, Öko-Institut.

While electricity cannot be easily stored and transported, except if origin and destination are connected via grid, hydrogen is expected to be shipped and internationally traded in the long term. Therefore, domestic production will be in competition with imports from around the world. The PtX-BOA tool (Heinemann, Mendelevitch, Haller, et al., 2024) allows to compare delivery costs for over 34 production countries to nine destination countries, including Germany, and France. Figure 95 illustrates the delivery costs of hydrogen to France for the 10 cheapest exporting countries and compares it to domestic production based on a hybrid system and based on nuclear power. Domestic production based on renewable electricity is most competitive, and cheaper than deliveries from Spain, Saudi Arabia, the USA, India, or China. Nuclear-based LCOH in France are about twice as high as delivery costs from India, China, or Brazil, and four times higher than deliveries from Spain.

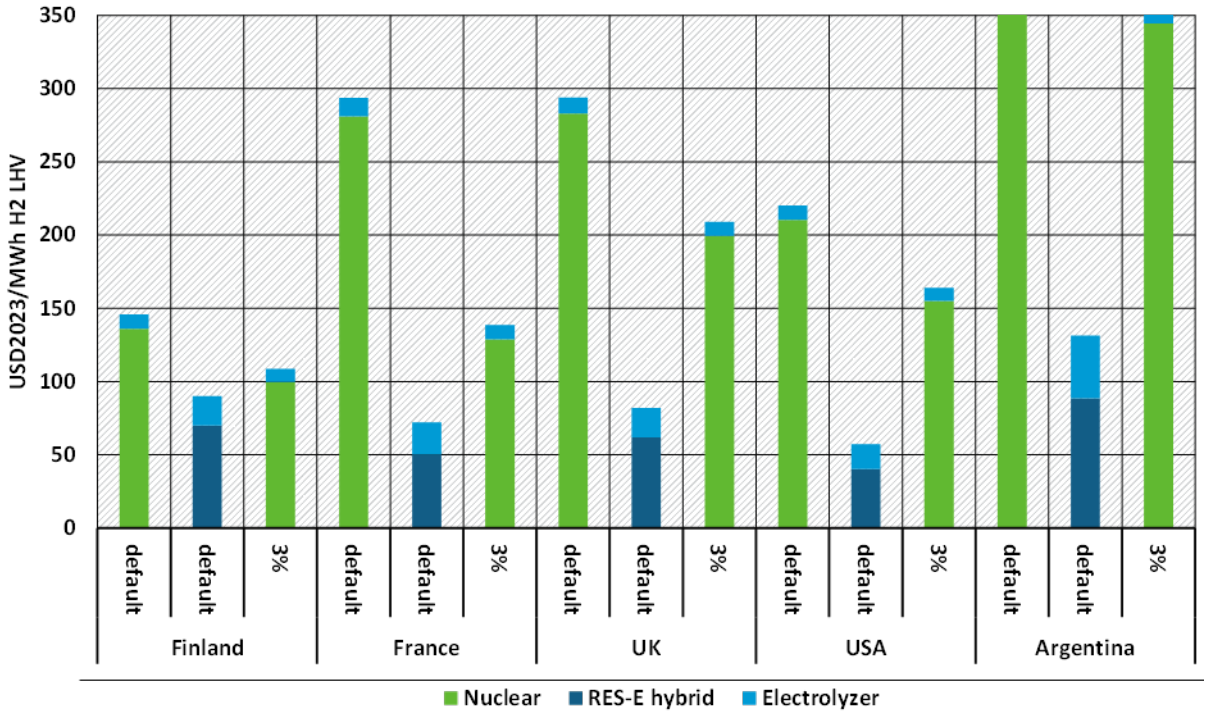
Figure 95: Comparison of levelized costs of hydrogen delivered to France from different countries, and hydrogen based on electricity from nuclear, in 2040



Source: Own calculation, Öko-Institut.

Costs of electricity supply is the largest cost component in LCOH based on nuclear, with a share exceeding 90% for all countries (cf. Figure 95). In combination with long lead times, results are sensitive to assumptions regarding the WACC. Figure 114 compares levelized costs of hydrogen based on nuclear electricity production with default WACC values and 3% WACC as a sensitivity to assess a situation where WACC can be substantially lowered, e.g., via state-based guarantees or loans. For all five countries, LCOH are still significantly lower with electricity produced by a hybrid RES-E system compared to nuclear-based power generation. The differential in LCOH is about 100% for France, and even higher for the other countries. In Finland, the country with the cheapest nuclear-based electricity production, LCOH are still about 20% higher for nuclear-based vs. RES-E-based production.

Figure 96: Comparison of levelized costs of hydrogen based on nuclear electricity production with default WACC values of 3%



Note: The 3% WACC applied to both the contingency and the net present value cost minimization underlying the optimization of capacities for the electricity generation and the electrolysis unit.
Source: Own calculation, Öko-Institut

Conclusion

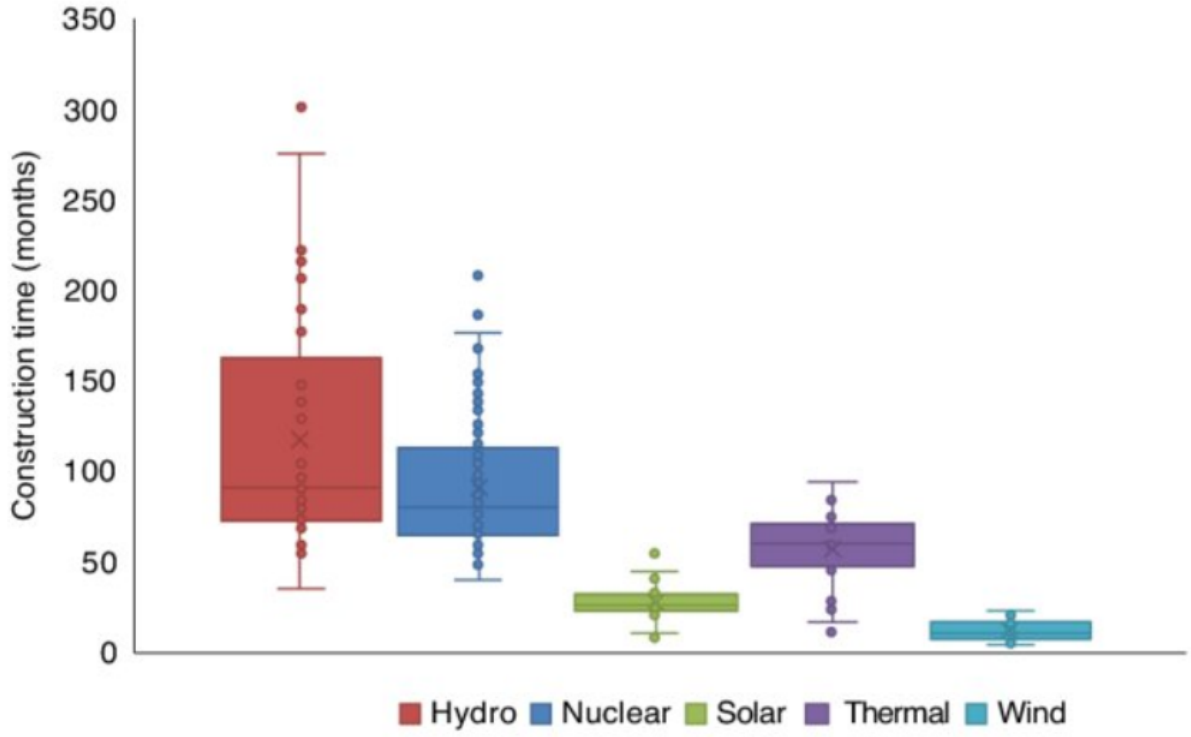
From the analysis above, we conclude that nuclear-based hydrogen production is not competitive with RES-E-based production in the assessed countries, from a 2040 perspective, even if only domestic production is considered. Given that hydrogen is expected to be an internationally traded commodity, domestic production also competes with production in other countries with even more favorable RES-E generation conditions, and with even lower costs of delivered hydrogen. Therefore, potential investments in nuclear power generation capacities that plan to supply electricity for electrolysis as their business case are at risk of becoming stranded assets in a future international hydrogen and PtX market.

Production routes for hydrogen that rely on high temperature heat inputs do not play a role in assessing the merits of nuclear-based hydrogen production because high temperature heat will not be available from nuclear power until 2040.

2.9.5 Realization time of different power technologies

While the previous subsections have focused on the integration of nuclear power into the power system, realization times are also an important aspect related to the discussion about their contribution to the decarbonization of the power system. The realization times, i.e., the time that must be considered for the planning and construction of abatement technologies play a decisive role in achieving the goals of the Paris Agreement.

Figure 97: Construction time for different power generation technologies



Source: Sovacool et al., 2020

Sovacool et al. (2020) analyse the construction times of various power generation technologies (Figure 97). The figure shows that the construction time of hydro is longest followed by nuclear power plants. Thermal power plants rank third, while dominant renewable energy sources (solar and wind) have the lowest installation times. The uncertainty range can be considerable, too. While average construction time for hydropower plants is 120 months (10 years), it ranges from less than 50 months (4 years) to 280 months (23 years). While average construction time for nuclear power is just below 100 months (8 years), it ranges from below 50 months (4 years) to almost 200 months (15 years). Against the background that the power system needs to be fully decarbonized by 2050 if climate targets are considered, it can be concluded that both hydropower and nuclear power are not favourable options for swiftly decarbonizing the power system. Thermal power plants have an average construction time of 60 months (5 years), with a range from one year to about 8 years. Based on construction time, thermal power plants may play a limited role, provided that they are based on sustainable biomass (which is limited) or on hydrogen. Thermal power plants based on natural gas or coal are certainly not an option for decarbonizing the power system. Main renewable energy sources (solar and wind) feature rather short construction times (around 3 years and 2 years, respectively) with a narrow uncertainty range. It can thus be concluded that solar and wind could play a major role in decarbonizing the power system.

Furthermore, two issues related to time scales are relevant to understand the role that nuclear power can play on a pathway towards a net zero energy system. The first issue is related to construction times. As discussed above, nuclear power plants projects exhibit lead times of 8 years and beyond, with a well-documented record of unexpected delays and cost overruns, onshore wind and large-scale photovoltaics projects deliver in less than five years, with photovoltaics projects in many cases on the even lower end. Depending on the distance to shore and other terrain conditions, offshore wind projects can also have longer lead times, if new grid

access points and connections need to be installed, with total lead times also coming to 10 years in such cases. Taking these lead times into account when designing the pathway towards a net zero energy system, relying on nuclear power requires a much higher degree of planning and coordination, as the decision to build the plant is potentially made in a totally different energy system, energy policy, and climate policy environment as the one that will prevail once the project is operational and start delivering electricity. Similarly, the risk profile of a pathway that relies on nuclear power is different from one that is built on renewables and flexibilities. With nuclear power, single projects are planned to deliver a significant share of electricity by a certain year, once they are operational. However, if a project fails, making up for the emerging supply gap through new nuclear projects will not be possible due to the mentioned lead times. Closing the gap with wind and photovoltaics might be possible in terms of planned electricity generation, but the system might not be equipped with the necessary flexibilities to accommodate this generation. If this is the case, dispatchable fossil units that were planned for shutdown could be kept online, in order to close the gap. This will counteract decarbonization efforts and put staying in planned carbon dioxide emissions budgets at risk.

The second issue related to timescales are the economic lifetimes of the different generation technologies. While wind and photovoltaics are typically designed for about 25 years of operation, nuclear power plants are designed for 60 years. This might sound like an advantage at first glance, but it could be a disadvantage on the system level: with the shorter lifetimes, wind and photovoltaics units can go through two innovation cycles, benefiting from increased efficiency and reduced environmental impacts. Moreover, parameters of new units can be adjusted to the overall needs of the system, with east-west orientation for photovoltaics instead of the standard south orientation, or weak-wind turbines, being just two prominent examples. Such adjustments are not possible with nuclear power generation.

3 Life cycle analyses of nuclear power

The life cycle is understood as the consideration of a product system as successive and interconnected stages of a product system from raw material extraction or raw material production to final disposal. The analysis includes all material and energy inputs as well as GHG emissions, raw material consumption, land consumption, water consumption, toxic emissions, health effects, accidents and conventional or nuclear waste to be treated.

In general, the results of life cycle emissions and life cycle costs are heavily dependent on methodological and data-related specifications. Against this background, the following section describes in more detail the definitions of system boundaries and investigation framework, impact categories and data sources and methods to be used.

In section 3.1 we introduce the corresponding steps in the nuclear life cycle chain. In section 3.2 we describe the methodology use to evaluate the corresponding life cycle chains. Sections 3.3 to 3.11 describe the different life cycle steps in more detail and list the chosen input data as well as their corresponding uncertainties as far as relevant.

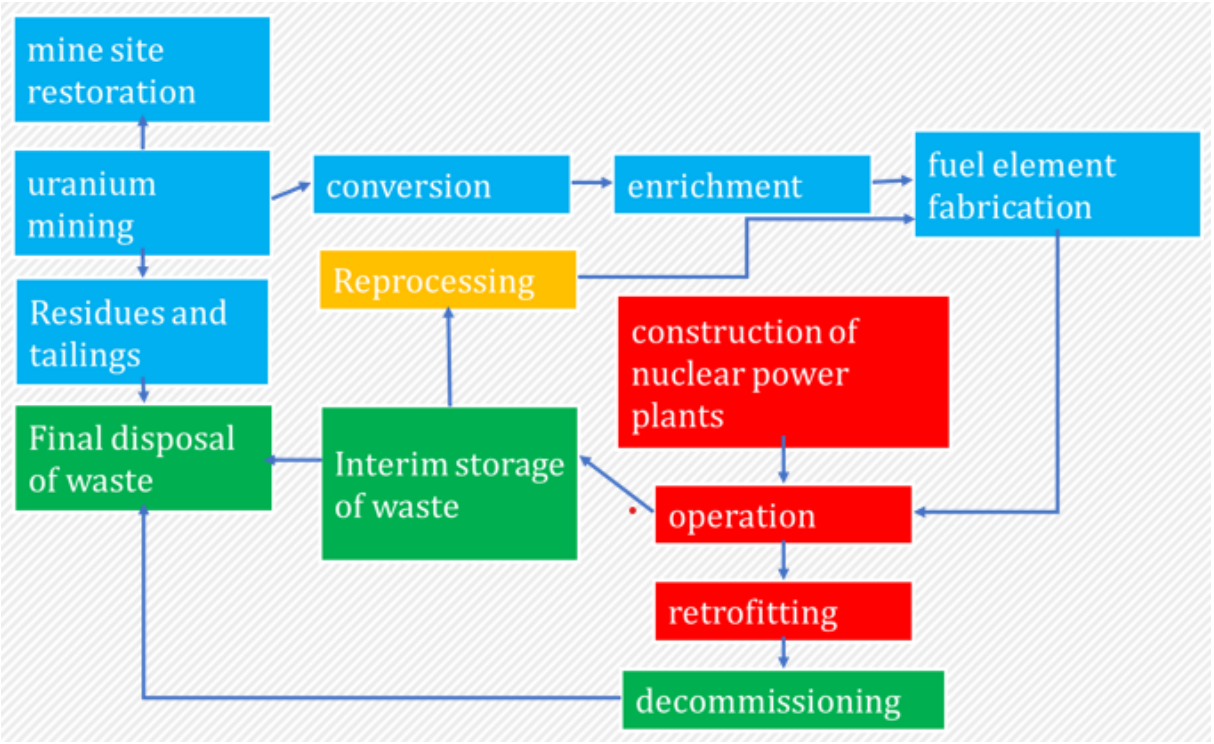
Section 3.12 discusses the results of the different life cycle chains. In this study, a clear focus is given on the GWP, other environmental impacts will only be discussed to a limited degree. Full results for all life cycle chains and all environmental impacts are given in Appendix B and C.

Finally, there are aspects related to the life cycle of nuclear power that are not sufficiently covered by current LCA methodology. We will discuss such aspects exemplarily in section 3.13 for severe accidents in nuclear power plants and in section 3.14 for proliferation aspects related to the nuclear fuel cycle.

3.1 General description of the nuclear power life cycle chain

The scope of the study covers the extraction of uranium as an energy source, its use in nuclear power plants and its final disposal after technical energy utilisation. The main process stages are analysed and the material and energy resources used and the emissions released, land conversion and occupancy, water consumption and toxic emissions are balanced for each stage. The aim is to calculate the environmental impacts – in particular the GHG emissions – for the generation of 1 kWh_{el} of electricity from nuclear energy into an electricity grid for individual modules of the life cycle chain. The basic life cycle chain of electricity generation from nuclear energy is shown in a simplified diagram in Figure 98.

Figure 98: Process stages of the nuclear energy life cycle chain



Pre-chain stages are shown in blue, stages after operation in green, the transport between the stages is not shown. Own illustration, Öko-Institut

The life cycle chain consists of the following process chain elements, which are presented below in as complete an overview as possible:

1. uranium mining and yellowcake production (construction, operation, dismantling and remediation of corresponding facilities),
2. conversion of uranium into uranium hexafluoride (construction, operation and dismantling of the plant),
3. enrichment in enrichment plants (construction, operation, and dismantling),
4. fabrication of fuel elements from uranium oxide (construction, operation and dismantling of the plant),
5. construction of nuclear power plants,
6. operation of nuclear power plants,
7. retrofitting (as part of ageing management, but also in particular in relation to a lifetime extension),
8. dismantling of the reactor,
9. interim storage of different types of radioactive wastes (construction and operation of facilities),
10. if applicable, reprocessing (construction, operation and dismantling of facilities),
11. if applicable, mixed oxide fuel assembly production (construction, operation and dismantling of the plant),
12. conditioning (construction, operation and dismantling of conditioning facilities, in particular for spent fuel elements or waste from reprocessing),
13. construction and operation of deep geological repositories (including their construction) and, if applicable, other repositories for low- and intermediate-level radioactive waste.

Between these different process steps, transportation of material is necessary:

14. transport of natural uranium from mines to conversion facilities,
15. transport of the uranium hexafluoride from conversion facilities to enrichment plants,
16. transport of the uranium oxide from enrichment plants to fuel element production,
17. transport of the fuel elements to the nuclear power plant,
18. if applicable, transport of spent fuel elements to reprocessing plants,
19. if applicable, transport of plutonium from reprocessing to fuel assembly production,
20. if applicable, transport of the mixed oxide fuel elements to the nuclear power plant,
21. transport of spent fuel elements to interim storage facilities,
22. transport of low- and intermediate-level radioactive waste to interim storage facilities,
23. transport to the final repository (transport containers and energy requirements for means of transport).

3.2 Methodology for LCA

3.2.1 Foundations and basic assumptions for key aspects

3.2.1.1 Methodological principles

The methodology of the study is based on a life cycle analysis of the environmental impacts of the individual life cycle modules and the aggregation of the emissions of these modules along the entire life cycle. Basically, the methodology is guided by the specifications of the EU Commission for the Product Environmental Footprint (PEF) as well as the international standards for Life Cycle Assessment (DIN EN ISO 14040 and DIN EN ISO 14044) and Product Carbon Footprint (PCF).

The methodology was implemented in accordance with the Commission Delegated Regulation of 4 June 2021 (EC, 2021). In addition, reference is made to the European Commission's Recommendation 2013/179/EU of 9 April 2013 (EC, 2013) on the use of common methods to measure and communicate the life cycle environmental performance of products and organizations and the Product Environmental Footprint Guide contained therein, although ISO 14067 or ISO 14064-1 can also be applied as an alternative. The standards and regulations mentioned above, as well as other standards, are discussed below in order to derive the resulting specifications for this study.

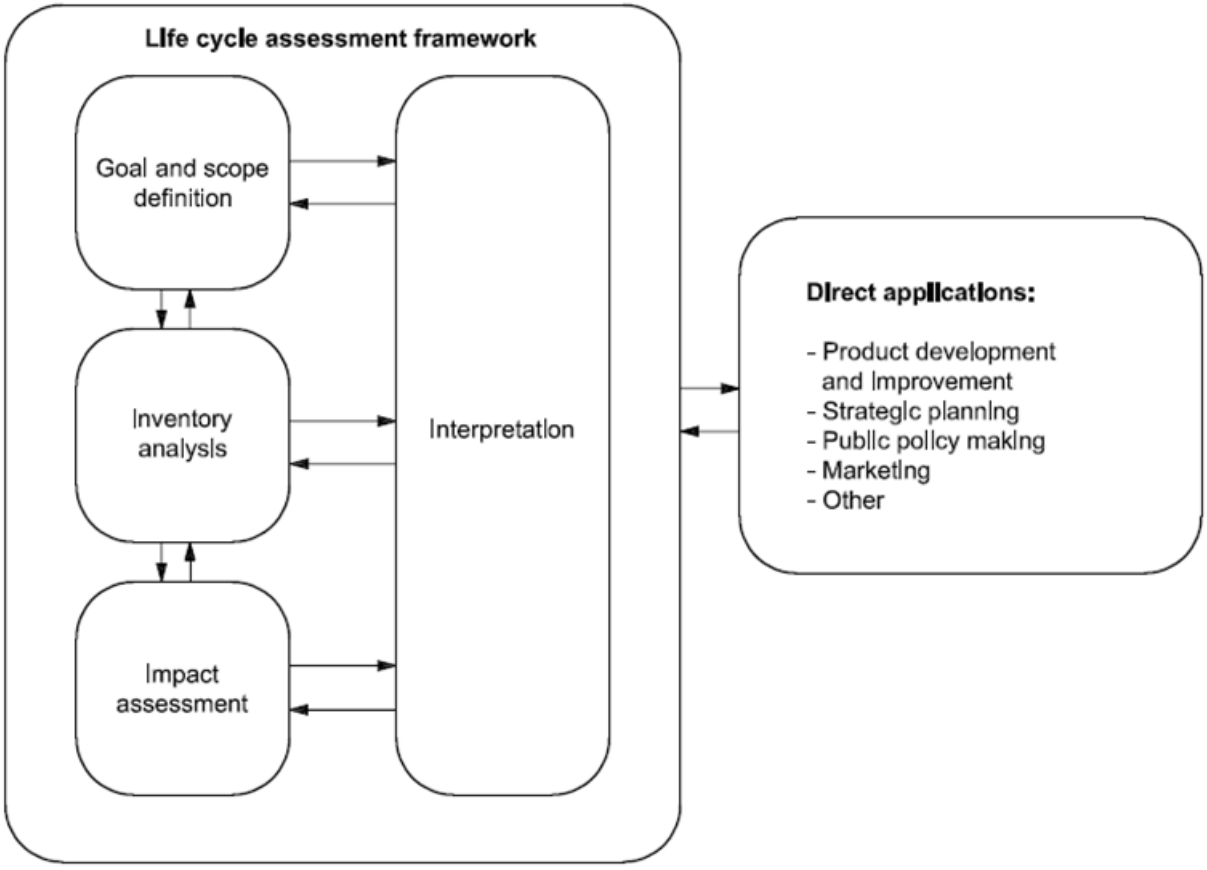
- (DIN, 2019a) (latest edition February 2019) relates to the carbon footprint of products and contains requirements and guidelines for quantifying the Product Carbon Footprint (PCF). The standard's fundamental orientation towards the entire life cycle and the reference to a functional unit, the fundamental procedural requirements and the reporting requirements are very closely related to the standards for product-related life cycle assessments according to DIN EN ISO 14040 and 14044 (see below). However, DIN EN ISO 14067 deals with specific issues that are particularly relevant for calculating the PCF. In particular, it contains specific requirements for the methodological treatment of fossil and biogenic carbon, biogenic carbon in products, the treatment of emissions from electricity generation (in particular avoiding double counting of green electricity and treatment of own production), land use and land use change, and emissions from aviation.
- (DIN, 2019b)[34] (last edition June 2019) contains requirements and instructions for the quantitative determination and reporting of greenhouse gas emissions at the organizational

[34] Part 2 of this standard refers to rules for the accounting of GHG reductions from climate protection projects, while Part 3 defines the requirements for the verification of GHG declarations in connection with GHG balances, GHG projects and the carbon footprint of products.

level. Since the GHG emissions in this study are to be related to the product 'electricity', this standard is not considered to be a suitable basis.

- (DIN, 2021b) and DIN (DIN, 2021a) (last editions in February 2021) are the currently valid standards for the internationally standardized life cycle assessment (LCA) method that has been in place since the mid-1990s. While DIN EN ISO 14040 describes the principles and framework conditions of product-related life cycle assessments, DIN EN ISO 14044 defines extensive requirements and provides comprehensive guidance on many issues (such as the allocation of co-products). The standards define a structured, process-oriented approach in four phases (see following table)

Figure 99: Phases of an LCA



Source: DIN EN ISO 14040:2021-02

In its communication published in spring 2013, the European Commission proposed EU-wide methods for measuring the environmental performance of products and organizations. In this communication, the member states and the private sector are recommended to use these methods. The starting points for this proposal were, in particular, the observation that the lack of reliable information is preventing the full potential of green markets and green growth from being realized and that the non-uniform methods for collecting and communicating product-related environmental performance data are creating an uneven playing field in the market. The European Commission's proposal essentially includes two methods for measuring the environmental performance of products or organizations: Product Environmental Footprint (PEF) and Organization Environmental Footprint (OEF). Member States, companies, private organizations and the financial sector are encouraged to apply these methods on a voluntary basis. Following a pilot phase (2013 to 2017) and a transition phase (2018 to 2020), on 16

December 2021 the European Commission again published a recommendation on the use of environmental footprint methods to measure and disclose the environmental performance of products and organizations along their life cycle (C(2021) 9332 final), which is essentially the same as the 2013 recommendation, but takes into account the current political framework at EU level (for example, through references to the Green Deal, the Circular Economy Action Plan, the Consumer Agenda, etc.). Furthermore, Annex I of the recommendation contains a revised method for calculating the PEF. The relevant changes to the previous version include the establishment of a benchmark, various modelling requirements, rules for the normalization and weighting of the impact indicator results, guidelines on the inclusion of biodiversity, the improvement of some impact assessment methods with a particular focus on toxicity-related methods[35], the establishment of characterization factors based on REACH data, and a type of guideline for PEF-compliant data sets.

In general, the PEF method closely follows the principles of the LCA standards DIN EN ISO 14040 and 14044 described above. However, these standards allow methodological freedom in many aspects, for example in the allocation of co-products and cross-system secondary raw materials, or in the selection of impact assessment models and methods for standardizing, ordering and weighting the results of the impact assessment. The PEF method provides binding specifications for precisely these points, with the aim of making the results more reproducible and comparable.

The EU Commission's proposal with the PEF method triggered some vehement criticism, particularly at the beginning (see, for example, (Finkbeiner, 2014) and the response by (Galatola & Pant, 2014)). The debate centered primarily on the terminology that deviates from DIN EN ISO 14040 and 14044, the implementation of a weighting of impact indicator results and the specification of impact assessment methods, some of which have not been sufficiently tested and/or are considered uncertain. In addition to these method-related objections, the lack of concrete or transparent implementation plans for the PEF on the part of the EU Commission was criticized in terms of policy; it is unclear whether there should be voluntary or mandatory labelling of products on the basis of the PEF, and the link with the existing product-related environmental policy and environmental labels is still open.

Even though some of the criticisms levelled at the PEF method still exist today, the methodology used for this study is strongly aligned with the PEF method. In particular, the binding specifications, such as the selection of impact indicators, represent an advantage and can ensure compatibility with other studies. In addition, the orientation towards the PEF method also facilitates the use of software models and available data sets from life cycle assessment databases.

However, there are also specifications in the PEF method that contradict the principles pursued in this study. For example, according to the PEF method, capital goods (including infrastructure) and the associated end of life should be excluded unless previous studies show that they are relevant. For this reason, deviating determinations were made for all methodological details for which the PEF method imposes insufficient or inappropriate requirements, and these deviations were documented transparently.

3.2.1.2 Scope and system boundaries

Firstly, the basic technical modules and relevant variants were described qualitatively. This description was followed by a discussion of the sensitive parameters within the process stages.

[35]These methods refer to Human toxicity – carcinogenic effects; human toxicity – non-carcinogenic effects; ecotoxicity freshwater, water use, land use, resources and particulate matter

This ensured a preliminary assessment and a level of knowledge very early on in the project in order to determine a sensible selection of modules for further consideration. To support this, a graphical representation was also created for the various impact categories, in which the individual technical stages of the life cycle chain and associated relevant parameters are clearly recognizable.

It was checked whether the key data relevant to GHG life cycle emissions is up-to-date and complete. In line with standard life cycle assessment practice, all data was stored using metadata with data quality indicators. This ensures a high level of transparency and reproducibility. In particular, the data was classified according to its technological, geographical and time-related representativeness. Furthermore, a distinction was made as to whether the data originated from an independent and externally audited study; in the case of individual data, the type of data collection was labelled (measured, calculated, estimated, etc.).

In summary, data quality requirements were defined as follows:

Table 44: Definition of requirements for the data quality of life cycle assessments

Aspect	Explanation
Time-related coverage area	Describes the age of the data that may be used
Geographical coverage	Defines the geographical area for which data should be collected for process modules
Technological coverage	Specifies the specific technology or a specific technology mix
Precision	Measure of the range of variation of values for all specified data
Completeness	Describes the percentage of an energy or material flow that is measured or estimated
Representativeness	Describes as a qualitative assessment the degree to which the amount of data used reflects the true population
Consistency	Describes, also as a qualitative assessment, whether the method of the study is applied consistently to the various components of the analysis
Reproducibility	Describes qualitatively the extent to which an independent preparer can reproduce the data values given in the study using the documented methods and data values
Data uncertainty	Takes into account the uncertainty of the information in the data, models and assumptions used

Source: own compilation based on DIN EN ISO 14044:2021-02

According to a review of numerous LCA studies by (Sovacool, 2008) , uranium mining and processing is responsible for 38% of GHG emissions, dismantling for 18%, operation for 17%, final disposal for 15% and the construction of nuclear power plants for 12%. A special focus was therefore also placed on the upstream chain emissions from mining and processing, as these appear to be very relevant in quantitative terms. At the same time, the ecoinvent database (Wernet et al., 2016), for example, shows that upstream emissions in particular are inaccurate for life cycle emissions. In addition, most of the data in ecoinvent still comes from version 2 of the database and is therefore based on data collected between 1995 and 2002. The data for uranium mining in the USA dates back to the early 1980s and does not include chemicals for leaching, for example, although in-situ leaching is now the most common mining method (United

Nations Economic Commission for Europe [UNECE], 2021). Proposals for updating and sourcing data have been developed to address data gaps.

For technologies that are still in the future or that are in an early planning and development stage (repository mines, small modular reactors, etc.), data was evaluated on the basis of knowledge of publicly available reports from operator organizations (national and international), committees and scientific literature, and corresponding module data was provided.

3.2.1.3 Data selection criteria and data sources

Existing LCA studies on nuclear energy, LCA studies from the scientific literature, from companies and from relevant organizations and relevant databases were used as data sources, as well as technical reports documenting various life cycle elements. More recent LCA studies were used in particular, as some of these have compiled and published much more up-to-date data.

The following databases were used for the analysis:

- Ecoinvent life cycle assessment database of the Swiss 'Centre for Life Cycle Inventories', an internationally recognized database containing data for areas such as energy (electricity, oil, coal, natural gas, biomass, biofuels, bioenergy, hydropower, nuclear energy, photovoltaics, wind power, biogas), materials, waste disposal (waste incineration, landfill, wastewater treatment), transport and metal processing. Compared to other databases, ecoinvent has the advantage that the datasets are described very transparently using metadata.
- GEMIS (Global Emissions Model of Integrated Systems) Version 5.1 (Internationales Institut für Nachhaltigkeitsanalysen und -strategien [IINAS], 2023), a computer model for life cycle and material flow analysis with an integrated database for energy, material and transport systems, originally developed by the Öko-Institut and now operated by IINAS and providing open-access data.
- GaBi LCA database from (Sphera Solutions, Inc [sphera], 2025), with free access to NREL's U.S. Life Cycle Inventory (LCI) database, which in turn has collected very detailed data sets on the environmental impacts of power generation technologies. This database provides a cradle-to-grave accounting of the energy and material flows associated with the manufacture of a material, component or assembly. The GaBi database also contains the official free data for life cycle analyses for the environmental footprint published by the European Commission. The disadvantage of the GaBi database, however, is that the basic data sets and the free data sets are shown in the database as a 'black box', so that checking the system boundaries of individual data sets is very time-consuming or even impossible.

Data that could not be found in the literature or in the databases had to be collected for the study. Depending on the type of data, this was done by contacting plant operators, manufacturers of life cycle elements or by contacting associations such as the World Nuclear Association, which provided a great deal of information on elements of the life cycle chain for the study, or by making enquiries to other international organizations such as the IAEA or the NEA.

3.2.1.4 Impact categories

With regard to the calculation of GHG life cycle emissions, greenhouse gas emissions were quantified as part of the life cycle analysis. In addition, energy consumption (broken down by primary energy source) was also analyzed. Raw material consumption, land consumption, water consumption, toxic effects, accidents and waste were also described.

Impact assessment methods are based on models for quantifying the causal relationships between the material/energy inputs and the emissions that are relevant for the life cycle (accounted for in the resource use and emissions profile) and the respective impact category analyzed.

Various recent LCA studies have analyzed comprehensive environmental impacts, e.g. UNECE (2021), Vattenfall (2019), Zhang and Bauer (2018). These sources have generally worked with the ecoinvent database to analyze the various environmental impacts, whereby this database allows the use of different impact assessment models with an identical life cycle inventory database. The effects of toxicity, eutrophication, ionizing radiation, consumption of mineral resources, land consumption, water consumption, air pollutants, acidification, particulates and ozone formation in the life cycle of various energy technologies, including nuclear power, were analyzed. Different environmental impacts of nuclear energy are also subject to analysis. Various environmental impacts of nuclear energy were also investigated in (European Commission Joint Research Centre [JRC], 2021).

Waste represents an element of the life cycle in the proposed life cycle chain. It is therefore not an impact category in itself, but rather the environmental impacts of waste transport, waste treatment and waste disposal or storage, and was therefore considered as part of the downstream process chain.

Effects on human health are primarily an effect of toxic and ionizing emissions and are not part of the standard impact categories of life cycle assessments (see Table 2 in (EC, 2013). UNECE (2021) measures the effects on human health with the indicators 'carcinogenic effects' and 'non-carcinogenic toxic effects' for human health. Gibon et al. (2017) on the other hand, quantify the damage to human health in 'disability adjusted life years'. For this indicator, the indicators of the number of years of life lost due to premature death are combined with the years of life during which a health disability exists. In addition to cancer caused by ionizing radiation and toxic chemicals, Treyer et al. (2014) also consider the number of deaths caused by climate effects such as heat, storms, floods, hurricanes, skin cancer caused by the destruction of the ozone layer, and deaths from respiratory diseases caused by air pollutants. Calculating the aggregated health effects, as Treyer or Gibon have done, would involve considerable effort and high uncertainties in converting the toxicological parameters into a lower or impaired life expectancy. The consideration of health effects was therefore limited to a general description of the substances used and their general health effects in the process stages, as in UNECE (2021), and the actual effects on human health were not quantified as part of the life cycle analysis.

Life cycle analyses normally assume production that complies with all regulations and authorization conditions and only the environmental impacts resulting from regular operation are considered. The European Commission has adopted a similar approach, for example, when analyzing the environmental impacts of nuclear power in the EU taxonomy. This approach systematically ignores the accident risks of technologies such as nuclear power and the serious consequences of such accidents, as well as other issues such as the risk of contributing to the proliferation of nuclear weapons. A discussion of the environmental impacts of severe accidents and nuclear proliferation can be found in sections 3.13 and 3.14. In addition, so-called fugitive emissions, i.e. emissions from leaks or other irregular operating conditions, are generally not recorded and mapped in data sets. In (JRC, 2021), only 6 of 387 pages were devoted to the question of the contribution of accidents to the environmental impact of nuclear energy. Only the maximum number of fatalities from severe accidents and the rate of fatalities from severe accidents in relation to the energy produced were analyzed. Even with this limited analysis, however, important methodological aspects were ignored (Pistner & Englert, 2021). In addition, other important indicators for the consequences of severe accidents, such as the contamination

of large areas of land and water or the economic costs, were not considered, although these aspects have been recognized in the scientific literature for decades as essential for the assessment of severe accidents in nuclear technology (Küppers et al., 1989). Due to the special risk quality of nuclear technology ('Damocles risk', i.e. very low probability of occurrence with very high accident consequences), a complete and quantitative discussion of the effects of severe accidents cannot be presented within the scope of this study. However, the main impact contributions were discussed and the wide range of estimates and their uncertainties (this concerns both the probability of occurrence of severe accidents and the possible consequences of accidents) were presented.

Regarding the selection and definition of the impact assessment models and impact indicators, it can be summarized that the present study is primarily based on the EU Commission's proposal in the context of the Product Environmental Footprint (PEF) and the Organization Environmental Footprint (OEF).

The indicators to be considered in the impact assessment are compiled in the following table.

Table 45: Selected impact categories and their significance thresholds

Impact category	Unit
Global warming potential	g CO2eq36
Cumulative energy demand (total)	MJ
Cumulative energy demand (fossil)	MJ
Abiotic depletion potential	kg Sb eq
Land use	pt
Water consumption (withdrawn)	m3
Ionizing radiation	kBq U235 eq
Human toxicity potential (non-cancerogenic effects)	CTUh
Human toxicity potential (cancerogenic effects)	CTUh
Radioactive waste (highly radioactive)	m3
Radioactive waste (low-level radioactive)	m3

Source: Own compilation

3.2.2 Regionalization

Different processes in the nuclear life cycle chain may take place in different regions or countries of the world. For some processes like uranium conversion and enrichment only very few facilities exist at all, compare sections 3.4 and 3.5. Other process step, there are several uranium mines in operation worldwide, compare section 3.3 and especially the actual electricity production takes place in several countries around the world, compare section 3.7.2.

[36] As the results of this study refer to 1 kWh of electricity, the global warming potential (GWP) is presented in the unit g CO_2eq/kWh.

For all process steps, we therefore define the specific country in which this process takes place for a specific life cycle chain. As only a limited number of facilities exist for some steps, these specific modules are used in several life cycle chains.

As the fundamental process is the electricity production in a NPP, the name of a specific life cycle chain will be given by the country or region where the NPP is located, see section 3.7.2. Overall, 40 life cycle chains are analysed: EU1-11, RU1-4, NA1-6, CN1-3 and seven chains for the rest of the world, for the reference chains EU1, RU1, NA1 and CN1 two variations each (three for NA) with a change of the plant type, compare section 3.7.1, are included.

It must be noted that the actual life cycle chains are build up from single modules (like a specific mine, a specific conversion and enrichment facility, a specific NPP etc.). They do therefore not represent the real environmental impact of a specific NPP in a specific country, nor do they give a real estimation on the average environmental impact of a nuclear fleet of a specific country, as we have not tried to statistically represent the detailed front-end and back-end situations of specific countries. Still, the corresponding life cycle chains were constructed to be reasonable candidates for a specific region or country, so that the range of the environmental impacts of the life cycle chains for that country or region should somewhat be representative.

3.2.3 Baseline year 2020 and projection to 2030

All life cycle chains are analysed based on data for the baseline year 2020.

For the 2030 process chains, relative reductions in the greenhouse gas emission factors for concrete, steel and electricity are assumed, which represent major inventory constituents.

- **Concrete:** For the cement industry, which is responsible for the majority of CO_2 emissions in concrete production, future projections indicate a 19% reduction in CO_2 emissions by 2030 compared to 2019 (Verein Deutscher Zementwerke e.V [VDZ], 2020). According to a more ambitious scenario, even a CO_2 reduction of about 27% compared to 2019 could be achieved (VDZ, 2020). Specifically for precast concrete products, a 40% reduction in emissions is predicted by 2030 (Peters et al., 2020). Given the cited range of data in the literature, we estimate a 30% GHG reduction (per kg of concrete) for concrete compared to the 2020 baseline in this study.

- **Steel:** The steel industry aims to reduce its CO_2 emissions by 30% by 2030. To achieve these reductions, approximately one third of primary steelmaking capacity is expected to be converted to hydrogen-based[37] direct reduction by 2030 (Wirtschaftsvereinigung Stahl, 2022). The introduction of other novel renewable technologies, such as molten oxide electrolysis and electric arc furnace energy, will further reduce CO_2emissions (Fortune Business Insights, 2025). Taking these factors into account, it can be estimated that the carbon footprint of steel in 2030 will be about 30-40% lower than in 2020. Therefore, this study estimates a 35% GHG reduction for steel (per kg of steel) compared to the 2020 baseline, which is the average of the given range.

- **Electricity:** According to the World Energy Outlook (IEA, 2024), the ambitious Net Zero Emission (NZE) scenario requires a reduction in CO_2 emissions in the electricity sector of roughly 70% by 2030 compared to 2020. This assumes a massive expansion of renewable energies and a rapid decline in coal-fired power generation. In reality, however, recent annual reduction in global emission intensity from electricity generation was 3% in 2024, compared to 1% in 2023. Over the 2025–2027 forecast period, global CO_2 intensity is

[37] The assumption is based on climate-neutrally produced 'green' hydrogen.

expected to fall by an average of 3.6% annually (IEA, 2025b). Reflecting the recently achieved reductions of CO_2 intensity as well as the current short-term forecasts, we estimate a GHG reduction for electricity of 35% (per kWh of electricity) by 2035 compared to the 2020 baseline.

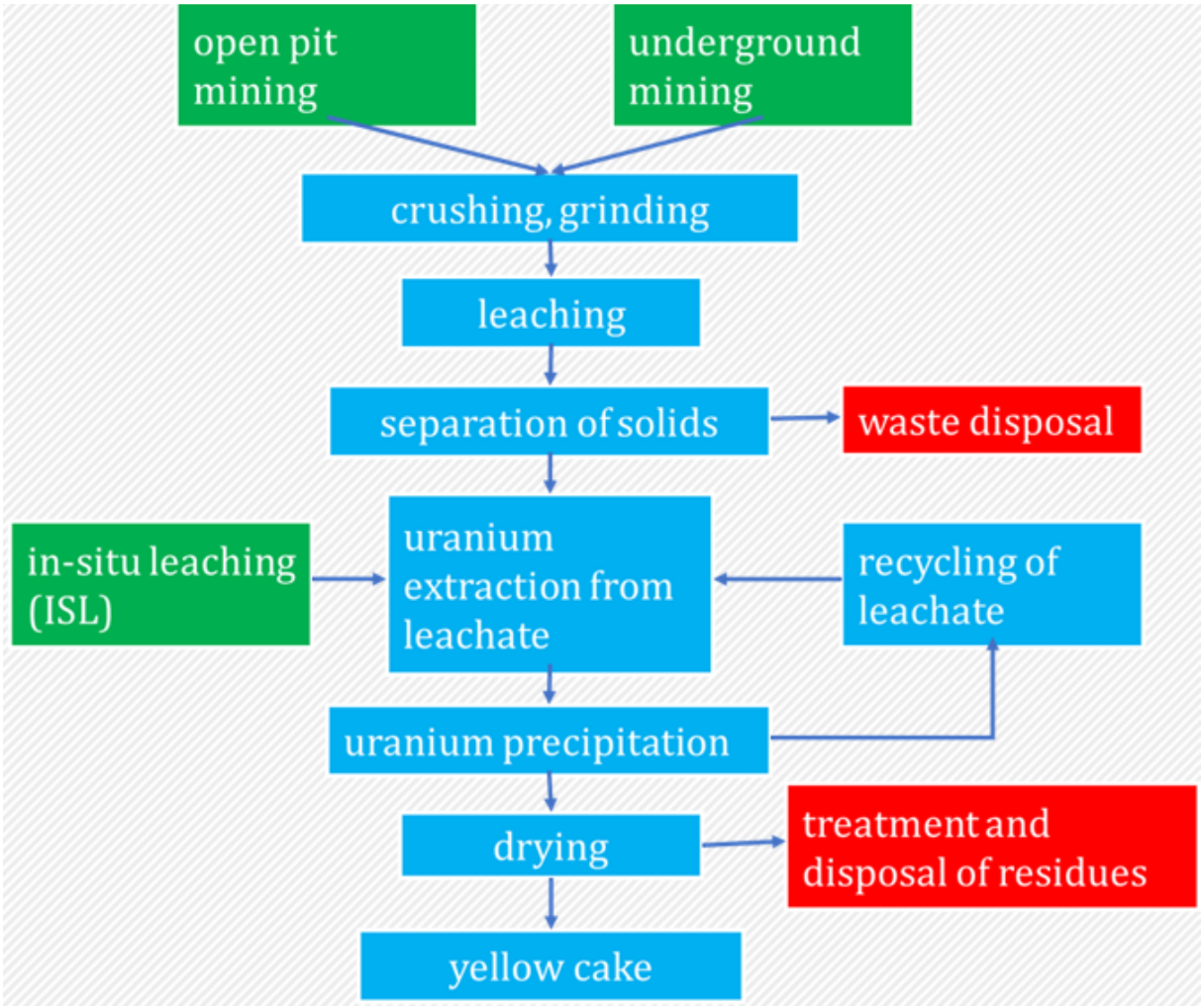
The remaining inventory components remain unchanged, as they contribute only a comparatively small share to the relevant process steps of the nuclear power chain.

3.3 Mining

3.3.1 Uranium Mining

Uranium is mined in open pit and underground mines and once extracted, it is crushed, ground into a fine slurry and leached in sulphuric acid. The uranium is then recovered from solution and concentrated into solid uranium oxide, known as "yellow cake", before being converted into hexafluoride and heated. Sandstone-bound uranium deposits can be utilised by solution mining (also known as ISL for in-situ leaching or ISR for in-situ recovery). The ore body is tapped by drilling and an oxidising fluid is introduced, which mobilises the uranium. This is usually diluted sulphuric acid. Uranium is also extracted as a by-product in the mining of copper, gold or phosphate.

Figure 100: Process steps in uranium mining



Source: Öko-Institut on the basis of (WNA, 2022)

The process chain of uranium mining also includes the dumping of overburden and the restoration of uranium mines. The latter is very often excluded from the system boundaries of LCA studies on nuclear power due to lack of data and site specific information. Table 47 shows the relevance of the different mining types for uranium production, with the ISL process dominating, followed by underground mining and open pit mining. This data shows that these three processes should be considered as basic modules in the life cycle analysis; extraction as a by-product of mining other raw materials such as copper could be included in the analysis in form of a sensitivity analysis.

Thorium is often discussed as an alternative fuel by countries such as India with limited national uranium reserves or for alternative reactor concepts (NEA, 2015). At present, thorium plays practically no role as a fuel in commercial nuclear energy utilisation. Since thorium itself does not contain a fissile isotope, unlike natural uranium, the availability of surplus fissile material (e.g. from reprocessing or through higher enrichment of uranium) is always required for thorium fuels. For these and other technical reasons, thorium will not play any quantitative role in commercial energy production in the foreseeable future (Pistner & Englert, 2017; Pistner, Englert, et al., 2024).

The literature agrees on the central importance of ore content for the energy balance and GHG emissions of nuclear energy (Fritsche, 2007; Sovacool, 2008; Warner & Heath, 2012; Zhang & Bauer, 2018) With a low ore content of approx. 0.01%, the ore processing of uranium becomes the process step with the highest energy input (over 40% of the total energy input). (Storm van Leeuwen, 2008) calculate the energy content and emissions when the ore grade of the uranium deposits changes. According to these calculations by Storm/Smith, the energy balance becomes negative from a limit ore grade of 0.013%. However, these findings about the energy demand of uranium extraction are disputed by other authors (3.12.1.1.1).

It is therefore important to include the ore content of uranium deposits in the analysis. (NEA & IAEA, 2025) have published the current uranium production by country and mine, the production processes, the uranium ore content and the extraction costs. On this basis, modules were developed for the life cycle elements of uranium mining that take into account differences in ore content.

In addition to greenhouse gas emissions from energy consumption, uranium mining is also a major contributor to land conversion from nuclear energy, water consumption and the use of toxic chemicals and the associated emissions and generation of tailings and waste.

3.3.1.1 Uranium resources

This year saw the OECD/NEA/IAEA publish a new edition of its “Redbook” covering all aspects of global uranium supply and demand (NEA & IAEA, 2025).

The Paris-based agency noted that there is almost no change in global uranium resource estimates for all resource and cost categories. They report “total identified recoverable resources at <USD 260/kgU of just over 7.9 million tU, comprised of 60% reasonably assured resources (1% increase from the previous edition) and 40% inferred resources. At <USD 130/kgU, total identified recoverable resources of 5.9 million tU decreased (-3%) compared to 2021, with decreases more pronounced (-6%; -14%) at <USD 80/kgU and <USD 40/kgU, respectively.”

Changes in the resource estimates of the Redbook are mostly due to reevaluations of deposits and reattribution to different cost categories. In the future, resources in the cheaper cost categories will decrease faster than others unless new cheap deposits can be found by prospection. However, there were no new large scale discoveries of uranium deposits in the last

decades despite significant exploration efforts leading to the hypotheses that large deposits with high ore grades remain rare.

Table 46 provides an overview of current reasonably assured resources (RAR) for which there is high confidence in estimates of grade and tonnage that are generally compatible with mining decision-making standards.

Table 46: Reasonably assured recoverable resources by production method (tU)

Production method	<USD 40/kgU	<USD 80/kgU	<USD 130/kgU	<USD 260/kgU
Open-pit mining	<8,100	<113,700	<904,900	1,041,400
Underground mining	0	312,300	936,200	1,453,400
In situ leaching acid	279,300	473,500	572,700	636,000
In situ leaching alkaline	24,200	57,000	132,900	135,300
Co-product/by-product	53,000	219,400	1,276,500	1,425,700
Unspecified	0	4,800	45,700	86,900
Total	364,700	1,180,700	3,868,800	4,778,700

Source: (NEA & IAEA, 2025) "as of 1 January 2023, tonnes U, rounded to nearest 100 tonnes"

Within the <USD 80/kgU cost bracket, in-situ leaching (both acid and alkaline) accounts for 45% of resources, followed by underground mining at 26% and by-product/co-product sources at 20%. At USD 130/kgU, by-product and co-product resources increase to 33% due to Australia's Olympic Dam, while underground and open-pit operations each account for around 25%. In the USD 260/kgU category, underground and by-product/co-product methods each represent approximately 30%, while open-pit accounts for 22% and In-situ leaching (ISL) for 16% (NEA & IAEA, 2025).

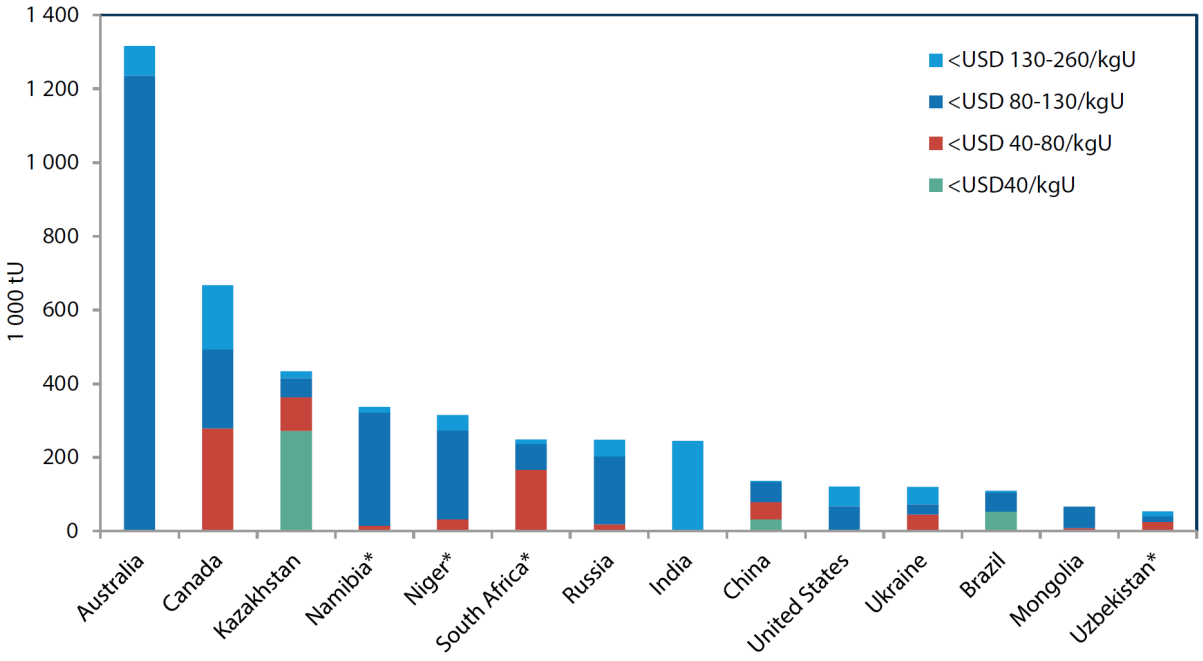
With regards to identified resources in the upper cost category, Australia leads in large part due to the Olympic Dam site, with Kazakhstan having the lead for lower cost categories (Figure 101 and Figure 102). Australia, Kazakhstan, and Canada collectively hold ~50% of global identified conventional uranium resources, with Australia alone accounting for 28% (<USD 130/kgU) and 24% (<USD 260/kgU), largely due to Olympic Dam. Kazakhstan ranks second with ~14% and ~11% in the respective categories, while Canada contributes ~10–11%. In the lowest cost category (<USD 40/kgU), Kazakhstan dominates with 75%, but data limitations (e.g., non-reporting by Australia and the U.S.) reduce the reliability of these estimates. Most identified resources (RAR and identified) are close to current production centers and no new large infrastructure would have to be build. (NEA & IAEA, 2025) gives an estimate of 88% of the resources below 80 USD/kgU and 65% below 130 USD/kgU are close to current production facilities (NEA & IAEA, 2025).

At almost 7.9 million tU, undiscovered resources (prognosticated and speculative) are seen as another source of potential future supply. In addition, there are another 57 million tU unconventional resources, resources from which uranium is only recoverable as a minor by-product, such as uranium associated with phosphate rocks, non-ferrous ores, carbonatite, black shale, and lignite. As noted by the NEA, in some cases, including those of major producing countries with large identified resource inventories, estimates of undiscovered resources and

unconventional resources are either not reported or have not been updated for several years (NEA & IAEA, 2025).

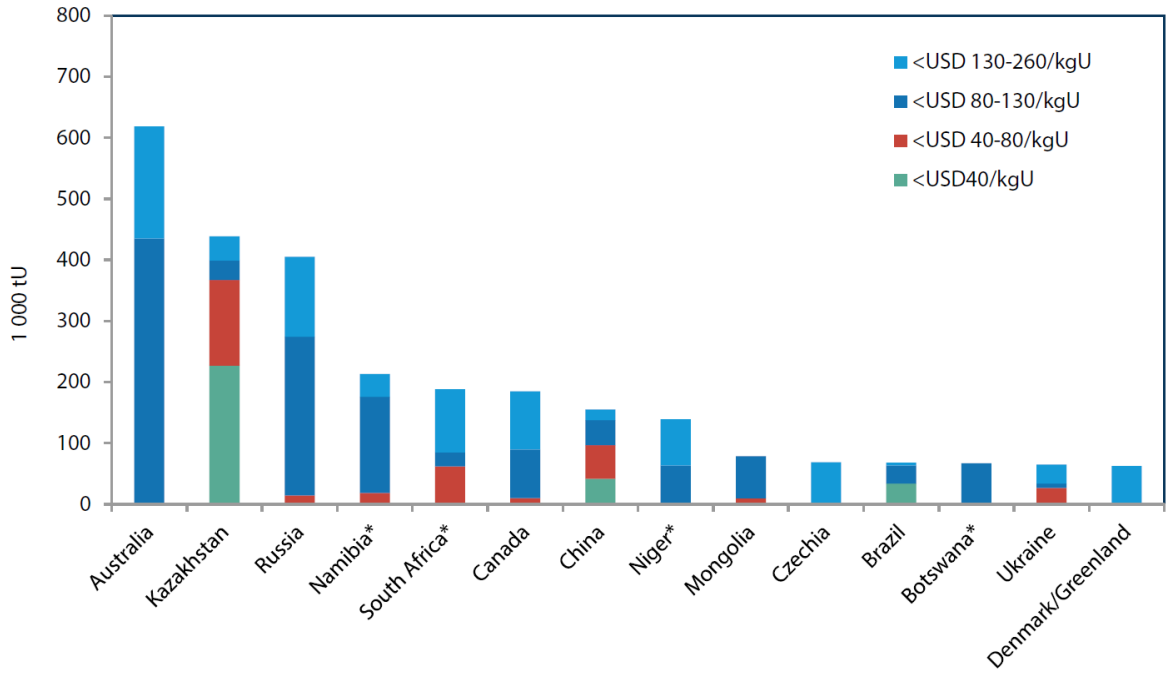
While some recent reports are optimistic towards uranium mining, for example in Australia, the OECD-NEA emphasized the downward trend observed in recent years in worldwide domestic exploration and mine development expenditures, which decreased to approximately USD 380 million in 2020 from USD 1-2 billion in the years since 2014. However there were indications of an recovery to 840 million USD in 2023 (NEA & IAEA, 2025).

Figure 101: Distribution of reasonably assured recoverable conventional uranium resources among select countries with a significant share of resources



Source: (NEA & IAEA, 2025) "* Secretariat estimate or partial estimate."

Figure 102: Distribution of inferred recoverable conventional uranium resources among select countries with a significant share of resources



Source: (NEA & IAEA, 2025) "* Secretariat estimate or partial estimate."

3.3.1.2 Supply and demand of natural uranium

Since uranium demand is driven by the operation of the global fleet of nuclear reactors, there is not much change in uranium demand since the end of the 1990s with the demand between roughly 56.000 to 70.000 tU per year (59018 tU in 2022 for 393.3 GWe net of reactor power) (NEA & IAEA, 2025). With the current demand of roughly 60.000 tU (2022) and without major discoveries, current RAR under 130$/kgU will last for decades. Also, there are additional inferred recoverable resources (IR) of 2.056.900 tU under 130$/kgU with a total of 4.778.700 RAR and 3.155.700 IR under 260$/kgU.

Table 47: World uranium production by production method

Production method	2020	2021	2022	2023
Open-pit mining [%]	18.5	16.9	15.9	15.6
Underground mining [%]	15.9	15.3	18.0	23.3
In-situ leaching (ISL) [%]	58.2	63.1	59.8	55.4
In-place leaching [%]	0.0	0.0	0.0	0.0
Co-product/by-product [%]	7.0	4.5	6.1	5.5
Heap leaching [%]	0.0	0.0	0.0	0.0
Other [%]	0.0	0.0	0.0	0.0
Total [%]	100.0	100.0	100.0	100.0

Source: (NEA & IAEA, 2025) "as of 1 January 2023, percent". 2023 in preliminary numbers.

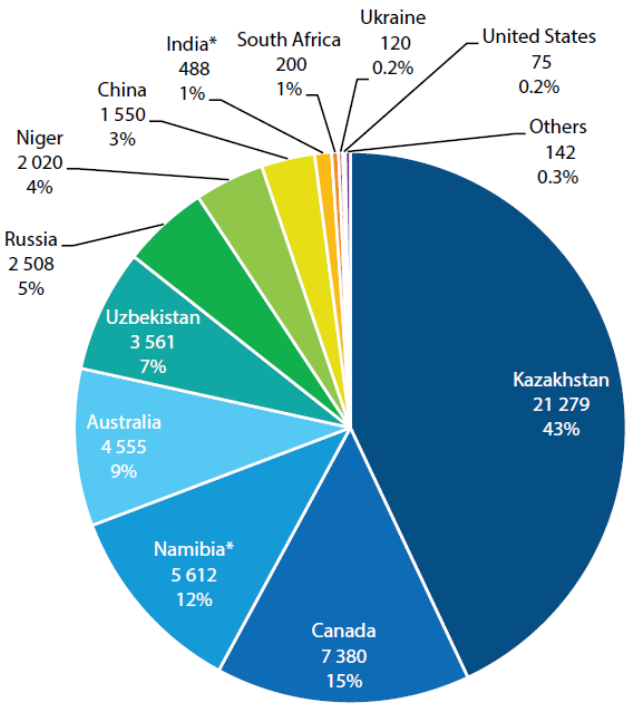
Currently over 50% of uranium is mined with ISL (Table 47), which is successful because it enables low-cost, low-impact extraction without extensive surface excavation, offering economic and environmental advantages in suitable geological formations. ISL will therefore be the most relevant production method for the foreseeable future. However, with the depleting of cheap RAR other production methods like open pit and underground mining might become more prominent in the future (cf. Table 46) (NEA & IAEA, 2025).

As the uranium deposits are globally distributed in only a few countries, uranium production is also dominated by only a few countries. In 2022 six countries were producing 91% of the global uranium supply, Kazakhstan, Canada, Namibia, Australia, Uzbekistan and Russia (Figure 103Figure 103:) (NEA & IAEA, 2025). With some changes over the years due to mine shutdowns and new openings, these countries dominated the uranium supply in the last decade and will be the dominant producers in the next decade.

Likewise, only a few companies dominate the market (Table 48). Kazakhstan's Kazatomprom leads the market with 23%, followed by Canada's Cameco (12%), France's Orano (11%), China's CGN (10%), Russia's Uranium One (9%), Uzbekistan's Navoi Mining (7%), China's CNCC (7%), Australia's BHP (6%), Russia's ARMZ (5%) and the US's General Atomics/Quasar (4%) (WNA, 2024d).

Global production of uranium was at 49.490 tU in 2022 (Figure 104) and estimated to rise again in 2023 (NEA & IAEA, 2025). However, production did not change significantly in the last decade. Following a period of contraction since 2016 (a fall of 5% in 2017 and 10% in 2018), stabilization of uranium production levels was significantly disrupted, among various reasons, by the pandemic crisis in 2020. Since then, the production recovered, but so far not to previous levels.

Figure 103: Uranium production by country in 2022: total 49.490 tU



* NEA/IAEA estimate.

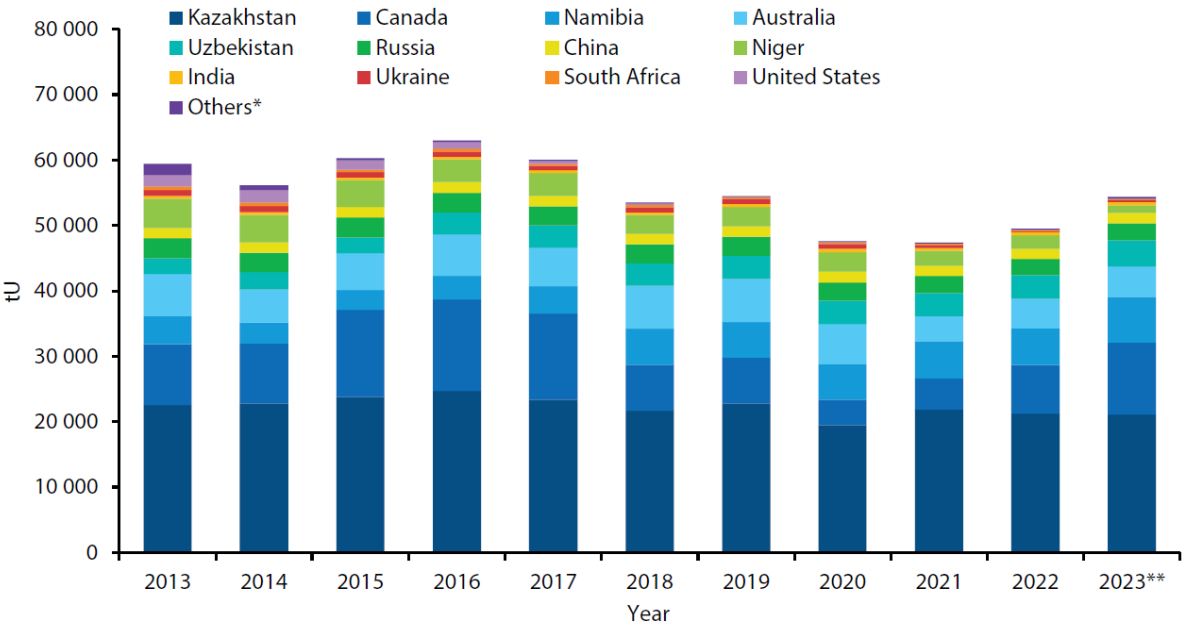
Source: (NEA & IAEA, 2025). As of January 2023 in tU and percent ot total production.

Table 48: Uranium production by company 2022

Company	tonnes U	% of world total
Kazatomprom	11,373	23
Cameco	5675	12
Orano	5519	11
CGN	4627	10
Uranium One	4454	9
Navoi Mining	3300	7
CNNC	3247	7
BHP	2813	6
ARMZ	2508	5
General Atomics/Quasar	1740	4
Other	4098	6

Source: (WNA, 2024d)

Figure 104: Last decade of uranium production by country in tU per year



* "Others" includes the remaining producers (see Table 1.18 and previous Red Book editions).

** NEA/IAEA estimate.

Source: (NEA & IAEA, 2025)

3.3.1.3 Ore mining

Ecoinvent assumes an efficiency of 95% production of U3O8 from the ore, 5% loss for the mining and milling. The same efficiency is assumed for all LCA chains.

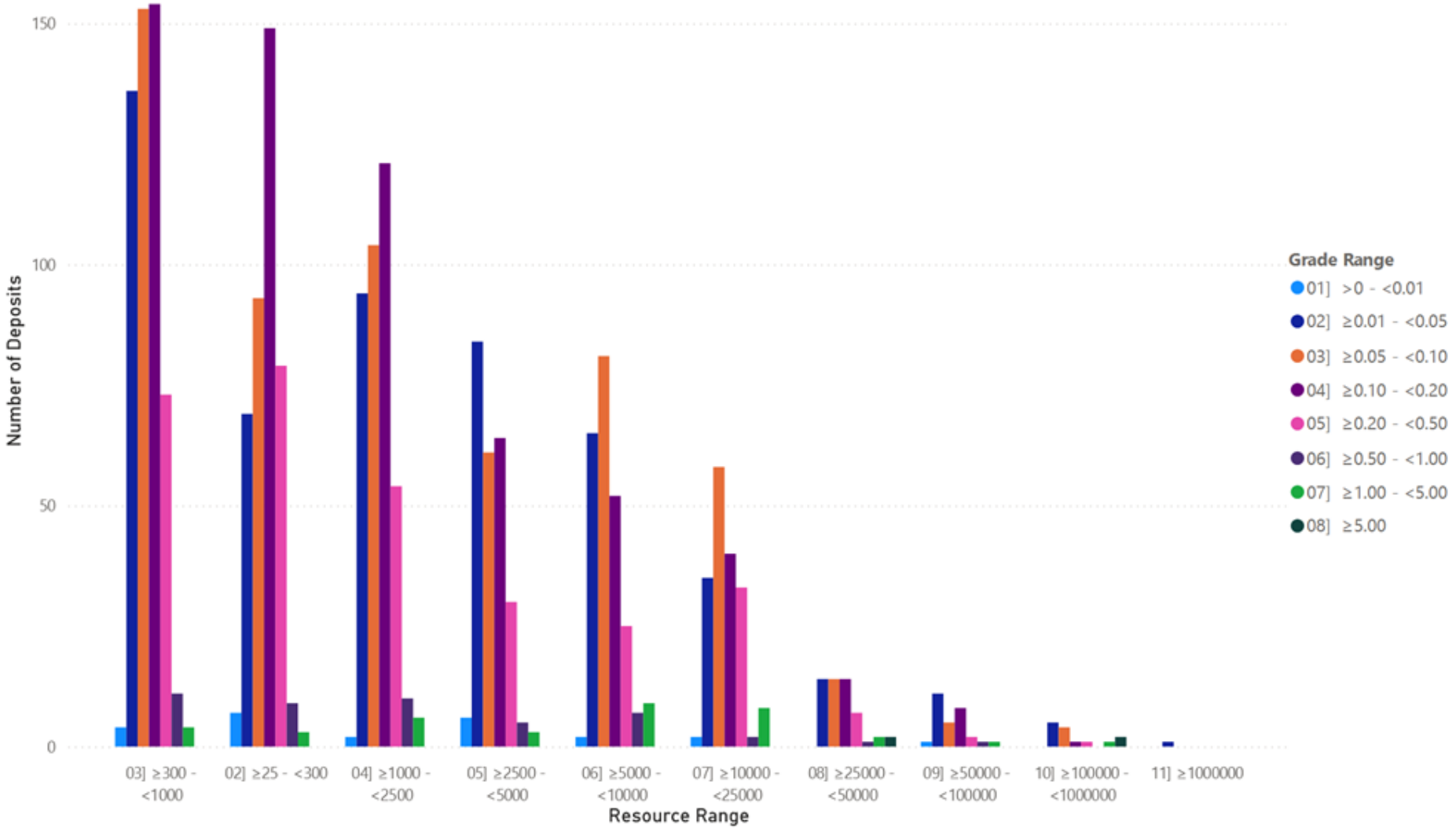
The energy demand of uranium mining will be discussed below.

3.3.1.4 Ore grades

The ore grade of a mining operation is a critical factor in selecting a mining method., as it will determine the work that has to be done for extracting uranium from the host rock. ISL is favored for deposits situated in low-grade, permeable sandstone due to its capacity to minimize surface disruption and operational costs. Open-pit mining requires enhanced environmental control and significant surface excavation, however it is employed for relatively shallow, moderate- to high-grade deposits, but also low grade mining is conducted. Underground mining targets deeper, often higher-grade ores, such as those in Canada's Athabasca Basin, where concentrations can exceed 10%U_3O_8, rendering operations lucrative despite elevated extraction costs. Lower-grade resources necessitate more cost-effective approaches like as in-situ leaching or extensive open-pit mining to maintain competitiveness, whereas high-grade deposits allow the expensive and complex technologies associated with underground mining. Worldwide, the distribution of conventional resources shows (Figure 105) that most identified resources are small and have a low ore grade. Large and higher grade deposits are scarce, which is significant because lower ore grades generally require more energy and material throughput, leading to higher environmental impacts per unit of uranium extracted.

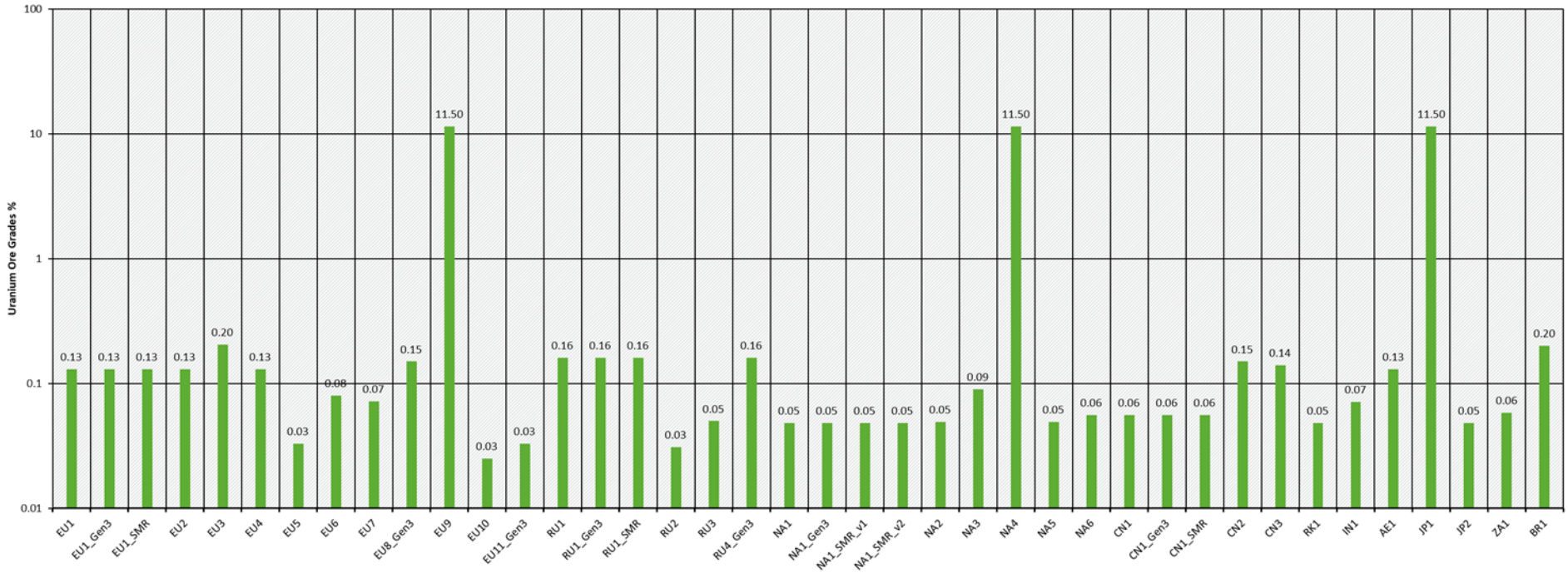
The mines selected for the LCA chains (Table 50) reflect a large span of ore grades (Figure 106), the selection is discussed below.

Figure 105: Number of deposits by resource range and grade range in tU



Source: IAEA UDEPO database https://infcis.iaea.org/UDEPO (last accessed on 01.10.2025) and (IAEA, 2018d).

Figure 106: Logarithmic depiction of ore grades for LCA chains in%U



Source: Öko-Institut

3.3.1.5 Infrastructure

Similarly to mining being dominated by several countries and companies currently the majority of uranium mining is conducted in only a few mining regions worldwide. Production numbers vary significantly by year due to incidents at the site, or new projects at the same site/within the same region and due to other factors. Ore grades are given on average, as ore grades can vary significantly. For the different LCA chains, typical mines were selected reflecting different ore grades, the mining method and the geologic location. In the following we describe some of the mines used for the different LCA chains. All numbers are based on (NEA & IAEA, 2025).

The highest production in 2022 (Table 49) came from the Cigar Lake mine in Canada. An underground mine opened in 2014 with an exceptional average ore grade of 11.5%U and 107200 tU resources and a yearly production of 6500 tU/y. However, to extract the material from under the lakes parts of the ore body must be artificially frozen to prevent groundwater inflows—an energy-intensive process that not only increases the environmental footprint but also poses potential risks to the surrounding hydrology. Cigar lake is owned by Cameco (54.547%), Orano (40.453%) and Tokyo Electric Power Company (5%).

The Husab mine in Namibia (formerly Rössing south) has currently the second largest production. Current mining was started in 2016 with an ore grade of 0.033%U and 147 096 tU recoverable resources and a production of 5700 tU/y owned 90% by Chinese CGN.

The Inkai mine in Kazakhstan uses in-situ leaching and is the third largest producing mine in 2022 with an ore grade of 0.056%U and a production of 3201 tU/y in 2022. Inkai is owned and operated by Cameco Corporation(40%) and KazAtomProm(60%).

The fourth largest production is from Olympic Dam in Australia. The mine produced uranium as a byproduct of its operation. Therefore the emission of Olympic Dam cannot be credited completely to uranium as a product. However, since the ore grade dominates GWP and other impact categories, all impact categories are attributed to uranium as a product in the LCA chains that use Olympic Dam as uranium mine. For a discussion on sensitivities cf. section 3.12.1.1.1.Olympic Dam has an average ore grade of 0.048%U and huge reserves with a production of 2813 tU/y owned by BHP Ltd.

The fifth largest mine in 2022 was Budenovskoye 2, an ISL mine with 2560 tU/y production, very similar to Inkai and operated by Karatau LLP.

Rössing mine, the sister site to the Husab mine, is a mine with a slightly lower ore grade of 0.025% and a production of 2255 tU/y. Rössing Uranium LLT is the developer of the mine owned about 70% by Chinese CNUC (China Nuclear International Uranium Corporation).

SOMAIR (Arlit) is also an open pit mine, but in Niger, owned in majority by ORANO with an ore grade of 0.13%U and a production of 2255 tU in 2022.

Other mines are not included in the top ten production list for 2022 (Table 49) were used to vary the ore grade (Table 50) in the LCA chains, but are basically a variation of the largest production mines.

The reference mines for underground and open pit mining used by ecoinvent (Dones et al., 2009) are based on (El-Bassioni, 1980; DoE, 1983). The ore grade of the ecoinvent reference mine is 0.2%U_3O_8 with a production capacity of 810 tU/y for the open-pit mine and 240 tU/y for

the underground mine with a lifetime of 20 years. The reference mine in ecoinvent for In-situ leaching has an ore-grade of 0.168%U_3O_8 (Doka, 2011).[38]

The lifetime of the mines used for the LCA chains in this study are varied. The lifetime was estimated based on resource estimates, past operation and production rates referenced in (NEA & IAEA, 2021, 2025). Due to changes in resource estimates, varying production rates due to market changes, and changes due to social (e.g. Niger) and technical issues (e.g. production stops in Cigar lake mine or production rates depending on co-production such as in Olympic-Dam) an exact estimate of the lifetime is not possible and estimates were used. Since the reference mine in ecoinvent uses a 20 year lifetime, a different lifetime assumption basically scales the ecoinvent reference facilities impact categories linearly.

Table 49: The largest-producing uranium mines in 2022

Mine	Country	Main owner	Type	Production (tonnes U)	% of world
Cigar Lake	Canada	Cameco/Orano	underground	6,928	14
Husab	Namibia	Swakop Uranium (CGN)	open pit	3,358	7
Inkai, sites 1-3	Kazakhstan	Kazatomprom/Cameco	ISL	3,201	7
Olympic Dam	Australia	BHP Billiton	by-product/underground	2,813	6
Karatau (Budenovskoye 2)	Kazakhstan	Uranium One/Kazatomprom	ISL	2,560	5
Rössing	Namibia	CNNC	open pit	2,255	5
SOMAIR	Niger	Orano	open pit	2,020	4
Four Mile	Australia	Quasar	ISL	1,740	3
Central Mynkuduk	Kazakhstan	Ortalyk	ISL	1,650	3
South Inkai 4	Kazakhstan	Uranium One/Kazatomprom	ISL	1,600	3
Top 10 total				28,125	57%

Note 1: SMCC, a joint venture between Kazatomprom and Uranium One, reported combined production of 2225 tU in 2022 at its two mines, South Inkai 4 and Akdala.

Note 2: KATCO, a joint venture between Kazatomprom and Orano, reported combined production of 2564 tU in 2022 across its two mines, Moinkum and Tortkuduk.

Source: (WNA, 2024d)

Table 50: Mines used in LCA chains

Country	Mine Name	Mining Type	Ore Grade (%U)	Lifetime est. (y)
Australia	Olympic Dam	Underground, by-product	0.048 (0.087)*	80

[38] The ISL mine has an ore grade of 0.168%U_3O_8 while both underground and open-pit mine have an ore grade of 0.2%U_3O_8 which an ore grade of 0.17% U.

Country	Mine Name	Mining Type	Ore Grade (%U)	Lifetime est. (y)
Brazil	Caetité	Open-pit	0.2	40
Canada	Cigar Lake	Underground	11.5	20
China	Fuzhou	Open-pit	0.15	60
Kazakhstan	Inkai	ISL	0.056	30
Kazakhstan	Katko	ISl	0.071	30
Kazakhstan	Khorasan	ISL	0.204	20
Kazakhstan	Zhalpek	ISL	0.031	20
Namibia	Husab	Open-pit	0.033 (0.076)*	30
Namibia	Rössing	Open-pit	0.025 (0.076)*	50
Niger	SOMAIR (Arlit)	Open-pit	0.13	55
Niger	SOMAIR (Arlit) Stocks	Open-pit	0.08	40
Niger	Imouraren	Open-pit	0.072 (0.076)*	40
Niger	Dasa	Open-pit	0.15	40
Russia	Priargunsky	Open-pit	0.16	70
Russia	Khiagda	Open-pit	0.05 (0.076)*	25
South Africa	Moab Knotsong	Underground	0.058 (0.087)*	30
USA	Lost Creek	ISL	0.049	20
USA	Smith Ranch	ISL	0.09	40

Source: (IAEA & NEA, 2018; NEA & IAEA, 2021, 2025). * artificial values for LCA calculation to implement lower and upper bounds on the energy demands in the sensitivity discussion section 3.12.1.

3.3.1.6 Transport

Especially with open-pit mining transport with diesel powered trucks plays a crucial role with regard to emissions. Ecoinvent assumes a waste rock to ore ratio of 30 and an average ore grade of 0.5% with 7t waste rock per kgU. 1 km transport is assumed for 40 m^3 trucks (Dones et al., 2009). For open-pit mines this reference assumption for transport is adapted in the LCA chains and scaled to the ore grade of the specific mine.

In underground mines transport is covered by the Diesel consumption assumed by ecoinvent as waste rock volume is much smaller (Dones et al., 2009). In ISL only liquids are transported and will be pumped to the processing facility. In these cases transport is excluded from the LCA chains.

See also section 3.11 for more on transportation.

3.3.2 Yellowcake production

Once the ore is brought to a processing facility the ore will be milled and processed. The purpose of processing is to separate the uranium from the waste rock (host rock) using chemical processes. The product of this process is uranium concentrate ("yellowcake").

Most uranium ore processing techniques worldwide employ hydrometallurgical methods like those used for other metal ores. The processes can be categorized into four distinct stages: ore preparation (mixing, crushing, grinding), chemical treatment (oxidation, leaching, solid/liquid separation), metal extraction (ion exchange, solvent extraction), and product extraction (precipitation, product washing, drying, packaging). Methods commonly referred to as solution mining encompass underground in-situ leaching and above-ground basin or heap leaching. In-situ leaching involves extraction and processing simultaneously. Solution mining offers the benefit of allowing leached solutions to be directly processed in ion exchange columns. This avoids the need for mechanical comminution of ores and solid/liquid separation.

3.3.2.1 Uranium processing

Ecoinvent assumes an efficiency of 95% production of U3O8 from the ore, 5% loss for the yellowcake production process. The same efficiency is assumed for all LCA chains.

The energy demand of yellowcake production will be discussed below.

3.3.2.2 Infrastructure

The lifetime of a yellowcake production facility is assumed to be 15 years in ecoinvent. For all LCA chains we are assuming the same age for the uranium processing facilities as for the reference plant in ecoinvent with 15 years lifetime except for the ISL mine.

For ISL mining the ecoinvent there is only one dataset for mining and uranium processing. It is assumed for all LCA chains that the complete uranium processing infrastructure is scaled with the lifetime of the mine.

3.4 Conversion

Uranium hexafluoride UF_6 as a precursor for uranium enrichment is produced from the yellowcake, which is known as uranium conversion. UF_6 is chemically and thermally stable although it has a low sublimation point (56.5 °C). It is highly corrosive especially towards metals. Uranium hexafluoride (UF_6) is produced on an industrial scale using "wet" and "dry" conversion processes. Uranium ore concentrate is first dissolved in heated nitric acid to form uranylnitrate in wet conversion. Before fluorinating to UF_6, the uranium is separated from any remaining impurities using solvent extraction. The dry conversion method avoids aqueous purification by first converting uranium compounds straight to UF_6, which is afterwards refined using fractional distillation. Wet processes are still widely used in the industry because of their efficient cleaning ability before fluorination. The dry process reduces the amount of liquid chemical waste. In the wet process uranium ore concentrate is dissolved in nitric acid requiring thermal energy. Also, the processes of drying, calcination, and fluorination require thermal energy. Pumps, compressors, vacuum technology, automated process controls, and, to a lesser extent, heating systems are the primary devices that use electrical energy.

Conversion requires dedicated facilities, which can be located at the site of enrichment plants or at dedicated sites (IAEA, 2022b). Co-locating conversion facilities near enrichment plants is often preferred for logistical efficiency and to minimize the transport of uranium hexafluoride (UF_6), which is chemically reactive and requires stringent handling and security measures. This spatial integration reduces transport risks, simplifies material accountancy under safeguards,

and can lower overall infrastructure costs. Table 51 gives an overview of some of the major conversion centers worldwide. A small number of large-scale producers control the majority of the global market for conversion services.

Table 51: Estimated world primary conversion capacity and UF6 production 2022

Company	Country	Location	Licensed capacity (tU)	UF6 production (tU)
Cameco	Canada	Port Hope	12,500	10,600
CNNC (est.)*	China	Lanzhou & Hengyang	15,000	10,500
ConverDyn	USA	Metropolis	7000	0
Orano	France	Pierrelatte, Malvesi	15,000	8900
Rosatom (est.)	Russia	Seversk	12,500	12,000
Total			62,000	42,000

Source: (WNA, 2024a)

3.4.1 Infrastructure

The reference conversion facility in ecoinvent is based on the wet process, which is in general more energy intensive than the dry process, a conservative assumption (Dones et al., 2009).

In this study, conversion is assumed in

- France (EU1, EU1_Gen3, EU1_SMR, EU2, EU4, EU5, EU6, EU7, EU8_SMR, EU9_SMR, EU11_Gen3, NA5, NA6, RK1, AE1, JP2),
- Japan (JP1),
- Russia (EU3, EU10, RU1, RU1_Gen3, RU1_SMR, RU2, RU3, RU4_Gen3, CN2, IN1, ZA1),
- China (CN1, CN1_Gen3, CN1_SMR, CN3),
- USA (NA1, NA1_Gen3, NA1_SMR_v1, NA1_SMR_v2, NA2, NA3, NA4, JP1).

Canada as a producing country with an operating conversion plants is omitted since it brings no variation to the LCA chain in contrast to the US plant. We assumed a lifetime of 40 years for all facilities for the LCA chains.

3.5 Enrichment

Uranium enrichment refers to the various processes used to increase the proportion of the isotope uranium-235 in uranium for reactor fuel. Depending on the target burn-up (operating time in the reactor), the concentration of uranium-235 must typically be more than 3.2% for light water reactors; for more modern fuels with higher burn-ups, enrichments of between 4 and 5% are also common. A few reactor types, such as the Canadian CANDU reactor, can use natural uranium as fuel without enrichment. The uranium hexafluoride coming from the conversion step is enriched using the gaseous diffusion process or by means of gas centrifuges. The gas centrifuge process is the more common method of uranium enrichment internationally today and has now overtaken gaseous diffusion in terms of importance (see Table 52)

Table 52: Global relevance of uranium enrichment processes

Enrichment process	2000	2010	2020
Diffusion	50%	25%	0
Centrifuge	40%	65%	97%
Laser (planned before 2020 but not yet realised)	0	0	3%

Source: (WNA, 2022)

The main reasons for this are the considerably lower energy consumption and greater flexibility in capacity planning. There is also the process of laser enrichment, which was to be realised in a plant in Kentucky in the USA. So far, however, this has not been successful and the authorisation process for the plant is currently on hold (U.S. Nuclear Regulatory Commission [NRC], 2020b). Laser technology promises lower energy consumption, lower capital costs and lower tails assays and therefore economic benefits compared to centrifuge enrichment, but is not yet in commercial use. The life cycle chains will therefore be limited to the use of centrifuge technology, but will include various enrichment and depletion stages and will be based on the associated SWU effort in relation to the achievable burn-up.

Many LCA studies on the GHG emissions of nuclear energy in the literature still assumed high proportions of gas diffusion (e.g. (Sovacool, 2008)), so that in these studies the enrichment process contributes considerably stronger to the life cycle emissions.

3.5.1 Enrichment Level

A relevant parameter in enrichment is the enrichment level, i.e. the desired concentration of uranium-235 in the fuel, and the uranium-235 concentration remaining in the depleted uranium (degree of depletion). Higher concentrations are also associated with higher enrichment effort measured in separative work unit (SWU) and higher costs.

After enrichment, about 85% of the original oxide accumulates as depleted uranium, which must be transported and stored. In order to supply enough enriched fuel for a standard 1000 MWel reactor for 1 year, around 200 tonnes of natural uranium must be processed. Global demand is about 60.000 tU natural Uranium to fuel the global reactor fleet (WNA, 2025b).

Natural uranium (feed) has to be enriched in an enrichment plant to be used in the fuel of a typical LWR. The enrichment level of the product stream (product) in an enrichment facility will depend on reactor specifics and on the time the fuel has to stay in the reactor. The longer the fuel stays in the reactor, the more enrichment is needed to keep the reactor critical. While uranium-235 is fissioned to produce energy, the burnup of the fuel is measured in Megawattdays per ton heavy metal (MWd/tHM). Typical enrichment levels are between 3 and 4.5% in the fresh fuel. Modern fuel types optimize the fuel for higher burnups and therefore need higher initial enrichments. The less uranium-235 is contained in the depleted uranium (waste) stream of an enrichment plant, the less mass of natural uranium is needed to reach a certain enrichment level.

For some of the alternative reactor types or "Small Modular Reactors", higher assay low enriched fuels (HALEU) are required, in some cases enrichments of up to 19.75% which is the internationally recognised limit between low-enriched uranium (LEU) for civilian purposes and highly enriched uranium (HEU) for military purposes. However light water based SMR usually operate with the enrichments comparable to PWR.

Separative Work Unit (SWU) is the unit usually used to indicate enrichment capacity and is calculated using a value function V as

$$SWU = V(Np)Lp + V(Nw)\,Lw - V(Nf)Lf$$

using the equation

$$V(N) = (2N - 1)\mathrm{Log}(N/(1 - N)).$$

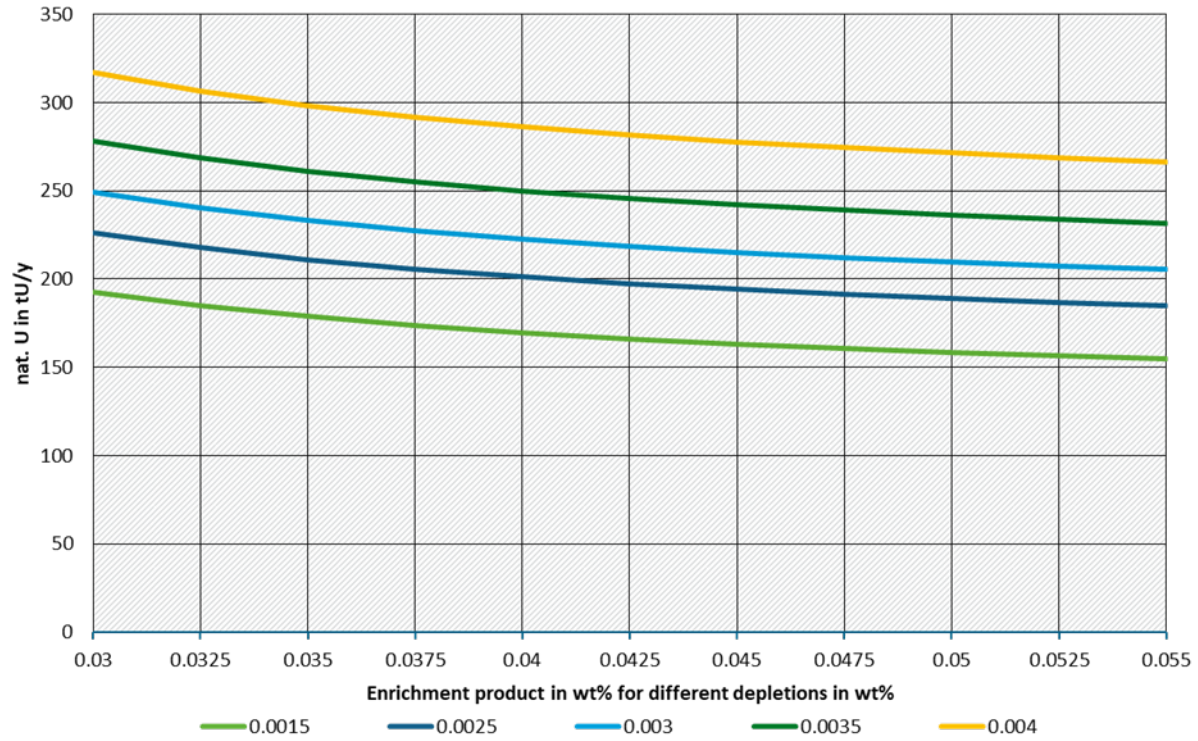
The value function V is unitless, N stand for the concentration of uranium-235, L for the mass flow, p, w and f for product, waste and feed respectively. When calculating the separation work requirement in terms of enrichment or depletion of total masses, kg SWU or kSWU or thousand SWU is used as the unit. If mass flows are used, the term used is separation power requirement, which is usually given in the unit SWU per year (or kg SWU/y). The specification of the enrichment capacity of large enrichment plants also refers to the specification of the separation power.

The equation for the separation work includes the balance between the separation work in the feed stream and the separation work in the waste and product stream, the difference of which corresponds to the total separation work. The separation work of the individual terms scales with the material stream. The separative work necessary for the enrichment process will depend nonlinearly on the depletion and enrichment (see Figure 107).

For the purpose of this analysis we linearized and simplified these dependencies and assumed only three different enrichment levels (%U235) in the LCA chains, with 3.8, 4.0 and 4.2%U235 for burnups of 45, 50 and 55 MWd/tHM respectively. The depletion level is kept constant at 0.26%U235, following the ecoinvent assumptions, which sill reflects current market practices of balancing the amount of SWU needed for enrichment and the costs in energy with the costs of uranium (WNA, 2025b). This value represents a widely used economic optimum in current commercial enrichment operations. Overall fuel cycle costs are minimized by balancing the price of natural uranium and the energy intensity of enrichment. The higher the costs of uranium and the cheaper the energy price, the more it pays off to lower the depletion level and the higher the energy prices and the cheaper the uranium, the more it pays off to use higher depletion levels. Depletion levels are usually kept constant as changing the depletion level in industrial practice is non-trivial, as it requires re-optimizing cascade configurations and operational parameters in the enrichment plant. Adjustments to the depletion level are typically only made if uranium or electricity prices shift significantly.

The corresponding ratios of feed to product mass flows and the production of enriched uranium per SWU respectively the necessary feed of natural uranium per SWU to produce this mass flow is shown in Table 53.

Figure 107: Example for the demand of natural uranium for different uranium enrichments and depletions for a typical 3400 MWth PWR



Example of the natural uranium demand per year for a 3400 MWth PWR with a gross efficiency of 36% and an average load factor of 90%. The different colors show different depletion levels. In the study an depletion level of 0.26% was assumed
Source: own illustration, Öko-Institut

Table 53: Enrichment grade factors

Enrichment%U235	kgUnat / kgUenr	kSWU / kgUenr	kgUnat / kSWU
3.8	7.85	5.31	1.478
4	8.29	5.71	1.451
4.2	8.74	6.12	1.428

KgUnat: kilogram natural uranium; kgUenr: kilogram enriched uranium; kSWU: 1000 SWU. Depletion of 0.26%U235.
Source: Öko-Institut

3.5.2 Energy Consumption

The energy consumption of the centrifuge facilities in this study are those assumed by ecoinvent as 40 kWh/SWU for all western centrifuge facilities (FR, DE, GB, NL, US) as well as 80 kWh/SWU for the Russian enrichment plants and 170 kWh/SWU for the Chinese plant. These values reflect differences in plant age, centrifuge technology generations, and assumed operational efficiency. Energy consumption per SWU is a key parameter influencing the overall greenhouse gas emissions of the enrichment stage and thus has a significant impact on life cycle assessments of nuclear fuel. Regional differences in enrichment energy demand are therefore relevant, as together with regional grid emission factors they translate directly into regional variations in the resulting carbon footprint of uranium enrichment.

3.5.3 Infrastructure

Currently the uranium market for the nuclear industry is dominated by few companies and countries (see Table 54).

Table 54: Operating commercial uranium enrichment facilities, with approximate 2020 capacity

Operator	Capacity in (thousand SWU/year)		
	2022	2025	2030
CNNC (China)	8,900	10,000	17,000
Orano (France)	7,500	7,500	7,500
Rosatom (Russia)	27,100	27,100	27,100
Urenco (Netherlands, Germany, Great Britain, USA)	17,900	17,900	17,900
Other (INB, JNFL)	100	400	800
Total	61,500	62,900	70,300

Source: (WNA, 2025b)

The largest supplier is Rosatom with a capacity of 27.1 millionSWU/y. This corresponds to a dominant share of global enrichment capacity, making countries dependent on Russian services for a critical stage of the nuclear fuel cycle. These dependencies entail geopolitical risks, especially in the context of supply disruptions, trade restrictions, or political tensions. They have therefore become a focus of recent diversification efforts in enrichment capabilities. Russia is also supplying enriched uranium for the European market. Urenco has three plants operating in Europe in the Netherlands, UK, and Germany. Is also provides the gas centrifuge technology for the Orano plant in France. Urenco also operates an enrichment plant in the US with a capacity of 4.9 million SWU/y, which has not reached its full capacity yet. China is building up its enrichment capacity and CNCC can provide 8.9 millionSWU/y and will increase its enrichment capacities in the coming years. Other companies such as Brazil's Indústrias Nucleares do Brasil (INB), Japan Nuclear Fuel Limited (JNFL) have only limited capacities but plan to expand the capacities in the future. Also North Korea, Pakistan and India are operating enrichment facilities, but do not sell products on the international market, and Argentina reopened its small gaseous diffusion plant in 2010, but halted operation again in 2018. Argentina has plans to build a centrifuge enrichment plant (WNA, 2025b). In this study, only centrifuge enrichment is assumed in

- Netherlands (EU5, NA5),
- Germany (EU7),
- Great Britain (EU8_SMR),
- France (EU1, EU1_Gen3, EU1_SMR, EU2, EU4, EU6, EU9_SMR, EU11_Gen3, NA6, RK1,AE1, JP2),
- Japan (JP1),
- Russia (EU3, EU10, RU1, Ru1_Gen3, Ru1_SMR, RU2, RU3, RU4_Gen3, CN2, IN1, ZA1),
- China (CN1, CN1_Gen3, CN1_SMR, CN3),

- USA (NA1, NA1_Gen3, NA1_SMR_v1, NA1_SMR_v2, NA2, NA3, NA4, and
- Brazil (BR1).

The nameplate capacity of the plant in ecoinvent is 1500 thousand SWU/y. Lifetime is difficult to attribute, since new generations of centrifuges and replacements due to failure will be built in the same building. An average lifetime of 30 years is assumed by ecoinvent and used for all enrichment plants in the LCA chains of this study.

3.6 Fuel element fabrication

The uranium, which is enriched to varying degrees depending on the reactor type, is converted from uranium hexafluoride into the chemically stable uranium dioxide (UO_2). This may require separate facilities, which may be located at the site of enrichment plants or fuel element production or at separate sites.

The uranium dioxide is processed in the form of pressed and sintered pellets into fuel rods or fuel elements (cladding tubes and structural elements such as fuel element heads and bases as well as spacers). The production of fuel elements used in light water reactors takes place in three main stages:

1. Production of pure uranium dioxide (UO_2) from UF_6 or UO_3
2. Production of ceramic UO_2 pellets with high density and precise specification (mould).
3. Loading the fuel pellets into the fuel rods, sealing the rods, manufacturing the rigid metal framework for the fuel element – mainly from a zirconium alloy – and assembling the rods into the final fuel element structure.

The conversion of UF_6 into UO_2 can be done in a "dry" or "wet" process (cf. section 3.4). The wet processes are somewhat more complex and result in more waste, but the greater flexibility in terms of the properties of the UO_2 powder is an advantage (WNA, 2022).

Various forms of zirconium alloys are the main materials used for the metal framework of the fuel rods. This zirconium alloy contains small amounts of tin, niobium, iron, chromium and nickel to ensure the required strength and corrosion resistance. For future reactors, so-called Accident Tolerant Fuels (ATF) are also being discussed, in which the cladding tube alloy itself or, for example, a coating is intended to prevent chemical reactions during incidents and accidents. The use of such fuels is also being discussed in the context of the EU taxonomy as a prerequisite for "sustainable" nuclear energy (EC, 2022).

The fuel assemblies are manufactured specifically and individually for the various reactors and differ in their technical design.

In nuclear technology, mixed oxide fuel elements or MOX fuel elements (MOX = mixed oxide) are fuel elements which, in contrast to fuel elements made of pure uranium dioxide, contain an additional oxide. This is usually plutonium dioxide. The plutonium comes from the reprocessing of uranium fuel. In Europe, nuclear fuel today is only reprocessed to produce MOX in France, and to a lesser extent in Russia. The manufacturing process for MOX fuel elements is similar to that for uranium dioxide fuel elements (WNA, 2022).

However, plutonium is a much more dangerous working material than uranium due to its stronger radioactivity and its tendency to form aerosols. Significantly greater safety precautions must therefore be taken. International experience with the commercial production of MOX fuel elements is mixed. For example, a MOX plant built in the United Kingdom was closed again after a short period of operation due to design faults, and the construction of a new MOX plant for weapons plutonium disposal in the USA was cancelled after considerable financial and time

investment. In the EU, an average of around 10 tonnes of plutonium per year from reprocessing has been used as MOX fuel over the last 25 years. This has saved an average of approx. 1000 tonnes of natural uranium per year (European Supply Agency [ESA], 2021).

The life cycle analyses in the literature generally do not differentiate between production processes in fuel element production, although the ecoinvent life cycle assessment database (version 3.8) differentiates between the natural uranium and reprocessing routes upstream of fuel element production.

Worldwide there are a number of fuel cycle facilities, an overview is given in Table 55 for LWR fuel production and for MOX in Table 56.

Table 55: World LWR fuel fabrication capacity, tonnes/yr

Country	Fabricator	Location	Conversion	Pelletizing	Rod assembly
Brazil	INB	Resende	160	120	400
China	CJNF Jianzhong	Yibin	800	800	800
ConverDyn	CBNF	Baotou	0	0	400
Orano	CNNFC	Baotou	200	200	200
France	Framatome-FBFC	Romans	1800	1400	1400
	Orano	Malvési	Under const.		
Germany	Framatome-ANF	Lingen	800	650	650
India	DAE Nuclear Fuel Complex	Hyderabad	48	48	48
Japan	NFI (PWR)	Kumatori	0	383	284
	NFI (BWR)	Tokai-Mura	0	250	250
	Mitsubishi Nuclear Fuel	Tokai-Mura	450	440	440
	Global Nuclear Fuel – Japan	Kurihama	0	620	630
Kazakhstan	Ulba	Ust Kamenogorsk	0	108	200
Korea	KNFC	Daejeon	700	700	700
Russia	TVEL-MSZ*	Elektrostal	1500	1500	1560
	TVEL-NCCP	Novosibirsk	450	1200	1200
Spain	ENUSA	Juzbado	0	500	500
Sweden	Westinghouse AB	Västeras	787	600	600
UK	Westinghouse**	Springfields	950	600	860
USA	Framatome Inc	Richland	1200	1200	1200
	Global Nuclear Fuel – Americas	Wilmington	1200	1000	1000

Country	Fabricator	Location	Conversion	Pelletizing	Rod assembly
	Westinghouse	Columbia	1600	1594	2154
Total			**12,645**	**13,913**	**15,476**

Source: (WNA, 2021). "* Includes approx. 220 tHM for RBMK reactors. ** Includes approx. 200 tHM for AGR reactors. Source: World Nuclear Association Nuclear Fuel Report 2021, Table 8.2 NB the above figures are about 40% above operational capacities, which meet demand."

Table 56: World MOX fuel fabrication capacity, tonnes/yr

Country	Fabricator	Location	Pelletising	Rod/assembly
France	Orano	Marcoule	195	195
India	DAE Nuclear Fuel Complex	Tarapur	50	50
Japan	JAEA	Tokai-Mura	5	5
Orano	JNFL	Rokkasho-Mura*	130	130
Russia	MCC	Zheleznogorsk	60	60
Total			440	**440**

Source: (WNA, 2021)." * Operational by 2022 *Source: World Nuclear Association Nuclear Fuel Report 2019, Table 8.7, updated*"

3.6.1 Infrastructure

Ecoinvent uses only one infrastructure dataset for MOX and UO_2 fuel fabrication due of the lack of particular data on MOX production facilities. The production of MOX fuel reduces the need for fresh U235 and therefore the upstream supply depending on the MOX to LWR fuel in the LCA chain. The reference facility in (Dones et al., 2009) has a namelplate capacity of 900 tU/y and a lifetime of 30 years.

In this study, fuel fabrication is assumed as shown in Table 57.

Canada as a producing country with an operating conversion plant is omitted since it brings no variation to the LCA chain in contrast to the US plant. We assumed a lifetime of 40 years for all facilities for the LCA chains.

Table 57: Fuel fabrication plants used in LCA chains

Country	Lifetime	Type
Brazil		LWR
China	40	LWR
France	30-40	LWR/MOX
Japan	30	LWR
Russia	40	LWR/MOX

Country	Lifetime	Type
South Korea	30	LWR
Sweden	40	LWR
USA	40	LWR

Source: Öko-Institut

3.7 Power Plants

The environmental impacts of NPPs can be allocated firstly to the construction of the facility, secondly to the operational phase and thirdly to the decommissioning of the facility after it's operational lifetime. In addition, fourthly, efforts to prolong the initial design lifetimes of currently operating NPPs must be taken into account.

(Dones et al., 2009) describes several different modules in ecoinvent, that cover the infrastructure (construction and demolition) of NPPs in different countries. The modules cover pressurized water reactors (PWRs) and boiling water reactors (BWRs). The differences between the modules of different countries are mainly due to the electricity mix in the corresponding country. A standard module refers to a NPP of 1000 MWe power of the PWR-type. While reactors with smaller power of 350 MWe were still in operation in Switzerland at the time of assessing the material balances for NPP construction and demolition, they were not explicitly covered in the ecoinvent modules, as no reactor with comparably low power had been constructed in Europe in the past decades. Small reactors are covered in several LCE chains (section 3.7.1.3 and 3.7.4.2.3). While reactors with higher power in Germany and France are covered, differences in the size of the reactors are not explicitly covered in the material balances for the plants, but are addressed by correction factors (Dones et al., 2009, p. 164).

In addition, several modules are defined that cover the operation of NPPs. Major differences refer to the life cycle chain, especially the origin of the uranium fuel as well as the amount of spent uranium fuel reprocessed and of mixed plutonium-uranium (MOX) fuel being used (Dones et al., 2009, p. 164).

For our analysis, we will first discuss the types of NPPs relevant for the baseline year 2020 and the year for the projection of GWP values 2030 and the regions and countries to be considered.

For the major life cycle steps of construction, operation and decommissioning of NPPs we will then discuss major input parameters, summarize the relevant results for the corresponding life cycle step and analyse major sensitivities. As the current fleet of existing reactors ages, long-term operation of NPPs is becoming more important, which is usually not specifically covered in life cycle assessments for nuclear energy. We will therefore also discuss, how a significant prolongation of original design lifetimes of NPPs influences LCA results.

3.7.1 Types of Nuclear Power Plants

According to (IAEA, 2025), as of Mai 15, 2025,

- 417 NPPs with a total of 377.2 GWe are "in operation",
- 23 NPPs with 19.7 GWe are "in suspended operation",
- 61 NPPs with 63.8 GWe are "under construction" and
- 214 NPPs with 108.4 GWe are "permanently shut down".

3.7.1.1 Existing NPPs

Of the NPPs in operation, with 307 NPPs the large majority is of PWR type (pressurized water reactors using light water for cooling and moderation, with an additional four PWRs being in suspended operation), follow by 46 PHWRs (pressurized heavy water reactors, with an additional two PHWRs being in suspended operation) and 43 BWRs (boiling water reactors using light water for cooling and moderation, with an additional 17 BWRs being in suspended operation). While historically PHWRs and BWRs had a relevant share in worldwide NPPs, of the 61 NPPs under construction, 54 are PWRs and only two are BWRs and one is of PHWR type (IAEA, 2025).

Overall, PWRs are the clearly dominant NPP type today and in the foreseeable future.

Besides water-cooled reactors, different so-called novel reactor concepts like liquid metal cooled, gas cooled or molten salt reactors are under development (NEA, 2021a, 2024; Pistner, Englert, et al., 2024). (Pistner, Englert, et al., 2024) recognizes, that for the seven technology lines considered in that study, extensive research and development work has been taking place for several decades, in some cases since the middle of the last century and that the most extensive technical experience is available for the sodium cooled fast reactor (SFR) and very high temperature reactor (VHTR) technology lines. Nevertheless (Pistner, Englert, et al., 2024) concludes, that the time still required for the development of so-called novel reactor concepts is probably in the range of several decades and that it cannot be assumed that such reactor concepts will be used on a relevant scale by the middle of this century. There are currently only two SFR and one high temperature gas cooled reactor (HTGR) in operation worldwide, and only four fast breeder reactors under construction, including the Indian PFBR, which is under construction since 2004, and the Russian lead cooled BREST-OD-300, construction of which officially started in 2021 (IAEA, 2025).

Based on these numbers, we will focus our analysis on NPPs on water-cooled reactors of the PWR type.

Most of the currently operating NPPs have been build more than 20 years ago. During the last 20 years, on average less than seven NPPs have become operational per year. Therefore, the majority of the existing fleet is made up of PWRs of the so-called Generation 2 type (NEA, 2021a; Pistner, Englert, et al., 2024), which are represented by ecoinvent modules for standard PWRs of 1000 MWe power.

3.7.1.2 New NPPs of the Generation 3 type

Since about two decades, evolutionary PWRs of the so-called Generation 3 type have been developed and started to be build. In Europe, the first such plant (Olkiluoto-3) entered operation in Finland in 2022, followed by France (Flamanville-3) in 2024. Other evolutionary PWRs have entered operation in the US, Russia and China amongst others. While they are still of minor importance for the baseline year 2020, we will still take them into account as variations to representative life-cycle chains for four major regions (EU, Russia, the US and China). The changes implemented with respect to the standard ecoinvent module will be described in the following sections.

3.7.1.3 SMRs

Another trend with respect to different NPP technologies is the development of so-called Small Modular Reactors (SMRs) (IEA, 2025a; NEA, 2024; Pistner, Englert, et al., 2024; Pistner et al., 2021). While no universal definition exists, SMRs are usually understood to be NPPs with an electric power output of 300 MWe or less (although some prominent SMR concepts like the

Rolls-Royce SMR have even larger capacity). Depending on the understanding of SMRs, they may encompass traditional water-cooled reactor concepts of PWR or BWR type, but potentially also so-called novel reactor concepts. (NEA, 2024) identified 63 different reactor concepts under development with an additional 35 reactor concepts not under active development in 2024. Several of these concepts have been under development for a decade or longer, with the concepts claimed to be "under development" changing continuously (Pistner et al., 2021).

According to (IAEA, 2025), two water-cooled reactors of SMR-type are in operation in Russia (Akademic Lomonosov-1 and -2), and two prototypes of reactors are currently being build (the Carem-25 being under construction in Argentina since 2005 and the ACP-100 being under construction in China since 2021). If so-called novel reactor concepts are included in the definition of SMRs, there is also one HTR in operation in China since 2023 and one lead-cooled fast reactor in construction in Russia since 2021. While the future relevance of SMRs is still extremely uncertain, it is to be expected that only water-cooled reactor concepts could play any relevant role within the next two to three decades (Pistner, Englert, et al., 2024; Pistner et al., 2021). (IEA, 2025a) assesses, that under current policy settings, SMRs might reach an installed capacity of 40 GWe by 2050, around 10% of today's total installed capacity. Under extremely optimistic assumptions concerning the achievable overnight costs of SMRs, (IEA, 2025a) assesses that SMRs might arrive at a total installed capacity of 190 GWe by 2050. While SMRs play no practical role as of the baseline year 2020, we will still take them into account as variations to representative life-cycle chains for four major regions (EU, Russia, the US, China) comparable to Generation-3 reactor types. The changes implemented for SMRs with respect to the standard ecoinvent module will be described in the following sections.

3.7.2 Regions and Countries with NPPs

The major regions, in which nuclear power is used as of May 2025 are Europe with 167 NPPs in operation (36 of which in Russia), North America with 111 NPPs and Asia with 130 NPPs. Of only minor importance is Latin America with 7 NPPs and Africa with 2 NPPs. For NPPs under construction, 42 of which are located in Asia, 13 in Europe (four of which in Russia), four NPPs in Africa and two in Latin America (of which one is a prototype small modular reactor of only 25 MWe capacity), no commercial NPP is under construction in the US (IAEA, 2025).

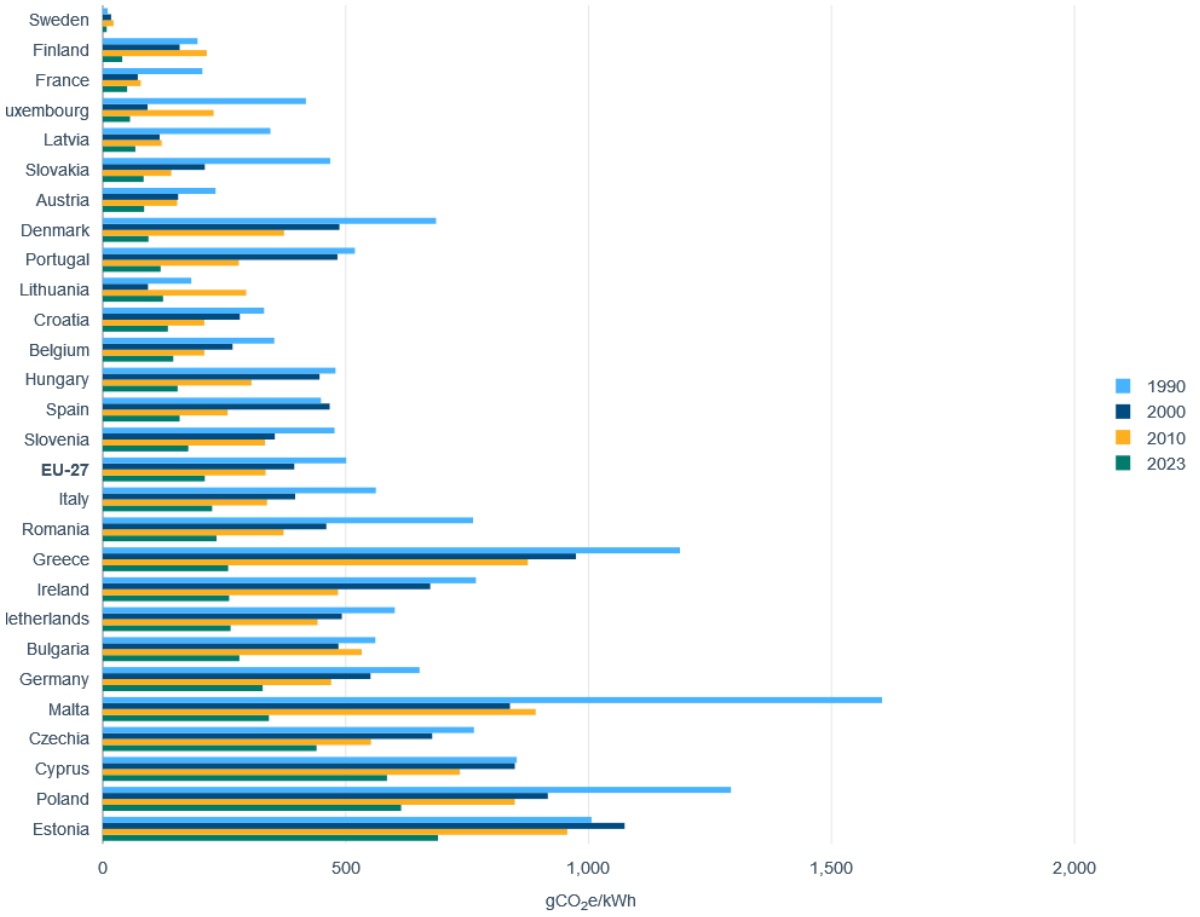
The NPPs in operation are located in 32 countries (including Taiwan), 23 of which operate less than 10 NPPs (IAEA, 2025). As of May 2025, most NPPs in operation are located in

- the US (94), followed by
- China (57),
- France (57),
- Russia (36),
- the Republic of Korea (26) and
- India (21).

One relevant input parameter for the construction and operation of a NPPs is the electricity mix used, which depends on the country where the NPP is located. While the GWP of electricity generation in the EU has dropped from around 500 g CO_2eq/kWh in 1990 to about 250 g CO_2eq/kWh in 2020 (European Environment Agency [EEA], 2025), there is still a large spread within the EU countries. In 2023, for some countries like Sweden or France, the GWP is less than 50 g CO_2eq/kWh, the EU-27 average is at 210 g CO_2eq/kWh and for countries like

Poland it is still above 600 g CO_2eq/kWh, see Figure 108. For other countries worldwide, the GWP of the national electricity mix in 2020 ranges from less than 60 to more than 1500 g CO_2eq/kWh (Bastos et al., 2024). Overall, the country specific GWP of electricity varies by a factor of more than 25.

Figure 108: GWP of electricity generation in EU-27 countries



Source: (EEA, 2025)

Based on the analyses presented in chapter 2 and the above numbers, we will therefore analyse the NPP infrastructure and operation in the following regions and countries:

- three countries chosen as representative for the EU-27 with a low, medium and high GWP of their respective electricity mix as EU (low), EU (medium) and EU (high);
- Russia as a country with a large existing fleet and Turkey as a European country where Russia is building new NPPs;
- the United States of America as representative for North America;
- China, where 28 out of 61 NPPs are being build; as well as
- India, Japan, the Republic of Korea and the United Arab Emirates as countries with either a (relatively) large existing fleet or where new NPPs have recently been build;
- South Africa as the only country in Africa already using nuclear power and

- Brazil as representative for Latin America.

3.7.3 Operation of Nuclear Power Plants

For the operation of a NPP, the major material input is the fuel used to produce energy. While the environmental impacts of the fuel itself arise in the front-end and back-end processes (mining, conversion, fabrication, enrichment, reprocessing and (final) storage), during operation of the NPP the type (uranium fuel vs. MOX fuel), amount (fuel mass) and characteristics (enrichment level and burn-up) of the fuel are determined.

The total energy released by the fission process in the fuel during operation of the NPP determines the thermal power of the plant (for a more formal definition of the terms introduced here see Appendix A). This thermal power is used to produce steam, which is transported to a turbine that drives a generator to produce electricity. The amount of electricity produced is given by the gross capacity of the NPP. Parts of this electricity are needed within the NPP for the operation of equipment like cooling pumps or I&C equipment. The remaining amount of electricity fed into the electricity grid is given by the net capacity of the plant. The ratio of the net capacity to the thermal power of the plant determines its (net) electric efficiency.

During operation, NPPs typically have to be shut down for a certain time frame to unload used fuel and reload fresh fuel. Furthermore, NPPs may lower their power output or be shut down completely for either operational reasons like high external cooling water temperatures or low water availability during hot or dry summers or for safety reasons like malfunctions of components or findings at periodic inspections. In addition, NPPs may take part in load following operations, which also reduces its overall power output. The fraction of the nominal power being produced defines the load factor of a NPP.

Finally, during operation of the NPP, other material and energy inputs are needed for operational and maintenance purposes.

3.7.3.1 Fuel: type, burnup and enrichment

NPPs use either uranium fuel or a mixed-oxide (MOX) fuel with plutonium arising from reprocessing spent nuclear fuel as the fissile component and uranium as a matrix, compare section 3.6. Fuel production is discussed in detail in (IAEA, 2015b), current development are discussed in (IAEA, 2024f).

Uranium fuel consist of uranium oxide that is enriched in its fraction of the (fissile) uranium-235 content, compare section 3.5. Depending on the grade of enrichment and the fuelling scheme in the reactor, a specific fuel burn-up can be achieved.

The fuel burn-up is defined as (NEA, 2006):

“The discharge burn-up of nuclear fuel is usually defined as the thermal energy output during the lifetime of the fuel divided by the initial mass of heavy metal (denoted HMi). The unit of burn-up (or thermal energy production) is Giga-Watt days per tonne of initial heavy metal. One GWd corresponds to an energy of 1E12 x 24 x 60 x 60 Joules = 8.64E13 Joules, and is a more convenient unit than Joules. The energy output is related to the initial heavy metal mass as a fixed reference point; the actual heavy metal mass varies with burn-up as the fissile elements are converted to fission products. … A burn-up of 1 GWd/tHM corresponds roughly to a fission fraction of 0.1%; therefore fuel at 50 GWd/tHM will have fissioned approximately 5% of the heavy atoms.”

An increase in fuel burn-up has some advantages for NPP operation. First, it gives the operators more flexibility with respect to fuel usage and fuel loading schemes. Second, with increasing

burn-up, the amount of fresh fuel needed and spent fuel arising for a given energy output decreases. This reduces costs of fuel production and assembly as well as storage cost for spent fuel. Furthermore, less transports are needed for fresh and spent fuel. On the other hand, costs of enrichment increase, so depending on cost for natural uranium and enrichment services, there may be a (changing) optimum concerning fuel cycle cost. On the other hand, higher burn-ups also lead to higher burden for the fuel during operation, including fission gas production in the fuel, neutron damage to the fuel and cladding, cladding corrosion and thermal and mechanical loads.

Concerning the burn-ups achieved in different NPPs, (NEA, 2006) gave the following numbers:

"Average discharges are currently in the region of 50 GWd/t and for burn-ups up to and at least a little beyond this figure, there is a clear economic incentive to continue the trend. But the question for which there is no definitive answer at present is whether this historic trend will continue indefinitely or whether there will be a technological limit to PWR burn-ups."

With respect to the expected future development, (NEA, 2006) stated:

"It is unclear whether the almost constant rate of increase of historical region average discharge burn-ups will continue in the future. It is conceivable that there may be a lack of incentive for increasing burn-ups much beyond 60 GWd/t (for instance, due to the need for enrichments higher than the current 5.0 w/o criticality limit) or that technological barriers may intervene."

Overall, the development from the 1970 till 2006 were summarized by (NEA, 2006):

"In the past 10 years, in the face of growing electricity demand, some PWRs have been up-rated by as much as 10%, with initial enrichments now as high as 4.6 w/o. Core reload management has been further optimised and peaking factor criteria relaxed in order to meet the demands imposed by up-rating. Other significant developments have included the introduction of mixer vanes and intermediate mixer grids designed to increase thermal-hydraulic margins. The use of thinner RCCA guide tubes has in some instances led to a loss of rigidity of fuel assemblies during irradiation and the consequent increased risk from incomplete rod insertion (IRI). Very recently, grid-to-rod fretting has become the dominant fuel failure mechanism in some plants, possibly caused by irradiation-induced relaxation of grid-retaining forces at the higher burn-ups that are now routine. Through these developments, licensed maximum average assembly discharge burn-ups gradually evolved from approximately 37 GWd/t in the 1970s to typically around 55 GWd/t today, and as high as 60 GWd/t in Germany and Switzerland.

Since that, burn-ups have not been substantially increased. Current and future developments are summarized by (IAEA, 2024e):

"Nuclear fuel vendors and NPP operating organizations continue extending the discharge burnup of nuclear fuel assemblies within the operating envelope accepted by regulatory bodies. The current operational limit for the discharge burnup varies slightly among licensees, but in many Member States it corresponds to a rod average burnup of 62 gigawatt-day/tons of uranium (GWd/tU) (average fuel sub-assembly of 55 GWd/tU), or other equivalent criteria. Nuclear fuel vendors and NPP operating organizations might obtain economic benefits, combined with the strategic approach for the nuclear fuel cycle, from such high burnup operation via, for example, longer reactor cycle operation, as well as purchase, transport and handling of fewer fuel assemblies for the core reloading.

Currently, increased rates of the fuel discharge burnup (e.g. beyond 62 GWd/tU) are also being pursued by Member States in the framework of the development of advanced technology for nuclear fuel (which include so-called Accident Tolerant and Advanced Technology Fuels, ATFs). In particular, higher rates of the nuclear fuel discharge burnup are researched in association

with advanced fuel and cladding materials, which might involve higher fissile enrichment rates (in some cases exceeding 5%) in order to counterbalance increased parasitic neutron absorption in the cladding."

In summary, historically, the burn-ups have increased from initially around 30 GWd/tHM in the 1970s to somewhat more than 50 GWd/tHM in the 2000s. While advanced fuels with better safety features and possibly higher burn-ups may be introduced to a larger degree at some point in the future, during the last two decades the increase in burn-ups was rather limited compared to the development between the 1970s and the 2000s.

(Dones et al., 2009, Tab. 9.12) lists specific burnups achieved with fuel elements of different enrichment in a Swiss PWR in the years 2000-2002. With an initial enrichment of 4.1%, burnups of 48.6-60 GWd/tHM have been achieved, with an enrichment of 4.3% burnups of 51.4-64.4 GWd/tHM.

While ecoinvent (Dones et al., 2009, Tab. 9.13) assumed average burnups of 42.8, 45, 50 and 53 GWd/tHM for different countries, with corresponding enrichments of 3.8%, 3.9%, 4.0% and 4.2%, for the situation in the baseline year 2020 and the projection year 2030 we will assume somewhat higher average fuel discharge burn-ups of 45-55 GWd/tHM.

The enrichment needed to achieve a given burn-up is again dependent on the specific fuel element design and the fuel reloading scheme. Typically, depending on the fuel burn-up, the fuel stays for 3-5 years in the reactor. Depending on the length of one fuel cycle (the time between two fuel reloads), that typically lies between 12 and 24 month, one third to one fifth of the full core of an NPPs is replaced after one fuel cycle.

One specific relation between the initial fuel enrichment and the achieved burn-up depending also on the cycle length is shown in Table 58.

Table 58: Initial uranium-235 enrichment versus average assembly burn-up for a specific reactor type and reloading scheme

Number of feed assemblies	Average assembly discharge burn-up [GWd/tHM]	Average initial uranium-235 enrichment [% U-235]
64	46.441	3.894
60	49.537	4.077
56	53.075	4.283
52	57.154	4.537
48	61.973	4.834

Source: (NEA, 2006, Table 2)

(Pistner, 2006b) analysed the achievable burn-up for uranium and MOX fuels depending on the initial enrichment and the number of cycles the fuel remains in the reactor for a generic reactor based on a linear reactivity model. For uranium fuels used for three cycles in the reactor (typically used for lower burn-ups), an initial enrichment of 3.74%, 4.10% and 4.47% corresponds to an achievable burn-up of 45, 50 and 55 GWd/tHM. With four cycles in the reactor (typically used for higher burn-ups), the corresponding burn-ups can be achieved with 3.52%, 3.86% and 4.20% enrichment.

The numbers show a relatively linear relationship between enrichment and burn-up in the burn-up range considered here. Due to the uncertainties related to this relationship depending on the

actual reactor type, reactor core design and refuelling scheme and the minor overall impact of small changes in the relation between initial enrichment and achieved burn-up in comparison to the overall difference between the lower and upper bound of the burn-up assumed in the different life cycle chains, we define three burn-up values (Low, Medium, High) as defined in Table 59.

Table 59: Burn-up and uranium-235 enrichment used in the life cycle chains

Burn-up	Average initial uranium-235 enrichment [%]	Average assembly discharge burn-up [GWd/tHM]
Low	3.75	45
Medium	4.00	50
High	4.20	55

Source: Oeko-Institute

The amount of fresh fuel (in kg uranium) needed to produce one kWh of electricity is related to the burn-up (in GWd/tHM) and the (net) electric efficiency (see next section) according to

Equation 1: Demand of fresh fuel per kWh of electricity produced

$$fuel = \frac{1}{Burnup * 24 * 1000 * efficiency}$$

Source: Oeko-Institute

For example, with an average burn-up of 50 GWd/tHM and a (net) electric efficiency of 0.33, a fuel demand of

- 2.52E-6 kg/kWh

arises.

If parts of the spent fuel are reprocessed, separated plutonium arises which is used as fissile material to produce MOX fuel, compare sections 3.6 and 3.9. This MOX fuel replaces a certain fraction of fresh uranium fuel, thus reducing the necessary uranium fuel input. As the use of MOX fuel increases fuel cycle costs and the use of MOX fuel in current reactors is typically limited due to safety and licensing reasons, only very few countries make use of MOX fuel today. Still, for some life cycle chains, we assume that a certain fraction of the fuel is made up of MOX fuel.

(Dones et al., 2009, Tab. 9.13) assumed MOX fractions of 0.08 to 0.15, but at the same time made independent assumptions on the fraction of spent (uranium) fuel being reprocessed. If more plutonium arises from reprocessing of spent fuel than is used to produce MOX fuel, stockpiles of separated plutonium are being built up, which is what happened in countries reprocessing spent fuels during the last decades. The amount of separated plutonium stored at the beginning of 2023 was 560 tonnes, of which 420 tonnes were produced outside of weapons programs (International Panel on Fissile Materials [IPFM], 2024). The future disposal of these stockpile either as MOX fuel or as waste to be disposed of will lead to additional costs and environmental impacts.

To cover impacts of reprocessing and MOX use of the plutonium, we will therefore assume a balance between the fraction of MOX fuel used in NPPs and the amount of reprocessed spent fuel, such that no separated plutonium remains, that must be stored and disposed of in the future.

According to (Pistner, 2006b), for MOX fuels used for three cycles in the reactor (typically used for lower burn-ups), an initial total plutonium content of 7.7%, 8.6% and 9.4% corresponds to an achievable burn-up of 45, 50 and 55 GWd/tHM. With four cycles in the reactor (typically used for higher burn-ups), the corresponding burn-ups can be achieved with 7.2%, 8.0% and 8.8% total plutonium content. We will therefore use the total plutonium content given in Table 60 for the three burn-up values (Low, Medium, High) as defined above.

Table 60: Burn-up and total plutonium content in MOX fuel used in the life cycle chains

Burn-up	Total plutonium concentration in fresh MOX fuel [%]	Average assembly discharge burn-up [GWd/tHM]
Low	7.7	45
Medium	8.3	50
High	8.8	55

Source: Oeko-Institute

With an average assembly burn-up of 50 GWd/tHM, the fraction of total plutonium in spent fuel is around 1% of the initial heavy metal mass. To reach an equivalent burn-up with MOX fuel, the total plutonium content of fresh MOX fuel must be approximately x=8.3%. Therefore, for 1% of MOX fuel, 8.3% of spent fuel must be reprocessed. MOX fuel itself is not reprocessed today. As the amount of fresh uranium fuel is reduced by the amount of MOX fuel used, if all spent uranium fuel is reprocessed, a maximum MOX fuel fraction of (100/(x+1))% = 10.75% will result. This means that MOX can replace a maximum of only around 10% of the fuel.

We will thus assume three different MOX fuel fractions in the life cycle chains, the maximum value corresponding to a full recycling of all spent uranium fuel, corresponding to a MOX fuel fraction of 10.2%, 10.75% or 11.5% depending on the assumed burn-up, as well as one halve or one quarter of these values.

3.7.3.2 Thermal Power and Efficiency

NPPs do have different thermal power and a different efficiency in transforming the released thermal power to electric energy feed into the electric grid. While the thermal power fundamentally corresponds to a different construction effort, compare section 3.7.4, a difference in thermal power at the same time changes the electricity output and the fuel consumption and thus does not fundamentally change the operational impacts of a NPP.

Depending on the thermal efficiency, for a given amount of fuel use in the reactor up to a given burn-up as discussed in the last section, a different amount of electricity is produced. Different types of NPPs have different design efficiencies, depending on internal parameters like the operational temperatures, the efficiencies of the turbine and generator systems or the internal power consumption of operational and safety systems. In addition, the temperature of the external cooling water is relevant for the achievable temperature delta and therefore the efficiency of the system. The specific location of the plant and the available cooling options therefore also play a role in the life cycle assessment of a plant. Data on the electricity production of nuclear power plants in operation worldwide and their nominal output are listed in IAEA databases, for example, so that conclusions can be drawn about the efficiency levels (IAEA, 2025)

3.7.3.2.1 Existing NPPs

To estimate the efficiency of NPPs on a regional basis, taking into account differences in reactor types, the age of the nuclear fleet, use of cooling towers or river or sea water for cooling and regional and local external parameters like water and air temperatures, we evaluate the actual values for the NPP fleet in operation in the countries covered by the life cycle chains. To this end, we calculate the total net electric capacity of all NPPs listed as "in operation" in the IAEAs Power Reactor Information System (IAEA, 2025) as well as the total thermal capacity of the fleet. The average efficiency of the respective country fleet is then given by the ratio of the net electric capacity to the thermal capacity. The corresponding values are listed in Table 61.

Table 61: Total net electric capacity and total thermal capacity for the operational fleet of NPPs in the countries covered by the life cycle chains

Country	Net electric capacity [MW]	Thermal Capacity [MW]	Average efficiency of the respective country fleet
EU (low)	61.040	182.540	0.334
EU (medium)	2.188	7.259	0.301
Russia	27.612	89.331	0.309
United States	90.319	295.024	0.306
China	52.893	154.214	0.343
Korea, Republic of	23.832	70.862	0.336
India	6.301	22.730	0.277
UAE	3.930	11.949	0.329
Japan	9.486	29.432	0.322
South Africa	1.842	5.550	0.332
Brasil	1.854	5.646	0.328

Source: Data according to (IAEA, 2025) as of 2023

These values will be used for the calculation of the life cycle impacts for the baseline year 2020. For the EU (high) country we chose input values for a country without NPPs in operation. Therefore, we assumed an efficiency value for a Generation 3 type reactor as discussed below. Also, for Turkey we assumed the average value for the reactor fleet under construction. We further assume, that the national average efficiency values will not change significantly between 2020 and 2030. Nevertheless, for some countries larger NPPs of the Generation 3 type or possibly even so called small modular reactors (SMRs) will be build, compare section 3.7.1. The variation between the average efficiency in different countries is around 2 percentage points, only India has a significantly lower average efficiency due to the high share of pressurised heavy water reactors, that have a lower design efficiency than typical other light water reactors.

3.7.3.2.2 New NPPs of the Generation 3 type

Generic data on different reactor types in operation and under construction today are given in (IAEA, 2024a) and listed in Table 62.

Table 62: Net electric capacity and thermal capacity for NPPs of different types in operation and under construction in the countries covered by the life cycle chains

Type	Thermal Capacity [MW]	Net Capacity [MWe]	Efficiency
ABWR	3,926	1,350	0.34
AP1000	3,400	1,100-1,200	0.324-0.353
APR1000	2,815	1,000	0.355
APR1400	3,983	1,400	0.351
EPR	4,590	1,650	0.359
VVER	3,200	1,082	0.338

Source: Data according to (IAEA, 2024a) as of 2023

While these generic values are representative for the specific reactor design, actual values for specific projects may differ. For specific NPPs currently under construction, which are typically of the Generation 3 type, different efficiencies will be achievable. Table 63 lists data for reactors under construction as of 2023 according to (IAEA, 2025).

Table 63: Net electric capacity and thermal capacity for NPPs of different types under construction in the countries covered by the life cycle chains as of 2023

Country and Type	Project	Thermal Capacity [MW]	Reference Unit Power (Net Capacity) [MWe]	Efficiency
China AP-1000	HAIYANG-1 and 2	3415	1170	0.343
China AP-1000	SANMEN-1 and 2	3415	1157	0.339
China CPR1000	FANGCHENGGANG-1-2	2905	1000	0.344
China CPR1000	FANGJIASHAN-1-2	2905	1012	0.348
China EPR	TAISHAN-1 and 2	4590	1660	0.362
China HPR1000	FANGCHENGGANG-3-4	3150	1000	0.317
China HPR1000	CHANGJIANG-3-4	3190	1000	0.313
China HPR1000	FUQING-5	3050	1075	0.352
France EPR	FLAMANVILLE-3	4300	1630	0.379
ROK APR1400	SHIN-HANUL-1	3983	1414	0.355
ROK APR1400	SHIN-HANUL-2	3983	1340	0.336
Russia VVER V-491	LENINGRAD 2-2	3200	1101	0.344
Turkey VVER V-509	AKKUYU-1-4	3200	1114	0.348

Country and Type	Project	Thermal Capacity [MW]	Reference Unit Power (Net Capacity) [MWe]	Efficiency
UAE APR1400	BARAKAH 1-4	3983	1337	0.329
US AP-1000	VOGTLE-3 and 4	3400	1117	0.329

Source: Data according to (IAEA, 2025) as of 2023

Therefore, the thermal efficiencies for the

- AP-1000 are 32.9% (US) and 33.9% and 34.3% (both China),
- APR1400 are 32.9%, 33.6% and 35.5%,
- CPR1000 are 34.4% and 34.8%,
- EPR are 36.0%, 36.2%, 37.2% and 37.9% (France),
- HPR1000 are 31.3%, 31.7% and 35.2% and
- VVERs are 34.4% (Russia) and 34.8% (Turkey).

Country specific values (an average value for China) for the corresponding plant types will be used in the life cycle chains for Generation 3 reactors, the variation between the same reactor type in different countries is typically around 2 percentage points.

3.7.3.2.3 SMRs

As discussed in section 3.7.1, we restrict our evaluation of SMRs to water cooled reactor concepts, as we do not expect different types of reactor designs to be available on a commercial basis for some decades to come. Typical design values for the most relevant water-cooled SMR designs are given in Table 64 based on (IAEA, 2024a).

Table 64: Net electric capacity and thermal capacity for SMRs of different types possibly relevant in the countries covered by the life cycle chains

Type	Country	Thermal Capacity [MWth]	Net Capacity [MWe]	Efficiency
ACP100	China	385	100	0.260
BWRX-300	US, Canada	870	300	0.345
CAREM-25	Argentina	100	25	0.250
KLT-40S	Russia	150	32	0.213
NuScale	US (licensed)	200	57	0.285
	US (planned)	250	77	0.308
NUWARD	EU (low)	540	170	0.315
SMART	ROK	365	90	0.247
UK-SMR	UK	1358	470	0.346

Source: Data according to (IAEA, 2024a)

It is evident from the table, that efficiencies of water cooled SMRs differ strongly by more than 10 percentage points, depending on the design, but are generally lower than those of typical

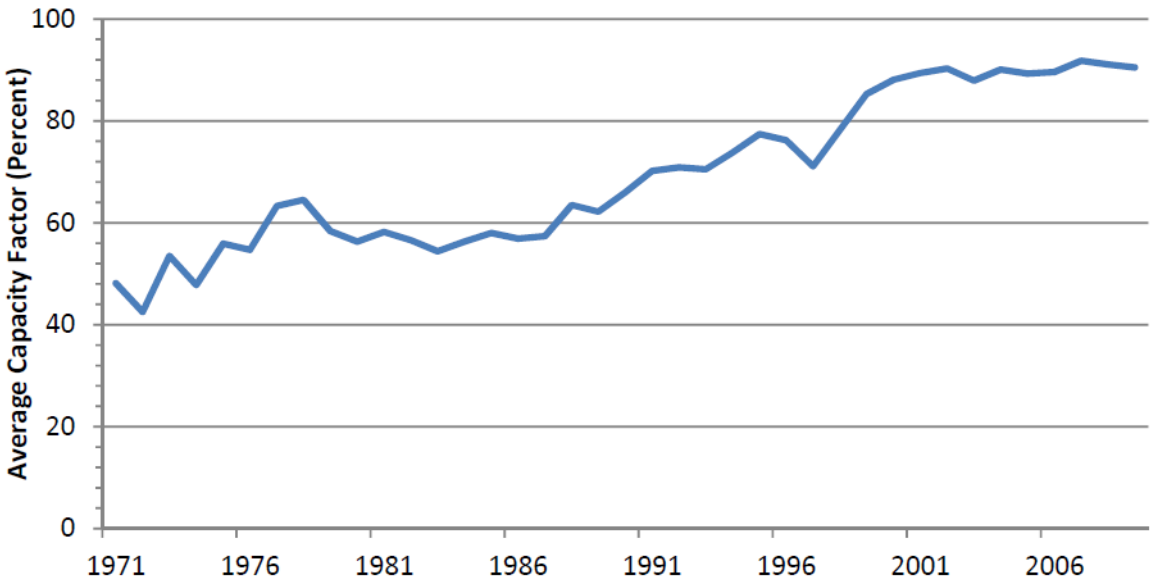
larger light water reactors. The final efficiency for a commercial system may vary from the values given above, as can be deduced from the case of the NuScale project, for which the design that was licenced by the US NRC had an efficiency of 28.5%, while the current design under development shall have an efficiency of 30.8%.

3.7.3.3 Load factors

Another important parameter for the operation of NPPS is the load factor (LF, or capacity factor, see appendix A) (Lenzen, 2006; Sovacool, 2008). (Sovacool, 2008) reports that many studies on the GHG emissions of nuclear power plants assume load factors/capacity factors of 85-98%, whereby the actual availability is lower. The capacity factor of nuclear power plants will possibly decrease significantly in the long term in a system with a high proportion of renewable energies. But for the baseline year 2020 and the projection year 2030 we assume, that current values are still representative.

An evaluation of the capacity factors from 1971 to the 2009 in the US is given by (Skone et al., 2012). The load factors increased considerably due to a continued optimization of planned downtimes of the reactors in combination with an increase in fuel burn-up and associated longer fuel cycles, compare Figure 109. A part of the increase is also allocated to power uprating in existing plants, which led to higher electricity production compared to initial reference power levels which were used to calculate the corresponding load factors.

Figure 109: Average capacity factors in the US between 1971 and 2009



Source: (Skone et al., 2012), Figure 2-1

The load factor or the unit capability factor is determined by several different factors.

One factor is due to the design of the facility. Depending on the design, a planned downtime is required for refuelling every one to two years. Furthermore, in some designs, necessary safety checks could be performed during operation of the plant, with other designs, such checks can only be performed during planned downtimes.

Depending on the requirements in the country where the plant is operated, periodic safety checks must be performed typically every ten years, that also require prolonged planned downtimes of the facility. Especially with ageing plants, downtimes may become longer due to the need for repair, replacement of aging parts or necessary safety enhancements. These

planned downtimes may be prolonged depending on the operator's performance, its maintenance strategy and the availabilities of qualified staff as well as spare part needed for maintenance and repair. In addition to planned downtimes, the facility may be operated in load following mode, compare section 2.9. In load following mode, the output power is reduced depending on the electricity need at a certain point in time. This will reduce the overall produced electricity during the lifetime of a plant.

Besides such planned restrictions in power productions, unplanned downtimes or load reductions may take place. Reasons for such unplanned reductions may be incidents or accidents happening in the plant or country, requiring downtimes for safety reasons. Other reasons may be restrictions in the supply of cooling water capacity due to draught or high water-temperatures, compare section 2.8.

As all of these factors may depend on the country where a plant is operated as well as on the performance of the actual plant itself.

Therefore, we have analysed the country specific average load factor according to (IAEA, 2025) and (IAEA, 2024c) achieved during the time period 2011 until 2021. For each country and year, we calculated the annual average load factor as the quotient of the sum of the net capacities of all reactors in operation, weighted with the reactor specific load factor and the sum of the net capacities of all reactors in operation, see Table 65.

Table 65: Annual average load factors (LF) for countries covered by the life cycle chains

Year	EU (low)	Russia	US	China	ROK	India	Japan	SA	Brasil
2021	72.72%	79.10%	92.68%	89.50%	68.54%	n.a	n.a	75.38%	n.a
2020	n.a.	n.a.	n.a	n.a.	n.a	n.a	n.a	n.a	n.a
2019	74.01%	79.01%	93.22%	90.08%	71.58%	n.a	22.72%	83.60%	n.a
2018	76.41%	74.26%	92.64%	90.91%	61.14%	66.40%	16.77%	66.65%	90.36%
2017	73.16%	76.38%	91.90%	89.88%	71.02%	37.64%	8.45%	94.35%	89.66%
2016	75.97%	75.95%	92.48%	90.68%	77.14%	64.78%	7.97%	93.60%	90.17%
2015	80.76%	80.17%	91.06%	88.39%	80.28%	77.52%	1.16%	68.30%	84.74%
2014	80.90%	77.91%	91.78%	88.56%	82.33%	89.29%	0.00%	92.05%	88.57%
2013	77.97%	77.16%	90.94%	90.07%	75.94%	86.43%	3.66%	83.95%	83.89%
2012	79.70%	77.56%	86.53%	89.25%	82.69%	91.64%	9.79%	77.50%	92.05%
2011	80.74%	77.44%	89.80%	88.89%	81.75%	91.53%	45.40%	82.40%	95.77%
Average	77.23%	77.50%	91.30%	89.62%	75.24%	75.65%	12.88%	81.78%	89.40%
Used	77%	78%	91%	90%	75%	76%	50%	82%	90%

Sources: (IAEA, 2025) and (IAEA, 2024c) as of 2023

For EU (medium) and EU (high) we assumed average load factors of 92% and 90% respectively. For the UAE, only very limited information on actual reactor performance was available, based on the available data we assume a load factor of 78%, which might be too low for the relatively new fleet of reactors.

A clear outlier with respect to the annual load factors is Japan, where several NPPs are officially listed as "in operation" in (IAEA, 2025) and have only recently been relisted as being in "suspended operation". Based on the performance between 2011 and 2021of all NPPs not being permanently shutdown, the Japanese fleet has only achieved an average load factor of 12.88% in this time frame due to shutdowns following the Fukushima accident, which is not representative for the total lifetime of the Japanese fleet. Therefore, we calculated the weighted average load factor for the Japanese fleet based on the cumulative load factor for all Japanese NPPs in operation or suspended operation in 2023, which gives an average value of 50.03% for a total of 33 NPPs.

From the average load factors given in Table 65, several conclusions can be drawn.

It is evident, that in no country an average load factor of 95% or higher was achieved. Such high load factors are sometimes assumed in life cycle assessments and are the values typically claimed by developers of nuclear power plant as values for the lifetime-performance of new reactors.

Real values for load factors spread between 75.24% and 91.30% for South Korea and the US respectively, showing that a large country specific difference in load factors is to be expected.

Finally, the impact of events with high safety importance becomes evident in the specific case of Japan. After the severe accident in the Fukushima-Daiichi plant on March 11, 2011, Japan has shutdown most of its reactor fleet. While it still intends to bring back online at least some parts of its existing fleet, the average load factor for the power plants still being officially claimed to be "in operation" was only 12.88%, a value that might be used as a sensitivity parameter for the load factor in our assessment.

3.7.3.4 Other inputs

Energy is required for the operation of the nuclear power plant, for example for the necessary cooling energy, the energy for maintenance and the energy for the emergency diesel generators (Sovacool, 2008). This requires gas, fuel and electricity. Various materials are also required: e.g. chemicals for cooling water treatment, operating materials such as resins, oils, greases, activated carbon filters or boric acid. Energy is also required for changing fuel elements and maintaining the reactors, as well as for spare parts and necessary modernisation measures. The LCA study by (Vattenfall, 2019) also includes the impacts for the construction of the transmission grid in the operation step of NPPs.

The external energy requirement is particularly relevant for overhauls (approximately 1 week per year) and longer-term plant shutdowns (e.g. for retrofits) and must be taken into account accordingly in a data module for the operation of nuclear power plants. Even when not producing electricity, nuclear power plants require external power to maintain essential safety functions, including cooling of the reactor core and spent fuel as well as operation of instrumentation and control systems.

The annual materials demand for the standard 1000 MWe PWR in econinvent is given in Tables 9.16, 9.18 and 9.19 in (Dones et al., 2009) and comprises especially resins, boric acid and bitumen.

During operation, water is used to dispose of heat via cooling towers and/or auxiliary cooling water circuits. The total amount of water withdrawn from either sea or river reservoirs is given as 8.43 kg/kWh (Dones et al., 2009, p. 196).

For the test of emergency diesel groups, an energy demand of 3.7×10^{-4} MJ/kWh is assumed (Dones et al., 2009, p. 197).

During operation of a NPPs, different radioactive waste forms arise. Typically, the radioactive wastes are categorized as high-level or low- and medium-level wastes. During operation, the spent nuclear fuel constitutes the high-level waste arising and will be covered by the following life cycle steps of interim storage, conditioning and final disposal or of reprocessing.

Besides this, different low- and medium-level wastes arise. These may have the form of ion exchange resins, evaporator concentrates or sludges; burnable wastes such as clothing, packaging or active oil residues; and non-burnable radioactive residues such as mineral wool from thermal insulations or electric cables (Dones et al., 2009).

Low- and medium level wastes from reactor operation will first be stored and then conditioned, typically either by direct immobilization with cement, by incineration and immobilization of the ashes with cement or by pressing (for volume reduction) and immobilization with cement. The resulting wastes will typically arise as steel barrels of 200 l volume. The typical volume arising for a NPP of 1000 MWe is about 1.8×10^{-9} m^3/kWh. For the conditioning of this low- and medium-level wastes, 4×10^{-7} kg/kWh of steel and 9.2×10^{-7} kg/kWh of concrete is needed, the amounts of which are included in the ecoinvent module for operation of NPPs (Dones et al., 2009, p. 216).

3.7.4 Construction of Nuclear Power Plants

For the life cycle analysis, both the materials needed for NPP construction as well as the energy needed during the construction phase are relevant. Furthermore, the environmental impact associated with the construction of an NPP has to be allocated to the total electricity produced, which depends on the lifetime of the plant.

NPPs have different design lifetimes, resulting in a different actual plant lifetime and thus a different amount of total electricity produced. The assumptions made concerning the country specific plant lifetimes used in the different life cycle chains will be discussed in the following subsection 3.7.4.1. These plant lifetimes also change with time and depend on measures taken to enable longer plant lifetimes, which are discussed in section 3.7.6.

NPPs are complex constructions: A typical nuclear power plant contains large quantities of steel, concrete, cement, as well as approx. 80 kilometres of piping with approx. 25,000 welds, 1400 km of electrical cables, thousands of electric motors and batteries, cooling systems with the necessary pumps, valves, seals, the interim storage facility for the spent fuel and much more (Sovacool, 2008). These materials are highly relevant since the production of materials such as steel and cement is associated with significant greenhouse gas emissions. Therefore, the material intensity of the plant has a direct impact on its life cycle carbon footprint. Different NPP types require different amounts of materials as well as energy during the construction phase. These differences will be discussed in subsection 3.7.4.2

3.7.4.1 Plant Lifetimes and total electricity production

The environmental impact caused by the energy and material consumption during the construction phase of an NPP must be allocated to the total electricity produced by the facility. The country specific average annual electricity E(ann) in MWh/a produced is given by the net electric capacity P(net) of a NPP given in MWe, multiplied with one year (8760 hours) and the average (country specific, dimensionless) load factor as given in Table 65. The country specific total electricity E(tot) in kWh produced is then given by the average annual electricity production multiplied with a factor of 1000 and with the country specific total lifetime (l) of a NPP:

$$E(tot) = E(ann) * 1000 * l = P(net) * 8760 * LF * 1000 * l$$

For a NPP with a net electric capacity of 1000 MWe, a load factor of 90% and a plant lifetime of 40 years, this would correspond to a total electricity production of 3.2×10^{12} kWh.

The fraction of one such NPP needed to produce one kWh is then given by the reciprocal value of

- 3.17×10^{-12} items/kWh.

When assessing the lifetime to be expected for today's NPPs, it makes sense to compare the age distribution of the reactors currently in operation with those that have already been decommissioned. Of course, it must also be considered that the plants built in the 1960s and 1970s were planned for a service life of 30-40 years, whereas plants built today are already designed for longer lifetimes.

The average age of the worldwide nuclear fleet as of mid-2024 is 32 years. Out of 408 NPPs in operation in mid-2024, 22 are older than 50 years and 105 are older than 40 years. (M. Schneider & Froggatt, 2024). At the same time, 213 NPPs have been permanently shutdown with an average age of 28.3 years. Out of these,

- 42 NPPs were between 41 and 50 years,
- 56 NPPs were between 31 and 40 years,
- 58 NPPs were between 21 and 30 years,
- 29 NPPs were between 11 and 20 years and
- 28 NPPs were between 0 and 10 years (M. Schneider & Froggatt, 2024).

The average age of NPPs being shutdown has increased over time. While in the 1980 and 1990 it was below 30 years, for the last 29 NPPs shutdown in between 2019 and 2023 the average age was 42.8 years (M. Schneider & Froggatt, 2024).

In more recent LCA studies for nuclear energy, a lifetime of 60 years is assumed (UNECE, 2021; Vattenfall, 2019), although no reactor in the world has yet reached such an age. Whether such lifetimes can be achieved in existing plants depends on ageing and safety considerations (Frieß et al., 2023; Haverkamp, 2014; IAEA, 2018a) as well as economic aspects (IEA & NEA, 2020). The plant lifetimes as originally considered depending on NPP types as well as current plans for lifetime extensions in different countries are discussed in (IAEA, 2024c). It is important to note that the 60-year value is a theoretical assumption used for consistency in modelling, not an empirical average. Actual achievable lifetimes are yet uncertain and depend on plant-specific technical and regulatory conditions. The average age of the worldwide nuclear fleet as of July 1, 2024, was 32 years, with only 22 out of 408 reactors older than 50 years and none older than 60 years. Of 213 reactors that have been shut down until July 1, 2024, only 42 were older than 40 years and none older than 50 years (M. Schneider & Froggatt, 2024).

Based on this information, we assume country specific plant lifetimes as given in Table 66. For NPPs of Generation 3 and SMRs considered for the projection year 2030, we assume a standard design lifetime of 60 years, although the actual achievement of such average lifetimes is highly speculative up to now.

Table 66: Country specific average NPP lifetimes assumed in the different life cycle chains

Country	2020	2030
EU (low)	40-60	60

Country	2020	2030
EU (medium)	45	
EU (high)	60	
Russia	45	60
Turkey	60	
USA	50-60	60
China	60	60
Korea, Republic of	50	
India	50	
UAE	60	
Japan	45	
South Africa	50	
Brazil	50	

Source: Own assumptions based on (IAEA, 2024c)

3.7.4.2 Construction Materials and Energy

According to (Dones et al., 2009, p. 179), during the construction of a NPPs electricity from the national grid is consumed for various uses such as welding, building machines and lighting. Besides energy, major material inputs include concrete and steel for components and reinforcement steel. In addition, minor inputs encompass steel for construction purposes, copper, aluminium, wood and paper as well as additional energy provided by diesel and heating oil. In addition, energy for excavation work is included.

The major inputs for a standard NPP of 1000 MWe power according to (Dones et al., 2009) are

- 5.31×10^8 kWh (1.9×10^9 MJ) electricity,
- 169.200 m^3 of concrete,
- 21.911 t of steel for components,
- 33.680 t of reinforcement steel,
- 1.9×10^8 MJ of diesel for building machines and
- 1.4×10^8 MJ of light fuel oil for heating purposes.

While the energy needed in form of diesel and light fuel oil is one order of magnitude lower than that of electricity, the worldwide country specific GWP of electricity also varies by a factor of more than 25 as discussed in 3.7.2.

(Dones et al., 2009) notice, that no detailed assessment of the material inputs for NPPs of 1300 MWe as used in some European countries in comparison to NPPs of 1000 MWe existed at that time. With respect to the inputs for construction of NPPs of 1300 MWe, (Dones et al., 2009) estimates a correction factor of 1.2 compared to NPPs of 1000 MWe, based on a comparison of the size and mass of major components.

For early NPPs, the material input especially for concrete was lower, (Bryan & Dudley, 1974, Tab. 1) gives an amount of 75,025 m³ of concrete and 32,731 tonnes of carbon steel for the construction of a typical 1000 MWe PWR reactor in the US. With increasing requirements especially concerning the protection of the facility against external events, the material requirements increased.

Table 67 shows the quantities of concrete and steel for pressurised water reactors in France (Électricité de France [EDF], 2022). It shows that the reactor size naturally plays a decisive role in the amount of materials used, but also that the specific material requirements change with time. If one compares specific material requirement per GW installed electric capacity, for the 1350 MW plants it is increased compared to the 900 MW plants by about a factor of 1.3. For the 1450 MW plants, the specific material requirements are somewhat reduced compared to the 1350 MW plants.

Table 67: Main construction materials for pressurised water reactors in France

	Reactor 900 MW	Reactor 1350 MW	Reactor 1450 MW
Concrete [kt] / [kt/GW]	199.1 / 221	384.7 / 285	393.5 / 271
Reinforcing steel [kt] / [kt/GW]	16.1 / 17.9	32.3 / 23.9	33.0 / 22.8
Finishing steel [kt] / [kt/GW]	17.2 / 19.1	25.6 / 19.0	25.1 / 17.1

Source: (EDF, 2022)

A literature review of by (Lenzen, 2006) provides a more comprehensive overview of the main building materials and at the same time shows the wide range in the literature on the building materials used, but these , see Table 68.

Table 68: Quantities of essential construction materials for nuclear power plants from a literature review in kt

Hardened steel	Stainless steel	Cement/Concrete	Copper	Aluminium
34-61.2	2-25	70-659	0.7-2.7	0.02-0.2

Source: (Lenzen, 2006)

Estimates of the energy required for the construction of nuclear power plant also vary widely. (Lenzen, 2006) gives a range of 1,177-26,944 GWh of thermal energy needed for the construction of one GW installed electric capacity, the main factors influencing the results of various studies are the methodology of the study and the type and capacity of the reactor: Heavy water moderated reactors (HWRs) and gas cooled graphite moderated reactors (GCRs) and fast breeder reactors (FBRs) require comparatively more energy to build than LWRs. However, this literature review included hardly any studies using an LCA method, but mainly studies based on an economic input-output analysis.

According to (Peterson et al., 2005), 95% of the material energy inputs for the construction of a NPP can be assigned to the mass of steel and concrete used. For a 1970s PWR, they estimate that 40 metric tons of steel and 90 m³ of concrete per MWe installed capacity are required.

A further analysis of the relevant construction materials for NPPs was undertaken by (Peterson et al., 2005). Detailed input data for the 1970s PWR was evaluated. (Peterson et al., 2005) scaled the material needs of smaller plants to the material needs of larger plants depending on parameters like the electric output or the size of buildings. For the scaling of material requirements with the net electric output P, (Peterson et al., 2005) derived at a scaling law, where the ratio of the electric capacities of the respective plants with an exponent of 0.82 is used:

Equation 2: Scaling of material requirements for NPPs of different capacities

$$m(large) = m(small) * \left(\frac{P(large)}{P(small)}\right)^{0.82}$$

Source: based on (Peterson et al., 2005)

For NPPs of EPR and ABWR type, both reactor types heavily relying on active safety systems, they estimate an increase in steel requirements of 20% and in concrete requirements of 70% compared to a 1970s PWR per MW installed electric capacity. In comparison, for the AP-1000 and the ESBWR, both reactor types more strongly relying on passive safety features, the ESBWR needs only 73% of steel and 50% of the concrete of an ABWR.

Another estimate of the material requirements for a NPP of AP-1000 type is given by (Carless et al., 2016).

Table 69: Main construction materials for different NPP types in the US

	1970s PWR	EPR (1600 MWe)	AP-1000 (1090 MWe)
Concrete [m^3]	74,876	204,498	100,000
Total steel [kt]	36,069	70,903	35,710

Source: (Peterson et al., 2005)

3.7.4.2.1 Existing NPPs

Base on the above discussion, for the calculation of the environmental impact of the construction phase of a standard 1000 MWe NPP, we will therefore use the energy and material inputs as given by (Dones et al., 2009).

3.7.4.2.2 New NPPs of the Generation 3 type

For more modern designs of the Generation 3 type, we will assume two types of design, one being based on more active safety systems with larger material requirement, with the European Pressurised Reactor (EPR) as a representative design, the other based on more passive safety systems with lower material requirements, based on the AP-1000 as a representative design. The environmental impact of the standard 1000 MWe NPP will be scaled, based on a weighted average scaling factor. We calculate the weighted average scaling factor based on the ratio of the material requirements for the different design types. For the importance of the different material inputs especially with respect to the corresponding GWP, we assume a ratio of 1:4 concerning the importance of the concrete in relation to steel. Based on these assumptions, we estimate weighted average scaling factors according to Table 70.

Table 70: Estimation of a weighted average scaling factor for the environmental impacts of Generation 3 type reactors compared to the standard 1000 MWe PWR NPP

	Standard PWR	Active type (EPR)	Passive type (AP-1000)
Net electric capacity [MWe]	1000	1600	1090
Total concrete [m^3] / [m^3/MWe] / ratio to Standard PWR	169,000 / 169 / 1	204,498 / 128 / 0.76	100,000 / 92 / 0.54
Total metal [t] / [t/MWe] / ratio to Standard PWR	61,170 / 61.2 / 1	70,903 / 44.3 / 0.72	35,711 / 32.8 / 0.54
Weighted average scaling factor	1	0.73	0.54

Source: own calculation based on (Carless et al., 2016; Dones et al., 2009; Peterson et al., 2005)

3.7.4.2.3 SMRs

In Table 64, typical SMRs in operation, under construction or discussed for deployment in different countries are summarized. For Europe, we take the Nuward design as an "active" type design to be representative, for Russia we take the KLT-40S design which we also categorize as an "active" design. For the US we will evaluate the NuScale design both in its licensed (old) and currently planned (new) version, for China we will evaluate the ACP-100 design, all of which we categorize as "passive" designs.

To estimate their material and energy input for construction, we first use the scaling law as developed by (Peterson et al., 2005) given in Equation 2 to calculate a capacity specific scaling factor. We then use the material inputs given in Table 70 for either active type (EPR) or passive type (AP-1000) to estimate the different material inputs for the corresponding SMR types. Based on these numbers, we again calculate an average weighted scaling factor. The results are summarized in Table 70.

Table 71: Estimation of a scaling factor for the environmental impacts of different SMR types compared to the standard 1000 MWe PWR NPP

	Europe (NUWARD)	Russia (KLT-40s)	US (NuScale old)	US (NuScale new)	China (ACP-100)
Net electric capacity [MWe]	170	32	57	77	100
Scaling factor according to Equation 2	0.159	0.040	0.089	0.088	0.141
Total concrete [m^3] / [m^3/MWe] / ratio to Standard PWR	32,530 / 191 / 1.13	8,271 / 258 / 1.53	8,895 / 156 / 0.92	8,760 / 114 / 0.67	14,103 / 141 / 0.83
Total metal [t] / [t/MWe] / ratio to Standard PWR	11,279 / 66.3 / 1.08	2,868 / 89.6 / 1.46	3,176 / 55.7 / 0.91	3,128 / 40.6 / 0.66	5,036 / 50.3 / 0.82

	Europe (NUWARD)	Russia (KLT-40s)	US (NuScale old)	US (NuScale new)	China (ACP-100)
Weighted average scaling factor	1.09	1.48	0.91	0.67	0.83

Source: own calculation

3.7.5 Decommissioning of Nuclear Power Plants

Decommissioning comprises the dismantling of the nuclear power plant, the decontamination of the site and components and the treatment of the waste produced at the end of its life. Decommissioning consists of three main phases. Firstly, several years after the final shutdown are required to remove the spent fuel elements from the internal wet storage facility (spent fuel pool) and transfer them typically to dry interim storage or in some countries to external wet storage sites. At the same time, the buildings are prepared for decommissioning. Finally, the decommissioning itself takes place, including the dismantling of equipment and the demolition of buildings. For some plants, dismantling is postponed for several decades with the aim to reduce the radiologic inventory in the plant to ease the process of decommissioning, the so called long-term enclosure.

As of March 15, 2025, a total of 215 NPPs worldwide have been permanently shut down, approximately one third of all NPPs build until today (IAEA, 2025). Until mid-2024, only 23 NPPs have been fully decommissioned and only four of those have been released from regulatory oversight as greenfield sites, with important countries like Canada, France, Russia or the U.K. not having fully decommissioned a single NPP (M. Schneider & Froggatt, 2024). As a consequence, there is limited real-world experience with fully completed decommissioning of reactors operated over such extended lifespans, which introduces additional uncertainty into life cycle- and end-of-life assessments.

The process of decommissioning up to now takes on average 20 years but with a very large range (M. Schneider & Froggatt, 2024).

While the decommissioning phase is taken into account in the design phase of current NPPs, this has not fully been the case for earlier NPP designs. Thus, decommissioning of early NPPs will differ from the decommissioning process of NPPs currently being built, leading to a relatively high uncertainty with respect to the efforts needed for decommissioning.

The literature data on the energy required for decommissioning vary considerably according to (Wallner et al., 2011), as is the case for the construction phase.

The emissions from the decommissioning phase and dismantling depend on the size of the reactors, similar to construction. The major input responsible for the emissions from the decommissioning phase are due to the energy demand. In ecoinvent, the energy demand during decommissioning is estimated at 75% of the energy demand for construction (Dones et al., 2009).

In addition, materials are required for conditioning the dismantling waste. (Dones et al., 2009) assumes that materials are immobilised in large containers and that this results in a material requirement primarily in the form of steel and concrete. For the standard PWR with an electrical output of 1000 MW, this results in a specific concrete requirement of 8.8E-9 m^3/kWh, a specific reinforcing steel requirement of 4.7E-7 kg/kWh and a specific requirement for low-alloy steel of 1.2E-6 kg/kWh. With respect to local transport needs for the disposal of the large amounts of decommissioning wastes, a typicall transport distances of 20 km and a transport by trucks is assumed.

Finally, in addition to very large quantities of conventional dismantling waste, activated and contaminated waste is also produced during dismantling. (Dones et al., 2009) estimates this at around one per cent of the total mass from dismantling. According to (Dones et al., 2009), a total of 3040 tonnes of contaminated waste, 735 tonnes of activated waste and 900 tonnes of radioactive secondary waste (from the decontamination of plant components) are produced.

3.7.6 Long-term operation of Nuclear Power Plants

An important factor for the future role of nuclear energy is the extension of the operating life of existing nuclear power plants beyond the originally authorised operating time of typically 40 years. This also involves the removal, replacement, and repair of core components of the power plant or – sometimes extensive – retrofitting. To date, the energy and material inputs for overhaul or modernisation have not been systematically considered in LCA studies, even if they assume a service life of 60 years or more.

For example, (Fthenakis & Kim, 2007) analyse the GHG emissions of nuclear power for the U.S. case in 2007. They discuss a best case, baseline and worst case scenario. With respect to retrofitting, in the baseline and best-case scenario, they do not assume any replacement at all, while in the worst case scenario they assume that 10% of the initial material required for reactor construction would be replaced every 10 years, independent of a plant lifetime extension.

(Carless et al., 2016) calculate the greenhouse gas impact of maintenance and repair during normal operation of a NPP based on the economic input output method (EIO-LCA), using data provided by (Fthenakis & Kim, 2007). As a best estimate, they derive at a value of 0.0039 kg CO_2-eq/kWh.

(JRC, 2021, p. 138) argues, that long-term operation (LTO) will have little or no impact on the front-end and back-end environmental impacts of nuclear power, while the lifecycle impacts per kWh originating from the concrete, steel and other building materials used in the construction of the plant will decrease substantially, as the construction inputs will increase only marginally, due only to the need to replace some structures and components for the life extension period.

According to (EDF, 2022), maintenance in the framework of LTO (including replacements of large components and the programs included in the “grand carénage”, see below) were included in the LCA for the French fleet, but no details are given on the underlying assumptions.

As detailed information on the actual energy and material inputs with respect to lifetime extensions in different countries is scare, in the following we collect existing information on the refurbishment and replacement work performed for lifetime extensions and the corresponding costs.

We compare these costs with the cost given for nuclear new build in the corresponding countries, assuming that the cost structure of major refurbishments in the context of lifetime extensions is comparable to the cost structure during new build, see below.

It has to be kept in mind, that overall there are large uncertainties concerning the actual cost of necessary refurbishments for LTO (Frieß et al., 2023).

Based on this cost information, we deduce a “retrofitting factor”, estimating the energy and material inputs needed for retrofitting during normal lifetime and lifetime extensions compared to the construction of a new NPP.

As the material input is typically needed for a lifetime extension of 10-20 years, while the design lifetime of a new NPP will be at least 40 years, we calculate the “retrofitting factor” (Rf) by

building the quotient of overnight costs for LTO (OC(LTO)) and overnight construction costs for new build (OCC(NPP)) and divide this by the ratio of the lifetime extension (lt_e) in years and the original design lifetime (lt_d) in years.

Equation 3: Calculation of a retrofitting factor

$$Rf = \frac{OC(LTO)}{OCC(NPP)} \Big/ \frac{lt_e}{lt_d}$$

Source: Own representation, Oeko-Institute

The environmental impacts of plant retrofitting are then estimated by scaling the environmental impact of the NPP construction (with the exception of land use) by this retrofitting factor Rf.[39]

3.7.6.1 General information

According to (IAEA, 2018a, 2.30) "long term operation of a nuclear power plant is operation beyond an established time frame defined by the licence term, the original plant design, relevant standards or national regulations."

The original design lifetimes lt_d of nuclear power plants in operation today were country and type specific, but ranged from 30 to 40 years for typical PWR and BWR reactors, current planned design lifetimes range from 40 to 60 years (IAEA, 2002; NEA, 2021b).

(IEA & NEA, 2020) evaluates costs for the LTO of nuclear power plants. According to this analysis, while the operational costs of a nuclear power plant are relatively stable during normal plant life, at the end of the original design lifetime the operators have to invest larger amounts of money to perform major refurbishments for the extension of plant lifetimes (IEA & NEA, 2020, 147). While there is no clear criterion to distinguish investments in LTO from normal expenses for the maintenance of the plant, in the context of LTO larger systems, structures and components (SSCs) will be replaced (IEA & NEA, 2020, 147–148), typically including:

- mechanical equipment like pressure vessel upper heads, steam generators, turbines, pumps, motors or large diameter piping,
- electrical equipment like alternators or transformers,
- instrumentation and control equipment like cables and sensors and
- civil works including cooling towers.

Besides hardware, costs of LTO also includes labour work and project management as well as regulatory and licencing work, compare also (IAEA, 2002, Table 20).

An assessment of the costs of LTO is not straight forward, as spendings for LTO might overlap with spendings for other plant enhancements like power uprates or enhancements for flexible operations. Furthermore, spendings to enhance the possible lifetime of a plant may have been performed already for several years before the end of normal plant lifetime (IEA & NEA, 2020, p. 148). In addition, the maintenance policies are different depending on the utilities' and the regulatory requirements (NEA, 2012). For those cases, where plant's components are preventively replaced, the need for equipment upgrade and replacement would be smaller for LTO. Thus, even during the original design lifetime of a NPP, relevant refurbishment and retrofitting might be needed.

[39] For the land use indicator, the direct impact of the plant site dominates the power plant results. These are covered by the overall plant life as input parameter to the power plant construction and power plant operation steps.

In addition to that, several plants worldwide have to install safety improvements following the Fukushima accident including new SSCs like filtered venting systems or additional diesel generators in special emergency buildings (NEA, 2021b).

According to (NEA, 2021b, p. 129), the cost structure of the overnight cost for LTO consists mostly of the replacement of heavy components and other work, including the labour necessary for their installation, while indirect costs associated with project management, regulatory and licensing interfaces and the initial engineering efforts typically account for 20-25% of the total investment. In the following, it is therefore assumed that this cost structure is comparable with that of overnight cost of reactor construction for new power plants.

In (IEA & NEA, 2020), four countries reported on the estimated cost of LTO, namely France, Sweden, Switzerland and the United States. According to Table 3.1 in (IEA & NEA, 2020), the overnight cost for LTO of a 1000 MWe plant range from 391 US$/kWe to 629 US$/kWe with a mean value for OC(LTO) of 504 US$/kWe. This can be compared with the estimated overnight cost for the construction of a new nuclear power plant, for which a range of 2157 US$/kWe to 6920 US$/kWe with a mean value of OCC(NPP) of 3606 US$/kWe is given.

In an earlier study, (NEA, 2012) also collected investment costs for different countries. According to the participants of that study, OC(LTO) were 500-1100 $US\$_{2010}$/kWe, a somewhat larger spread than the values given above, but no cost estimates for nuclear new build were given for comparison. (IAEA, 2018c) also assesses the economics of LTO, but the overnight costs used in this study are based on (NEA, 2012).

In its own assessment, (IEA & NEA, 2020, p. 149) assumes that the an average OC(LTO) investment could range from 450 US$/kWe to 950 US$/kWe with an mean of 700 US$/kWe. These investments could result in an lifetime extension period lt_e of either 10 or 20 years, compare Table 8.1 in (IEA & NEA, 2020)

Based on these numbers, the OC(LTO) are 19% of OCC(NPP) (assuming the above mean value of 3606 US$/kWe), with a range of about 14-21% for a lt_e of 10 or 20 years. Compared to an original design lifetime lt_d of 40 years, these numbers result in a “retrofitting factor” Rf of

- Rf = 78% (50-105%) based on 10 years lt_e and
- RF = 39% (25-53%) based on 20 years lt_e.

According to (IAEA, 2024b, p. 59) average OC(LTO) can range from 300-2700 US$/kWe, depending on existing infrastructure, regulatory requirements and reactor technology. This would correspondingly result in a “retrofitting factor” Rf being lower by a factor of 0.75 or higher by a factor of 2.8.

3.7.6.2 Country specific discussion

3.7.6.2.1 United States

Commercial power reactors in the U.S. were originally licenced for an operational period lt_d of 40 years. Starting in 1998, the U.S. NRC allowed the renewal of licences for an additional 20 years of operation.

(IAEA, 2002) collected cost data for LTO in several countries. They reported the corresponding country specific values only with respect to the quintiles of overall reported costs, by which the country values are covered. The total estimated OC(LTO) ranges from 122-680 US_{2000}\$/kWe. For the U.S., the corresponding value lies in the third quartile, i.e. between 413-680 US_{2000}\$/kWe.

For OC(LTO) in the U.S., (NEA, 2012, p. 93) gave specific investment costs of 750 US$$_{2010}$/kWe with a significant level of uncertainty and estimated the OCC (NPP) in the U.S. with 4500 US$$_{2010}$/kWe.

Based on these numbers, the OCC(LTO) for a lt_e of 20 years would be approximately 17% of that of new build. Compared to the original design lifetime lt_d of 40 years, these numbers result in a "retrofitting factor" Rf of

- Rf = 33% based on 20 years lt_e, but associated with a significant level of uncertainty.

(IEA & NEA, 2020) also lists country specific values for LTO programmes in Table 3.4a and 3.4b. For the United States, OC(LTO) are 9.2% of OCC(NPP) are given (391 US$/kWe and 4250 US$/kWe respectively), approximately halve of the above value. These numbers result in a "retrofitting factor" Rf of

- Rf = 18% based on 20 years lt_e.

3.7.6.2.2 France

As of February 2025, France has 57 NPPs in operation with a total net installed capacity of 63 GWe, of which 32 are PWRs of the 900 MWe class, 20 of the 1300 MWe class, 4 of the 1400 MWe class and one EPR of 1630 MWe. For the French reactor fleet, an extension of the service life (original design lifetime lt_d) of the 900 MWe plants from 40 to 50 years (corresponding to a lt_e of 10 years) is currently being implemented.

For France, (IAEA, 2002) reported the corresponding country specific values to lie in the first quintiles of overall reported OC(LTO), the corresponding value thus lies between 252-413 US$$_{2000}$/kWe.

For OC(LTO) in France, (NEA, 2012) gave specific investment costs of 1090 US$$_{2010}$/kWe, including an 10% share for post Fukushima measures. Maintenance work on the 900 MWe reactors included an exchange of the steam generators between 1990 and 2010, work on the turbines, generators, and main transformers as well as other components.

(NEA, 2012, p. 72) gives an estimate for the total investment in the french fleet until 2025 of 55 billion Euros$_{2011}$ corresponding to 875 Euro$_{2011}$/kWe (1090 US$$_{2011}$/kWe).

According to (NEA, 2021b, p. 87), the Tricastin-1 plant was the first plant to finalize the fourth decennial outage, in which major work for the LTO was performed, including the installation of two ultimate emergency diesel generators, additional diversified emergency cooling systems for the secondary circuit, spent fuel pools and the containment, U5 filter vents, a corium stabiliser, reinforcement of the protection against earthquakes and an additional control room for operation under extreme events. This refurbishment work alone caused a total investment of 250 million Euros, corresponding to 280 Euros/kWh.

Due to the largely standardized plant design, the LTO work for the 900 MWe plants as well as preparatory work for the other plants are performed by EDF under a specific program called "Grand Carénage", for which a total investment of 49.4 billion Euros is planned for 20 projects (NEA, 2021b, p. 104). According to (EDF, 2024), the first phase of the Grand Carénage programme was completed on 31 December 2021. For the second phase from 2022-2028, 33 billion Euros are planned for. In addition, 1.2 billion Euros were spent between 2022 and 2025 for repair work relating to stress corrosion.

Country specific values are also given in Table 3.4a and 3.4b of (IEA & NEA, 2020) For France, OC(LTO) is 629 US$/kWe, corresponding to 15.6% of that of OCC(NPP) of 4013 US$/kWe.

Compared to the lt_d of 40 years, these numbers result in a "retrofitting factor" Rd of

- Rf = 63% based on 10 years lt_e and
- Rf = 31% based on 20 years lt_e.

3.7.6.2.3 Belgium

Belgium had seven NPPs built between 1969 and 1978 with an original design lifetime lt_d of 40 years. In 2003, Belgium decided to phase out nuclear power gradually. In 2012, this was amended insofar as Tihange 1 should perform LTO for lt_e of 10 more years (NEA, 2012).

At the beginning of 2025, four plants in Belgium are still in operation (Doel 2 and 4 and Tihange 1 and 3), Doel 1 was shut down on February 14, 2025, after 50 years of commercial operation, Doel 3 and Tihange 2 after 40 years of commercial operation (IAEA, 2025).

For LTO in Belgium, (NEA, 2012) gave specific OC(LTO) of 650 $US\$_{2010}$/kWe, including an 11% share for post Fukushima measures. The OCC(NPP) for an EPR-type 1600 MWe plant was given with 5545 $US\$_{2010}$/kWe, thus, LTO would cost about 12% of nuclear new build.

According to figure 5.2 in (NEA, 2012), approximately 25% of this were due to engineering, documentation, safety reviews and licensing, approx. 20% for instrumentation and control, electrical systems and cables, 22% for design upgrades and approx. 30% for the RPV head, turbogenerators and condenser replacements.

Compared to the lt_d of 40 years, these numbers for a lt_e of 10 years result in a "retrofitting factor" Rf of

- Rf = 48% based on 10 years lt_e.

3.7.6.2.4 Switzerland

In 2021, the four NPPs Beznau-1 and -2, Gösgen and Leibstadt in Swizerland provided 13% of the installed capacity and 29% of the electricity generation. Lifetimes of the Swiss plants are not formally limited. Currently they are assumed to operate for 50 or 60 years, but there is ongoing discussion to prolong the lifetimes even longer (NEA, 2022). Another NPP, the Muehleberg plant was shut down in 2019 after 47 years of commercial operation (IAEA, 2025). According to (NEA, 2022), this was ultimately an economic decision based on the expectation of the need for expensive retrofitting, that would have made continuation of operation unprofitable.

According to (NEA, 2012) it is not straightforward to calculate LTO investments, as the Swiss plants were regularly refurbished over their lifetime. Still, in 2012 there were major investments necessary in the nuclear island, safety systems, I&C but also conventional systems and components such as turbogenerators and condensers for an LTO to reach a lifetime of at least 50 years, corresponding to a lt_e of 10 years based on a typical lt_d of 40 years.

For OC(LTO) in Switzerland, (NEA, 2012) gave specific investment costs of 490-650 $US\$_{2010}$/kWe, but including future investments for refurbishments and maintenance they gave an estimate of 980-1300 $US\$_{2010}$/kWe.

(NEA, 2022) discussed an LTO scenario for Switzerland, in which the Gösgen and Leibstadt reactors (with 2.2 GW of installed electrical capacity) will be operated for an extended LTO period, which is compared among others with nuclear new build scenarios (for 1.6 or 3.2 GW of new electrical capacity).

For an LTO period of 20 years, (NEA, 2022, Table 3.6) gives OC(LTO) of 550 US$/kWe for the specific Swiss case, while for OCC(NPP) with a design lifetime of 60 years costs of

4013 US$/kWe are given based on French EPR construction costs. These numbers are based on (IEA & NEA, 2020) and result in a "retrofitting factor" Rf of

- Rf = 41% based on 20 years lt_e.

According to (NEA, 2022, p. 28), axpo, the operator of the swiss Beznau plant (2x365 MW of net electric capacity), has invested over US$ 2.5 billion (3400 US$/kWe) for maintenance and modernisation for 60 years of operation, corresponding to an lt_e of 20 years, and US$ 825 million have been invested over a 10 year period in the Gösgen plant (750 US$/kWe). This results in a "retrofitting factor" Rf of

- Rf = 254% based on 20 years lt_e for Beznau and
- Rf = 56% based on 20 years lt_e for Gösgen.

3.7.6.3 Conclusion

There is a very large spread of refurbishment and replacement work taking place during normal operational lifetime and in the course of lifetime extensions. Up to now, lifetime extensions cover a period of 10-20 years, compared to an original plant design lifetime of typically 40 years. Based on the costs associated with such lifetime extensions in comparison to the cost for nuclear new build, a "retrofitting factor" Rf of

- Rf = 78% (50-105%) based on 10 years lt_e and
- Rf = 39% (25-53%) based on 20 years lt_e, assuming no additional retrofitting.

with a corresponding additional uncertainty of a factor of 0.75 to 2.8 can be derived.

For exemplary countries, a "retrofitting factor" Rf of

- Rf = 18-33% for the U.S. (depending on the costs, based on 20 years lt_e),
- Rf = 31-63% for France (based on 10-20 years lt_e),
- Rf = 48% for Belgium (based on 10 years lt_e) and
- Rf = 41-254% for Switzerland (depending on cost assumptions based on 20 years lt_e)

can be derived.

Due to these large uncertainties, we will assume a "retrofitting factor" Rf of

- Rf = 0-25% as a lower bound,
- Rf = 50% as a medium case and
- Rf = 100% as an upper case.

3.8 Interim Storage

The spent fuel elements continue to generate radiation and non-negligible heat due to the further decay of the fission products and the activity of the materials. For this reason, the fuel elements must be deposited in an interim storage facility for several years before reprocessing or final disposal until the heat and radiation generation has subsided to a lower level. There are two types of interim storage facilities for spent fuel elements: dry storage and wet storage. In dry storage facilities, the fuel assemblies are stored in sealed containers in halls and cooled by

air, with no active cooling system required. In wet storage facilities, the fuel assemblies are stored in water pools with a water cooling system. As no final storage facility for high-level radioactive waste has yet been completed anywhere in the world, it is necessary to leave the spent fuel elements in interim storage facilities for many decades. Protective measures must also be taken against accidental or civilisation-related release (terrorism, war) and for fissile material control.

Ecoinvent assumes two separate paths for interim storage in Switzerland. One for low-level and transient intermediate-level waste (ILLW) headed for the low-level waste repository; the other consists of high-level and long-lived intermediate-level waste headed for the high level radioactive waste repository. To map these two waste streams in a unique way, two separate data sets were generated in ecoinvent.

In this study these two different waste streams are also addressed separately. Low-level waste from all process steps and their individual life cycle modules is summarized and treated in the module on low-level waste interim storage. This includes conversion, enrichment, fuel fabrication, power plant operation, and reprocessing. Another waste stream is untreated and is also summarized and taken as input, together with the output from low-level waste interim storage, for the module on low-level waste final storage (ILLW). This includes waste from power plant operation and decommissioning. The other stream is spent fuel from the nuclear power plant and MOX fuel which is stored in high-level waste (HLW) interim storage facilities. The distinction between interim and final storage is important. They serve fundamentally different purposes and are subject to different technical, regulatory, and temporal requirements. Interim storage is designed for several decades with active control and oversight, whereas final disposal must ensure long-term containment of nuclear waste over geological timescales without reliance on active safety systems.

Both ILLW and HLW interim storage is always placed in the country where the power plant is located in all LCA chains, except for chain RU4_Gen3, where the plant is in Turkey and interim storage is assumed to be in Russia.

The interim storages are assumed to have a storage of 28,300 m^3 for low-level waste and 5700 m^3 for high-level waste and a lifetime of 55 years. For the purpose of this analysis, a utilisation efficiency of 100% is assumed, meaning the full design volume is effectively used over the facility's lifespan.

3.9 Reprocessing

Some of the fuel elements used in reactors are reprocessed so that the plutonium they contain, as well as some of the uranium, can be reused as fuel. In contrast to direct disposal, reprocessing allows the recovery of uranium and plutonium thereby reducing the demand for natural uranium and enrichment services. The Plutonium Uranium REdoX (PUREX) process is the standard method for reprocessing. It involves dissolving spent fuel in hot concentrated nitric acid to separate uranium (~95%), plutonium (~1%), and fission products (~4%). After mechanical chopping and dissolution, uranium and plutonium are extracted using an organic solvent in a counter-current process. This is followed by successive purification steps to achieve high recovery factors. Radioactive waste streams from extraction, solvent degradation, and gaseous emissions (e.g., Kr, I) are treated through concentration, filtration, and abatement systems. Due to residual decay heat, the concentrated fission product solutions must be interim-cooled for at least two years before being immobilized and vitrified in glass for geological disposal. The plutonium is used to fabricate fuel in a MOX fuel fabrication plant.

In the EU, an average of around 10 tonnes of plutonium from reprocessing has been used per year as MOX fuel over the last 25 years. This has saved an average of approx. 1000 tonnes of natural uranium per year (ESA, 2021). Data on the energy requirements of reprocessing in France can be found, for example, in the study by (EDF, 2022).

Various countries have ruled out reprocessing due to concerns in the area of nuclear non-proliferation (diversion of plutonium for nuclear weapons purposes), and reprocessing is not economical due to the high radioactivity of the plutonium, which in turn leads to higher fuel production costs due to e.g. the necessity for shielding, remote handling and higher safety requirements. Finally, reprocessing contributes significantly to the normal operational release of radionuclides (especially gaseous fission products) and leads to considerable quantities of low- and intermediate-level radioactive waste. For this reason, only very few countries currently utilise this option.

Currently there are only three commercial facilities for reprocessing LWR fuel: The plant in La Hague in France with a throughput of 1700 tHM/y, the plant in Ozersk (Mayak) in Russia with 400 tHM/y and the plant in Rokkasho Japan, which is still not operated with 800 tHM/y.

Ecoinvent is basing their assumptions on a reprocessing plant with a throughput of 1200 tHM/y and a 30 year lifetime.

Reprocessing is only assumed to being conducted in France (EU1, EU1_Gen3, EU1_SMR, EU7, EU9, EU10, EU11_Gen3, JP2) and Russia (RU3). The French plant has a lifetime of 40 y and the Russian plant of 50 y.

The ratio of spent fuel input to outpur of high level radioactive waste (HLW) is assumed to be the ecoinvent reference value of 0,00447 m3/kgHM.

Different fractions of spent fuel are assumed to being reprocessed in different LCA chains (%): 20%, 40%, 80%, 100% (see section 3.7.3.1).

3.10 Final Disposal

A distinction must be made between low, medium and high-level radioactive waste for final disposal. As of 2024, there is no active repository for high-level radioactive waste in operation. In Finland, the Posiva repository is under construction at the Olkiluoto NPP site, which should start operation in 2026. Some countries are at an advanced planning stage (Sweden, Switzerland, USA). However, none of these countries has yet granted a licence for construction. The suitability of granite, clay and salt formations is being investigated worldwide. As a result, there is some data from implementation practice that is available for calculating the environmental impact of the construction and operation of a repository.

Before final disposal in surface or deep repositories, the waste is conditioned for storage by reducing the volume and transferring the waste to a state as stable as possible. This requires the construction and operation of appropriate conditioning facilities. Furthermore, final storage containers are required for storage.

While a site for a planned repository in Germany is to be found by 2031 and the construction of the repository is to take place by around 2050, these timelines are highly uncertain, latest estimates expect the search process for a repository site to take until 2074 in a baseline scenario (Krohn et al., 2024). The subsequent operation of the storage facility will continue until at least the early 2100s. After emplacement and closure, the repository is to be monitored for a further 500 years so that the waste can be retrieved. After that, the repository should ensure the containment of the highly radioactive waste without the need for active measures. These are

targets for the disposal of highly radioactive waste, but the achievability of this target is fraught with uncertainty due to the very long containment times required.

3.10.1 Conditioning

In the conditioning facility spent fuel elements (HLW waste) that were not treated by reprocessing are taken out of the interim storage containers and sealed in steel containers intended for final disposal in a geologic repository. Ecoinvent provides a dataset for the infrastructure and the operation of the conditioning facility.

The HLW conditioning facilities are always placed in the country where the power plant is located in all LCA chains, except for chain RU4_Gen3, where the power plant is in Turkey and conditioning is assumed to be conducted in Russia.

The HLW conditioning facility is assumed to have a throughput of 45 tHM/y and a lifetime of 40 years and a ratio of spent fuel input to HLW output of 0,0024 m^3/kgHM. As a typical reactor will produce about 20-30 tonnes of spent fuel per years, this would amount to about 48-72 m^3 per year.

3.10.2 HLW and ILLW final repositories

The ecoinvent dataset contains a module that represents the storage of high-level (HLW) and low- and intermediate-level radioactive waste (ILLW) in Switzerland. For other plants in France see e.g. (EDF, 2022). (UNECE, 2021) has compiled environmental data on the planned repository construction in Sweden and the containment of high-level radioactive waste.

The Swiss disposal concept foresees two types of deep geological repositories. The first is designed for spent fuel and vitrified high-level waste from reprocessing, and long-lived intermediate-level waste (ILW). The second repository is for low- and short-lived intermediate-level waste (LLW), originating from nuclear operations, medicine, industry, research, and reprocessing. The ecoinvent assumption is that the host rock will be clay.

High-level waste containers with spent fuel are cylindrical steel casks with an outer diameter of 1.05 m and a maximum length of 5 m, holding 4 LWR fuel assemblies. Containers with waste from reprocessing consist of a vitrified waste canister enclosed in a robust steel overpack, with a diameter of 0.94 m and a length of 2.0 m. Long-lived intermediate-level waste is packaged in various forms, including steel drums and concrete containers, and contains metallic, organic, and inorganic materials from reprocessing activities and power plant operation. Low-level waste (LLW) is mostly contained in steel drums and concrete containers.

The HLW and ILLW final repositories are always placed in the country where the power plant is located in all LCA chains, except for chain RU4_Gen3, where the power plant is in Turkey and final waste disposal is assumed to be conducted in Russia.

The final repositories are assumed to have a storage capacity of 100,000 m^3 for low- and intermediate-level waste (ILLW) and 16,000 m^3 for high-level waste (HLW), which are realistic values for an medium sized nuclear power program. The lifetime is assumed to be 20 years of operation and both 8 years to build and to close both the HLW and ILLW repository for a total of 36 years.

3.11 Transportation

Most of the material used for nuclear fuel is transported several times on its way through the fuel cycle. The waste from the various stages is also transported. Transport is frequently international and often over long distances. Figure 110 shows the various transport stages and

the containers required. The Nuclear Waste Management Organisation (Nuclear Wase Management Organization [NWMO], 2005) has published the number of transports and the means of transport used for various countries. Considerable expenditure is required for safety and security, particularly for the transport of fissile material and highly radioactive waste.

The nuclear transport necessities between all facilities involved in a country is quite complex. As an example see Figure 111 for MOX transports in France and for the nuclear fuel cycle in the USA in Figure 112.

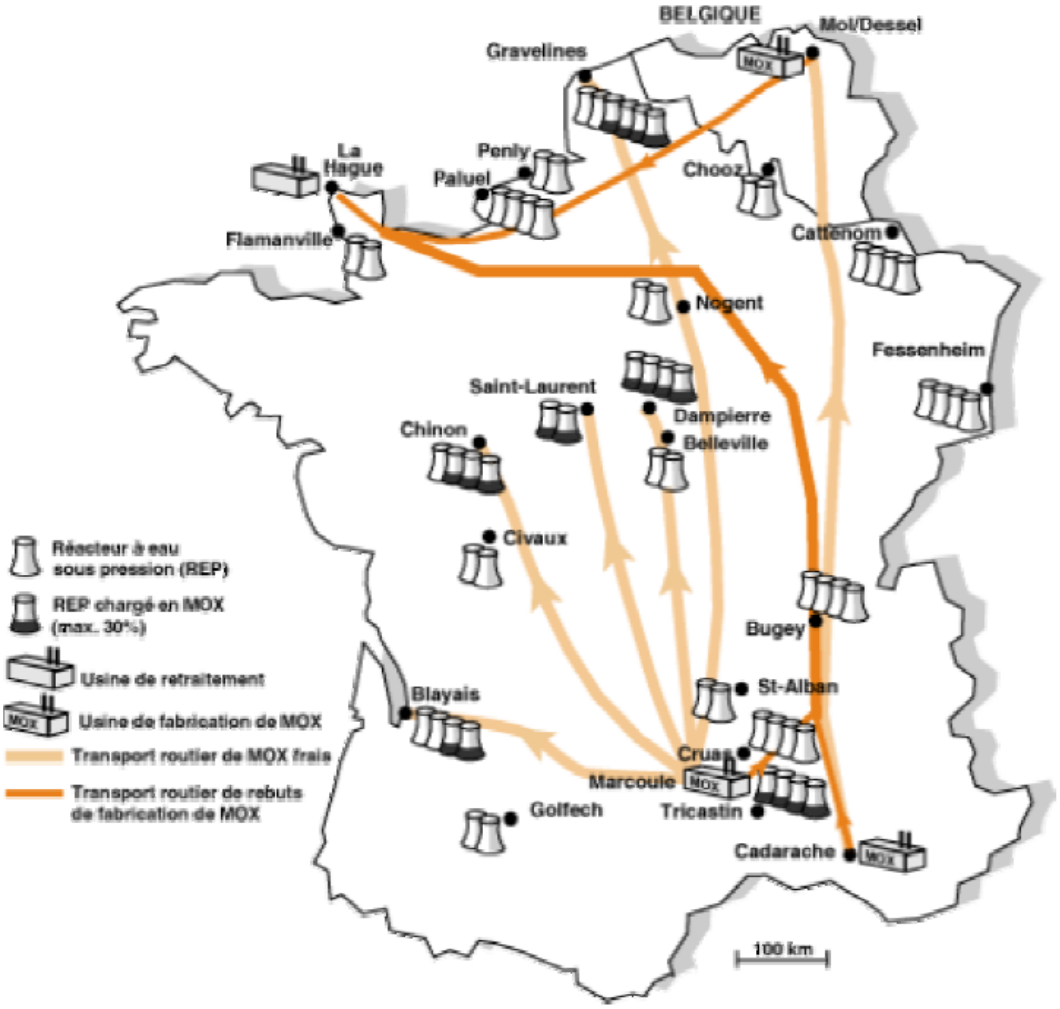
Figure 110: Transport stages for nuclear fuel and waste

Stages of nuclear transport

From:	To:	Material	Notes
Mining	Milling	Ore	Rare: usually on the same site
Milling	Conversion	Uranium oxide concentrate ('yellowcake')	Usually 200-litre drums holding 400 kg, in standard six-metre transport containers
Conversion	Enrichment	Natural uranium hexafluoride (UF_6)	Special UF_6 containers, Type 48Y
Enrichment	Fuel fabrication	Enriched UF_6	Special UF_6 containers, Type 30B
Fuel fabrication	Power generation	Fresh (unused) fuel	Type A casks unless MOX fuel (Type B)
Power generation	Used fuel storage	Used fuel	After onsite storage, large Type B casks
Used fuel storage	Disposal*	Used fuel	Large Type B casks
Used fuel storage	Reprocessing	Used fuel	Large Type B casks
Reprocessing	Conversion	Uranium oxide	Called reprocessed uranium (RepU)
Reprocessing	Fuel fabrication	Plutonium oxide	
Reprocessing	Disposal*	Fission products	Vitrified (incorporated into glass)
All facilities	Storage/disposal	Waste materials	Sometimes on the same site

Source: (WNA, 2022)

Figure 111: Transport of MOX fuel for the nuclear fuel cycle in France



Source: (World Information Service on Energy [WISE], 2004)

Figure 112: Transport for the nuclear fuel cycle in the United States

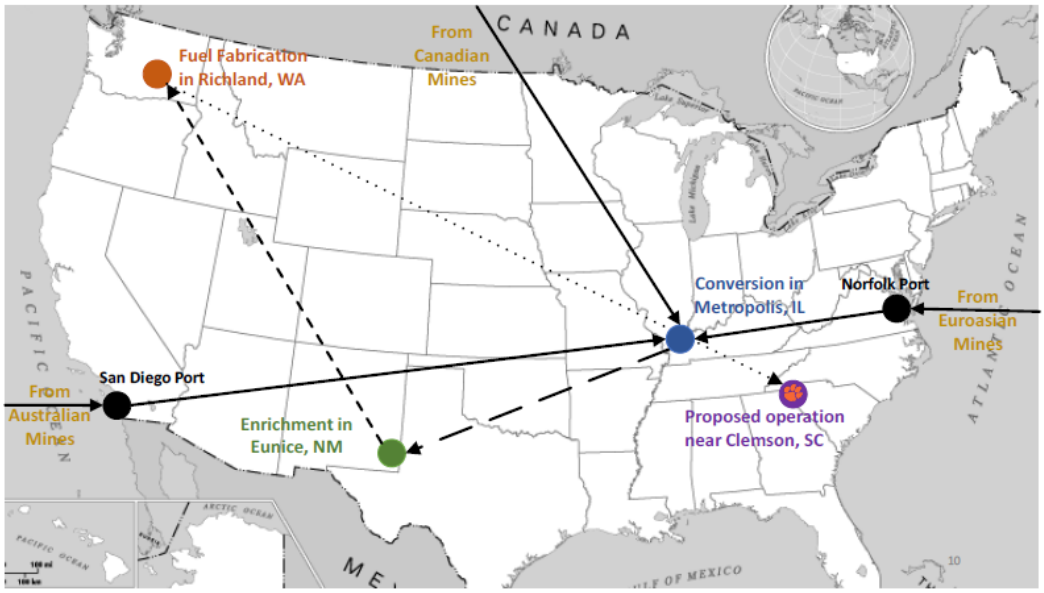


Figure 3.1. Map showing approximate locations for the U.S. fuel cycle facilities as well as the line-of-sight transportation paths between all stages of the LCA.

Source: (Godsey, 2019)

3.11.1 Inputs

Three means of transport are being used in the LCA chains: transport in trucks, freight train or cargo ship. The total weight transported is the goods plus the weight of the appropriate container. The standard ecoinvent values for the environmental impact categories are used for the different means of transport and adapted regionally. Since only transport of mined uranium ore contributes significantly to GWP, only the four main LCA chains were modelled (EU1, RU1, NA1, CN1) in detail. For several facilities of one category, such as several nuclear power plants, a mean distance was assumed for the transport between e.g. the fuel cycle facility and the NPP or from the NPP to interim storage or a reprocessing facility. Also transport means might differ in reality from the assumptions here for the four main chains. The transport assumptions for distances for the LCA chains EU1, RU1, NA1 and CN1 are taken for all chains in that global region (EU1 for all EUx LCA chains etc.) except for the following:

- EU1 was assumed similar to RK1, JP1, JP2, AE1,
- CN1 was assumed similar to IN1
- NA1 was assumed similar to BR1, ZA1

In Europe distances except for uranium transport are quite low. Russian transport is dominated by fright train with large distances. North America is dominated by truck transport, cargo ship distance stems from the assumption that the mine in LCA chain NA1 is Olympic Dam in Australia. China is also dominated by freight train with some truck transport. Distances were calculated with google maps taking street connections for truck transport and straight line distance for train and ship transport.

Table 72: Transportation distances in km

Transportation Means	EU1	RU1	NA1	CN1
Cargo ship	7000	0	15000	0
Freight train	1750	20601	0	13500
Trucks	5812	11	12807	3655

Source: Öko-Institut. For the four main LCE chains all transports between all process steps were considered and modelled with distances for concrete facilities. The facilities were chosen to resemble the average distance for that transport step if more than one facility existed (they are not extremes, e.g. neither the shortest nor the longest existing transport distance).

3.12 Discussion of results and conclusions from LCA

In this section, the results of the different life cycle steps will be presented, and major sensitivities will be discussed. Finally, the total GWP of all life cycle chains for the baseline year 2020 and its future projections to 2030 will be presented in section 3.12.10. Results of other environmental impacts will only be covered where major impacts arise. The detailed input data and corresponding results for all life cycle chains as well as the breakdown of the environmental impacts to the different life cycle steps are given in Appendix B. Full results of the environmental impact categories other than GWP are given in Appendix C, as they are of minor relevance for the intended aim of this study, to contribute to a fact-based international climate policy discussion on the possible future role of nuclear energy on the path to GHG neutrality.

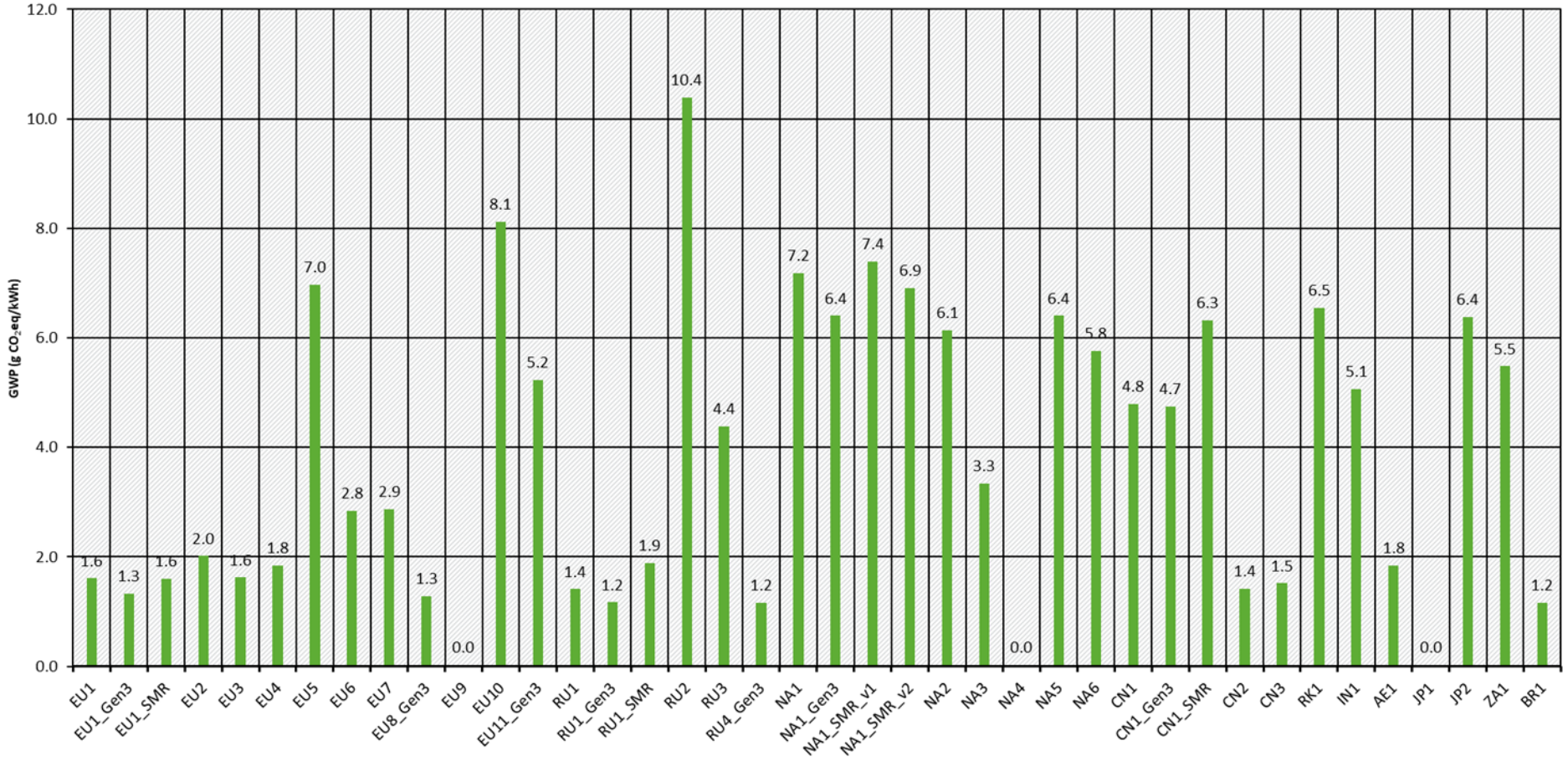
3.12.1 Mining

Figure 113 and Figure 114 show the GWP for uranium production and the infrastructure of the mining operation for the different LCA chains. The process steps of mining and yellowcake production as well as the infrastructure for mining and yellowcake production is cumulated respectively. For LCA chains with ISL mines (EU3, RU2, NA2, NA3, NA5, CN1, CN1_Gen3, CN1_SMR, IN1) there is only one dataset and numbers for production include the infrastructure and are represented in Figure 113. Correspondingly these LCA chains have no contribution in Figure 114.

The largest impact on differences in GWP for mining operations is caused by the variation in ore grade between the different LCA chains. A mine like Cigar Lake with an ore grade above 10% will have almost no impact on the overall GWP in chains with that specific mine. Other LCA chains with a mine like Arlit in Niger with a still high ore grade of 0.13% still profit with relatively low GWP. The lower the ore grade the higher the GWP. Mines with ore grades <0.05% have GWP in production of around 5-6 g CO_2eq/kWh.

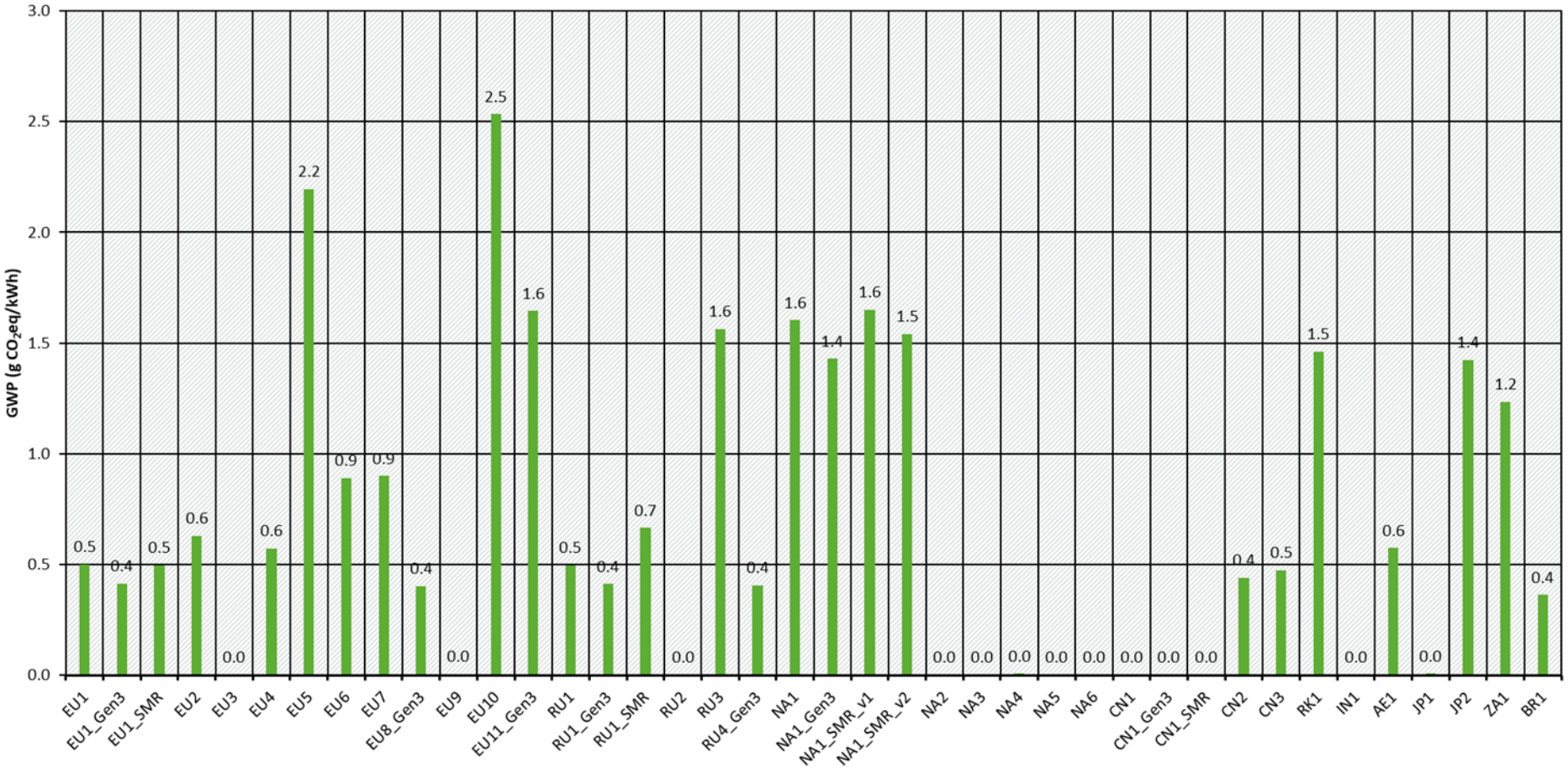
The ISL mine in Russia (RU2) has the highest GWP (10.4 g CO_2eq/kWh) due to the Russian electricity mix and a low ore grade of 0.031% (infrastructure is included for ISL). But similarly the LCA chain EU10, with the Rössing mine and an ore grade of 0.025% has a GWP of 10.6 g CO_2eq/kWh (8.1 g CO_2eq/kWh production and 2.5 g CO_2eq/kWh infrastructure).

Figure 113: Uranium Ore Mining And Yellowcake Production: GWP (g CO_2eq/kWh)



Source: Öko-Institut. Values for EU3, RU2, NA2, NA3, NA5, CN1, CN1_Gen3, CN1_SMR, IN1 are in-situ leaching mines. Their infrastructure contribution is included in the production numbers here (cf. Figure 114).

Figure 114: Mining And Yellowcake Mill Infrastructure: GWP (g CO_2eq/kWh)



Source: Öko-Institut. Values with values of zero are in-situ leaching mines. Their infrastructure contribution is included in the production.

3.12.1.1 Sensitivities

3.12.1.1.1 Uranium mining and processing assumptions

The assumptions on the energy demand of ecoinvent for open-pit mining is based on the Key Lake mine in Canada (Dones et al., 2009) with an ore grade of 2.6%U_3O_8 that was operated mostly in the 1980s. The authors assume a 2 MWe diesel power station with a 36% efficiency operating nonstop leading to an energy production of 63 TJ electric energy per year. The mine produces 4800 tU so that an energy demand of 36.5 MJ_{th}/kgU results for the electricity of the mining operation, mostly pumps. With 75 g CO_2eq/MW_{th} for Diesel, this results in a specific emission of 2.74 kg CO_2eq/kgU. The authors give also a lower estimate in other their reference mines of 12 MJ_{th}/kgU or 0.9 kg CO_2eq/kgU with an ore grade of 0.17%U.

Additionally, based on conservative assumptions regarding volume, density, and machine efficiency, there is an assumption for Diesel consumed to transport the ore with excavation material conveyer bridges which is given as 16 MJ_{th}/kgU as a reference (Dones et al., 2009) taken from the Key Lake mine with an ore grade of 2.2%U. The upper value for diesel consumption for other reference mines is 240 MJ_{th}/kgU for the DOE reference mine with an ore grade of 0.17%U, however it is unclear if this includes transport of ore and/or waste rock.

The reference value which is scaled by ore-grade in the LCA chains for the open-pit mining operation therefore is 36.5 MJ_{th}/kgU for electricity and 16 MJ_{th}/kgU ore transport (Dones et al., 2009) giving a total of 52.5 MJ_{th}/kgU with a range of 28–276.5 MJ_{th}/kgU. This is equivalent to 3.9 kg CO_2eq/kgU, with a range of 2.1–20,7 kg CO_2eq/kgU assuming diesel.

The diesel consumption for transporting waste rock during building of the mine is discussed under transportation. However, assuming a waste-to-ore ratio of 30:1, a uranium oxide content of 0.5% (resulting in 7 t overburden per kgU), a transport distance of 1 km, and a CO_2 emission factor of 0.15167 kg CO_2/tkm for 32 t trucks, the transport of overburden to the tailings results in 1.06 kg CO_2eq/kgU.

The energy consumption for underground mining is assumed to be 300 MJ/kgU in ecoinvent and selected from a range between 15-620 MJ/kgU. The waste rock to ore ratio is assumed to be low and much less energy is needed for pumping water. It is unclear if transportation of ore is included in the energy demand or in transportation. The data quality of this dataset is therefore limited (Dones et al., 2009).

For ISL mining ecoinvent assumes a proxy Diesel generator of 10 MW for the inventory and energy consumption of 253 MJ/kgU from a range of 167–440 MJ/kgU (Dones et al., 2009).

Ecoinvent does not distinguish between hard rock and soft rock mining with regard to the energy demand (Dones et al., 2009).

Also, for lower ore grades than 1%, the recovery yield will decrease. This would linearly effect the mining operation but is not considered in this study and is generally covered by the variation of ore grades in the LCA chains and an average loss of 10% for the combined process steps for mining, milling and yellowcake production (Dones et al., 2009). (Norgate et al., 2014) shows a relationship for a declining yield curve based on Storm van Leuwens earlier work but mentions that this data is contested by other findings. Also (Mudd, 2014) give yield curves for different mines and sediments.

The energy demand of ore processing is assumed by ecoinvent to be 176 MJ_{th}/kgU (range 97–255 MJ_{th}/kgU) consumed as electric energy from a generator and processing heat of 264 MJ_{th}/kgU (range 8.5–570 MJ_{th}/kgU). That is a total energy consumption of 440 MJ_{th}/kgU

(range 105.5–820 MJ_{th}/kgU) for uranium processing. That corresponds to approximately 33 kg CO_2eq/kgU, (range: 7,9–61,5 kg CO_2eq/kgU).

For uranium mining, milling and yellowcake production, the total energy intensities are given in Table 73. For the ranges we assumed all the minimum and maximum values cumulate (mining, milling, yellowcake production), which is a conservative assumption to get the maximum ranges. The range values are based on different mines in (Dones et al., 2009) with different ore grades than the value of 0.17%U (0.14%U for ISL) ore grade from the DOE-reference mine that is the basis for the infrastructure demand of the uranium mine in ecoinvent. E.g., the lower range value 15 MJ_{th}/kgU as energy demand for the underground mine is based on assumptions for the UMO mine in (Dones et al., 2009) with an ore grade of 0.56%U. The upper range value of 620 MJ_{th}/kgU comes from the reference DOE mine with an ore grade of 0.17%U a factor of 3.3 lower than ore grade than the UMO mine. Using the average value of 300 MJ_{th}/kgU therefore, would correspond to an average ore grade of 0.36%U assuming a strictly linear functional relationship between energy demand and ore grades.

Table 73: Energy and carbon intensity for uranium mining, milling and processing

Mining Method	Total average Energy ecoinvent (MJ_{th}/kgU)	Energy Range ecoinvent (MJ_{th}/kgU)	CO_2 Intensity ecoinvent ($kgCO_2$/kgU)	CO_2 Range ecoinvent ($kgCO_2$/kgU)	Factor range to average value	Ore grade variation in LCA chains (%)	Inv. factor to reference value of 0.17% (0.142% ISL)
Open-pit	492.5	134-1097	36.9	10-82.2	0.27-2.23	0.2-0.025 (0.2-0.075)*	0.8-6.72 (0.8-2.23)*
Underground	740	121-1060	55.5	9.04-108	0.16-1.95	11.5-0.048 (0.3-0.087)*	0.015-3.5 (0.54-1.95)*
ISL	693	606-880	51.98	45.4-66	0.87-1.27	0.2-0.031	0.7-4.6

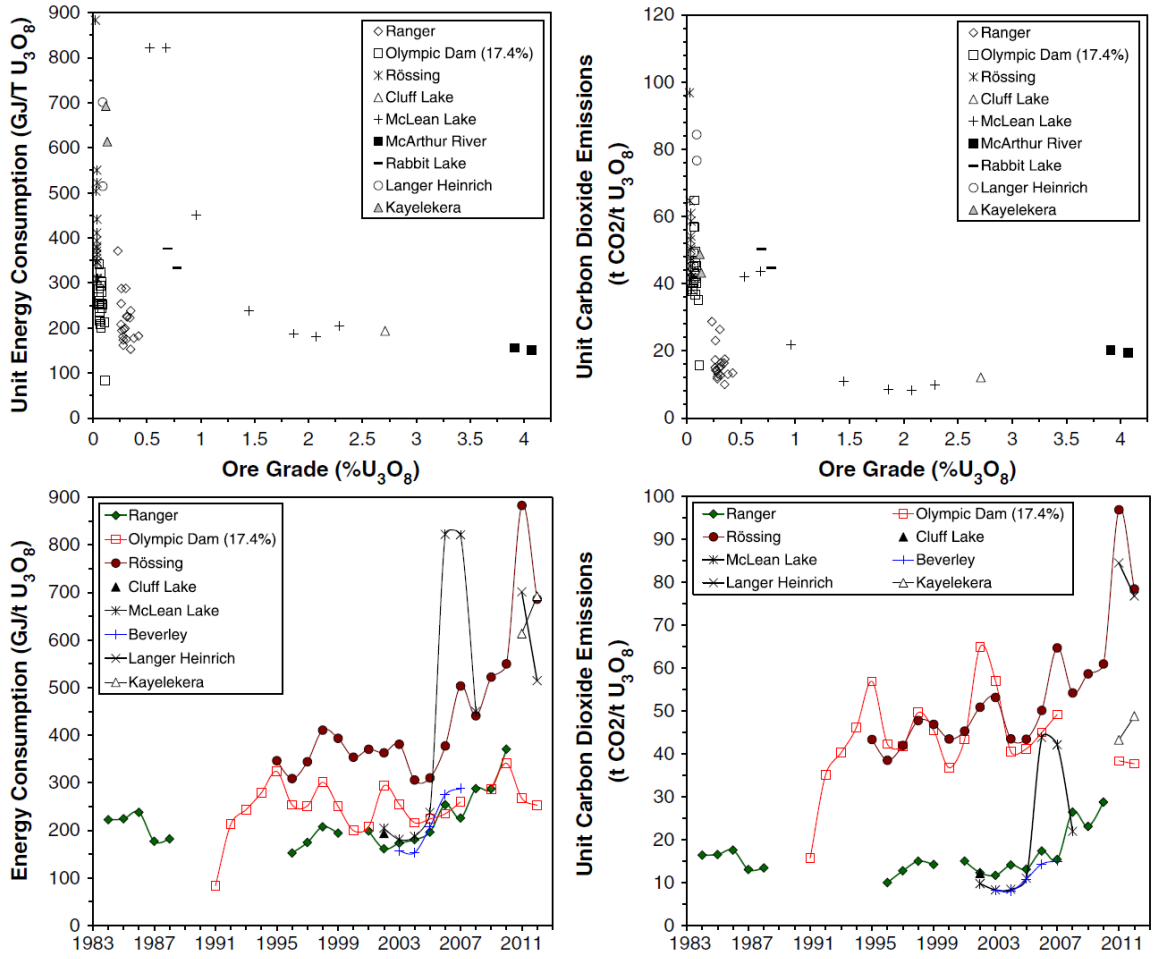
Source: (Dones et al., 2009). Open-pit mining has additional transport of waste rock of 1.06 kg CO_2eq/kgU. *artificial ore grade for lower and upper bounds on the energy demands.

The authors of (Mudd, 2010) give a detailed overview of the carbon intensity of mining operations in Australia. In Figure 115 the carbon intensity of some uranium mining operations is shown in dependence of the ore grade as well as the energy consumption of several typical underground and open-pit mines over the years of operation from 1983-2007. The authors calculate a mean of 26.4 kg CO_2eq/kgU_3O_8 and a deviation of ±17.6 kg CO_2eq/kgU_3O_8 or 31.15 ± 20.76 kg CO_2eq/kgU (Olympic Dam is excluded in these mean numbers). But (Mudd, 2010) include Olympic Dam into their figures and attribute 20% of the resources intensities to the mining of uranium as a by-product, with the revenue of uranium being 20% versus other metals such as copper. From visual reading of Figure 115 a range of roughly 5-60 kg CO_2eq/kgU_3O_8 or 6-71 kg CO_2eq/kgU. Ore grades above 0.3% cluster around 5-20 kg CO_2eq/kgU_3O_8 (6–24 kg CO_2eq/kgU) with some outliers as the Rabbit Lake mine. Below 0.3% ore grade the values cluster between 40-60 kg CO_2eq/kgU_3O_8 (47–71 kg CO_2eq/kgU). However, even the high ore grade mines like Mac Arthur River/Key Lake or McLean Lake report 5-20 kg CO_2eq/kgU3O8 (6–24 kg CO_2eq/kgU). Also observe the nonlinearity of the data points that makes an inverse-linear first order or power law assumption for the functional relationship

between ore grade and energy demand plausible with an offset of at least 6 kg CO_2eq/kgU even for very high-grade mines.

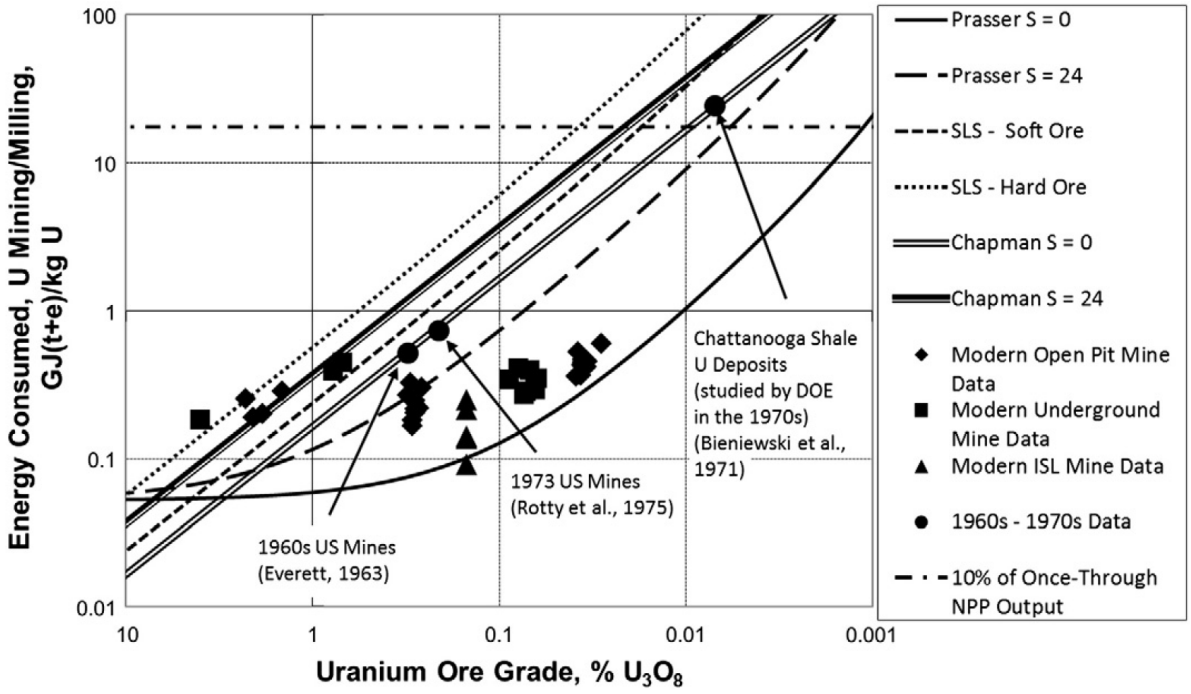
Also (E. Schneider et al., 2013b) reports different functional relationships between ore grades and energy consumptions and relates them to old and newer data from mines (Figure 116). The data shows, that older models such as those from (Storm van Leeuwen, 2008) do not fit data well and affirm the general assumptions of the ecoinvent dataset for energy consumption which is generally below 1000 MJ_{th}/kgU.

Figure 115: Carbon intensity versus grade



Source: (Mudd, 2014). Top left: energy intensity over ore grade for selected uranium mines. Top right: energy intensity over time for selected uranium mines. Bottom left: carbon intensity over ore grade for selected uranium mines. Bottom right: carbon intensity over time for selected uranium mines.

Figure 116: Energy intensity versus grade



Source: (E. Schneider et al., 2013b) Grade-to-energy models of (Chapman, 1975), (Storm van Leeuwen, 2008) (SLS) and (Prasser et al., 2008) (Prasser) and data points for individual mines.

From these numbers we conclude that using the reference values of ecoinvent and scaling linearly (simple model) the mining operation and yellowcake production and their infrastructure demand with the different ore grades used in the LCA chains is sufficient to cover the ranges of assumptions. This circumvents to make an explicit assumption about functional relationships between energy demand of the mining operation and the ore grade, which is difficult to obtain, for a discussion see e.g. (Norgate et al., 2014; E. Schneider et al., 2013b) and (Figure 116). Assuming a linear scaling of GWP by ore-grade for uranium mining and processing will overestimate GWP for medium ore-grades and potentially underestimate for low ore grades compared to inverse-linear or power-law functional relationships.

The reference value for the ore grade in ecoinvent is 0.17%U (ISL 0.142%U).[40] Table 73 shows the ore grade variation of the different LCA chains and calculates the scaling factors that result compared to the reference ecoinvent assumption of 0.17%U (0.14%U for ISL) (inverse relationship, the higher the ore grade the lower the emissions and vice versa). Given the range of ore grades used for the LCA chains in this study from 0.025-11.5% with a factor of 460 between the minimum and maximum, we assume that this covers the possible differences in real mining operation quite well, with some exceptions.

Using 11.5% ore grade for Cigar Lake mine in LCA chains EU9_SMR, NA4 and JP1 would lead to a factor of 0.015 reduction of emission in comparison to the reference value of 55.5 kg CO_2eq/kgU resulting in 0.8 kg CO_2eq/kgU or almost no emissions. This is clearly not covered by emission data in (Mudd, 2010; Parker et al., 2016) for typical high-ore grade Canadian underground mines from the Athabasca Basin (Rabbit Lake, Cigar Lake, McArthur River, McClean Lake, Cluff Lake) (see Figure 115). In his article (Parker et al., 2016) report intensities of three Canadian uranium mine-mill pairs with 81, 64, and 34 kg CO_2eq/kgU3O8 at average ore grades of 0.74%,

[40] This assumption is based on the reference mines in Doka (2011); Dones et al. (2009) However for other calculations like the referenced calculation for transport and others, different average ore grades are being used like 0.3% or 0.5%.

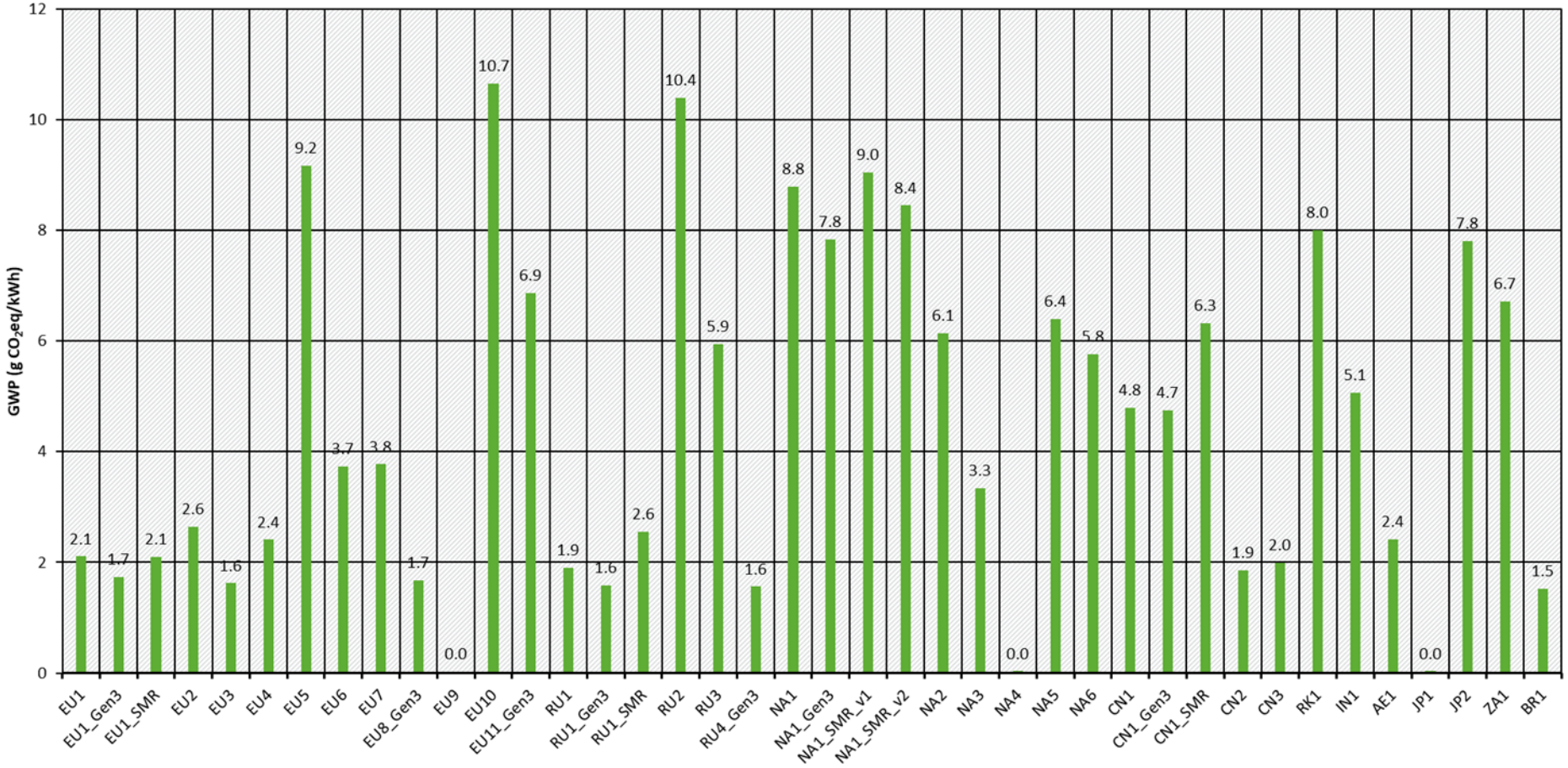
1.54%, and 4.53%U3O8 respectively. The production-weighted average emissions is 42 kg CO_2eq/kgU3O8 from ore with an average grade of 3.81% U3O8 (Parker et al., 2016). Using a power law to fit the three datapoints (E(oregrade) = 61.57*oregrade^(−0.49)) to 11.5% for Cigar Lake would correspond to emissions of 24 kg CO_2eq/kgU_3O_8 or 28.6 kg CO_2eq/kgU. Much higher than simply scaling the reference value of 55.5 kg CO_2eq/kgU with an ore grade of 11.5% leading to 0.8 kg CO_2eq/kgU. For the sensitivity analysis we therefore assume a lower limit of emissions of 30 kg CO_2eq/kgU. (Mudd, 2014) report also numbers down to 15 kg CO_2eq/kgU for Cluff Lake, however these reserves were easy to mine. To implement it into our calculation we assume that the ore grade of underground mines such as Cigar Lake has an upper limit of 0.3%.

Similarly the low ore grade of Olympic Dam leads to an overestimation of the energy consumption for underground mining when scaling with the ore grade of 0.048%U. Uranium mined at Olympic Damn is also a byproduct and some of the energy intensity has to be attributed to other products such as copper. (Mudd, 2014) give a value of 43.5 kg CO_2eq/kgU_3O_8 or 51.3 kg CO_2eq/kgU for Olympic Dam at an 17.5% share of energy intensity for uranium as product and at a recovery rate of about 70%. We assume therefore the ecoinvent upper limit of 108 kg CO_2eq/kgU as an upper bound for emissions for underground mining. This is a conservative assumption given the data available for Olympic Dam. To implement it into our sensitivity calculation we have to use an artificial high ore grade of 0.087% for underground mines such as Olympic Dam.

Also, with open pit mining the low ore grade of Rössing and Husab with 0.025%U and 0.033%U lead to an overestimation of energy intensity if scaling linearly by ore-grade. (Mudd, 2014) report 63 kg CO_2eq/kgU for Rössing and 95 kg CO_2eq/kgU for Langer Heinrich. Also the numbers from the 2023 report from Rössing mine itself (Rössing Uranium & China National Nuclear Corporation [CNNC], 2023) support this assessment. They report a release of 150,000 tCO_2eq for a production of 2476 tU (0.027%U ore grade) resulting in 60.6 kg CO_2eq/kgU. We therefore introduced an upper limit to the sensitivity analysis in accordance with the ecoinvent data of 82 kg CO_2eq/kgU corresponding to an artificial high ore grade of 0.076% for all open-pit mines like Rössing and Husab etc.

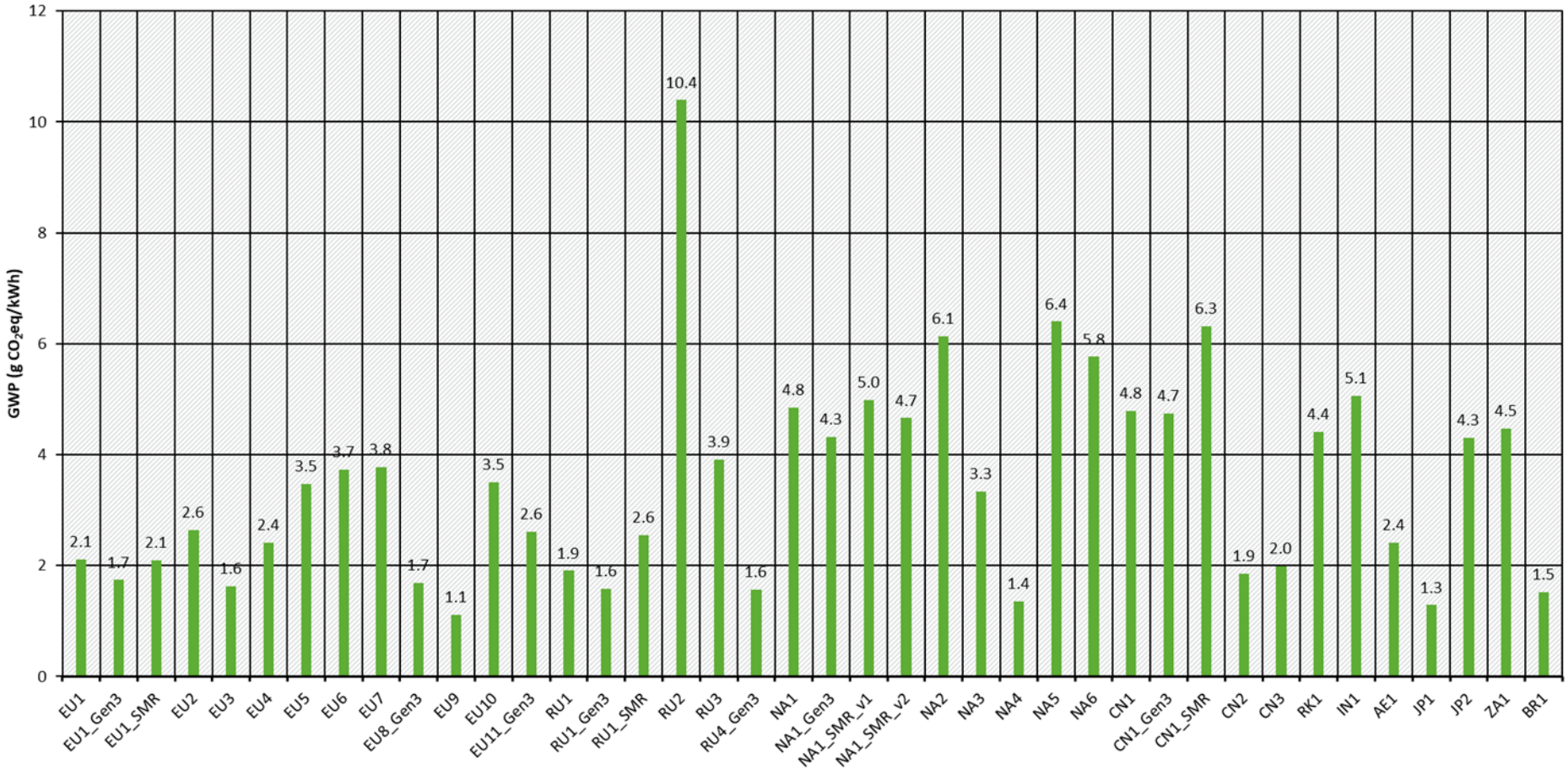
We integrated upper and lower bounds for the ore grade and introduced artificial ore grades for those mines that have higher or lower ore grades for underground and open-pit mining. Due to lack of data, there are no such limits for ISL mining techniques. The difference between the undisturbed simple model of scaling mining operation by ore-grade, to the imposition of upper and lower bounds is shown in Figure 117 and Figure 118. The low grade ISL mines now dominate GWP. The high grade, Canadian mine Cigar Lake (EU9, NA4, JP1) does not result in zero GWP, but has a lower threshold GWP impact of over 1 g CO_2eq/kWh. The low grade open-pit mines like Rössing (EU10), Husab (EU4, EU11_gen3) and Khiagda (RU3) do have significantly lower GWP than without lower bound. Also, by-production mines like Olympic Dam (NA1, NA1_Gen3, NA1_SMR_v1, NA1_SMR_v2, RK1, JP2) have significantly less GWP. Due to the high uncertainties of ore-grade and energy consumption data the sensitivity study shows a more compressed range of GWP in mining from 1.1-10.4 g CO_2eq/kWh compared with the undisturbed simple assumption of scaling mining GWP with ore grade with a range of 0.03-10.7 g CO_2eq/kWh. For the effect of changing the ore grade in a specific life cycle chain, see also section 3.12.5.1.1.

Figure 117: Mining: GWP (g CO_2eq/kWh)



Source: Öko-Institut. Total mining GWP for mining, milling and yellowcake production

Figure 118: Sensitivity Mining: GWP (g CO_2eq/kWh)



Source: Öko-Institut. Total mining GWP for mining, milling and yellowcake production with upper and lower limits for the ore grade.

3.12.1.1.2 Uranium mining future – ore grade and resource size

Estimating future mining operations is difficult. Based on today's estimate however, there will be more and more low-grade mines that have to be used in the future, after higher grade mines have been depleted. Additionally large resources will be mined first. There are also much more smaller sized resources (Figure 105) worldwide so that the infrastructure demand will increase in the future. Future uranium resources would probably also lie deeper underground, potentially increasing the energy needed to remove overburden and waste rock.

In the supporting information to (Warner & Heath, 2012) the authors give e.g. different scenarios of future ore grades based on growth assumptions of the nuclear industry and known resources. The authors model a decrease of the maximum ore grad to 1.1% down to 0.012% until 2050. Since the lowest ore grade in this study is used in LCA chain EU10 with the Rössing mine and an ore grade of 0.025% such pessimistic assumption of future maximum ore grades would change the GWP of EU10 by a factor of 2 to 21.2 g CO_2eq/kWh (16.0 g CO_2eq/kWh production and 5.2 g CO_2eq/kWh infrastructure). However, electrification of the mining industry could also lower the GWP, which is not yet modelled in the results presented here.

Also (Norgate et al., 2014) predict a decline of ore grades in the future that could affect the GWP of mining operations. Based on a declining yield curve and the assumption that no new high-grade resources can be found they conclude that the GWP for mining from their study of 33.9 g CO_2eq/kWh (2014) would almost double to 60 g CO_2eq/kWh over 50 years.

3.12.1.1.3 Construction and Decommissioning/Remediation

Ecoinvent does not assume any decommissioning or remediation measures of the mines. This typically involves large scale movement of tailings and waste dumps and cleaning operations. There seem to be no good estimates on the energy demand on remediation in the literature.

3.12.1.1.4 Uranium as by-product

The assumption above that the full GWP for co-production mines is attributed to uranium as a product is reasonable within the scope of this report. LCA chains that use Olympic Dam as mine (NA1, NA1_Gen3, NA1_SMR_v1, NA1_SMR_v2, RK1, JP2) have comparable GWP of 7.6-8.8 g CO_2eq/kWh to other mining operations. Taking into account that other by-products of mining, such as copper, would have to be attributed a percentage of the mining operation, the GWP would be lower. Based on assumption on upper limits of the energy demand for mining and uranium processing (artificial ore grade of 0.087%U) would result in a 55% share of the energy demand (Figure 118).

3.12.1.1.5 Transportation

For open pit mining ecoinvent assumes a waste rock/ore ratio of 30 and a uranium oxide content of 0.5%, this results in transport costs of around 7 tkm per kg of uranium, based on a 1 km journey with 32-tonne trucks for the waste rock (Dones et al., 2009).

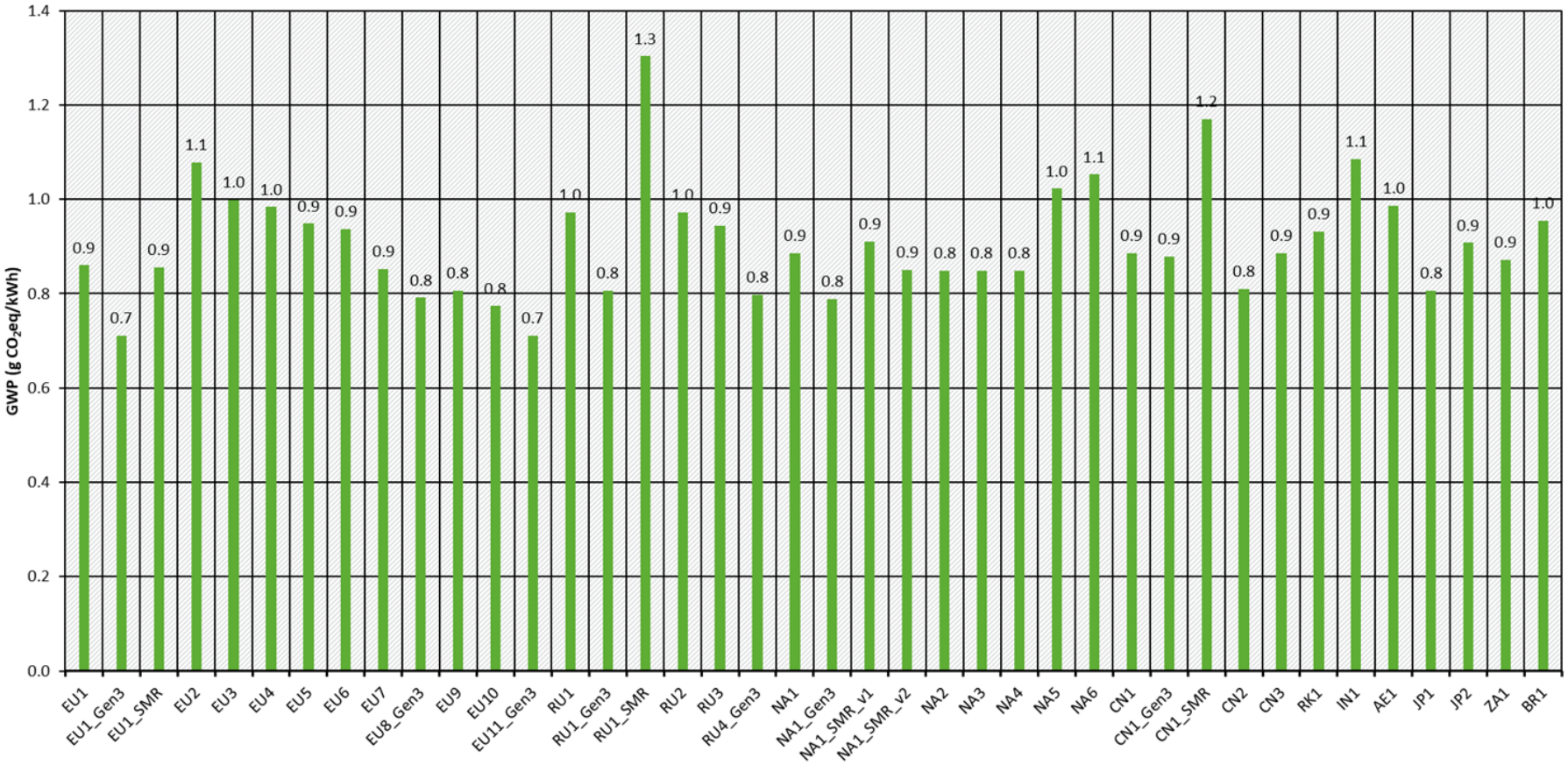
(Dones et al., 2009) give other plausibility argumentations for this reference value. They show that the waste rock to ore ratio for the Key Lake mine is 72:1. In the ranger mine in Australia a ratio of only 3:1 is given by (Dones et al., 2009) but with an ore grade of 0.3%. Altering the assumptions about the rock to ore ratio would linearly scale the energy demand for transportation.

An additional 1 km transport, which is realistic given maps of e.g. Arlit mine will increase the GWP from 0.34 g CO_2eq/kWh for the standard assumption of 1 km to 0.54 g CO_2eq/kWh in LCA chain EU1. The additional transport is assumed also with 32t trucks and a 30:1 waste rock/ore ratio.

3.12.2 Conversion

The infrastructure contributes only marginally to the GWP with a range of 0.01-0.03 g CO_2eq/kWh. The GWP emission of conversion for all LCA chains is given in Figure 119 with a range of 0.71-1.3 g CO_2eq/kWh, a significant contribution to total GWP emissions.

Figure 119: Conversion: GWP (g CO_2eq/kWh)



Source: Öko-Institut

3.12.2.1 Sensitivities

3.12.2.1.1 Conversion: energy consumption

Ecoinvent assumes an energy intensity of 700 MJ_{th}/kgU produced by natural gas. For the reference facilities they give a possible range of 110-1300 MJ_{th}/kgU. However, (Dones et al., 2009) mention, that the reference for the higher value also gives three other energy intensities, which are all an order of magnitude lower. Therefore, the assumption of 700 MJ_{th}/kgU seems to be conservative.

Other data from (Norgate et al., 2010) is summarized in Table 74 for the thermal energy consumption of uranium conversion with a range of 18.3-1425 MJ_{th}/kgU and a mean value of 531 MJ_{th}/kgU (Norgate et al., 2010). The lowest value by AREVA is a factor of seven smaller than the next value of 131 MJ_{th}/kgU.

In summary there is a large uncertainty with a possible factor of two to the upside for energy consumption for conversion or a factor 8-9 reduction given the data cited.

Table 74: Different values for uranium conversion energy consumption

Reference	Electrical (MWhel/tU)	Thermal (GJth/tU)	Totall (GJth/tU)
This study (Areva, 2008)	7.0	18.3	94
WNA (2006)			850
ISA (2006)	14.6	1425.0	1584
Storm van Leeuwen & Smith (2005)	14.6	1425.0	1584
Franklin et al (1971)	11.0	131.0	251
Rombough & Koen (1974)	15.1	234.0	397
Rotty et al (1975)	14.6	1425.0	1584
SRI (1975)	10.3	1313.0	1424
Chapman (1975)	15.9	195.0	367
ERDA (1976)	14.6	1425.0	1584
Mortimer (1977)	12.1	235.0	365
Weis (1990)			25
Australian Coal Association (2001)			317
Torfs et al (1998)	10.3	700.0	811
Oliver & McLeod (2001)			25
MEAN2	12.0	531.0	661

Source: (Norgate et al., 2010)

3.12.2.1.2 Deconversion

Deconversion of enriched UF6 to a stable oxide form like UO2 is part of the process step between enrichment and fuel fabrication. But both the enriched as well as the depleted UF6 will have to be reconverted. We discuss deconversion here as the deconversion of depleted Uranium is not covered in the ecoinvent datasets. The depleted uranium can be stored over long times in the form of UF6 at enrichment plants, as many countries see it as an eventual source to extract more

U235 under the right market conditions. For the purpose of LCA however, we assume that all UF6 is at some point converted back to UO2 or U3O8, either for fuel fabrication (covered by ecoinvent) or to dispose of the depleted uranium (not covered by ecoinvent). (E. Schneider et al., 2013a) reports some estimates from previous studies with a range from 0.46 kg CO_2eq/tDU to 19.21 kg CO_2eq/tDU and show in their Figure 7.3 data from (Storm van Leeuwen, 2008) and (Fthenakis & Kim, 2007) indicating GWP higher than 1 g CO_2eq/kWh. However, their own assumption of 1700 kg CO_2eq per tU of their reference fuel cycle (Burnup 51 MWdth/kgHM, Efficiency 0.33%, Unat/Uenriched 8.41) suggest a much lower GWP of only 0.04 g CO_2eq/kWh. Also comparing the energy requirements with the original data reference in (DoE, 2004) with about 1 kg CO_2eq/kgDU is in line with a much lower value for GWP. Therefore, we do not include Deconversion in the LCA chains, because it is not part of ecoinvent and has only marginal impact.

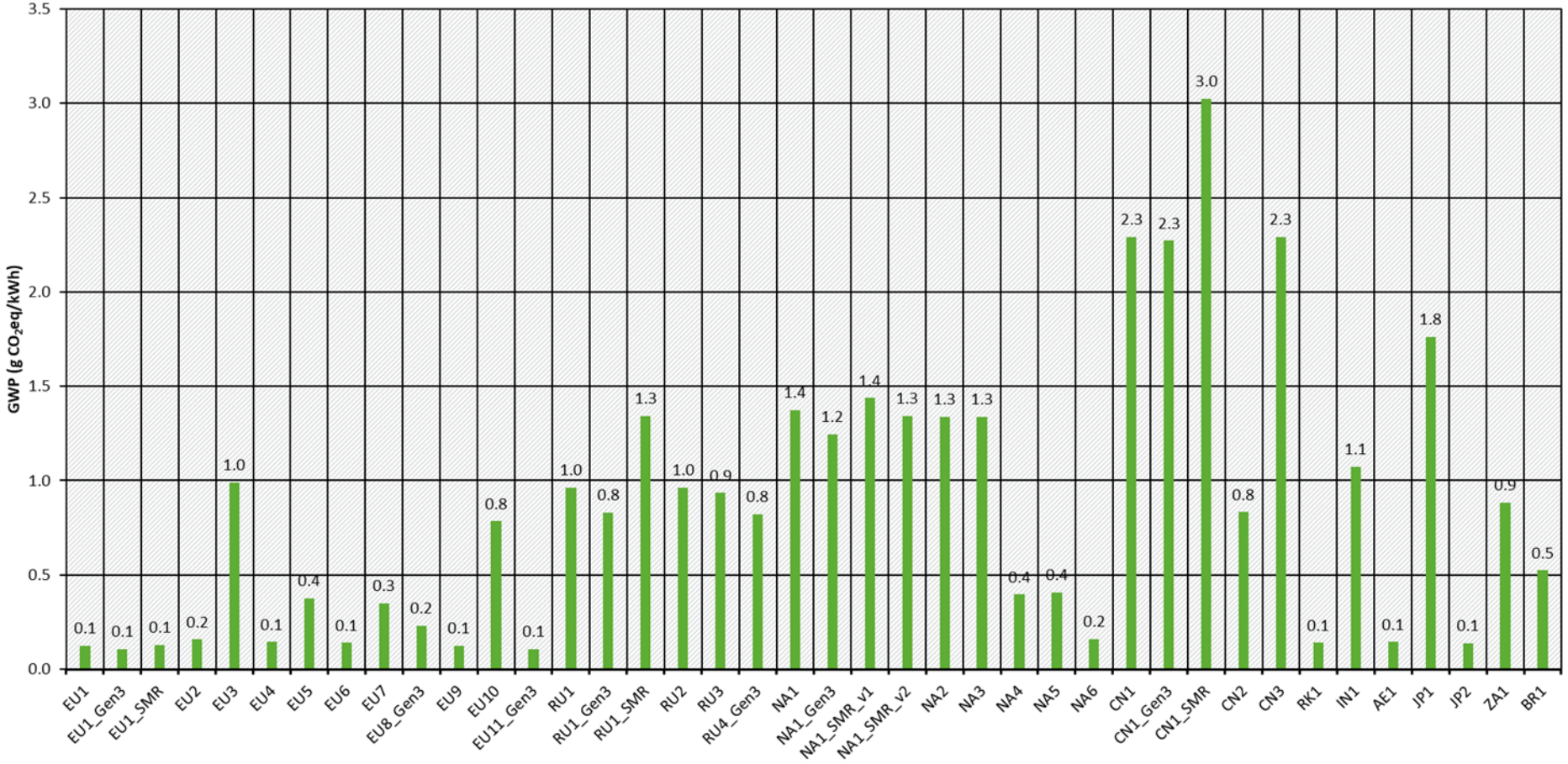
3.12.3 Enrichment

Depending on the country choice, the GWP emissions differ due to the facility specific energy consumption and the country specific electricity mix in the different countries between 0.09-2.82 g CO_2eq/kWh with the lowest emissions from the French enrichment plant and the highest in China (Figure 120) depending on the electricity mix and the energy consumption (kWh/thousandSWU).

For the infrastructure the GWP emissions differ by a factor of two but on a very low level from 0.08 to 0.19 g CO_2eq/kWh.

The burnup dependent enrichment requirements only have a marginal impact on the GWP emissions. For the LCA chain EU1 the GWP for the three different enrichment choices would be 0.116 g CO_2eq/kWh for 3.8%U235, 0.112 g CO_2eq/kWh for 4%U235 and 0.109 g CO_2eq/kWh for 4.2%U235.

Figure 120: Enrichment Centrifuge: GWP (g CO_2eq/kWh)



Source: Öko-Institut

3.12.3.1 Sensitivities

3.12.3.1.1 Enrichment and depletion levels

The depletion level is kept constant in all LCA chains. Due to changes in the optimal price point as a balance of enrichment costs ($/SWU) vs. natural uranium price ($/kgUnat) this assumption might be changing in the future. For a depletion level of 0.15% roughly 15% less natural uranium would be required assuming a very high uranium price and cheap enrichment costs. For a depletion level of 0.4% roughly 40% more natural uranium would be required assuming a very cheap uranium price and high enrichment costs. Of course, all frontend emissions would be as well affected, since less respectively more natural uranium would have to be mined and processed. This amounts to a factor of 0.85-1.4 for all emission from these process steps.

In the future laser enrichment might lower the energy demand even further, although ecoinvent reports similar energy demands of 40 kWh/kgSWU or higher for different laser enrichment methods. But centrifuge enrichment will be the workhorse of enrichment companies for the next decades, as large investments into expansion and new build of centrifuge enrichment plants have been made in the last decade by France, the US, and for the Urenco plants.

For the recent generation of large scale LWR enrichments of up to 5% or even more for very high burnup fuels might become relevant. However, at about 5% enrichment 2/3 of the separation work has been done[41] and further enrichment will not increase the amount of separative work substantially. Also, the additional burnup will reduce the GWP per kWh, as more electricity can be produced. Therefore, the additional energy required for further enrichment will not have a significant impact on GWP emissions.

3.12.3.1.2 Depleted Uranium

Currently the depleted uranium from centrifuge facilities is stored in containers mostly at the sites of the enrichment plants in the form of uraniumhexafluoride or as uranium-oxide after deconversion. Since the depleted uranium still contains U235, it is often seen as a possible asset to further extract uranium, if the uranium price will increase in the future or the separation price will further decrease. Depleted uranium is also used to fabricate ammunition.

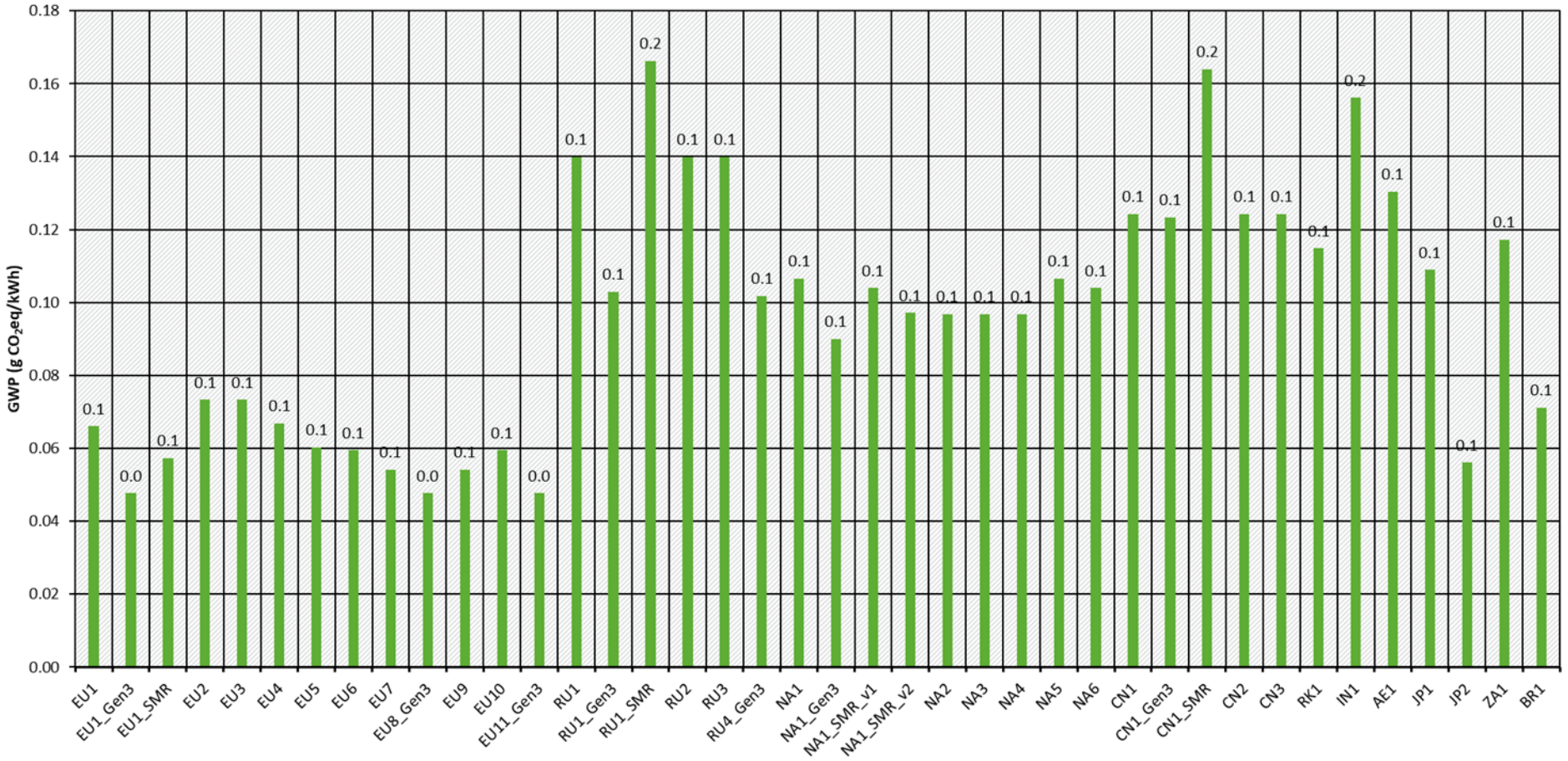
In ecoinvent the depleted uranium is missing from the mass flows of low-level radioactive waste. The assumption being that the depleted uranium still contains U235 and will be used as breeding material in future fast reactors, as ammunition or to further extract U235 in the future. In this study the depleted uranium mass is also not included in the low-level radioactive waste flows, but explicitly accounted for as an additional material stream. We consider the likelihood of further use of depleted uranium as low and a use as ammunition as highly problematic. In Germany depleted uranium waste has to be disposed of as radioactive waste. In similar cases of declaring depleted uranium as radioactive waste, it does significantly contribute to the impact categories of low-level radioactive waste.

3.12.4 Fuel element fabrication

The infrastructure for fuel element fabrication contributes only marginally to the GWP with a range of 0.005-0.01 g CO_2eq/kWh. The GWP emission of fuel fabrication for all LCA chains is given in Figure 121 with a range of 0.05-0.17 g CO_2eq/kWh, a small contribution to total GWP emissions.

[41] To enrich 1 t natural uranium to 3.8%U235 needs about 676 thousand SWU to produce 127 kg product (waste 0.26%U235). To enrich to 5% about 738 thousand SWU is necessary to enrich 97 kg. Per kg product the SWU requirements will raise almost linearly, however a reactor with higher enriched fuel will need also less fuel mass for criticality (neglecting secondary effects, e.g. losses to absorption or geometric effects).

Figure 121: Fuel element fabrication: GWP (g CO_2eq/kWh)



Source: Öko-Institut

3.12.4.1 Sensitivities

3.12.4.1.1 MOX Facility

Due to differences in the handling of plutonium, for MOX fabrication both infrastructure and operational demand for materials and energy will differ from typical LWR fuel fabrication plants. As there is no valid data available for MOX production and only very few countries currently follow reprocessing and MOX use in light water reactors, this difference is not covered in our life cycle chains. As the specific GWP for fuel fabrication infrastructure is very low, even a ten fold increase due to the more demanding MOX fuel production would not lead to a significant change of results.

3.12.4.1.2 Energy Demand

Ecoinvent (Dones et al., 2009) assumes an energy demand for LWR fuel fabrication of 80% electricity (36 kWh/kgU) and 20% thermal energy (32 MJth/kgU) from oil based on a study of the Hanau fuel element factory (Pink et al., 1984). Other values given by (Dones et al., 2009) as references are 50 kWh/kgU electricity and 100 MJth/kgU thermal energy from natural gas for the DOE Reference plant (DoE, 1983) and 97 kWh/kgU electricity and 232 MJth/kgU by (El-Bassioni, 1980). Other values from the literature are given in Figure 122, a reproduction by (Carless et al., 2016) of a collection of earlier data originally published in (Norgate et al., 2010). Except for the very high values in the studies by (Rombough & Koen, 1975; Rotty et al., 1975) from the 1970s, the range indicate that the ecoinvent value might be somewhat low. Also (E. Schneider et al., 2013a) report numbers for the Mitsubishi Nuclear Fuel Ltd. (MNF) facility that provides UF6-to-UO2 and fuel assembly fabrication for PWRs in Japan, with an energy demand of 209 GJ/tHM. and final GWP results could be a factor 3-5 higher.

Figure 122: Fuel fabrication energy consumption

Table A3
Fuel fabrication energy consumption [45].

Reference study	Year	Electrical energy (MWh_{el}/t U)	Thermal energy (GJ_{th}/t U)
Franklin et al.	1971	109.0	0
USAEC	1972	53.5	137
Rombough & Koen	1974	168.8	6,169
Rotty et al.	1975	303.0	2,720
SRI	1975	98.0	262
Chapman	1975	49.2	142
Mortimer	1977	65.0	341
Orita	1995	56.3	120
Australian Coal Association	2001	54.3	154
Reported mean	–	105.3	1,101

Note: This table contains reproduced from data from Norgate et al. (2010) [18].

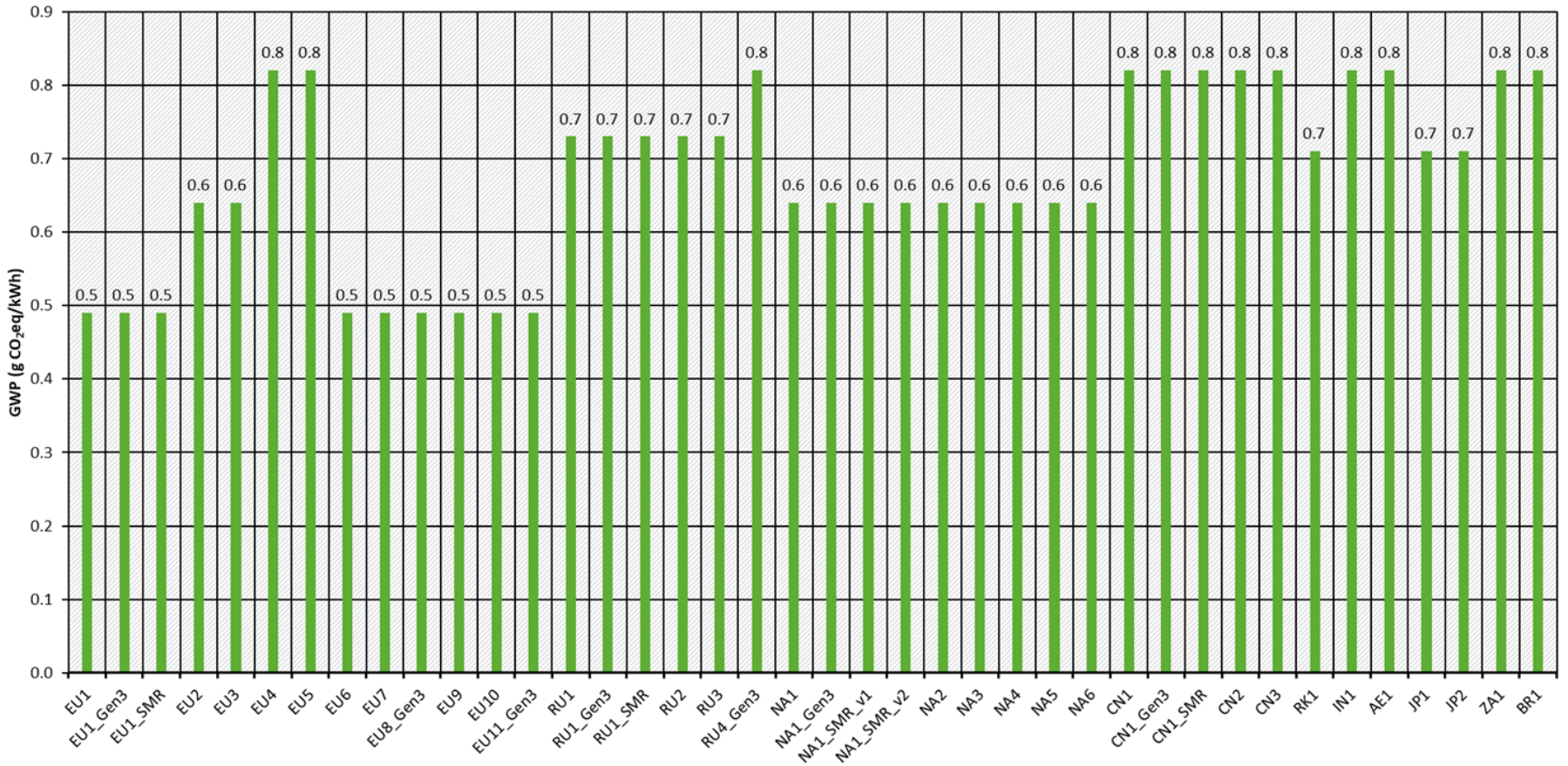
Source: (Carless et al., 2016)

3.12.5 Power Plants

3.12.5.1 Operation

The country specific GWP due to the operational phase of NPPs differ only slightly in the range of 0.49 to 0.83 g CO_2eq/kWh, see Figure 123.

Figure 123: NPP operation: GWP (g CO_2eq/kWh)



Source: Öko-Institut

As the used fuel from reactor operation represents the largest share of high-level wastes (HLW) arising during the whole life cycle chain, the operational parameters effect the amount of HLW to be reprocessed or be disposed of directly. The total volume of spent fuel after conditioning for the life cycle chains without reprocessing varies between 4.8E-9 m^3/kWh and 8.5E-9 m^3/kWh. For life cycle chains that include reprocessing of spent fuel, the total volume of HLW due to spent uranium fuel is reduced, but additional volumes of HLW from reprocessing arise. In total over all life cycle chains, the total volume of HLW varies between 4.8E-9 and 1.2E-10 m^3/kWh or a factor of approximately two.

The operational phase of NPPs is responsible for approximately one third of the total low-level wastes arising from the life cycle chains.

3.12.5.1.1 Sensitivities

The total difference between the lowest and highest country specific GWP of 0.34 g CO_2eq/kWh due to the life cycle step of NPP operation corresponds to only 2-7% of the range of the total GWP of all life cycle chains analysed (approx. 4-20 g CO_2eq/kWh).

The major differences in fuel types, burnup and corresponding enrichment, efficiencies, and load factors as discussed above have a major influence on the fuel needs to produce one kWh of electricity, while the environmental impact of the fuel production and disposition as such is not covered by the LCA step of NPP operation but leads to differences in the preceding and following LCA steps.

3.12.5.1.1.1 Enrichment level

Reducing the enrichment increases the amount of natural uranium needed and thus typically increases the GWP due to the front-end processes. The reduction of the enrichment level to 3.75% for life cycle chains NA1 and CN1 increase the total GWP by 3% and 6% respectively, reducing the enrichment level to 4.0% increases the GWP of CN1 by 3%, compare Table 75.

Vice versa, an increase in enrichment level to 4.0% reduces the total GWP of EU1 and RU1 by -3% and -2% respectively and an increase to 4.2% reduces the total GWP of EU1, RU1 and NA1 by -6%, -4% and -3% respectively.

3.12.5.1.1.2 MOX fraction

A change of the assumed MOX fraction changes the need for natural uranium as well as conversion and enrichment services but leads to additional burdens from the reprocessing stage.

For the EU1 life cycle chain, where a full recycling of spent uranium fuel is assumed while at the same time a mine with a relatively high ore grade as well as a conversion and enrichment step with a very low GWP of the corresponding electricity mix is assumed, a change in MOX fraction from the maximum value to one half and or quarter of the value leads to slight decrease (-1% or -2%) in total GWP, compare Table 75. Contrarily, for the life cycle chains RU1, NA1 and CN1, an increase of the MOX fraction to one quarter, one half or even full recycling would reduce the total GWP by -3%, -6% (-5% for CN1) or -11% respectively. It is therefore evident, that the effect of reprocessing with respect to the total GWP depends on the efficiency of the front-end processes. With respect to the effect of MOX use on the GWP, it has to be kept in mind, that MOX fuel production is not specifically covered by the data implemented in ecoinvent, compare section 3.12.4.1.1.

3.12.5.1.1.3 Load factor

With a change of the load factor, the overall electricity produced in the NPP changes. As less electricity is produced, correspondingly less fuel is consumed. Therefore, the absolute contribution of the front-end and back-end steps in the life cycle chain do not change. On the other hand, the environmental impact due to construction and decommissioning of the NPP per produced kWh of electricity increases.

Assuming a very high load factor of 95% would decrease the total GWP for EU1, RU1, NA1 and CN1 by -4%, -6%, -1% and -1% respectively, compare Table 75. For a load factor of 75%, the total GWP for EU1, RU1, NA1 and CN1 changes by 1%, 1%, 3% and 3%. Only with the assumption of a rather low load factor of 50%, a somewhat more significant increase of the total GWP for EU1, RU1, NA1 and CN1 of 11%, 18%, 10% and 12% results. From these numbers it is evident, that with respect to the total GWP a variation of the load factor is not very significant, as the total GWP is dominated by front-end and back-end processes, except for very low load factors, that might become possible in a system with high shares of renewables.

3.12.5.1.1.4 Efficiency of the NPP

A variation of the efficiency of a NPP directly translates to a change in fuel consumption. For an increase of the efficiency of two percent points, a decrease of total GWP of -5% to -6% results for the life cycle chains EU1, RU1, NA1 and CN1, compare Table 75. With a decrease of the efficiency by two percent points, the total GWP increases by 5% to 6%. Thus, higher efficiencies directly translate in lower GWP. This effect is specifically relevant for SMRs, as their design efficiency compass a range of 21.3-34.6%, compared to Generation 3 NPPs with design efficiencies of 31.3-37.9%.

3.12.5.1.1.5 Comparison with the effect of a change in ore grade

While the effects of changes in enrichment, MOX fraction, load factor and efficiency of the NPP on overall GWP are typically well below 10%, a change in ore grade by a factor of two is rather significant for most life cycle chains. Total GWP might change by -30% to +60% for a change in ore grade by a factor of two, compare Table 75. Overall, this is the most important factor with respect to total GWP.

Table 75: Change of total GWP in g CO_2eq/kWh for a variation of selected parameters in selected life cycle chains

Value	Variation	EU1 Abs.	Rel.	RU1 Abs.	Rel.	NA1 Abs.	Rel.	CN1 Abs.	Rel.
	None	6.88		8.90		15.08		11.70	
Ore grade	x 2	5.67	-18%	7.83	-12%	10.65	-29%	9.31	-20%
	/ 2	9.61	40%	11.29	27%	24.04	59%	16.49	41%
Enrichment	3.75%	-	-	-	-	15.54	3%	12.39	6%
	4.0%	6.68	-3%	8.71	-2%	-	-	12.07	3%
	4.2%	6.48	-6%	8.50	-4%	14.58	-3%	-	-
MOX frac.	Max.	-	-	7.92	-11%	13.41	-11%	10.47	-11%
	Half	6.80	-1%	8.41	-6%	14.25	-6%	11.09	-5%
	Quarter	6.76	-2%	8.66	-3%	14.67	-3%	11.40	-3%

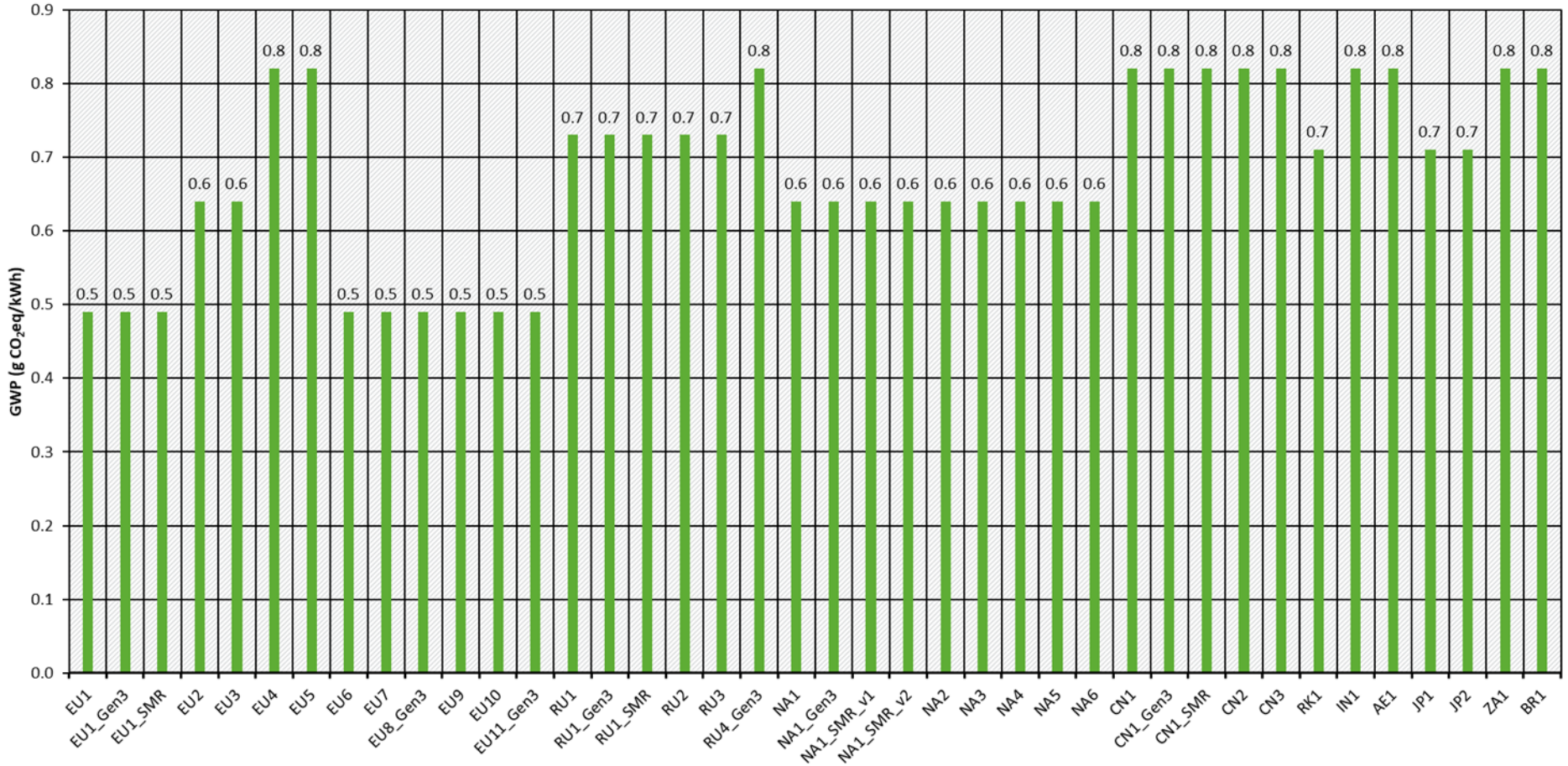
Value	Variation	EU1 Abs.	Rel.	RU1 Abs.	Rel.	NA1 Abs.	Rel.	CN1 Abs.	Rel.
Load factor	95%	6.60	-4%	8.39	-6%	15.00	-1%	11.62	-1%
	75%	6.92	1%	9.02	1%	15.49	0.03	12.04	3%
	50%	7.66	11%	10.51	18%	16.65	10%	13.05	12%
Efficiency	+2%	6.54	-5%	8.43	-5%	14.23	-6%	11.13	-5%
	-2%	7.26	6%	9.44	6%	16.05	6%	12.34	5%

Sources: Own calculation

3.12.5.2 Construction

The GWP range due to construction of a NPP is 0.53-2.93 g CO_2eq/kWh with a typical value around 1 g CO_2eq/kWh.

Figure 124: NPP construction: GWP (g CO_2eq/kWh)



Source: Öko-Institut

3.12.5.2.1 Sensitivities

3.12.5.2.1.1 Material and energy demand

With a total spread of a factor of nearly six between the lowest and highest GWP due to the construction phase, this value is highly dependent on the input parameters. The major contribution can be attributed to the differences in the material and energy balance assumed for the construction phase as was discussed in section 3.7.4. Literature values for energy and material input show differences of up to a factor of ten, thus the spread in GWP as determined in our life cycle chains is well within such a range.

3.12.5.2.1.2 Plant lifetime

With a change of the plant lifetime, the overall electricity produced in the NPP changes. As more electricity is produced, correspondingly more fuel is consumed. Therefore, the absolute contribution of the front-end and back-end steps in the life cycle chain change proportionally to the change in plant lifetime. On the other hand, the environmental impact due to construction and decommissioning of the NPP per produced kWh of electricity decreases with increasing plant lifetime. Overall, the effect of changing plant lifetime is therefore limited.

For an increase of the plant lifetime to 50 or 60 years, in EU1 the total GWP is reduced by -4% and -7% respectively, for RU1 by -3% and -8%. Decreasing the plant lifetime to 50 or 40 years will increase the total GWP for the CN1 life cycle chain by 3% or 7% respectively. The absolute changes in total GWP due to a variation in plant lifetime range between and 0.3 and 0.84 g CO2eq/kWh, compare Table 76.

Table 76: Change of total GWP in g CO2eq/kWh for a variation of plant lifetime in selected life cycle chains

Value	Variation	EU1 Abs.	Rel.	RU1 Abs.	Rel.	NA1 Abs.	Rel.	CN1 Abs.	Rel.
	None	6.88		8.90		15.08		11.70	
Plant lifetime	40 a			9.26	4%	15.56	3%	12.54	7%
	50 a	6.58	-4%	8.62	-3%			12.04	3%
	60 a	6.39	-7%	8.19	-8%	14.76	-2%		

Sources: Own calculation

Besides the parameters covered by the life cycle chains, an additional uncertainty results from the fact, that a relevant fraction of plant constructions is not being finished once they have been started.

The history of nuclear technology shows a high number of plants that were started but never completed. Of the four new plants started in the USA since 2000, two have since been cancelled after considerable investment had already been made in their construction.

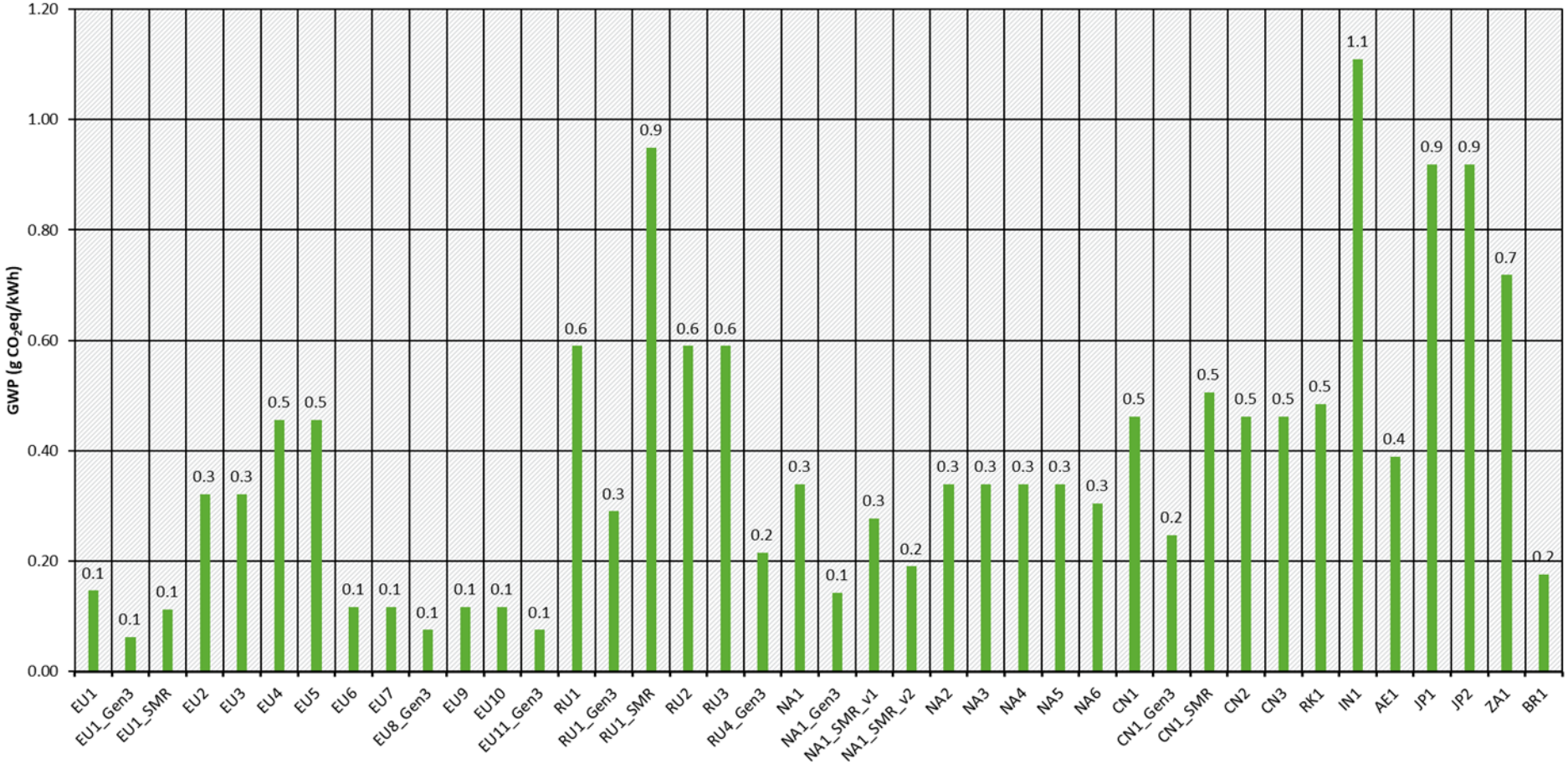
(M. Schneider & Froggatt, 2021) state that of 783 reactors whose construction has begun since 1951, at least 93 plants corresponding to 12% of all construction starts heave not been completed (construction cancelled or postponed indefinitely) as of 2021.

Assuming that a fraction of one third to two thirds of the total construction efforts has already been performed for the plants that have been cancelled or postponed indefinitely, this would increase the GWP due to NPP construction by 4-6% or 0.02-0.18 g CO_2eq/kWh.

3.12.5.3 Decommissioning

The GWP range due to the decommissioning phase of a NPP is 0.06-1.11 g CO_2eq/kWh with a typical value around 0.5 g CO_2eq/kWh.

Figure 125: NPP decommissioning: GWP (g CO_2eq/kWh)



Source: Öko-Institut

Decommissioning is responsible for approximately one third of the total low-level wastes arising from the life cycle chains.

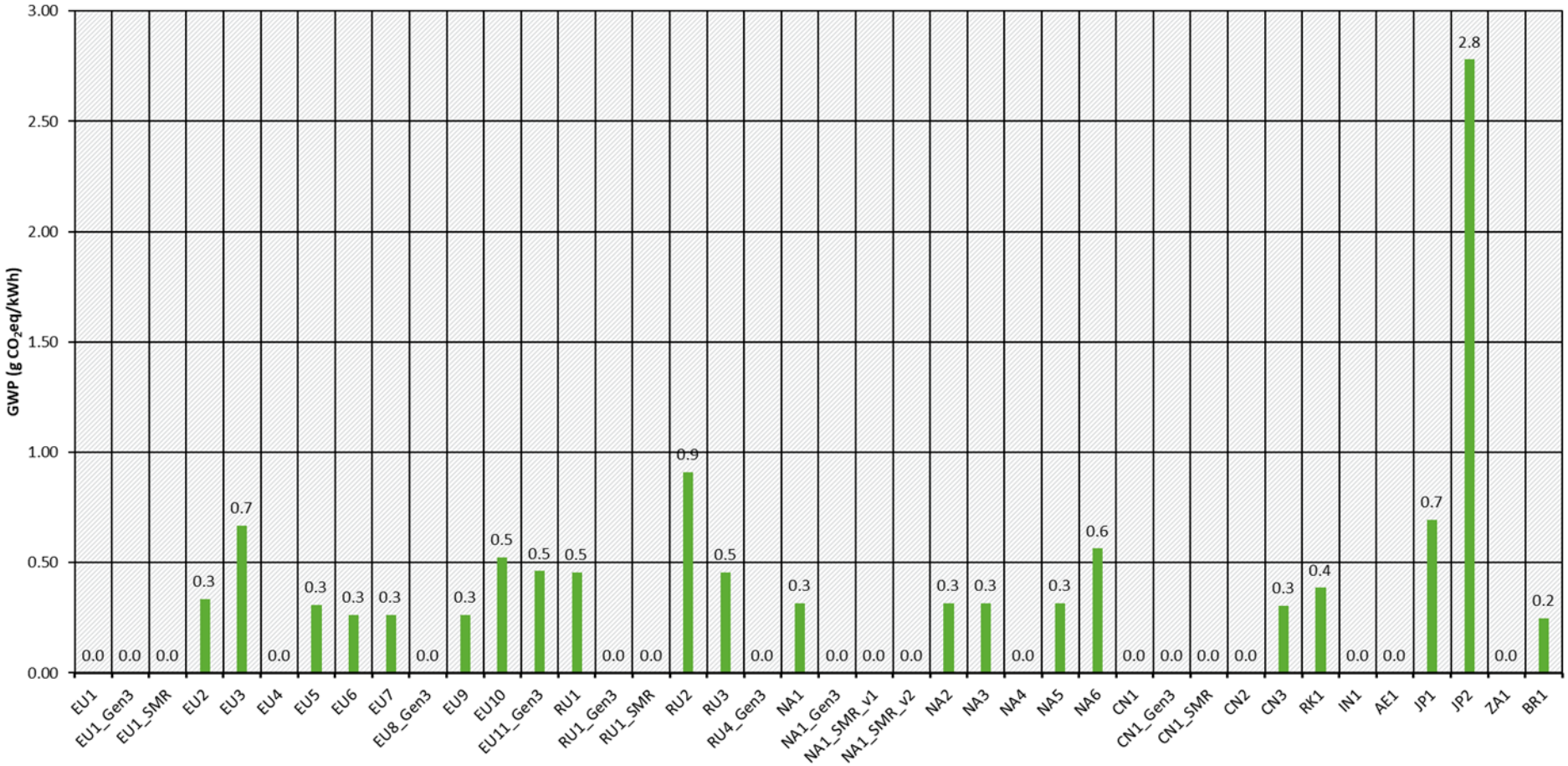
3.12.5.3.1 Sensitivities

The major input to the decommissioning phase is the energy needed. Therefore, the differences in GWP due to the decommissioning phase is due to different amounts of energy assumed for decommissioning as well as their (country specific) GWP. As the results already spread by more than one order of magnitude, a large variation is already included in the life cycle chains analysed.

3.12.5.4 Long term operation

In the life cycle chains analysed with an assumed retrofitting factor Rf not equal to zero, the Rf leads to an additional GWP of typically 0.26-0.91 g CO_2eq/kWh, corresponding to 3-8% of the total GWP of the corresponding life cycle chain. Only for a very high Rf of 100% which we introduced as an upper bound for the impact of retrofitting on the GWP, a very high specific GWP for retrofitting of 2.78 g CO_2eq/kWh results, which is responsible for 16% of that specific life cycle chain (JP2).

Figure 126: NPP retrofitting: GWP (g CO_2eq/kWh)



Source: Öko-Institut

3.12.5.4.1 Sensitivities

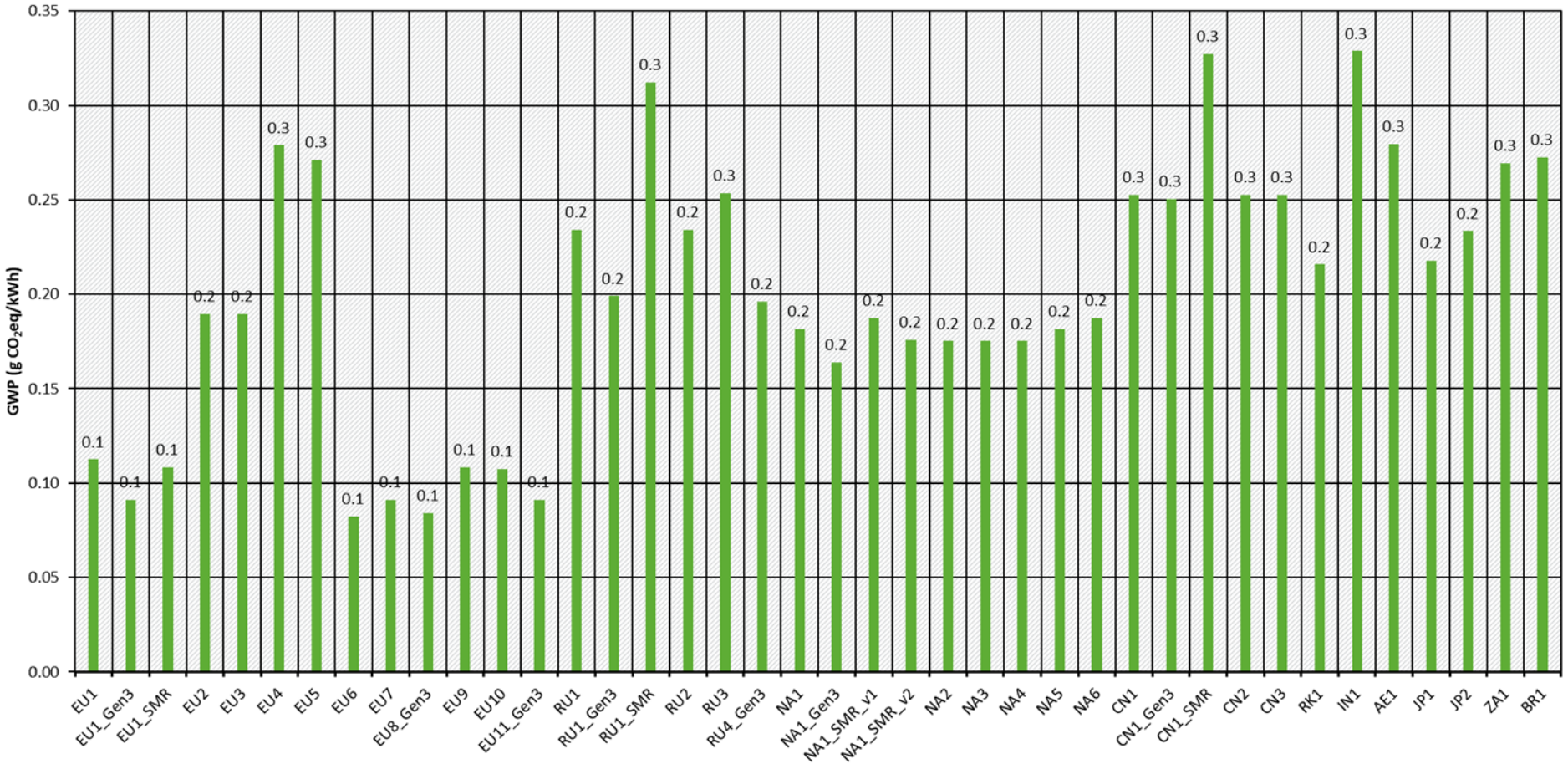
In the above calculations, we assumed a standard design lifetime of 40 years for the calculation of the "replacement factor" for a lifetime extensions of 10 or 20 years. For current new build, design lifetimes of 60 years are assumed.

If we assume that current lifetime extensions lead to the material inputs as derived in section 3.7.6, while current new build has a design lifetime of 60 years (for which we do not assume different material inputs in the NPP construction phase), the "replacement factor" would be 50% higher for a 10 or 20 year lifetime extension. On the other hand, for NPPs currently being built with a design lifetime of 60 years, it is not known today to which extend comparable retrofitting and replacements will have to take place in the future, they might as well be lower than for plants in operation today.

3.12.6 Interim Storage

The infrastructure of both HLW and ILLW contributes only marginally to the total GWP with a range of 0.005-0.008 g CO_2eq/kWh for ILLW and 0.006-0.013 g CO_2eq/kWh for HLW. The GWP emission of ILLW storage operation for all LCA chains is given in Figure 127 with a range of 0.08-0.33 g CO_2eq/kWh, a small contribution to total GWP emissions. The operation of HLW interim storage is not considered in the LCA chains due to lack of data, but as HLW waste is typically stored in passively cooled storage containers, the GWP from operation of a HLW storage can be assumed to be very low.

Figure 127: Interim storage ILLW: GWP (g CO_2eq/kWh)



Source: Öko-Institut

3.12.6.1 Sensitivities

3.12.6.1.1 Capacities of facilities

All facilities are calculated with 100% efficiency. This is usually not realistic as the waste will be produced over time and an interim storage facility will be filled over time. Also, some overcapacity is not untypical, as earlier expectations on the future use of nuclear power led to overbuild of capacity. As the importance of the infrastructure is low, this has a very limited effect on overall GWP.

3.12.6.1.2 Energy demand

Combustible low-level radioactive waste is vitrified according to ecoinvent based on the Swiss treatment of low level radioactive waste from reprocessing and nuclear power plant operation. The incineration plant is using a high-performance plasma burner at temperatures of up to 1500°C. During this process, organic and inorganic waste is converted into molten ash and metallic waste is also melted down. In other countries there is no heat treatment of low-level waste and numbers can be somewhat lower. This assumption leads to the somewhat high levels of GWP from operation of low-level radioactive waste.

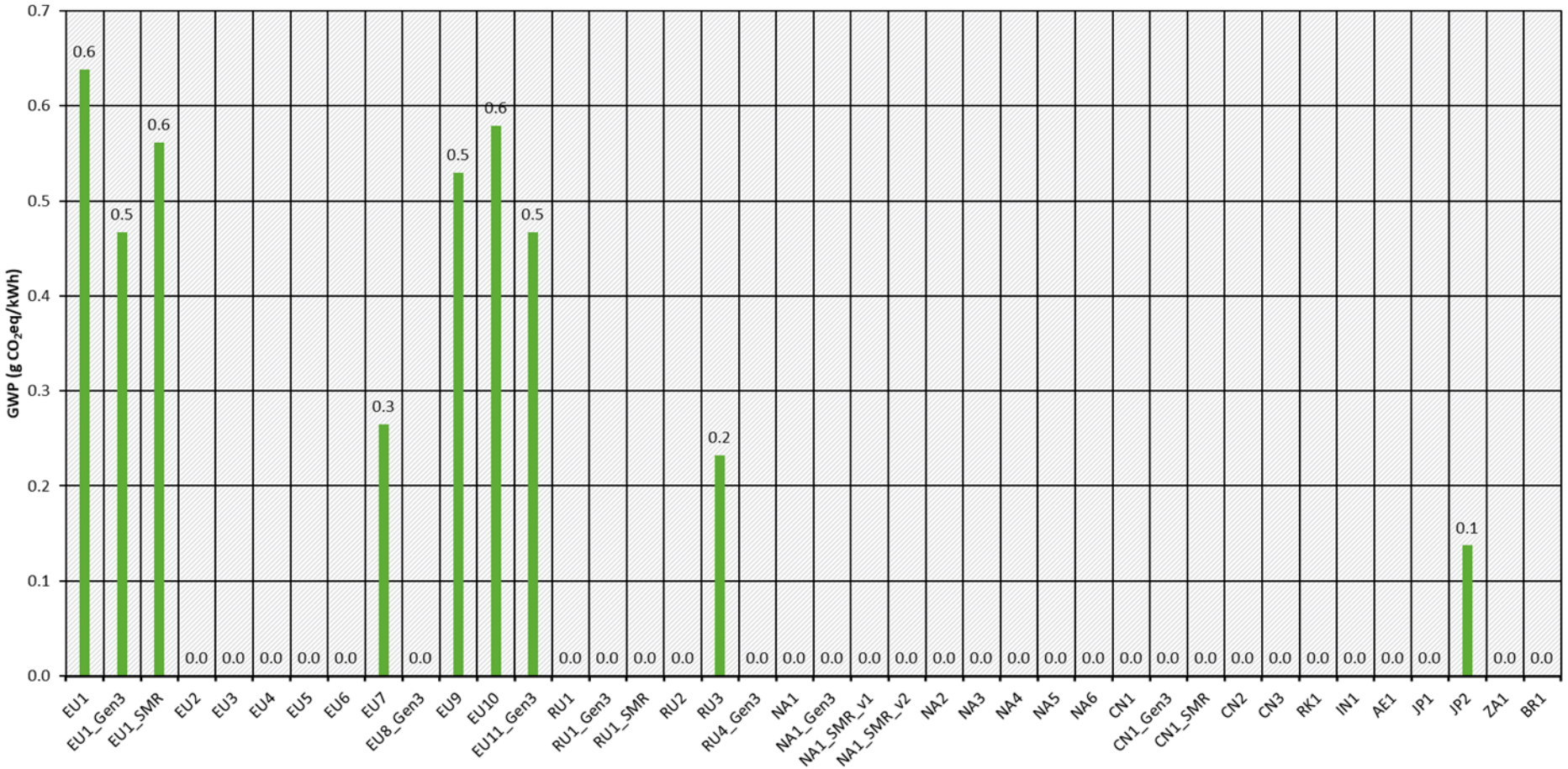
3.12.6.1.3 Interim Storage: Time

Interim storage time was fixed at 55 years. In many countries both ILLW and HLW is stored already over longer times. However, rebuilding interim storage facilities even five times over, will not have a significant impact on GWP and also energy demand during operations is very low, it may have a relevant impact on land use though.

3.12.7 Reprocessing

The infrastructure of reprocessing contributes only marginally to the GWP with a range of 0.01-0.06 g CO_2eq/kWh. The GWP emission of operation of a reprocessing facility is given in Figure 128 for all LCA chains with a range of 0.14-0.64 g CO_2eq/kWh, depending on the fraction of spent uranium fuel foreseen for reprocessing.

Figure 128: Reprocessing: GWP (g CO_2eq/kWh)



Source: Öko-Institut

3.12.7.1 Sensitivities

If the path of reprocessing spent fuel for plutonium production is taken, reprocessed uranium (RepU) with a residual content of typically around 1% U235 will also be produced. This can also be re-enriched in principle. Due to radiologically unfavourable uranium isotopes in this RepU, the use of RepU is severely restricted today.

RepU has the theoretical potential to replace natural uranium requirements, but actual reuse remains low. Neither is it used for re-enrichment, nor for MOX fabrication to replace depleted uranium on a relevant scale. Although France and Russia are currently the only countries routinely conducting RepU recovery, its global contribution remains under 1% of annual uranium demand. However, this could change if China realizes its plans to commercialize reprocessing (NEA & IAEA, 2025). This study considers RepU as radioactive waste.

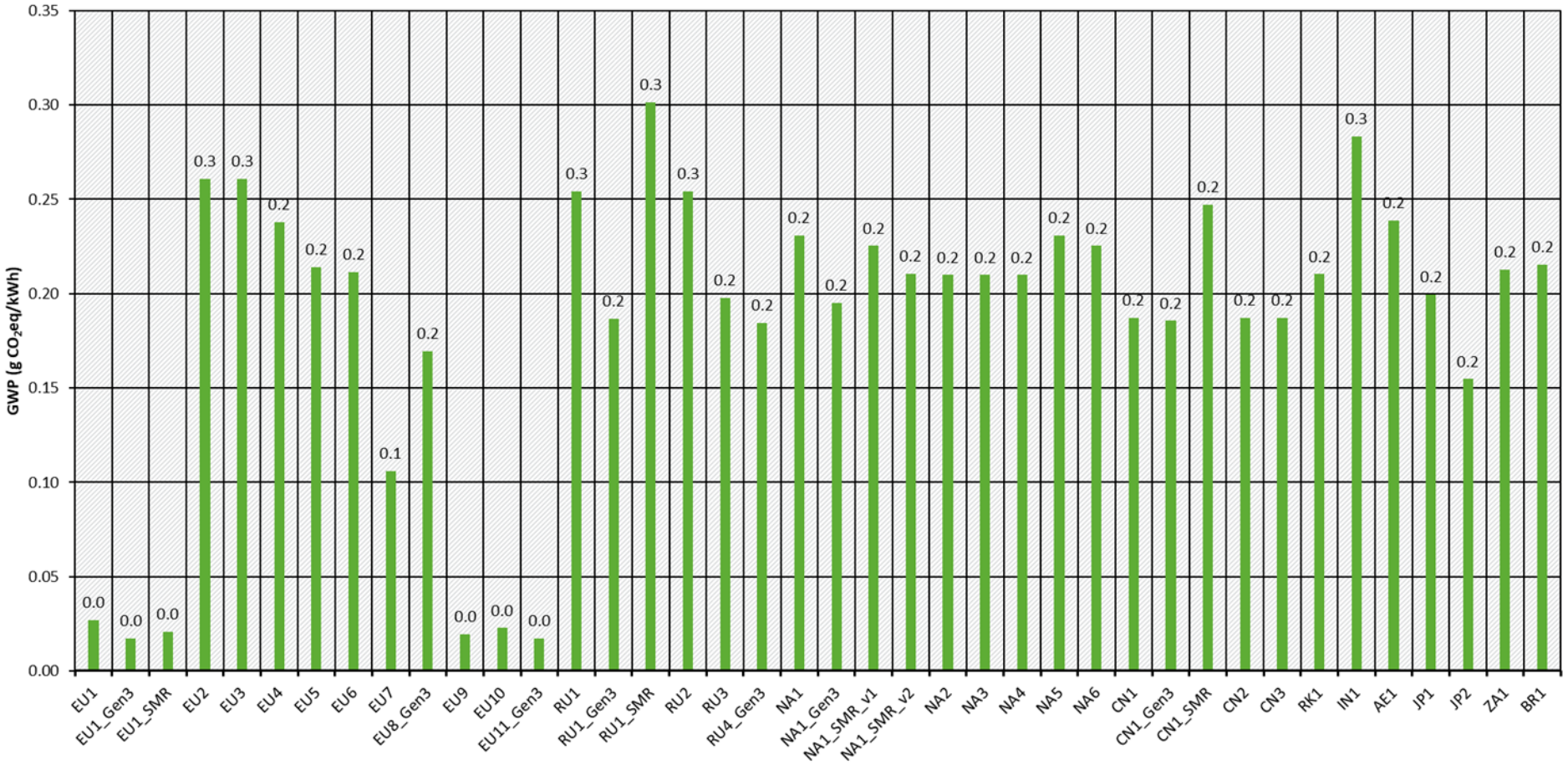
Reprocessing spent fuel several times and multirecycling the plutonium in LWRs is not possible for reasons of reactor physics. Reactors with a fast neutron spectrum would therefore also have to be available in the reactor park for multirecycling, but as discussed in section 3.7.1, we do not expect such reactor types to have any significant role before 2050 if at all. Against this background, many studies exclude reprocessing from the process chain under consideration (UNECE, 2021).

3.12.8 Final Disposal

3.12.8.1 Conditioning

The infrastructure of conditioning contributes only marginally to the GWP with a range of 0.005-0.008 g CO_2eq/kWh. The GWP emission of the operating phase of conditioning for all LCA chains is given in Figure 129 with a range of 0.02-0.30 g CO_2eq/kWh, a small contribution to total GWP emissions. The influence of MOX use and reprocessing in the fuel cycles EU1, EU1_Gen3, EU1_SMR, EU7, EU9, EU10, EU11_Gen3 can be seen clearly, as much less spent fuel has to be conditioned, but therefore, additional GWP from the reprocessing step arises. The MOX use in RU3 and JP2 does not lead to a significant reduction of GWP from conditioning for these LCA chains due to only a low MOX fuel percentage in the fuel cycle.

Figure 129: Conditioning: GWP (g CO_2eq/kWh)

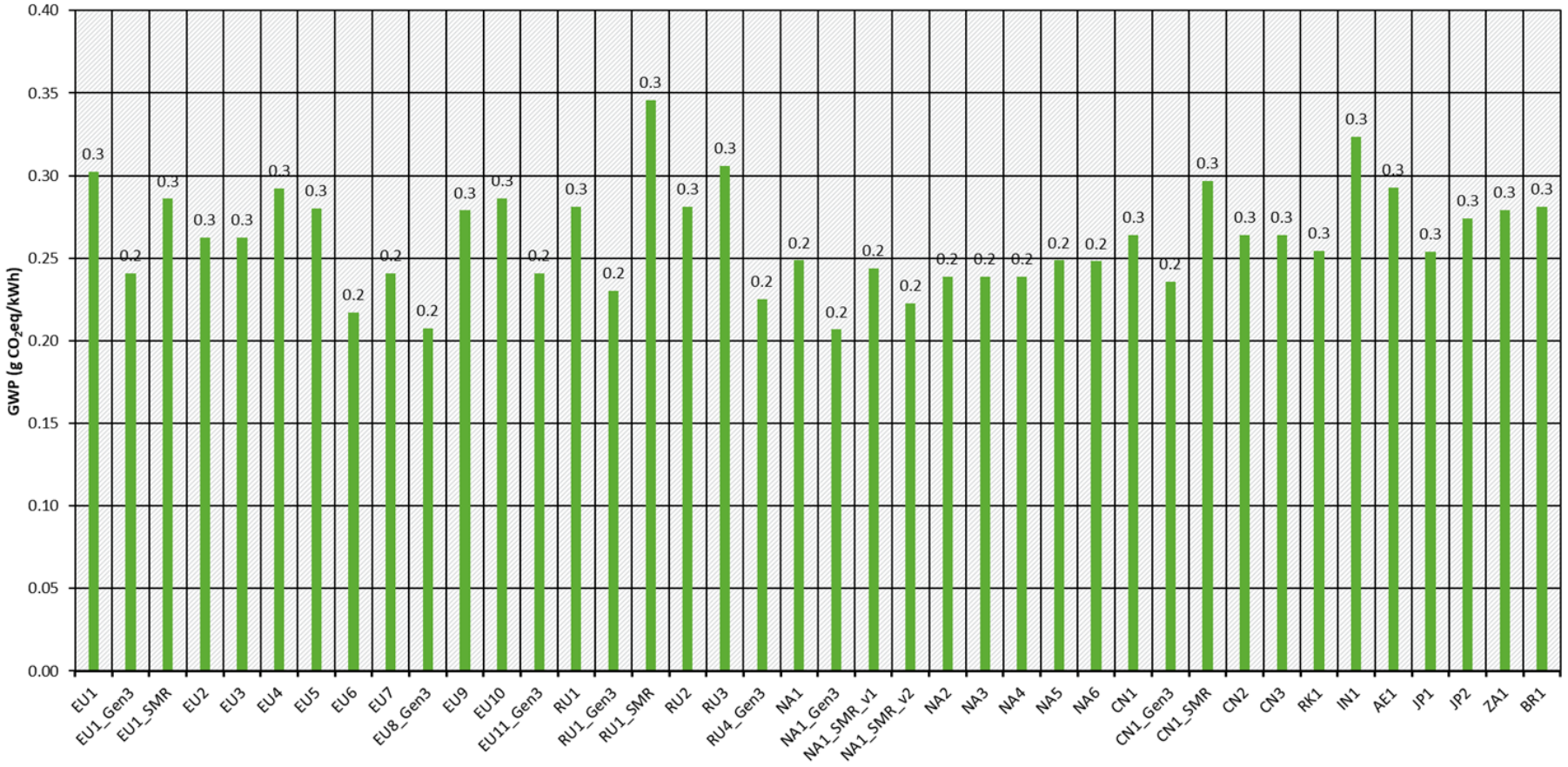


Source: Öko-Institut

3.12.8.2 HLW and ILLW final repository

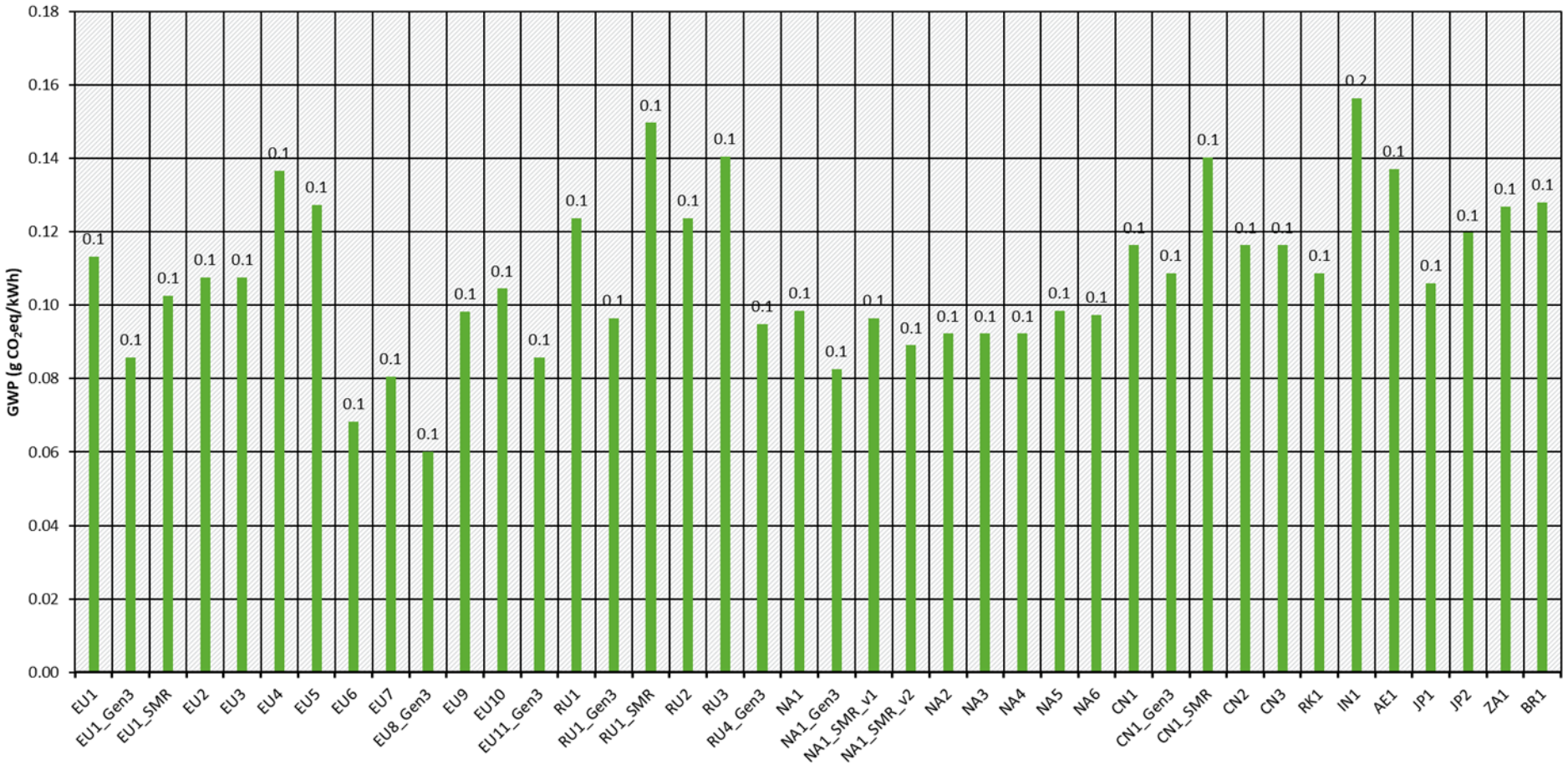
All results for HLW and ILLW are summarized in a combined GWP for infrastructure for final disposal and its operation. The infrastructure of the final repository contributes to a small degree to the GWP with a range of 0.21-0.35 g CO_2eq/kWh (Figure 130). The GWP emission of final disposal operation for all LCA chains is given in Figure 131 with a range of 0.07-0.16 g CO_2eq/kWh, a small contribution to total GWP emissions.

Figure 130: Final disposal infrastructure: GWP (g CO_2eq/kWh)



Source: Öko-Institut

Figure 131: Final disposal: GWP (g CO_2eq/kWh)



Source: Öko-Institut

3.12.8.3 Sensitivities

3.12.8.3.1 HLW final repository: Time

A total operation time of 26 years could be seen as an optimistic estimate. However, even assuming a fivefold increase in the building and operation/maintenance time of a final repository will not increase GWP significantly, it may have a relevant impact on land use though.

Considering an active monitoring of the disposal site would potentially add a large factor to any GWP impact of such an activity, as potentially such a monitoring activity would have to be conducted for very long timespans. However, all repository concepts assume, that the concept has to be selfcontained after a certain time, without the need for active methods, as the risk is very high that active measures would be interrupted by social of civilisation-related events. Also, active monitoring could be conducted with a very low GWP profile, especially also under the assumption of a low carbon future.

There is no detailed discussion in ecoinvent how the infrastructure demand would change for other rock types, especially crystalline rock as a host formation. Potentially the excavation energy would increase from soft to hard rocks.

3.12.9 Transportation

In most LCA chains transport contributes only marginally to the GWP with a range of 0.07-0.4 g CO_2eq/kWh. In LCA chains EU6 and EU7 but especially in chains EU5, EU10, EU11_Gen3 and RU3, the impact of transport at the uranium mines due to very low ore grades from open pit mining can be seen with a range from 0.72-5.6 g CO_2eq/kWh. A very high value results e.g. for the Rössing mine in Namibia with a very low ore grade of 0.025%.

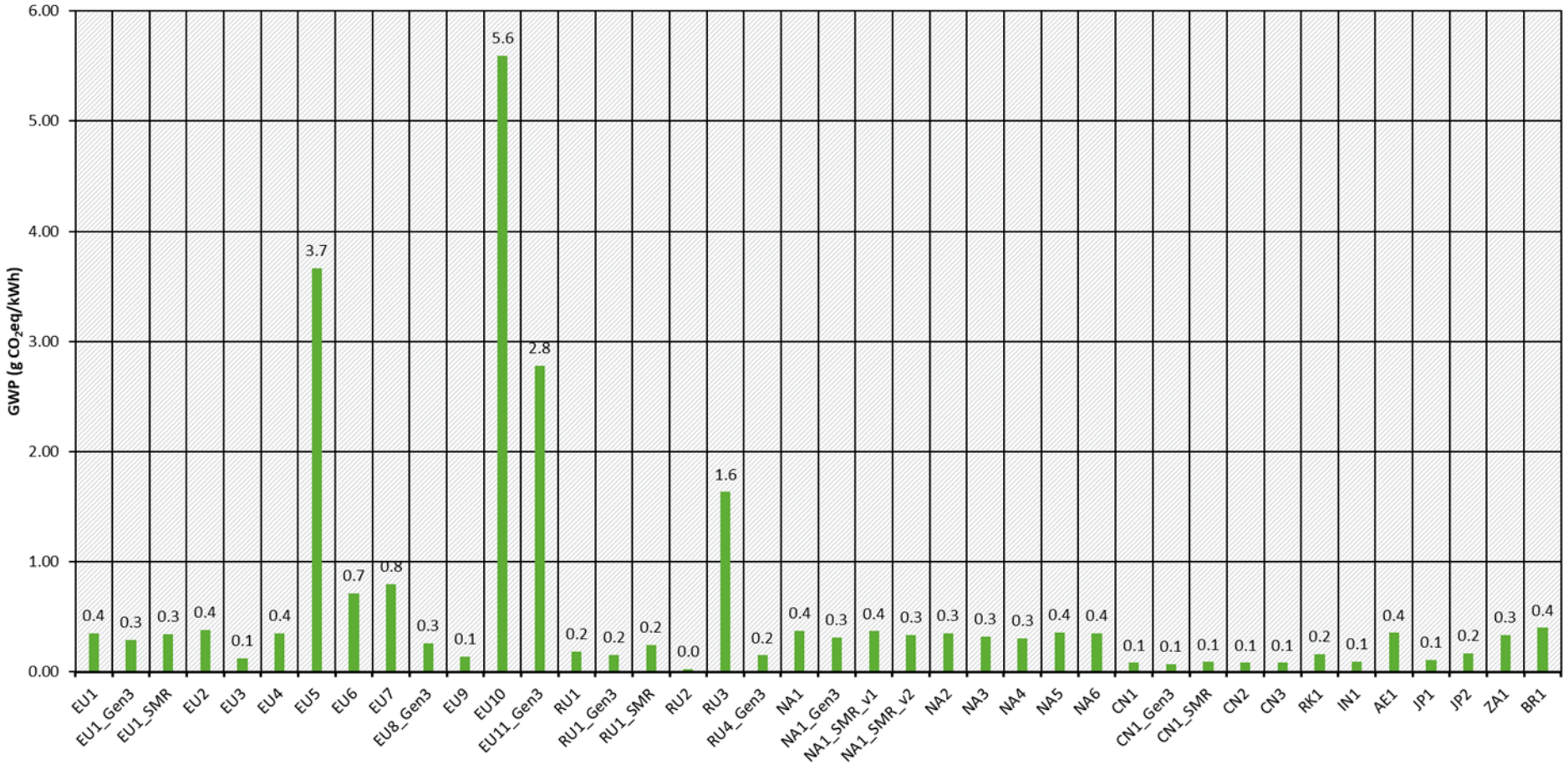
In LCA chain EU1, mining dominates the GWP in transport with 53%, followed by transport of low-level waste with 30% and the transport of yellowcake to the conversion facility with 6%.

In LCA chain RU1, mining dominates the GWP in transport with 70%, followed by transport of low-level waste with 12% and the transport of yellowcake to the conversion facility with 6% and fuel transport with 5%.

In LCA chain NA1, waste rock transport in uranium mining is not contributing to transport in an underground mine. The GWP is dominated with 54% transport of low-level waste with 14% for ore transport to the processing plant, the transport of yellowcake to the conversion facility with 13% and transport of HLW from the NPP to the conditioning facility with 12%.

In LCA chain CN1, neither waste rock nor ore transport in uranium mining is contributing to transport in an ISL mine. The GWP is dominated with 75% transport of low-level waste, with 19% transport of yellowcake to the conversion facility.

Figure 132: Transport: GWP (g CO_2eq/kWh)



Source: Öko-Institut

3.12.9.1 Sensitivities

In the sensitivity study for uranium mining, we already introduced that for open pit mining the low ore grade of Rössing and Husab with 0.025%U and 0.033%U lead to an overestimation of the energy intensity if scaling linearly by ore-grade. For a discussion of GWP from e.g. Rössing see also section 3.12.1.1.1.

Especially with open-pit mining transport with diesel powered trucks plays a crucial role with regard to emissions. Ecoinvent assumes a waste rock to ore ratio of 30 and an average ore grade of 0.5% with 7 t waste rock per kgU. A transport distance of 1 km is assumed with 40 m^3 trucks (Dones et al., 2009). For open pit mines this reference assumption for transport is adapted in the LCA chains and scaled to the ore grade of the specific mine. For the reference mines in ecoinvent (Dones et al., 2009) also cites overburden with a ratio of 70:1. In general, it is highly specific for the mining region and the specific mine, how the waste rock is transported, either by conveyer bands or by trucks. The high values here therefore do not reflect the actual conditions in mines like Husab and Rössing, but can be seen as an upper value, for mining of low-grade uranium ore in an open pit mine with large overburden and a transport by trucks.

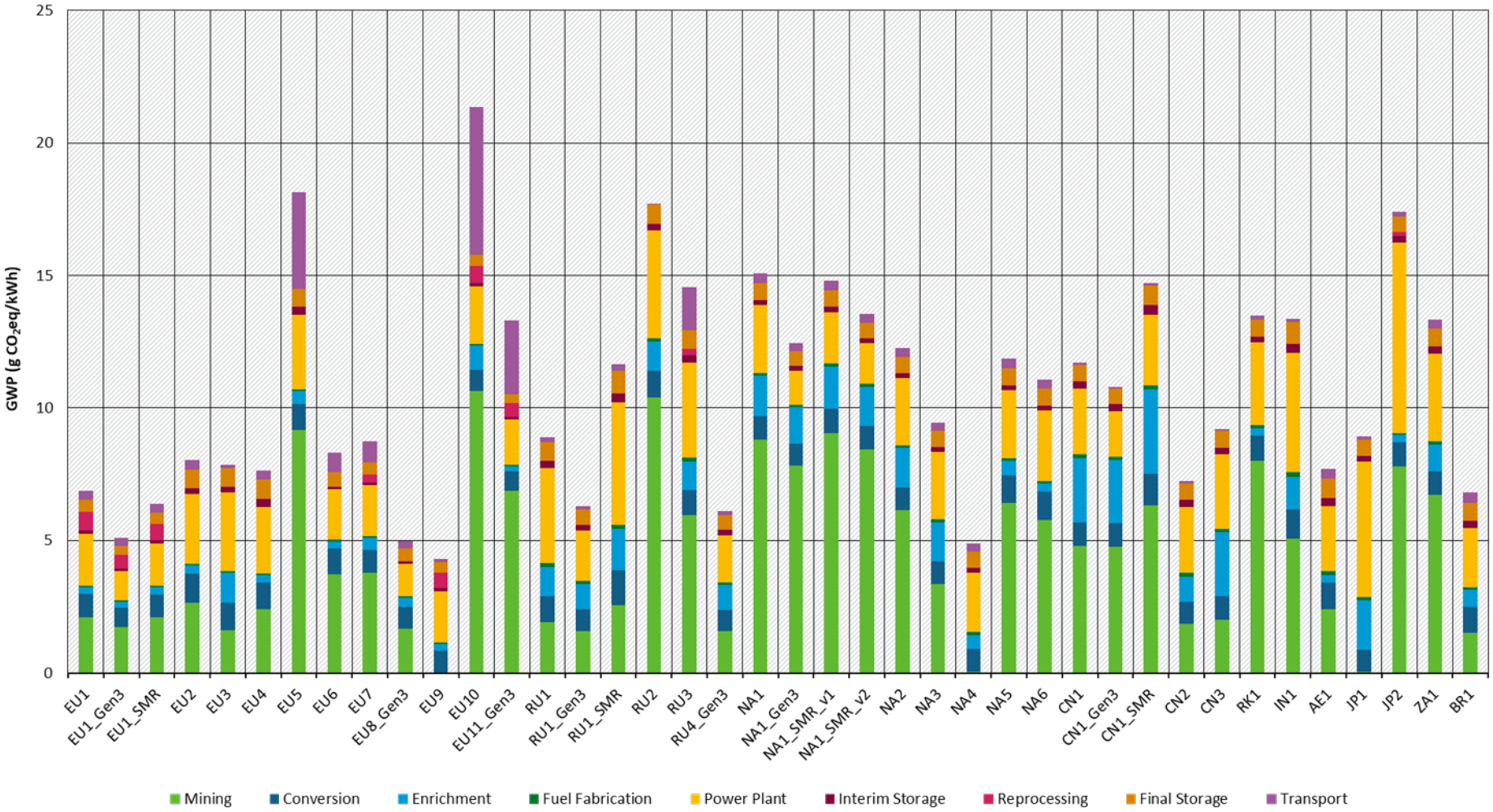
Already in section 3.12.1.1.5 an additional 1 km transport of waste rock was assumed for LCA chain EU1, which is realistic given maps of e.g. Arlit mine. This will increase the GWP from 0.34 g CO_2eq/kWh for the standard assumption of 1 km to 0.54 g CO_2eq/kWh. The additional transport is assumed also with 32 t trucks and a 30:1 waste rock/ore ratio. Similarly an additional 1 km for EU10 with the Rössing mine ore grade would change GWP for transport of waste rock from 5.6 g CO_2eq/kWh for the standard assumption of 1 km to 10.9 g CO_2eq/kWh, which is most likely an overestimation compared to the published values from Rössing (Rössing Uranium & CNNC, 2023).

3.12.10 Total GWP

3.12.10.1 Baseline year 2020

The results for the total GWP of the life cycle chains analysed as well as the corresponding contribution of the different life cycle steps is summarized in Figure 133 for the baseline year 2020. Detailed results for the individual life cycle chains are given in Appendix B and for other environmental impacts than GWP also in Appendix C.

Figure 133: Breakdown of GWP for life cycle chains – baseline year 2020



Sources: Öko-Institut

The typical range of total GWP from the life cycle chains for the baseline year 2020 spans values of 5-15 g CO_2eq/kWh.

Only very few life cycle chains with exceptionally good input parameters show a total GWP below 5 g CO_2eq/kWh (EU_Gen3, EU9 and NA4), with the lowest calculated value being 4.3 g CO_2eq/kWh. On the other hand, a few life cycle chains show also higher GWP values (EU5, EU10, RU2, NA1, and JP2) up to a total GWP of 21 g CO_2eq/kWh.

As discussed above, the total GWP is typically dominated by the impact of uranium mining of up to 10.7 g CO_2eq/kWh and transportation in connection with uranium mining of up to 5.6 g CO_2eq/kWh, followed by the impact of NPP infrastructure and operation with up to 5.1 g CO_2eq/kWh (and up 7.2 g CO_2eq/kWh for the case of JP2 with the assumption of a very high retrofitting factor in combination with a very low load factor), enrichment with up to 3.2 g CO_2eq/kWh and conversion with up to 1.3 g CO_2eq/kWh. The other process steps contribute less than 1 g CO_2eq/kWh to the total GWP.

Within the different regions covered by the life cycle chains, the corresponding values of total GWP show a large spread compared to the standard chains (EU1, RU1, NA1, CN1). Within the European chains, total GWP may be 63-311% of the EU1 chain. For Russia, the corresponding chains show values of 69-199% of the RU1 chain, for North America 32-98% of NA1, for China 62-126% of CN1 and for the rest of the world 58-149% compared to the Chinese CN1 chain.

Numerous studies on the GWP of nuclear power can be found in the literature of the past two decades, that encompass a broad range of results from very low values of below 5 g CO_2eq/kWh (EDF, 2022) up to well above 100g CO_2eq/kWh (Sovacool, 2008; Warner & Heath, 2012). Several of these studies are country or region-specific like (Lenzen, 2006) for Australia, (Vattenfall, 2019) for Sweden, (EDF, 2022) for France, (Zhang & Bauer, 2018) for Switzerland or (Norgate et al., 2010) for the US. Others cover different countries or regions in comparison (Fritsche, 2007; Fthenakis & Kim, 2007), focus on specific possible difference like the chosen fuel cycle (Poinssot et al., 2014) or perform a review of literature values and the underlying methodology, data and assumptions (Lenzen, 2008; Sovacool, 2008; Storm van Leeuwen, 2017; UNECE, 2021; Wallner et al., 2011; Warner & Heath, 2012).

Major sensitivities explaining the broad spread in literature values are (Beerten et al., 2009): the assessment method (like economic input-output vs. process chain analysis) which may lead to very large differences in results, the input data (like the energy inputs of the various process steps, compare the discussions in sections 3.12.1 to 3.12.9) and further chosen estimates and assumptions (like plant lifetimes or load factors, compare the discussions in sections 3.3 to 3.11).

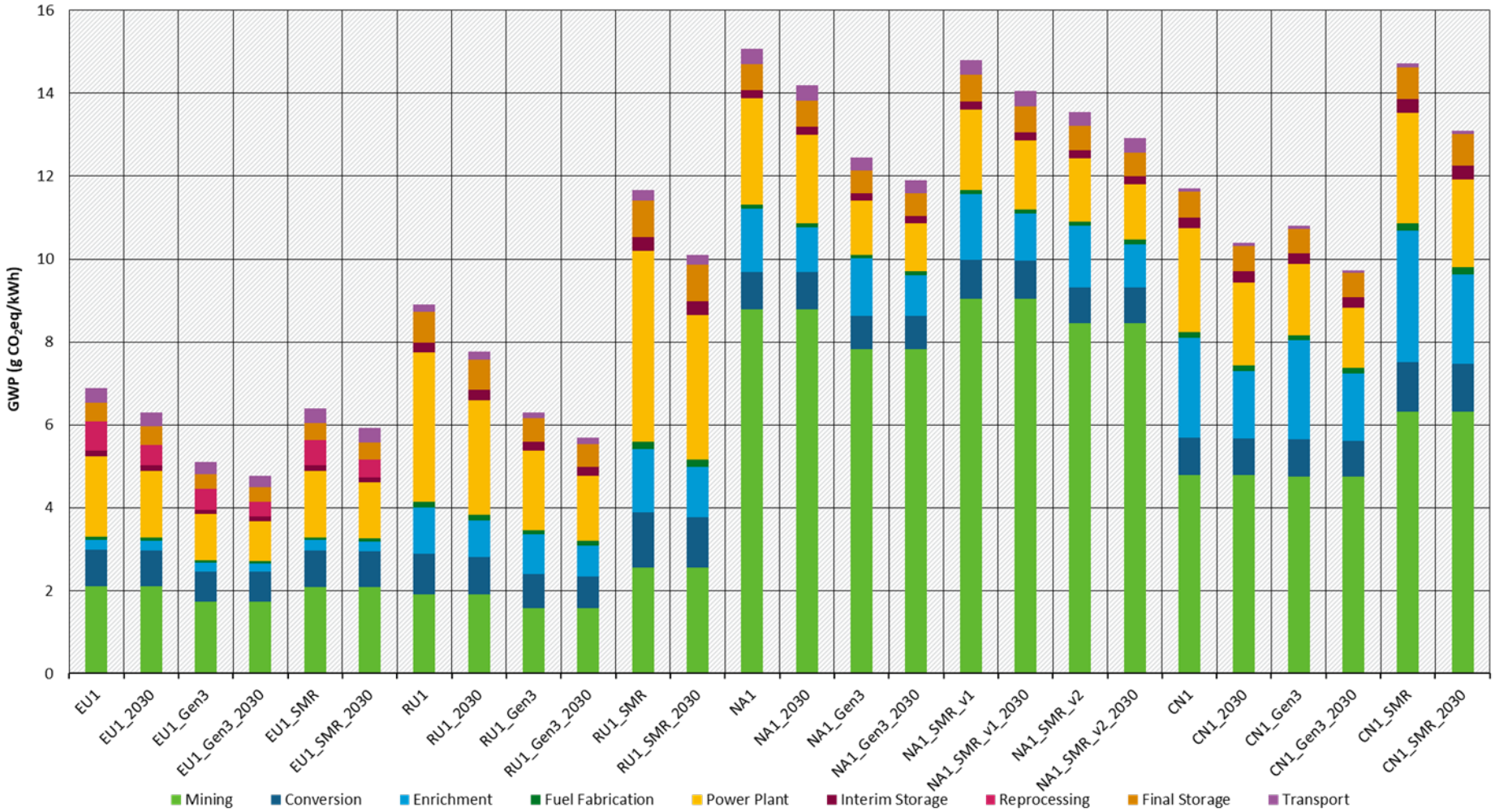
Additionally, studies from the early 2000s still consider gaseous diffusion as enrichment technology, which at that point in time still had a share in worldwide total enrichment capacities of about 50% (compare section 3.5) but is no longer of relevance as of today. Finally, the region specific energy intensities as well as material intensities have changed due to worldwide decarbonisation efforts (compare for example section 3.7.2) and (Ng et al., 2025).

Considering these differences, the GWP values derived in our studies are quite consistent with the spectrum of literature values, taken into account the chosen methodological approach, the covered technologies, the up to date data on energy and material intensities with respect to GWP and the regional differences covered by our approach.

3.12.10.2 Projections 2030

The results for the total GWP of the life cycle chains analysed as well as the corresponding contribution of the different life cycle steps is summarized in Figure 134 for the projection year 2030, including the original values for the baseline year 2020 for comparison. Detailed results for the individual life cycle chains are given in Appendix B and for other environmental impacts than GWP also in Appendix C.

Figure 134: Breakdown of GWP for life cycle chains – projections 2030



Sources: Öko-Institut

The typical range of total GWP from the life cycle chains for the projection year 2030 spans values of 4.8-14.2 g CO_2eq/kWh.

The specific reduction of total GWP for the life cycle chains evaluated for the projection year 2030 compared to the baseline year 2020 amounts to 4.4-13.4% of the total GWP and is thus not fundamentally different from the baseline year 2020.

As we kept all other input parameters unchanged, this change is due to the reduction in specific GWP for the energy, concrete and steel input to selected life cycle steps (only GWP of life cycle steps above 0.5 g CO_2eq/kWh have been changed as the impact of the other life cycle steps is not relevant for total GWP).

Another relevant factor for the total GWP in the projection year 2030 is the possible enhanced use of Generation 3 plant and possibly first reactors of the SMR type, see section 3.7.1.

Due to a typically higher efficiency and the assumption of a longer design lifetime for Generation 3 plants, their total GWP is 8-29% lower than the corresponding total GWP of the life cycle chain with the standard PWR.

While the SMR concepts assessed in the life cycle chains also have a corresponding design lifetime of 60 years, they typically have a much lower efficiency. Thus, their total GWP may be 10% lower or up to 31% higher than the corresponding total GWP of the life cycle chain with the standard PWR. Compared with life cycle chains with Generation 3 reactors, their total GWP may even be higher by 9-85%.

For the future development of the total GWP until 2050, different trends would have to be taken into account. On the one hand, the specific GWP of the material and energy inputs to the different life cycle steps will further decrease with time. On the other hand, depending on the future use of nuclear power, the availability of high ore grade uranium may decrease. As uranium mining clearly dominates the total GWP for basically all life cycle chains when the ore grade is low, a decrease in world average available ore grades might result in a higher total GWP as discussed in section 3.12.1. Besides the ore grade, also the average load factor has a relevant impact on the total GWP, if the load factor comes down to very low values (below 50%). On the one hand, this might be expected for future energy systems with a high share of renewable energy, compare section 2.9, which – on the other hand – is not to be expected for purely economic reasons (see also chapter 4).

3.13 (Environmental) impacts of severe accidents in nuclear power plants

The (environmental) consequences of accidents in nuclear power plants are not covered by the above life cycle analysis of nuclear energy. In this section, an exemplary discussion of empirical and theoretically estimated (environmental) consequences of nuclear accidents is given.

The following discussion on the consequences of severe accidents is based on (Pistner & Englert, 2021) and (Pistner, Kopp, & Englert, 2024) and includes additional information with a special focus on the environmental consequences of nuclear accidents.

Severe nuclear accidents can lead to significant off-site consequences due to the release of large amounts of radioactivity. The release of radioactivity will impact human health by inhalation of airborne radionuclides, ingestion of radionuclides by food or water or by direct radiation due to radionuclides deposited on land. To minimise the consequences to human health, different countermeasures will be taken after a nuclear accident. These countermeasures include sheltering, evacuation, short- or long-term relocation of humans as well as restrictions on land use or drinking water supplies (Walter et al., 2015). While these countermeasures can drastically reduce the impact on human health (and thus the number of fatalities and

corresponding fatality rates), they will result in significant consequences concerning other indicators of severe accidents like land loss or costs. In the following, a specific focus is given on environmental aspects of severe reactor accidents.

The IAEA has defined the International Nuclear and Radiological Event Scale (INES) as a tool for communicating to the public the safety significance of nuclear and radiological events (IAEA, 2013). The INES scale ranges from events without safety significance (level 0) to major accidents (level 7). Until today, two major accidents have taken place.

On 26 April 1986, Unit 4 of the Chernobyl nuclear power plant in Ukraine suffered the worst accident in the history of civilian nuclear technology. A massive, short-term increase in nuclear power destroyed the reactor and subsequent fires in the graphite used as a moderator in the reactor released a significant proportion of the reactor's radioactive inventory into the environment. The accident occurred during a safety test carried out during the shutdown of the reactor. This serious reactivity accident was caused by mistakes made by personnel in conjunction with deficiencies in the planning of the test and errors in the safety design of the reactor (Cort et al., 1998; Pistner, 2006a; United Nations Scientific Committee on the Effects of Atomic Radiation [UNSCEAR], 2011).

(UNSCEAR, 2011) estimates the total release of ^{131}I due to the Chernobyl accident as 1760 PBq and that of ^{137}Cs with about 85 PBq.

On 11 March 2011, a severe earthquake shook the east coast of Japan. The resulting tsunami flooded large coastal regions and caused serious incidents at several Japanese nuclear power plant sites, including the catastrophic accident at the Fukushima Dai-ichi plant. The immediate trigger for the accident at Fukushima Dai-ichi was the earthquake off the east coast of Japan. The magnitude of the earthquake at the site was greater than the seismic strength on which the design of the plant was based. The earthquake caused a complete loss of the external power supply in all six units at the Fukushima Dai-ichi site. The further damage at the plant caused by the tsunami was central to the entire course of the accident (IAEA, 2015a; Pistner, 2013; UNSCEAR, 2013, 2021).

(UNSCEAR, 2021) estimates the total release of ^{131}I due to the Fukushima accident in the range of 100 to 500 PBq and that of ^{137}Cs in the range of 6 to 20 PBq, which corresponds to about 2-8% of the ^{131}I and 1-3% of the ^{137}Cs contained at the time of the accident in the three operating reactors from which the releases occurred. Of this, large amounts (up to 80%) were deposited on to the North Pacific Ocean and only approximately 20% were deposited on land.

A discussion of severe accidents has to take into account a variety of different impacts. These may cover

- consequences for life and health of humans including direct and indirect deaths, acute and chronic illnesses, genetic damage, psychological damage, fear of further accidents;
- consequences for infrastructure including consequences for drinking water supplies, land contamination, removable and non-removable surface contamination, land loss, loss of neighbouring facilities, loss of further infrastructure;
- consequences for other lifeforms including loss of livestock, loss of wildlife, loss of rare species, loss of biotopes;
- economic costs including cost for civil protection, remediation activities, evacuations, loss of production, damage to image of companies or industries;

- social and political consequences including changes in behaviour of individuals or groups, changes of social or political standards, consequences for international relations and finally
- ecological consequences including impacts on biosphere, ecological resources and natural condition.

In the following, selected consequences of the actual major accidents in Chernobyl and Fukushima are summarized, as well as the results of theoretical studies on the possible consequences of future (major) accidents. To start with, a short discussion of the known or expected frequency of major accidents is given.

3.13.1 Theoretical estimates of the frequency of nuclear accidents by means of probabilistic safety assessment

For nuclear power, the probabilities of severe accidents are often not based on actual empirical data (which is sparce) but on theoretically derived values based on so called probabilistic safety assessments (PSA).

PSA is a very valuable tool to estimate the (theoretical) safety level of a nuclear power plant design. It is used to identify weaknesses in the design and to identify possible safety enhancements (Facharbeitskreis Probabilistische Sicherheitsanalyse für Kernkraftwerke [FAK PSA], 2005a, 2005b, 2016). Nevertheless, use of PSA results to estimate the actual risk of operating nuclear power plants faces several hurdles. PSA analysis may be limited to internal events or take into account only selected external events like earthquakes or flooding. For example, (Kumar et al., 2015) discuss the PSA results for the Fukushima Dai-ichi nuclear power plant which were published before the accident took place. They highlight that:

"The Core Damage Frequency (CDF) and Containment Failure Frequency (CFF) for the Fukushima Dai-ichi plants were determined only for internal initiating events. The results obtained by TEPCO … for the CDF of up to 10^{-7} per year were very low compared to other results for other Boiling Water Reactors (BWR), including those with more backfitting and/or newer designs."

Based on today's knowledge, the authors conclude:

"It is recognized today that the determination of the design basis tsunami for the Fukushima Dai-ichi site underestimated both the maximum probable tsunami height as well as the tsunami height for a likelihood of 10^{-4} per year. This led to a false belief in sufficient safety margins even for beyond design tsunamis."

Some external hazards are often not (yet) taken into account in PSA, especially with respect to man-made hazards like intentional terrorist attacks on a nuclear facility or possible consequences of military conflicts. Nuclear power plants, but potentially also other facilities of the nuclear supply chain like reprocessing facilities could be targets of terrorist attacks or could be impacted by consequences of military conflicts (be it intentional or by accident).

Current PSA approaches usually do not cover the risks of terrorist attacks or military conflicts. For the risk of terrorist attacks there are some first-of-its-kind analyses (Hirschberg et al., 2016). Other literature did also discuss at least qualitatively the risks associated with nuclear facilities in crises regions, even before the war in Ukraine showed the actual risk of nuclear facilities under wartime conditions (Ustohalova & Englert, 2017). According to (Burgherr & Hirschberg, 2014), 0.5% of the accidents in the energy sector analysed are due to conflicts, making clear that this aspect cannot be ignored with respect to severe accidents in nuclear facilities.

The methodologies for PSA have developed considerably during the past decades (FAK PSA, 2016; NRC, 2020a). Especially the consideration of human factors as well as common cause failures in PSA has a relevant impact on results. Thus, usually relevant uncertainties have to be taken into account, especially when assessing severe accidents, i.e. extremely rare events. Several limitations of this approach are also recognized by (Burgherr & Hirschberg, 2014; Hirschberg et al., 2016).

(Hirschberg et al., 2016) conclude:

"Overall the uncertainties are lowest for severe accidents in the fossil energy chains due to the large number of historical events, moderate for the normal operation, quite large for hydro and PSA-based estimates for nuclear accidents and largest for the terrorist threat."

A very simplified calculation can illustrate significant uncertainties associated with the use of the theoretically derived fatality rates especially for severe accidents. The annual nuclear electricity production has risen since the 1970s and amounts to about 2,500 TWh today. Assuming an average nuclear electricity production of 2,000 TWh per year during the timeframe 1970 to 2008, which is the evaluation period analysed in (Hirschberg et al., 2016), roughly 75,000 TWh electric energy has been produced. (Burgherr & Hirschberg, 2014) estimate the total amount of fatalities for the Chernobyl accident, the only severe accident in the evaluation period, for which they estimate the fatality rates, between 9,000 and 33,000 latent cancer deaths. Assuming as a lower bound just 10,000 fatalities for this accident alone, one would receive an empirical value of approx. 10^{-4}/GWh for the fatality rate of nuclear power. This has to be compared with the theoretically derived number of less than 10^{-6}/GWh for today's Gen II power plants as estimated by (Hirschberg et al., 2016), a difference of more than two orders of magnitude.

An early critic of the probabilistic approach to risk assessment was formulated already in (Hsü, 1987). (Wheatley et al., 2016) take up these thoughts and criticise the approach to assess nuclear accident risks based on probabilistic safety analysis, as such techniques are known to poorly predict events and to under-appreciate incidents that cascade into failures. They estimate the rate of severe accidents in nuclear facilities based on a database including 216 nuclear accidents and incidents. They conclude, that for an operational fleet of 388 nuclear reactors, there is a 50% chance that a Fukushima event (or a more costly one) occurs every 60–150 years.

In addition to the limitations of the theoretically derived PSA numbers, further problems with respect to the significance of a purely statistical value like the fatality rate exist. Within the European Research Project ExternE, a methodology to assess external costs of different energy technologies was developed, which is largely also the basis for the work of Hirschberg et al. With respect to accidents, the ExternE project concludes (Institute of Energy Economics and the Rational Use of Energy [IER], 2018):

"Accidents are rare unwanted events in contrast to normal operation. A distinction can be made between impacts to the public and occupational accident risks. Public risks can in principle be assessed by describing the possible accidents, calculating the damage and by multiplying the damage with the probability of the accidents. An issue not yet accounted for here is the valuation so-called 'Damocles' risks, for which high impacts with low probability are seen as more problematic than vice versa, even if the expected value is the same. A method for addressing this risk type has still to be developed.

This is also clearly addressed in (Bünger & Matthey, 2018):

"In principle, the expected value of the damage is to be used for estimating environmental costs. …

However, there are cases where the assessment of risks based on expected values falls short.

Firstly, this applies to risks for which there is risk aversion in the population. This means that people are willing to invest more resources to avoid the risk than this is reflected in the amount of the expected value of the damage. Risk aversion is particularly pronounced in the assessment of so-called disaster risks. Disaster risks are characterised by the fact that they occur with a very low probability, but cause very high damage if they do occur (e.g. extreme floods, chemical accidents, risk of a nuclear power accident).

Secondly, these include risks about whose probability of occurrence or damage potential there is a very high degree of uncertainty …"[42]

As (Kumar et al., 2015) conclude on the use of PSA:

"PSA results are often narrowed down to very few numbers or even one risk-aggregate figure of merit. … While this certainly simplifies the problem space for the decision maker, this kind of risk aggregation can obfuscate or distort specific PSA results and related plant vulnerabilities. Risk-informed decision making should consider the risk profile of the plants based on sets of PSA risk measures/metrics …, which are understood and presented as uncertainty distributions. These should be accompanied with sensitivity analyses demonstrating the influence of different important sources of uncertainty. Risk-informed decision making should consider always potential long-term consequences of accidental releases. Moreover, the decision making should take into account uncertainty assessments on safety margins, particularly those to known or suspected cliff-edge effects."

3.13.2 Human casualties and the need for evacuation and permanent relocation

(Burgherr & Hirschberg, 2014) estimate that for the Chernobyl accident "expected latent fatalities range from about 9000 for Ukraine, Russia and Belarus to about 33,000 for the whole northern hemisphere in the next 70 years."

(UNSCEAR, 2021, p. 193) lists a number of 116,000 evacuated people in 1986 after the Chernobyl accident, and in addition 220,000 people relocated from 1989 to 1992.

According to (Ashley et al., 2017), following the Chernobyl nuclear accident, a total of 335,000 people have been evacuated from highly contaminated area.

(Aliyu et al., 2015) discuss different estimates for human health effects of the Fukushima nuclear accident and estimate the maximum mortality due to all causes at 10,000.

For the Fukushima accident, (UNSCEAR, 2021) list 118,000 evacuated and relocated people. (Ashley et al., 2017) estimate that about 48,000 people who lived in the restricted area have moved outside of the Fukushima prefecture. As of 1 May 2023, according to the Fukushima Prefecture, 27,020 people were still away from home (M. Schneider et al., 2023).

With respect to the maximum number of casualties for a catastrophic nuclear accident, (Burgherr & Hirschberg, 2014) give a number of 6,596 for a Swiss Generation II PWR and a number of 46,990 for a Generation III EPR (with the higher number due to a much larger radioactive inventory of the EPR compared to the Generation II PWR analysed).

(Ashley et al., 2017) analyse a potential severe accident in a hypothetic U.K. nuclear power plant. The radiologic release of this accident is assumed to be about one order of magnitude lower than the release at Fukushima and two orders of magnitude lower than at Chernobyl (Ashley et al., 2017, Table 9). Based on these assumptions, they estimate a mean number of 44,000 evacuees

[42] Translation by the authors.

and a maximum number of 390,000. With respect to the need for permanent relocation, they estimate a maximum number of 41,000 people.

(Frédéric-Paul et al., 2019) analyse the consequences of a major accident in a Swiss nuclear power plant. They estimate that the number of people to be evacuated and resettled could on average reach 250,000 for the smaller Beznau NPP and up to 500,000 for the larger Leibstadt NPP.

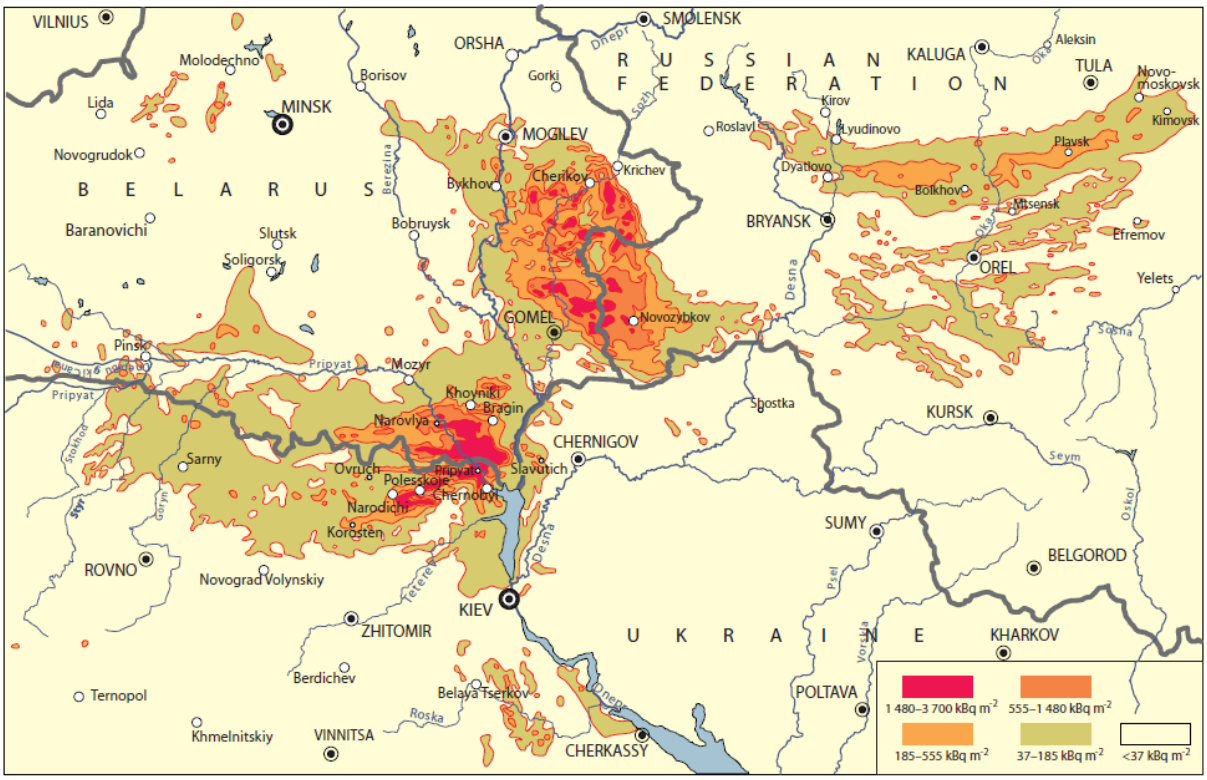
3.13.3 Land loss

According to (Cort et al., 1998), following the Chernobyl accident in 1986 an evacuation zone was initially defined as an area within a radius of 30 km around the plant plus other areas where the dose rate exceeded 50 µSv per hour. Further criteria were established by the soviet authorities, including for a total exclusion zone (> 200 µSv per hour), for evacuation of the whole population (> 50 µSv per hour) and for partial evacuation (30-50 µSv per hour). The corresponding areas for the total exclusion zone and the evacuation zone in May 1986 were 1,100 km^2 and 2,940 km^2. About 50,000 km^2 were contaminated up to a dose level of 2 µSv per hour.

Different zones in Belarus, Russia and Ukraine were finally defined according to the ground contamination by long-lived radionuclides. For the concentration of ^{137}Cs, the limits are 555-1,480 kBq per m^2 for the zone with permanent control (dark orange color inFigure 135) and > 1,480 kBq per m^2 for the zone with strict control (red color in Figure 135). According to (Cort et al., 1998, Table III.1), these limits were only reached in Belarus, Ukraine and Russia, the corresponding areas are 8,100 km^2 and 2,800 km^2 respectively.

According to (UNSCEAR, 2011) in total, 150,000 km^2 with more than 5 million inhabitants were classified as contaminated areas in the former Soviet Union. The area classified as contaminated is gradually shrinking as the ^{137}Cs decays with a half-live of 30 years, e.g. it is expected to fall from 23% of the Belarusian territory in 1986 to 16% in 2016 and 10% in 2046, corresponding to roughly a factor of 2.5 in 60 years.

Figure 135: Map of ^{137}Cs deposition levels following the Chernobyl accident as of December 1989



Source: (UNSCEAR, 2011)

In order to deal with the consequences of the Fukushima Dai-ichi accident, large decontamination work took place in the Fukushima Prefecture. According to (UNSCEAR, 2021), until march 2017, most of the remediation work taking place in Japan after the Fukushima accident was completed. A total of 23,000 residential lots, 8.7 km² of farmland, 7.8 km² of forest, and 1.5 hectares of roadways have been remediated. This led to a lifting of evacuation orders for an area of 780 km², about 70% of the total area affected by evacuation orders.

(Hirschberg et al., 2003) give an estimate on land contamination for a hypothetical accident in a nuclear power plant. They distinguish between interdicted area, which can successfully be decontaminated within 20 years and then resettled, and condemned area, which cannot be decontaminated within 20 years. They estimate possible maximum consequences in terms of lost land at 3,500-4,500 km² (about twice the size of the state of Luxembourg).

(Gering et al., 2012) estimate, that for the accident scenarios analysed for German power plants, an evacuation of the population would have to take place in areas of 20 up to 160 km², a long-term relocation would have to take place in areas of 20 up to 400 km².

(Institut de Radioprotection et de Sûreté Nucléaire [IRSN], 2013) estimates the possible sizes of contaminated land for major accidents in a French 900 MW nuclear power plant. Areas of up to 18,800 km² may be contaminated in the case of a major accident. 1,300 km² of those may be contaminated to a degree that people would have to be relocated from that area.

The consequences of a severe accident in German nuclear power plants have been analysed in (Walter et al., 2015). With respect to a high land contamination (of more than 40,000 kBq/m²) the authors conclude that areas in a distance up to 65 km and a total area of approx. 312 km² could be affected. Permanent relocation of adults results for distances up to 82 km.

3.13.4 Impact on water bodies

(UNSCEAR, 2021) estimates for the Chernobyl accident, that maximum concentrations of ^{137}Cs in the sea (Baltic and Black Sea) was limited to about 2,400 Bq/m^3. In comparison, the accident in Fukushima led to peak concentrations three to four orders of magnitude higher. This can be compared with the concentrations of ^{137}Cs due to atmospheric nuclear weapons test in the 1950s and 1960s, which corresponds to 1-2 Bq/m^3.

To prevent radionuclide transport by rivers from the Chernobyl environment, 140 dams and dikes were constructed and the banks of all rivers close to the nuclear power plant were diked. The space below the NPP site was contained by an impermeable clay layer with a depth of 29-32 m and a length of 2.3 km to prevent the flow of contaminated water into the Prypiat river. In addition, various underground drainage systems, several tens of kilometres in length were constructed (Cort et al., 1998).

The impact of severe accidents on water bodies could be very significant. (Aliyu et al., 2015) discuss the impact of the Fukushima nuclear accident on marine ecosystems and conclude that the impact is still largely unknown.

Based on the lessons learned from Fukushima, an analysis of the possible consequences of a severe accident in a Swiss nuclear power plant shows a strong impact on drinking water supplies not only in Switzerland but also in Germany, as the lakes under consideration and the flowing waters of the Aare and Rhine would be at high risk in the event of an accident (Ustohalova et al., 2014).

3.13.5 Wastes

(UNSCEAR, 2021) describes the remediation work undertaken in Japan following the accident in Fukushima.

This work resulted in the production of large amounts of radioactive waste stored at temporary storage sites. According to (UNSCEAR, 2021), 2.68 million tonnes of radioactive waste was stored at the end of May 2020. Additionally, 22 million m^3 of contaminated soil was removed and stored.

Temporarily stored wastes are transported to an interim storage facility with 10-ton dump trucks, where the wastes will await final disposal (Government of Japan, Ministry of the Environment [MoE], 2025). The Japanese government expects a total amount of 14 million m^3 of waste. Final disposal of this waste is planned outside the Fukushima prefecture within 30 years from the start of the interim storage facility in 2017. There are three types of final disposal facilities under discussion, as of 2024 no final decision on the final disposal was taken (IAEA, 2024d).

As of March 2023, a total of 11.55 million m^3 of contaminated soil is still stored in interim storage facilities (M. Schneider et al., 2023).

3.13.6 Costs

To estimate the actual cost of a nuclear accident is by far not straightforward. (NEA, 2000) already discussed relevant methodological aspects and a comparison of different approaches was given in (NEA, 2018). Several authors have performed cost estimates for historic events as well as for different classes of hypothetical accidents.

(NEA, 2000) cites estimated for the cost of the 1979 accident in the U.S. nuclear power plant Three Mile Island of US$ 130 billion and for the Chernobyl nuclear accident of US$ 20-320

billion. They further cite the results of theoretical studies on the costs of severe accidents, that span more than five orders of magnitude with respect to the resulting costs in cents/kWh.

(Ashley et al., 2017) cite estimates of losses of up to hundreds of billions of US$ following the Chernobyl nuclear accident.

For the Fukushima nuclear accident, (Ashley et al., 2017) cite an amount of US$ 38.9 billion in compensations paid by TEPCO up to 2015 and an estimate for further costs for decontamination and renovation of US$ 65.9 billion, US$ 105 billion in total.

As of June 2023, the total compensation amount paid out by TEPCO is 10,817 billion yen (US$ 77.5 billion) (M. Schneider et al., 2023).

(Kobayashi et al., 2019) estimates the clean-up costs after the Fukushima accident to 35-80 trillion yen (around 270-617 billion Euros).

(UNSCEAR, 2021) gives an estimate for the total cost of the remediation work as of September 2017 at 29 trillion yen (around 220 billion Euros), with about 15 trillion yen contributed by the Government and about 14 trillion yen by municipalities. According to this, 77,000 workers were involved in these activities in the period 1 January 2012 to 31 December 2016.

(Wheatley et al., 2016) estimate, that the average cost of nuclear energy events per year worldwide is around the cost of the construction of a new plant. They estimate the cost of the Fukushima accident at US$ 166 billion.

An analysis for an accident in a 900 MW power plant in France is performed by (IRSN, 2013). They estimate the total cost and distinguish grave and major accidents. For grave accidents, they estimate an average value of 120 billion Euros with an error margin of 50 to 250 billion Euros. For major accidents, they estimate an average value of 450 billion Euros with an error margin of 200 to 1,000 billion Euros.

(D'haeseleer, 2013) estimates the external cost of nuclear energy due to accidents with a order of magnitude of 1 Euro/MWh and the range of uncertainty with 0.3-3 Euros/MWh.

(Sovacool et al., 2016) assess the risks of energy accidents based on a database of 686 actual accidents over the period 1950-2014. They analyse the frequency, fatality, and scope. By scope they estimate the property damage inflicted by the accidents. An average accident in their database inflicts a mean of US$ 388 million in damage.

For accidents in nuclear energy, they evaluate a mean value of US$ 1.4 billion in property damage, approx. twice the value for hydro and more than fifty times the value for other renewables (wind, solar, hydrogen, biofuels, biomass, geothermal). Even the normalised risk in terms of damage per TWh amounts to US$ 3 million for nuclear, compared to between US$ 35,500-235,400 for the other technologies. Thus, the authors conclude that nuclear accidents are the most expensive, inflicting a total of US$ 265.1 billion (or 90.8 percent of the total damage of energy accidents). For the Fukushima accident, they assume property damage of US$ 162.7 billion, the Chernobyl accident is listed with a total property damage of only US$ 7.7 billion and the Three Miles Island accident accounts for US$ 2.7 billion.

3.13.7 Discussion

Commercial nuclear energy generated approximately 100.000 TWh (10^{14} kWh) worldwide from 1965 until 2021 (Energy Institute, 2025). Until 2025, nuclear power reactors accumulated approx. 20,000 reactor-years of operation (WNA, 2025a).

Radioactivity release:

The two accidents in Chernobyl and Fukushima resulted in an estimated 91-105 PBq of ^{137}Cs released to the environment, corresponding to approx. 1 kBq of ^{137}Cs released to the environment per kWh of electricity generated worldwide.

Frequency of major accidents:

While theoretical analysis for the frequency of severe accidents in nuclear power plants based on probabilistic safety assessments results in values of typically 10^{-5} to 10^{-7} per reactor year depending on the reactor design, an "empirical" result based on two major accidents in 20,000 reactor years would correspond with a frequency of 10^{-4} per reactor-year. Major accidents are understood here as such events that have been rated as Level 7 (major accident) of the International Nuclear and Radiological Event Scale (IAEA, 2024d). So far, only the two events in Chernobyl and Fukushima Dai-ichi have been rated as INES level 7 events, see abouve, although other events rated as serious accidents (level 6) or accidents with wider or local consequences (level 6 or 5) have happened.

Number of evacuees:

The total number of evacuees for the accidents in Chernobyl and Fukushima amount to approx. 500,000, thus 25 people had to evacuated from their homes per reactor-year of operation or $5x10^{-9}$ per kWh.

Land loss:

The zone with strict control around Chernobyl covered an area of 2,800 km^2. Under the (optimistic) assumption that this area is halved every 30 years (due to the decay of ^{137}Cs), this would result in a land loss of 1.7 km^2a or $1.7x10^{-3}$ m^2a/kWh. Considering additionally the zone with permanent control of 8100 km^2, this number would increase to 6.5 km^2a or $6.5x10^{-3}$ m^2a/kWh. Multiplying these values with the conversion factor (Occupation, unspecified) for the respective country (Ukraine) of 75.571 pt per m^2a, this would correspond to

- $1.3x10^{-1}$/kWh or $4.9x10^{-1}$/kWh respectively.

These values can be compared with the above LCA results for the normal operation of nuclear power plants, which correspond to

- $1.9x10^{-2}$/kWh (min) to $9.3x10^{-2}$/kWh (max).

The land loss only due to the Chernobyl accident is therefore equivalent to or up to an order of magnitude higher than the land loss due to normal operation as covered by the above LCA approach.

Low-level nuclear waste:

The remediation work after the Fukushima Dai-ichi accident resulted in approx. 22 million m^3 of additional contaminated soil i.e. low-level nuclear waste corresponding to

- $2.2x10^{-7}$ m^3/kWh.

This value must be compared with the above LCA results for the normal operation of nuclear power plants, which correspond to

- $6.3x10^{-8}$/kWh (min) to $9.8x10^{-8}$/kWh (max).

The amount of low-level nuclear waste produced from contaminated soil only due to the Fukushima accident alone is therefore a factor of 2 to 4 higher than the amount of low-level nuclear waste due to normal operation as covered by the above LCA approach.

Costs:

Different estimates for the costs of the Chernobyl accident cover a range of US$ 20 to several hundred billion. For the Fukushima accident, estimates cover a range of US$ 100-600 billion. These costs are in good agreement with the theoretical estimates for future major accidents.

A total damage of US$ 100-1000 billion for these two accidents alone would amount to 0.1-1 cent/kWh of nuclear electricity produced until today.

In Japan, between 1965 and 2022, 8,027 TWh of electricity was produced by nuclear power (Energy Institute, 2025). For Japan, this would mean additional costs of 1.2 to 7.5 cent/kWh due to the cost of the Fukushima accident.

Overall, it is evident from the discussion above, that a the (environmental) impact of accidents in nuclear power plants do have significant impact on the overall (environmental) impact of nuclear power.

3.14 Proliferation Aspects

The spread of nuclear weapons, as well as the nuclear technologies or fissile materials needed to produce them, is known as 'proliferation'. Many nuclear technologies are used in the civilian field of nuclear energy production, but they can also be used for military purposes in nuclear weapons programmes. However, not all technologies and fissile materials are equally suitable for military use the most sensitive being uranium enrichment and reprocessing. Therefore, actors can exploit this civil-military ambivalence or dual-use characteristic of nuclear technologies.

Before the Nonproliferation Treaty entered into force in 1970, several states pursued nuclear weapons programs or initially stayed outside the treaty; today, however, all non-nuclear-weapon states are members. They could only acquire nuclear arms through clandestine development, by withdrawing from the treaty (“break-out”), or by advancing a civilian nuclear program to maintain a latent weapons capability.

In any case access to fissile materials is crucial for producing nuclear weapons. There are two distinct possibilities:

- Access to stocks of fissile materials. These are stocks of separated plutonium or highly enriched uranium. An quantitative attractiveness level can be used as a criterion for proliferation resistance. This takes into account the isotopic composition and chemical form of the fissile material, allowing it to be divided into three categories: unattractive, attractive and preferred. Plutonium, for example, may be present in spent fuel, while uranium may be enriched to varying degrees.
- Access to production technologies that can be diverted from their intended use. One criterion for proliferation resistance is the probability of detecting and preventing the diversion of material or production capabilities within declared production facilities in a timely manner. This applies in particular to sensitive technologies such as uranium enrichment and reprocessing. Additionally, there is the possibility of setting up covert production facilities.

3.14.1 Uranium enrichment and Highly Enriched Uranium

Since natural uranium contains only about 0.7% of the fissile isotope uranium-235, this proportion must be enriched for use in light water reactors. Today, gas centrifuges are the standard industrial technology used for this purpose. These enrichment facilities pose a

proliferation risk, especially when countries want to build up national enrichment capacities. Gas centrifuge facilities are comparable to large supermarkets in terms of their heat signature and power consumption, making secret facilities virtually undetectable by remote sensing methods (Kemp 2016). Due to the negative pressure in the enrichment plant, there are hardly any emissions of isotopes that could give the plant away. Secret plants can therefore only be detected by intelligence methods. Declared plants must be continuously inspected to ensure that they are used for purely civilian purposes. However, this requires the cooperation of the state concerned and membership of international treaty regimes such as the Non-Proliferation Treaty.

Only highly enriched uranium (HEU) with a uranium-235 content of > 90% in metallic form is directly suitable for weapons. Some research reactors use HEU in other chemical forms. However, LWR reactor designs are designed for low enrichment levels of < 20% uranium-235, typically in the range of 3-5%. Such low-enriched uranium (LEU) would then have to be further enriched for use in a nuclear weapon. However, once enrichment reaches approx. 3-5%, two-thirds of the enrichment work required to achieve high enrichment has already been completed; in the case of 19.75% low-enriched uranium, over 95% of the separation work has been completed. This significantly reduces the time and plant capacity required for enrichment to > 90% uranium-235.

Recent considerations of deploying SMR with nearly 20% enriched uranium, so called High Assay Low Enriched Uranium (HALEU) reopened the debate about the weapon usability of enrichments between 12-20%, if large amounts of the material would be used, produced and transported (R. S. Kemp et al., 2024).

3.14.2 Reprocessing and Plutonium

Plutonium is produced in every reactor that uses uranium as fuel. When a neutron is absorbed by uranium-238, plutonium-239 is produced. The plutonium-239 produced in this way can also absorb neutrons. The longer uranium is irradiated with neutrons, i.e., the longer a uranium fuel element is in a reactor, the higher the plutonium isotopes produced, i.e., plutonium-240, plutonium-241, etc. The even-numbered higher plutonium isotopes have rather negative properties for nuclear weapons purposes. They generate neutrons that can lead to premature initiation of the chain reaction during the detonation of a nuclear weapon. In addition, they decay rapidly due to their half-life and produce heat and radiation. Both of these properties are negative when handling plutonium, e.g., in production or storage. Depending on the proportion of higher plutonium isotopes, a distinction is often made between weapons-grade plutonium (> 90% plutonium-239), which is ideal for military purposes, and reactor plutonium, which is less suitable for weapons. However, both can be used in nuclear weapons.

For power generation, fuel elements should be used in a reactor for as long as possible. Therefore, spent fuel elements in commercial use typically contain reactor plutonium. However, if a fuel element is used in the reactor for a shorter period of time (e.g., in a shortened cycle or when a reactor is commissioned), weapons-grade plutonium can also be produced with an LWR fuel element. However, the plutonium produced in this way is still contained in the spent, highly radioactive fuel. This is a barrier to military use (radiation barrier). In order to separate the plutonium, the fuel element would have to be mechanically crushed and dissolved, followed by chemical extraction of the plutonium. In the so-called open fuel cycle, the plutonium is not separated and is therefore protected from access by the radiation barrier. All reactor designs that provide for the separation of plutonium are therefore less proliferation-resistant.

3.14.3 Proliferation risks, proliferation resistance and safeguards

Historically, states have exploited the dual-use nature of nuclear technologies (Sagan, 2011). The establishment of a civilian nuclear energy programme creates the necessary infrastructure, facilities, know-how, materials and manufacturing processes. This latent potential (latent proliferation) is then available for misuse or use in a parallel or subsequent military nuclear weapons program. In addition, there is also the possibility of fissile material being stolen by non-state actors.

Proliferation therefore depends on a number of technical and non-technical factors, which in turn depend on the motivation of an actor, its goals and resources, the technical possibilities and available nuclear technology, such as the choice of technologies for fuel processing and disposal, and fissile material. However, national and international monitoring measures also play an important role. Any attempt to increase proliferation resistance must therefore include a range of intrinsic technical measures as well as extrinsic institutional measures.

The International Atomic Energy Agency (IAEA) carries out safeguards to monitor the civilian use of nuclear energy. In the European Union, this task is performed by the European Atomic Energy Community (EURATOM) in agreement with the IAEA. All members (non-nuclear weapon states) of the Nuclear Non-Proliferation Treaty (Treaty on the Non-Proliferation of Nuclear Weapons – NPT) are obliged to accept these safeguards. They are concluded in internationally binding treaties between the states and the IAEA. The IAEA ensures that the use of fissile material is monitored as comprehensively as possible, from fuel production to disposal. It has a range of monitoring technologies at its disposal, including radiological methods, visual monitoring, intelligence methods, and remote sensing. The IAEA also analyzes the necessity and frequency with which acquisition channels must be monitored in order to detect diversion. Safeguards are an essential element of non-proliferation. Safeguards-by-design refers to the consideration of control requirements in the design of a nuclear facility.

4 Life cycle costing and greenhouse gas abatement costs

Complementing the investigation of GHG life cycle emissions, the life cycle costs and GHG abatement costs of nuclear energy were analyzed for selected regions and compared with those of renewable energies. The ultimate goal of this investigation is to provide a transparent picture of the current costs of electricity generation from newly built nuclear power plants of different capacity levels.

4.1 Basic principles and methodological approach to life cycle costing

Life cycle costing (LCC) allows products and process chains to be compared in terms of their economic efficiency, taking into account all relevant costs. The costs of a product or service (in this case, electricity from nuclear power as well as from renewable sources) are calculated over the entire life cycle, usually using the net present value method. Life cycle costing is primarily used in public procurement or in the construction and property sector, as it takes into account not only the purchase price of a product but also the follow-up costs for the procurer or investor during the utilization and disposal phase (e.g. costs for maintenance, dismantling, decommissioning, demolition, etc.) and therefore also considers costs that are less obvious than the pure purchase or investment price (see (BMWK, 2022; SMART SSP, 2011; Umweltbundesamt [UBA], 2025). Depending on the perspective from which the costs are calculated (i.e. who bears the costs: companies, consumers, society), social costs (or external costs[43]) have to be included in the calculation (cf. e.g. (Hunkeler et al., 2008)).

For power generation technologies, it is common practice to calculate and compare the levelized cost of electricity (LCOE) of the technologies. The LCOE is the cost of converting another form of energy into electricity and is usually expressed in euros or dollars per megawatt hour (MWh). Alternatively, (euro or dollar) cents per kilowatt hour (kWh) is another common unit. The LCOE results from the capital costs (including the financing costs of borrowed capital and opportunity costs for equity), the fixed and variable operating costs, the fuel costs (if applicable), as well as other cost components such as the CO_2 costs for fossil fuels and the targeted return on capital over the operating period. Average LCOE are calculated using the Net Present Value (NPV) method and enable a comparison of power plants with different generation and cost structures.

In principle, the NPV method is a dynamic method of business investment calculation used to evaluate the profitability of an investment or project. It calculates the present value of all future cash flows, both positive and negative (i.e., income and expenditure), and subtracts the initial investment cost. NPV takes into account the time value of money by discounting future cash flows to their present value using a specified discount rate. A positive NPV indicates that the project is expected to be profitable and add value to the company, while a negative NPV suggests the project may result in a net loss. The NPV method is widely used in capital budgeting decisions and helps managers compare different investment opportunities on a consistent basis.

When calculating the NPV, the concepts of compounding and discounting play a central role. When compounding is applied, the future value of a current amount of money is calculated. It takes into account the fact that money increases in value over time when it is invested.

The compounded value is calculated according to the formula

$$compounded\ value\ = original\ value * (1 + i)^n$$

[43] External costs are, by definition, costs that are not borne by those who cause them (e.g. operators of nuclear power plants), but which society has to pay for, e.g. costs resulting from climate change, environmental pollution or health damage.

where *i* is the interest rate and *n* is the number of periods.

The time *t(0)* in the NPV calculation is usually defined as the starting point of the investment. It represents the moment at which the initial investment decision is taken and the initial investment payment is made.

Discounting is particularly important for the NPV calculation, allowing the present value of future cash flows to be determined. The formula for the discounted value reads as follows:

$$discounted\ value\ =\ original\ value * \frac{1}{(1+i)^n}$$

Taking into account the time value of money through compounding and discounting makes it possible to fairly compare investments with different payment dates and to precisely assess their profitability.

In practice, the LCOE essentially corresponds to a life cycle cost calculation from the perspective of power plant operators or investors, but systematically neglects or underestimates external costs and follow-up costs, especially in the case of nuclear power (Wissenschaftliche Dienste Deutscher Bundestag, 2021), as these are usually not or not fully borne by the power plant operator, but by society. That can distort comparisons with renewable energy sources such as wind and solar power, as these usually bear their own environmental and follow-up costs. For example, the downstream costs for dismantling are also only taken into account in (IEA & NEA, 2020) with a flat-rate factor on the overnight costs[44] and are therefore not very reliable. The difference between the price paid by the plant operator and the social damage costs is correspondingly very high and is not adequately taken into account when considering only the electricity generation costs.

This report therefore quantifies the life cycle costs for all elements of the defined process chains (see section 3.1), both the real costs, i.e. the costs to be borne by one of the directly involved actors (e.g. plant operators), as well as the relevant social costs (e.g. eternal costs of final disposal), which are currently still largely borne by the general public (e.g. taxpayers).

The electricity production costs provide an initial basis for LCC, particularly for the upstream processes, construction and operation of the power plant itself. These take into account all real costs incurred by the operator for the provision of electricity and, with the limitations described above, generally cover the entire life cycle. Comprehensive documentation on the LCOE is available for nuclear power plants (e.g. (IEA & NEA, 2020)). For uranium mining, (NEA & IAEA, 2021) have at least published ranges for the costs of uranium extraction. The World Nuclear Association has documented costs for process stages such as enrichment.

Specifically, the calculation of the LCOE in this report was based on an analysis of current nuclear reactor construction projects. The focus was on countries and regions where construction and financing frameworks can be assumed to be close to market conditions. Consequently, construction projects in Europe and North America formed the center of attention, while reactor construction in China and Russia was not considered in detail due to a lack of reliable data.

In a step-by-step approach, the investment costs (overnight costs for construction, see section 4.2.1) for the reviewed construction projects were initially researched and the resulting data was verified with experts (Steigerwald et al., 2023; Thomas, 2024).

[44] See section 4.2.1.

As a second step, the respective capital costs were determined. On this basis, the annuities were calculated using standard market discount rates (see section 4.2.3). Annuities are annual payments that include interest and a pro-rata repayment of loans granted. The longer the construction time (see section 4.2.2) recorded or assumed for individual projects, the higher were the capital costs and the resulting annuities:

$$I_t = I_{total} \frac{i(1+i)^{SL}}{(1+i)^{SL} - 1}$$

where

I_t is the annuity,

I_{total} is total loan amount of the investment,

i is the interest rate,

SL is the service life of the investment.

After that, the fixed and variable operating costs as well as the fuel costs were determined for all the considered reactors. In this context, the efficiency (see section 4.2.4), and the load factor (see section 4.2.5), as well as the service life (see section 4.2.6) were considered as key parameters. This was followed by the calculation and discounting of the costs for post-operation, decommissioning and disposal (see section 4.2.8).

4.2 Key parameters, data and assumptions

The key parameters mentioned above are explained in more detail below and substantiated by the associated assumptions.

4.2.1 Overnight costs for construction

Overnight costs in the context of nuclear power plant construction refer to the total investment required to build a nuclear power plant, assuming it could be built immediately or "overnight" (WNA, 2023). Overnight costs are typically expressed in terms of the generating capacity of the plant, such as euros per kilowatt (€/kW).

Key aspects of overnight costs include:

- Site preparation;
- Construction materials and labour;
- Fabrication of plant components;
- Commissioning;
- Engineering, Procurement and Construction (EPC) costs;
- Owner's costs (land, cooling infrastructure, associated buildings, site works, switchyards, project management, licenses, etc.);
- Contingencies.

It is important to note that overnight costs do not represent the total costs of building a nuclear power plant, as they do not include important cost factors such as financing costs (e.g. interest on debt), cost escalation over time and potential delays. It is important to note that these non-included cost factors can amount to up to 40% of the total costs, particularly in the case of long

construction periods (see following section). In order to take these aspects into account, an analysis and compilation of actual investment costs from recently completed as well as currently ongoing construction projects in Europe and North America has been carried out.

The following table provides a record of the construction projects analyzed with data on geographical coverage, reactor type, reactor model, net capacity, as well as the start of construction and commercial operation.

Table 77: Compilation of analysed construction projects

Construction project	Country	Reactor type	Reactor model	Capacity net [MW_e]	Construction start	Commercial operation	Source
Olkiluoto 3	Finland	PWR	EPR	1575	12.08.2005	16.04.2023	WNA 2025a
Flamanville 3	France	PWR	EPR	1630	03.12.2007	Summer 2025 (expected)	WNA 2025b; WNN 2025
Hinkley Point C	United Kingdom	PWR	EPR-1750	3260	Block C1: 11 December 2018; Block C2: 12 December 2019	2029-2031 (expected)	EDF 2024; WNA 2025c; WNA 2025d;
Sizewell C	United Kingdom	PWR	EPR	3340	2025 or later (expected)	2037-2041 (expected)	Thomas 2023
Vogtle 3&4	USA	PWR	AP1000	2234	Block 3: 2 March 2013; Block 4: 19 November 2013	Block 3: 31 July 2023; Block 4: 29 April 2024	WNA 2025e; WNA 2025f

Source: Own compilation

The overnight costs for the analyzed construction projects can be found in Table 79 and Table 80 (see section 4.3.1).

4.2.2 Construction time

The construction time of a power plant is the time between the start of physical construction and the beginning of commercial operation. In other studies, construction time is also referred to as 'construction lead time' or just 'lead time' (Walstra, 2024).

It needs to be stressed that construction times do not include the planning and permitting phases that take place prior to the start of physical construction. These pre-construction activities can add several years to the total project duration, especially in the case of nuclear power plants. The construction time is therefore a critical factor for the economics of a power plant, as longer construction times can significantly increase costs due to financing costs, inflation and potential regulatory changes during the construction process (WNA, 2008).

In the case of a long construction period with no income from the investment, the interest on borrowed funds can add up to very high amounts. This can be illustrated by modelling the

interest payments for a planned construction time of five years compared to a realized construction time of 15 years. With a five-year construction time, the share of interest during the construction time in the total construction cost is calculated to be around 16%. With a construction time of 15 years, the share is 41% of total construction costs, making interest during the construction period the main cost driver (Wealer et al., 2019).

The construction times for the analyzed construction projects were obtained on the basis of the period between the start of construction and commercial operation as given in Table 77 and can be found in Table 78 in section 4.2.7. For one reactor concept (NuScale), that is not yet being built anywhere, we use the construction time estimate given by the developer.

4.2.3 Discount rate

The discount rate is an interest rate that is used to convert future costs or benefits to their present value, allowing a fair comparison of cash flows at different points in a project's life cycle. It represents the opportunity cost of capital or the minimum rate of return required on an investment, taking into account factors such as risk, inflation and alternative investment opportunities (FasterCapital, 2024).

The choice of discount rate can significantly affect the outcome of an LCC analysis. A higher discount rate gives more weight to short-term costs, while a lower rate gives more weight to long-term costs. Because of this sensitivity, it is useful to perform a sensitivity analysis using different discount rates to understand how changes in the rate affect the overall cost assessment.

In many economic calculations, including the LCOE, the weighted average cost of capital (WACC) is used. The WACC takes into account the costs of both equity and debt capital, weighted according to their share in the financing of the project. The return expectations of equity providers and the interest costs for debt capital are thus included.

Accordingly, the WACC is calculated according to the following formula:

$$WACC = \left(\frac{E}{V}\right) r^E + \left(\frac{D}{V}\right) r^D (1 - t_c)$$

where

E is the market value of the equity,

D is the market value of the debt,

V is the market value of both equity and debt,

r^E is the cost of equity,

r^D is the cost of debt,

t_c is the corporate tax rate.

For the calculation of the LCOE, a discount rate of 7% is assumed in this study (see Table 78 in section 4.2.7). The assumption corresponds well with other recent studies on the LCOE of nuclear power (see section 4.5.2.1) and reflects the situation over the past 15 years (KPMG, 2022). Nevertheless, it should be noted that applying a uniform discount rate to different technologies is methodologically challenging, given that their risks, capital structures and political conditions can vary greatly. Sensitivity analyses with variations of the discount rate are therefore essential (see section 4.3.4).

4.2.4 Efficiency

The efficiency of a nuclear power plant is defined as the ratio of electrical energy output to the total thermal energy produced by the reactor. It represents the ability of the plant to convert the heat generated by nuclear fission into usable electricity.

Nuclear power plants typically achieve efficiencies around 33-37%. Nuclear plants currently being built have about 34-36% efficiency, also depending on the site (water temperatures), with some designs approaching 40% efficiency. The efficiency of older plants is often only around 32-33% (WNA, 2020).

For the analyzed construction projects listed in Table 77, 37% efficiency is assumed for EPR reactors and 33% for AP1000 reactors. An efficiency of 29% is estimated for SMR reactors (see Table 78 in section 4.2.7). The significantly lower efficiency of SMRs is caused by the smaller size of the reactors. With SMR, the proportion of auxiliary systems and infrastructure per kilowatt hour of electricity generated is higher, which reduces the overall efficiency.

4.2.5 Load factor

The load factor of a nuclear power plant is calculated as the ratio of its actual energy output over a given period to its potential output if it had operated continuously at full nameplate capacity over the same period. It is typically calculated on an annual basis but can be determined for any specified period. In this case, the calculation is the total kilowatt-hours generated by the unit divided by the unit's capacity in kilowatts times the number of hours in the year. A higher load factor indicates more efficient use of the plant's capacity and generally implies better economic performance (Maloney, 2003).

For the analyzed construction projects listed in Table 77, country-specific load factors were taken from the IAEA PRIS database, with the mean value for the years 2011-2021 being formed in each case (see Table 78 in section 4.2.7).

4.2.6 Service life

The service life of a nuclear power plant is the period during which the plant is expected to operate effectively, from its initial commissioning to its final shutdown and decommissioning.

Although plants may be designed or licensed for a specific lifetime, it is important to note that their actual service life may be shorter or longer depending on a variety of economic, technical and regulatory factors.

In this study, a service life of 60 years is assumed for all EPR and AP1000 reactor projects. The same applies to SMR reactor design, with the exception of 40 years for the CAREM reactor in Argentina (see Table 78 in the following section).

4.2.7 Overview of assumptions for NPP construction and operation

The following table summarizes the key modelling parameters for NPP construction and operation presented in the previous sections as well as the corresponding assumptions.

Table 78: Compilation of key modelling parameters and corresponding assumptions

Construction project	EPR / FIN (Olkiluoto 3)	EPR / FRA (Flamanville 3)	EPR / UK (Hinkley Point C)	EPR / UK (Sizewell C)	AP1000 / USA (Vogtle 3&4)	SMR / USA (NuScale)	SMR / ARG (CAREM)
Construction time (months)	212	211	120-156	155-203	124-125	36	168
Discount rate	7%	7%	7%	7%	7%	7%	7%
Efficiency	37%	37%	37%	37%	33%	29%	29%
Load factor	93%	77%	75%	75%	91%	91%	75%
Service life (years)	60	60	60	60	60	60	40

Source: Own compilation

4.2.8 Post-operation, decommissioning and disposal

The costs of downstream elements of the process chain (i.e. post-operation, decommissioning and final disposal) are only partially taken into account, if at all, in conventional LCOEs. There is a high degree of uncertainty surrounding these elements of the process chain, as the Finnish Onkalo repository is the only geological repository for high-level radioactive waste and spent fuel elements under construction in the world as of 2024. This aspect is illustrated by the example of the United Kingdom, where the estimated total costs (including site selection and approval, construction, operation, closure, aftercare and contingencies) vary widely, ranging from £18.7 billion to £53 billion. These cost estimates were carried out and published around the same time by Nuclear Waste Services (Nuclear Waste Services [NWS], 2023) and the Committee on Radioactive Waste Management (Committee on Radioactive Waste Management [CoRWM], 2022). The cost data for the LCOE is therefore based exclusively on publicly available planning data. This must always be taken into account when interpreting the results.

At the start of the project, the plan was to use basic data on the costs of dismantling and final storage in Germany as compiled by the Commission for the Review of the Financing of the Nuclear Phase-out purpose (Kommission zur Überprüfung der Finanzierung des Kernenergieausstiegs [KFK], 2016). During the expert discussions on the project, it became clear that planning data from Switzerland was available that could be considered more up to date and for which the basic methodological and data-related framework conditions and assumptions were very transparent. Against this background, it was decided to use this data as a reference point for the LCOE.

Cost studies are generally based on a cost structure that systematically distinguishes between post-operation costs, decommissioning costs and disposal costs in the narrower sense. This is because these costs are financed differently (power plant operators vs. funds). Although such a distinction is not absolutely necessary from an LCOE perspective, it contributes significantly to transparency and traceability and prevents important cost items from being overlooked.

Post-operation begins when the plant ceases power operation and serves primarily to comply with nuclear safety targets. Post-operation ends when the plant is free of nuclear fuel, followed by decommissioning as part of the closure process.

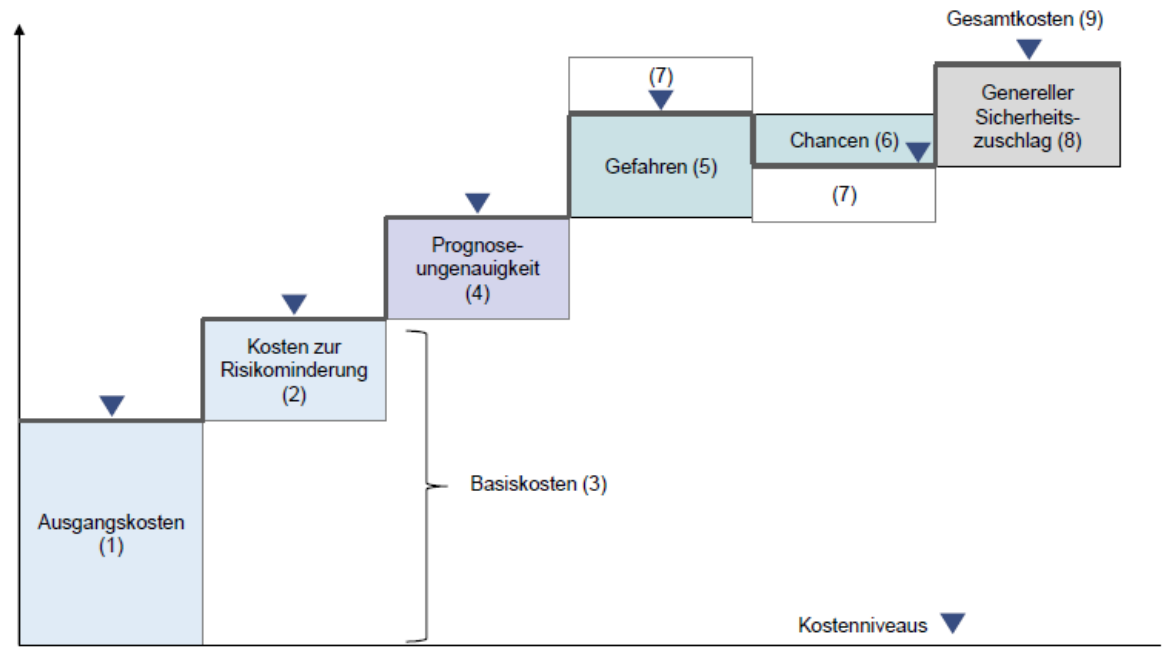
The decommissioning costs depend in turn on the decommissioning objectives pursued. In the most recent Swiss cost study published in 2021, three different objectives are distinguished (in contrast to previous studies):

- Decommissioning objective 1: Release from nuclear energy legislation;
- Decommissioning objective 2: Complete dismantling, including removal of foundations and concrete structures to a depth of 2 m below ground level;
- Decommissioning objective 3: Complete dismantling, including removal of all foundations.

The cost structures for disposal include the costs of interim storage, transport and containers, the costs of project planning and construction, operation and closure of deep geological repositories, and the costs of reprocessing.

In addition to this cost structure, Swiss cost studies are prepared according to a uniform cost classification system, which is bindingly prescribed by the Administrative Commission. This cost classification takes into account possible risks in the cost determination and distinguishes between the calculated initial costs and the costs for risk mitigation measures, as well as cost surcharges for forecast inaccuracies and risks and cost deductions for opportunities and, finally, an additional general safety margin, see the figure below.

Figure 136: Graphical representation of the specified cost breakdown



Source: (swissnuclear, 2021); Gesamtkosten (cost breakdown), Ausgangskosten (initial costs), Kosten zur Risikominderung (costs for risk reduction), Basiskosten (base costs), Prognoseungenauigkeit (forecast inaccuracies), Gefahren (foreseeable risk potential), Chancen (opportunities), Genereller Sicherheitszuschlag (general safety margin)

The individual elements of this cost breakdown (Gesamtkosten, 9) can be summarised as follows:

Initial costs (Ausgangskosten, 1) include all costs that are foreseeable for the planning, approval, implementation and completion of the planned decommissioning and disposal projects, including the post-operational phase. They are determined on the basis of estimated quantities (materials, machinery and equipment, working hours, etc.), reference prices (unit prices or flat rates) and empirical values. These are probable costs; surcharges for forecast inaccuracies, risks and uncertainties are not included.

The costs for risk reduction (Kosten zur Risikominderung, 2) are also determined in the same way as the initial costs, without surcharges. These include measures that mitigate risks or support opportunities. The sum of the initial costs and the costs for risk mitigation are the so-called base costs (Basiskosten, 3).

Since cost estimates are subject to inaccuracies, especially in the early phases of a project, and since the Swiss cost study does not use confidence intervals, these inaccuracies are taken into account with cost surcharges for forecast inaccuracies (Prognoseungenauigkeit, 4). These surcharges are determined 'bottom-up' for each element of the project structure plan as a percentage of the initial costs or the costs for the risk mitigation measures, initially reported as individual values, and justified, and then aggregated to the level of the total costs.

As a further element of the cost breakdown, cost surcharges to take account of foreseeable risk potential (Gefahren, 5) are included in the calculation. These cost surcharges are determined on a top-down basis using a quantitative risk analysis, whereby the probability of occurrence and the cost consequences of each relevant risk are estimated on the basis of expert knowledge.

Conversely, cost deductions for opportunities (Chancen, 6) that may arise, for example, from new technologies, alternative concepts or accelerated approval procedures are also taken into account.

Exceptional events (risks and opportunities) with a very low, mostly unknown frequency of occurrence and very large impacts (so-called high-impact/low-frequency events) are not included in the total costs but are identified and recorded separately and described with estimated absolute costs and probabilities of occurrence (7).

Finally, a general safety margin (Genereller Sicherheitszuschlag, 8) is calculated in such a way that, according to estimates at the time of completion of the cost study, the tolerance level for possible cost overruns is limited to a maximum of 20 per cent.

4.3 Results

Based on the methodological approach described in section 4.1 and the data and assumptions given in section 4.2, the LCC results were calculated.

In order to track the calculation steps and the data used, the construction and operation costs (see section 4.3.1) will be presented first, followed by the costs for post-operation, decommissioning and disposal (see section 4.3.2). Based on these determinants, the LCOE are calculated[45] both for the base year 2020 and for the 2030 projection (see section 4.3.3). Section 4.3.4 presents a sensitivity analysis on parameters that are crucial for the LCOE result. Finally, a comparison with renewable and fossil power generation technologies is given in section 4.3.5.

[45] To make the results for 2020 and 2030 comparable and independent of inflation effects, the cost base for both years was set at 2020. This applies equally to the LCOE values for nuclear and renewable energy.

4.3.1 Construction and operation costs

The results for recently completed construction projects that represent the baseline year 2020 are presented first (see section 4.3.1.1), followed by the results for future outlook that are based on data for ongoing construction projects to be finalised around 2030 as well as SMR data (see section 4.3.1.2).

4.3.1.1 Baseline year 2020

The following table contains the costs for power plant construction and operation for the completed construction projects Olkiluoto 3, Flamanville 3, and Vogtle 3&4, that were examined and used as input data for the baseline year 2020. In detail, the table shows the investment costs (overnight costs), the fixed and variable operating costs, and the fuel costs. The references used for each item can also be found in the table. Ranges are specified for the individual cost types, where relevant.

With regard to the investment costs for the Vogtle 3&4 construction project, it should be noted that, due to restrictions of the source used, the WACC is already included in the figures; therefore, the figures shown are already capital costs.

Table 79: Costs for power plant construction and operation (baseline year 2020, cost basis 2020)

Construction project	EPR / FIN (Olkiluoto 3)		Source	EPR / FRA (Flamanville 3)		Source	AP1000 / USA (Vogtle 3&4)		Source
	min.	max.		min.	max.		min.	max.	
Investment costs (EUR/kW)	7.619	7.619	DIHK 2024	8.098	8.098	EDF 2022	14.506	14.506	Georgia Recorder 2023 / Thomas 2024
Fixed operating costs (EUR/kW/Jahr)	126	146	Lazard 2024	126	146	Lazard 2024	126	146	Lazard 2024
Variable operating costs (EUR/MWhe)	4	5	Lazard 2024	4	5	Lazard 2024	4	5	Lazard 2024
Fuel costs (EUR/MWhe)	5	9	Lazard 2024	5	9	Lazard 2024	6	10	Lazard 2024

Source: Own compilation

4.3.1.2 Future projection for 2030

Table 80 shows the costs of power plant construction and operation for the ongoing construction projects Hinkley Point C und Sizewell C in the UK, which were examined and used as input data for conventional NPP construction projects for 2030 future projection. With regard to SMRs that could become relevant by 2030, data are provided for first-of-a-kind (FOAK) and n^{th}-of-a-kind (NOAK) reactors in the US, supplemented by data for the CAREM project in

Argentina. Again, the table lists investment costs (overnight costs), fixed and variable operating costs and fuel costs, as well as the corresponding references. It is evident from the data, that assumptions for the NOAK NuScale reactor (decrease in investment costs from 18.639 to 3.209 Euro/kW, decrease in construction time from currently more than 10 years to 3 years) are extremely optimistic and will not be feasible for the year 2030 (at least), as not even a first-of-a-kind reactor is currently under construction. We will therefore consider this case as a best case sensitivity analysis, but not take it into account for the further discussion of the future projection for 2030.

Table 80: Costs for power plant construction and operation (future projection for 2030, cost basis 2020)

Construction project	EPR / UK (Hinkley Point C)		Source	EPR / UK (Sizewell C)		Source	SMR / USA (NuScale, FOAK)		Source	SMR / USA (NuScale, NOAK)		Source	SMR / ARG (CAREM)		Source
	min.	max.		min.	max.		min.	max.		min.	max.		min.	max.	
Investment costs (EUR/kW)	15.518	16.601	BBC 2024; Thomas 2024	14.089	16.555	Thomas 2023	18.639	18.639	Climate & Capital 2024	3.209	3.209	Steigerwald et al. 2023	21.701	21.701	Climate & Capital 2024
Fixed operating costs (EUR/kW/Jahr)	126	146	Lazard 2024	126	146	Lazard 2024	126	146	Lazard 2024	126	146	Lazard 2024	126	146	Lazard 2024
Variable operating costs (EUR/MWhe)	4	5	Lazard 2024	4	5	Lazard 2024	4	5	Lazard 2024	4	5	Lazard 2024	4	5	Lazard 2024
Fuel costs (EUR/MWhe)	5	9	Lazard 2024	5	9	Lazard 2024	7	12	Lazard 2024	7	12	Lazard 2024	7	12	Lazard 2024

Source: Own compilation

4.3.2 Costs for post-operation, decommissioning and disposal

The results of this cost analysis are summarized in Table 81. It can be seen that disposal costs in the narrower sense dominate the total back-end costs at around 85%. Furthermore, there are significant variations, which are not only due to costs, but also to the different operating lives of the power plants and the net electricity volumes generated. As shown elsewhere, however, these variations are of lesser importance compared to other items in the LCOE.

Table 81: Costs for post-operation, decommissioning and disposal (cost basis 2020)

	Kkw Beznau (KKB)	Kkw Mühleberg (KKM)	Kkw Gösgen (KKG)	Kkw Leibstadt (KKL)		
Calculated costs based on net electricity production					minimum, rounded value	maximum, rounded value
Disposal	11.838 €/GWh	14.425 €/GWh	9.511 €/GWh	9.397 €/GWh	9.400 €/GWh	14.500 €/GWh
Decommissioning	2.522 €/GWh	4.122 €/GWh	1.671 €/GWh	1.751 €/GWh	1.700 €/GWh	4.100 €/GWh
Post-Operation	1.200 €/GWh	2.224 €/GWh	686 €/GWh	725 €/GWh	690 €/GWh	2.200 €/GWh

Source: Own compilation

4.3.3 Levelized Cost of Electricity

The levelized costs of electricity (LCOE) are calculated for both the base year 2020 as well as the future projection for 2030.

4.3.3.1 Baseline year 2020

The following table compiles the results of the life cycle cost analysis for the base year 2020. The capital costs are based on the investment costs and are calculated with the annuity method and the assumptions on construction time and discount rate. The operating and fuel costs represent the sum of fixed and variable operating costs as well as fuel costs. Finally, end-of-life costs comprise post-operational costs, decommissioning costs and disposal costs.

Table 82: LCOE ranges (min./max.) for electricity from new nuclear power (in ct/kWh, baseline year 2020, cost basis 2020, 7% discount rate)

Construction project	EPR / FIN (Olkiluoto 3)		Source	EPR / FRA (Flamanville 3)		Source	AP1000 / USA (Vogtle 3&4)		Source
	min.	max.		min.	max.		min.	max.	
Capital costs (ct/kWhe)	12,53	12,53	Own calculation	15,60	15,60	Own calculation	12,96	12,96	Own calculation

Construction project	EPR / FIN (Olkiluoto 3)		Source	EPR / FRA (Flamanville 3)		Source	AP1000 / USA (Vogtle 3&4)		Source
	min.	max.		min.	max.		min.	max.	
Operating and fuel costs (ct/kWhe)	2,46	3,16	Own calculation	2,78	3,54	Own calculation	2,57	3,32	Own calculation
End-of-lfe costs (ct/kWhe)	0,02	0,04	Own calculation	0,02	0,04	Own calculation	0,02	0,04	Own calculation
TOTAL (ct/kWhe)	**15,02**	**15,73**	Own calculation	**18,41**	**19,18**	Own calculation	**15,55**	**16,32**	Own calculation

Source: Own compilation

4.3.3.2 Future projection for 2030

Table 83 compiles the results of the life cycle cost analysis for the 2030 future projection. As for 2020, the capital costs are calculated based on the investment costs using the annuity method and the assumptions on construction time and discount rate. The operating and fuel costs represent the sum of fixed and variable operating costs as well as fuel costs. Finally, end-of-life costs comprise post-operational costs, decommissioning costs and disposal costs. As discussed above, the values for a NOAK NuScale reactor are listed as a best case sensitivity analysis but will not be taken into account for the future projections for 2030.

Table 83: LCOE ranges (min./max.) for electricity from new nuclear power (in ct/kWh, future projection for 2030, cost basis 2020)

Construction project	EPR / UK (Hinkley Point C)		Source	EPR / UK (Sizewell C)		Source	SMR / USA (NuScale, FOAK)		Source	SMR / USA (NuScale, NOAK)		Source	SMR / ARG (CAREM)		Source
	min.	max.		min.	max.		min.	max.		min.	max.		min.	max.	
Capital costs (ct/kWhe)	23,24	27,88	Own calculation	23,68	32,54	Own calculation	16,65	16,65	Own calculation	3,07	3,07	Own calculation	39,91	39,91	Own calculation
Operating and fuel costs (ct/kWhe)	2,83	3,59	Own calculation	2,83	3,59	Own calculation	2,65	3,45	Own calculation	2,65	3,45	Own calculation	2,98	3,84	Own calculation
End-of-lfe costs (ct/kWhe)	0,02	0,04	Own calculation	0,02	0,04	Own calculation	0,02	0,04	Own calculation	0,02	0,04	Own calculation	0,08	0,14	Own calculation
TOTAL (ct/kWhe)	26,10	31,51	Own calculation	26,54	36,17	Own calculation	19,32	20,14	Own calculation	5,74	6,56	Own calculation	42,97	43,89	Own calculation

Source: Own compilation

4.3.4 Sensitivity analyses

As mentioned in section 4.2.3 the choice of the discount rate can significantly affect the outcome of an LCC analysis. In fact, the discount rate is the parameter that has the greatest impact on the overall LCOE results. This is demonstrated by two sensitivity analyses. In other existing LCOE studies on nuclear power, the discount rates vary between 3% and 10%, with some studies presenting results for 3%, 7% and 10% (IEA & NEA, 2020; Kost et al., 2024). Against this background, the two sensitivity analyses carried out with a discount rate of 3% and 10% respectively represent the lower and upper end of the range found in literature. For the sake of clarity, the sensitivities are limited to the reference year 2020 and the analyzed construction projects in Europe (Olkilouto 3 and Flamanville, see the following two tables).

Table 84: LCOE ranges (min./max.) for electricity from new nuclear power in Europe (in ct/kWh, baseline year 2020) – sensitivity analysis with 3% discount rate

Construction project	EPR / FIN (Olkiluoto 3)		Source	EPR / FRA (Flamanville 3)		Source
	min.	max.		min.	max.	
Capital costs (ct/kWhe)	4,43	4,43	Own calculation	5,46	5,46	Own calculation
Operating and fuel costs (ct/kWhe)	2,46	3,16	Own calculation	2,78	3,54	Own calculation
End-of-lfe costs (ct/kWhe)	0,20	0,35	Own calculation	0,20	0,35	Own calculation
TOTAL (ct/kWhe)	**7,10**	**7,95**	Own calculation	**8,45**	**9,35**	Own calculation

Source: Own compilation

Table 85: LCOE ranges (min./max.) for electricity from new nuclear power in Europe (in ct/kWh, baseline year 2020) – sensitivity analysis with 10% discount rate

Construction project	EPR / FIN (Olkiluoto 3)		Source	EPR / FRA (Flamanville 3)		Source
	min.	max.		min.	max.	
Capital costs (ct/kWhe)	23,46	23,46	Own calculation	29,36	29,36	Own calculation
Operating and fuel costs (ct/kWhe)	2,46	3,16	Own calculation	2,78	3,54	Own calculation
End-of-lfe costs (ct/kWhe)	0,00	0,01	Own calculation	0,00	0,01	Own calculation
TOTAL (ct/kWhe)	25,93	26,63	Own calculation	32,15	32,91	Own calculation

Source: Own compilation

A comparison with Table 86 shows that the results differ considerably (i.e. by about a factor of 2) both up and down. The change in end-of-life costs is also interesting to note in this context: While end-of-life costs increase significantly in the sensitivity analysis with a 3% discount rate compared to the baseline scenario (0.20-0.35 cents/kWh vs. 0.02-0.04 cents/kWh), the increase is more than offset by the significantly reduced capital costs. A further discussion of the results can be found in section 4.5.2.1. The end-of-life costs (i.e., dismantling and disposal) are much more significant when discount rates are low. At just 3%, these costs become clearly visible, whereas at 10% they are almost completely disregarded. This is because costs in the distant future are heavily discounted when interest rates are high. Such a capital investment plan may make economic sense for investors, but not for society, because the long-term costs are still real.

4.3.5 Comparison with renewable and fossil power generation technologies

In this section, LCOE values resulting from a detailed analysis of costs for nuclear power plants (section 4.3.3) are compared with LCOE ranges for wind, photovoltaics, and hard coal electricity generation. The comparison is done in two different settings. In the first, base year 2020 setting (section 4.3.5.1), the LCOE comparison is performed for units that come online by 2020. In the second, projection 2030 setting (section 4.3.5.2), LCOE are compared for units that could come online in the early 2030's.

Wind and photovoltaics LCOE are determined by technology costs and financing costs, as well as attainable full load hours. The latter depend on the concrete location of an installation. Full load hours of photovoltaics especially depend on the region, i.e., irradiation is generally higher in lower latitudes (e.g., North Africa) than in higher latitudes (e.g., Central Europe). Full load hours also depend on the location within a country or region. For instance, wind speeds are generally higher on the coast than in the inland. Also, wind speeds differ within regions in a country depending on topography. With strong increase in installations, technological learning and economies of scale have led to considerable cost decreases in recent years. Financing costs vary considerably, depending on the general financing situation in the respective country, as well as those of the specific project.

Hard coal-based power generation exhibits high upfront investment costs, hence the capital costs part of LCOE varies significantly depending on attainable capacity factors, and costs of financing. In contrast to nuclear-based or renewables-based electricity generation, variable costs can also make up a substantial share of LCOE. Their magnitude depends on coal prices which vary considerably depending on whether coal is a domestic or an imported resource. A second important factor is the existence and level of CO_2 pricing, which may have a strong impact on the LCOE. Both the fuel price and the CO_2 price also influence marginal generation costs, which in turn determine the attainable capacity factor. Both international fuel prices and regional CO_2 prices have shown high variation in the past and projections are associated with a substantial degree of uncertainty.

4.3.5.1 Baseline year 2020

For wind (onshore and offshore), and photovoltaics, LCOE for units that came online by 2020 are available from (IRENA, 2020). While weighted average values and 5th and 95th quantiles are available for on- and offshore wind, for different geographical regions, ranges and weighted average for photovoltaics are only available as global values.

For hard coal-based generation, there is no similar comprehensive source available that would report LCOE of newly constructed units. However, IEA's World Energy Outlook (IEA, 2024) presents an approved methodology to assess the development of the energy system in different regions and project future deployment and costs. Starting with its 2018 version, it reports LCOE

for different technologies, including those for hard coal-fired generation, for different regions, current and future commissioning dates and different climate policy ambition scenarios. As described above, LCOE of this technology are sensitive to changes in fuel prices, CO_2 pricing, and attainable capacity factors. Using data from different climate ambition scenarios and different publication years for the same geographical region sheds light on the uncertain future development of these factors. Due to moderate lead times for construction, long technological lifetimes and no significant technological improvements, it is a fair assumption to treat the LCOE data from the different publication years as valid for the baseline year 2020. To get upper and lower bounds of LCOE similar to those of the renewable technologies, values from the New Policies Scenario of WEO 2018[46] (IEA, 2018) are taken as the lower bounds and values from the Announced Pledges Scenario of WEO 2024 are taken as the upper bounds. The lower end of the LCOE range reported for North America can be assumed as typical for a system with no CO_2 pricing scheme, with coal as a domestic, cheaply available resource, and high attainable capacity factors of 60%. The higher end assumes CO_2 pricing introduced for a significant period of the plant's operation, thus tripling variable costs, and half of the capacity factor of the lower bound. For the European case, CO_2 pricing prevails in both the upper and the lower bound case, however at very low levels of 24-42 €$_{2020}$/t CO_2, for the latter. Capacity factor is at 40% for the lower case and drops to 15% for the upper case, which is in line with the high and increasing share of renewables generation and a fuel switch towards gas-fired generation induced by significant CO_2 prices. For instance, in Germany, the share of renewable electricity of gross electricity consumption was 52.5% in 2023 (UBA, 2024). With substantial CO_2 pricing and an overall increasing level for fuel prices, variable costs almost fourfold in the upper case.

Table 86: Comparison of LCOE (in €ct$_{2020}$/kWh) for units that came online by 2020 (baseline year 2020) for nuclear power with power from hard coal (reference), wind and photovoltaics

	Nuclear power[1]	Hard coal[2]	Wind onshore[3]			Wind offshore[4]			Photovoltaics[5]		
			5%	w. avg.	9%	5%	w. avg.	95%	5%	w. avg.	95%
Europe	15.0-19.2	11.7-26.9	3.2	4.2	6.0	6.1	7.7	12.1			
North America	15.6-16.3	7.3-15.8	2.6	3.4	5.0						
Global	-	4.9-26.9	2.4	3.6	7.7	6.1	7.8	17.1	4.6	5.3	14.8

Notes: 1.08 USD/EUR was applied as currency conversion factor; 1.06 to inflate USD2017 to USD2020; 0.87 to deflate USD2023 to USD2020. [1] own calculations, see section 4.3.3; [2] For lower bound: (IEA, 2018): New Policies Scenario, value for 2017 for European Union and United States, and China, for upper bound: (IEA, 2024): Announced Pledges Scenario, value for 2023 for European Union and United States; [3] 5% and 95% percentiles and weighted averages for LCOE reported by (IRENA, 2020): bounds and weighted averages for Europe and North America are reported in table 2.3; global weighted averages are reported in figure 2.1., bounds are estimated from figure 2.1; [4] 5% and 95% percentiles and weighted averages for LCOE reported by (IRENA, 2020): bounds and weighted averages for Europe are reported in table 4.3; global weighted averages are reported in figure 4.1., bounds are estimated from figure 4.1; [5] 5% and 95% percentiles and weighted averages for LCOE reported by (IRENA, 2020): global weighted averages are reported in figure 3.1., bounds are estimated from figure 3.1.

Source: (IEA, 2018, 2024), and (IRENA, 2020), as well as own calculations by Öko-Institut

[46] Values for the more conservative Current Policies Scenario where not available in this publication.

Table 86 compares the LCOE for nuclear power with power from hard coal (reference technology), wind onshore, wind offshore, and photovoltaics for units that came online by 2020 (baseline year 2020).

For Europe, LCOE values of nuclear power plants calculated in section 4.3.3.1, range between 15-19 ct2020/kWh. For hard coal-fired generation, costs range between 12-27 ct2020/kWh. 5% percentiles and weighted averages for any of the three renewable generation technologies are significantly lower than the lower bounds of nuclear or hard coal-based generation. Only the 95% percentile of photovoltaics and wind offshore is above the lower bound for hard coal but still below the one for nuclear.

For North America, LCOE values for nuclear power calculated in section 4.3.3.1, range around 16 ct2020/kWh. For hard coal-fired generation, costs range between 7-16 ct2020/kWh. 5% percentiles and weighted averages for any of the three renewable generation technologies[47] are significantly lower than the value for nuclear-based generation. 5% percentiles and weighted averages for wind onshore and photovoltaics are also lower than generation costs for hard coal-based units. The 5% percentile of wind offshore (6.1 ct2020/kWh) is also below the lower bound LCOE of hard coal (7.3 ct2020/kWh). The weighted average of wind offshore (7.8 ct2020/kWh) is slightly above. 95% percentile of photovoltaics is below the lower bound for nuclear-based generation, while the upper bound for wind offshore is slightly above the one for hard coal-based units.

Globally, weighted average LCOE for onshore wind and photovoltaics are below or about as high as the lower bound for hard coal-fired generation which is defined by Chinese units.

To sum up, Table 86 shows that wind-based generation and photovoltaics are providing electricity at lower costs than nuclear or hard coal-based generation in most cases in Europe and North America, and globally. Given average conditions, LCOE of wind-based generation and photovoltaics is also lower than those of hard coal-fired generation with no CO2 pricing, high capacity factor, and domestically available coal, already for units that came online by 2020.

4.3.5.2 Projection for 2030

Wind and photovoltaics have seen strong technological learning and benefited from economies of scale driven by the offtake in installations in China but also other parts of the world which has again many-folded between 2020 and 2025. Correspondingly, LCOE for new installations declined further. On the global scale, weighted average LCOE for onshore and offshore wind declined by about 20%, and by about 30% for photovoltaics. Notably, also 95% percentiles for all three technologies declined by 10%-30%, and 5% percentiles declined by 10%-40% between 2020 and 2030. Current studies assume that all three technologies will experience further technological learning, but learning rates will be much lower than in the past. Hence costs and respective LCOE are expected to decline further, but at a significantly lower rate (Kost et al., 2024). Following a conservate mindset for the comparison with nuclear and hard coal-based generation, no further cost reductions are assumed for the three renewables technologies beyond 2024.

With no technological learning and increasing shares of renewables with reduced the capacity factors for conventional units, LCOE of hard coal-fired generation can be expected to further increase towards 2030. For example, LCOE increase to above 15 ct/kWh in the United States for units commissioned in 2030 even in the Current Policies Scenario with no CO2 pricing (IEA, 2024, table B 4a). However, with low capital costs and high assumed utilization rates, hard coal-

[47] As no values for offshore wind and photovoltaics are available for North America in the IRENA 2020 publication, global values are compared, instead.

fired generation is assumed to have LCOE of around 5.1 ct/kWh in 2030, according to the WEO Announced Pledges Scenario (IEA, 2024). Note that this values potentially underestimates LCOE as capital costs seem not to have been updated for China since WEO 2018. In both publications capital costs are assumed to be 800 USD/MWe; however, there has been substantial inflation between the two publications. Presumably due to prohibitively high CO2 prices and low utilization rates, the WEO does not provide LCOE for newly commissioned hard coal-fired units in 2030. Nevertheless, it is left as the upper bound for 2030, representing a setting with high ambitions on climate change mitigation.

According to section 4.3.3, the prospective LCOE results for nuclear power plants range from 26.1-36.2 ct/kWh and 19.3-43.9 ct/kWh for SMR (for the best-case sensitivity of a NOAK reactor, the range would be 5.7-6.6 ct/kWh).

Table 87 provides a comparison of the LCOE for nuclear power with power from hard coal (reference technology), wind onshore, wind offshore, and photovoltaics in 2030. Lower bounds for LCOE of the two nuclear technologies exceed costs for renewables-based generation at any of the reported projects in 2024 within the 95% percentile by a factor of two or more. Weighted average LCOE for onshore wind and photovoltaics are lower than the lower bound for hard coal-based generation, and lower than the best-case sensitivity of 5.7 ct/kWh for a NOAK SMR. This is also true for offshore wind with favorable wind and financing conditions.

Table 87: Comparison of LCOE (in €$_{2020}$ct/kWh) for nuclear power with power from hard coal (reference), wind and photovoltaics (projection for 2030)

	Nuclear power[1]		Hard coal[2]	Wind onshore[3]			Wind offshore[4]			Photovoltaics[5]		
	Conventional	SMR		5%	w. avg.	95%	5%	w. avg.	95%	5%	w. avg.	95%
Global	26.1-36.2	19.3-43.9	4.7-26.9	2.0	2.8	6.2	3.7	6.0	11.8	2.6	3.5	10.8

Notes: 1.08 USD/EUR was applied as currency conversion factor; 0.92 to deflate USD2023 to USD2020; 0.89 to deflate USD2024 to USD2020. [1] own calculations, see section 4.3.3; [2] For lower bound: (IEA, 2024): Announced Pledges Scenario, value for 2030 for India, for upper bound: (IEA, 2024): Announced Pledges Scenario, value for 2023 for European Union; [3] 5% and 95% percentiles and weighted averages for LCOE reported by (IRENA, 2025); bounds from text on page 81, weighted average from figure 2.8; conservative assumption with no cost reduction assumed between 2024 and 2030; [4] 5% and 95% percentiles and weighted averages for LCOE reported by (IRENA, 2025); bounds from text on page 125, weighted average from figure 4.8; conservative assumption with no cost reduction assumed between 2024 and 2030; [5] 5% and 95% percentiles and weighted averages for LCOE reported by (IRENA, 2025); bounds from text on page 103, weighted average from figure 3.8.; conservative assumption with no cost reduction assumed between 2024 and 2030.
Source: (IEA, 2024), and (IRENA, 2025), as well as own calculations by Öko-Institut

To sum up, Table 87 shows that wind-based generation and photovoltaics will be providing electricity at lower costs than nuclear or hard coal-based generation in most cases globally. Given average conditions, LCOE of wind-based generation and photovoltaics will continue to be lower than those of hard coal-fired generation with no CO2 pricing, high capacity factor, and domestically available coal.

4.4 Greenhouse gas abatement costs

This section analyses greenhouse gas abatement costs for units that came online around 2020 and for units that will be commissioned in 2030. In order to calculate greenhouse gas abatement costs for different technologies, the cost (LCOE) difference of abatement technologies x

(renewables, nuclear) to the reference technology REF (hard coal) is compared to the specific life cycle GHG emission difference between the reference technology e(REF) and the abatement technologies e(x) (Equation 4).

Equation 4: Calculation of GHG abatement costs

$$GHG\ abatement\ cost\ (x) = \frac{LCOE(x) - LCOE(REF)}{e(REF) - e(x)}$$

Source: Own representation, Öko-Institut

Life-cycle emissions of nuclear power generation are calculated in section 3.12.10. Similar to the structure of emissions for nuclear, life cycle emissions for wind-based generation and photovoltaics are predominately due to emissions related to manufacturing and construction, with no emissions associated with operation itself. Hence, life-cycle emissions are highly sensitive to attainable full load hours on the one hand, and energy inputs for production processed for steel and concrete for wind and electricity consumption for solar grade silicon refining and module efficiency and solar irradiation for photovoltaics, see (UNECE, 2021). Emission intensities of concrete and steel production and in particular for electricity generation have already declined due to efficiency improvements, climate policy regulations, and renewables deployment in many regions of the world. For a consistent comparison of life-cycle emissions it is therefore important to relate emissions to the same year of commissioning (as for LCOE). For photovoltaics, life-cycle emissions are sensitive to technology choice. As shown in Table 88, using thin film technologies instead of polycrystalline silicon reduces life-cycle emissions from 37 g CO2e/kWh to 11 g CO2e/kWh in the European context[48]. For the former, electricity consumption for solar-grade silicon refining makes up about 40% of the climate change impact (UNECE, 2021). Polysilicon consumption currently varies between 1.7 g/W and 1.9 g/W, depending on the size of the wafer, with this projected to drop below 1.4 g/W by 2030 (IRENA, 2025). For wind, improvements of rotor blade design and increasing rotor size and height have increased efficiency and hence reduced specific environment impact of per unit of electricity generated. The effect is estimated to be about 14% reduction per doubling of global capacity (UNECE, 2021).

By contrast, life-cycle emissions of hard coal-based generation is dominated by emissions from fuel combustion and upstream emissions from coal production where associated coal-bed methane emissions significantly contribute to total life-cycle emissions. The emission factor for coal-based generation depends on the plant efficiency and the energy content and quality of the coal, which in turn is related to the efficiency. For instance, Colombian coal is of high quality and has a high energy content, so does coal from the Appalachian region in the USA. Thermal coal[49] from South Africa and India have predominantly low energy content. Only high-quality coal is suitable for modern technology (supercritical and ultrasupercritical) hard coal-fired generation that can achieve high efficiency rates (Oei & Mendelevitch, 2019). Ultra-supercritical power plants can achieve an electrical efficiency of 45% under ideal operating conditions. Outside of ideal operating conditions, efficiency decreases. In order to achieve ideal conditions, the cooling water must also be sufficiently cold to create the necessary temperature differential. In hot regions such as Southeast Asia in particular, efficiency is also limited by this factor and will not reach 45%. For a conservative estimate of the abatement costs, an efficiency of 45% and a corresponding coal quality are assumed, for both 2020 and 2030. In addition, the upstream CO2

[48] Regionalization related to energy and electricity mix for inputs and attainable capacity factors based on existing installations UNECE United Nations Economic Commission for Europe (UNECE) (2021).

[49] For heat and electricity generation, in contrast to metallurgic coal for iron and steelmaking.

and methane emissions associated with coal mining, which would have to be taken into account for a life cycle assessment, are not included in the reference emission factor that forms the basis for calculating GHG abatement costs. This, in turn, adds to the conservativeness of the reference emission factor.

Table 88: Comparison of life cycle GHG emissions e (in g CO_2e/kWh) for nuclear power with power from hard coal (reference), wind, and photovoltaics (baseline year 2020)

Technology	Direct emissions	Upstream emissions incl. external energy inputs	totals	Source
Nuclear power Europe		5.1	5.1	Section 0
Nuclear power North America		12.4	12.4	Section B.28
Hard coal	340/0.45 =**755.7**	42.5/0.45 =94.3	850.0	(Lauf et al., 2025)
Wind onshore Germany	-	17.8	17.8	(Lauf et al., 2025)
Wind onshore Europe	-	-	12.4	(UNECE, 2021)
Wind onshore global Min/Median/Max	-	-	7.0/**11**/56	(Schlömer et al., 2014)
Wind offshore Germany	-	9.7	9.7	(Lauf et al., 2025)
Wind offshore Europe	-	14.2	14.2	(UNECE, 2021)
Wind offshore global Min/Median/Max	-	-	8.0/**12**/35	(Schlömer et al., 2014)
Photovoltaics Germany	-	56.1	56.1	(Lauf et al., 2025)
Photovoltaics Europe tech mix	-	37.0	37.0	(UNECE, 2021)
Photovoltaics Global average	-	52.0	52.0	(UNECE, 2021)
Photovoltaics Europe Poli-Si ground mount	-	36.7	36.7	(UNECE, 2021)
Photovoltaics Europe thin film ground mount	-	11.4	11.4	(UNECE, 2021)

Technology	Direct emissions	Upstream emissions incl. external energy inputs	totals	Source
Photovoltaics global utility scale Min/Median/Max	-	-	18/**48**/180	(Schlömer et al., 2014)

Note: The values marked in bold font are the ones that are taken for the analysis of GHG abatement costs.
Source: (Lauf et al., 2025), (UNECE, 2021), (Schlömer et al., 2014), assumptions and calculations, Öko-Institut

Table 88 compiles life-cycle emission factors for the different technologies from different sources. Note that the values in bold font are selected as a basis for the calculations of GHG abatement costs in the next sections. For the three renewables technologies, emission factors are available from three different sources. While (Lauf et al., 2025) calculates emissions for the German context (attainable capacity factors and technology mix) for the year 2023, (UNECE, 2021) reports life-cycle GHG emissions for the European context. Although, (Schlömer et al., 2014) is an older source, global median emission factors are well in the same range as the factors reported by the two more recent sources. With the global focus of this study, the median values from (Schlömer et al., 2014) are used for further calculations.

Based on Equation 4, GHG abatement costs are calculated for the baseline year 2020 (section 4.4.1) and for the projection year 2030 (section 4.4.2).

4.4.1 Baseline year 2020

Table 89 and Figure 137 compare GHG abatement costs for units that come online around 2020 for nuclear power, wind (onshore, offshore) and photovoltaics, with the reference technology being power generation from hard coal. For the three renewable technologies, GHG abatement costs are calculated based on 5th, and 95th percentile as well as weighted average costs. The relative difference between the weighted average costs and the two fringe values indicates where the majority of weight, i.e. the majority of installed capacities in situated. For nuclear, GHG abatement costs are calculated based on LCOE ranges calculated in section 4.3.3.

The GHG abatement costs for nuclear power from units that came online around 2020 range between 102 €$_{2020}$/t CO_2eq and 158 €$_{2020}$/t CO_2eq for Europe as well as 111 €$_{2020}$/t CO_2eq and 121 €$_{2020}$/t CO_2eq for North America. For all three renewable technologies abatement costs are negative based on the 5th percentile and weighted average LCOE. This is due to their LCOE being lower than those of the reference technology hard coal. For wind onshore this is true even for the 95th percentile LCOE. For photovoltaics and offshore wind, the various and LCOE and therefore also in GHG abatements cost is much higher than for onshore wind. For unfavorable locations, and/or financing conditions, 95th percentile LCOE-based GHG abatement costs for photovoltaics and offshore wind units that came online in 2020 are in the same range as costs for nuclear-based generation.

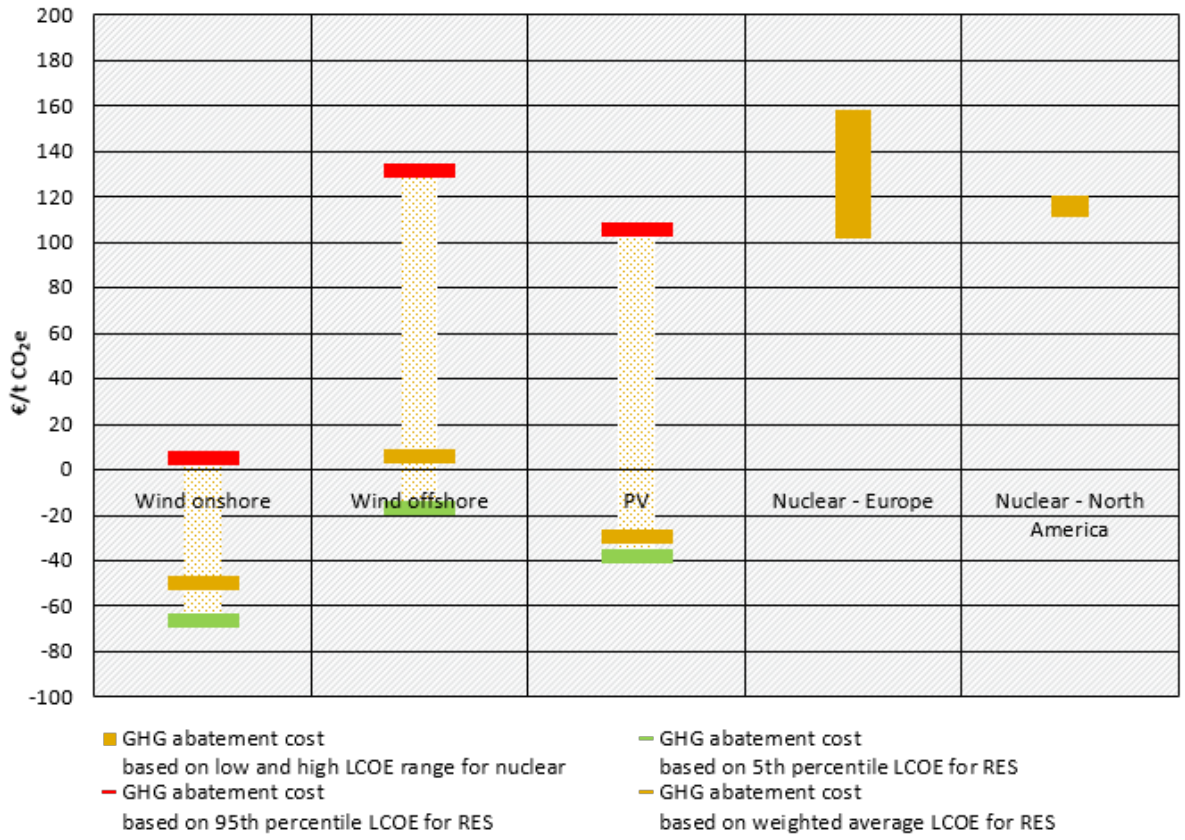
Table 89: Comparison of LCOE, life cycle GHG emissions, and GHG abatement costs for hard coal power (reference) with nuclear power, wind, and photovoltaics (base year 2020)

Item	Nuclear power		Hard coal	Wind onshore[3]			Wind offshore[3]			Photovoltaics[3]		
	Europe	North America		5th	Weighted average	95th	5th	Weighted average	95th	5th	Weighted average	95th
LCOE [€ct$_{2020}$/kWhe]	15.0-19.2[1]	15.6-16.3[1]	7.3[2]	2.4	3.6	7.7	6.1	7.8	17.1	4.6	5.3	14.8
Life cycle GHG emissions [g CO_2eq/kWhe]	5.1[4]	12.4[4]	755.7[5]	11[6]			12[6]			48[6]		
Abatement costs [EUR$_{2020}$/tCO_2eq]	102 to 158	111 to 121	-	-66	-50	5	-16	6	131	-38	-29	106

Notes: [1] as calculated in section 4.3.3; [2] LCOE for United States as reported in (IEA, 2024), assuming no CO_2 pricing, high capacity factor, and domestically available coal (see section 4.3.5 for more details);[3] 5th percentile, weighted average, and 95th percentile for global values as reported in Table 86; [4] as calculated in section 0 and B.28; [5] excluding upstream emissions and assuming 45% electrical efficiency; [6] global median values as reported in (Schlömer et al., 2014).
Source: own compilation of data, Öko-Institut

It can be concluded that renewable electricity, in favorable conditions (5% percentile and weighted average), constitutes a cost-effective GHG abatement option already in the baseline year 2020. The fact that assumptions for hard coal (potential underestimation of costs and assumed high efficiency) and renewables (potential overestimation of costs) are conservative as discussed above, may lead to GHG abatement costs from renewables becoming more negative, i.e., the bars for renewables in Figure 137 moving further down. Nuclear power constitutes an expensive abatement option both at the lower and at the higher end.

Figure 137: Comparison of GHG abatement costs (in €2020/t CO_2e) for nuclear power, wind, and photovoltaics (baseline year 2020, cost basis 2020)



Source: Calculations Öko-Institut

4.4.2 Projection for 2030

Table 90 and Figure 138 show a comparison of GHG abatement costs for nuclear power, wind (onshore, offshore) and photovoltaics for units that could come online by 2030. For the three renewable technologies, GHG abatement costs are calculated based on 5th, and 95th percentile as well as weighted average costs. The relative difference between the weighted average costs and the two fringe values indicates where the majority of weight, i.e. the majority of installed capacities in situated. For nuclear, GHG abatement costs are calculated based on LCOE ranges calculated in section 4.3.3.

The GHG abatement costs for nuclear power range between 285 $€_{2020}$/t CO_2e and 420 $€_{2020}$/t CO_2e for Generation 3 nuclear power plants in Europe as well as 196 $€_{2020}$/t CO_2e and 527 $€_{2020}$/t CO_2e for SMR in North America (for the best-case sensitivity of a NOAK NuScale

SMR, the range would be 10 to 25 €$_{2020}$/t CO_2e[50]). The high abatement costs are primarily the result of significant cost differences, given that nuclear power is generally considered to be much more expensive than coal. GHG abatement costs based on 5th to 95th percentile LCOE for all three renewable technologies are in a very similar range to costs for the 2020 case. Here, two effects are countervailing: on the one hand, the reference hard coal-fired generation is assumed to have very low construction costs (LCOE data for coal-fired power generation in India in 2030 from WEO 2024 (IEA, 2024)), hence reference plant LCOE for hard coal are lower compared to 2020. Leaving all other parameters equal this would increase abatement costs for all other technologies, relative to 2020. On the other hand, LCOE of all three renewables technologies have declined significantly, already between 2020 and 2024 (with the 2024 values taken as the values for further calculations for 2030). The two effects more or less equal each other out. As a result, photovoltaics and onshore wind have negative GHG abatement costs based on 5th percentile and weighted average LCOE, again. The difference between the two has further decreased, indicating that even more realized projects capacities have LCOE which are close to the 5th percentile. While abatement costs for offshore wind are negative for the 5th percentile LCOE and slightly positive the based on weighted average LCOE. In contrast to units that came online by 2020, for units that could come online by 2030, there is a gap of 100-450 EUR2020/tCO2e between GHG abatement costs of nuclear-based power generation and any of the three renewables-based technologies, even based on the 95th percentile LCOE.

The fact that assumptions for hard coal (potential underestimation of costs) and renewables (potential overestimation of costs) are conservative as discussed above, may lead to GHG abatement costs from renewables becoming more negative, i.e., the bars for renewables in Figure 138 moving further down.

Nuclear power does not constitute a cost-effective abatement option with GHG abatement costs, amounting to between 196 and 527 €/t CO_2e, the range being dominated by costs for a first-of-a-kind NuScale SMR and the maximum cost assumptions for the Carem SMR. Even for the best-case sensitivity of a NOAK NuScale SMR, GHG abatement cost are still positive, compared to negative costs for most cases of renewables-based generation. As already noted in section 4.3.1.2, the cost figures for NOAK SMR are extremely optimistic and will not be feasible for the year 2030 (at least). Therefore, the best-case sensitivity is not included in the following table.

[50] Assumptions on achievable reduction of investment costs by a factor of six and decreasing construction time from ten to three years for the NOAK NuScale are extremely optimistic and will not be feasible for the year 2030 (at least), as not even a first-of-a-kind reactor is currently under construction (also see section4.3.3.2).

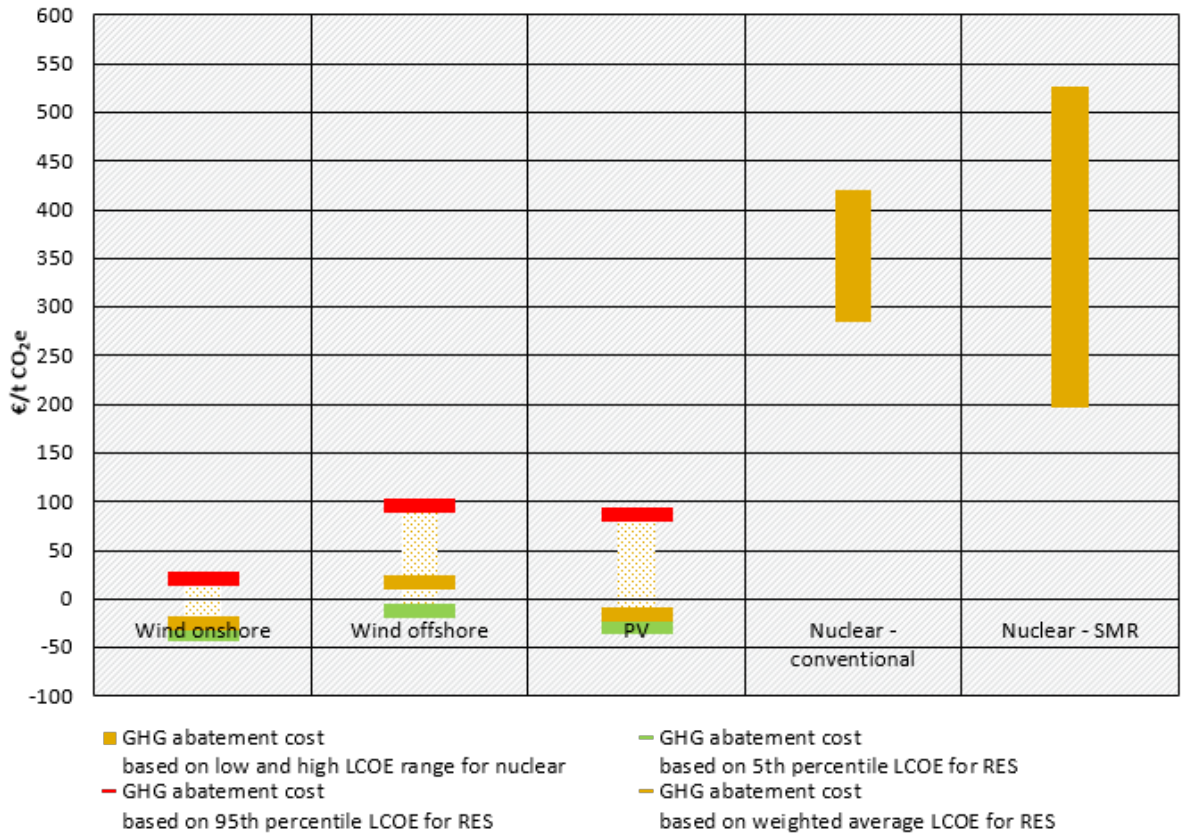
Table 90: Comparison of LCOE, life cycle GHG emissions, and GHG abatement costs for hard coal power (reference) with nuclear power, wind, and photovoltaics (projection for 2030)

Item	Nuclear power		Hard coal	Wind onshore[3]			Wind offshore[3]			Photovoltaics[3]		
	Europe	North America		5th	Weighted average	95th	5th	Weighted average	95th	5th	Weighted average	95th
LCOE [€ct$_{2020}$/kWhe]	26.1-36.2[1]	19.3-43.9[1]	4.7[2]	2.0	2.8	6.2	3.7	6.0	11.8	2.6	3.5	10.8
Life cycle GHG emissions [g CO_2eq/kWhe]	4.8[4]	11.9[4]	755.7[5]		11[6]			12[6]			48[6]	
Abatement costs [EUR$_{2020}$/tCO_2eq]	285 to 420	196 to 527	-	-37	-26	20	-16	6	131	-38	-29	106

Notes: [1] as calculated in section4.3.3; [2] LCOE for India in (IEA, 2024), assuming no CO_2 pricing, high capacity factor, domestically available coal, and low capital costs (see section 4.3.5 for more details), this assumption might not be consistent with high electrical efficiency assumptions underlying the life-cycle emissions which can only be attained using high-quality coal which needs to be imported in India;[3] 5% and weighted average for global values as reported in Table 87; [4] as calculated in sectionB.4 and B.29; [5] excluding upstream emissions and assuming 45% electrical efficiency; [6] global median values as reported in (Schlömer et al., 2014), assuming no reduction in life-cycle emissions for wind and photovoltaics is a very conservative assumption. As noted above, silicon demand for photovoltaics is expected to decrease by more than 20% by 2030 (IRENA, 2025). Moreover, emissions associated with electricity generation which is the major input for silicon-refining will decline due to the global ramp-up of renewables-based generation. For wind-based generation, production of steel and concrete will also become less emissions-intensive, just as assumed for nuclear power, see section 3.2.3.

Source: own compilation of data, Öko-Institut

Figure 138: Comparison of GHG abatement costs (in €/t CO_2e) for nuclear power, wind, and photovoltaics (projection for 2030, cost basis 2020)



Source: Calculations Öko-Institut

4.5 Discussion of results and conclusions

The results of the LCC analysis show that the LCOE from newly-built nuclear power plants range from 15.0-19.2 ct/kWh in 2020, depending on the geographical region where the construction project was carried out. This makes nuclear energy significantly more expensive compared to renewable energy sources such as photovoltaics and wind energy, which have mostly significantly lower LCOE values. Especially, LCOE ranges of wind onshore (2.4-7.7 ct/kWh) as well as photovoltaics (4.6-14.8 ct/kWh) are (partly considerably) below the corresponding figures for nuclear power, which is also applicable for the lower end of the range for wind offshore (6.1 ct/kWh). Only at its upper end (17.1 ct/kWh), the cost for wind offshore is higher than LCOE of nuclear power at its lower end. However, offshore wind power is more expensive than nuclear power only in unfavourable cases; on average, it is significantly cheaper. Hence renewable electricity generation, especially in favourable conditions, constituted a cost-effective GHG abatement option already in the baseline year 2020.

In the following, the results will be discussed in the context of other studies on the topic (see section 4.5.1). Moreover, a contribution analysis will be carried out in section 4.5.2 to identify the main cost drivers for nuclear power. Finally, section 4.5.3 will contextualize the LCOE outlook for 2030 with existing literature, focusing also on the potential role of SMRs in this context.

4.5.1 Comparison with other current studies

According to a recent study by Fraunhofer ISE, the LCOE of newly constructed nuclear power plants range from 13.6 to 49.0 ct/kWh (Kost et al., 2024). The analysis takes into account representative cost parameters for new power plant construction in the European economic context and in the context of energy policy planning for the German energy system. Costs for final storage have not been taken into account. A comparison of the results presented in section 4.3.3 with the results of (Kost et al., 2024) shows good concordance in the lower end of the range. Their wide range of costs and the significant higher figures at the upper end are primarily due to the different intervals used for the load factor. According to Kost et al. (2024) in an energy system with a high share of renewable energies, the LCOE of nuclear power plants would prospectively be significantly higher than that of natural gas or hydrogen power plants.

In its latest study (version 17.0), (Lazard, 2024) reports a LCOE range of $137-$222/MWh for new nuclear power plants in the United States. This corresponds to a range of approximately 11.2-18.1 €ct/kWh. The results given for 2020 in section 4.3.3 for North America (15.6-16.3 ct/kWh) correspond well with the current Lazard figures.

(Bowyer, 2024) analyse the costs of newly built nuclear power plants in the Australian context. For European EPR projects (like Olkiluoto 3 or Flamanville 3), an LCOE between AUD 250/MWh and AUD 346/MWh would be expected if they were built in Australia. Converted to Euro (with an exchange rate of approx. 1 € for 1.60 AUD), this results in around 156-216 €/MWh (15.6-21.6 €ct/kWh). For the most part, the result range presented in section 4.3.3 is within or slightly below these Australian-contextualized values for specific European projects.

4.5.2 Major cost drivers for nuclear power

4.5.2.1 Capital costs

The results in section 4.3.3 show that the capital costs account for the main component of LCOE of newly built nuclear power plants. Their share ranges from 80% to 85%, depending on the considered geographic region, making them the most important cost driver for the relatively high life cycle costs of nuclear power. This assessment is consistently confirmed by other sources in the literature (e.g., (Bowyer, 2024); (Deutscher Bundestag, 2022); (IEA & NEA, 2020; Walstra, 2024). High initial investments combined with long construction times (typically 10-18 years for recently completed construction projects), along with corresponding cost increases as well as the assumed discount rates, have a particularly high impact on the costs of newly built nuclear power plants. These risks underscore the need for government support in the form of guarantees or sureties, which effectively transfer the individual risks faced by plant operators to the public sector.

Concerning construction time, (Walstra, 2024) identified an average value of 14.3 years for current projects. In contrast, mean commissioning times of renewable power projects in OECD countries amount to only a fraction of this time span and vary between 2.3 years (photovoltaics), 2.7 years (wind onshore) and 5.4 years (wind offshore).

An important driver for cost increases during construction are quality assurance/quality control requirements and the advancing insights and regulations in that area. According to (Potter, 2023), it is estimated that quality control requirements make up 23% of the cost of concrete, and 41% of the cost for structural steel of nuclear power plants.

Moreover, an OECD NEA study that examined nuclear plant cost estimates from 2010 to 2020 found that increases in indirect cost are another main driver of nuclear plant cost overruns, with labour cost making up 80% of indirect cost (NEA, 2020).

Finally, the discount rate is a particularly sensitive parameter for the overall cost results. As shown in section 4.3.4, the discount rate has a significant influence on the discounting of future costs and thus on the level of the resulting LCOE and the relative competitiveness of newly built nuclear power plants. In existing literature on LCOE studies, the discount rates vary between 3% and 10%, with some studies presenting results for 3%, 7% and 10% ((IEA & NEA, 2020); (Kost et al., 2024)). In this context, the 7% rate used in the present study can be considered as a mid-range value, representing a conservative approach for a financially comparatively risky investment such as the construction of a nuclear power plant. In this context, it is worth mentioning that Kost et al. (2024) use an discount rate of 7.8% for nuclear power plants. (Lazard, 2024) also uses a higher WACC in its current LCOE analysis, consisting of 60% debt (at an interest rate of 8%) and 40% equity (at an interest rate of 12%).

In view of the high initial investment costs as well as cost increases during the long construction times, governments regularly intervene in the process of financing of nuclear power plants, either through direct financing, providing loans and guarantees, or via risk-sharing and interference with price measures. The share of governmental financing the construction of nuclear power plants finally results in costs to be paid by the taxpayer (Walstra, 2024).

4.5.2.2 Operational costs

The operating, maintenance and fuel costs are important components of the LCOE of newly built nuclear power plants, albeit significantly less important than the capital costs (Bowyer, 2024). In the examples examined, their combined share is typically between around 15% and 20% of the total LCOE, although the exact values depend heavily on the specific project and the economic conditions.

4.5.2.3 Post-operation, decommissioning and disposal

Costs for post-operation, decommissioning and disposal can reach considerable absolute sums and represent important factors to the total costs of nuclear energy (M. Schneider & Froggatt, 2024). The end-of-life costs calculated in this study range from 1.2 to 2.1 ct/kWh (figures before discounting, see section 4.3.2). In principle, they are accounted for in the operational stage of nuclear power plants in the form of a reservation of funds for these future costs and therefore need to be included in the assessment of the LCOE. According to (Walstra, 2024) there is clear evidence of too low reserves for past and running nuclear plants.

Nevertheless, their direct share of the LCOE turns out to be relatively low due to the dominating capital costs as well as the long lifetime of the plants and the discounting of future costs. High discount rates virtually eliminate the end-of-life costs, which is ultimately a result of life cycle costing methodology. Within this context, however, it has to be stressed that there are significant uncertainties in estimating the costs for post-operation, decommissioning and disposal, and the actual expenses can vary greatly depending on the reactor type, location and regulatory framework.

4.5.3 Future outlook

As the LCOE results for 2030 show, cost reduction potentials are not foreseeable for the future projection (see section 4.3.3.2). On the contrary, the expected cost ranges for conventional nuclear power plants are even significantly higher than the 2020 figures.

These findings are consistent with several other studies which stress that nuclear power becomes more expensive over time and suggest a negative learning curve for nuclear technology, i.e. experience leads to an escalation in capital costs rather than a reduction. The phenomenon of a negative learning curve can be explained by increasing technical complexity,

combined with increasing safety and containment requirements ((Portugal-Pereira, J., et al., 2016); (Walstra, 2024)).

In this context, SMR were brought into play with the claim to significantly reduce the high capital costs of conventional nuclear power plants. However, while theoretical models and vendor estimates suggest that SMR could achieve future LCOE of around 6-9 ct/kWh, these projections have yet to be confirmed by practical deployment, and early SMR projects are expected to face significant financial and technical challenges similar to those encountered by large-scale reactors. The hypothesis is impressively backed up by the LCOE results of this study for real-world SMR construction projects such as NuScale and CAREM, which are expected to have a cost range of 19.3-43.9 €ct/kWh (see section 4.3.3.2).

LCOE calculations for different SMR reactor types by (Steigerwald et al., 2023) show similar results. For example, SMR with high-temperature reactor have a cost range of 9.9-15.8 $ct/kWh (i.e., 9.2-14.6 €ct/kWh), and SMR with boiling water reactor or pressurized water reactor exhibit an even higher cost range of 19.8-99.1 $ct/kWh (i.e., 18.3-91.8 €ct/kWh). They conclude that none of the analysed SMR reactor concepts is able to compete economically with existing renewable technologies, not even when taking into account their variability and necessary system integration costs (Steigerwald et al., 2023).

In fact, due to further cost (and thus LCOE) decreases, renewable electricity constitutes a cost-effective power generation and GHG abatement option in comparison to nuclear power and hard coal for most options in 2030 (see section 4.4.2). Within this context, it must be noted that the estimated LCOE for hard coal is a conservative value. Especially rising CO_2 prices due climate regimes (emissions trading, etc.), may make the break-even point between hard coal and renewable electricity generation be reached even earlier.

Hence the bottom line is that any new nuclear power plant will be brought online too late to achieve significant and cost-effective greenhouse gas savings that could contribute to the climate targets for 2050 or earlier (Walstra, 2024)

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A Definitions

The following definitions are taken from (IAEA, 2025, Glossary)

- Capacity Factor (CF): see Load Factor (LF).
- Design Net Capacity: The original Design Net Capacity (electrical power) is the unit electrical output after deducting the self-consumption power assumed by the original unit design, no matter if it has ever been routinely achieved during operation. This value does not reflect possible power changes during subsequent operation.
- Energy Availability Factor (EAF): The energy availability factor over a specified period, is the ratio of the energy that the available capacity could have produced during this period, to the energy that the reference unit power could have produced during the same period. The energy availability factor is determined for each period as shown below:
  EAF (%) = (REG - PEL - UEL - XEL) / REG x 100
  Where:
  - REG = reference energy generation for the period
  - PEL = total planned energy losses
  - UEL = total unplanned energy loss
  - XEL = total external energy losses (beyond the plant management control)
- Gross Capacity: Reference gross electrical power of the plant expressed in MW(e). The maximum (electrical) power that could be maintained continuously throughout a prolonged period of operation under reference ambient conditions. The gross electrical power is measured at the output terminals of the turbine generator.
- Load Factor (LF), also called Capacity Factor, for a given period, is the ratio of the energy which the power reactor unit has produced over that period divided by the energy it would have produced at its reference power capacity over that period.
  Reference energy generation (net) is the energy that could be produced during a given time period if the unit were operated continuously at reference unit power.
  The unit load factor is calculated for each period as shown below:
  LF (%) = EG / REG x 100%
  Where:
  - EG = net energy generation (MW.h) for the period
  - REG = reference energy generation (net) (MW.h) for the period.
  This indicator reflects the actual energy utilization of the unit for electricity production.
- Reference Energy Generation (REG): Reference energy generation (MWh or GWh) for the period is the net electricity output that would be produced if a reactor unit is operated at its rated power output for the entire period.
- Reference Unit Power (RUP): The reference unit power expressed in units of megawatt (electrical) is the maximum (electrical) power that could be maintained continuously throughout a prolonged period of operation under reference ambient conditions. The power value is measured at the unit outlet terminals, i.e. after deducting the power taken by unit auxiliaries and the losses in the transformers that are considered integral parts of the unit. The reference unit power is expected to remain constant unless following design changes, or a new permanent authorization, the management decides to amend the original value.

- Thermal Capacity: The Reference thermal power of the plant expressed in MW(th). The reactor thermal power is the net heat transferred from the fuel to the coolant.

- Unit Capability Factor (UCF): Unit capability factor is defined as the ratio of the available energy generation over a given time period to the reference energy generation over the same time period, expressed as a percentage. Both of these energy generation terms are determined relative to reference ambient conditions.
  Available energy generation is the energy that could have been produced under reference ambient conditions considering only limitations within control of plant management, i.e., plant equipment and personnel performance, and work control.
  Reference energy generation is the energy that could be produced if the unit were operated continuously at full power under reference ambient conditions.
  Reference ambient conditions are environmental conditions representative of the annual mean (or typical) ambient conditions for the unit.
  The unit capability factor is determined for each period as shown below:
  value for a unit: UCF (%) = (REG - PEL - UEL)/REG x 100%
  Where:
  - REG = reference energy generation for the period
  - PEL = total planned energy losses for the period
  - UEL = total unplanned energy losses for the period
  The purpose of this indicator is to monitor progress in attaining high unit and industry energy production reliability. This indicator reflects effectiveness of plant programs and practices in maximizing available electrical generation, and provides an overall indication of how well plants are operated and maintained.

- Unplanned Capability Loss Factor (UCL): The ratio of the unplanned energy losses during a given period of time, to the reference energy generation, expressed as a percentage.
  Unplanned energy loss is energy that was not produced during the period because of unplanned shutdowns, outage extensions, or unplanned load reductions due to causes under plant management control. Energy loss is considered to be unplanned if it is not scheduled at least four weeks in advance.
  Reference energy generation is the energy that could be produced if the unit were operated continuously at full power under reference ambient conditions throughout the period.
  The unplanned capability loss factor is determined for each period as shown below:
  UCL(%) = UEL / REG x 100%
  Where:
  - UEL = total unplanned energy losses for the period
  - REG = reference energy generation for the period

B Life Cycle Chains: Inputs, Results, Breakdown of impacts by life cycle stage

B.1 EU1

Table 91: EU1 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.13
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	3.75
Enrichment_Centrifuge	Country	France
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	11.5
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	France
NPP_Construction	plant life (y)	40
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	EU(low)
Electricity_Production_Nuclear	Load Factor	0.77
Electricity_Production_Nuclear	Net Efficiency (%)	0.33
Electricity_Production_Nuclear	Country	EU(low)
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	France
Backend	Country	EU(low)

Source: Öko-Institut

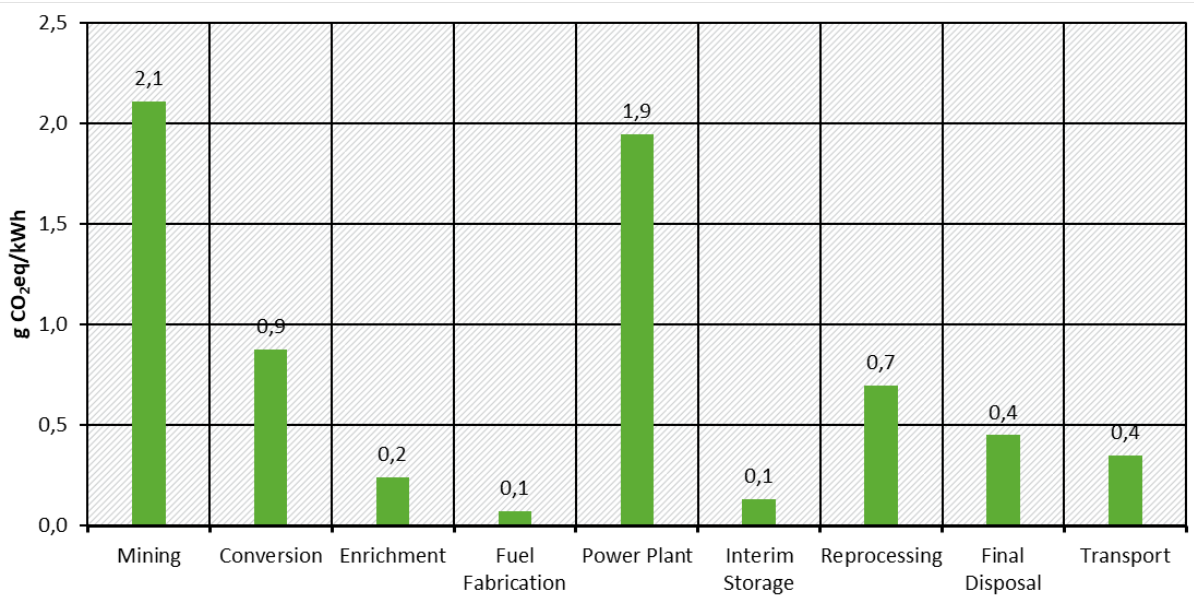
Table 92: EU1 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	6.9
CED - Total	MJ/kWh	1.6E+01
CED - fossil	MJ/kWh	1.2E-01
ADP	kg Sbeq/kWh	2.3E-06
Land use	dimensionless (pt)/kWh	3.7E-02
Water use	m^3/kWh	1.9E-02
Ionising radiation	kBq U235 eq/kWh	1.3E+00

Parameter	Unit	Result
Human toxicity, cancer	CTUh/kWh	2.8E-03
Human toxicity, noncancer	CTUh/kWh	1.5E-01
radioactive waste, high level	m³/kWh	1.2E-08
radioactive waste, low level	m³/kWh	9.3E-08
tailing, from uranium milling	m³/kWh	6.2E-06

Source: Öko-Institut

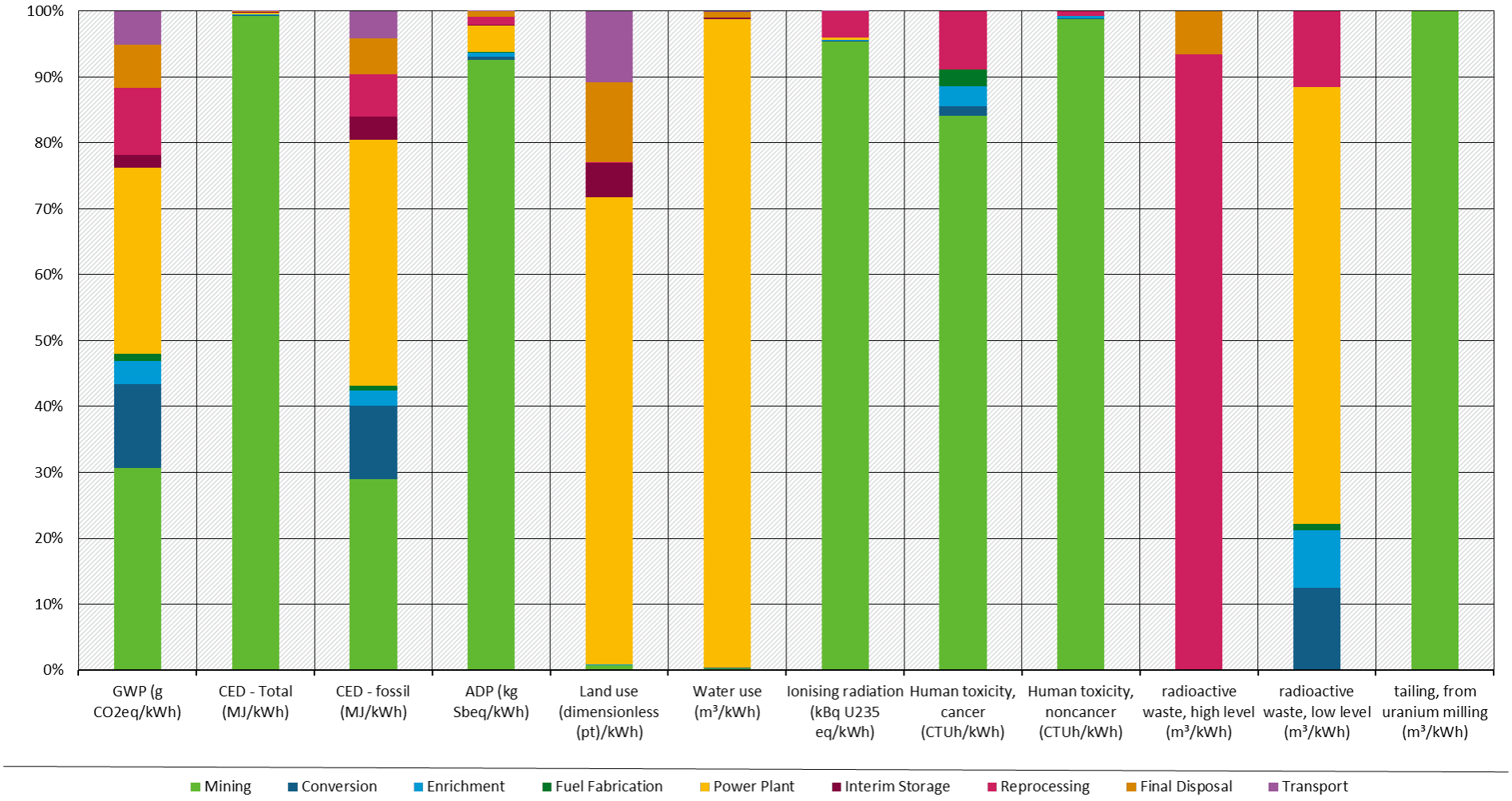
Figure 139: EU1 breakdown of GWP



Total GWP of EU1: 6.9 g CO2eq/kWh

Source: Öko-Institut

Figure 140: EU 1 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.2 EU1_2030

Table 93: EU1_2030 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.13
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	3.75
Enrichment_Centrifuge	Country	France
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	11.5
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	France
NPP_Construction	plant life (y)	40
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	EU(low)
Electricity_Production_Nuclear	Load Factor	0
Electricity_Production_Nuclear	Net Efficiency (%)	0.33
Electricity_Production_Nuclear	Country	EU(low)
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	France
Backend	Country	EU(low)

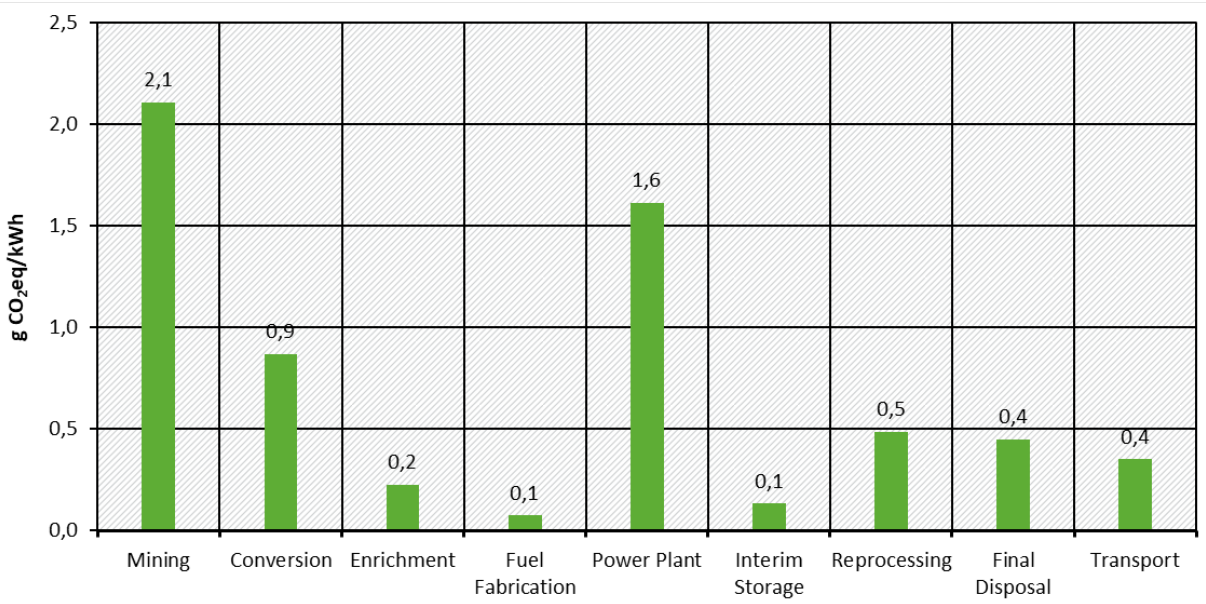
Source: Öko-Institut

Table 94: EU1_2030 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	6.3

Source: Öko-Institut

Figure 141: EU1_2030 breakdown of GWP



Total GWP of EU1_2030: 6,3 g CO2eq/kWh
Source: Öko-Institut

B.3 EU1_Gen3

Table 95: EU1_Gen3 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.13
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	France
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	10.2
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	France
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR (Gen3)
NPP_Construction	Country	EU(low)
Electricity_Production_Nuclear	Load Factor	0.77
Electricity_Production_Nuclear	Net Efficiency (%)	0.38
Electricity_Production_Nuclear	Country	EU(low)

Process Step	Parameter	Value
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	France
Backend	Country	EU(low)

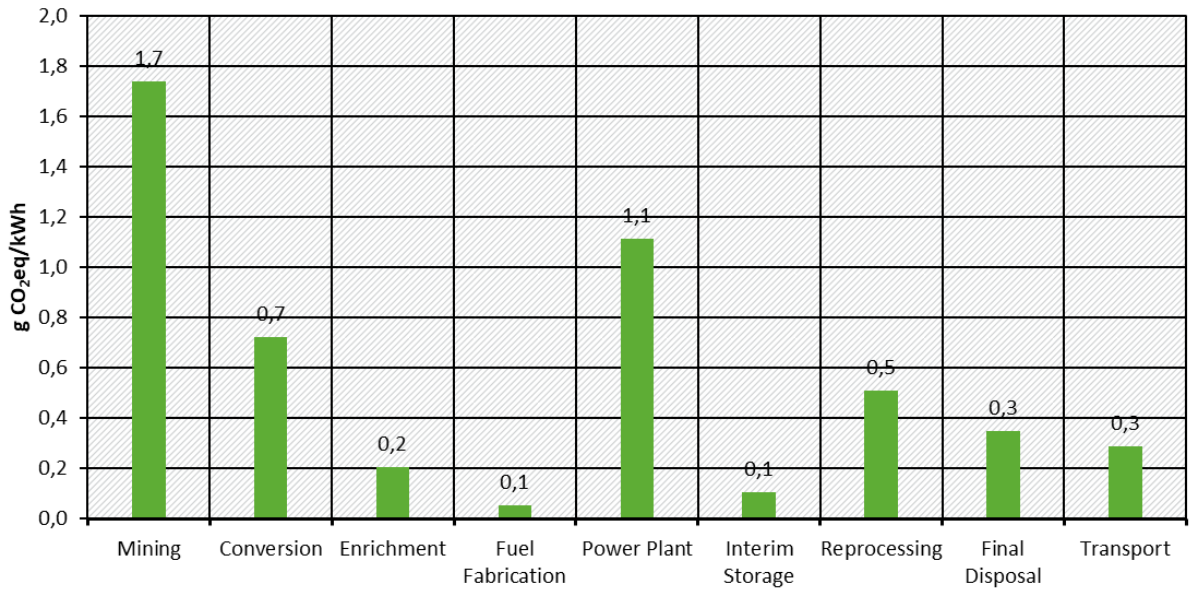
Source: Öko-Institut

Table 96: EU1_Gen3 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	5.1
CED - Total	MJ/kWh	1.3E+01
CED - fossil	MJ/kWh	8.6E-02
ADP	kg Sbeq/kWh	1.8E-06
Land use	dimensionless (pt)/kWh	2.2E-02
Water use	m³/kWh	1.9E-02
Ionising radiation	kBq U235 eq/kWh	1.1E+00
Human toxicity, cancer	CTUh/kWh	2.3E-03
Human toxicity, noncancer	CTUh/kWh	1.2E-01
radioactive waste, high level	m³/kWh	8.5E-09
radioactive waste, low level	m³/kWh	8.0E-08
tailing, from uranium milling	m³/kWh	5.1E-06

Source: Öko-Institut

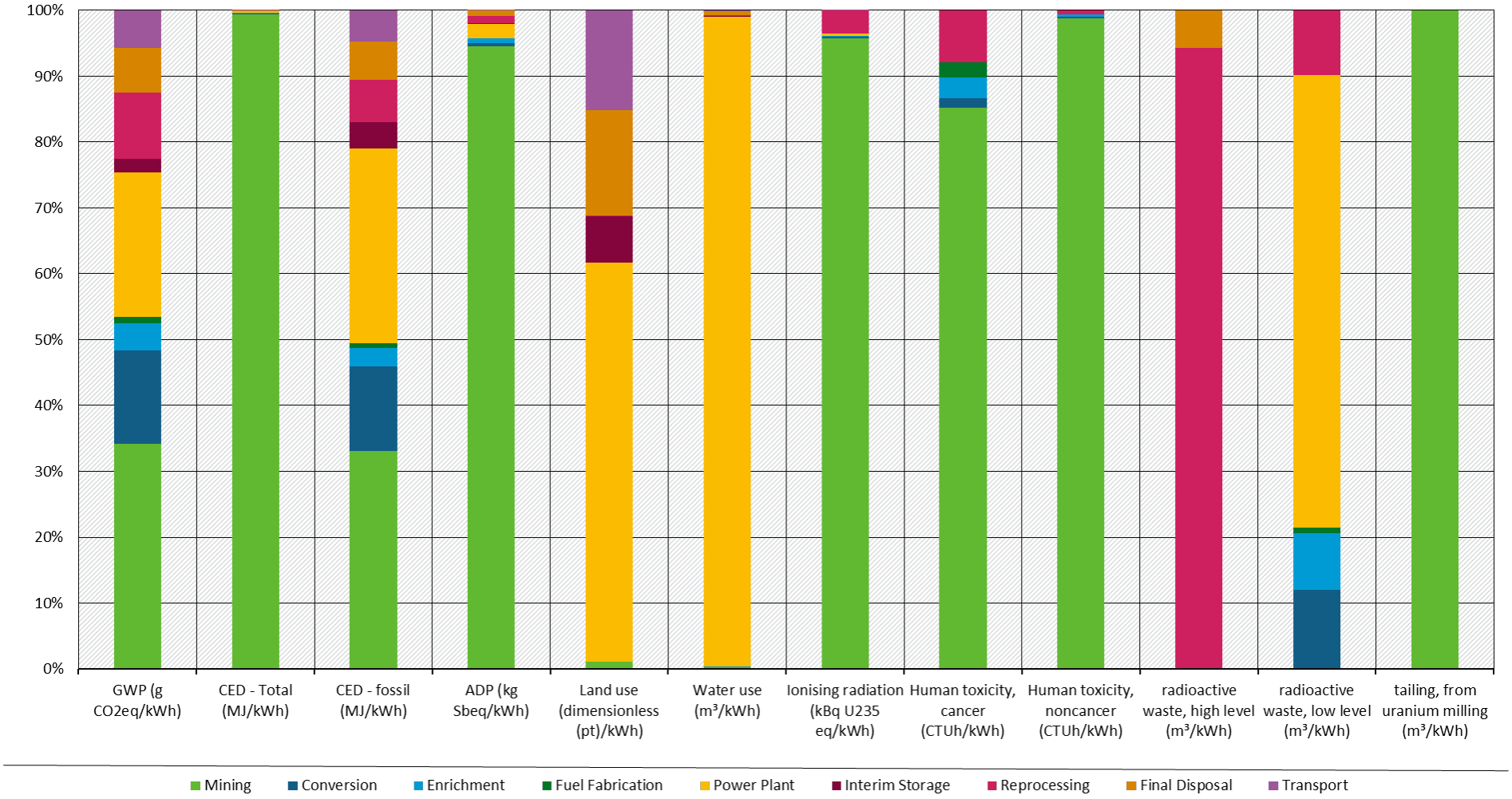
Figure 142: Gen3 breakdown of GWP



Total GWP of EU1_Gen3: 5,1 g CO2eq/kWh

Source: Öko-Institut

Figure 143: EU1_Gen3 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.4 EU1_Gen3_2030

Table 97: EU1_Gen3_2030 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.13
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	France
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	10.2
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	France
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR (Gen3)
NPP_Construction	Country	EU(low)
Electricity_Production_Nuclear	Load Factor	0
Electricity_Production_Nuclear	Net Efficiency (%)	0.38
Electricity_Production_Nuclear	Country	EU(low)
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	France
Backend	Country	EU(low)

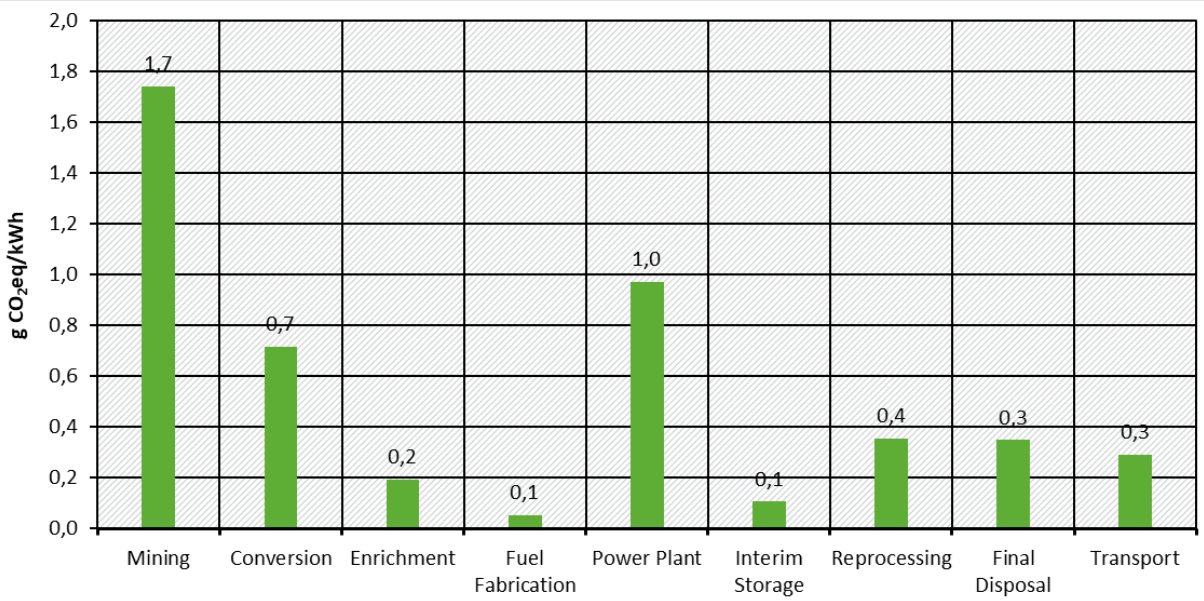
Source: Öko-Institut

Table 98: EU1_Gen3_2030 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	4.8

Source: Öko-Institut

Figure 144 Gen3_2030 breakdown of GWP



Total GWP of EU1_Gen3_2030: 4,8 g CO2eq/kWh
Source: Öko-Institut

B.5 EU1_SMR

Table 99: EU1_SMR life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.13
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	France
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	10.2
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	France
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	SMR
NPP_Construction	Country	EU(low)
Electricity_Production_Nuclear	Load Factor	0.77
Electricity_Production_Nuclear	Net Efficiency (%)	0.32
Electricity_Production_Nuclear	Country	EU(low)

Process Step	Parameter	Value
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	France
Backend	Country	EU(low)

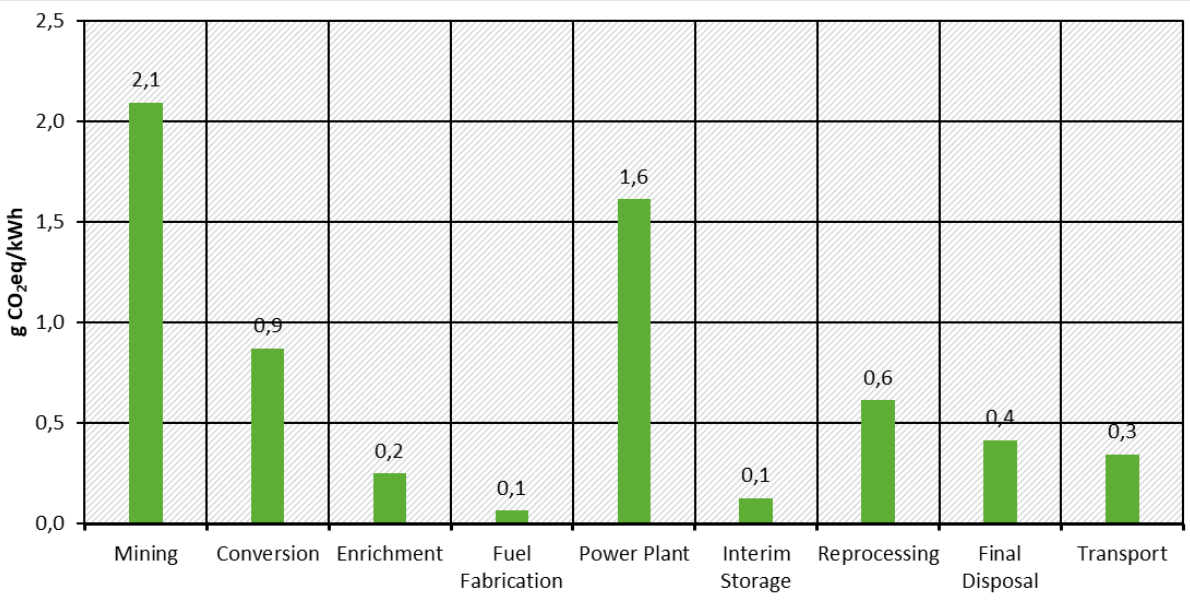
Source: Öko-Institut

Table 100: EU1_SMR life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	6.4
CED - Total	MJ/kWh	1.6E+01
CED - fossil	MJ/kWh	1.1E-01
ADP	kg Sbeq/kWh	2.2E-06
Land use	dimensionless (pt)/kWh	3.1E-02
Water use	m³/kWh	1.9E-02
Ionising radiation	kBq U235 eq/kWh	1.3E+00
Human toxicity, cancer	CTUh/kWh	2.8E-03
Human toxicity, noncancer	CTUh/kWh	1.5E-01
radioactive waste, high level	m³/kWh	1.0E-08
radioactive waste, low level	m³/kWh	9.4E-08
tailing, from uranium milling	m³/kWh	6.2E-06

Source: Öko-Institut

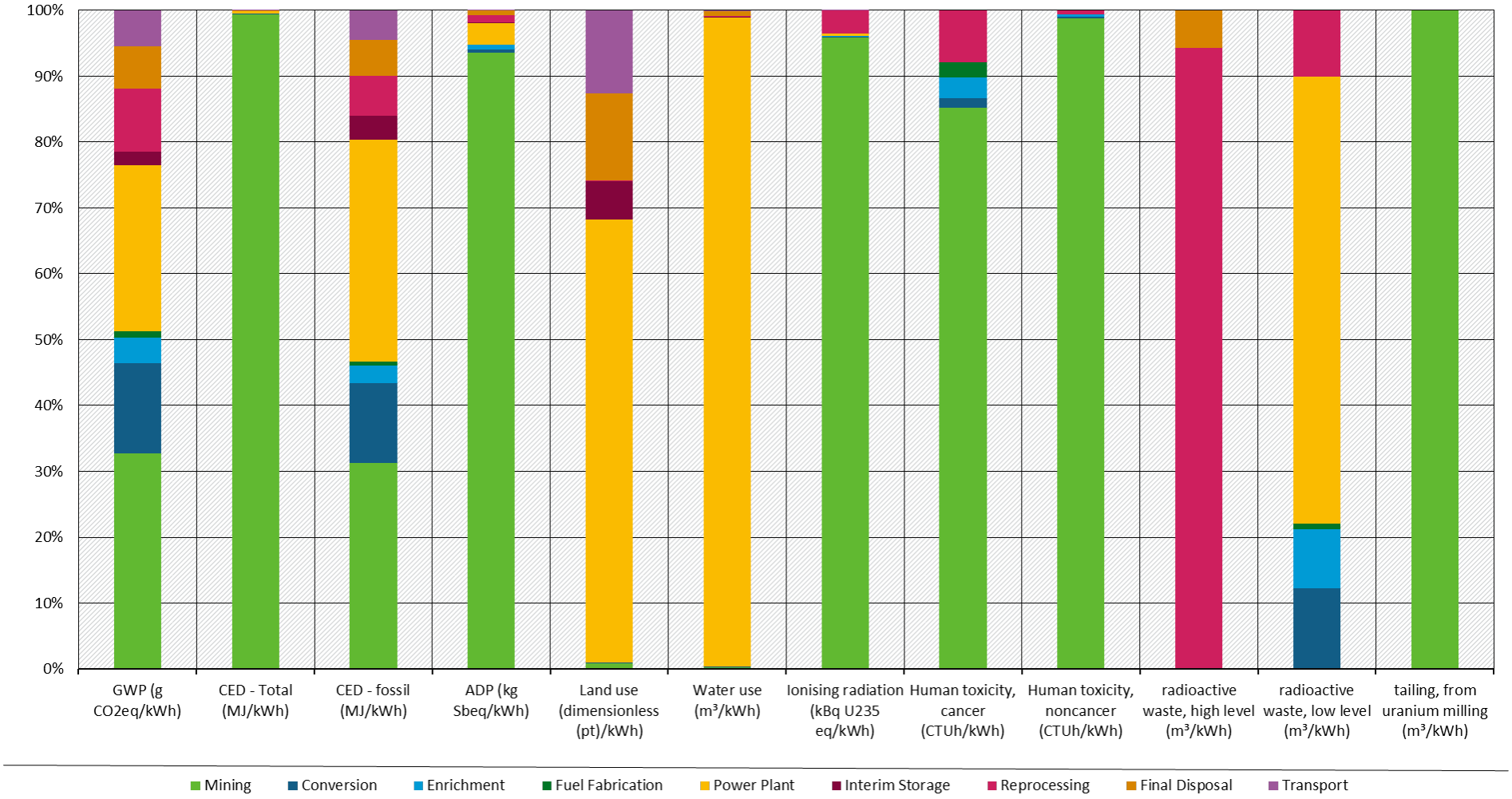
Figure 145: SMR breakdown of GWP



Total GWP of EU1_SMR: 6,4 g CO2eq/kWh

Source: Öko-Institut

Figure 146: EU1_SMR breakdown of impacts by life cycle stage



Source: Öko-Institut

B.6 EU1_SMR_2030

Table 101: EU1_SMR_2030 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.13
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	France
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	10.2
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	France
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	SMR
NPP_Construction	Country	EU(low)
Electricity_Production_Nuclear	Load Factor	0
Electricity_Production_Nuclear	Net Efficiency (%)	0.32
Electricity_Production_Nuclear	Country	EU(low)
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	France
Backend	Country	EU(low)

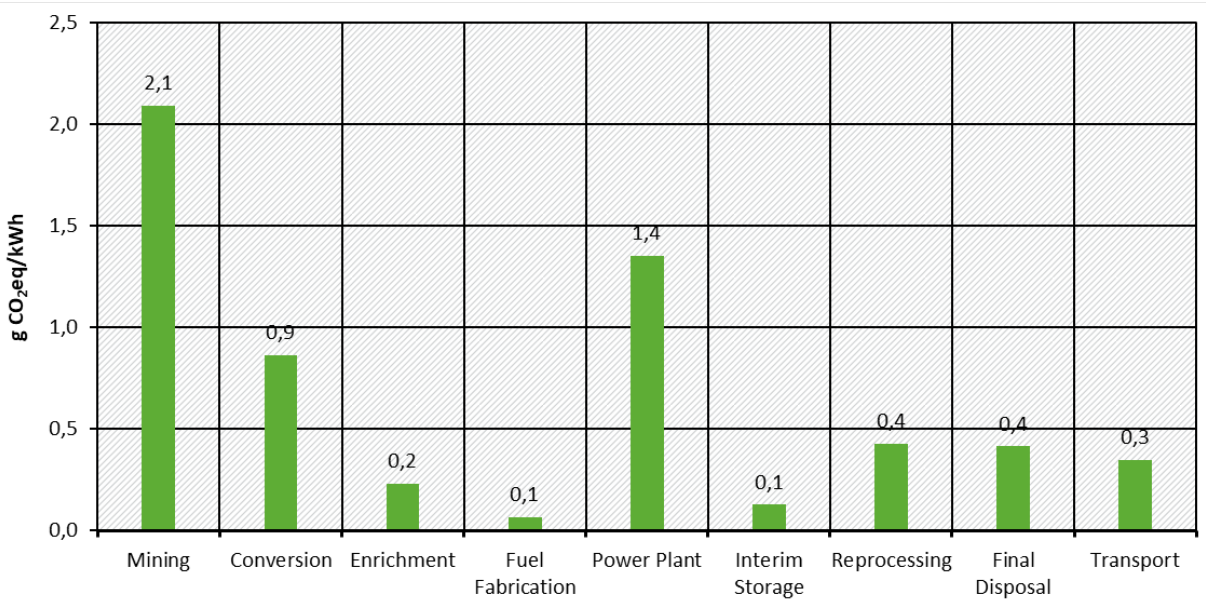
Source: Öko-Institut

Table 102: EU1_SMR_2030 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	5.9

Source: Öko-Institut

Figure 147: EU1_SMR_2030 breakdown of GWP



Total GWP of EU1_SMR_2030: 5,9 g CO2eq/kWh
Source: Öko-Institut

B.7 EU2

Table 103: EU2 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.13
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	3.75
Enrichment_Centrifuge	Country	France
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	45
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	EU(medium)
Electricity_Production_Nuclear	Load Factor	0.92
Electricity_Production_Nuclear	Net Efficiency (%)	0.30
Electricity_Production_Nuclear	Country	EU(medium)

Process Step	Parameter	Value
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	-
Backend	Country	EU(medium)

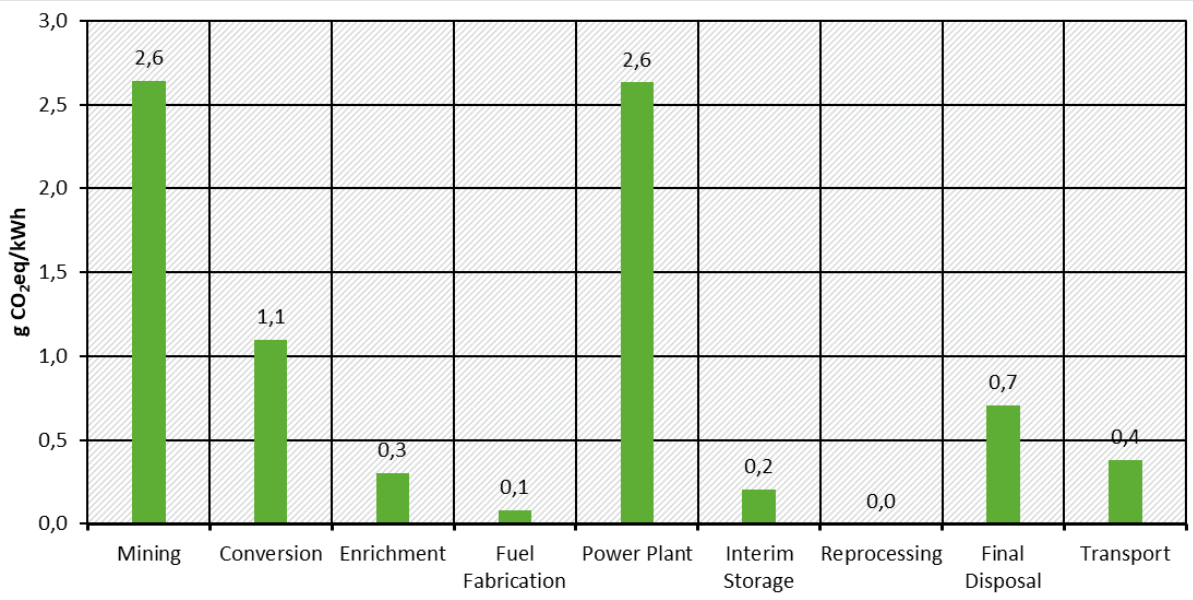
Source: Öko-Institut

Table 104: EU2 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	8.0
CED - Total	MJ/kWh	2.0E+01
CED - fossil	MJ/kWh	1.2E-01
ADP	kg Sbeq/kWh	2.8E-06
Land use	dimensionless (pt)/kWh	3.6E-02
Water use	m³/kWh	9.7E-02
Ionising radiation	kBq U235 eq/kWh	1.7E+00
Human toxicity, cancer	CTUh/kWh	3.2E-03
Human toxicity, noncancer	CTUh/kWh	1.8E-01
radioactive waste, high level	m³/kWh	7.4E-09
radioactive waste, low level	m³/kWh	8.0E-08
tailing, from uranium milling	m³/kWh	7.8E-06

Source: Öko-Institut

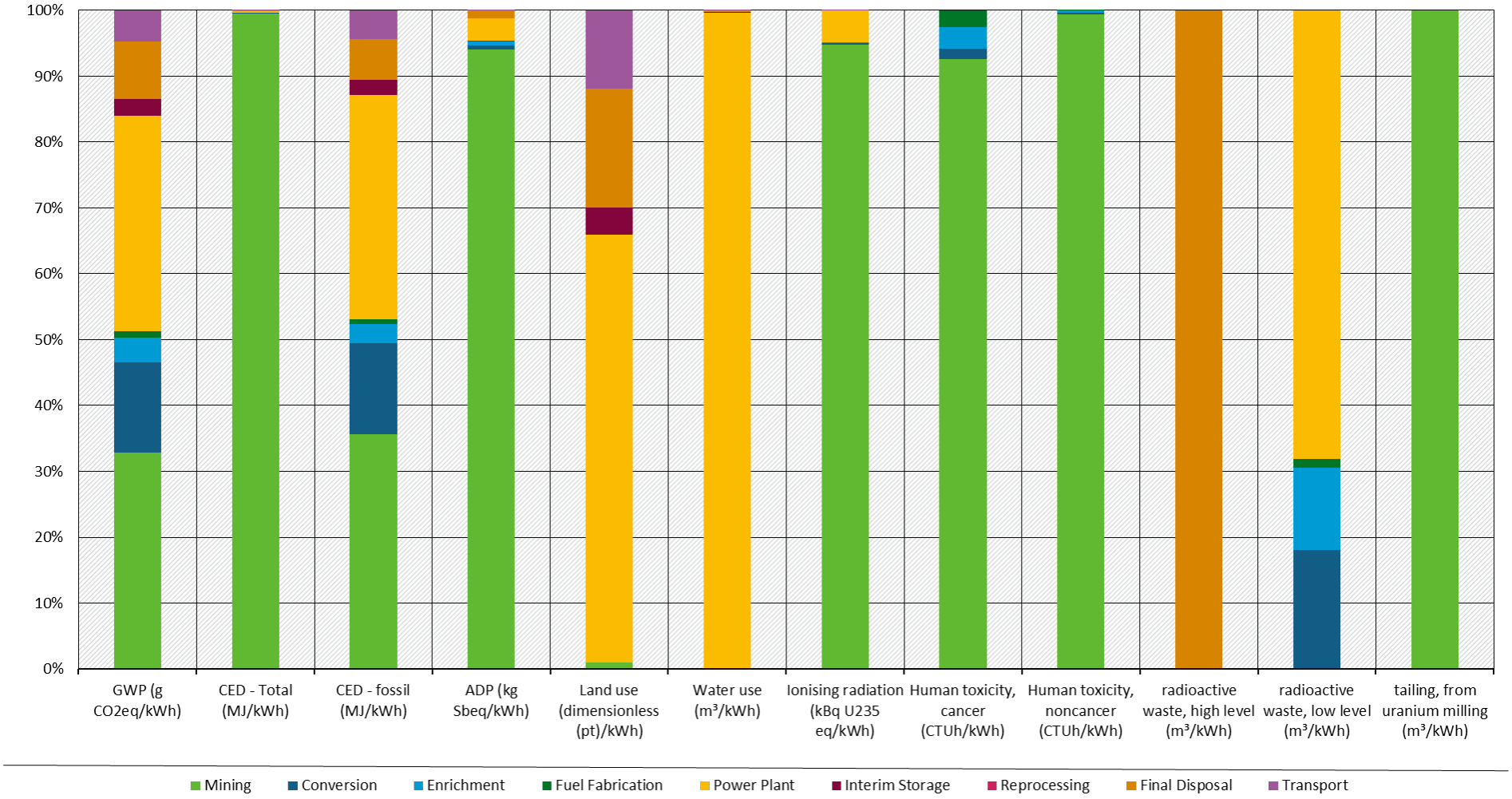
Figure 148: EU2 breakdown of GWP



Total GWP of EU2: 8 g CO2eq/kWh

Source: Öko-Institut

Figure 149: EU2 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.8 EU3

Table 105: EU3 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.20
Mine_Infrastructure	Mine Type	In-situ leaching
Conversion_UF6	Country	Russia
Enrichment_Centrifuge	enrichment grade (% U235)	3.75
Enrichment_Centrifuge	Country	Russia
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	Sweden
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	45
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	EU(medium)
Electricity_Production_Nuclear	Load Factor	0.92
Electricity_Production_Nuclear	Net Efficiency (%)	0.30
Electricity_Production_Nuclear	Country	EU(medium)
NPP_Retrofitting	Replacement Ratio (%)	0.5
Reprocessing	Country	-
Backend	Country	EU(medium)

Source: Öko-Institut

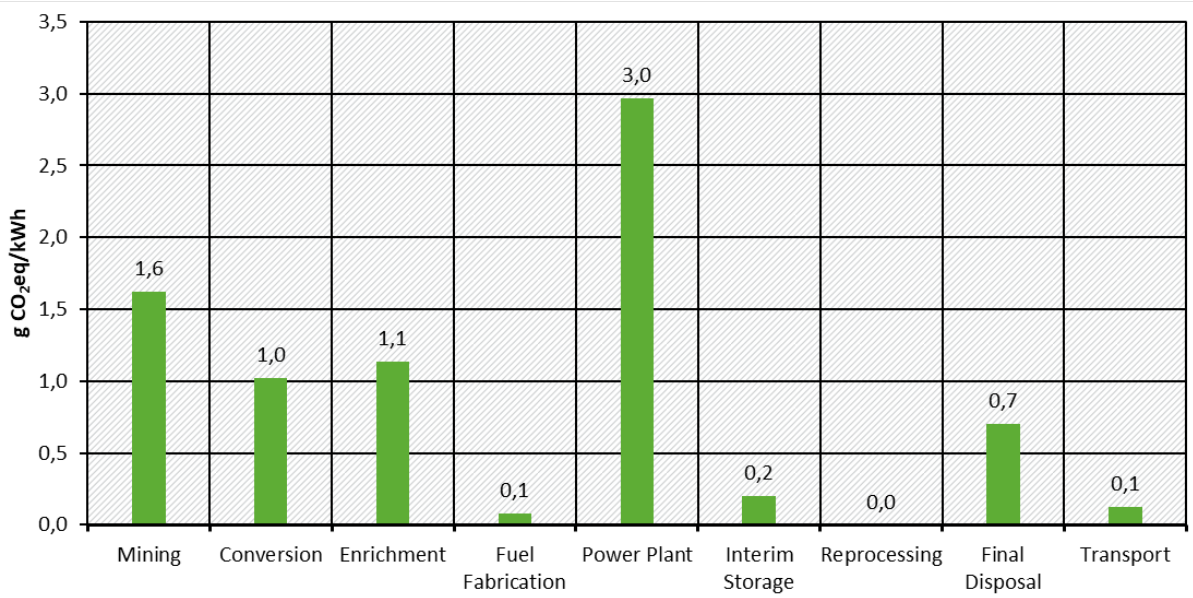
Table 106: EU3 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	7.9
CED - Total	MJ/kWh	2.7E+01
CED - fossil	MJ/kWh	1.4E+01
ADP	kg Sbeq/kWh	1.9E-06
Land use	dimensionless (pt)/kWh	3.3E-02
Water use	m^3/kWh	9.7E-02
Ionising radiation	kBq U235 eq/kWh	8.8E-02
Human toxicity, cancer	CTUh/kWh	4.2E-04

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	1.8E-02
radioactive waste, high level	m³/kWh	7.4E-09
radioactive waste, low level	m³/kWh	8.0E-08
tailing, from uranium milling	m³/kWh	0.0E+00

Source: Öko-Institut

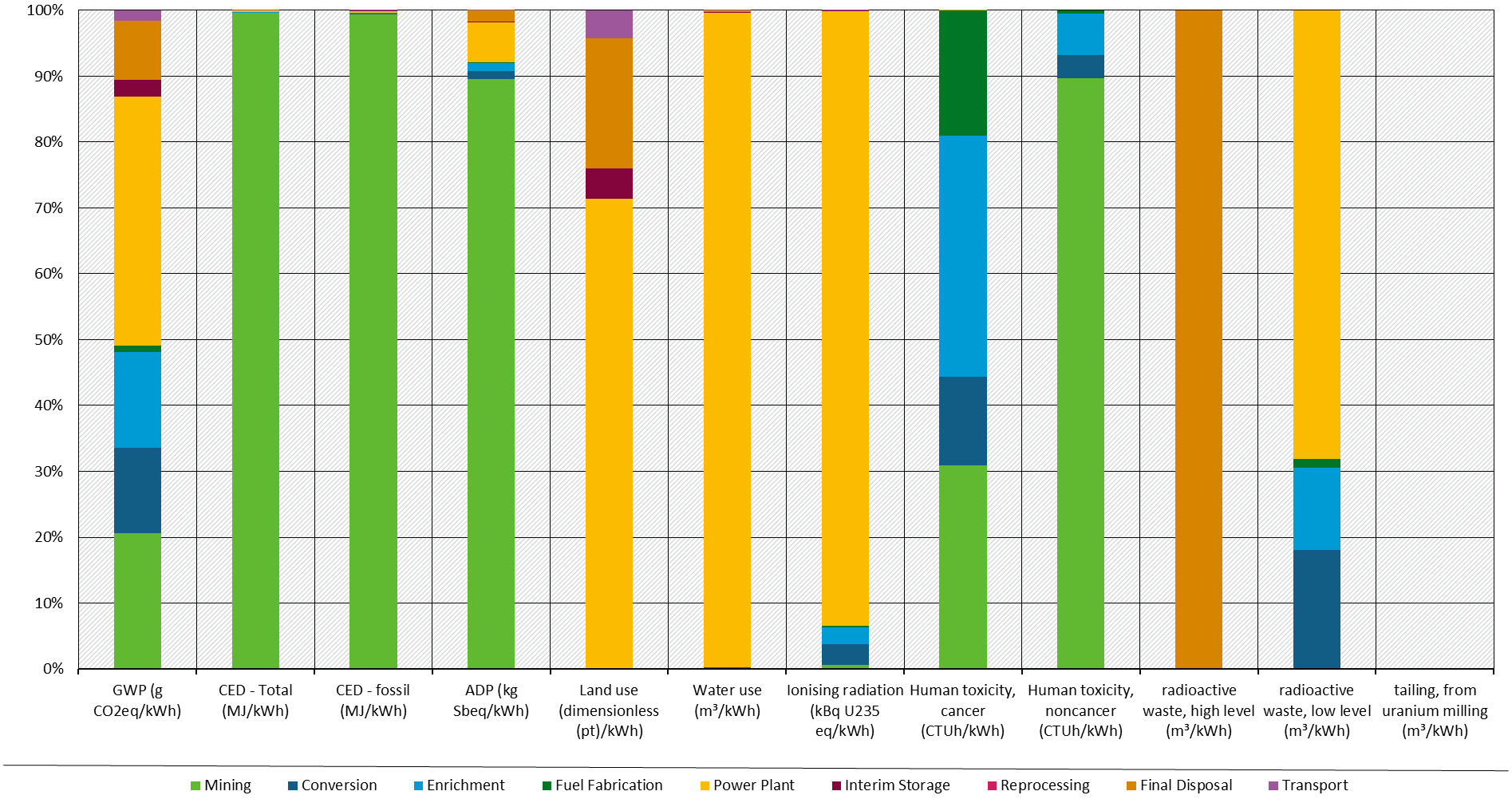
Figure 150: EU3 breakdown of GWP



Total GWP of EU3: 7,9 g CO2eq/kWh

Source: Öko-Institut

Figure 151: EU3 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.9 EU4

Table 107: EU4 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.13
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	3.75
Enrichment_Centrifuge	Country	France
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	EU(high)
Electricity_Production_Nuclear	Load Factor	0.9
Electricity_Production_Nuclear	Net Efficiency (%)	0.33
Electricity_Production_Nuclear	Country	EU(high)
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	EU(high)

Source: Öko-Institut

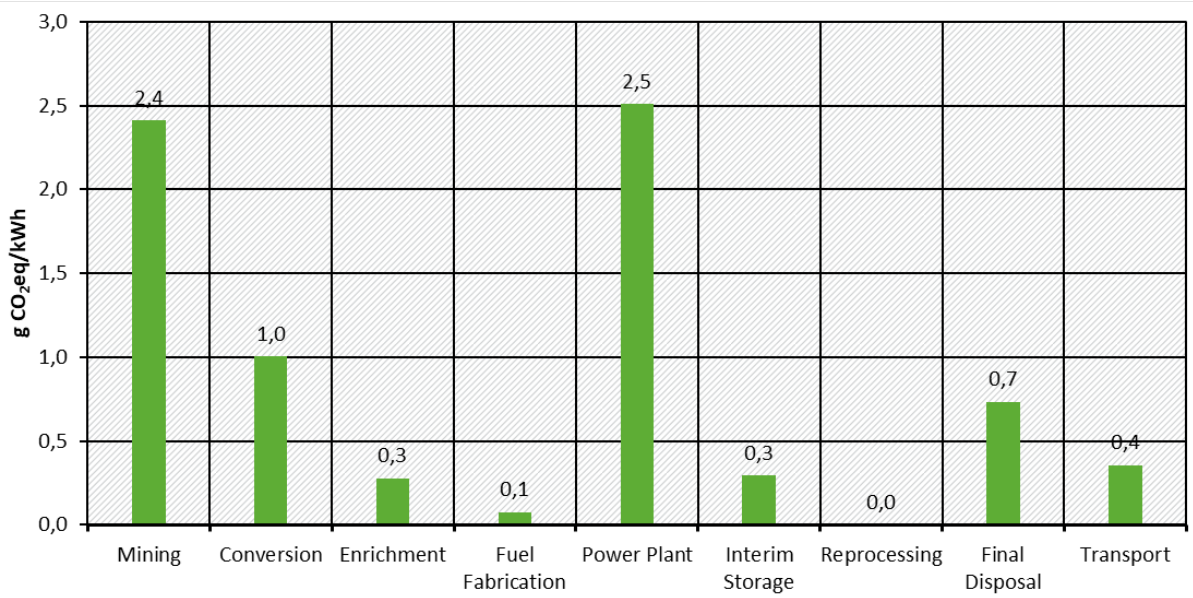
Table 108: EU4 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	7.6
CED - Total	MJ/kWh	1.8E+01
CED - fossil	MJ/kWh	1.0E-01
ADP	kg Sbeq/kWh	2.5E-06
Land use	dimensionless (pt)/kWh	3.0E-02
Water use	m^3/kWh	1.2E-01
Ionising radiation	kBq U235 eq/kWh	1.5E+00
Human toxicity, cancer	CTUh/kWh	3.0E-03

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	1.7E-01
radioactive waste, high level	m³/kWh	6.7E-09
radioactive waste, low level	m³/kWh	7.8E-08
tailing, from uranium milling	m³/kWh	7.1E-06

Source: Öko-Institut

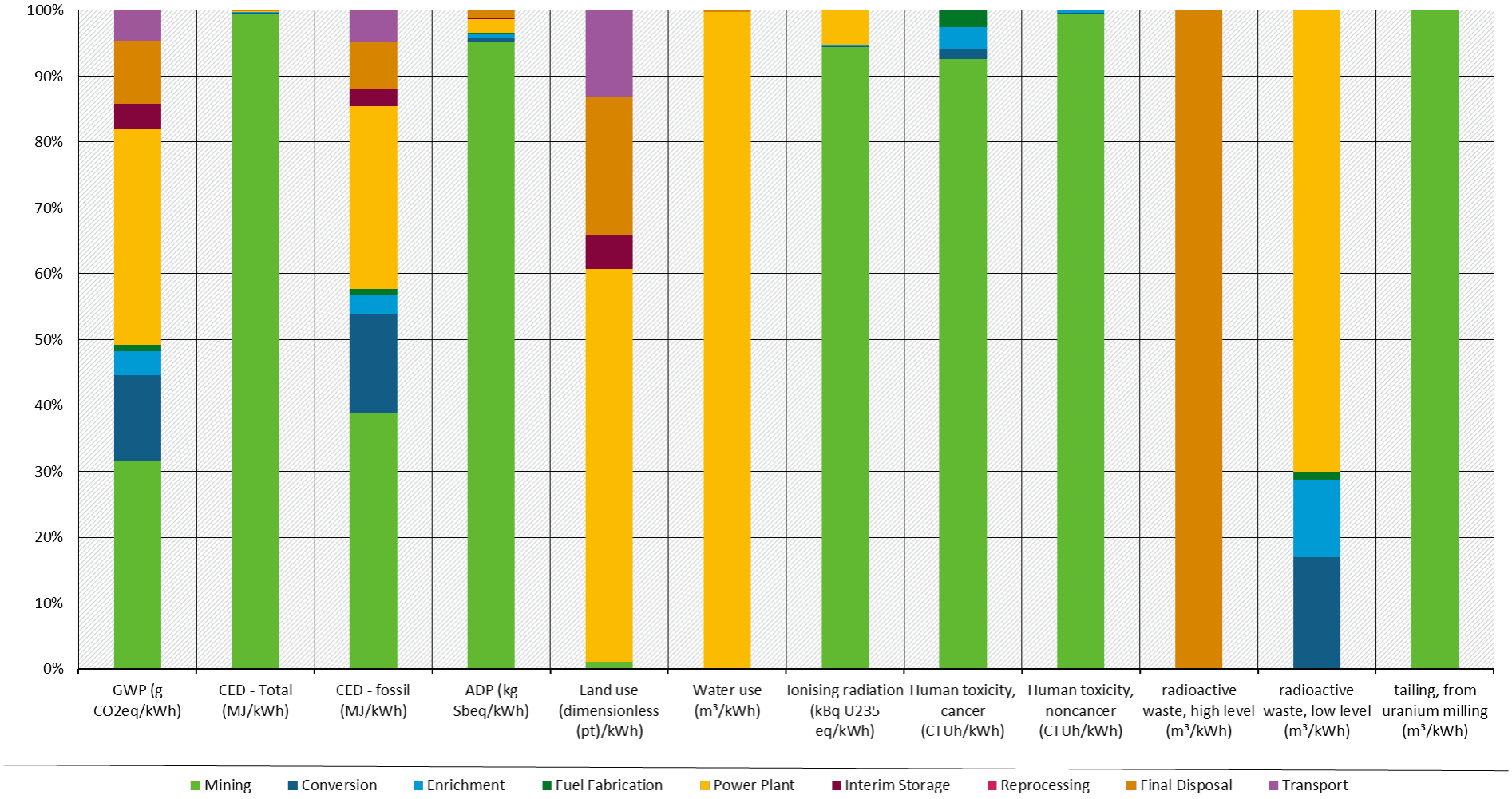
Figure 152: EU4 breakdown of GWP



Total GWP of EU4: 7,6 g CO2eq/kWh

Source: Öko-Institut

Figure 153: EU4 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.10 EU5

Table 109: EU5 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.03
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	4
Enrichment_Centrifuge	Country	Netherlands
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	EU(high)
Electricity_Production_Nuclear	Load Factor	0.9
Electricity_Production_Nuclear	Net Efficiency (%)	0.33
Electricity_Production_Nuclear	Country	EU(high)
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	-
Backend	Country	EU(high)

Source: Öko-Institut

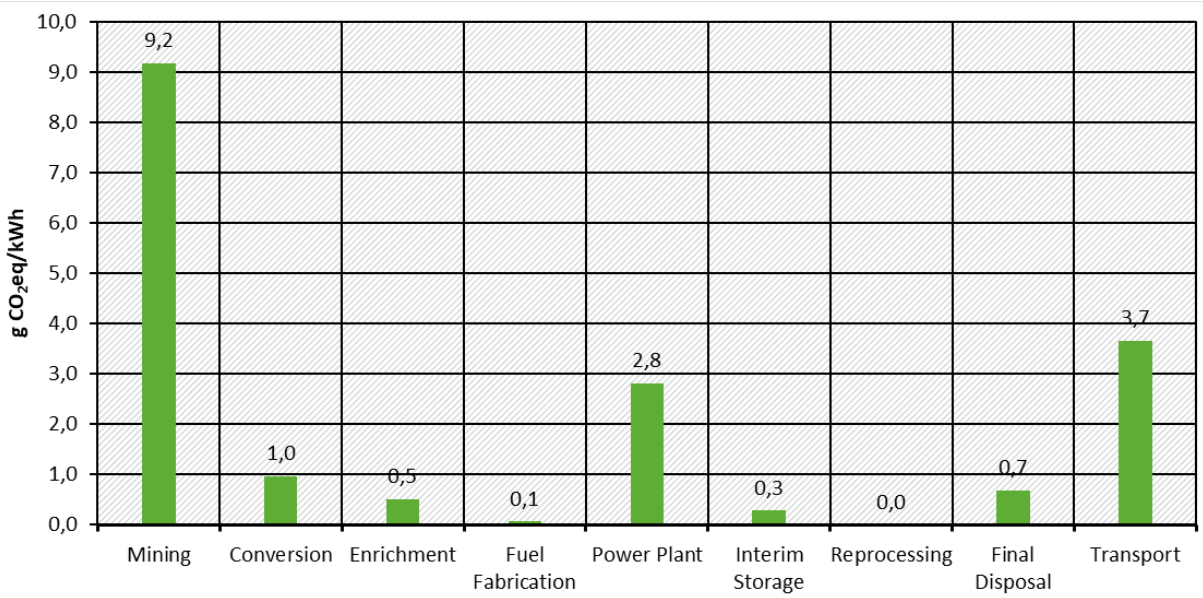
Table 110: EU5 life cycle chain results

Parameter	Unit	Result
GWP	g CO2eq/kWh	18.2
CED - Total	MJ/kWh	7.0E+01
CED - fossil	MJ/kWh	2.6E-01
ADP	kg Sbeq/kWh	9.3E-06
Land use	dimensionless (pt)/kWh	6.8E-02
Water use	m^3/kWh	1.2E-01
Ionising radiation	kBq U235 eq/kWh	5.6E+00
Human toxicity, cancer	CTUh/kWh	1.1E-02

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	6.3E-01
radioactive waste, high level	m³/kWh	6.1E-09
radioactive waste, low level	m³/kWh	7.8E-08
tailing, from uranium milling	m³/kWh	2.7E-05

Source: Öko-Institut

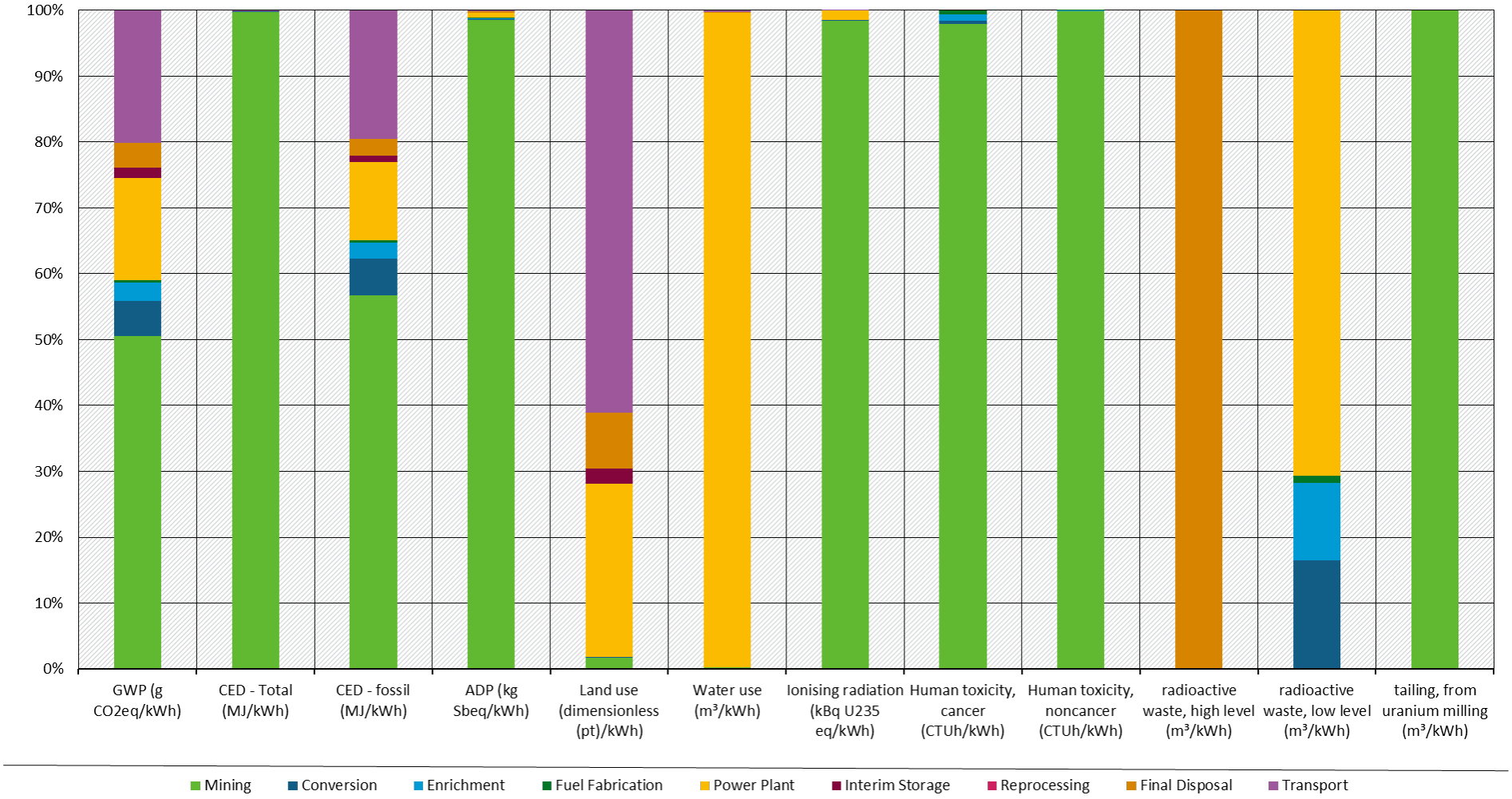
Figure 154: EU5 breakdown of GWP



Total GWP of EU5: 18,2 g CO2eq/kWh

Source: Öko-Institut

Figure 155: EU5 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.11 EU6

Table 111: EU6 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.08
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	4
Enrichment_Centrifuge	Country	France
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	EU(low)
Electricity_Production_Nuclear	Load Factor	0.77
Electricity_Production_Nuclear	Net Efficiency (%)	0.33
Electricity_Production_Nuclear	Country	EU(low)
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	-
Backend	Country	EU(low)

Source: Öko-Institut

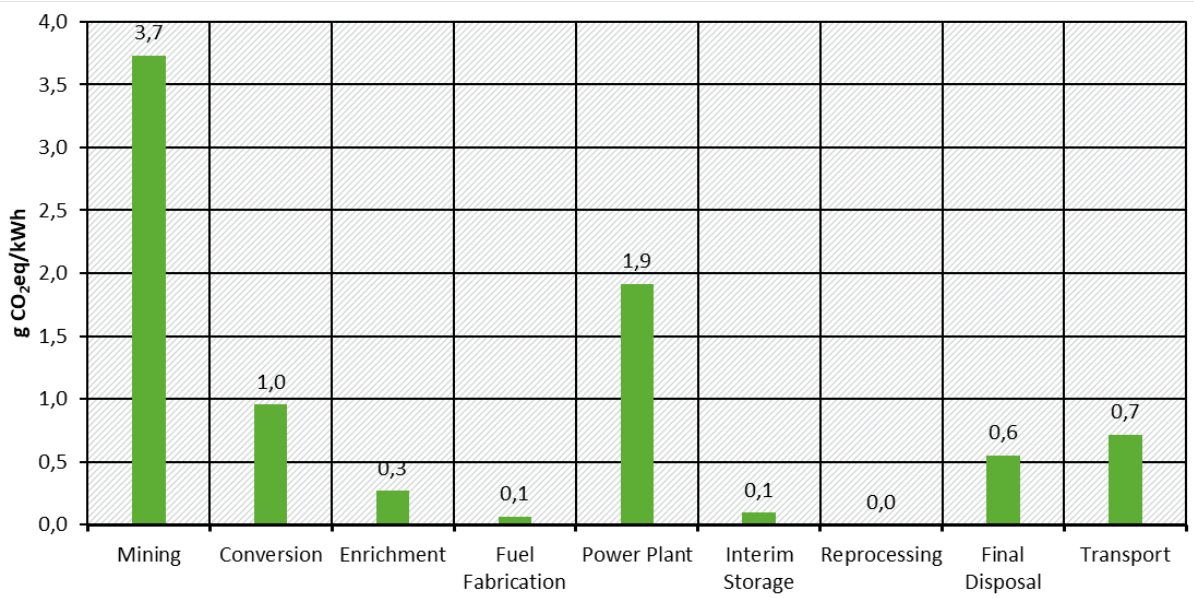
Table 112: EU6 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	8.3
CED - Total	MJ/kWh	2.9E+01
CED - fossil	MJ/kWh	1.4E-01
ADP	kg Sbeq/kWh	3.9E-06
Land use	dimensionless (pt)/kWh	3.7E-02
Water use	m^3/kWh	1.9E-02
Ionising radiation	kBq U235 eq/kWh	2.3E+00
Human toxicity, cancer	CTUh/kWh	4.4E-03

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	2.6E-01
radioactive waste, high level	m³/kWh	6.0E-09
radioactive waste, low level	m³/kWh	8.4E-08
tailing, from uranium milling	m³/kWh	1.1E-05

Source: Öko-Institut

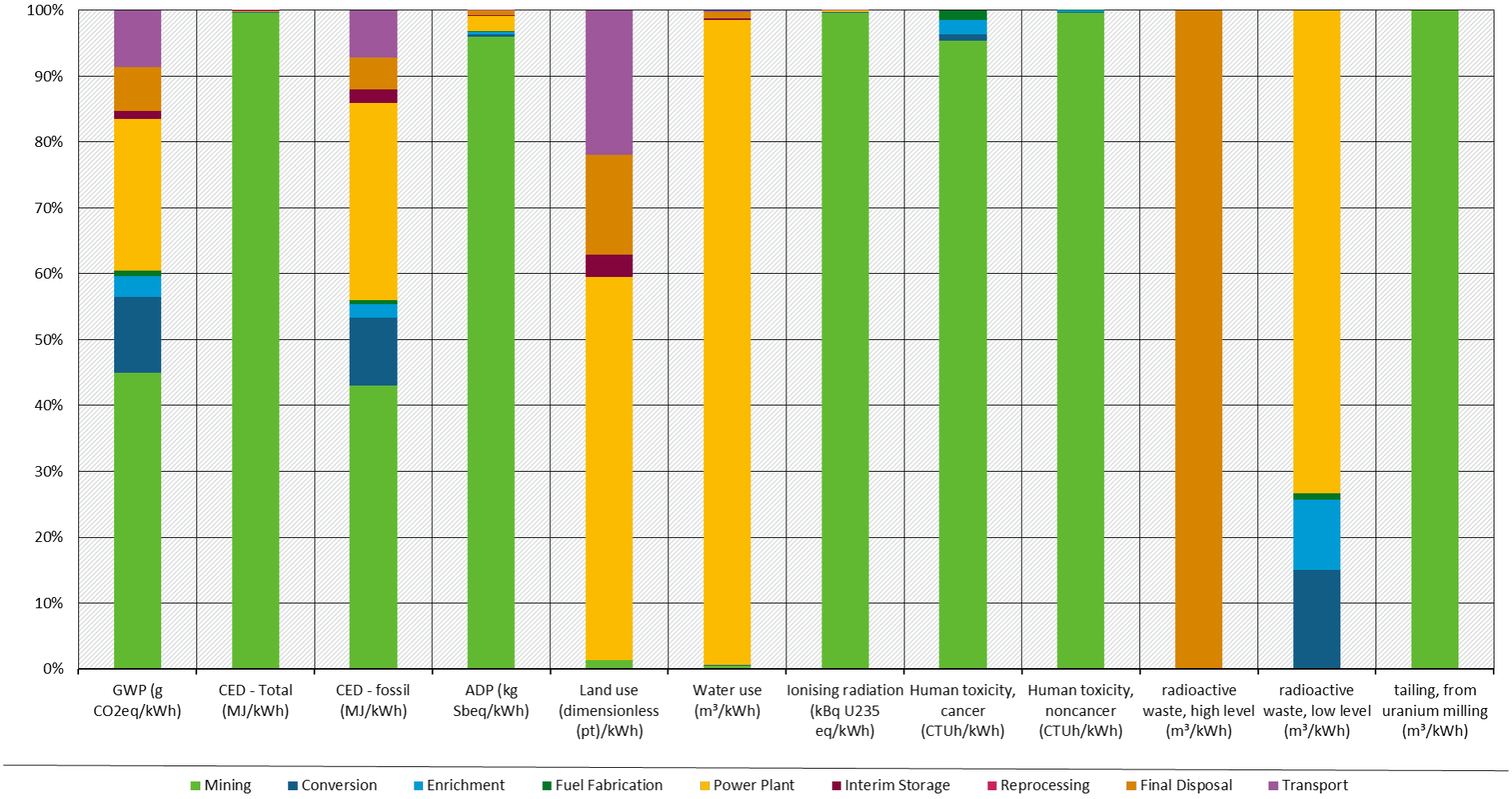
Figure 156: EU6 breakdown of GWP



Total GWP of EU6: 8,3 g CO2eq/kWh

Source: Öko-Institut

Figure 157: EU6 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.12 EU7

Table 113: EU7 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.07
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	Germany
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	5.1
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	France
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	EU(low)
Electricity_Production_Nuclear	Load Factor	0.77
Electricity_Production_Nuclear	Net Efficiency (%)	0.33
Electricity_Production_Nuclear	Country	EU(low)
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	France
Backend	Country	EU(low)

Source: Öko-Institut

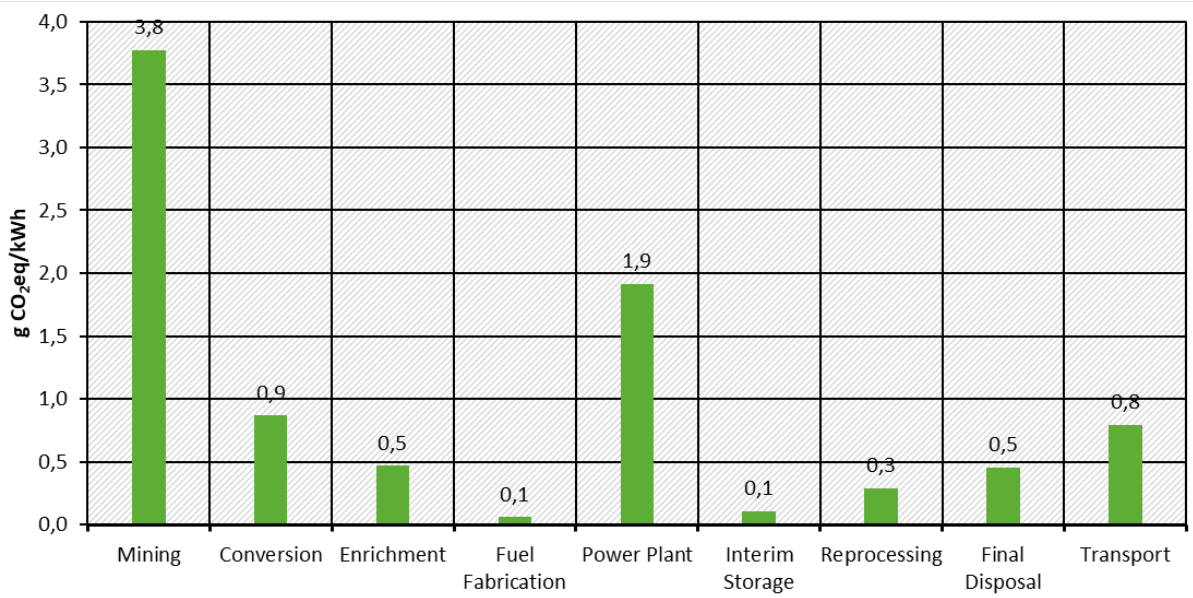
Table 114: EU7 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	8.7
CED - Total	MJ/kWh	2.9E+01
CED - fossil	MJ/kWh	1.5E-01
ADP	kg Sbeq/kWh	3.9E-06
Land use	dimensionless (pt)/kWh	3.7E-02
Water use	m^3/kWh	1.9E-02
Ionising radiation	kBq U235 eq/kWh	2.3E+00
Human toxicity, cancer	CTUh/kWh	4.6E-03

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	2.6E-01
radioactive waste, high level	m³/kWh	7.6E-09
radioactive waste, low level	m³/kWh	8.6E-08
tailing, from uranium milling	m³/kWh	1.1E-05

Source: Öko-Institut

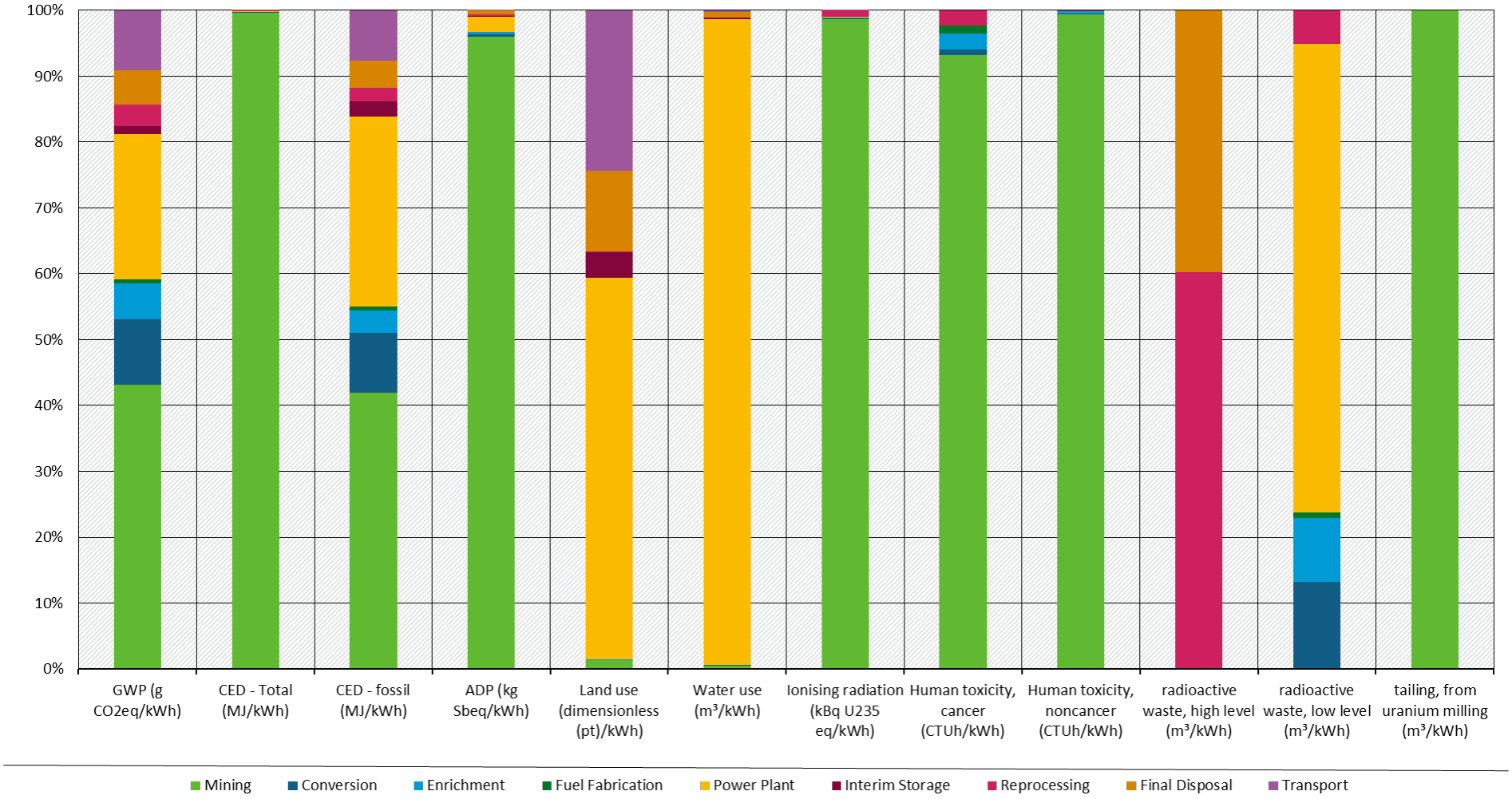
Figure 158: EU7 breakdown of GWP



Total GWP of EU7: 8,7 g CO2eq/kWh

Source: Öko-Institut

Figure 159: EU7 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.13 EU8_Gen3

Table 115: EU8_Gen3 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.15
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	Great Britain
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR (Gen3)
NPP_Construction	Country	EU(low)
Electricity_Production_Nuclear	Load Factor	0.77
Electricity_Production_Nuclear	Net Efficiency (%)	0.38
Electricity_Production_Nuclear	Country	EU(low)
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	EU(low)

Source: Öko-Institut

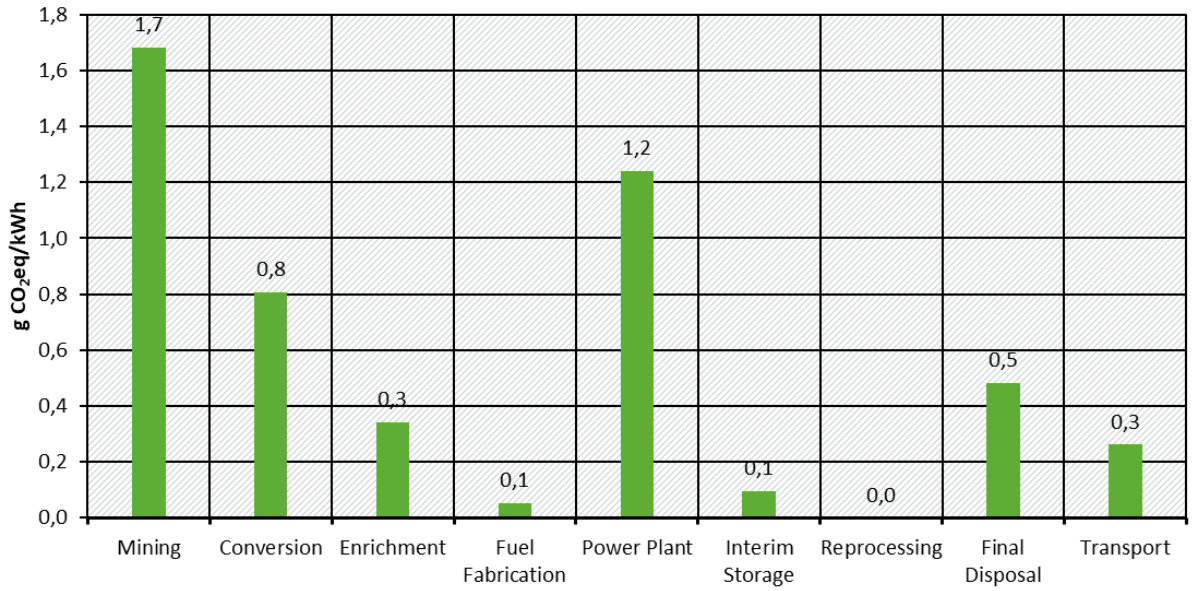
Table 116: EU8_Gen3 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	5.0
CED - Total	MJ/kWh	1.3E+01
CED - fossil	MJ/kWh	8.5E-02
ADP	kg Sbeq/kWh	1.8E-06
Land use	dimensionless (pt)/kWh	2.4E-02
Water use	m^3/kWh	1.9E-02
Ionising radiation	kBq U235 eq/kWh	1.0E+00
Human toxicity, cancer	CTUh/kWh	2.1E-03

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	1.2E-01
radioactive waste, high level	m³/kWh	4.8E-09
radioactive waste, low level	m³/kWh	7.4E-08
tailing, from uranium milling	m³/kWh	4.9E-06

Source: Öko-Institut

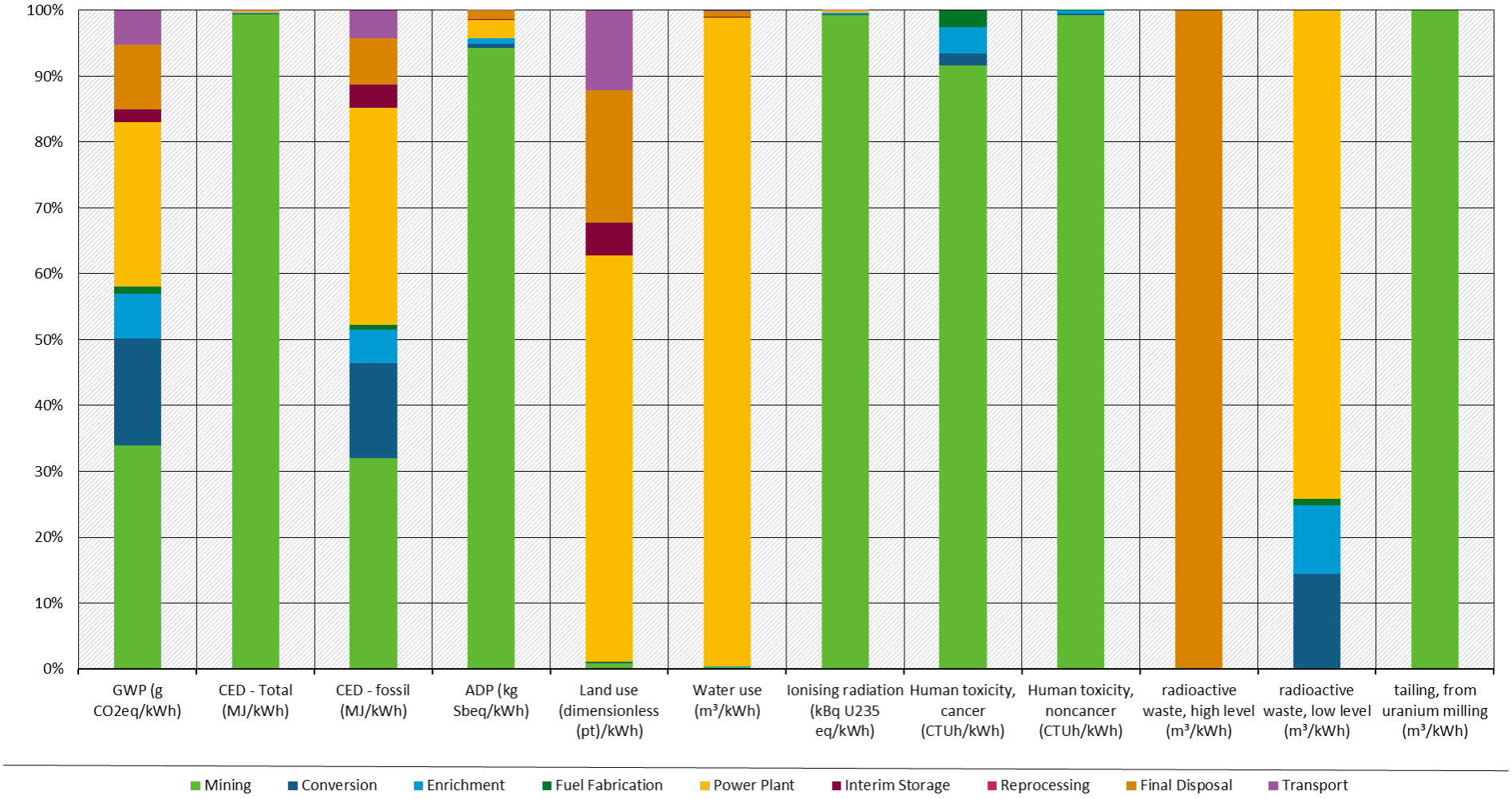
Figure 160: EU8_Gen3 breakdown of GWP



Total GWP of EU8_Gen3: 5 g CO2eq/kWh

Source: Öko-Institut

Figure 161: EU8_Gen3 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.14 EU9

Table 117: EU9 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	11.50
Mine_Infrastructure	Mine Type	Underground
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	France
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	10.2
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	France
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	EU(low)
Electricity_Production_Nuclear	Load Factor	0.77
Electricity_Production_Nuclear	Net Efficiency (%)	0.33
Electricity_Production_Nuclear	Country	EU(low)
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	France
Backend	Country	EU(low)

Source: Öko-Institut

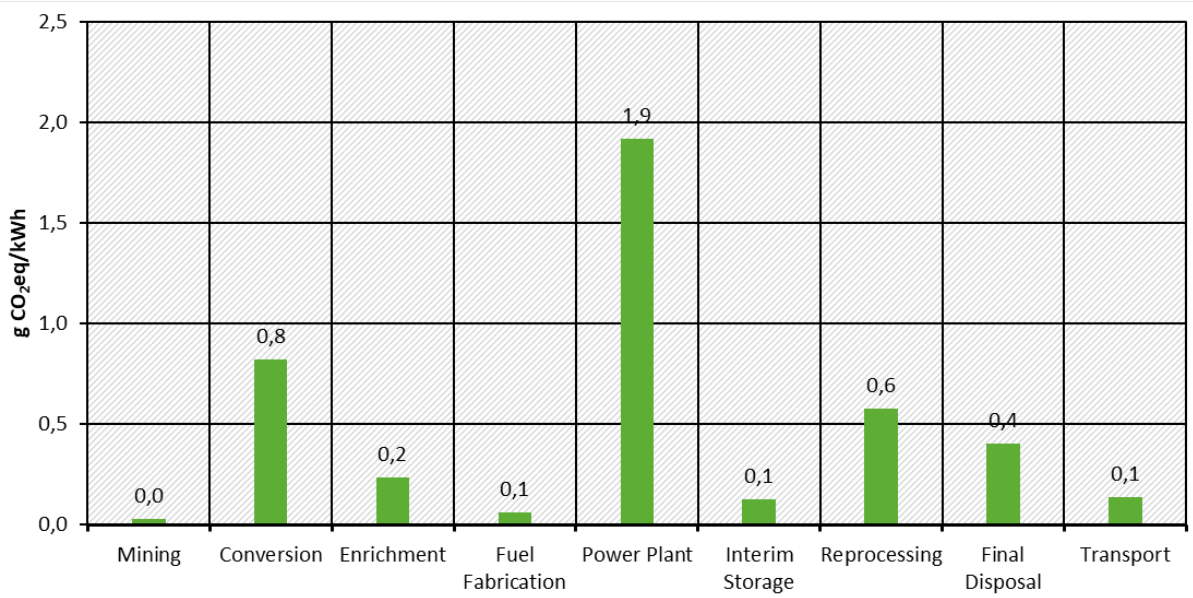
Table 118: EU9 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	4.3
CED - Total	MJ/kWh	2.8E-01
CED - fossil	MJ/kWh	7.6E-02
ADP	kg Sbeq/kWh	1.8E-07
Land use	dimensionless (pt)/kWh	2.9E-02
Water use	m^3/kWh	1.9E-02
Ionising radiation	kBq U235 eq/kWh	6.6E-02
Human toxicity, cancer	CTUh/kWh	4.2E-04

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	3.2E-03
radioactive waste, high level	m³/kWh	9.7E-09
radioactive waste, low level	m³/kWh	9.0E-08
tailing, from uranium milling	m³/kWh	6.6E-08

Source: Öko-Institut

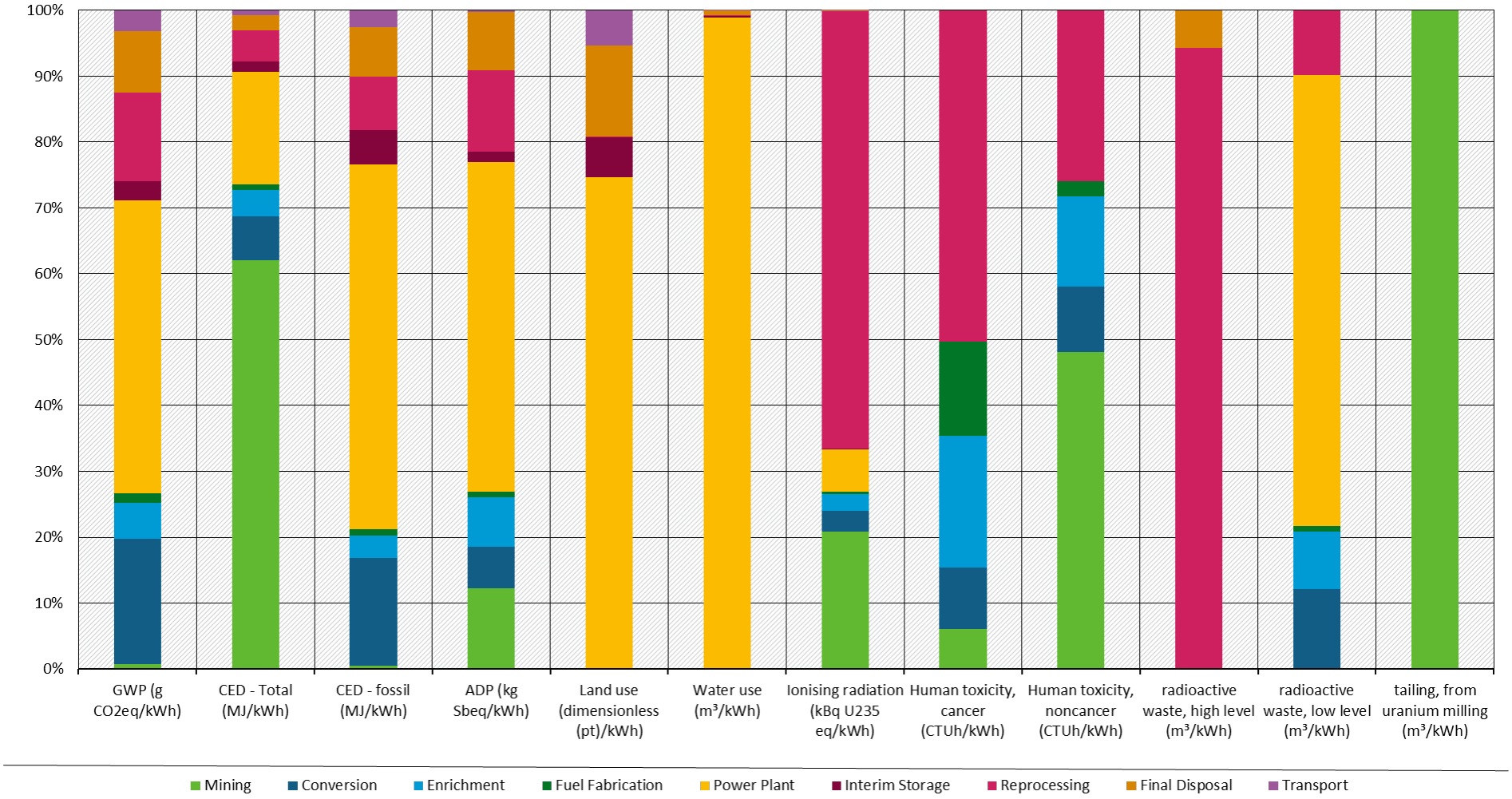
Figure 162: EU9 breakdown of GWP



Total GWP of EU9: 4,3 g CO2eq/kWh

Source: Öko-Institut

Figure 163: EU9 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.15 EU10

Table 119: EU10 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.03
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	Russia
Enrichment_Centrifuge	enrichment grade (% U235)	4
Enrichment_Centrifuge	Country	Russia
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	10.8
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	France
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	EU(low)
Electricity_Production_Nuclear	Load Factor	0.77
Electricity_Production_Nuclear	Net Efficiency (%)	0.33
Electricity_Production_Nuclear	Country	EU(low)
NPP_Retrofitting	Replacement Ratio (%)	0.5
Reprocessing	Country	France
Backend	Country	EU(low)

Source: Öko-Institut

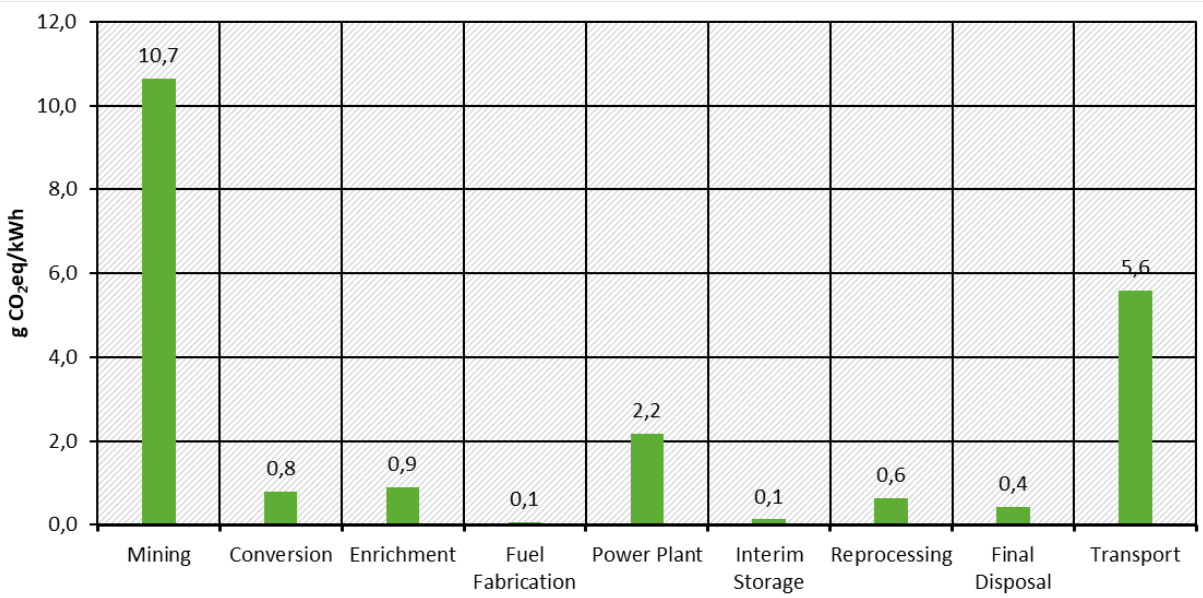
Table 120: EU10 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	21.4
CED - Total	MJ/kWh	8.2E+01
CED - fossil	MJ/kWh	3.4E-01
ADP	kg Sbeq/kWh	1.1E-05
Land use	dimensionless (pt)/kWh	9.3E-02
Water use	m^3/kWh	2.0E-02
Ionising radiation	kBq U235 eq/kWh	6.5E+00
Human toxicity, cancer	CTUh/kWh	1.3E-02

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	7.4E-01
radioactive waste, high level	m³/kWh	1.1E-08
radioactive waste, low level	m³/kWh	9.1E-08
tailing, from uranium milling	m³/kWh	3.1E-05

Source: Öko-Institut

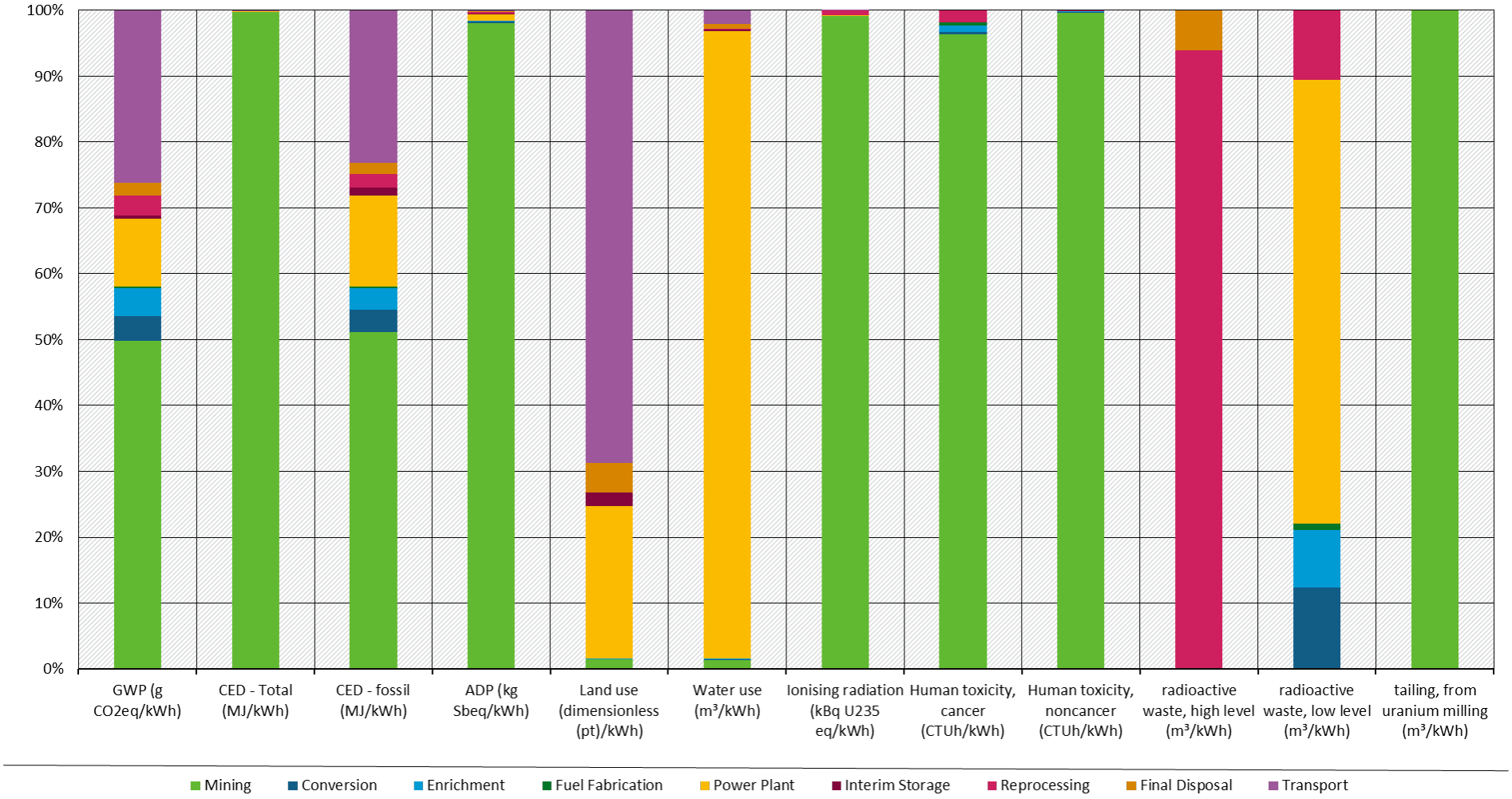
Figure 164: EU10 breakdown of GWP



Total GWP of EU10: 21,4 g CO2eq/kWh

Source: Öko-Institut

Figure 165: EU10 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.16 EU11_Gen3

Table 121: EU11_Gen3 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.03
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	France
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	10.2
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	France
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR (Gen3)
NPP_Construction	Country	EU(low)
Electricity_Production_Nuclear	Load Factor	0.77
Electricity_Production_Nuclear	Net Efficiency (%)	0.38
Electricity_Production_Nuclear	Country	EU(low)
NPP_Retrofitting	Replacement Ratio (%)	0.5
Reprocessing	Country	France
Backend	Country	EU(low)

Source: Öko-Institut

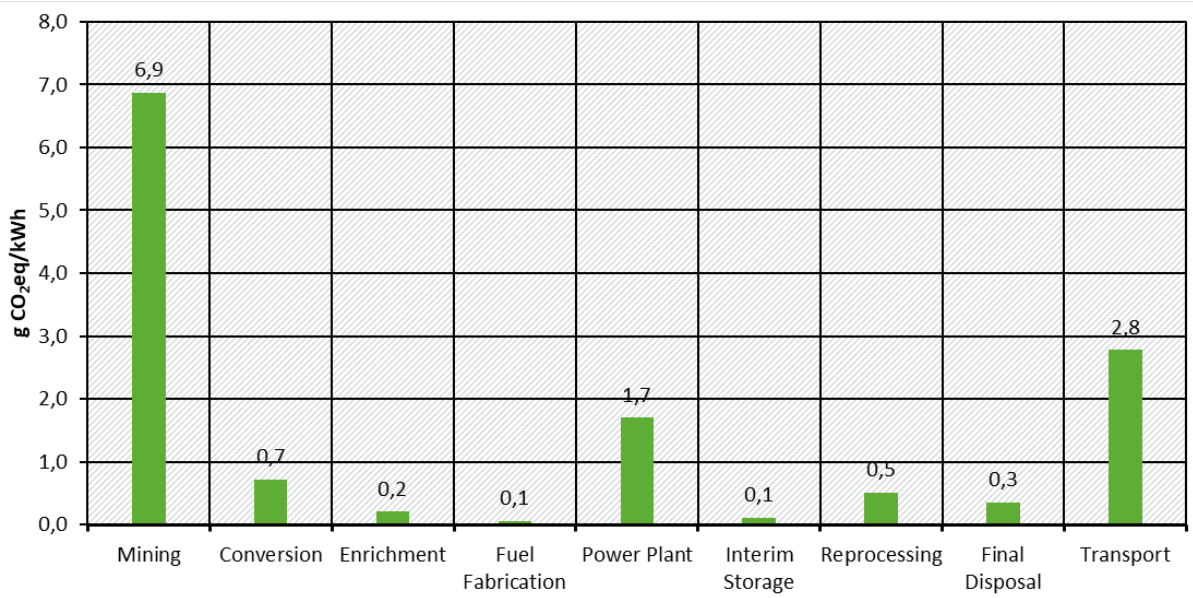
Table 122: EU11_Gen3 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	13.3
CED - Total	MJ/kWh	5.3E+01
CED - fossil	MJ/kWh	2.1E-01
ADP	kg Sbeq/kWh	7.0E-06
Land use	dimensionless (pt)/kWh	5.3E-02
Water use	m^3/kWh	1.9E-02
Ionising radiation	kBq U235 eq/kWh	4.2E+00
Human toxicity, cancer	CTUh/kWh	8.1E-03

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	4.8E-01
radioactive waste, high level	m³/kWh	8.5E-09
radioactive waste, low level	m³/kWh	8.0E-08
tailing, from uranium milling	m³/kWh	2.0E-05

Source: Öko-Institut

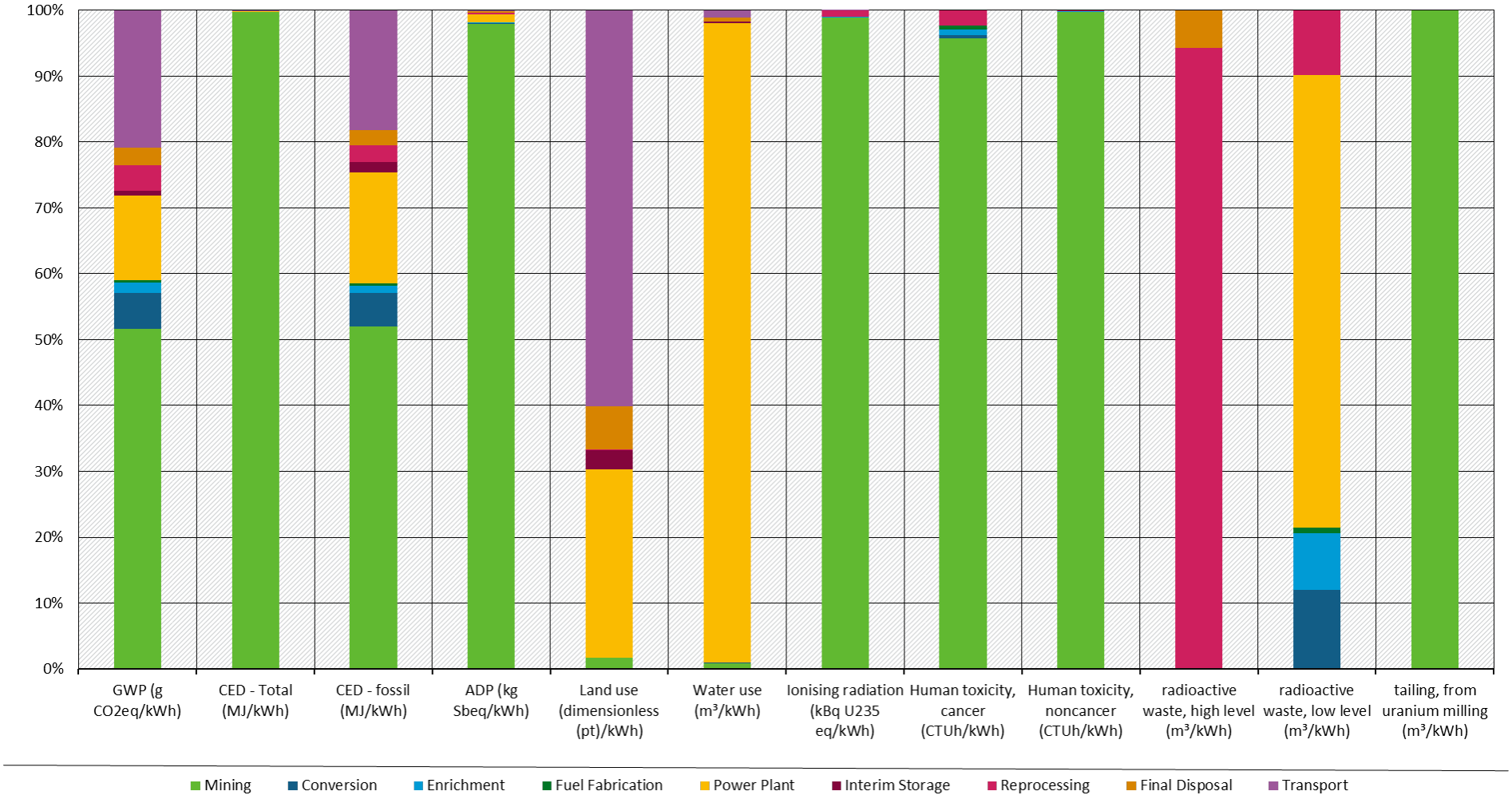
Figure 166: EU11_Gen3 breakdown of GWP



Total GWP of EU11_Gen3: 13,3 g CO2eq/kWh

Source: Öko-Institut

Figure 167: EU11_Gen3 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.17 RU1

Table 123: RU1 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.16
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	Russia
Enrichment_Centrifuge	enrichment grade (% U235)	3.75
Enrichment_Centrifuge	Country	Russia
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	Russia
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	45
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	Russia
Electricity_Production_Nuclear	Load Factor	0.78
Electricity_Production_Nuclear	Net Efficiency (%)	0.31
Electricity_Production_Nuclear	Country	Russia
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	-
Backend	Country	Russia

Source: Öko-Institut

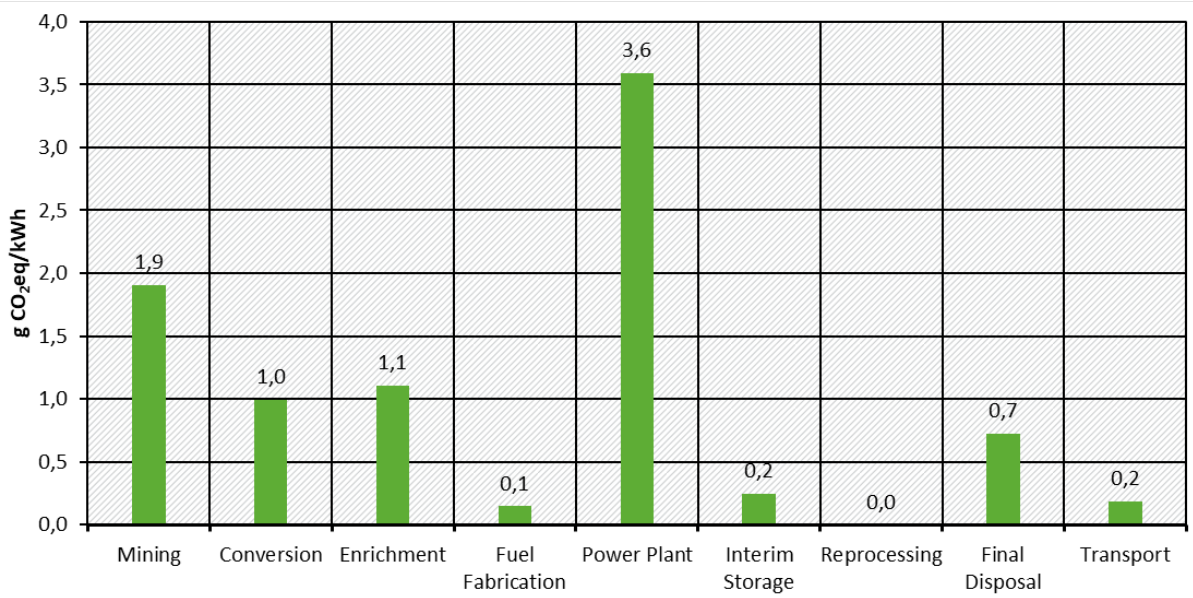
Table 124: RU1 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	8.9
CED - Total	MJ/kWh	1.6E+01
CED - fossil	MJ/kWh	1.3E-01
ADP	kg Sbeq/kWh	2.3E-06
Land use	dimensionless (pt)/kWh	2.9E-02
Water use	m^3/kWh	3.5E-02
Ionising radiation	kBq U235 eq/kWh	1.3E+00
Human toxicity, cancer	CTUh/kWh	2.6E-03

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	1.5E-01
radioactive waste, high level	m³/kWh	7.2E-09
radioactive waste, low level	m³/kWh	8.1E-08
tailing, from uranium milling	m³/kWh	6.1E-06

Source: Öko-Institut

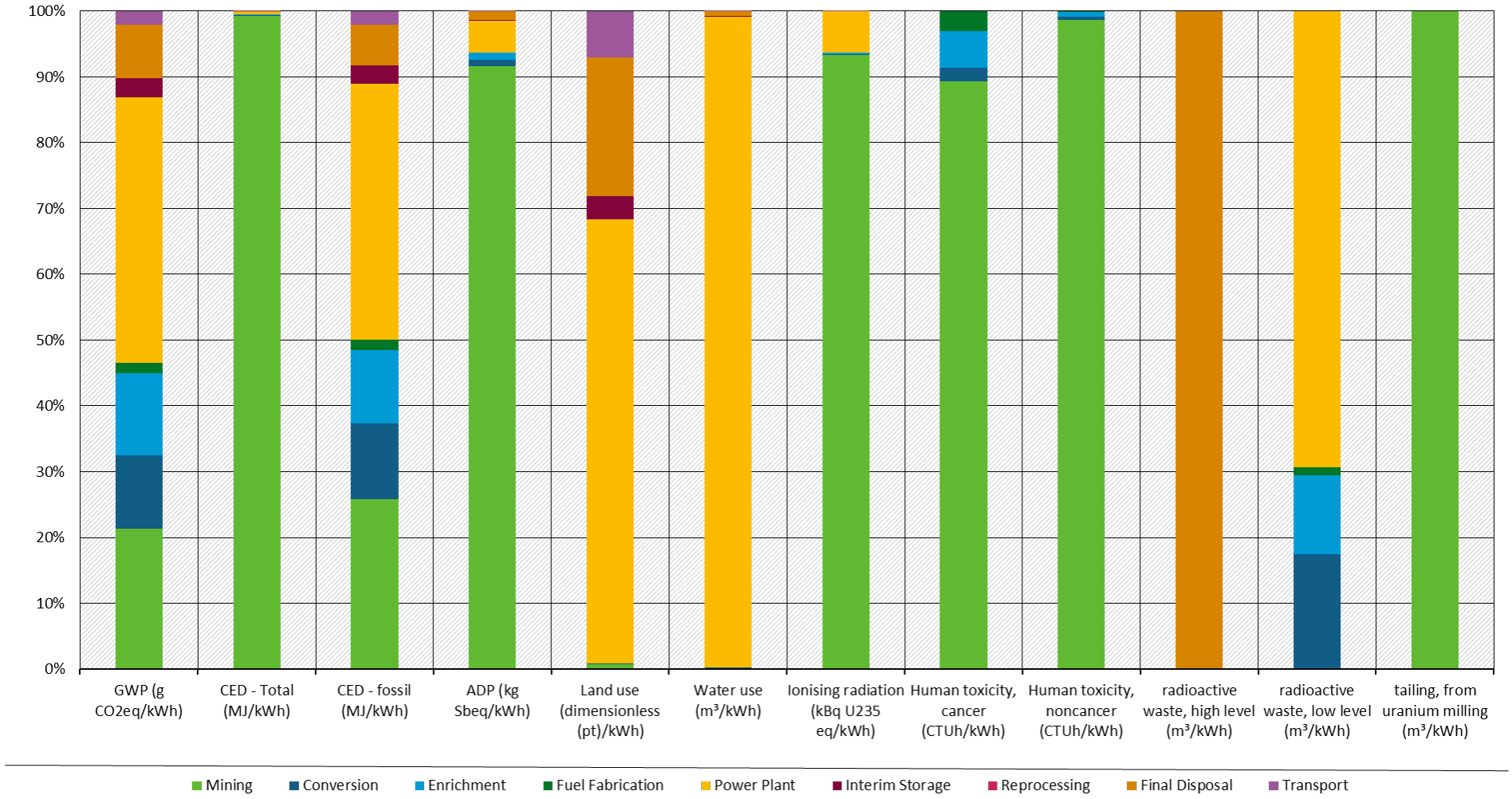
Figure 168: RU1 breakdown of GWP



Total GWP of RU1: 8,9 g CO2eq/kWh

Source: Öko-Institut

Figure 169: RU1 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.18 RU1_2030

Table 125: RU1_2030 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.16
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	Russia
Enrichment_Centrifuge	enrichment grade (% U235)	3.75
Enrichment_Centrifuge	Country	Russia
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	Russia
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	45
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	Russia
Electricity_Production_Nuclear	Load Factor	0
Electricity_Production_Nuclear	Net Efficiency (%)	0.31
Electricity_Production_Nuclear	Country	Russia
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	-
Backend	Country	Russia

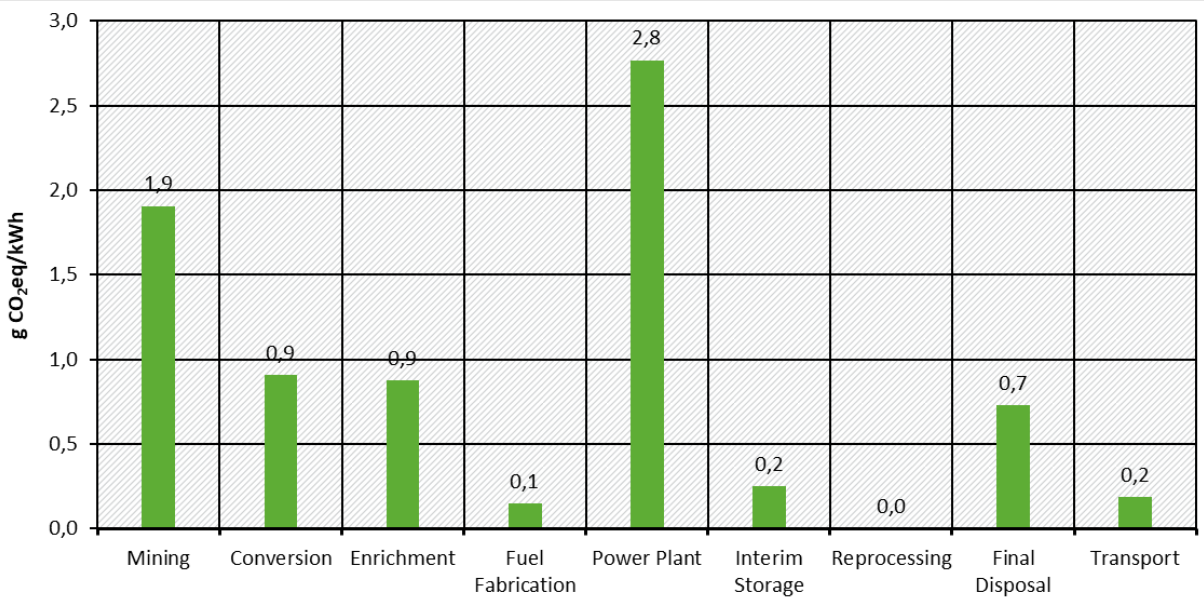
Source: Öko-Institut

Table 126: RU1_2030 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	7.8

Source: Öko-Institut

Figure 170: RU1_2030 breakdown of GWP



Total GWP of RU1_2030: 7,8 g CO2eq/kWh
Source: Öko-Institut

B.19 RU1_Gen3

Table 127: RU1_Gen3 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.16
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	Russia
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	Russia
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	Russia
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR (Gen3)
NPP_Construction	Country	Russia
Electricity_Production_Nuclear	Load Factor	0.78
Electricity_Production_Nuclear	Net Efficiency (%)	0.34
Electricity_Production_Nuclear	Country	Russia
NPP_Retrofitting	Replacement Ratio (%)	0

Process Step	Parameter	Value
Reprocessing	Country	-
Backend	Country	Russia

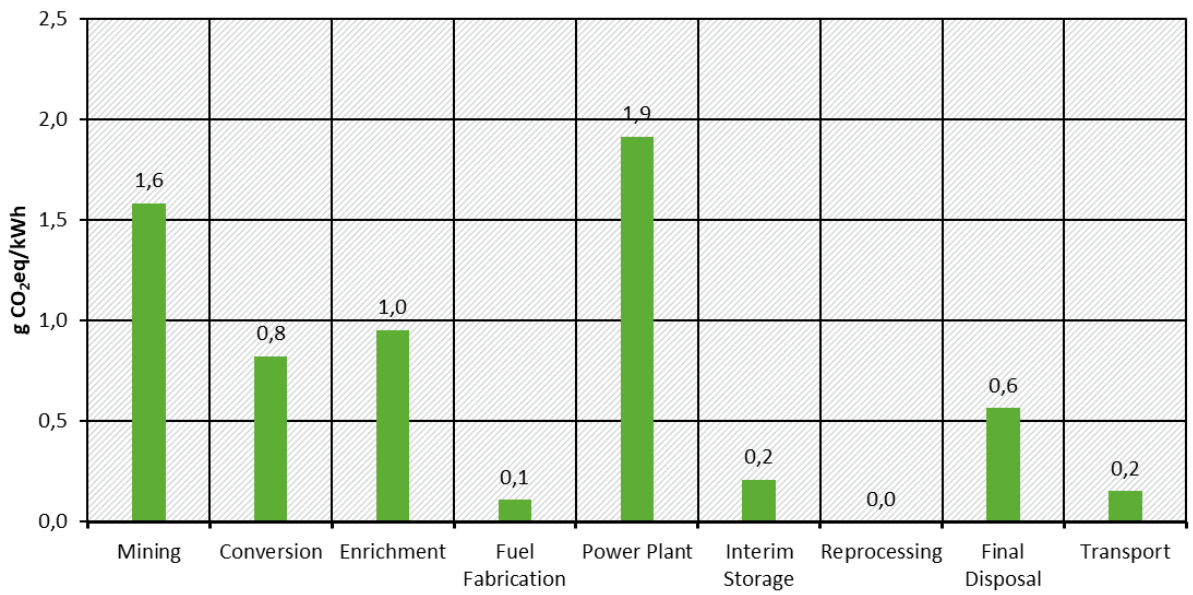
Source: Öko-Institut

Table 128: RU1_Gen3 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	6.3
CED - Total	MJ/kWh	1.3E+01
CED - fossil	MJ/kWh	9.0E-02
ADP	kg Sbeq/kWh	1.8E-06
Land use	dimensionless (pt)/kWh	1.9E-02
Water use	m^3/kWh	3.5E-02
Ionising radiation	kBq U235 eq/kWh	1.1E+00
Human toxicity, cancer	CTUh/kWh	2.2E-03
Human toxicity, noncancer	CTUh/kWh	1.2E-01
radioactive waste, high level	m^3/kWh	5.3E-09
radioactive waste, low level	m^3/kWh	7.1E-08
tailing, from uranium milling	m^3/kWh	5.1E-06

Source: Öko-Institut

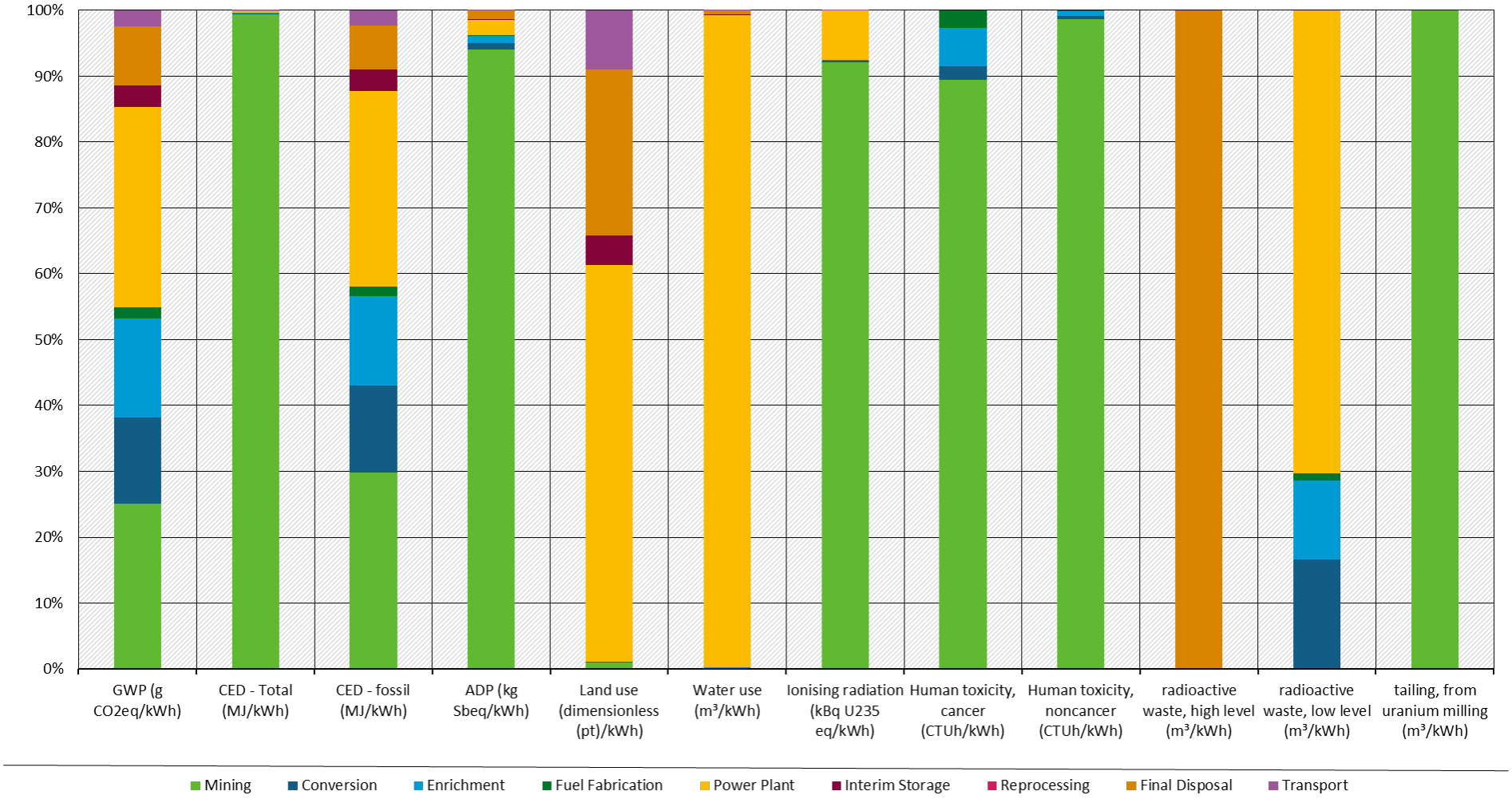
Figure 171: RU1_Gen3 breakdown of GWP



Total GWP of RU1_Gen3: 6,3 g CO2eq/kWh

Source: Öko-Institut

Figure 172: RU1_Gen3 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.20 RU1_Gen3_2030

Table 129: RU1_Gen3_2030 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.16
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	Russia
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	Russia
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	Russia
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR (Gen3)
NPP_Construction	Country	Russia
Electricity_Production_Nuclear	Load Factor	0
Electricity_Production_Nuclear	Net Efficiency (%)	0.34
Electricity_Production_Nuclear	Country	Russia
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	Russia

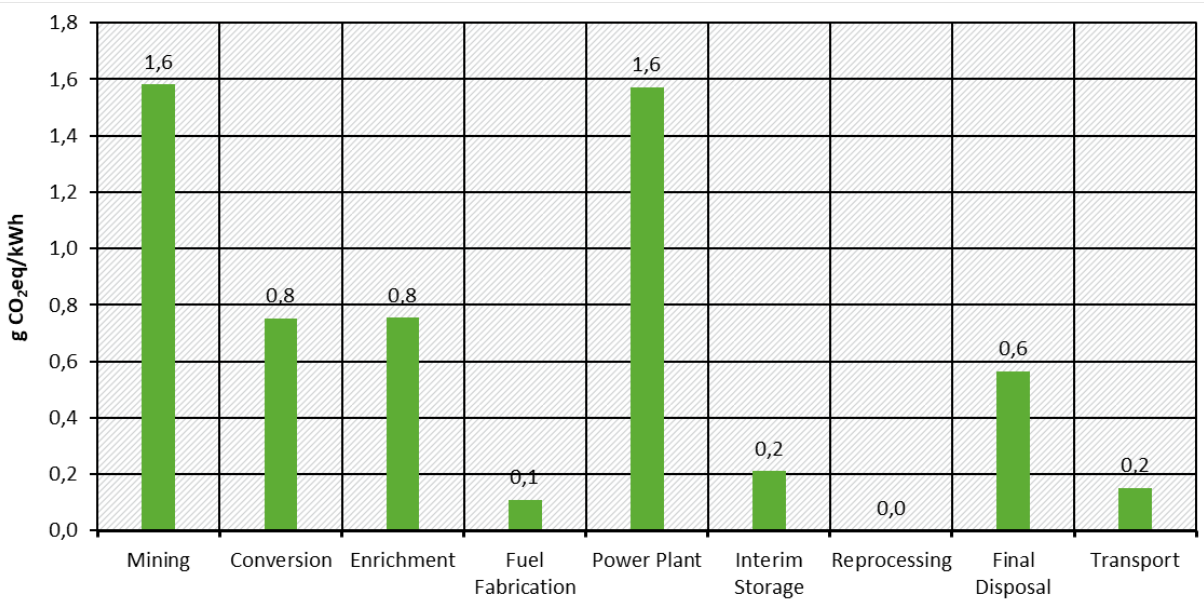
Source: Öko-Institut

Table 130: RU1_Gen3_2030 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	5.7

Source: Öko-Institut

Figure 173: RU1_Gen3_2030 breakdown of GWP



Total GWP of RU1_Gen3_2030: 5,7 g CO2eq/kWh
Source: Öko-Institut

B.21 RU1_SMR

Table 131: RU1_SMR life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.16
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	Russia
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	Russia
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	Russia
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	SMR
NPP_Construction	Country	Russia
Electricity_Production_Nuclear	Load Factor	0.78
Electricity_Production_Nuclear	Net Efficiency (%)	0.21
Electricity_Production_Nuclear	Country	Russia

Process Step	Parameter	Value
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	Russia

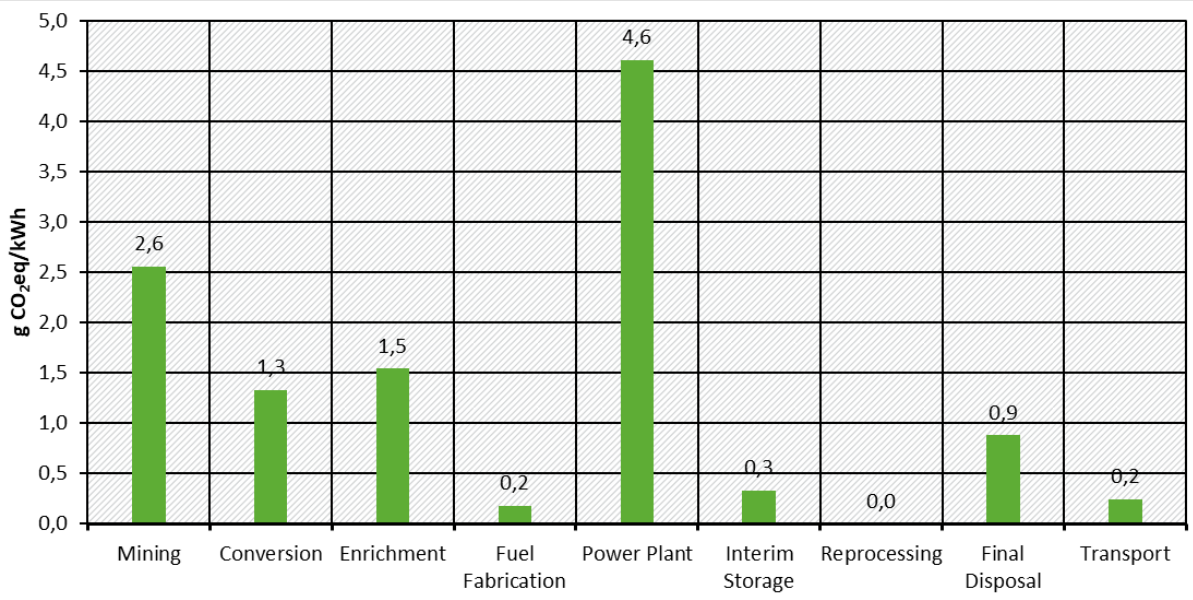
Source: Öko-Institut

Table 132: RU1_SMR life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	11.7
CED - Total	MJ/kWh	2.2E+01
CED - fossil	MJ/kWh	1.6E-01
ADP	kg Sbeq/kWh	3.0E-06
Land use	dimensionless (pt)/kWh	4.1E-02
Water use	m³/kWh	3.6E-02
Ionising radiation	kBq U235 eq/kWh	1.8E+00
Human toxicity, cancer	CTUh/kWh	3.5E-03
Human toxicity, noncancer	CTUh/kWh	2.0E-01
radioactive waste, high level	m³/kWh	8.5E-09
radioactive waste, low level	m³/kWh	1.0E-07
tailing, from uranium milling	m³/kWh	8.2E-06

Source: Öko-Institut

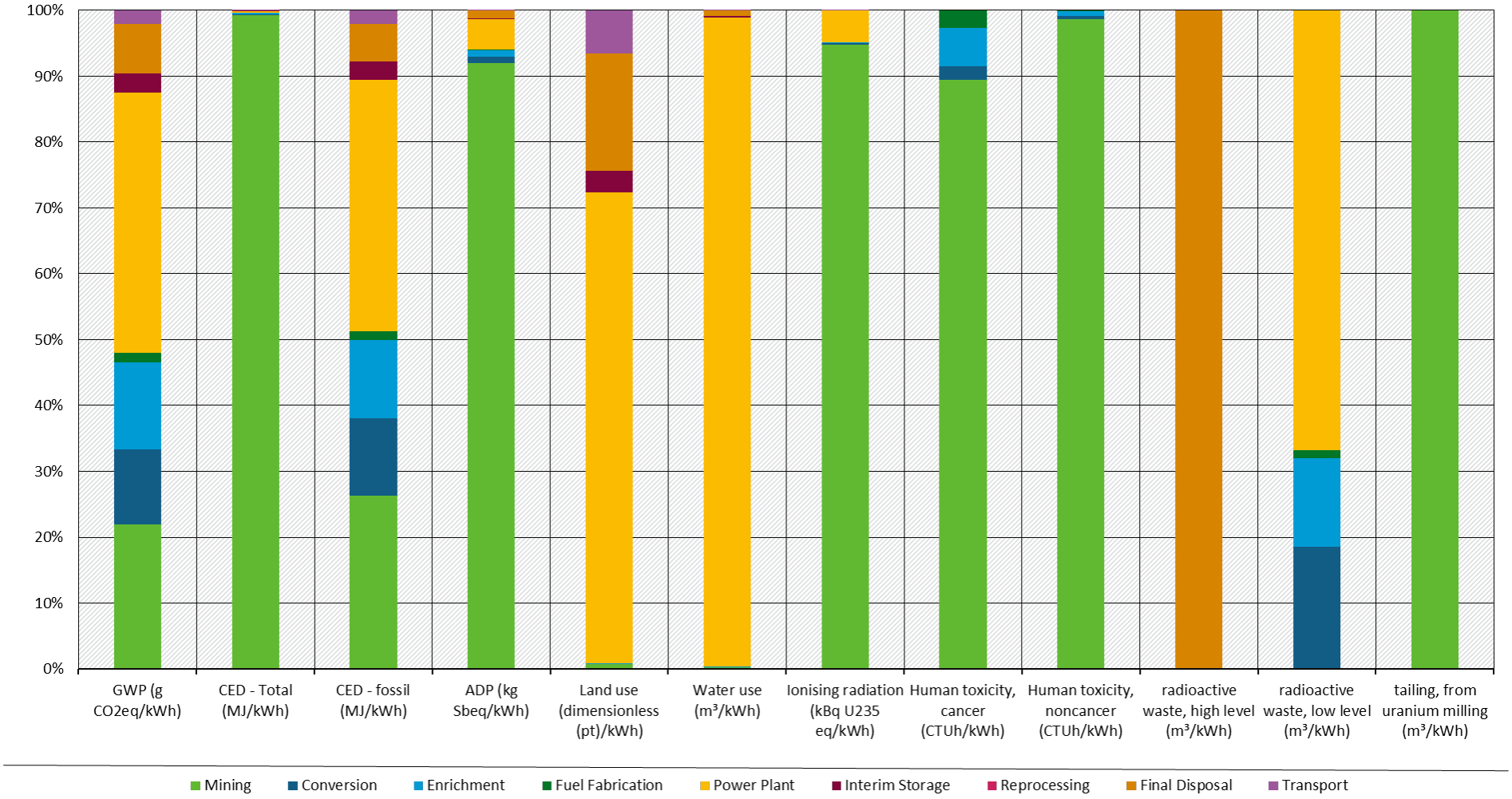
Figure 174: RU1_SMR breakdown of GWP



Total GWP of RU1_SMR: 11,7 g CO2eq/kWh

Source: Öko-Institut

Figure 175: RU1_SMR breakdown of impacts by life cycle stage



Source: Öko-Institut

B.22 RU1_SMR_2030

Table 133: RU1_SMR_2030 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.16
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	Russia
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	Russia
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	Russia
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	SMR
NPP_Construction	Country	Russia
Electricity_Production_Nuclear	Load Factor	0
Electricity_Production_Nuclear	Net Efficiency (%)	0.21
Electricity_Production_Nuclear	Country	Russia
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	Russia

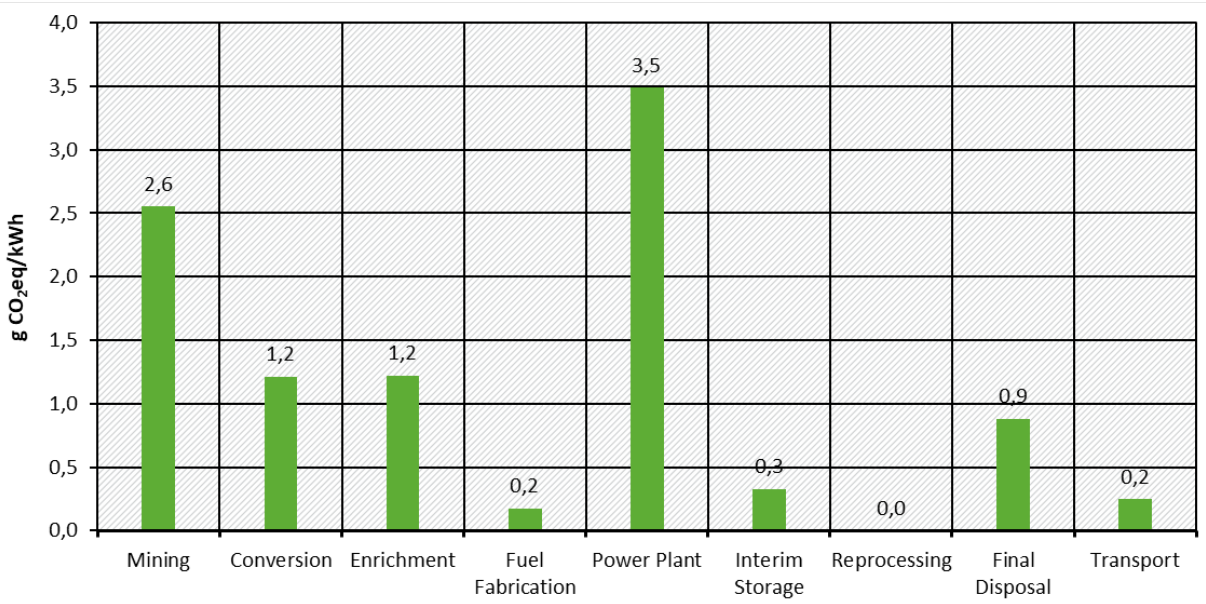
Source: Öko-Institut

Table 134: RU1_SMR_2030 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	10.1

Source: Öko-Institut

Figure 176: RU1_SMR_2030 breakdown of GWP



Total GWP of RU1_SMR_2030: 10,1 g CO2eq/kWh
Source: Öko-Institut

B.23 RU2

Table 135: RU2 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.03
Mine_Infrastructure	Mine Type	In-situ leaching
Conversion_UF6	Country	Russia
Enrichment_Centrifuge	enrichment grade (% U235)	3.75
Enrichment_Centrifuge	Country	Russia
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	Russia
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	45
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	Russia
Electricity_Production_Nuclear	Load Factor	0.78
Electricity_Production_Nuclear	Net Efficiency (%)	0.31
Electricity_Production_Nuclear	Country	Russia

Process Step	Parameter	Value
NPP_Retrofitting	Replacement Ratio (%)	0.5
Reprocessing	Country	-
Backend	Country	Russia

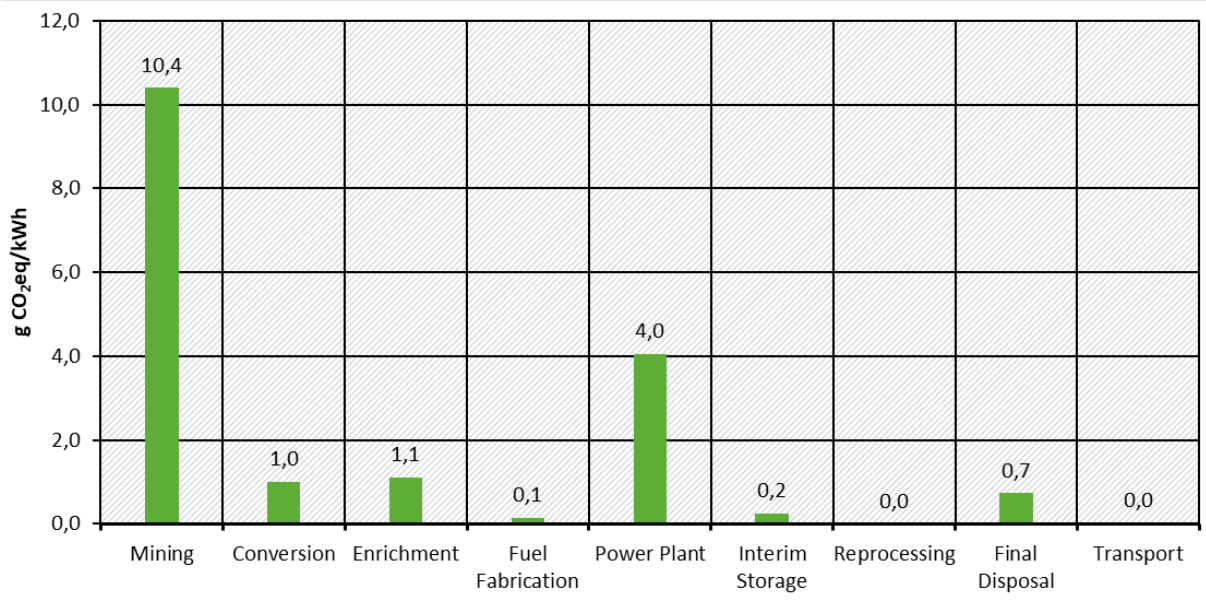
Source: Öko-Institut

Table 136: RU2 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	17.7
CED - Total	MJ/kWh	1.8E+02
CED - fossil	MJ/kWh	8.8E+01
ADP	kg Sbeq/kWh	1.1E-05
Land use	dimensionless (pt)/kWh	2.7E-02
Water use	m³/kWh	3.7E-02
Ionising radiation	kBq U235 eq/kWh	9.4E-02
Human toxicity, cancer	CTUh/kWh	1.1E-03
Human toxicity, noncancer	CTUh/kWh	1.1E-01
radioactive waste, high level	m³/kWh	7.2E-09
radioactive waste, low level	m³/kWh	8.1E-08
tailing, from uranium milling	m³/kWh	0.0E+00

Source: Öko-Institut

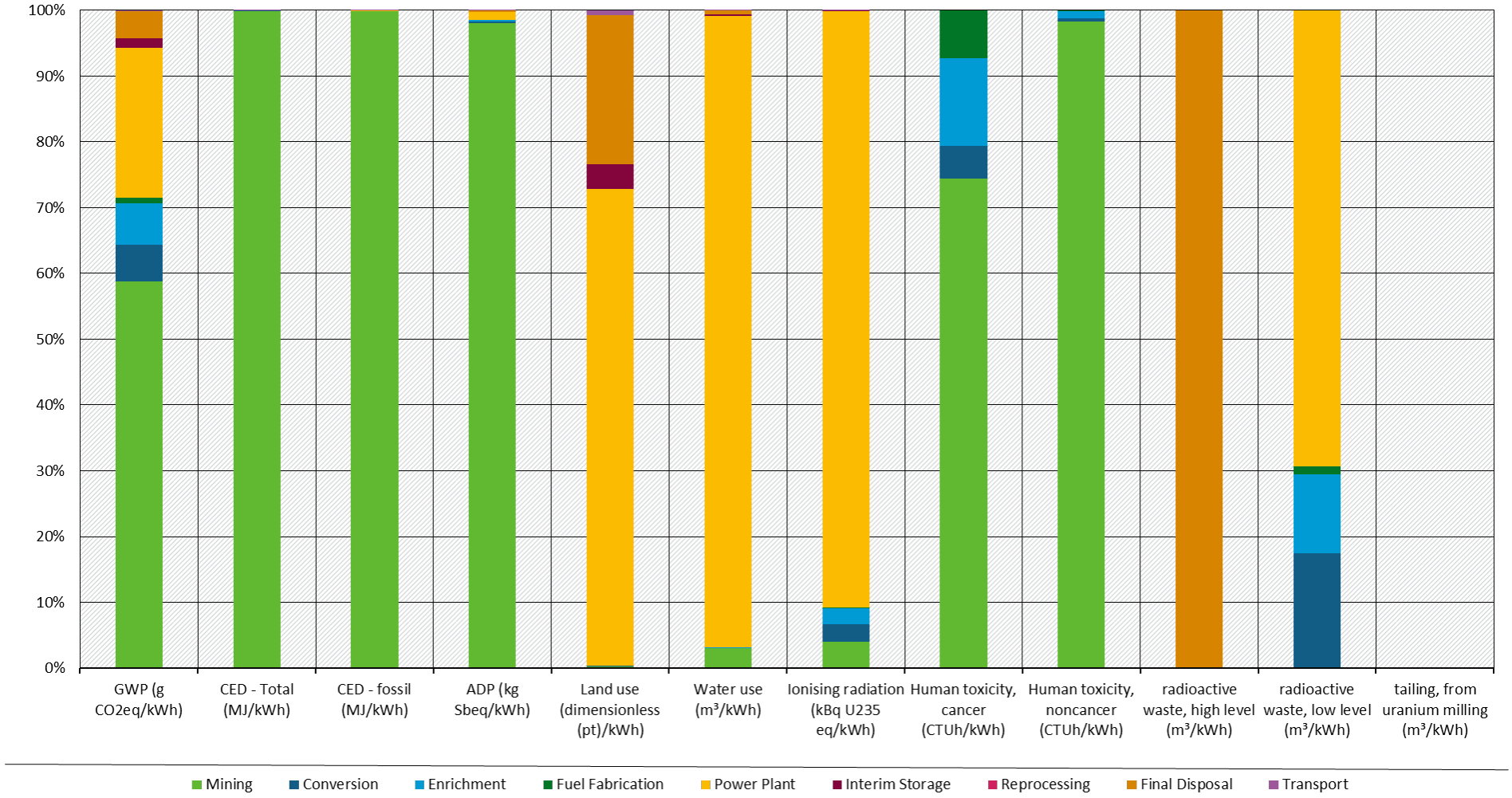
Figure 177: RU2 breakdown of GWP



Total GWP of RU2: 17,7 g CO2eq/kWh

Source: Öko-Institut

Figure 178: RU2 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.24 RU3

Table 137: RU3 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.05
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	Russia
Enrichment_Centrifuge	enrichment grade (% U235)	3.75
Enrichment_Centrifuge	Country	Russia
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	2.87
Fuel_Element_Fabrication	Country UOX	Russia
Fuel_Element_Fabrication	Country MOX	Russia
NPP_Construction	plant life (y)	45
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	Russia
Electricity_Production_Nuclear	Load Factor	0.78
Electricity_Production_Nuclear	Net Efficiency (%)	0.31
Electricity_Production_Nuclear	Country	Russia
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	Russia
Backend	Country	Russia

Source: Öko-Institut

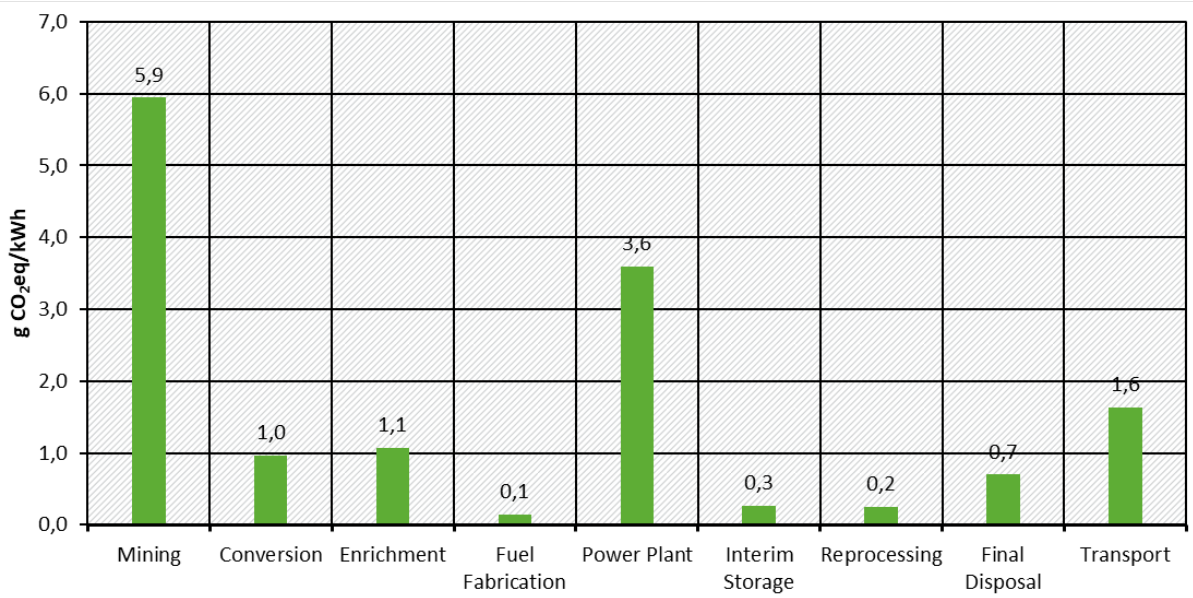
Table 138: RU3 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	14.6
CED - Total	MJ/kWh	5.0E+01
CED - fossil	MJ/kWh	2.2E-01
ADP	kg Sbeq/kWh	6.7E-06
Land use	dimensionless (pt)/kWh	4.5E-02
Water use	m^3/kWh	3.6E-02
Ionising radiation	kBq U235 eq/kWh	4.0E+00
Human toxicity, cancer	CTUh/kWh	7.7E-03

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	4.5E-01
radioactive waste, high level	m³/kWh	8.6E-09
radioactive waste, low level	m³/kWh	8.4E-08
tailing, from uranium milling	m³/kWh	1.9E-05

Source: Öko-Institut

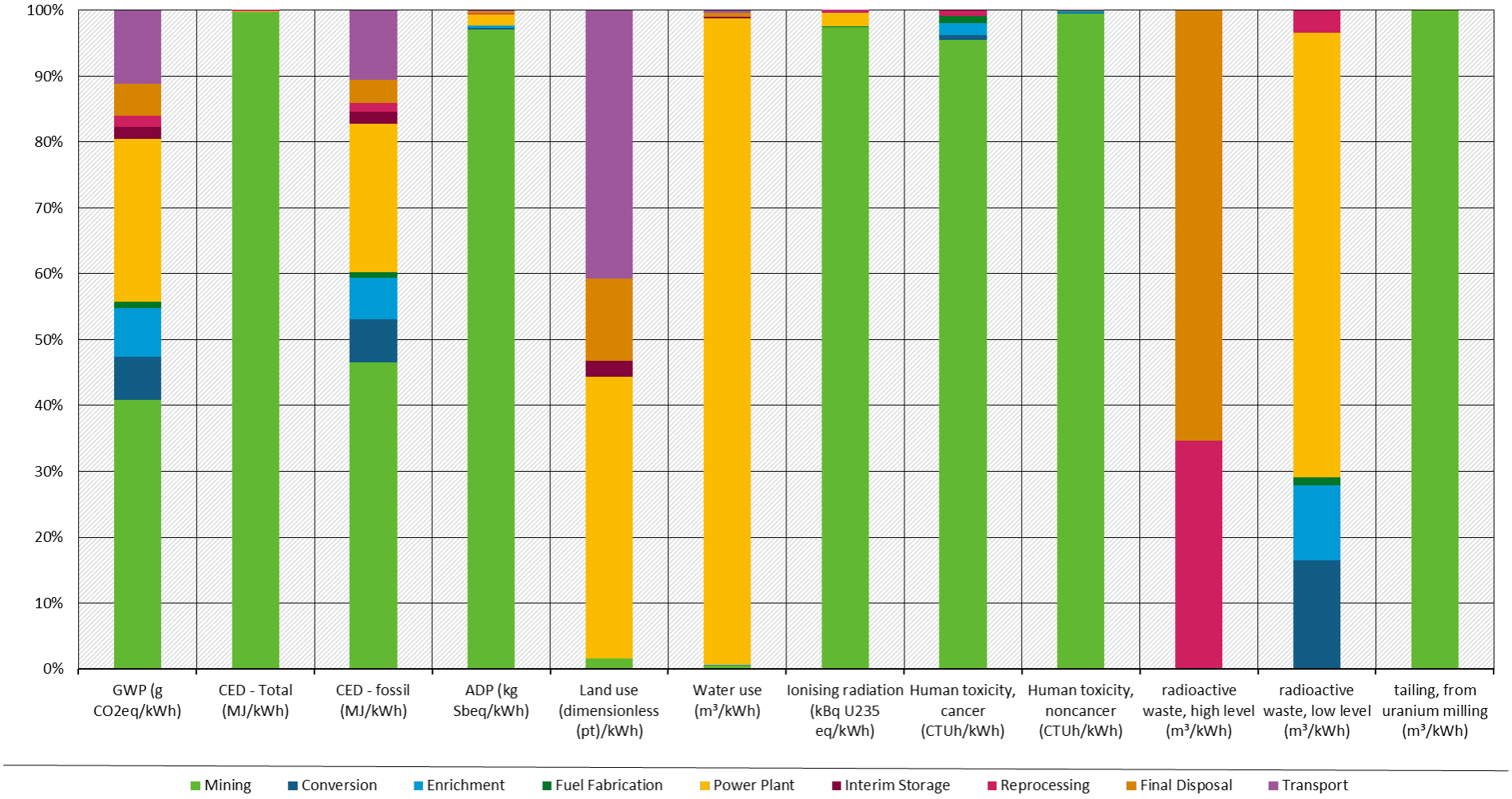
Figure 179: RU3 breakdown of GWP



Total GWP of RU3: 14,6 g CO2eq/kWh

Source: Öko-Institut

Figure 180: RU3 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.25 RU4_Gen3

Table 139: RU4_Gen3 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.16
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	Russia
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	Russia
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	Russia
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR (Gen3)
NPP_Construction	Country	Turkey
Electricity_Production_Nuclear	Load Factor	0.9
Electricity_Production_Nuclear	Net Efficiency (%)	0.35
Electricity_Production_Nuclear	Country	Turkey
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	Russia

Source: Öko-Institut

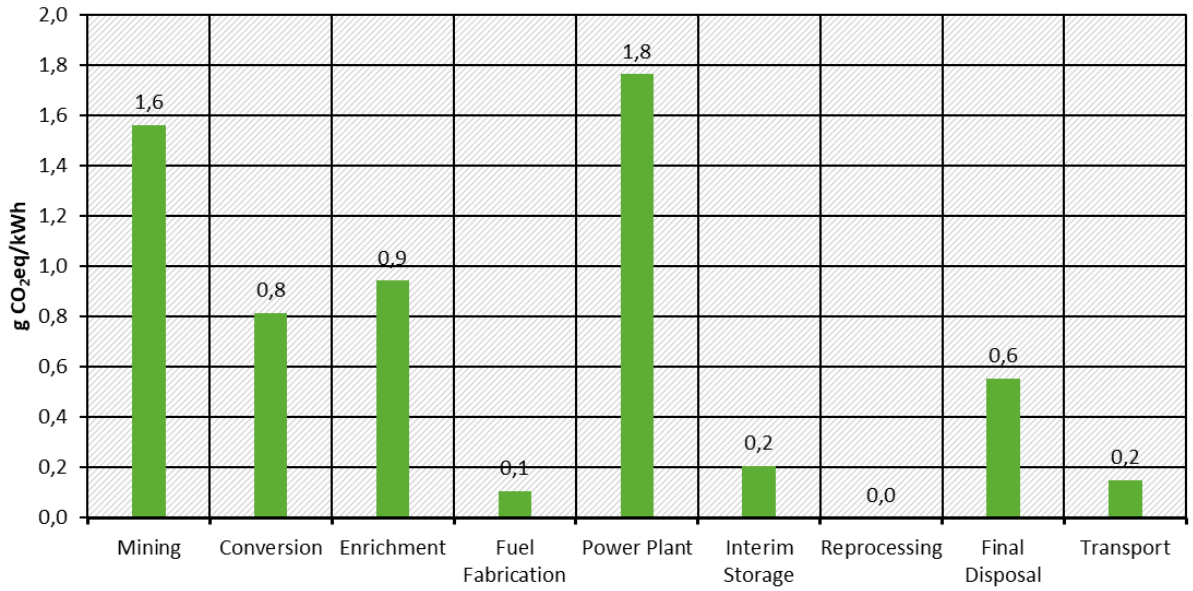
Table 140: RU4_Gen3 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	6.1
CED - Total	MJ/kWh	1.3E+01
CED - fossil	MJ/kWh	8.2E-02
ADP	kg Sbeq/kWh	1.8E-06
Land use	dimensionless (pt)/kWh	1.8E-02
Water use	m^3/kWh	1.2E-01
Ionising radiation	kBq U235 eq/kWh	1.1E+00
Human toxicity, cancer	CTUh/kWh	2.2E-03

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	1.2E-01
radioactive waste, high level	m³/kWh	5.2E-09
radioactive waste, low level	m³/kWh	6.9E-08
tailing, from uranium milling	m³/kWh	5.0E-06

Source: Öko-Institut

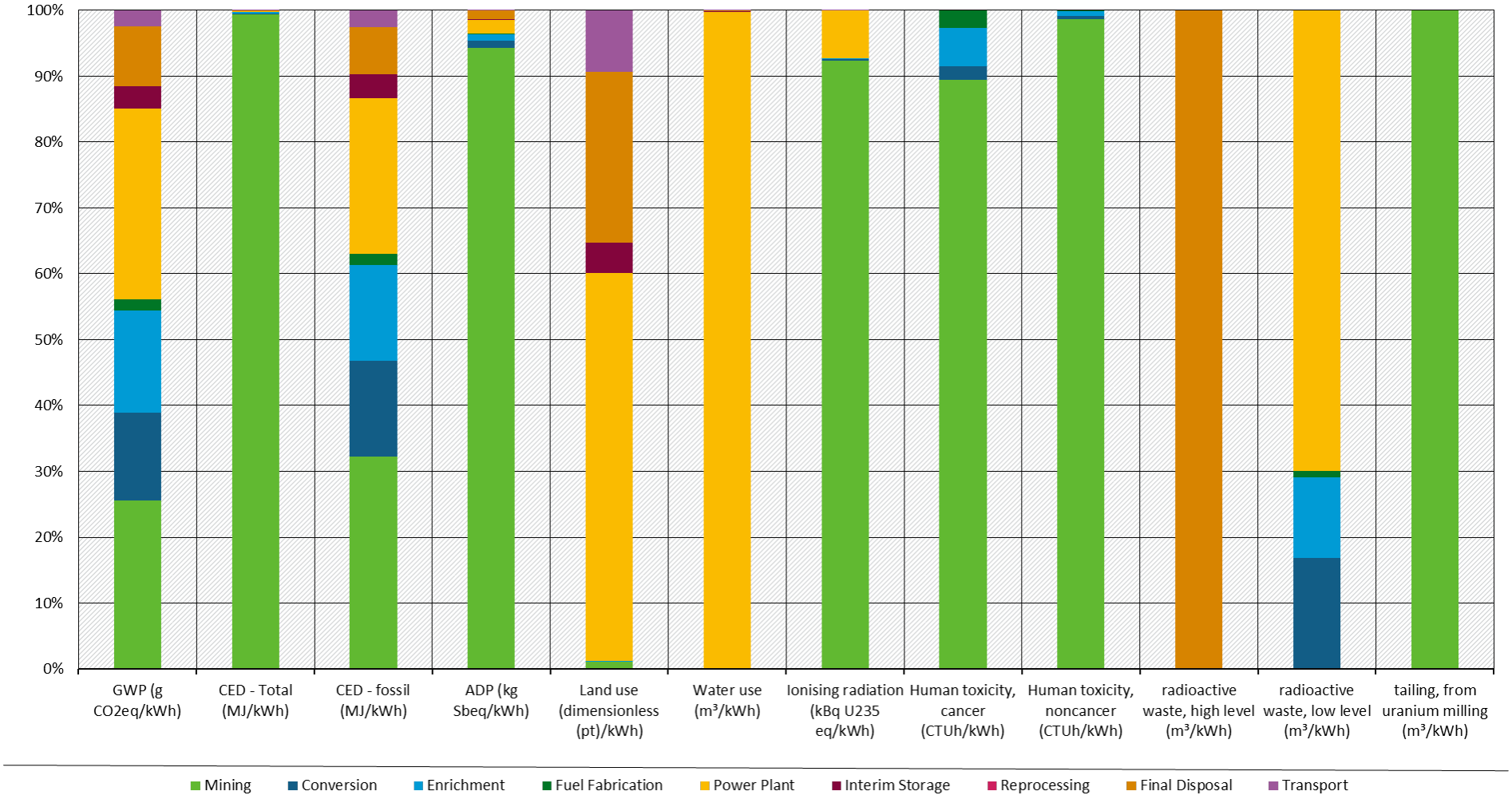
Figure 181: RU4_Gen3 breakdown of GWP



Total GWP of RU4_Gen3: 6,1 g CO2eq/kWh

Source: Öko-Institut

Figure 182: RU4_Gen3 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.26 NA1

Table 141: NA1 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.05
Mine_Infrastructure	Mine Type	Underground
Conversion_UF6	Country	United States
Enrichment_Centrifuge	enrichment grade (% U235)	4
Enrichment_Centrifuge	Country	United States
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	United States
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	United States
Electricity_Production_Nuclear	Load Factor	0.91
Electricity_Production_Nuclear	Net Efficiency (%)	0.31
Electricity_Production_Nuclear	Country	United States
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	-
Backend	Country	United States

Source: Öko-Institut

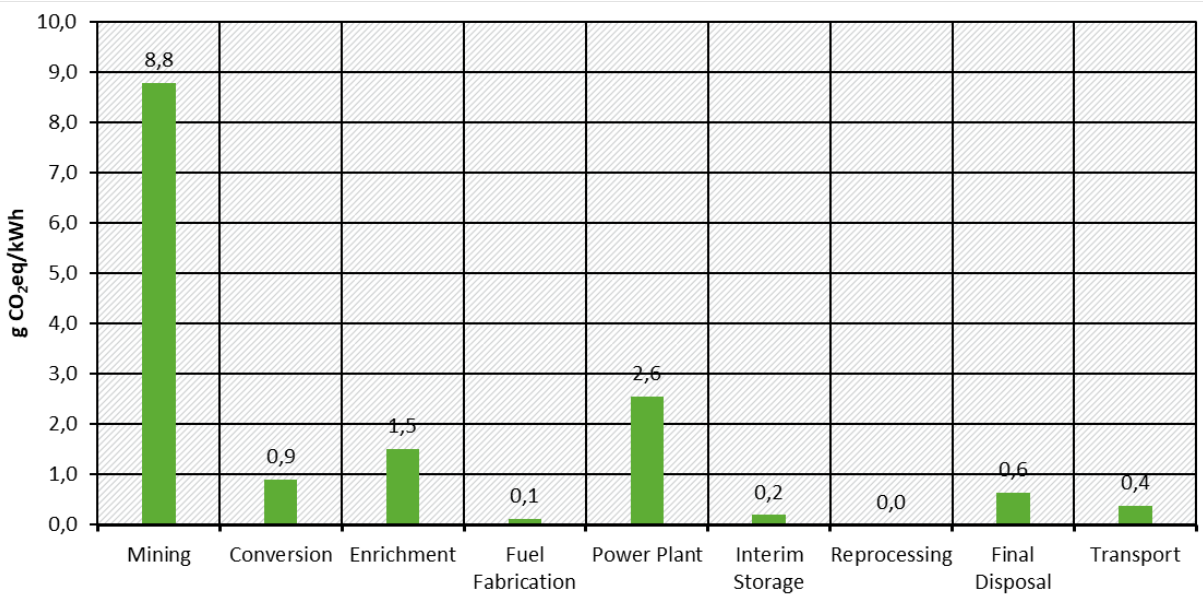
Table 142: NA1 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	15.1
CED - Total	MJ/kWh	5.2E+01
CED - fossil	MJ/kWh	1.9E-01
ADP	kg Sbeq/kWh	6.9E-06
Land use	dimensionless (pt)/kWh	3.0E-02
Water use	m^3/kWh	9.7E-02
Ionising radiation	kBq U235 eq/kWh	4.3E+00
Human toxicity, cancer	CTUh/kWh	8.0E-03

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	4.7E-01
radioactive waste, high level	m³/kWh	6.5E-09
radioactive waste, low level	m³/kWh	7.9E-08
tailing, from uranium milling	m³/kWh	2.0E-05

Source: Öko-Institut

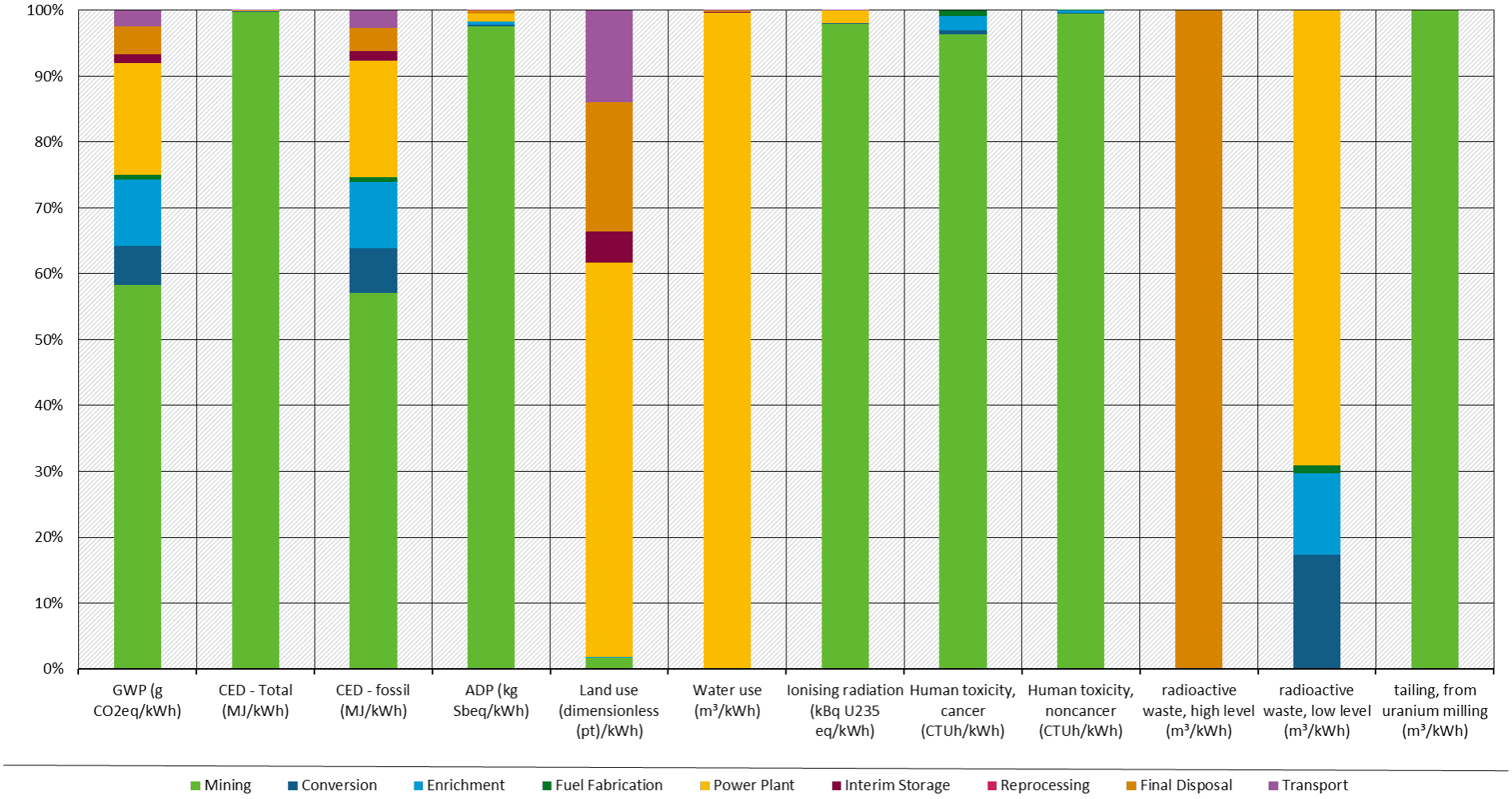
Figure 183: NA1 breakdown of GWP



Total GWP of NA1: 15,1 g CO2eq/kWh

Source: Öko-Institut

Figure 184: NA1 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.27 NA1_2030

Table 143: NA1_2030 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.05
Mine_Infrastructure	Mine Type	Underground
Conversion_UF6	Country	United States
Enrichment_Centrifuge	enrichment grade (% U235)	4
Enrichment_Centrifuge	Country	United States
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	United States
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	United States
Electricity_Production_Nuclear	Load Factor	0
Electricity_Production_Nuclear	Net Efficiency (%)	0.31
Electricity_Production_Nuclear	Country	United States
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	-
Backend	Country	United States

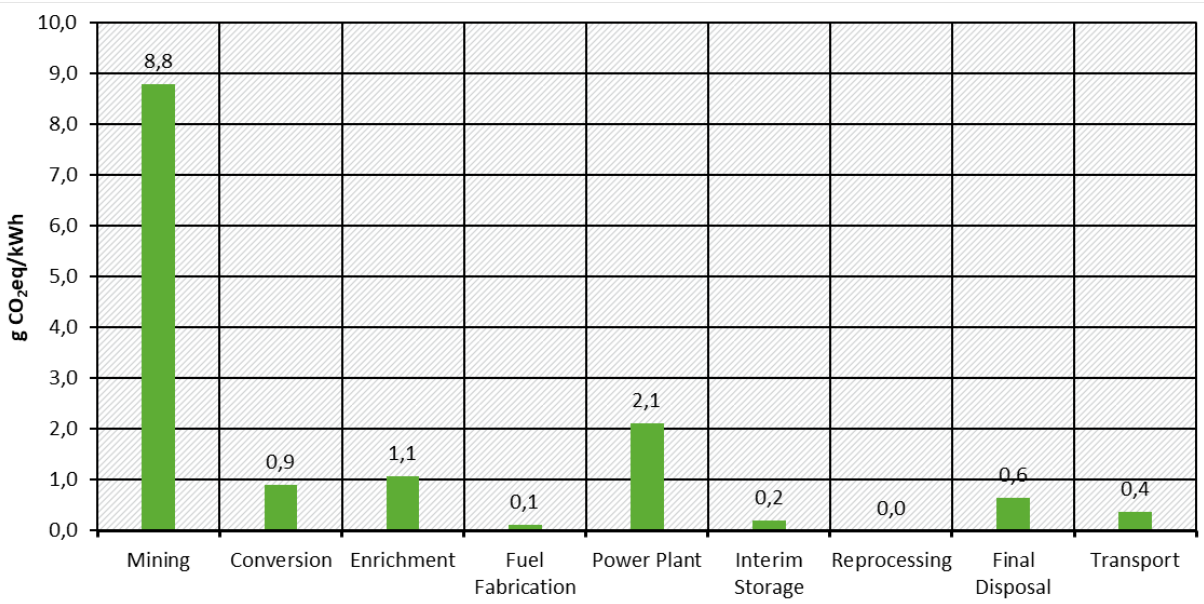
Source: Öko-Institut

Table 144: NA1_2030 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	14.2

Source: Öko-Institut

Figure 185: NA1_2030 breakdown of GWP



Total GWP of NA1_2030: 14,2 g CO2eq/kWh
Source: Öko-Institut

B.28 NA1_Gen3

Table 145: NA1_Gen3 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.05
Mine_Infrastructure	Mine Type	Underground
Conversion_UF6	Country	United States
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	United States
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	United States
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR (Gen3)
NPP_Construction	Country	United States
Electricity_Production_Nuclear	Load Factor	0.91
Electricity_Production_Nuclear	Net Efficiency (%)	0.33
Electricity_Production_Nuclear	Country	United States

Process Step	Parameter	Value
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	United States

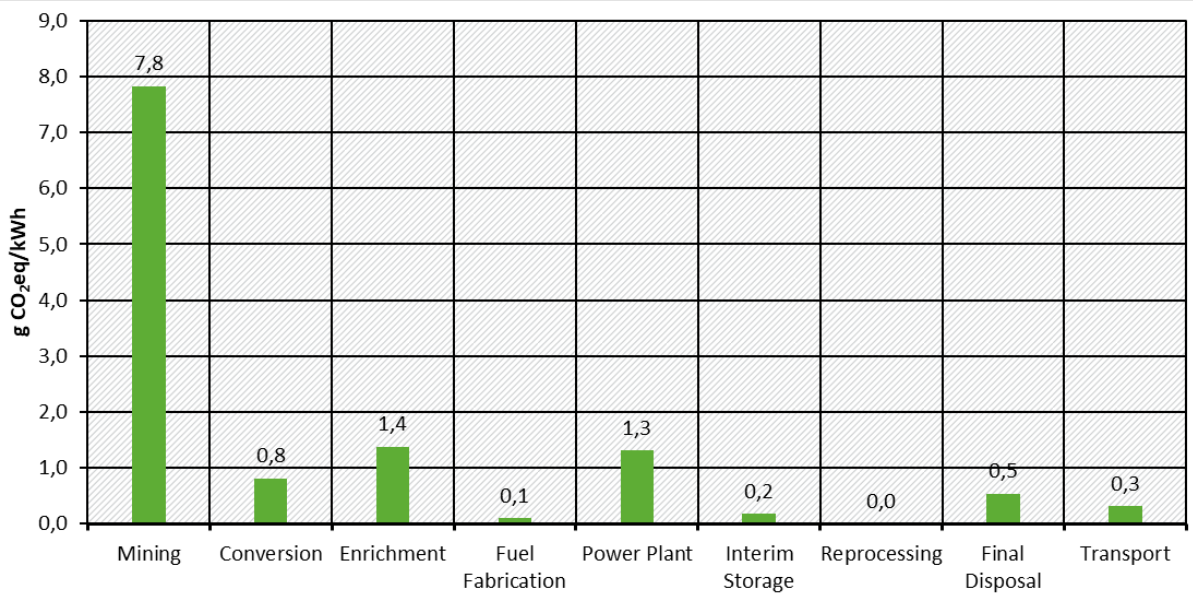
Source: Öko-Institut

Table 146: NA1_Gen3 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	12.4
CED - Total	MJ/kWh	4.6E+01
CED - fossil	MJ/kWh	1.6E-01
ADP	kg Sbeq/kWh	6.1E-06
Land use	dimensionless (pt)/kWh	2.0E-02
Water use	m³/kWh	9.6E-02
Ionising radiation	kBq U235 eq/kWh	3.8E+00
Human toxicity, cancer	CTUh/kWh	7.1E-03
Human toxicity, noncancer	CTUh/kWh	4.2E-01
radioactive waste, high level	m³/kWh	5.5E-09
radioactive waste, low level	m³/kWh	6.5E-08
tailing, from uranium milling	m³/kWh	1.8E-05

Source: Öko-Institut

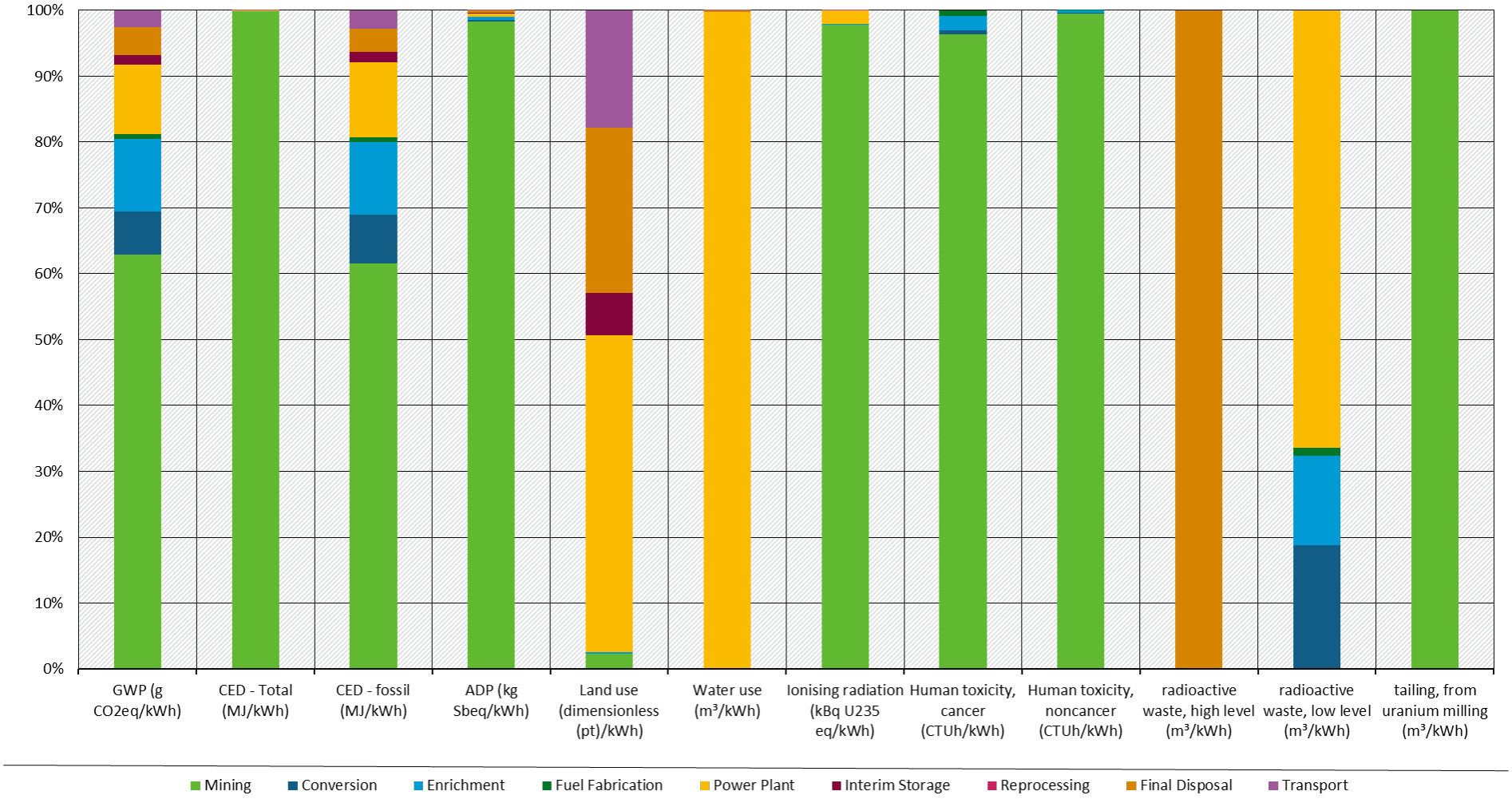
Figure 186: NA1_Gen3 breakdown of GWP



Total GWP of NA1_Gen3: 12,4 g CO2eq/kWh

Source: Öko-Institut

Figure 187: NA1_Gen3 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.29 NA1_Gen3_2030

Table 147: NA1_Gen3_2030 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.05
Mine_Infrastructure	Mine Type	Underground
Conversion_UF6	Country	United States
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	United States
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	United States
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR (Gen3)
NPP_Construction	Country	United States
Electricity_Production_Nuclear	Load Factor	0
Electricity_Production_Nuclear	Net Efficiency (%)	0.33
Electricity_Production_Nuclear	Country	United States
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	United States

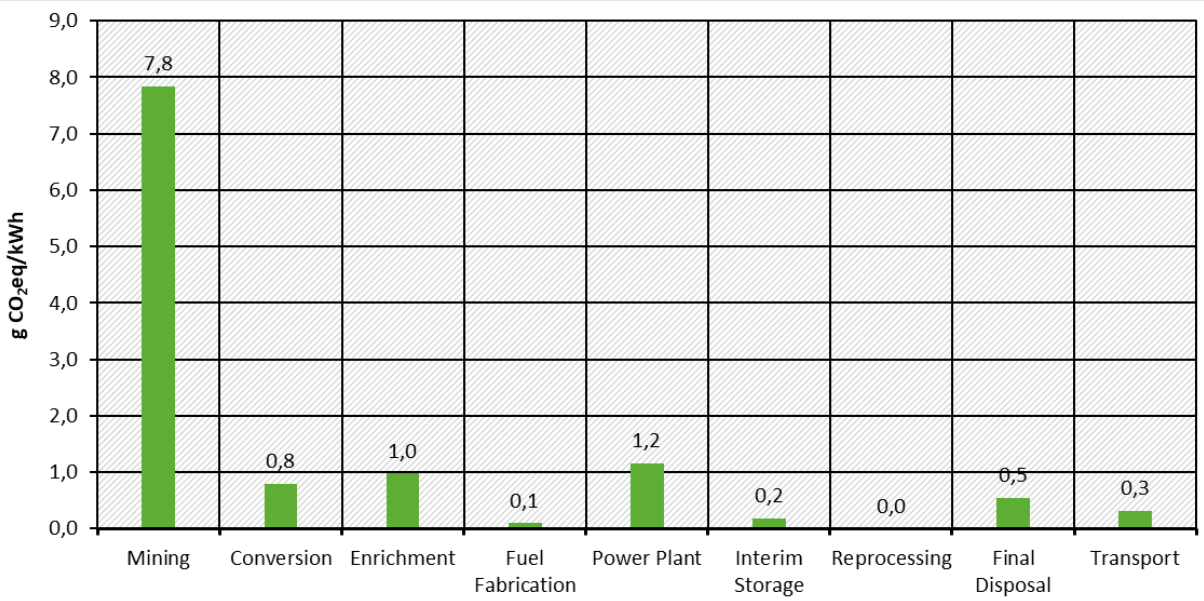
Source: Öko-Institut

Table 148: NA1_Gen3_2030 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	11.9

Source: Öko-Institut

Figure 188: NA1_Gen3_2030 breakdown of GWP



Total GWP of NA1_Gen3_2030: 11,9 g CO2eq/kWh
Source: Öko-Institut

B.30 NA1_SMR_v1

Table 149: NA1_SMR_v1 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.05
Mine_Infrastructure	Mine Type	Underground
Conversion_UF6	Country	United States
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	United States
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	United States
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	SMR
NPP_Construction	Country	United States
Electricity_Production_Nuclear	Load Factor	0.91
Electricity_Production_Nuclear	Net Efficiency (%)	0.29
Electricity_Production_Nuclear	Country	United States

Process Step	Parameter	Value
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	United States

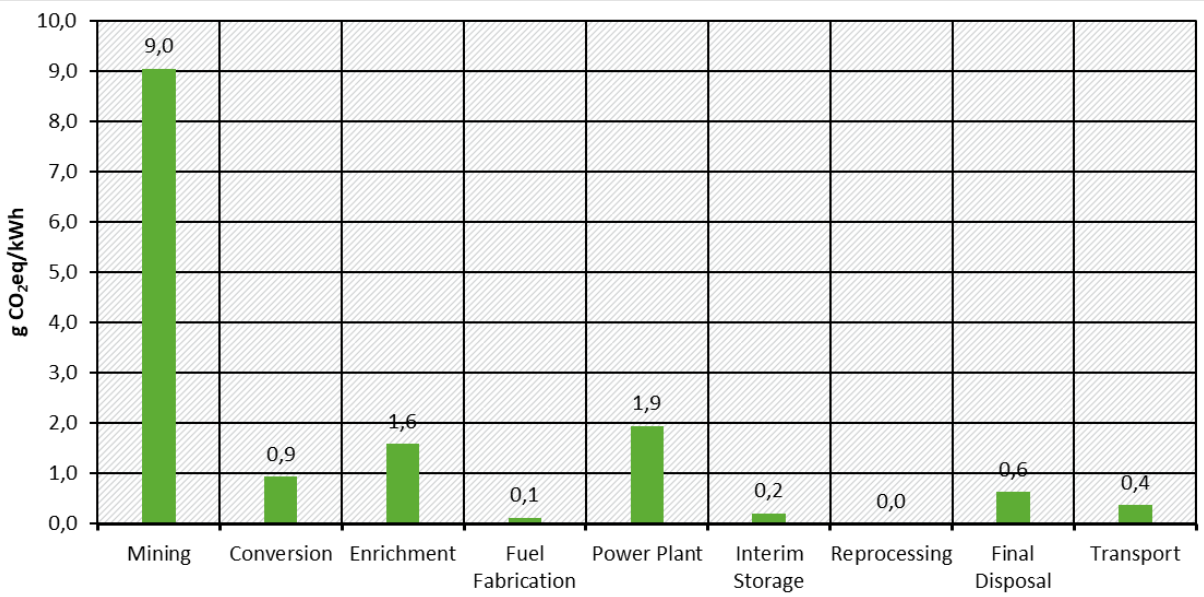
Source: Öko-Institut

Table 150: NA1_SMR_v1 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	14.8
CED - Total	MJ/kWh	5.3E+01
CED - fossil	MJ/kWh	1.9E-01
ADP	kg Sbeq/kWh	7.1E-06
Land use	dimensionless (pt)/kWh	2.7E-02
Water use	m³/kWh	9.7E-02
Ionising radiation	kBq U235 eq/kWh	4.4E+00
Human toxicity, cancer	CTUh/kWh	8.2E-03
Human toxicity, noncancer	CTUh/kWh	4.9E-01
radioactive waste, high level	m³/kWh	6.4E-09
radioactive waste, low level	m³/kWh	7.8E-08
tailing, from uranium milling	m³/kWh	2.1E-05

Source: Öko-Institut

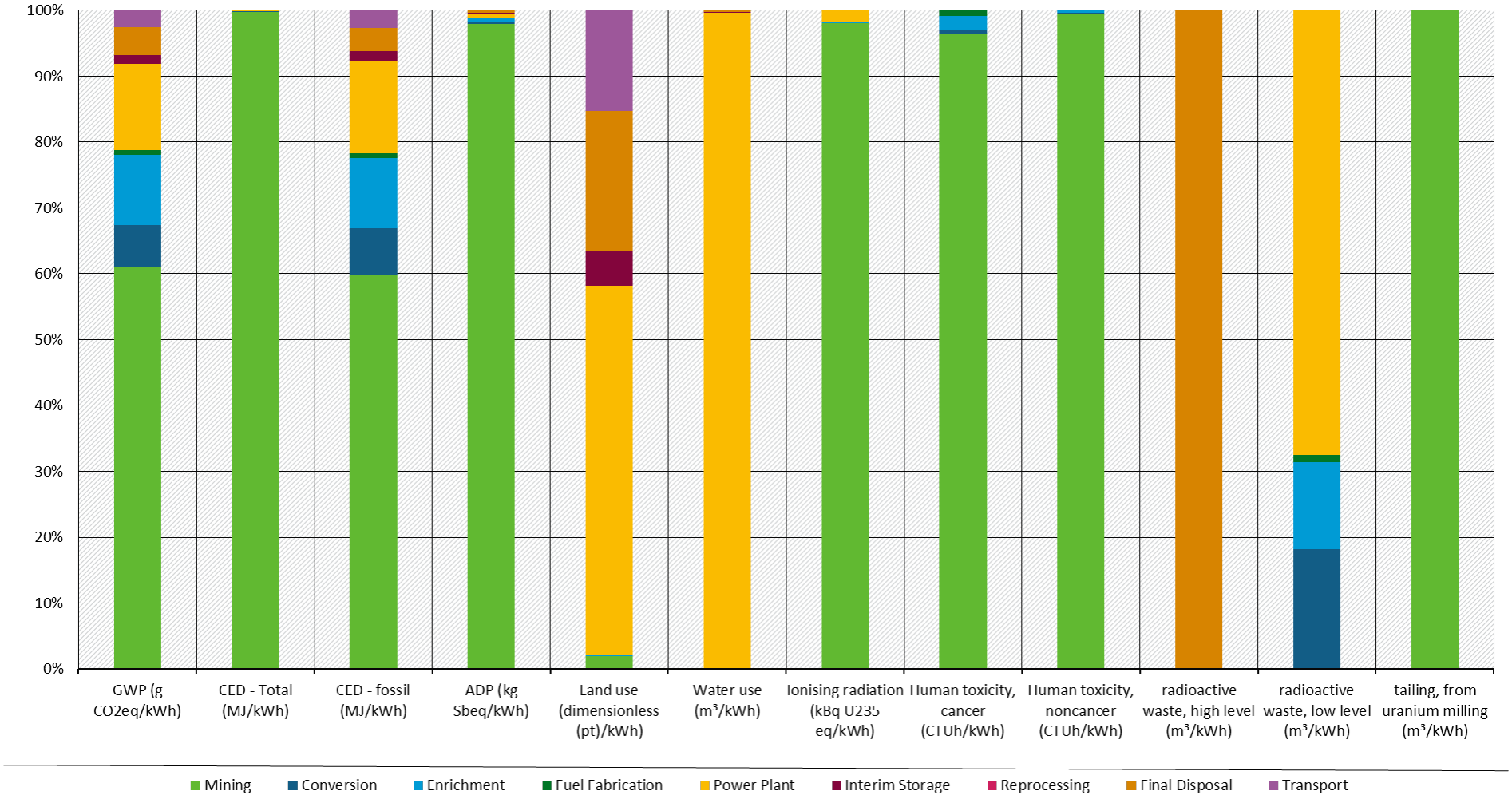
Figure 189: NA1_SMR_v1 breakdown of GWP



Total GWP of NA1_SMR_v1: 14,8 g CO2eq/kWh

Source: Öko-Institut

Figure 190: NA1_SMR_v1 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.31 NA1_SMR_v1_2030

Table 151: NA1_SMR_v_20301 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.05
Mine_Infrastructure	Mine Type	Underground
Conversion_UF6	Country	United States
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	United States
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	United States
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	SMR
NPP_Construction	Country	United States
Electricity_Production_Nuclear	Load Factor	0
Electricity_Production_Nuclear	Net Efficiency (%)	0.29
Electricity_Production_Nuclear	Country	United States
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	United States

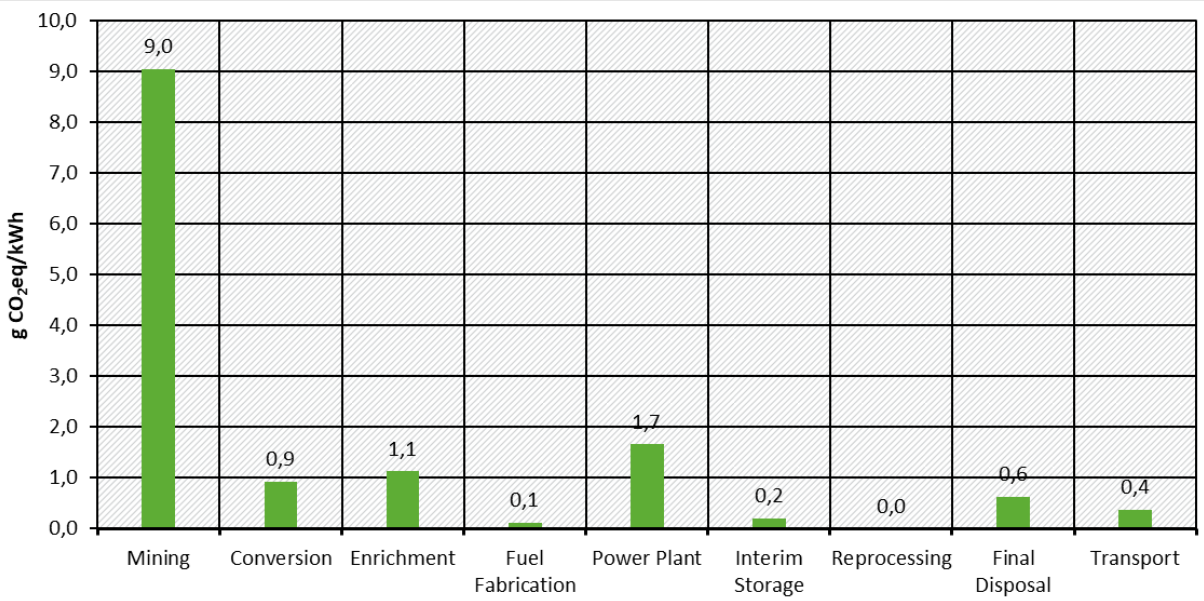
Source: Öko-Institut

Table 152: NA1_SMR_v1_2030 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	14.1

Source: Öko-Institut

Figure 191: NA1_SMR_v1_2030 breakdown of GWP



Total GWP of NA1_SMR_v1_2030: 14,1 g CO2eq/kWh
Source: Öko-Institut

B.32 NA1_SMR_v2

Table 153: NA1_SMR_v2 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.05
Mine_Infrastructure	Mine Type	Underground
Conversion_UF6	Country	United States
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	United States
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	United States
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	SMR
NPP_Construction	Country	United States
Electricity_Production_Nuclear	Load Factor	0.91
Electricity_Production_Nuclear	Net Efficiency (%)	0.31
Electricity_Production_Nuclear	Country	United States

Process Step	Parameter	Value
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	United States

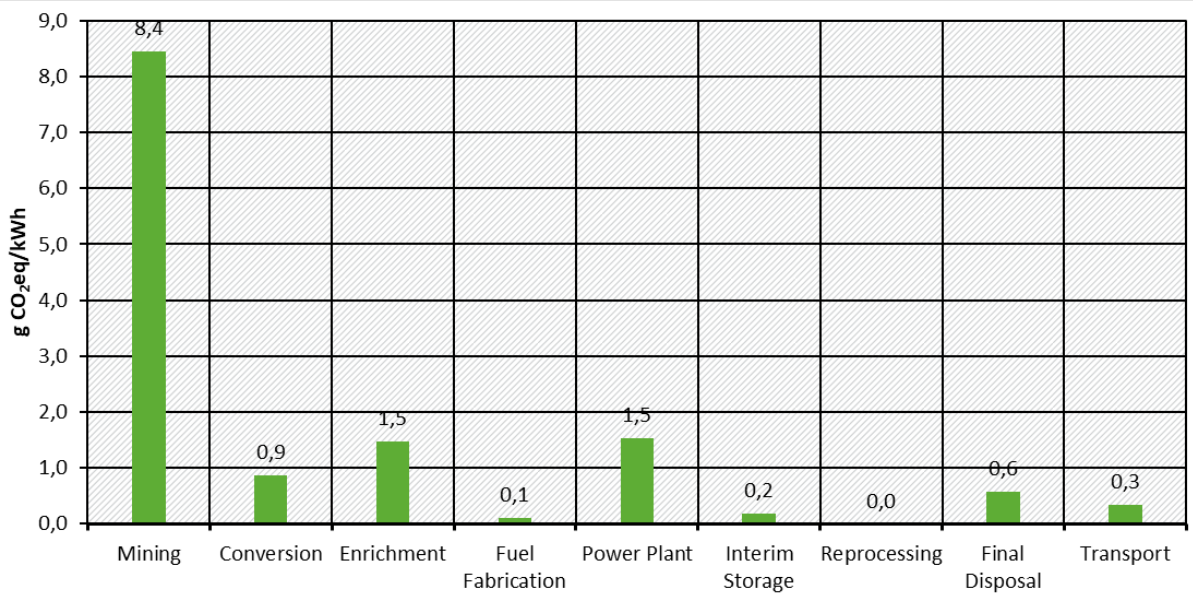
Source: Öko-Institut

Table 154: NA1_SMR_v2 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	13.5
CED - Total	MJ/kWh	5.0E+01
CED - fossil	MJ/kWh	1.7E-01
ADP	kg Sbeq/kWh	6.6E-06
Land use	dimensionless (pt)/kWh	2.3E-02
Water use	m^3/kWh	9.6E-02
Ionising radiation	kBq U235 eq/kWh	4.1E+00
Human toxicity, cancer	CTUh/kWh	7.7E-03
Human toxicity, noncancer	CTUh/kWh	4.5E-01
radioactive waste, high level	m^3/kWh	6.0E-09
radioactive waste, low level	m^3/kWh	7.0E-08
tailing, from uranium milling	m^3/kWh	1.9E-05

Source: Öko-Institut

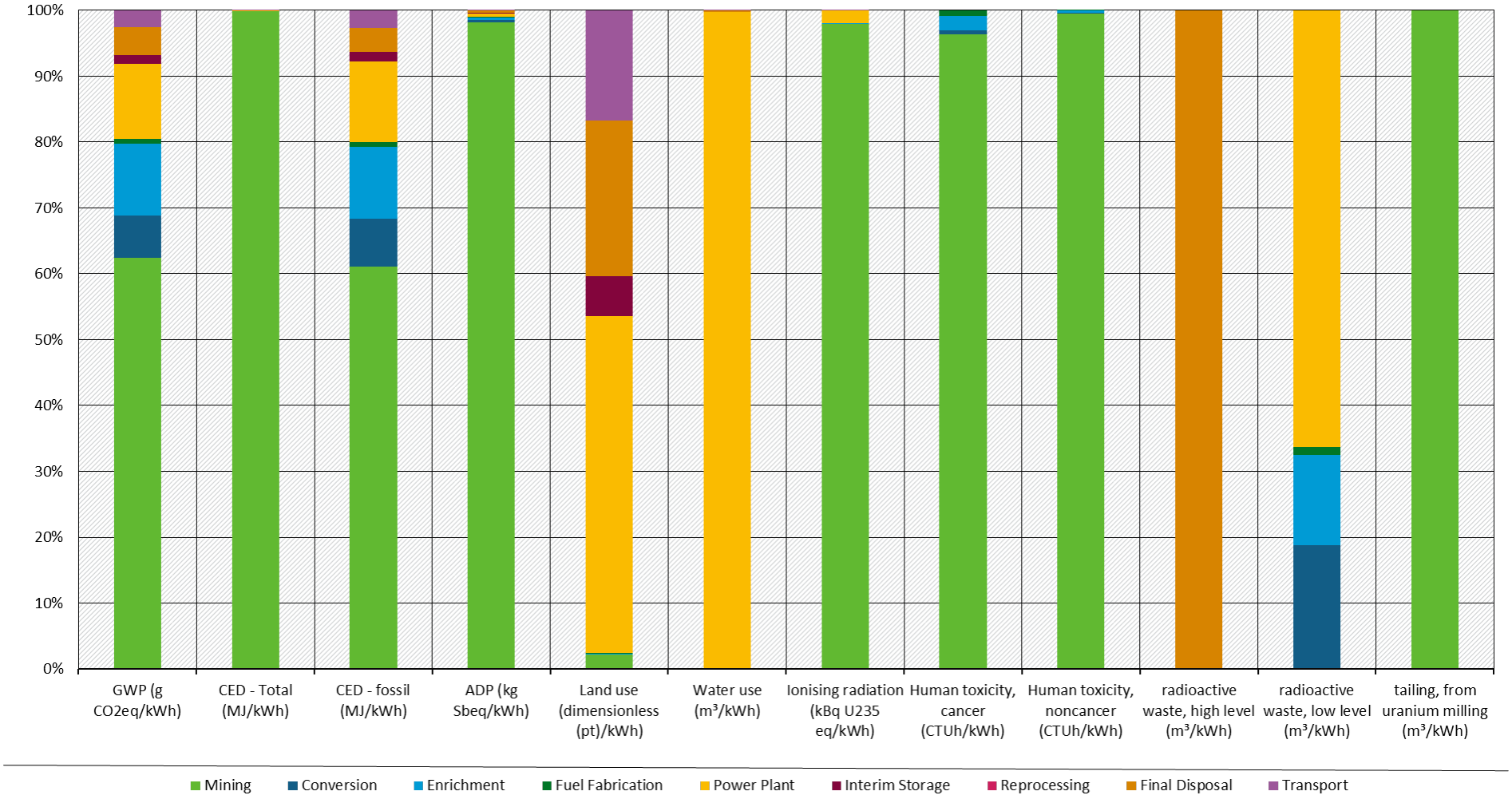
Figure 192: NA1_SMR_v2 breakdown of GWP



Total GWP of NA1_SMR_v2: 13,5 g CO2eq/kWh

Source: Öko-Institut

Figure 193: NA1_SMR_v2 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.33 NA1_SMR_v2_2030

Table 155: NA1_SMR_v2_2030 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.05
Mine_Infrastructure	Mine Type	Underground
Conversion_UF6	Country	United States
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	United States
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	United States
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	SMR
NPP_Construction	Country	United States
Electricity_Production_Nuclear	Load Factor	0
Electricity_Production_Nuclear	Net Efficiency (%)	0.31
Electricity_Production_Nuclear	Country	United States
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	United States

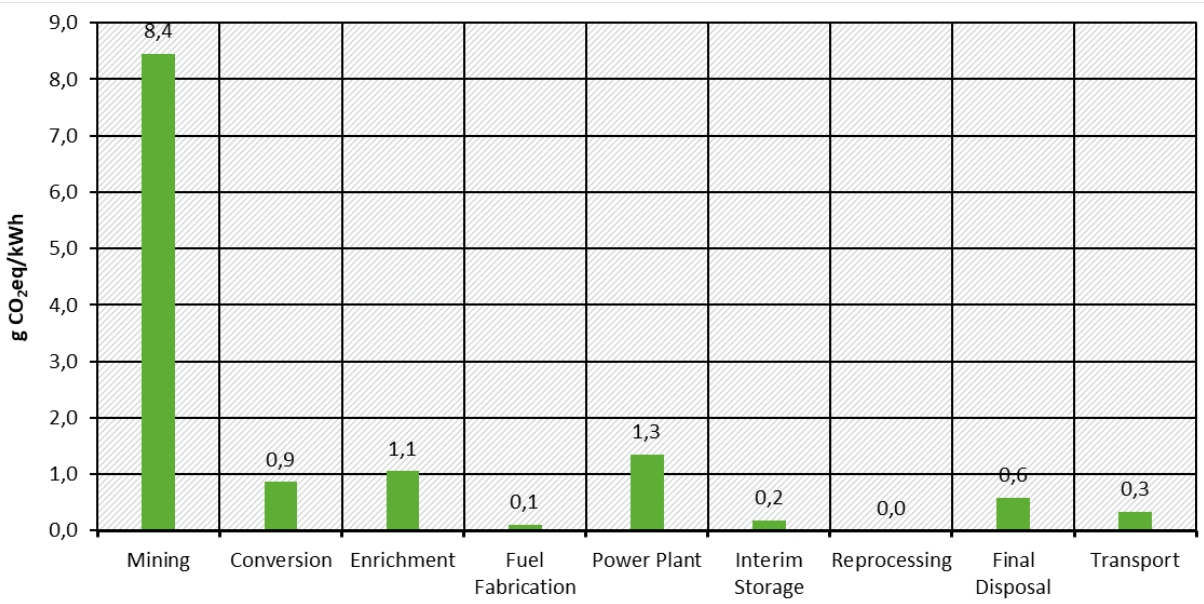
Source: Öko-Institut

Table 156: NA1_SMR_v2_2030 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	12.9

Source: Öko-Institut

Figure 194: NA1_v2_2030 breakdown of GWP



Total GWP of NA1_SMR_v2_2030: 12,9 g CO2eq/kWh
Source: Öko-Institut

B.34 NA2

Table 157: NA2 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.05
Mine_Infrastructure	Mine Type	In-situ leaching
Conversion_UF6	Country	United States
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	United States
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	United States
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	United States
Electricity_Production_Nuclear	Load Factor	0.91
Electricity_Production_Nuclear	Net Efficiency (%)	0.31
Electricity_Production_Nuclear	Country	United States

Process Step	Parameter	Value
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	-
Backend	Country	United States

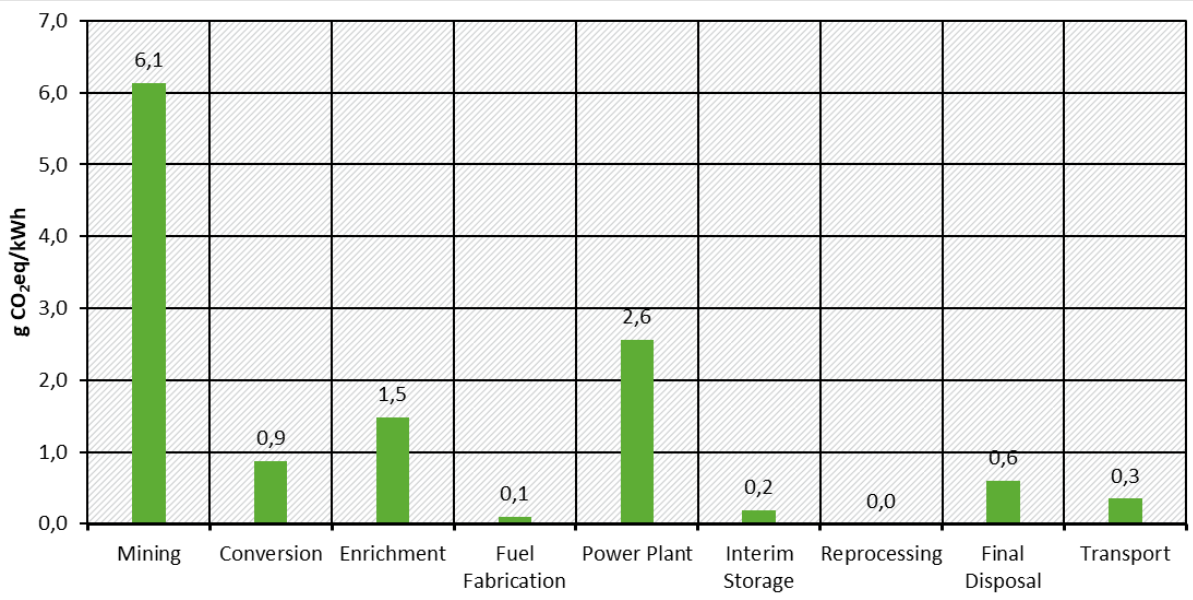
Source: Öko-Institut

Table 158: NA2 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	12.3
CED - Total	MJ/kWh	1.0E+02
CED - fossil	MJ/kWh	5.2E+01
ADP	kg Sbeq/kWh	6.5E-06
Land use	dimensionless (pt)/kWh	2.9E-02
Water use	m³/kWh	9.7E-02
Ionising radiation	kBq U235 eq/kWh	8.8E-02
Human toxicity, cancer	CTUh/kWh	7.7E-04
Human toxicity, noncancer	CTUh/kWh	6.5E-02
radioactive waste, high level	m³/kWh	5.9E-09
radioactive waste, low level	m³/kWh	7.8E-08
tailing, from uranium milling	m³/kWh	0.0E+00

Source: Öko-Institut

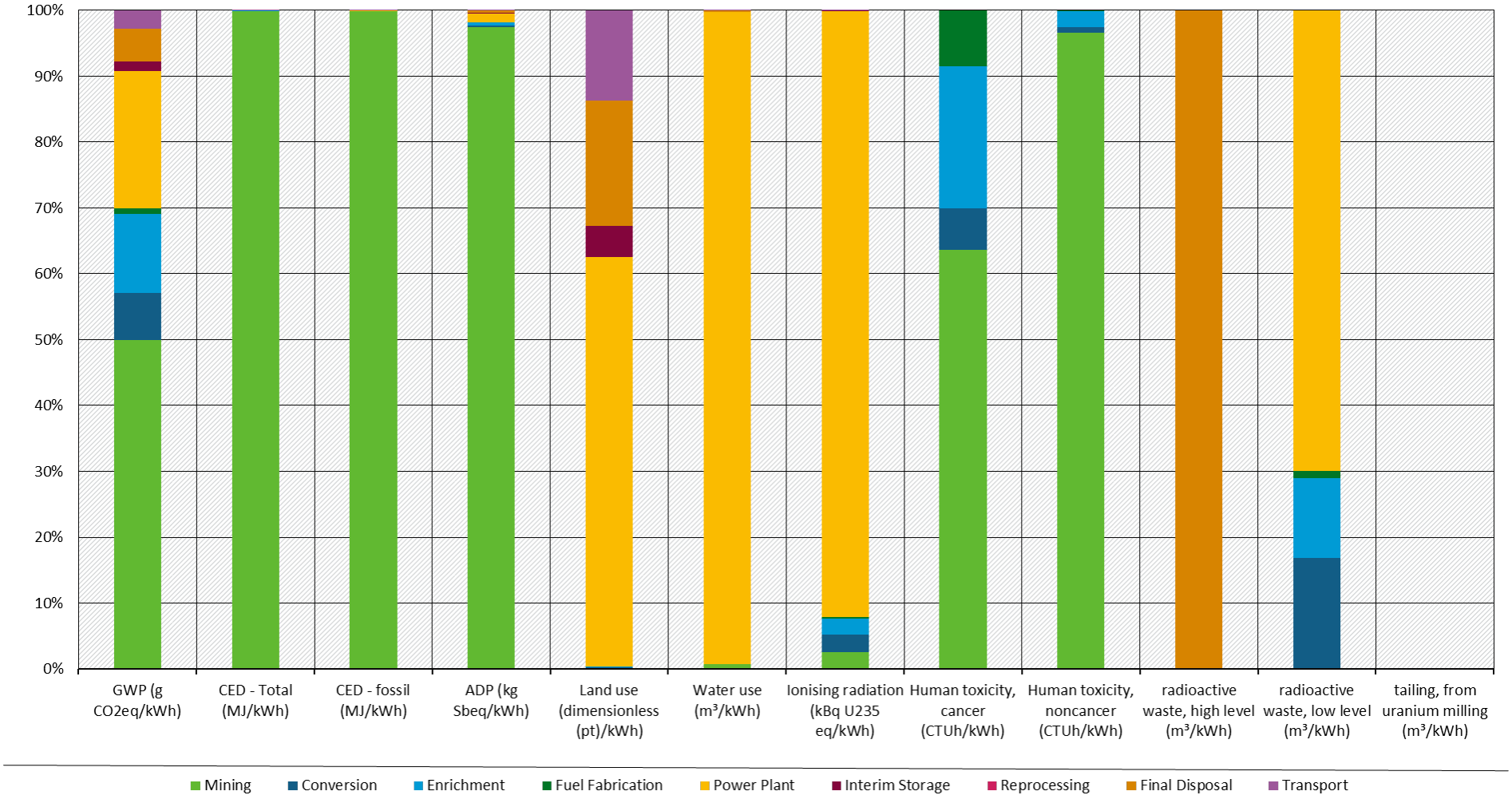
Figure 195: NA2 breakdown of GWP



Total GWP of NA2: 12,3 g CO2eq/kWh

Source: Öko-Institut

Figure 196: NA2 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.35 NA3

Table 159: NA3 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.09
Mine_Infrastructure	Mine Type	In-situ leaching
Conversion_UF6	Country	United States
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	United States
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	United States
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	United States
Electricity_Production_Nuclear	Load Factor	0.91
Electricity_Production_Nuclear	Net Efficiency (%)	0.31
Electricity_Production_Nuclear	Country	United States
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	-
Backend	Country	United States

Source: Öko-Institut

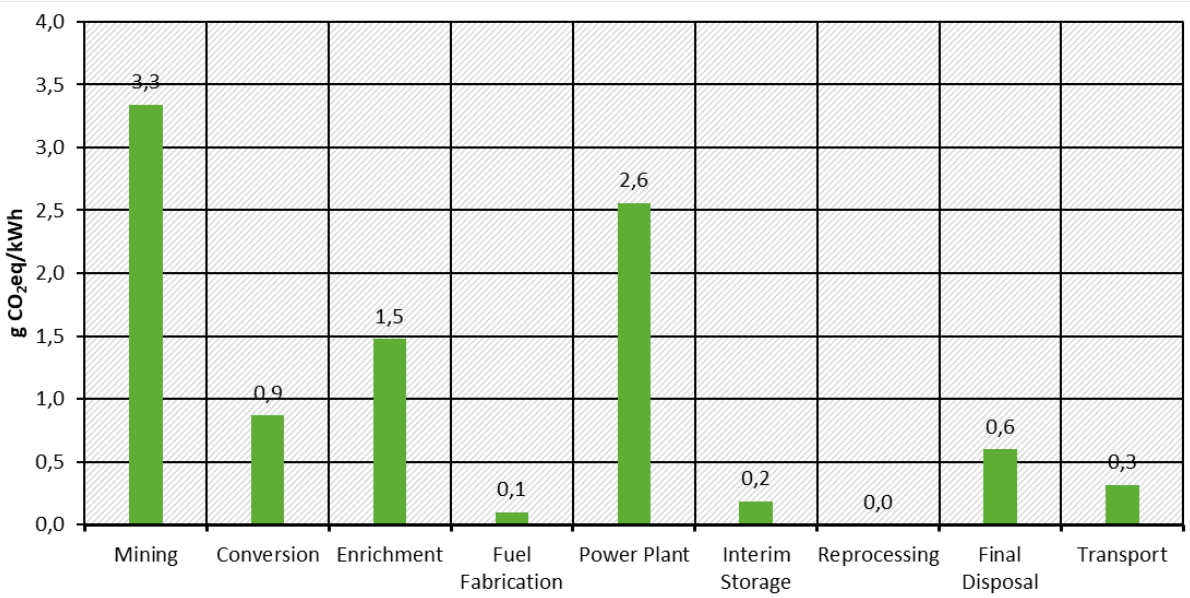
Table 160: NA3 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	9.4
CED - Total	MJ/kWh	5.6E+01
CED - fossil	MJ/kWh	2.8E+01
ADP	kg Sbeq/kWh	3.6E-06
Land use	dimensionless (pt)/kWh	2.9E-02
Water use	m^3/kWh	9.7E-02
Ionising radiation	kBq U235 eq/kWh	8.7E-02
Human toxicity, cancer	CTUh/kWh	5.4E-04

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	3.6E-02
radioactive waste, high level	m³/kWh	5.9E-09
radioactive waste, low level	m³/kWh	7.8E-08
tailing, from uranium milling	m³/kWh	0.0E+00

Source: Öko-Institut

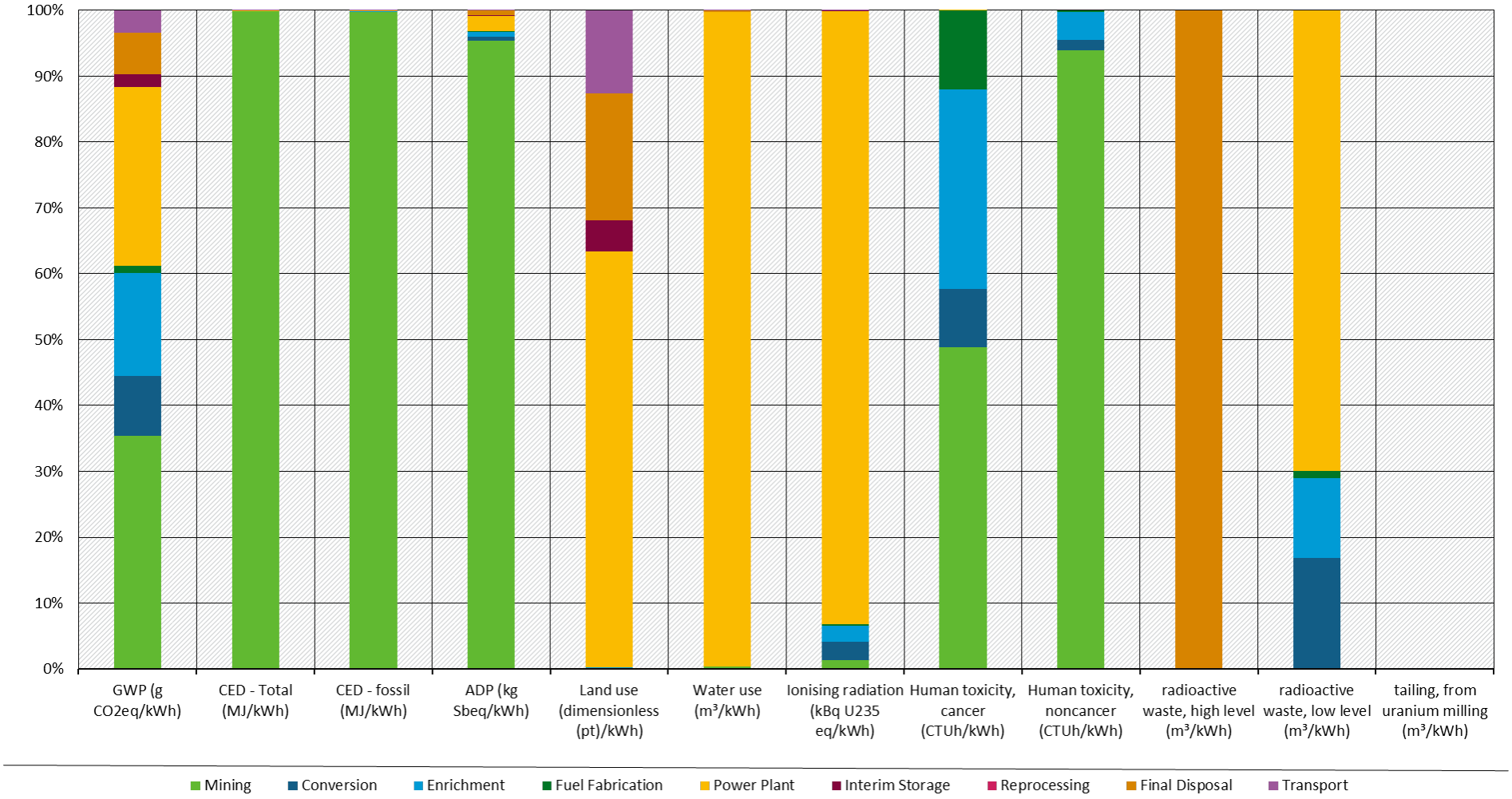
Figure 197: NA3 breakdown of GWP



Total GWP of NA3: 9,4 g CO2eq/kWh

Source: Öko-Institut

Figure 198: NA3 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.36 NA4

Table 161: NA4 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	11.50
Mine_Infrastructure	Mine Type	Underground
Conversion_UF6	Country	United States
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	Netherlands
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	United States
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	United States
Electricity_Production_Nuclear	Load Factor	0.91
Electricity_Production_Nuclear	Net Efficiency (%)	0.31
Electricity_Production_Nuclear	Country	United States
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	United States

Source: Öko-Institut

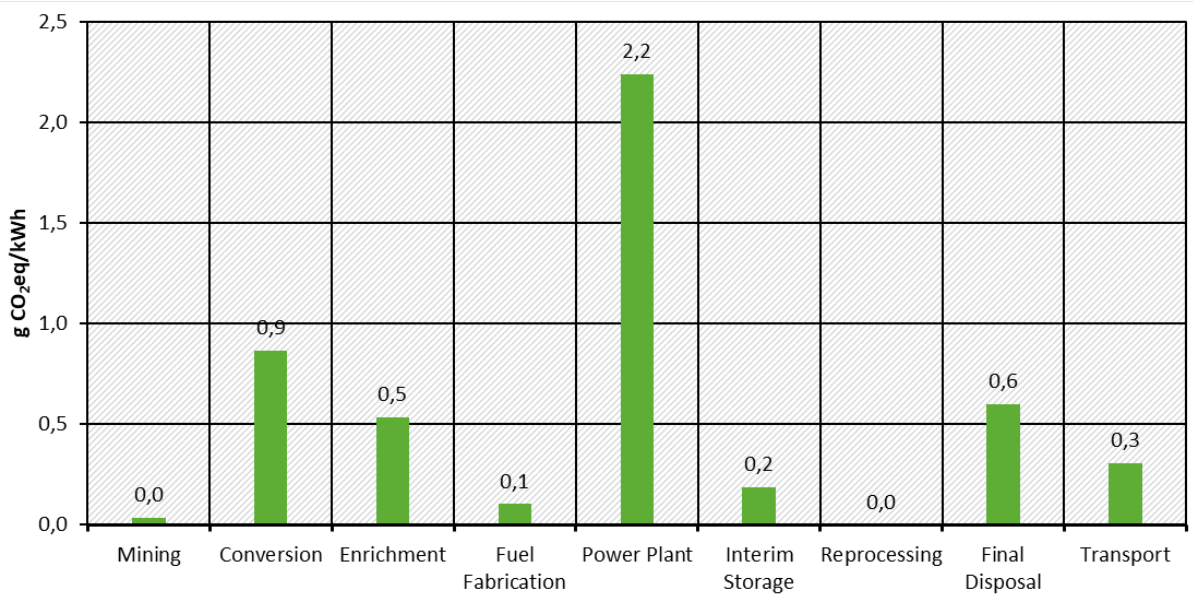
Table 162: NA4 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	4.9
CED - Total	MJ/kWh	2.9E-01
CED - fossil	MJ/kWh	6.5E-02
ADP	kg Sbeq/kWh	1.6E-07
Land use	dimensionless (pt)/kWh	2.8E-02
Water use	m^3/kWh	9.7E-02
Ionising radiation	kBq U235 eq/kWh	1.0E-01
Human toxicity, cancer	CTUh/kWh	2.5E-04

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	3.2E-03
radioactive waste, high level	m³/kWh	5.9E-09
radioactive waste, low level	m³/kWh	7.8E-08
tailing, from uranium milling	m³/kWh	8.0E-08

Source: Öko-Institut

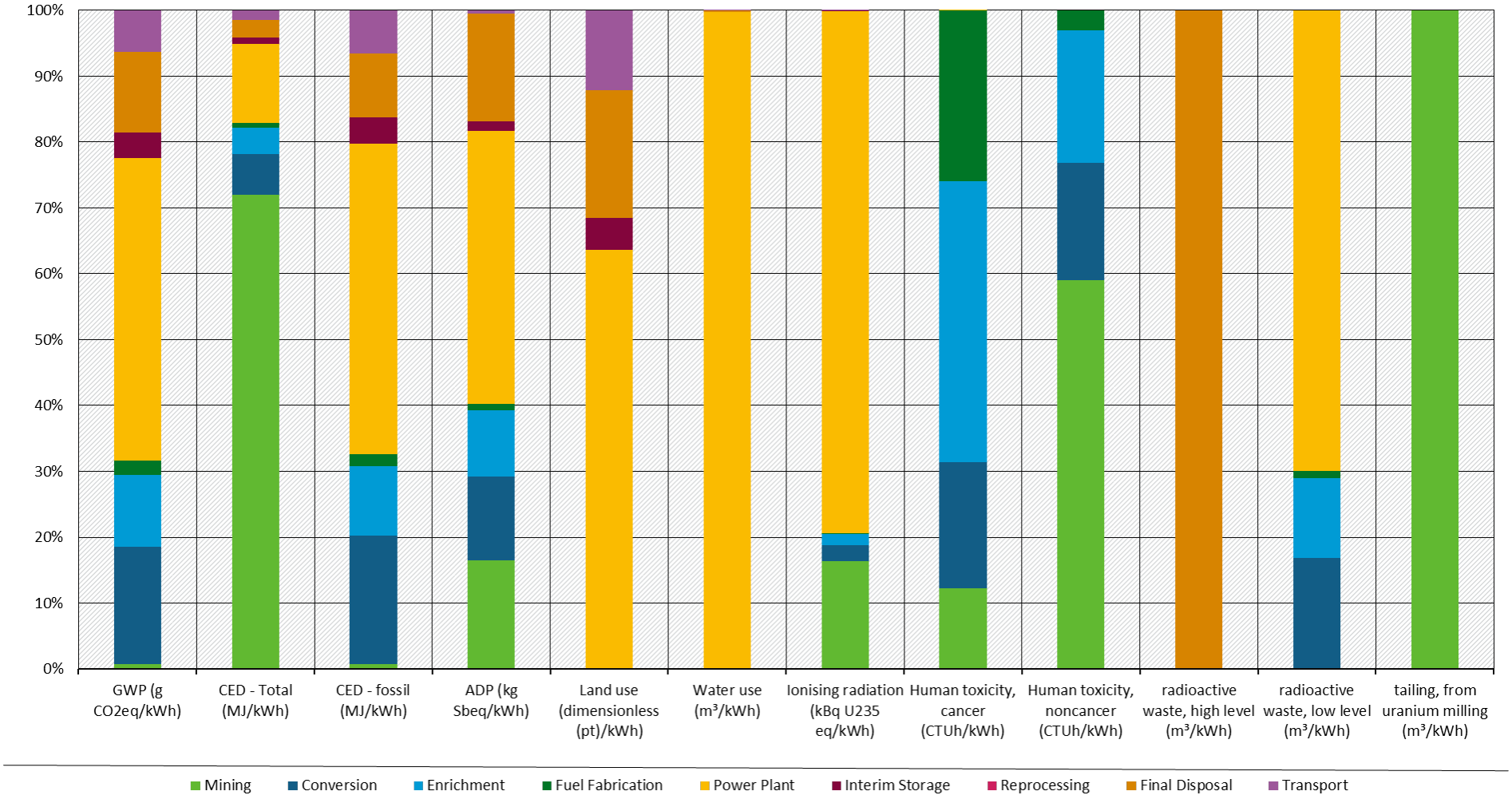
Figure 199: NA4 breakdown of GWP



Total GWP of NA4: 4,9 g CO2eq/kWh

Source: Öko-Institut

Figure 200: NA4 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.37 NA5

Table 163: NA5 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.05
Mine_Infrastructure	Mine Type	In-situ leaching
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	4
Enrichment_Centrifuge	Country	Netherlands
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	United States
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	United States
Electricity_Production_Nuclear	Load Factor	0.91
Electricity_Production_Nuclear	Net Efficiency (%)	0.31
Electricity_Production_Nuclear	Country	United States
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	-
Backend	Country	United States

Source: Öko-Institut

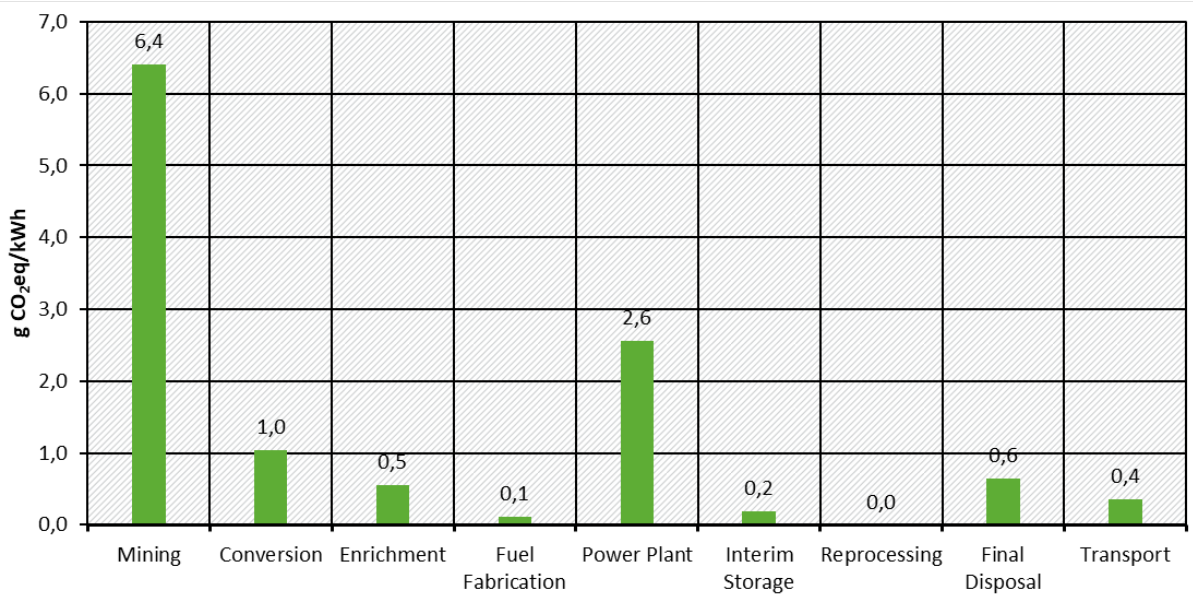
Table 164: NA5 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	11.9
CED - Total	MJ/kWh	1.1E+02
CED - fossil	MJ/kWh	5.4E+01
ADP	kg Sbeq/kWh	6.8E-06
Land use	dimensionless (pt)/kWh	3.0E-02
Water use	m^3/kWh	9.7E-02
Ionising radiation	kBq U235 eq/kWh	8.8E-02
Human toxicity, cancer	CTUh/kWh	7.4E-04

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	6.6E-02
radioactive waste, high level	m³/kWh	6.5E-09
radioactive waste, low level	m³/kWh	7.9E-08
tailing, from uranium milling	m³/kWh	0.0E+00

Source: Öko-Institut

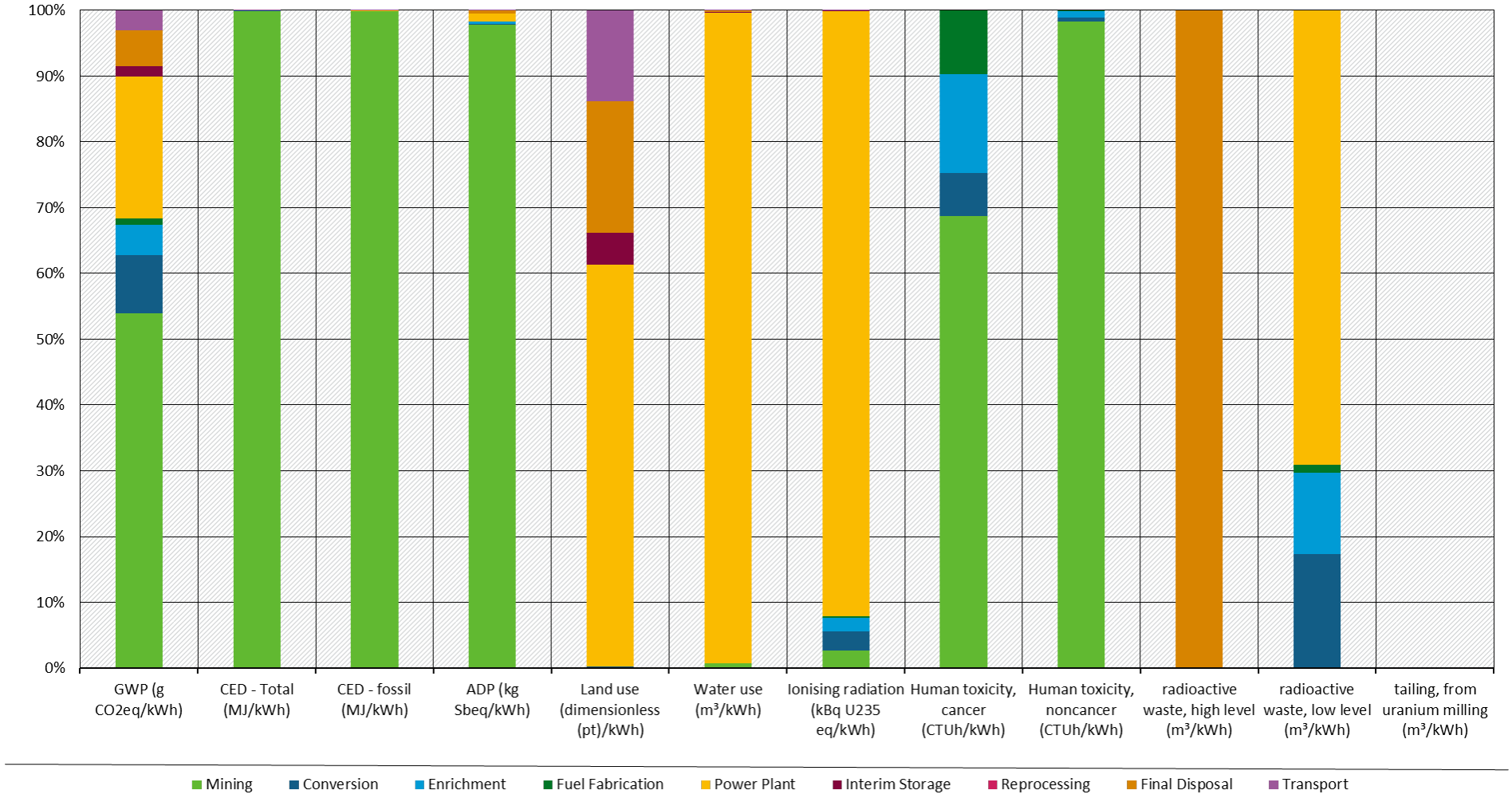
Figure 201: NA5 breakdown of GWP



Total GWP of NA5: 11,9 g CO2eq/kWh

Source: Öko-Institut

Figure 202: NA5 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.38 NA6

Table 165: NA6 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.06
Mine_Infrastructure	Mine Type	In-situ leaching
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	France
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	United States
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	United States
Electricity_Production_Nuclear	Load Factor	0.91
Electricity_Production_Nuclear	Net Efficiency (%)	0.29
Electricity_Production_Nuclear	Country	United States
NPP_Retrofitting	Replacement Ratio (%)	0.5
Reprocessing	Country	-
Backend	Country	United States

Source: Öko-Institut

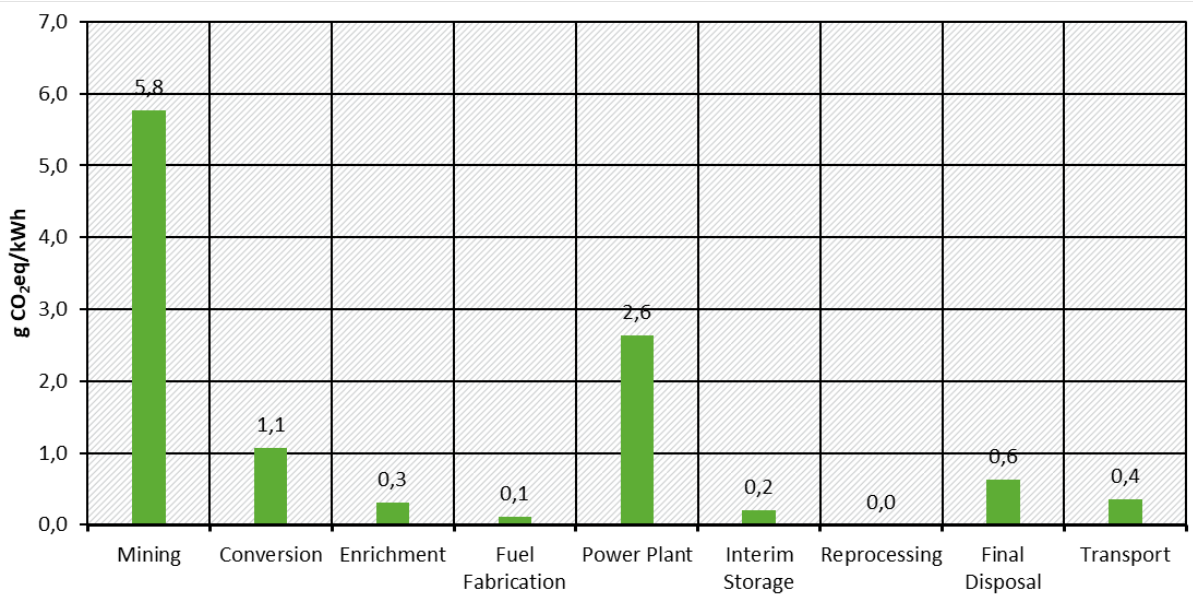
Table 166: NA6 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	11.1
CED - Total	MJ/kWh	9.7E+01
CED - fossil	MJ/kWh	4.9E+01
ADP	kg Sbeq/kWh	6.1E-06
Land use	dimensionless (pt)/kWh	2.8E-02
Water use	m^3/kWh	9.7E-02
Ionising radiation	kBq U235 eq/kWh	8.8E-02
Human toxicity, cancer	CTUh/kWh	6.9E-04

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	6.0E-02
radioactive waste, high level	m³/kWh	6.4E-09
radioactive waste, low level	m³/kWh	8.0E-08
tailing, from uranium milling	m³/kWh	0.0E+00

Source: Öko-Institut

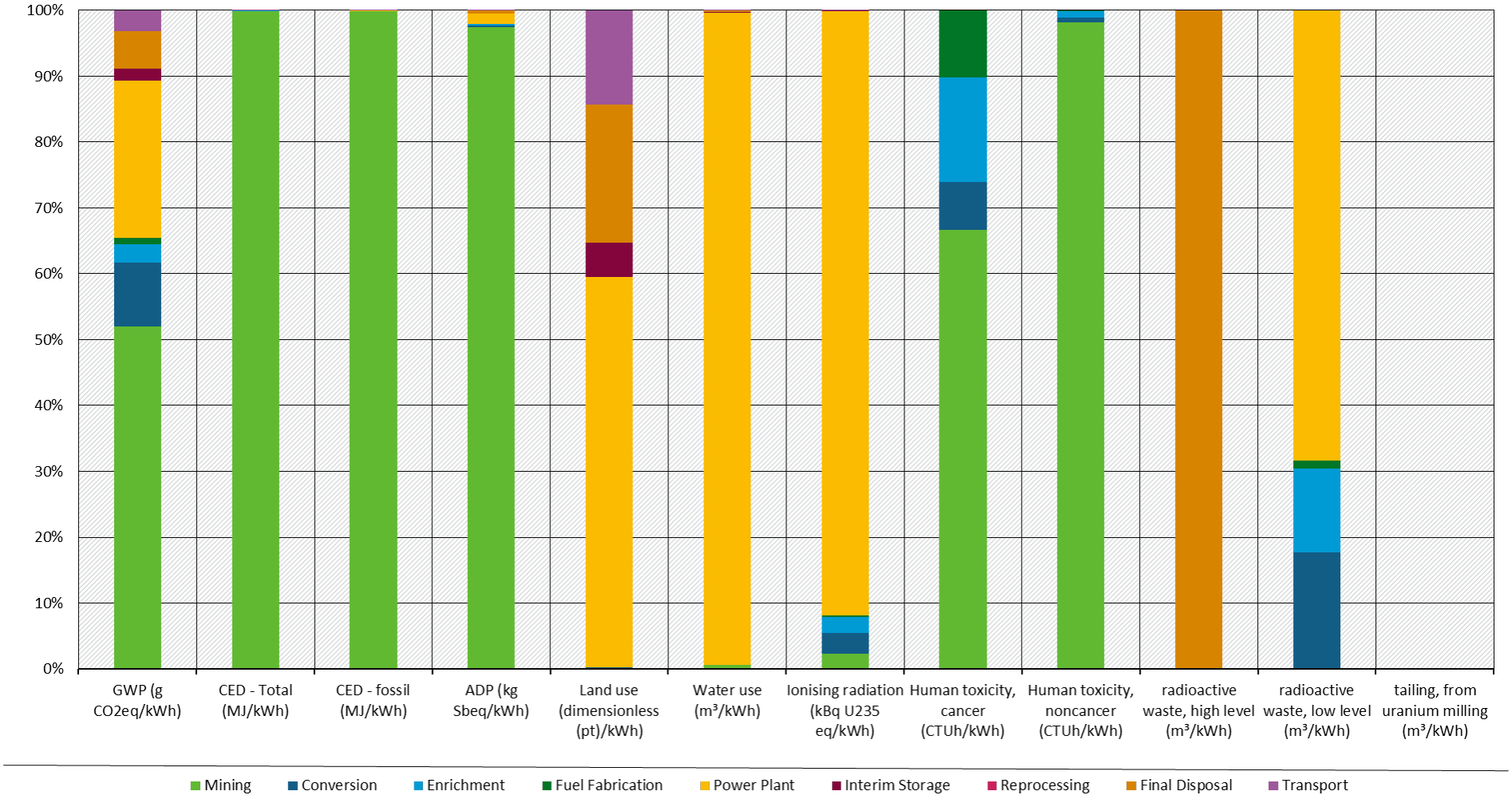
Figure 203: NA6 breakdown of GWP



Total GWP of NA6: 11,1 g CO2eq/kWh

Source: Öko-Institut

Figure 204: NA7 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.39 CN1

Table 167: CN1 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.06
Mine_Infrastructure	Mine Type	In-situ leaching
Conversion_UF6	Country	China
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	China
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	China
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	China
Electricity_Production_Nuclear	Load Factor	0.9
Electricity_Production_Nuclear	Net Efficiency (%)	0.34
Electricity_Production_Nuclear	Country	China
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	China

Source: Öko-Institut

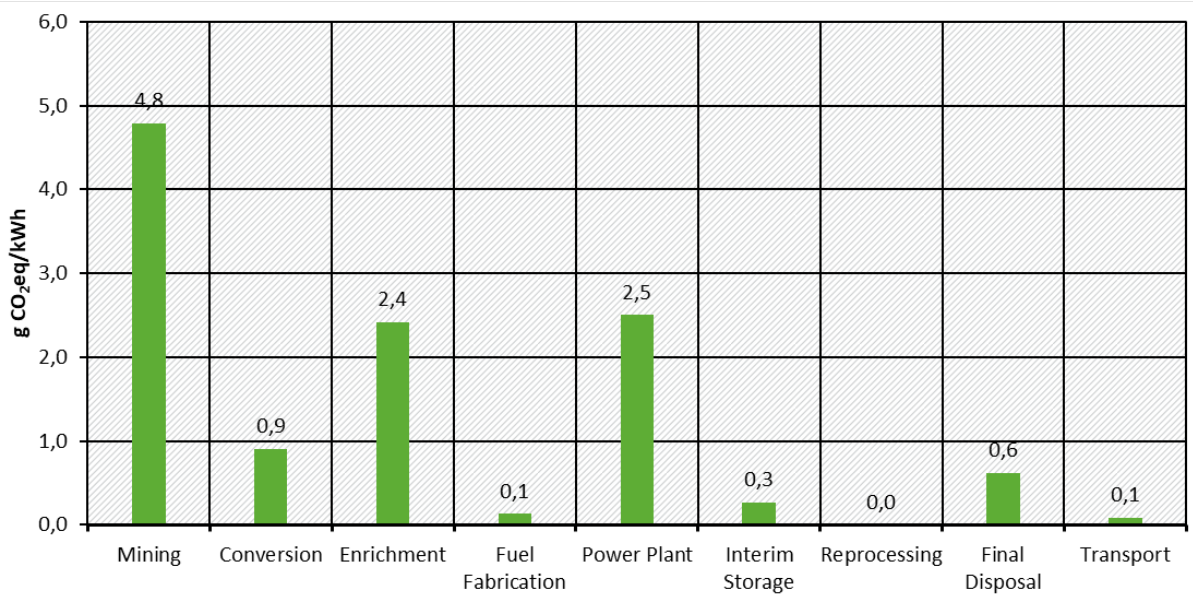
Table 168: CN1 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	11.7
CED - Total	MJ/kWh	8.1E+01
CED - fossil	MJ/kWh	4.0E+01
ADP	kg Sbeq/kWh	5.1E-06
Land use	dimensionless (pt)/kWh	2.3E-02
Water use	m^3/kWh	1.2E-01
Ionising radiation	kBq U235 eq/kWh	8.7E-02
Human toxicity, cancer	CTUh/kWh	6.5E-04

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	5.1E-02
radioactive waste, high level	m³/kWh	5.3E-09
radioactive waste, low level	m³/kWh	7.6E-08
tailing, from uranium milling	m³/kWh	0.0E+00

Source: Öko-Institut

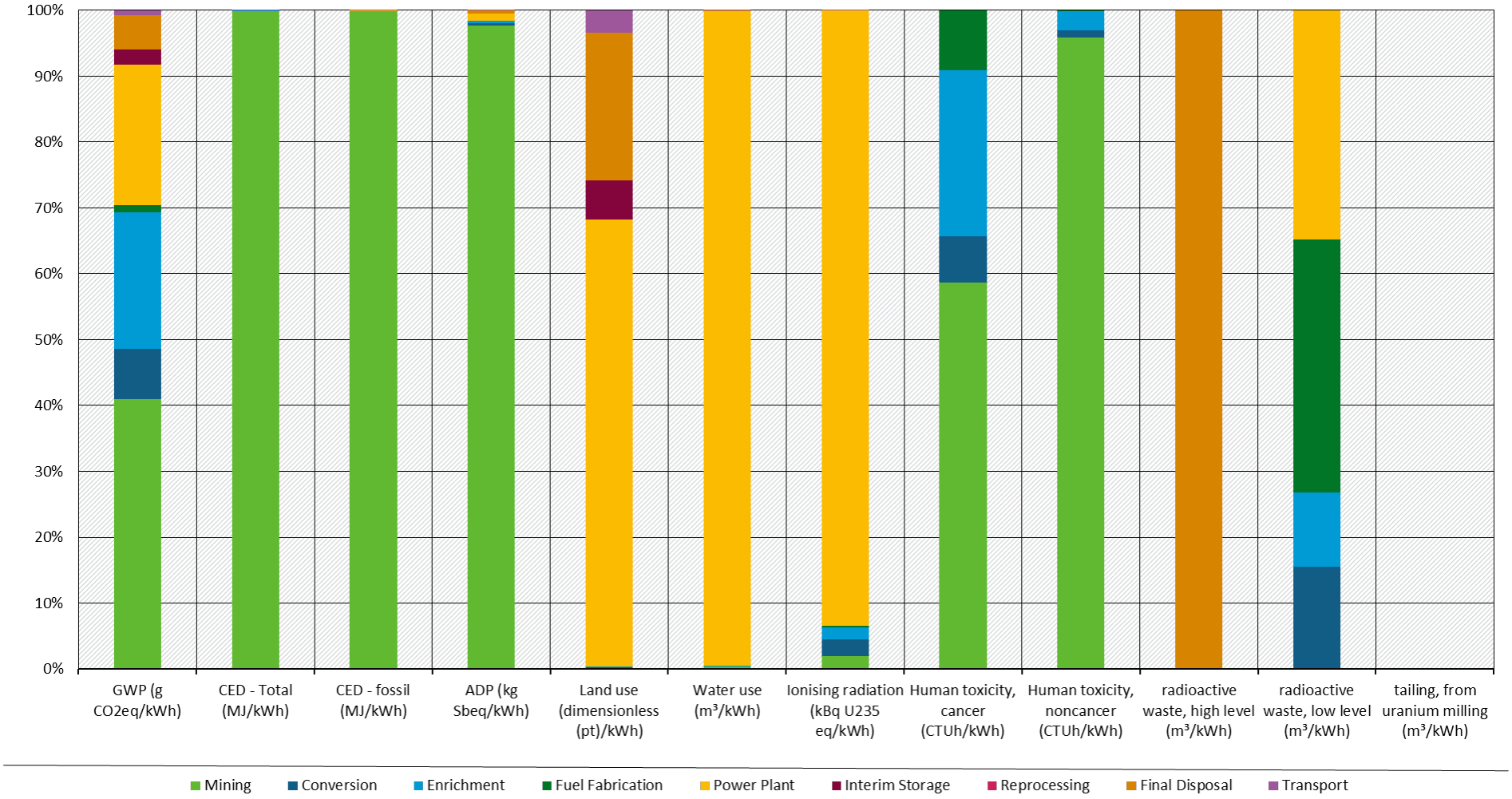
Figure 205: CN1 breakdown of GWP



Total GWP of CN1: 11,7 g CO2eq/kWh

Source: Öko-Institut

Figure 206: CN1 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.40 CN1_2030

Table 169: CN1_2030 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.06
Mine_Infrastructure	Mine Type	In-situ leaching
Conversion_UF6	Country	China
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	China
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	China
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	China
Electricity_Production_Nuclear	Load Factor	0
Electricity_Production_Nuclear	Net Efficiency (%)	0.34
Electricity_Production_Nuclear	Country	China
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	China

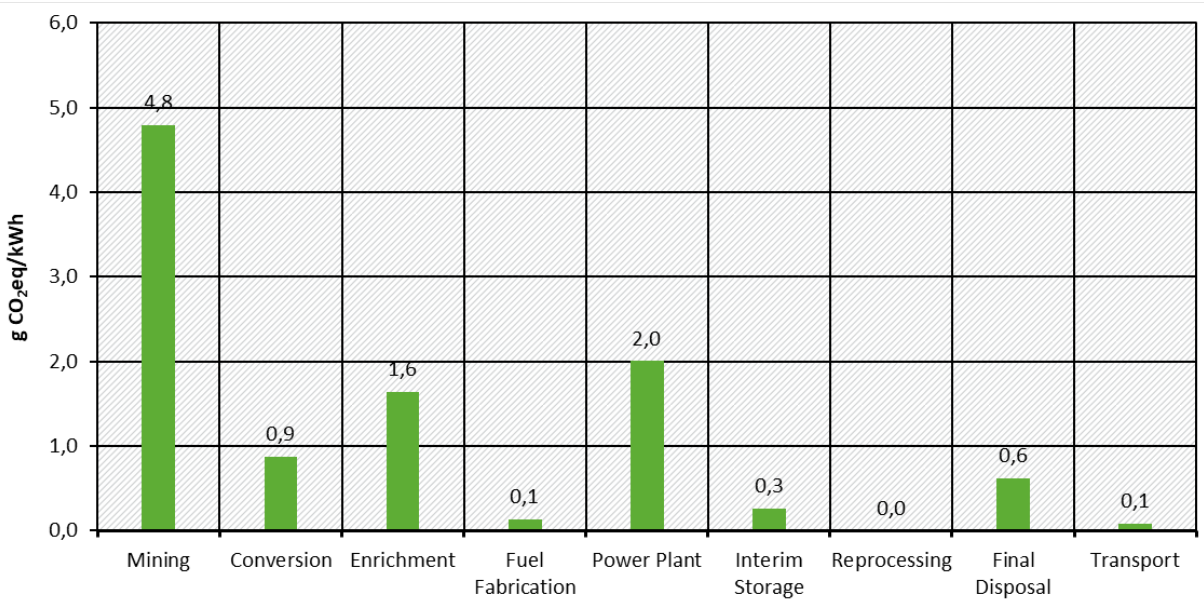
Source: Öko-Institut

Table 170: CN1_2030 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	10.4

Source: Öko-Institut

Figure 207: CN1_2030 breakdown of GWP



Total GWP of CN1_2030: 10,4 g CO2eq/kWh
Source: Öko-Institut

B.41 CN1_Gen3

Table 171: CN1_Gen3 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.06
Mine_Infrastructure	Mine Type	In-situ leaching
Conversion_UF6	Country	China
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	China
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	China
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR (Gen3)
NPP_Construction	Country	China
Electricity_Production_Nuclear	Load Factor	0.9
Electricity_Production_Nuclear	Net Efficiency (%)	0.35
Electricity_Production_Nuclear	Country	China

Process Step	Parameter	Value
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	China

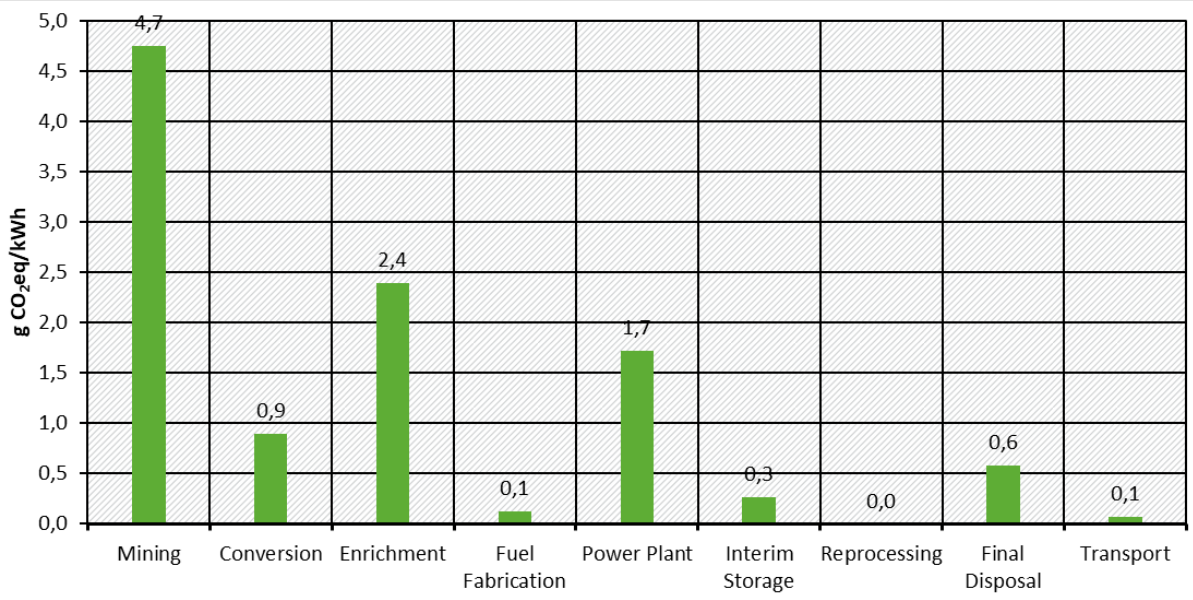
Source: Öko-Institut

Table 172: CN1_Gen3 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	10.8
CED - Total	MJ/kWh	8.0E+01
CED - fossil	MJ/kWh	4.0E+01
ADP	kg Sbeq/kWh	5.0E-06
Land use	dimensionless (pt)/kWh	1.7E-02
Water use	m^3/kWh	1.2E-01
Ionising radiation	kBq U235 eq/kWh	8.6E-02
Human toxicity, cancer	CTUh/kWh	6.4E-04
Human toxicity, noncancer	CTUh/kWh	5.0E-02
radioactive waste, high level	m^3/kWh	5.3E-09
radioactive waste, low level	m^3/kWh	6.4E-08
tailing, from uranium milling	m^3/kWh	0.0E+00

Source: Öko-Institut

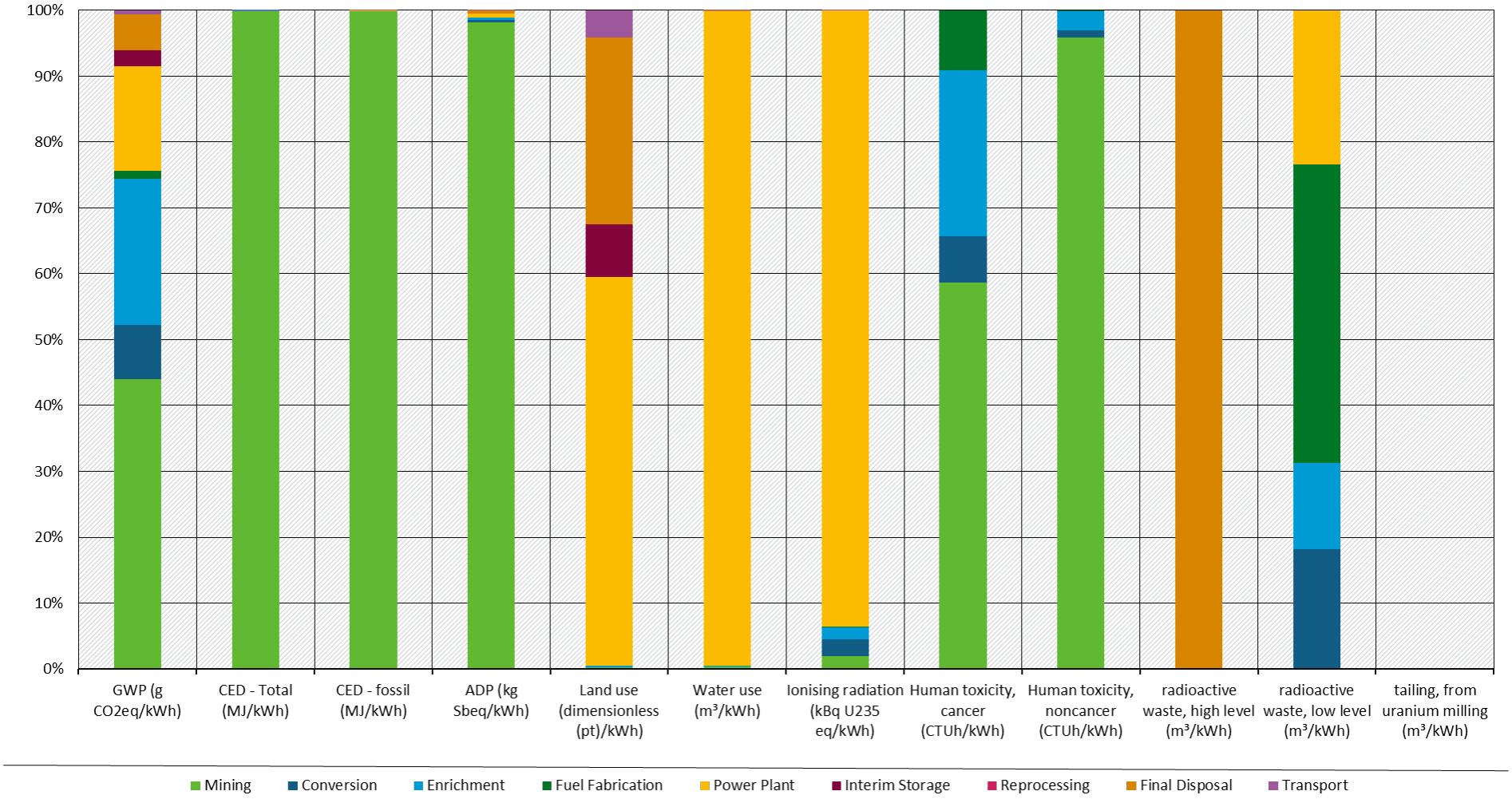
Figure 208: CN1_Gen3 breakdown of GWP



Total GWP of CN1_Gen3: 10,8 g CO2eq/kWh

Source: Öko-Institut

Figure 209: CN1_Gen3 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.42 CN1_Gen3_2030

Table 173: CN1_Gen3_2030 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.06
Mine_Infrastructure	Mine Type	In-situ leaching
Conversion_UF6	Country	China
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	China
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	China
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR (Gen3)
NPP_Construction	Country	China
Electricity_Production_Nuclear	Load Factor	0
Electricity_Production_Nuclear	Net Efficiency (%)	0.35
Electricity_Production_Nuclear	Country	China
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	China

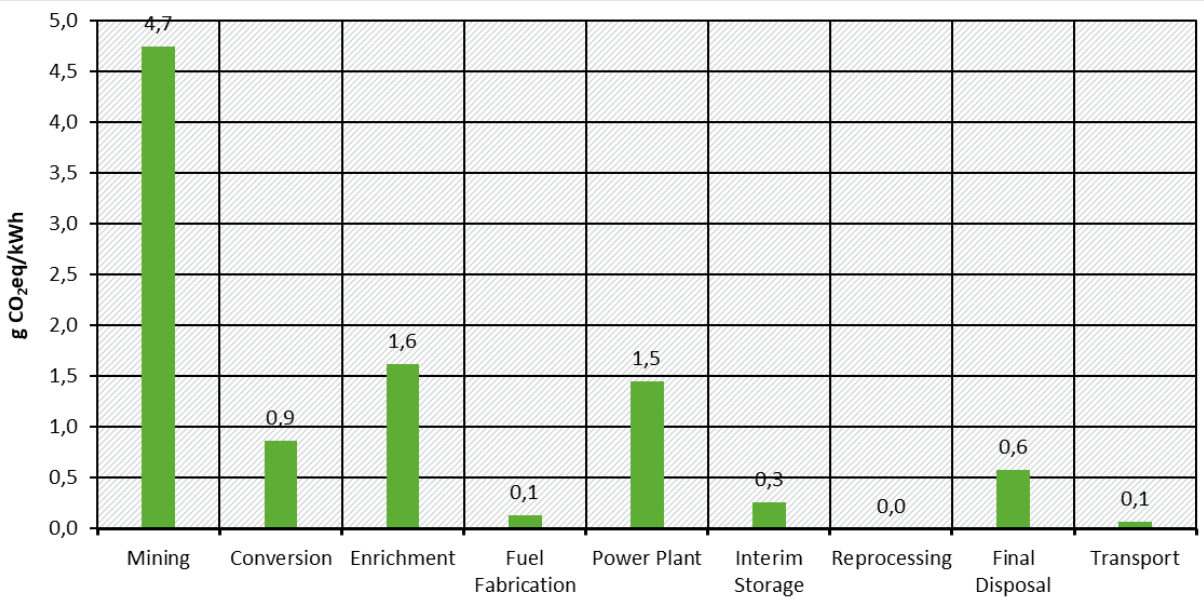
Source: Öko-Institut

Table 174: CN1_Gen3_2030 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	9.7

Source: Öko-Institut

Figure 210: CN1_Gen3_2030 breakdown of GWP



Total GWP of CN1_Gen3_2030: 9,7 g CO2eq/kWh
Source: Öko-Institut

B.43 CN1_SMR

Table 175: CN1_SMR life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.06
Mine_Infrastructure	Mine Type	In-situ leaching
Conversion_UF6	Country	China
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	China
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	China
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	SMR
NPP_Construction	Country	China
Electricity_Production_Nuclear	Load Factor	0.9
Electricity_Production_Nuclear	Net Efficiency (%)	0.26
Electricity_Production_Nuclear	Country	China

Process Step	Parameter	Value
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	China

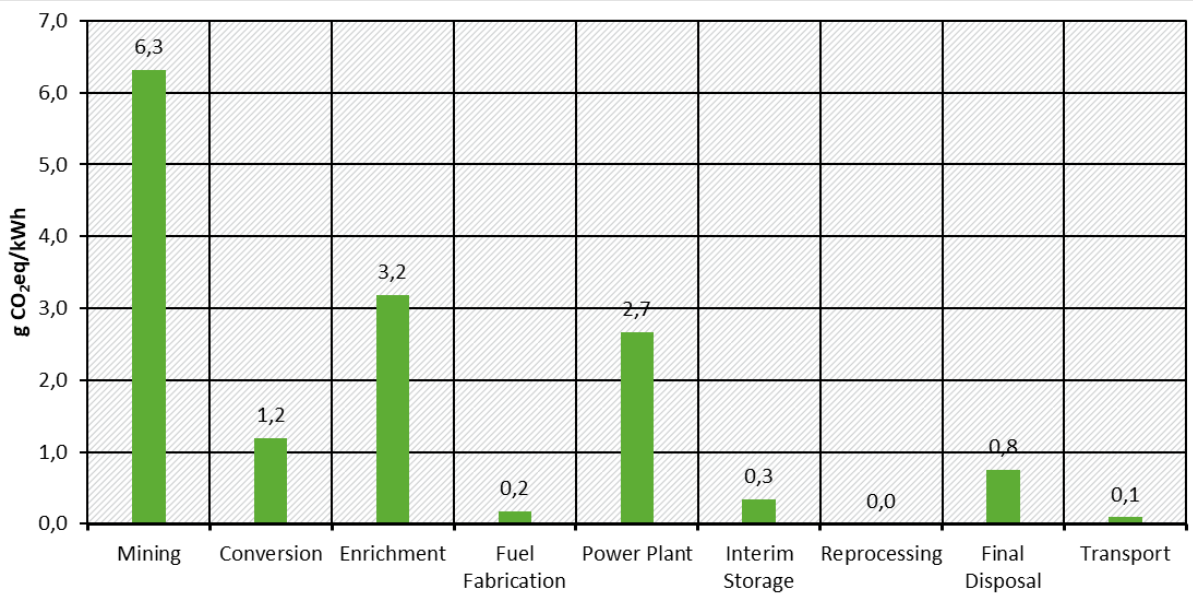
Source: Öko-Institut

Table 176: CN1_SMR life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	14.7
CED - Total	MJ/kWh	1.1E+02
CED - fossil	MJ/kWh	5.3E+01
ADP	kg Sbeq/kWh	6.7E-06
Land use	dimensionless (pt)/kWh	2.6E-02
Water use	m³/kWh	1.2E-01
Ionising radiation	kBq U235 eq/kWh	8.8E-02
Human toxicity, cancer	CTUh/kWh	8.6E-04
Human toxicity, noncancer	CTUh/kWh	6.7E-02
radioactive waste, high level	m³/kWh	7.0E-09
radioactive waste, low level	m³/kWh	7.8E-08
tailing, from uranium milling	m³/kWh	0.0E+00

Source: Öko-Institut

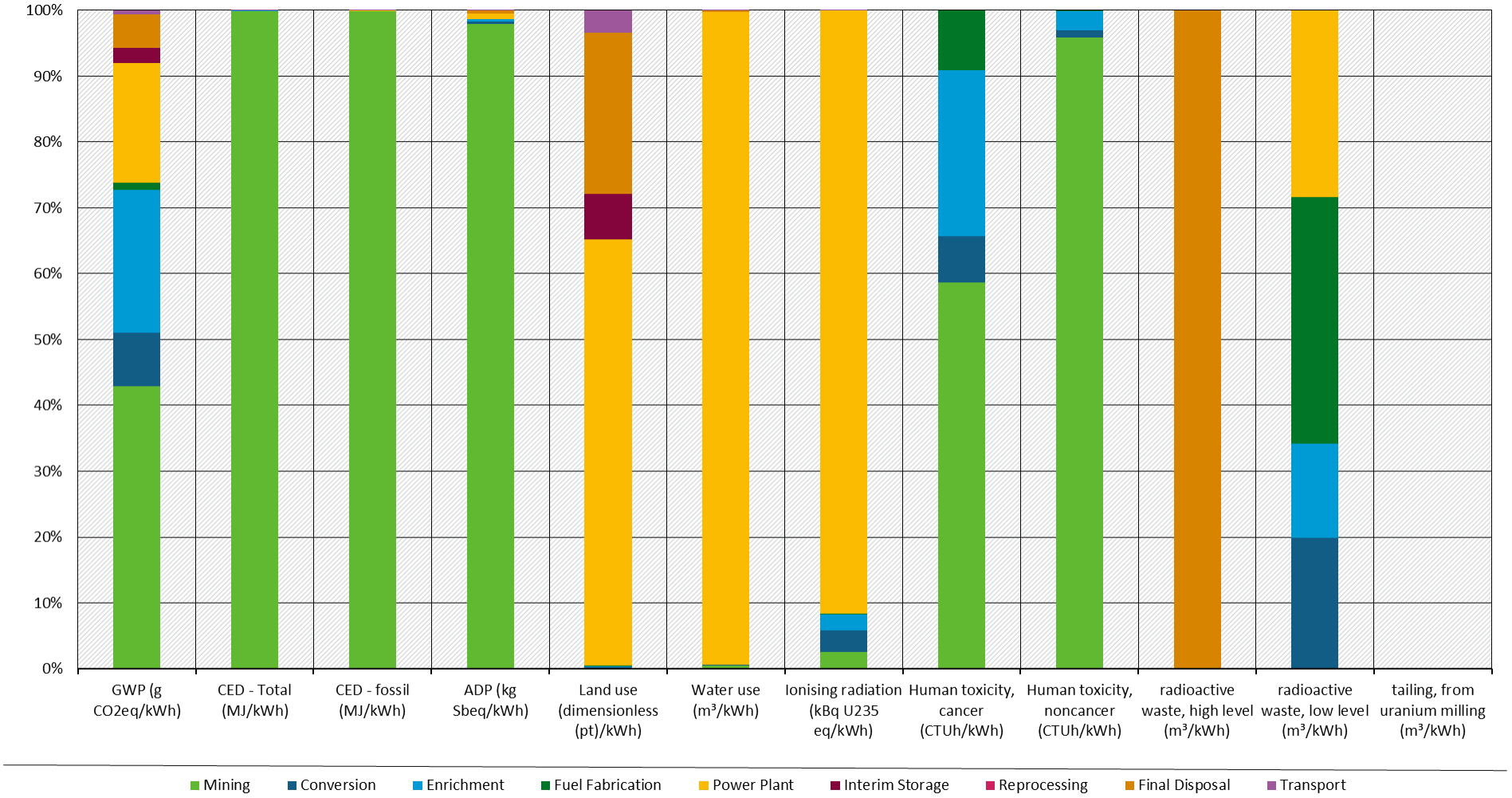
Figure 211: CN1_SMR breakdown of GWP



Total GWP of CN1_SMR: 14,7 g CO2eq/kWh

Source: Öko-Institut

Figure 212: CN1_SMR breakdown of impacts by life cycle stage



Source: Öko-Institut

B.44 CN1_SMR_2030

Table 177: CN1_SMR_2030 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.06
Mine_Infrastructure	Mine Type	In-situ leaching
Conversion_UF6	Country	China
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	China
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	China
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	SMR
NPP_Construction	Country	China
Electricity_Production_Nuclear	Load Factor	0
Electricity_Production_Nuclear	Net Efficiency (%)	0.26
Electricity_Production_Nuclear	Country	China
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	China

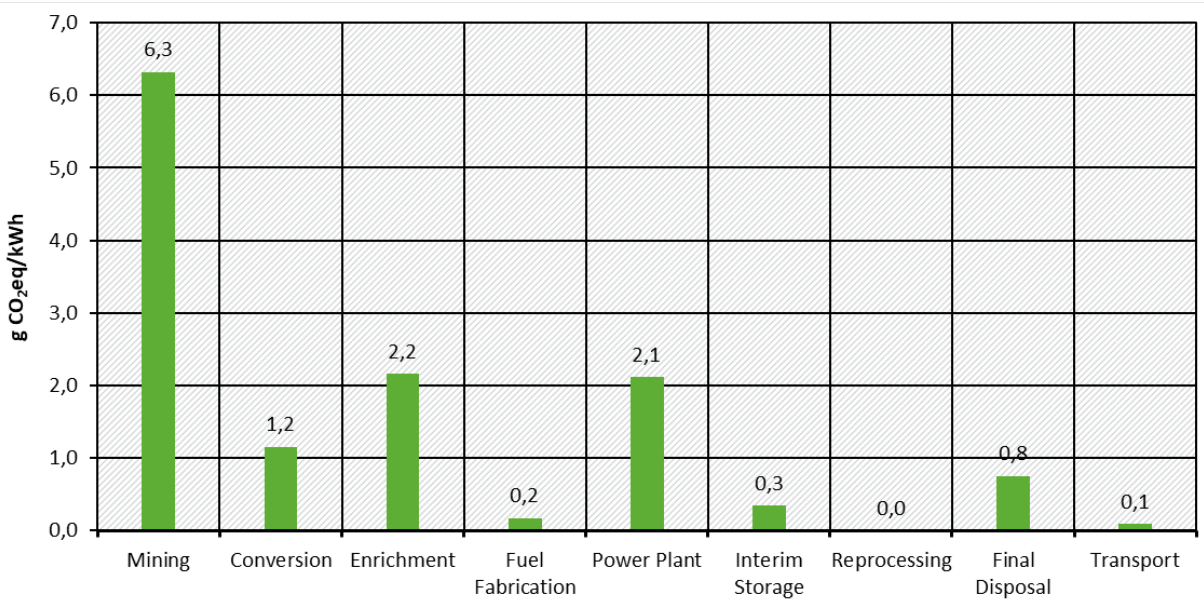
Source: Öko-Institut

Table 178: CN1_SMR_2030 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	13.1

Source: Öko-Institut

Figure 213: CN1_SMR_2030 breakdown of GWP



Total GWP of CN1_SMR_2030: 13,1 g CO2eq/kWh
Source: Öko-Institut

B.45 CN2

Table 179: CN2 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.15
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	Russia
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	Russia
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	China
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	China
Electricity_Production_Nuclear	Load Factor	0.9
Electricity_Production_Nuclear	Net Efficiency (%)	0.34
Electricity_Production_Nuclear	Country	China

Process Step	Parameter	Value
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	China

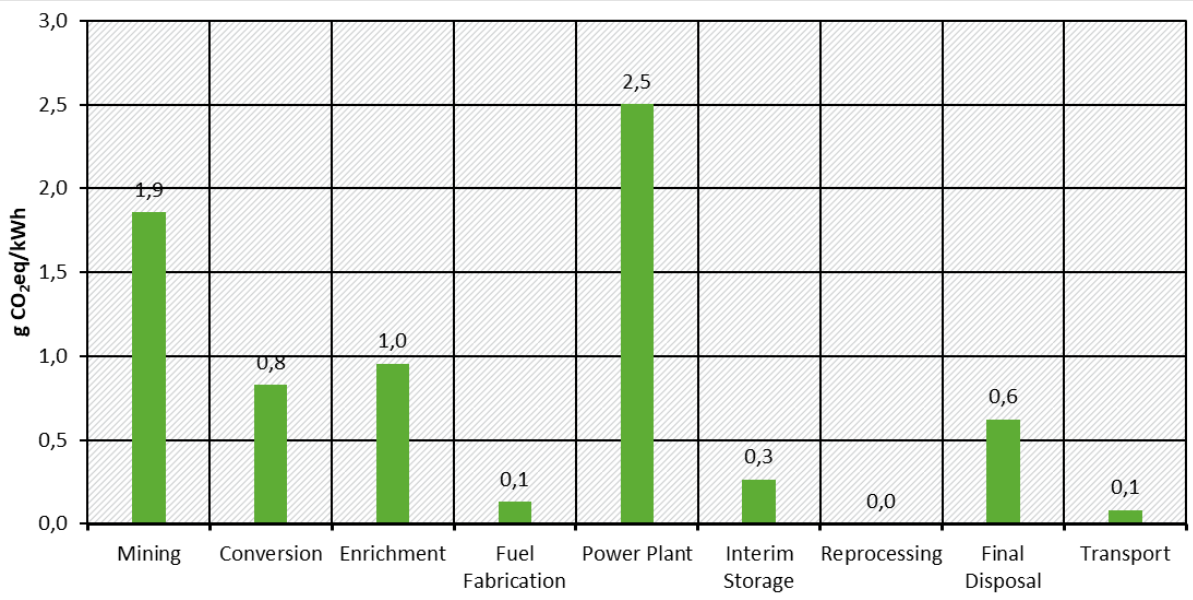
Source: Öko-Institut

Table 180: CN2 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	7.2
CED - Total	MJ/kWh	1.4E+01
CED - fossil	MJ/kWh	9.1E-02
ADP	kg Sbeq/kWh	2.0E-06
Land use	dimensionless (pt)/kWh	2.4E-02
Water use	m³/kWh	1.2E-01
Ionising radiation	kBq U235 eq/kWh	1.2E+00
Human toxicity, cancer	CTUh/kWh	2.3E-03
Human toxicity, noncancer	CTUh/kWh	1.3E-01
radioactive waste, high level	m³/kWh	5.3E-09
radioactive waste, low level	m³/kWh	7.6E-08
tailing, from uranium milling	m³/kWh	5.5E-06

Source: Öko-Institut

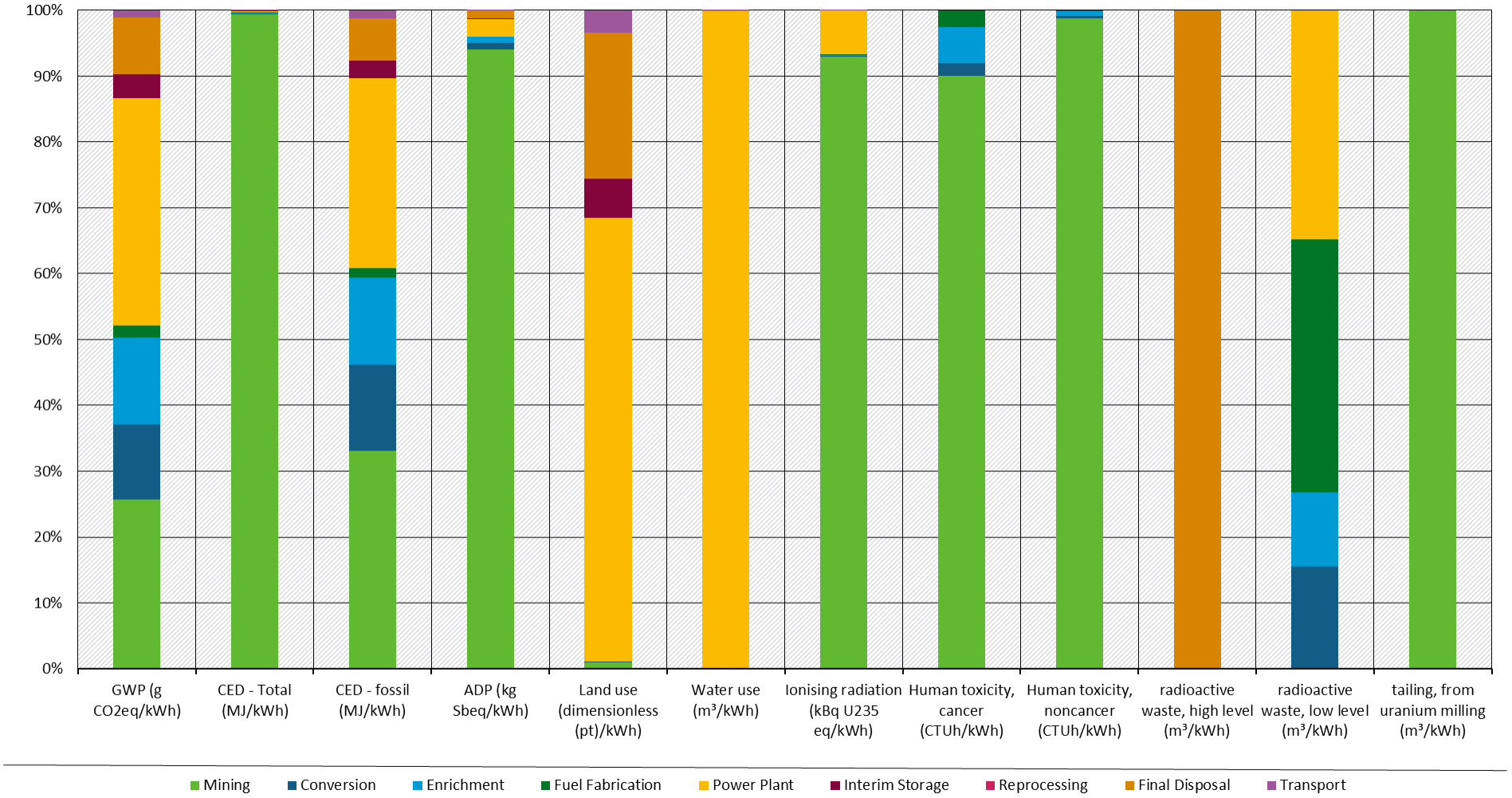
Figure 214: CN2 breakdown of GWP



Total GWP of CN2: 7,2 g CO2eq/kWh

Source: Öko-Institut

Figure 215: CN2 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.46 CN3

Table 181: CN3 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.14
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	China
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	China
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	China
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	China
Electricity_Production_Nuclear	Load Factor	0.9
Electricity_Production_Nuclear	Net Efficiency (%)	0.34
Electricity_Production_Nuclear	Country	China
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	-
Backend	Country	China

Source: Öko-Institut

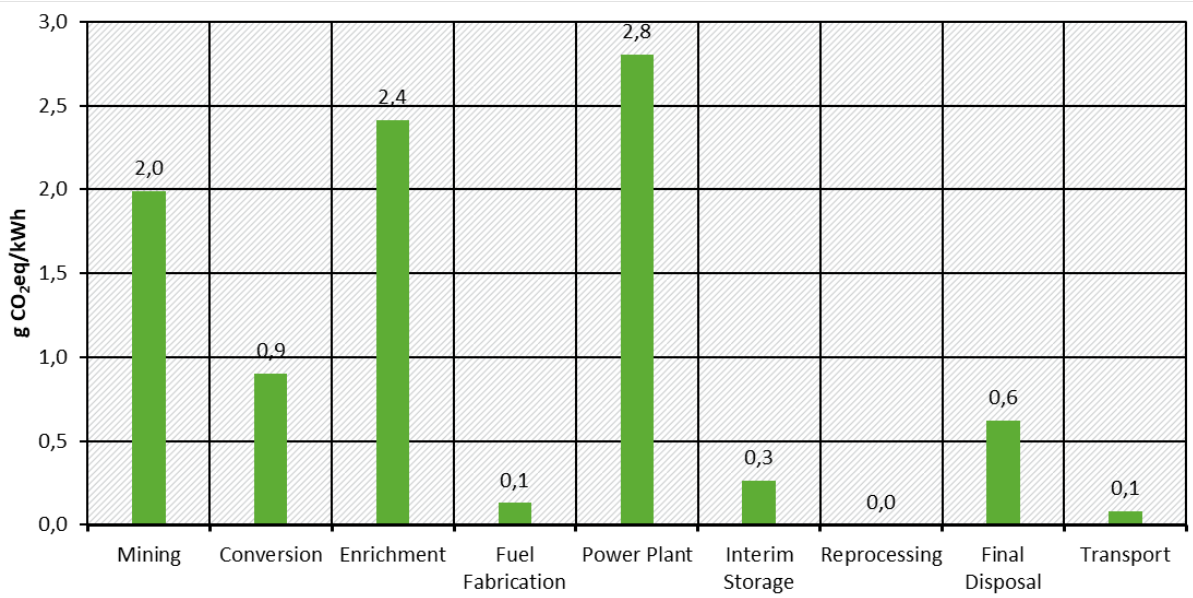
Table 182: CN3 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	9.2
CED - Total	MJ/kWh	1.5E+01
CED - fossil	MJ/kWh	1.1E-01
ADP	kg Sbeq/kWh	2.1E-06
Land use	dimensionless (pt)/kWh	2.4E-02
Water use	m^3/kWh	1.2E-01
Ionising radiation	kBq U235 eq/kWh	1.3E+00
Human toxicity, cancer	CTUh/kWh	2.5E-03

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	1.4E-01
radioactive waste, high level	m³/kWh	5.3E-09
radioactive waste, low level	m³/kWh	7.6E-08
tailing, from uranium milling	m³/kWh	5.8E-06

Source: Öko-Institut

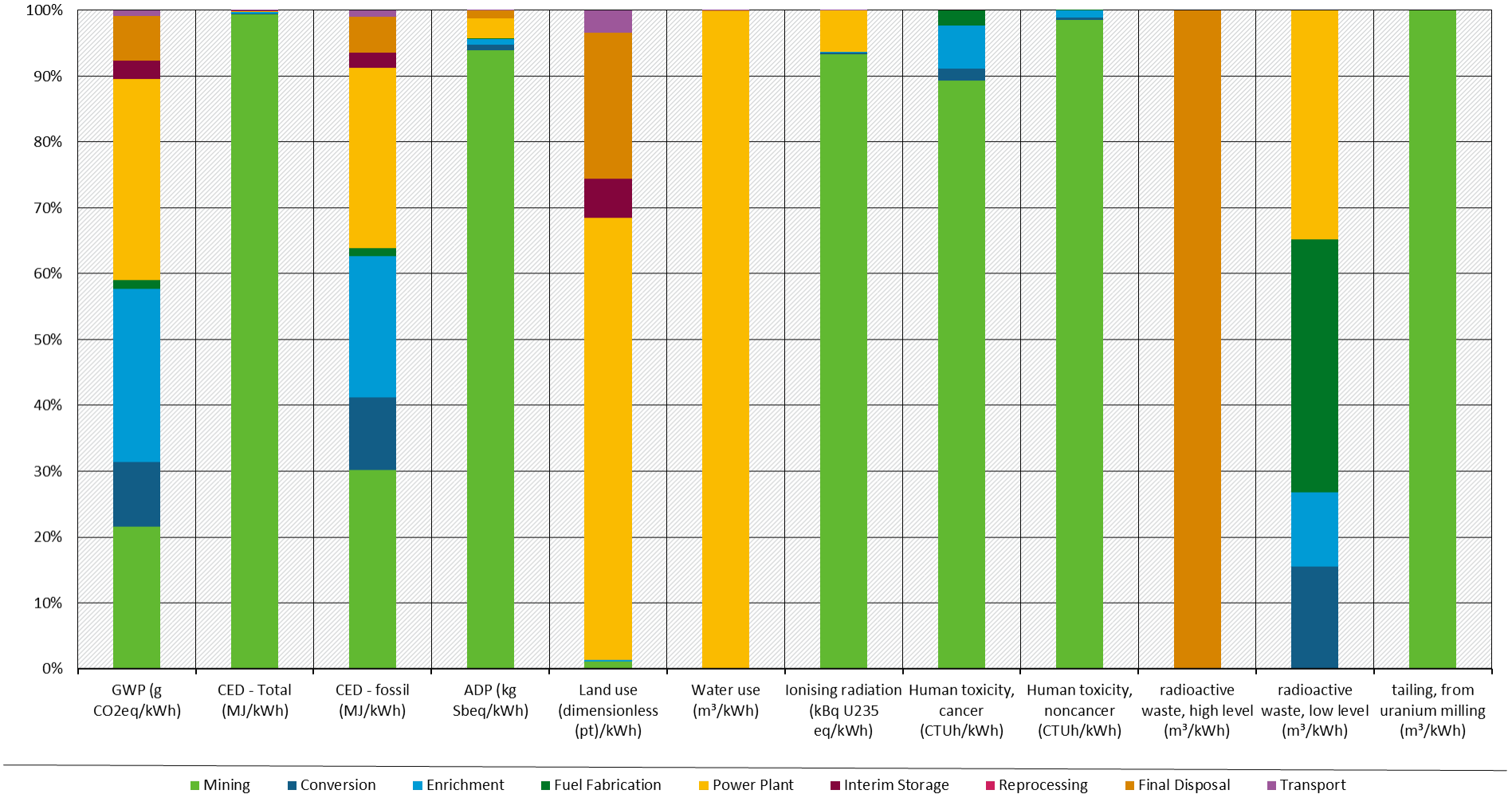
Figure 216: CN3 breakdown of GWP



Total GWP of CN3: 9,2 g CO2eq/kWh

Source: Öko-Institut

Figure 217: CN3 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.47 RK1

Table 183: RK1 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.05
Mine_Infrastructure	Mine Type	Underground
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	4
Enrichment_Centrifuge	Country	France
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	South Korea
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	South Korea
Electricity_Production_Nuclear	Load Factor	0.75
Electricity_Production_Nuclear	Net Efficiency (%)	0.34
Electricity_Production_Nuclear	Country	South Korea
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	-
Backend	Country	South Korea

Source: Öko-Institut

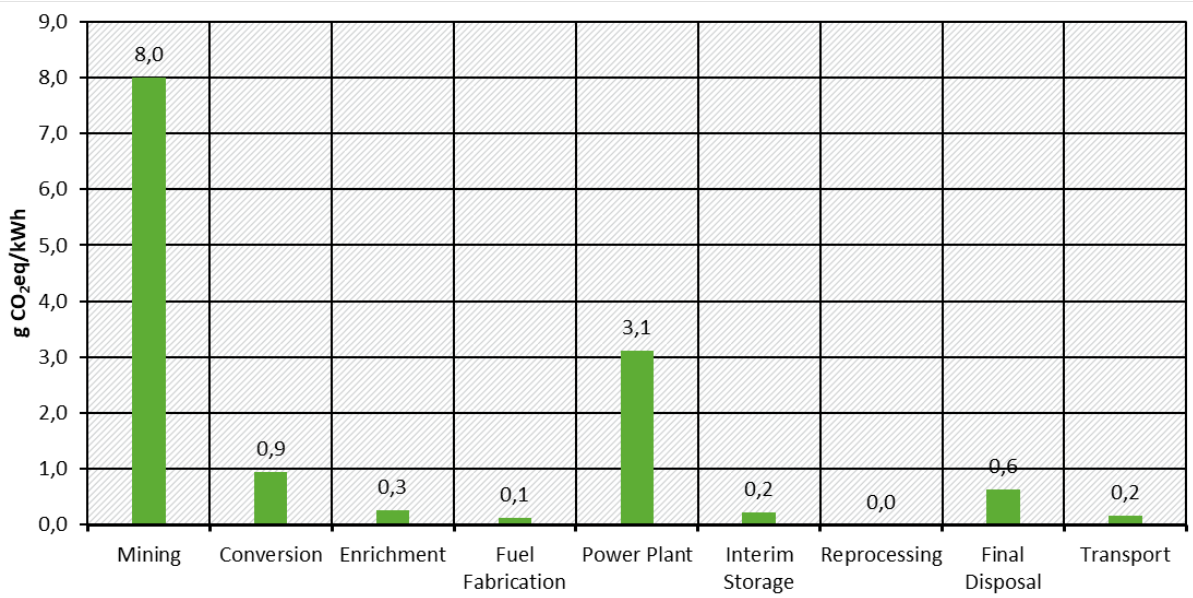
Table 184: RK1 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	13.5
CED - Total	MJ/kWh	4.7E+01
CED - fossil	MJ/kWh	1.7E-01
ADP	kg Sbeq/kWh	6.3E-06
Land use	dimensionless (pt)/kWh	3.2E-02
Water use	m^3/kWh	1.2E-01
Ionising radiation	kBq U235 eq/kWh	3.9E+00
Human toxicity, cancer	CTUh/kWh	7.2E-03

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	4.3E-01
radioactive waste, high level	m³/kWh	6.0E-09
radioactive waste, low level	m³/kWh	7.5E-08
tailing, from uranium milling	m³/kWh	1.8E-05

Source: Öko-Institut

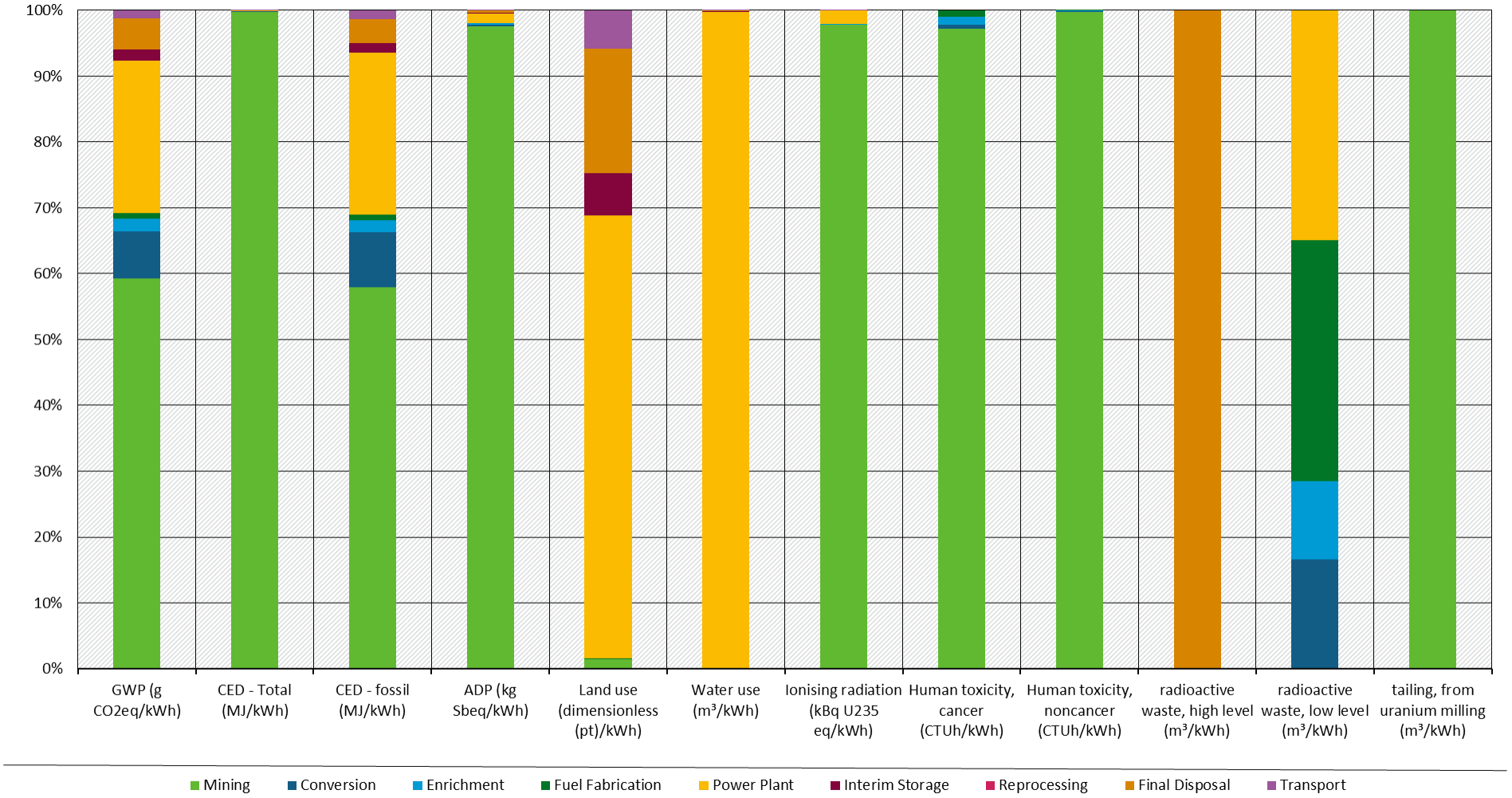
Figure 218: RK1 breakdown of GWP



Total GWP of RK1: 13,5 g CO2eq/kWh

Source: Öko-Institut

Figure 219: RK1 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.48 IN1

Table 185: IN1 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.07
Mine_Infrastructure	Mine Type	In-situ leaching
Conversion_UF6	Country	Russia
Enrichment_Centrifuge	enrichment grade (% U235)	3.75
Enrichment_Centrifuge	Country	Russia
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	Russia
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	India
Electricity_Production_Nuclear	Load Factor	0.76
Electricity_Production_Nuclear	Net Efficiency (%)	0.28
Electricity_Production_Nuclear	Country	India
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	India

Source: Öko-Institut

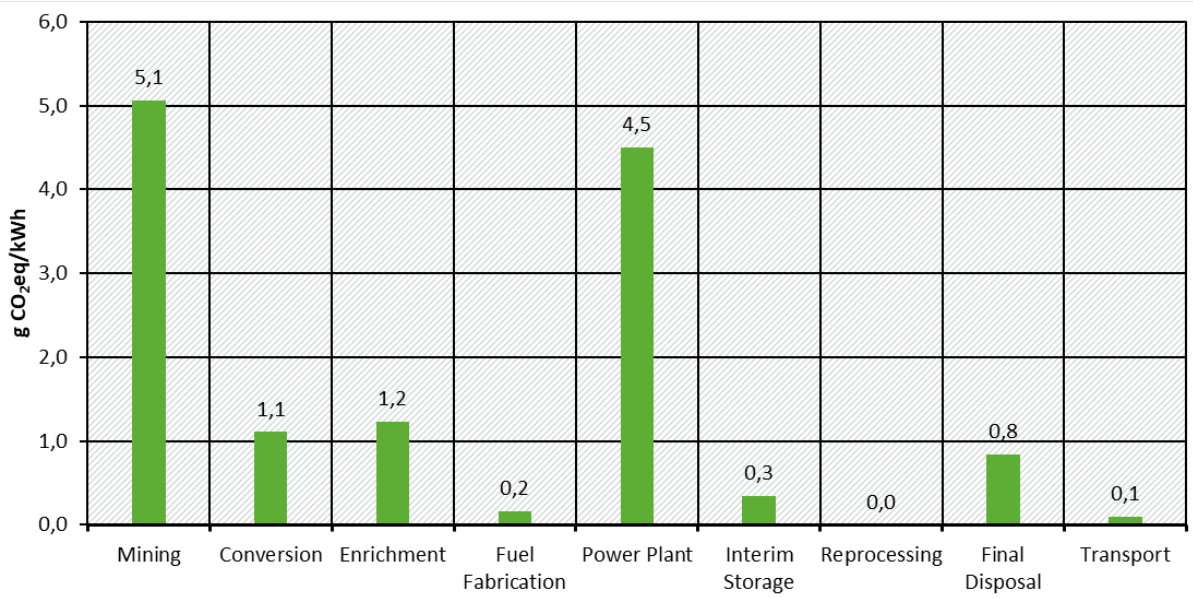
Table 186: IN1 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	13.3
CED - Total	MJ/kWh	8.6E+01
CED - fossil	MJ/kWh	4.3E+01
ADP	kg Sbeq/kWh	5.4E-06
Land use	dimensionless (pt)/kWh	4.0E-02
Water use	m^3/kWh	1.2E-01
Ionising radiation	kBq U235 eq/kWh	8.8E-02
Human toxicity, cancer	CTUh/kWh	7.2E-04

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	5.4E-02
radioactive waste, high level	m³/kWh	8.0E-09
radioactive waste, low level	m³/kWh	8.3E-08
tailing, from uranium milling	m³/kWh	0.0E+00

Source: Öko-Institut

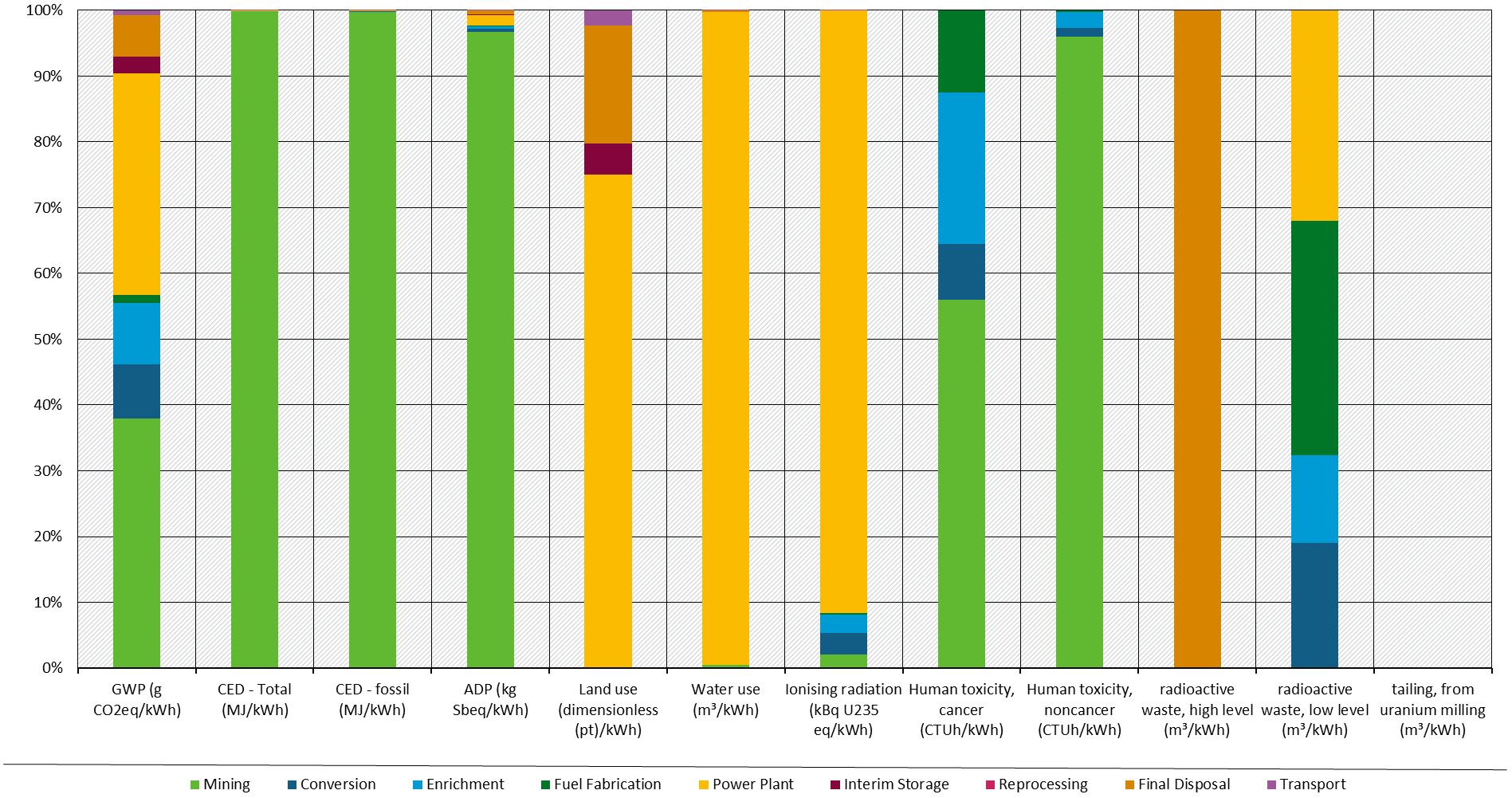
Figure 220: IN1 breakdown of GWP



Total GWP of IN1: 13,3 g CO2eq/kWh

Source: Öko-Institut

Figure 221: IN1 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.49 AE1

Table 187: AE1 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.13
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	3.75
Enrichment_Centrifuge	Country	France
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	South Korea
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	60
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	UAE
Electricity_Production_Nuclear	Load Factor	0.78
Electricity_Production_Nuclear	Net Efficiency (%)	0.33
Electricity_Production_Nuclear	Country	UAE
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	UAE

Source: Öko-Institut

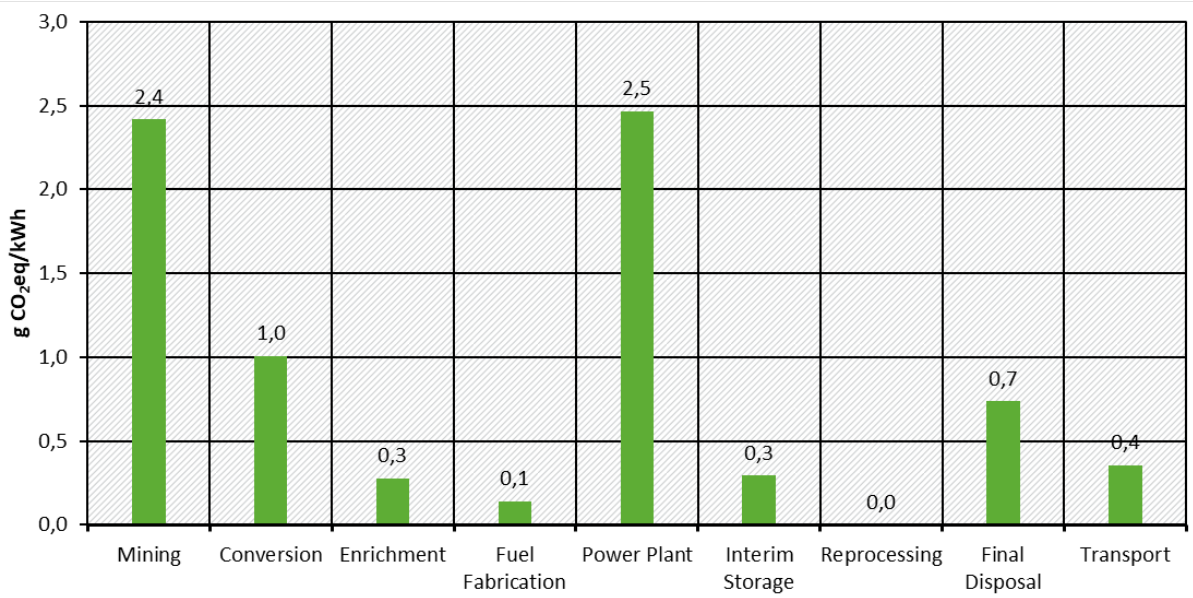
Table 188: AE1 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	7.7
CED - Total	MJ/kWh	1.9E+01
CED - fossil	MJ/kWh	1.0E-01
ADP	kg Sbeq/kWh	2.5E-06
Land use	dimensionless (pt)/kWh	2.4E-02
Water use	m^3/kWh	1.2E-01
Ionising radiation	kBq U235 eq/kWh	1.5E+00
Human toxicity, cancer	CTUh/kWh	3.0E-03

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	1.7E-01
radioactive waste, high level	m³/kWh	6.8E-09
radioactive waste, low level	m³/kWh	7.8E-08
tailing, from uranium milling	m³/kWh	7.1E-06

Source: Öko-Institut

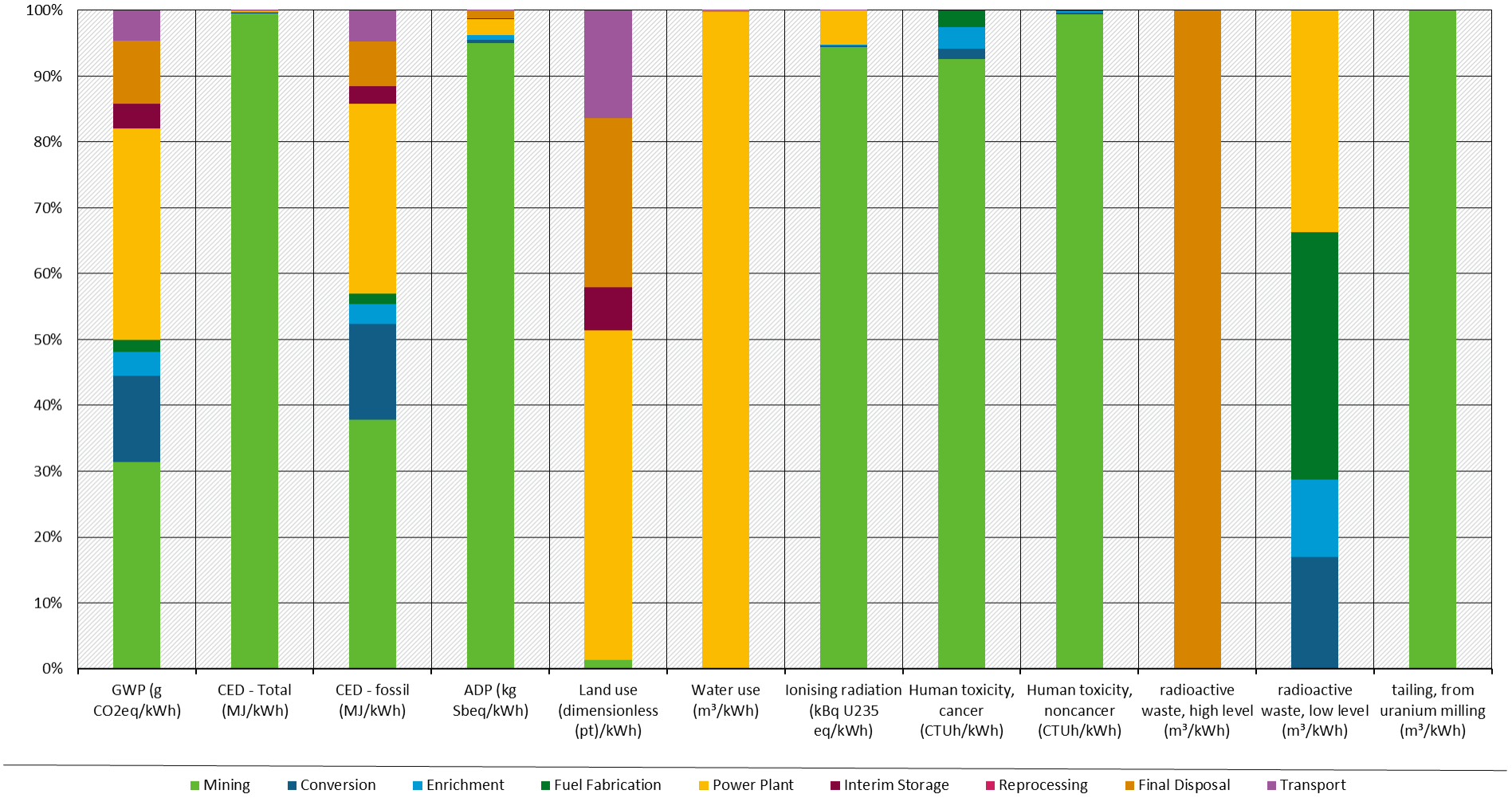
Figure 222: AE1 breakdown of GWP



Total GWP of AE1: 7,7 g CO2eq/kWh

Source: Öko-Institut

Figure 223: AE1 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.50 JP1

Table 189: JP1 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	11.50
Mine_Infrastructure	Mine Type	Underground
Conversion_UF6	Country	United States
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	Japan
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	Japan
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	45
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	Japan
Electricity_Production_Nuclear	Load Factor	0.5
Electricity_Production_Nuclear	Net Efficiency (%)	0.32
Electricity_Production_Nuclear	Country	Japan
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	-
Backend	Country	Japan

Source: Öko-Institut

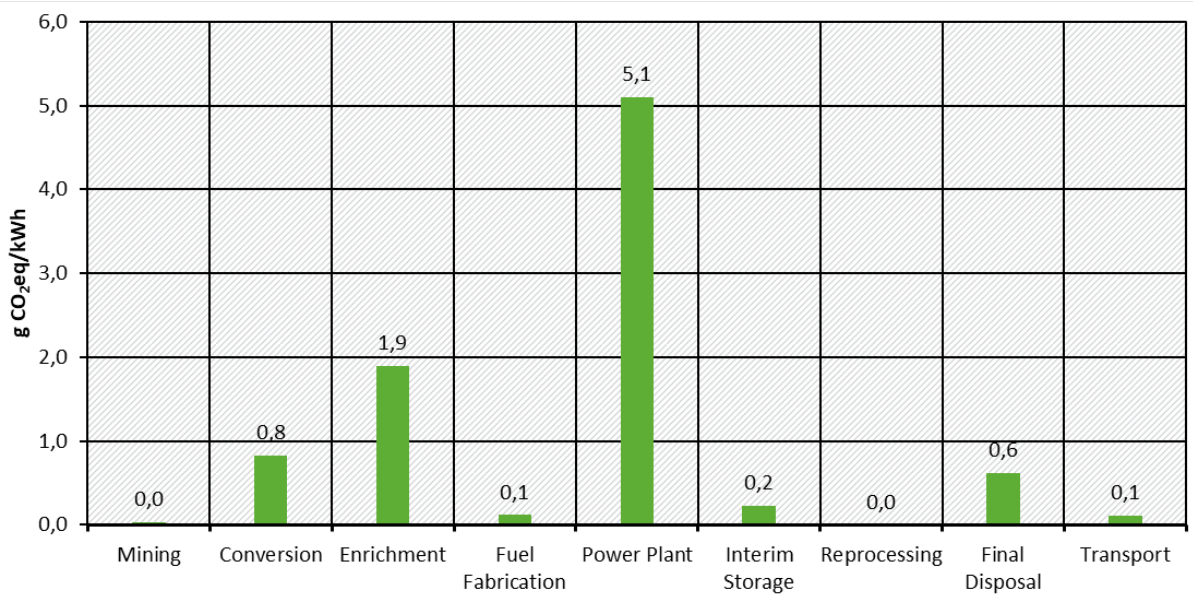
Table 190: JP1 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	8.9
CED - Total	MJ/kWh	3.3E-01
CED - fossil	MJ/kWh	1.1E-01
ADP	kg Sbeq/kWh	2.6E-07
Land use	dimensionless (pt)/kWh	5.1E-02
Water use	m^3/kWh	1.2E-01
Ionising radiation	kBq U235 eq/kWh	1.0E-01
Human toxicity, cancer	CTUh/kWh	2.9E-04

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	3.9E-03
radioactive waste, high level	m³/kWh	5.6E-09
radioactive waste, low level	m³/kWh	7.7E-08
tailing, from uranium milling	m³/kWh	7.6E-08

Source: Öko-Institut

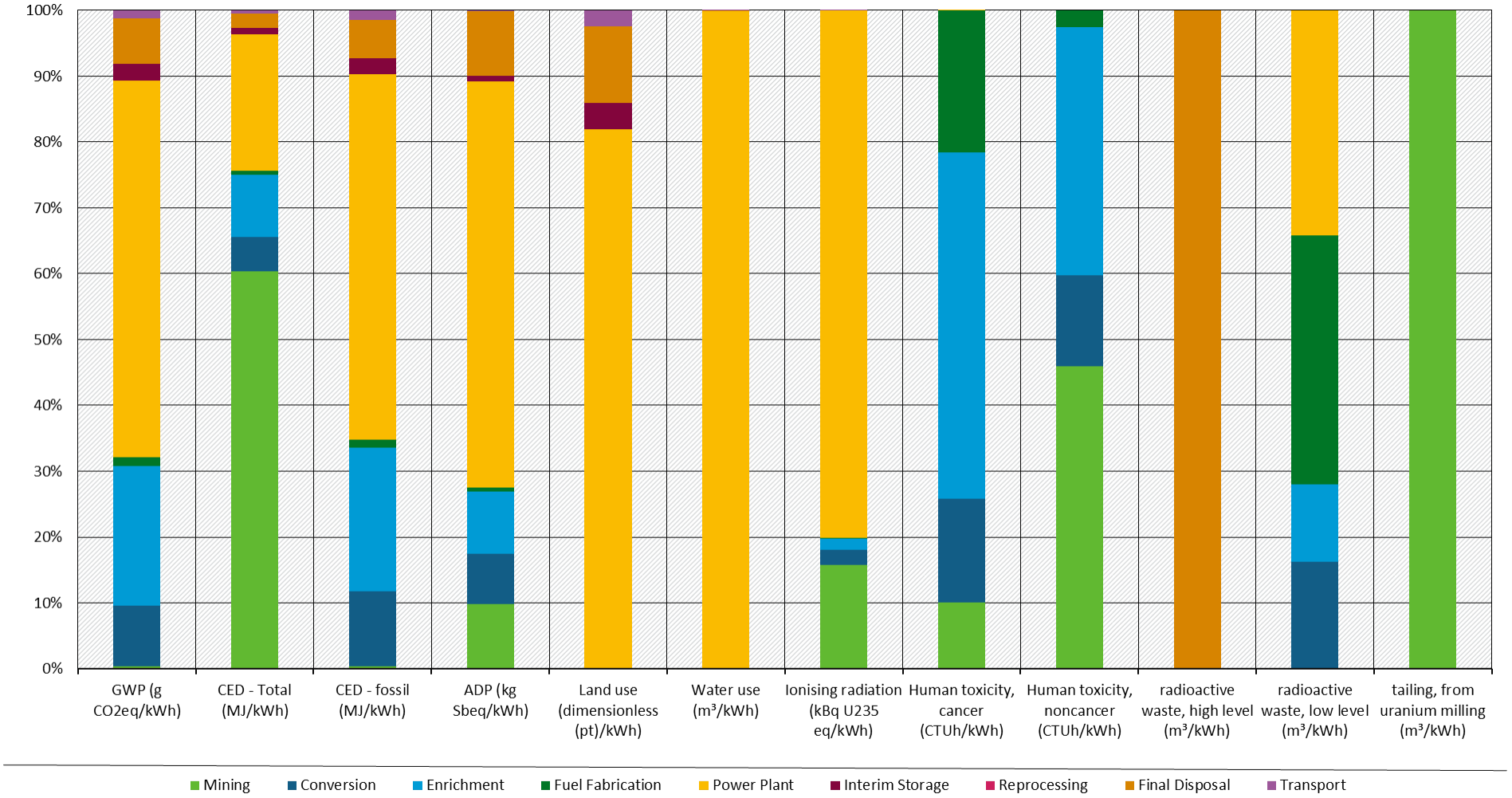
Figure 224: JP1 breakdown of GWP



Total GWP of JP1: 8,9 g CO2eq/kWh

Source: Öko-Institut

Figure 225: JP1 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.51 JP2

Table 191: JP2 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.05
Mine_Infrastructure	Mine Type	Underground
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	4.2
Enrichment_Centrifuge	Country	France
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	2.55
Fuel_Element_Fabrication	Country UOX	France
Fuel_Element_Fabrication	Country MOX	France
NPP_Construction	plant life (y)	45
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	Japan
Electricity_Production_Nuclear	Load Factor	0.5
Electricity_Production_Nuclear	Net Efficiency (%)	0.32
Electricity_Production_Nuclear	Country	Japan
NPP_Retrofitting	Replacement Ratio (%)	1
Reprocessing	Country	France
Backend	Country	Japan

Source: Öko-Institut

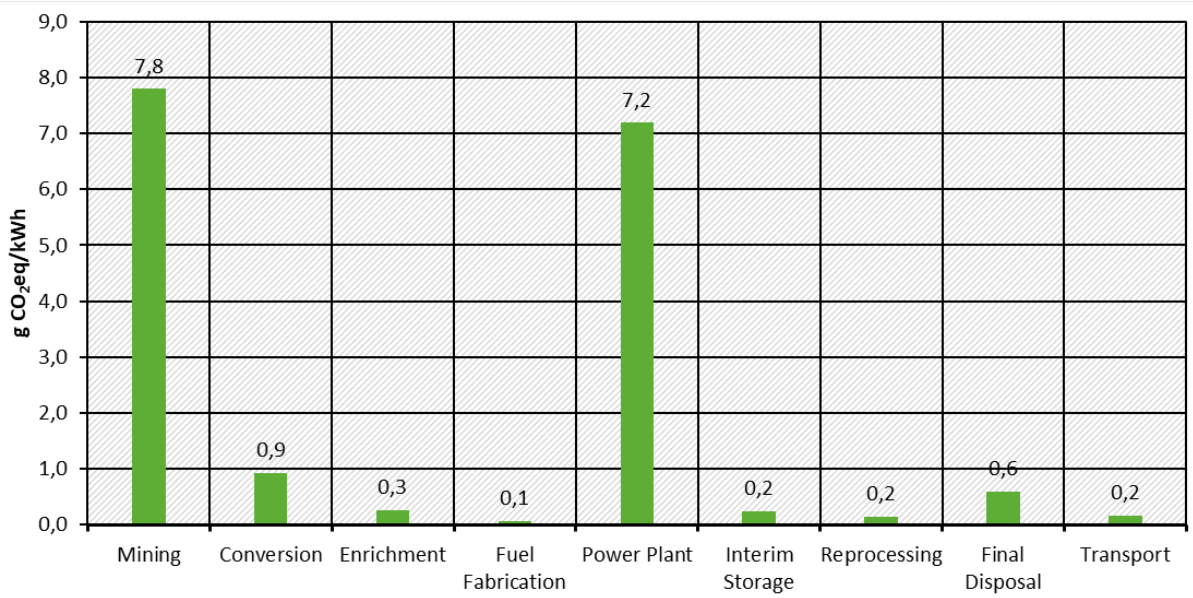
Table 192: JP2 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	17.4
CED - Total	MJ/kWh	4.6E+01
CED - fossil	MJ/kWh	2.1E-01
ADP	kg Sbeq/kWh	6.3E-06
Land use	dimensionless (pt)/kWh	5.2E-02
Water use	m^3/kWh	1.2E-01
Ionising radiation	kBq U235 eq/kWh	3.8E+00
Human toxicity, cancer	CTUh/kWh	7.1E-03

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	4.2E-01
radioactive waste, high level	m³/kWh	6.7E-09
radioactive waste, low level	m³/kWh	7.9E-08
tailing, from uranium milling	m³/kWh	1.8E-05

Source: Öko-Institut

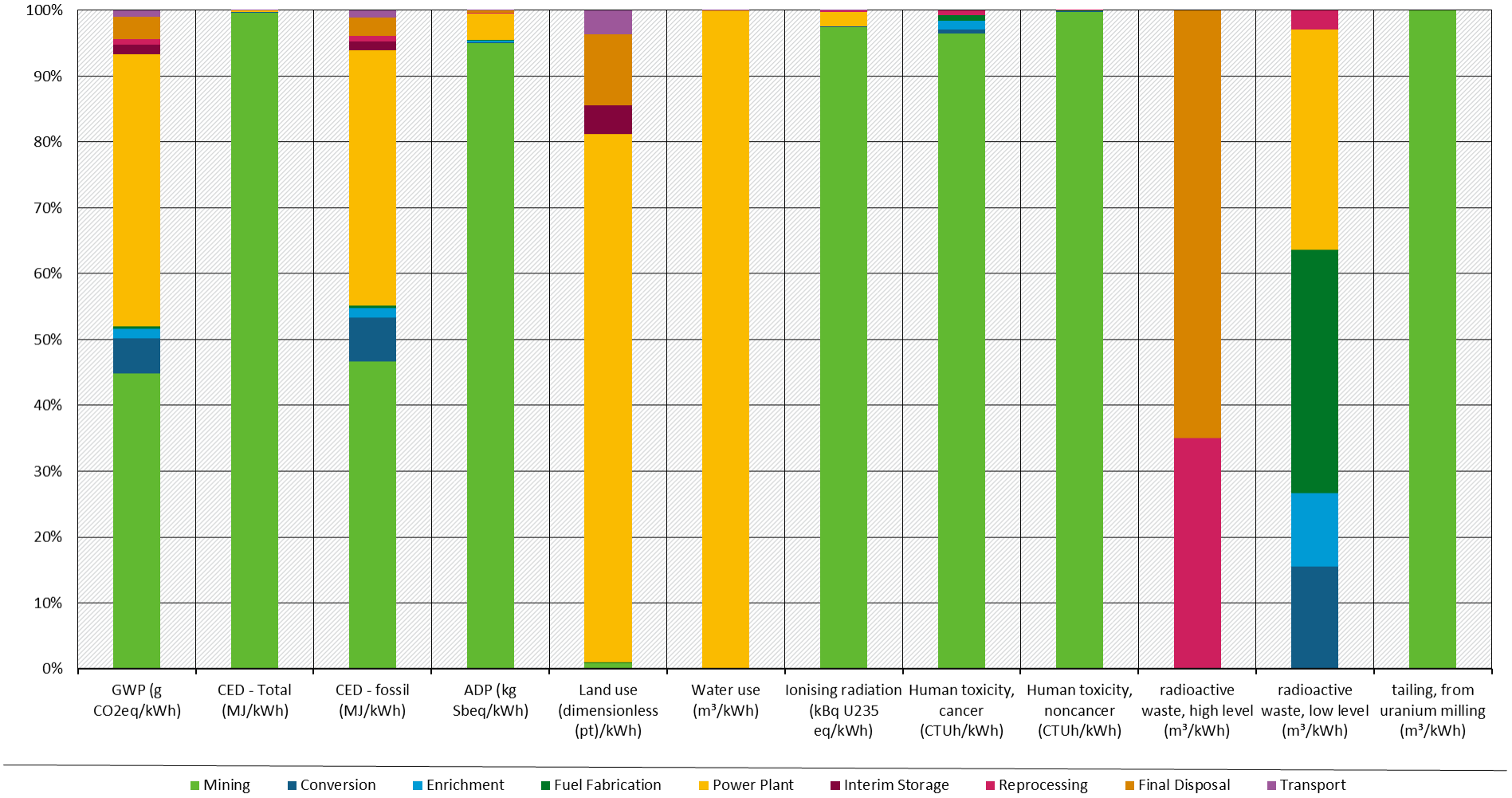
Figure 226: JP2 breakdown of GWP



Total GWP of JP2: 17,4 g CO2eq/kWh

Source: Öko-Institut

Figure 227: JP2 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.52 ZA1

Table 193: ZA1 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.06
Mine_Infrastructure	Mine Type	Underground
Conversion_UF6	Country	Russia
Enrichment_Centrifuge	enrichment grade (% U235)	4
Enrichment_Centrifuge	Country	Russia
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	Russia
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	South Africa
Electricity_Production_Nuclear	Load Factor	0.82
Electricity_Production_Nuclear	Net Efficiency (%)	0.33
Electricity_Production_Nuclear	Country	South Africa
NPP_Retrofitting	Replacement Ratio (%)	0
Reprocessing	Country	-
Backend	Country	South Africa

Source: Öko-Institut

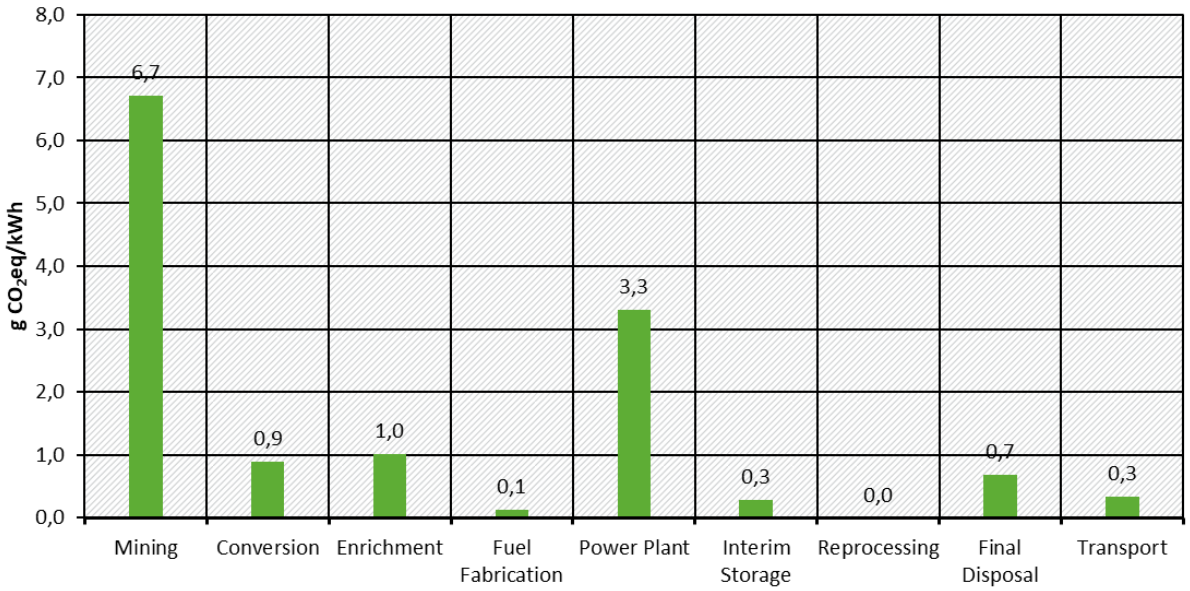
Table 194: ZA1 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	13.3
CED - Total	MJ/kWh	4.0E+01
CED - fossil	MJ/kWh	1.7E-01
ADP	kg Sbeq/kWh	5.3E-06
Land use	dimensionless (pt)/kWh	3.1E-02
Water use	m^3/kWh	1.2E-01
Ionising radiation	kBq U235 eq/kWh	3.3E+00
Human toxicity, cancer	CTUh/kWh	6.1E-03

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	3.6E-01
radioactive waste, high level	m³/kWh	6.0E-09
radioactive waste, low level	m³/kWh	7.7E-08
tailing, from uranium milling	m³/kWh	1.5E-05

Source: Öko-Institut

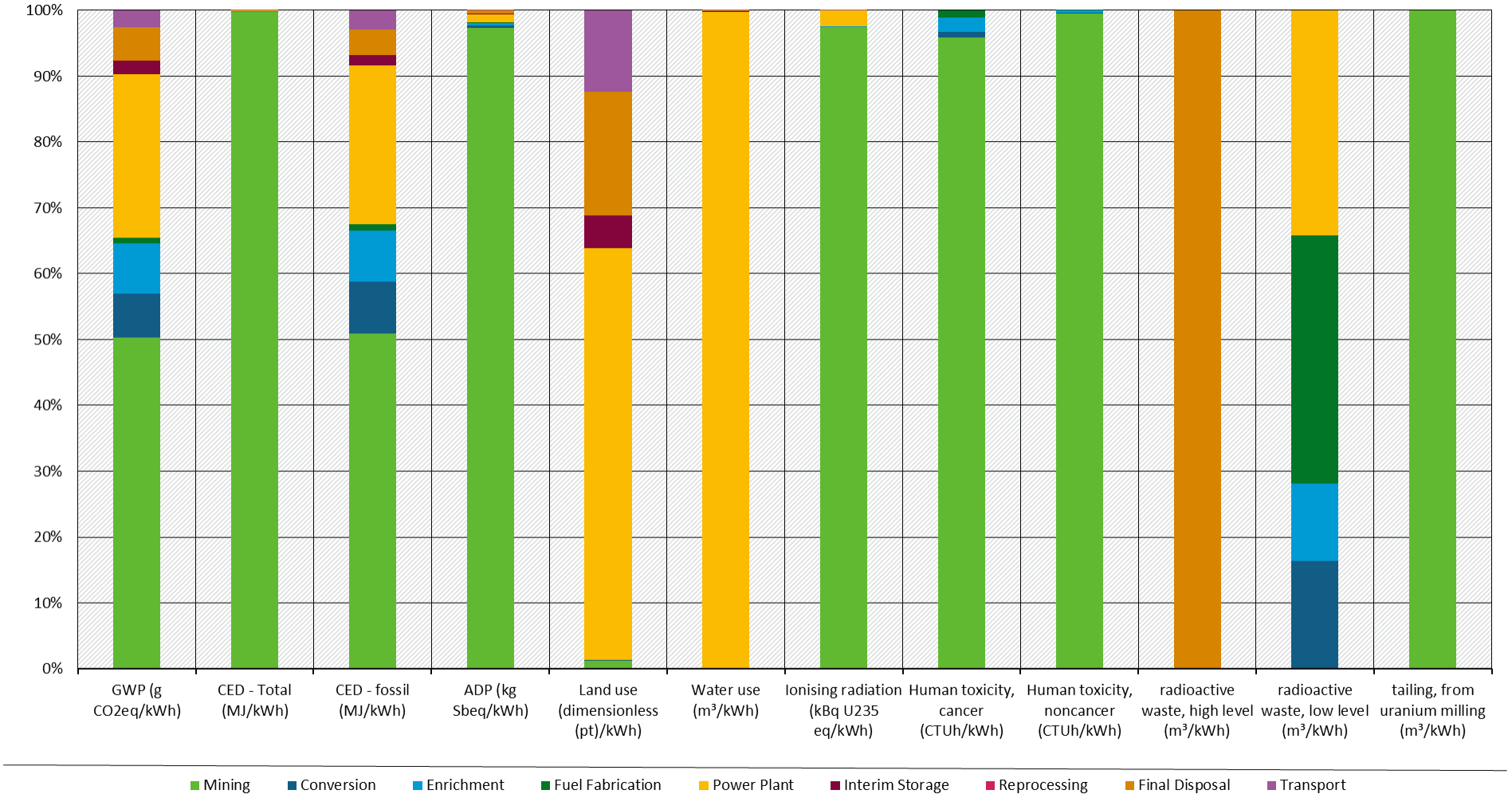
Figure 228: ZA1 breakdown of GWP



Total GWP of ZA1: 13,3 g CO2eq/kWh

Source: Öko-Institut

Figure 229: ZA1 breakdown of impacts by life cycle stage



Source: Öko-Institut

B.53 BR1

Table 195: BR1 life cycle chain parameters

Process Step	Parameter	Value
Uranium_Ore_Mining	Mine Name/Country	Arlit/Niger
Uranium_Ore_Mining	ore grade (%)	0.20
Mine_Infrastructure	Mine Type	Open cast
Conversion_UF6	Country	France
Enrichment_Centrifuge	enrichment grade (% U235)	4
Enrichment_Centrifuge	Country	Brazil
Fuel_Element_Fabrication	Fraction of MOX Fuel (%)	0
Fuel_Element_Fabrication	Country UOX	Brazil
Fuel_Element_Fabrication	Country MOX	-
NPP_Construction	plant life (y)	50
NPP_Construction	Plant Type	PWR
NPP_Construction	Country	Brazil
Electricity_Production_Nuclear	Load Factor	0.9
Electricity_Production_Nuclear	Net Efficiency (%)	0.33
Electricity_Production_Nuclear	Country	Brazil
NPP_Retrofitting	Replacement Ratio (%)	0.25
Reprocessing	Country	-
Backend	Country	Brazil

Source: Öko-Institut

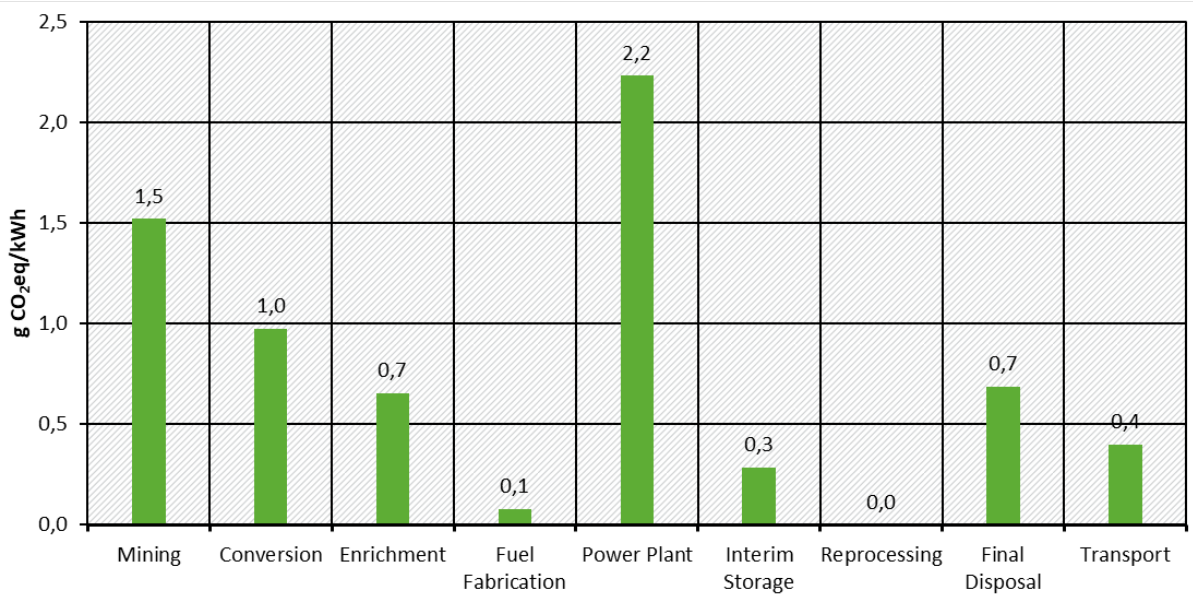
Table 196: BR1 life cycle chain results

Parameter	Unit	Result
GWP	g CO_2eq/kWh	6.8
CED - Total	MJ/kWh	1.2E+01
CED - fossil	MJ/kWh	8.6E-02
ADP	kg Sbeq/kWh	1.7E-06
Land use	dimensionless (pt)/kWh	3.1E-02
Water use	m^3/kWh	1.2E-01
Ionising radiation	kBq U235 eq/kWh	1.0E+00
Human toxicity, cancer	CTUh/kWh	2.0E-03

Parameter	Unit	Result
Human toxicity, noncancer	CTUh/kWh	1.1E-01
radioactive waste, high level	m³/kWh	6.1E-09
radioactive waste, low level	m³/kWh	7.8E-08
tailing, from uranium milling	m³/kWh	4.5E-06

Source: Öko-Institut

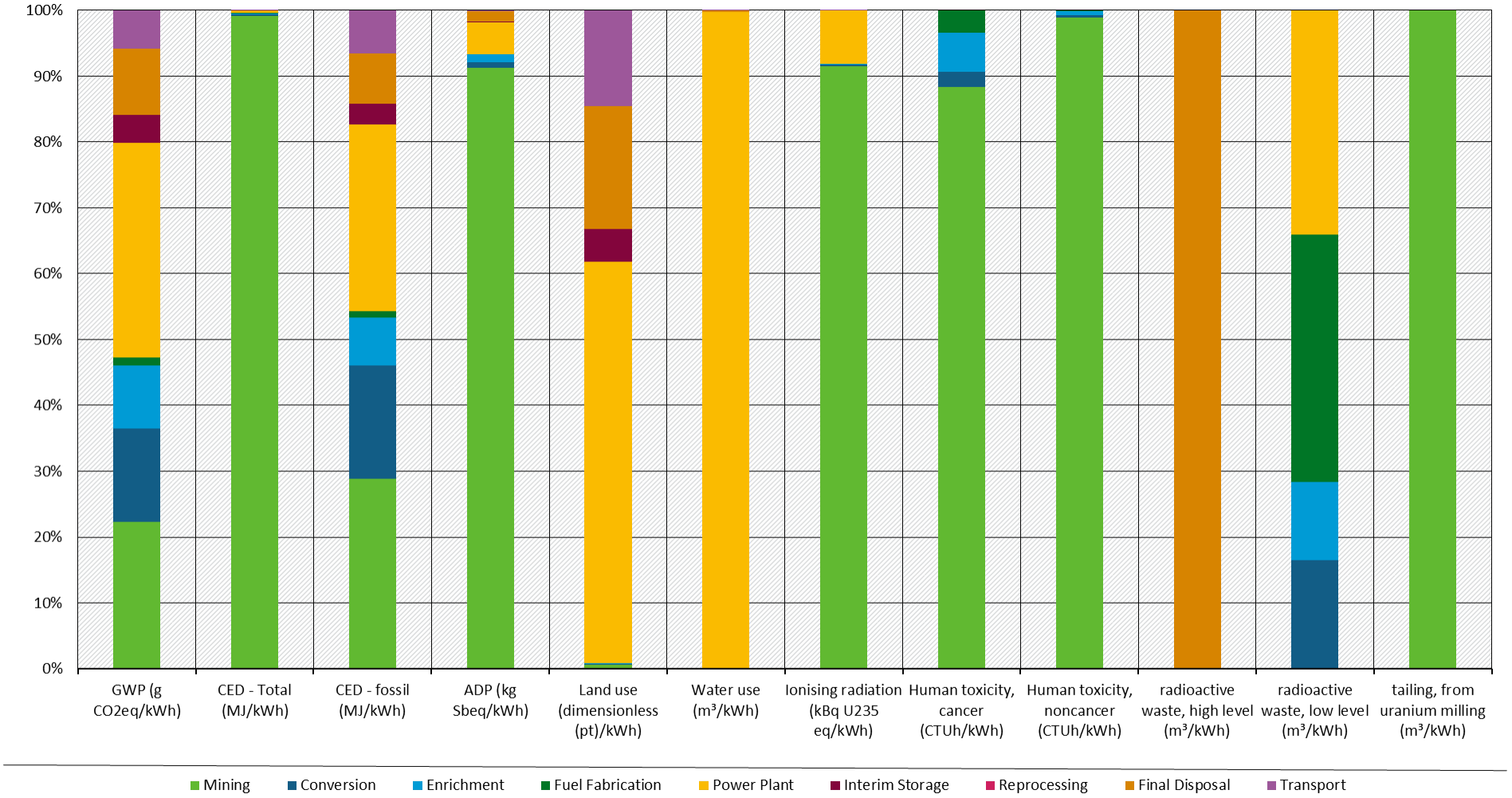
Figure 230: BR1 breakdown of GWP



Total GWP of BR1: 6,8 g CO2eq/kWh

Source: Öko-Institut

Figure 231: BR1 breakdown of impacts by life cycle stage

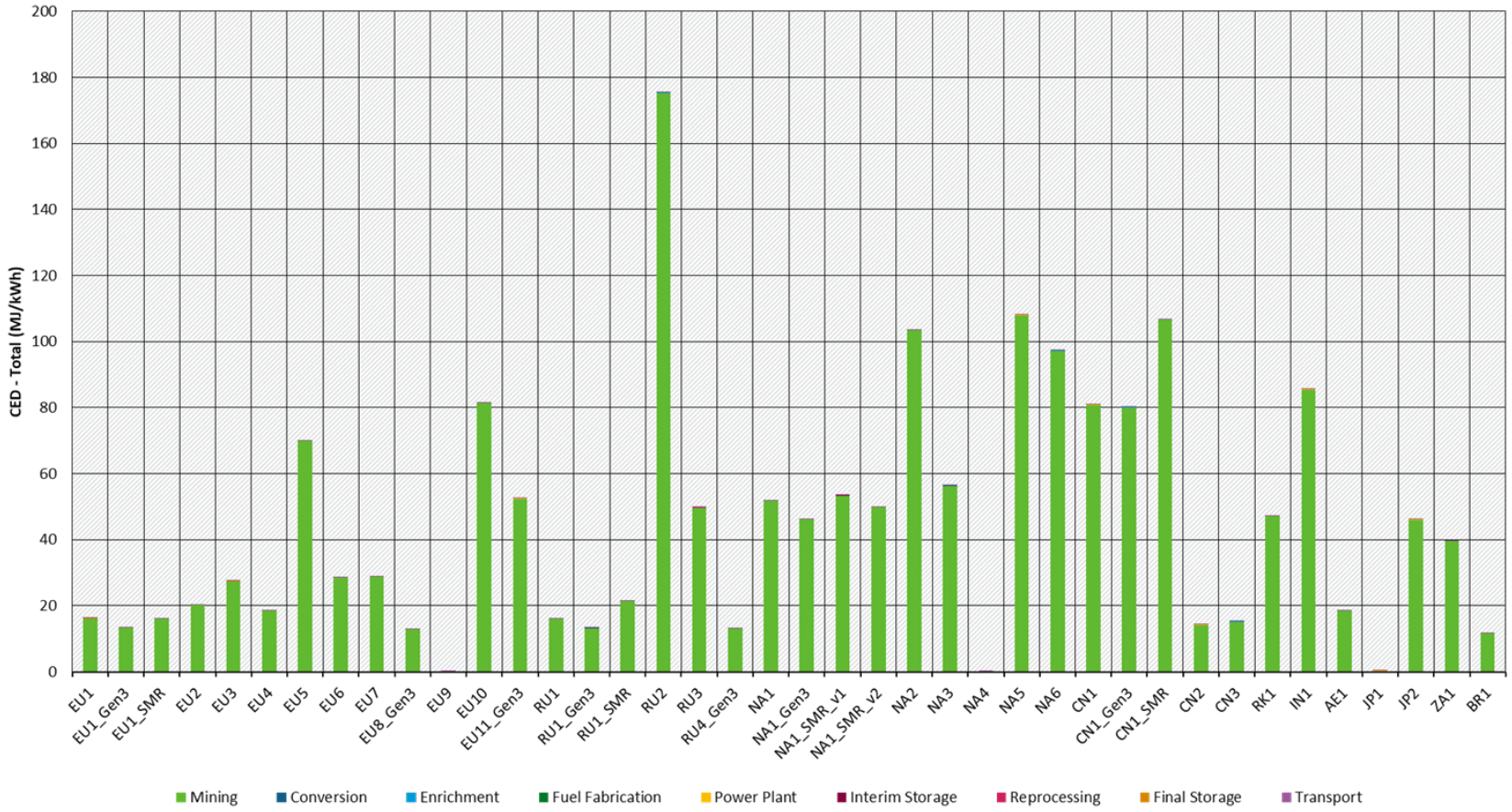


Source: Öko-Institut

C Life Cycle Chains: Total results for environmental impacts other than GWP

C.1 Total CED

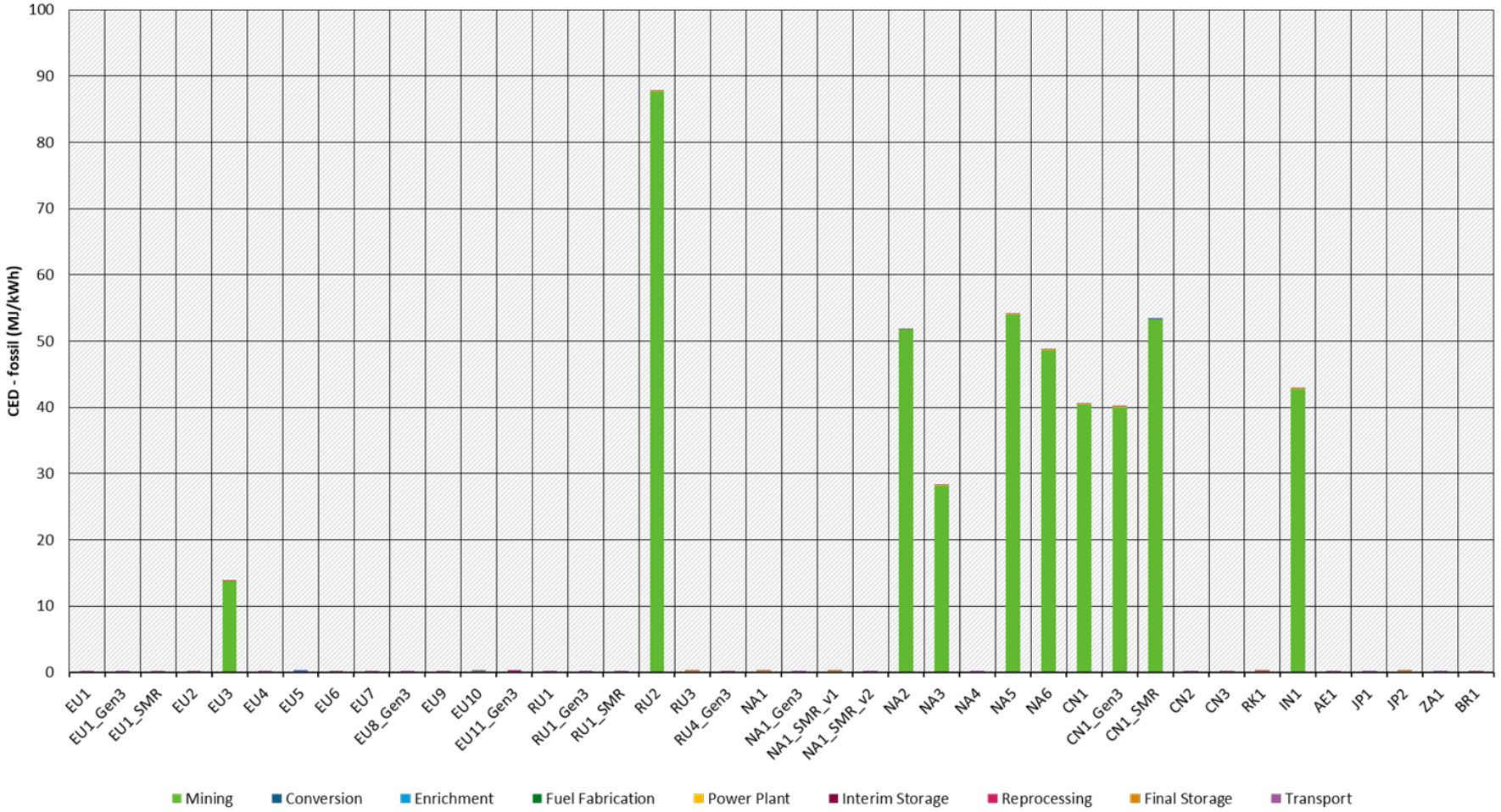
Figure 232: Breakdown of total CED for life cycle chains



Sources: Öko-Institut

C.2 Fossile CED

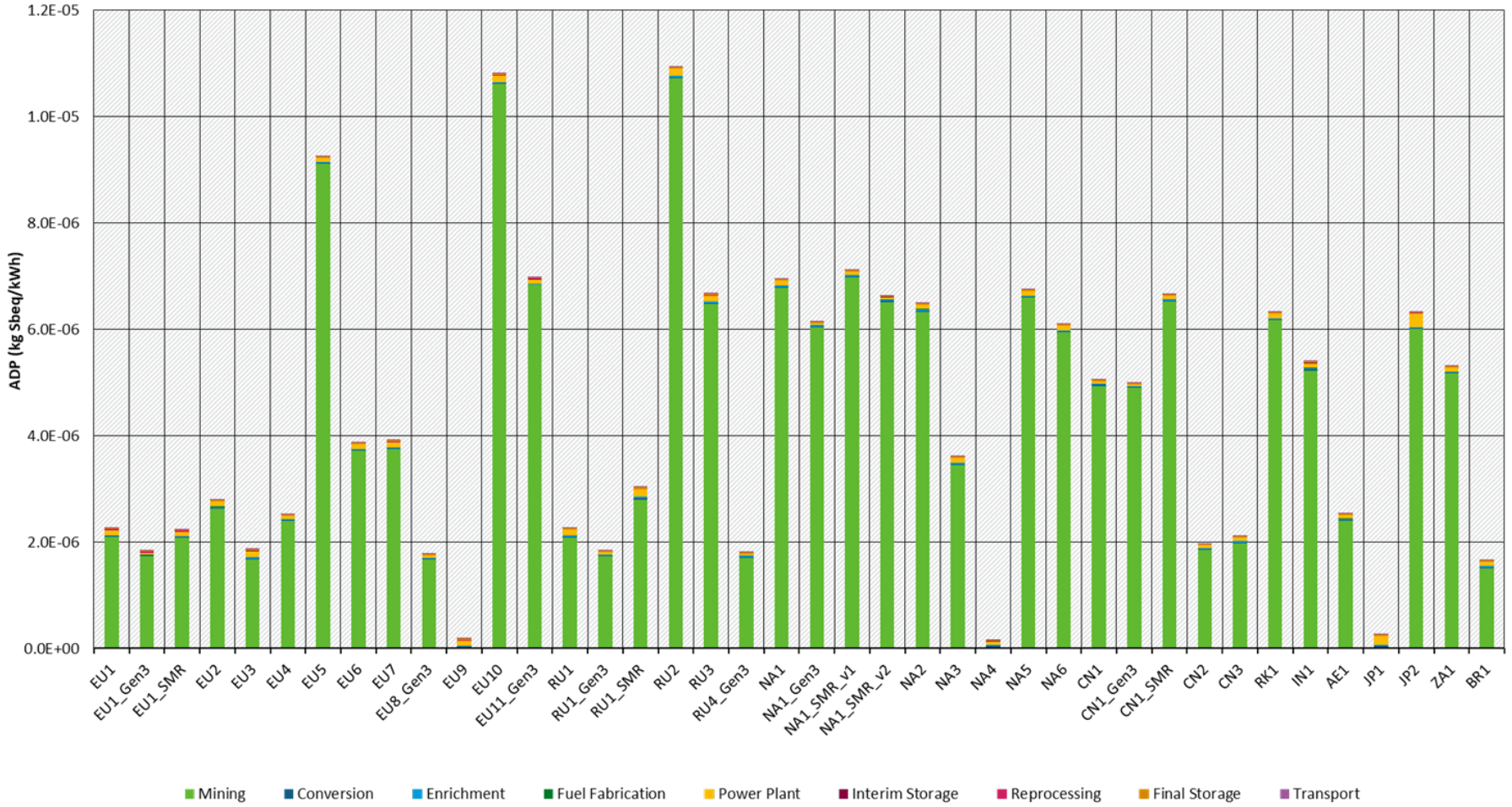
Figure 233: Breakdown of fossil CED for life cycle chains



Sources: Öko-Institut

C.3 ADP

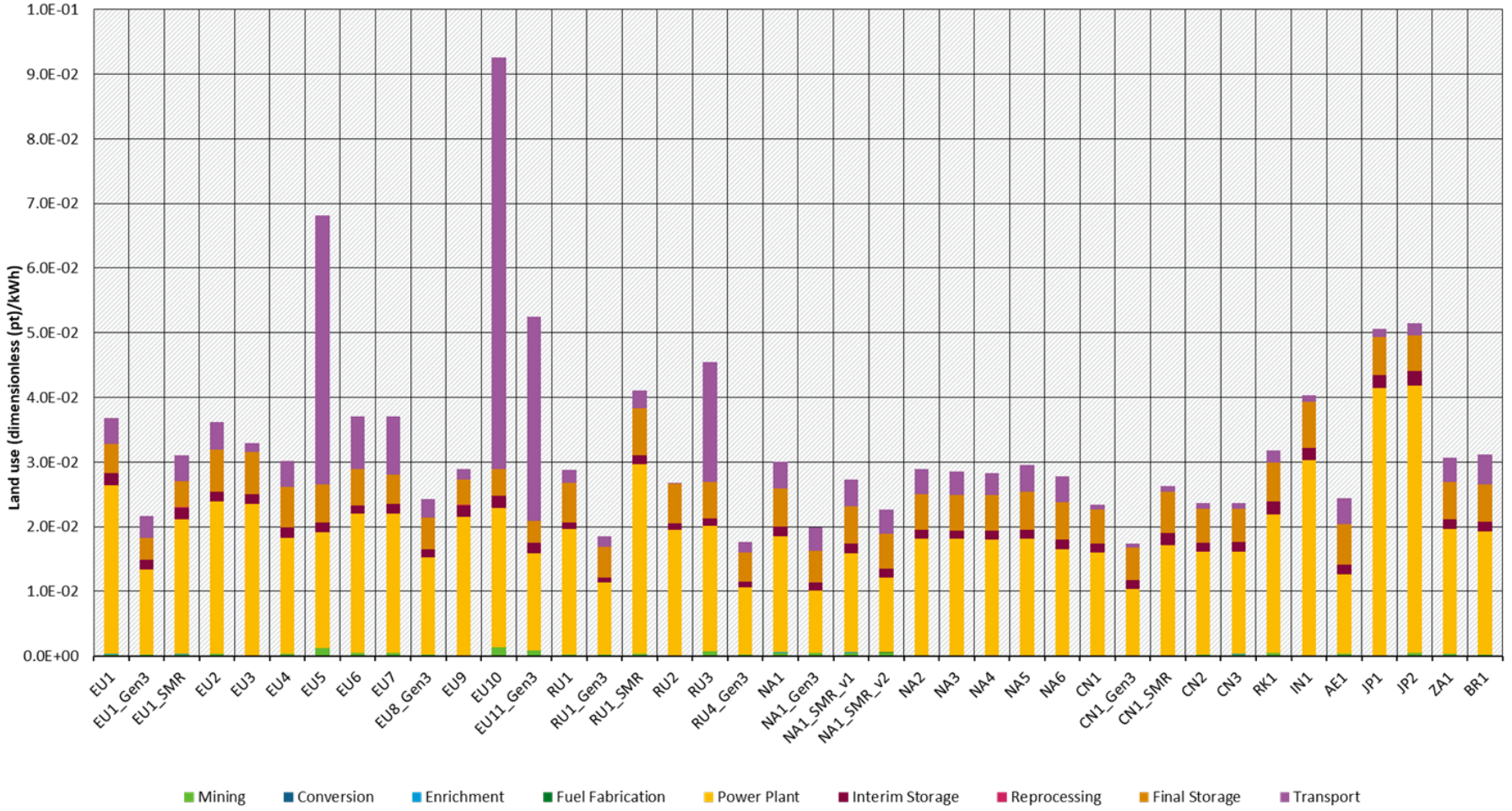
Figure 234: Breakdown of ADP for life cycle chains



Sources: Öko-Institut

C.4 Land use

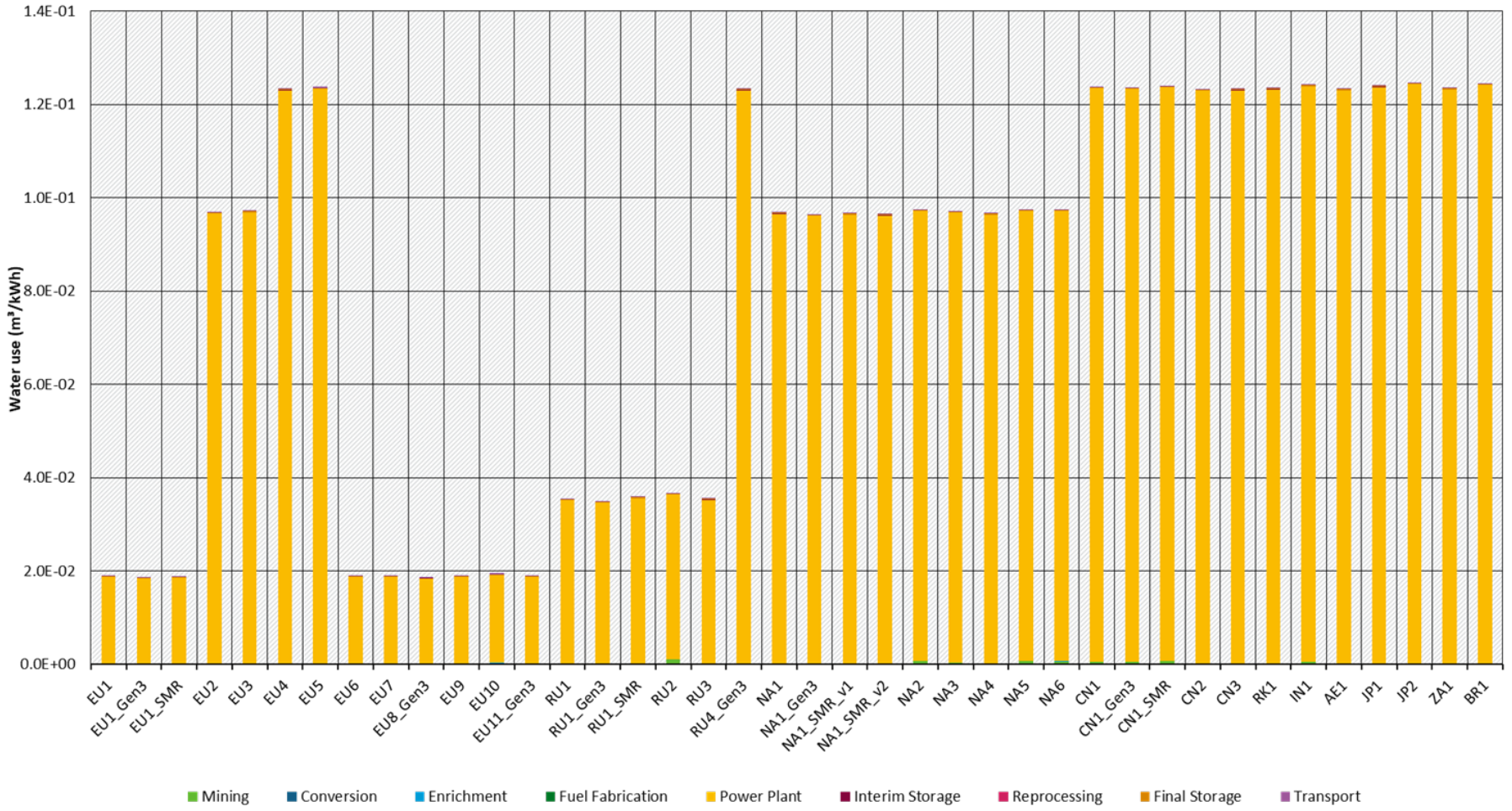
Figure 235: Breakdown of land use for life cycle chains



Sources: Öko-Institut

C.5 Water Use

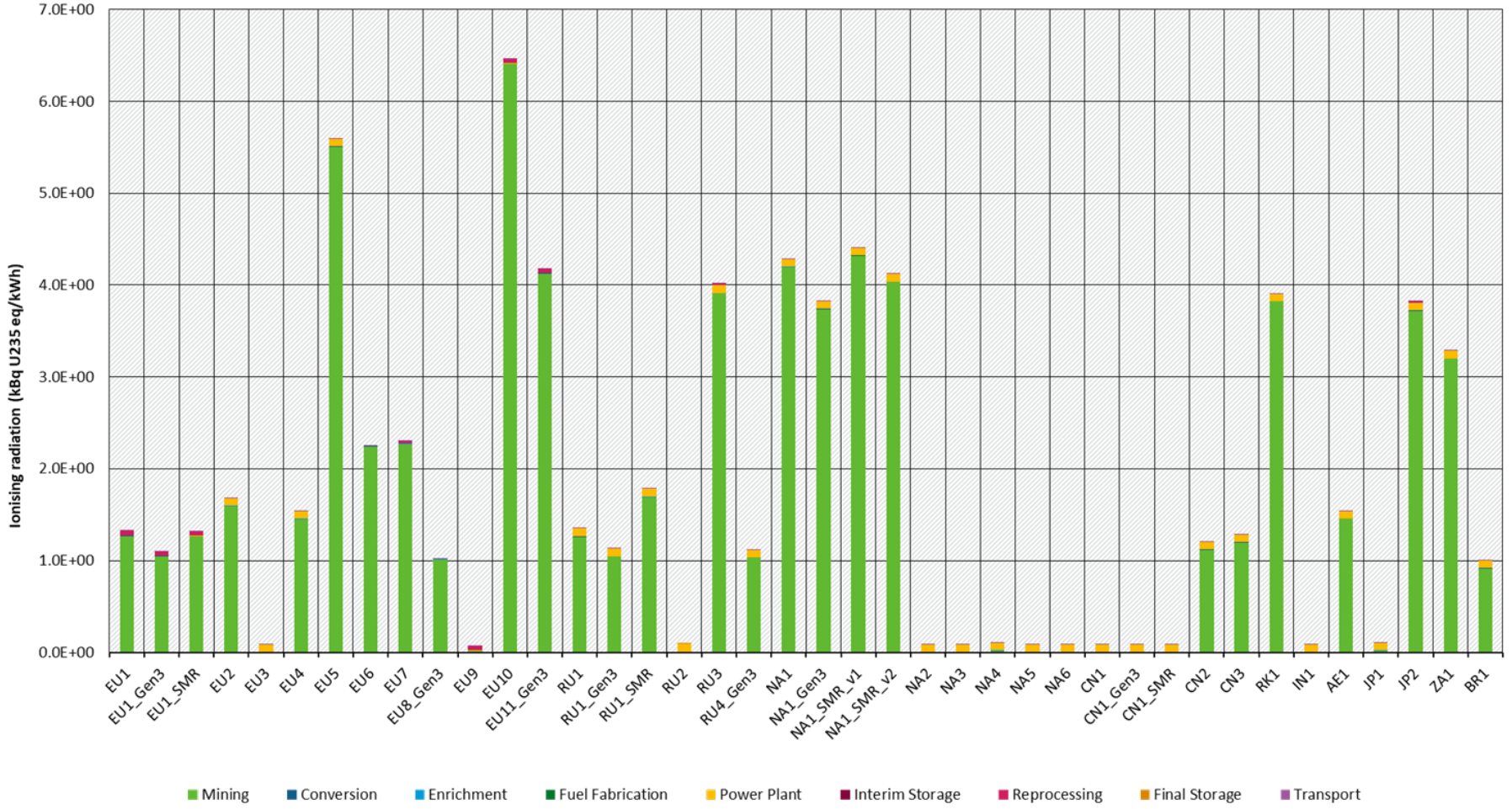
Figure 236: Breakdown of water use for life cycle chains



Sources: Öko-Institut

C.6 Ionizing radiation

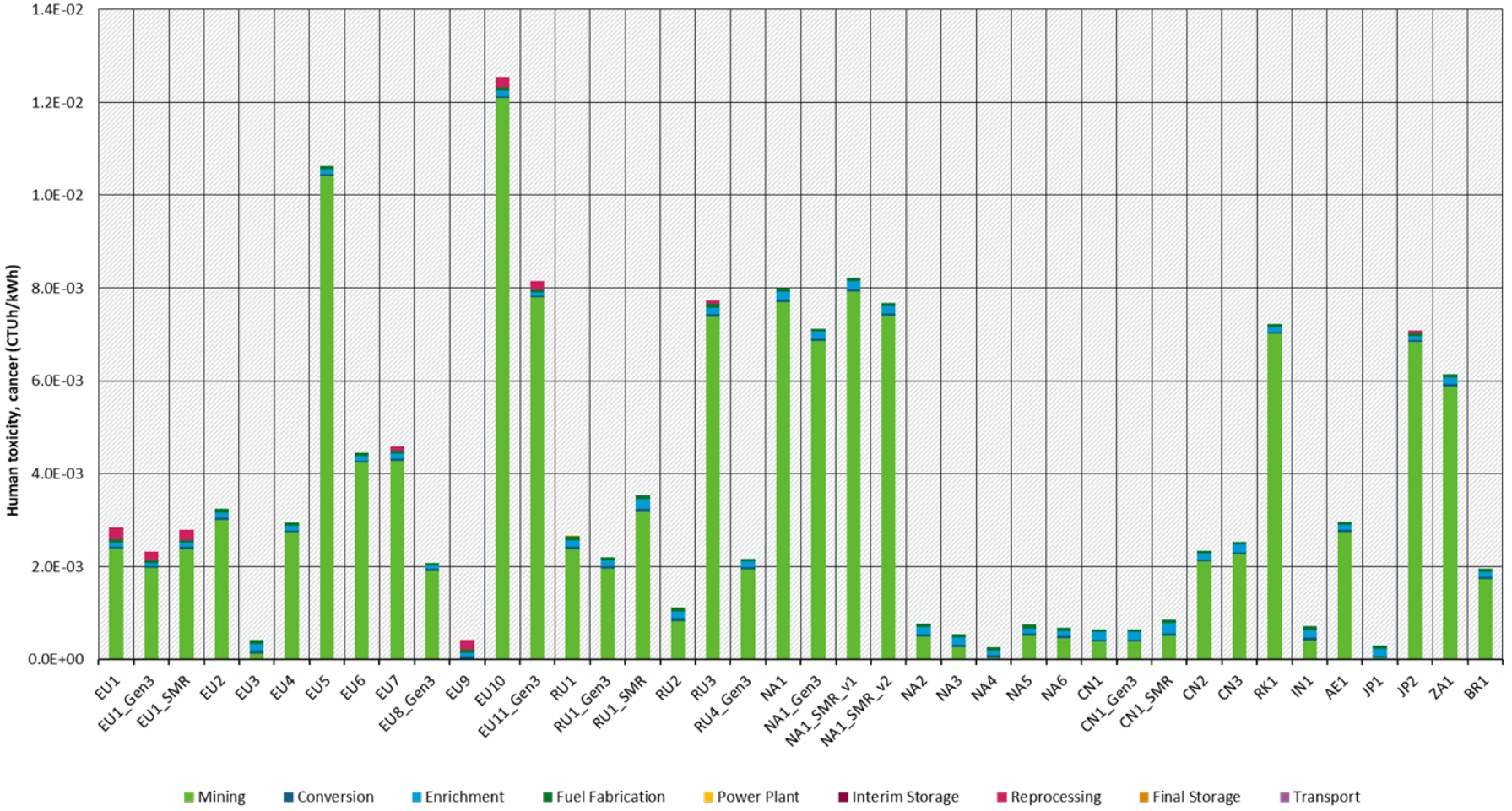
Figure 237: Breakdown of ionizing radiation for life cycle chains



Sources: Öko-Institut

C.7 Human Toxicity (Cancer)

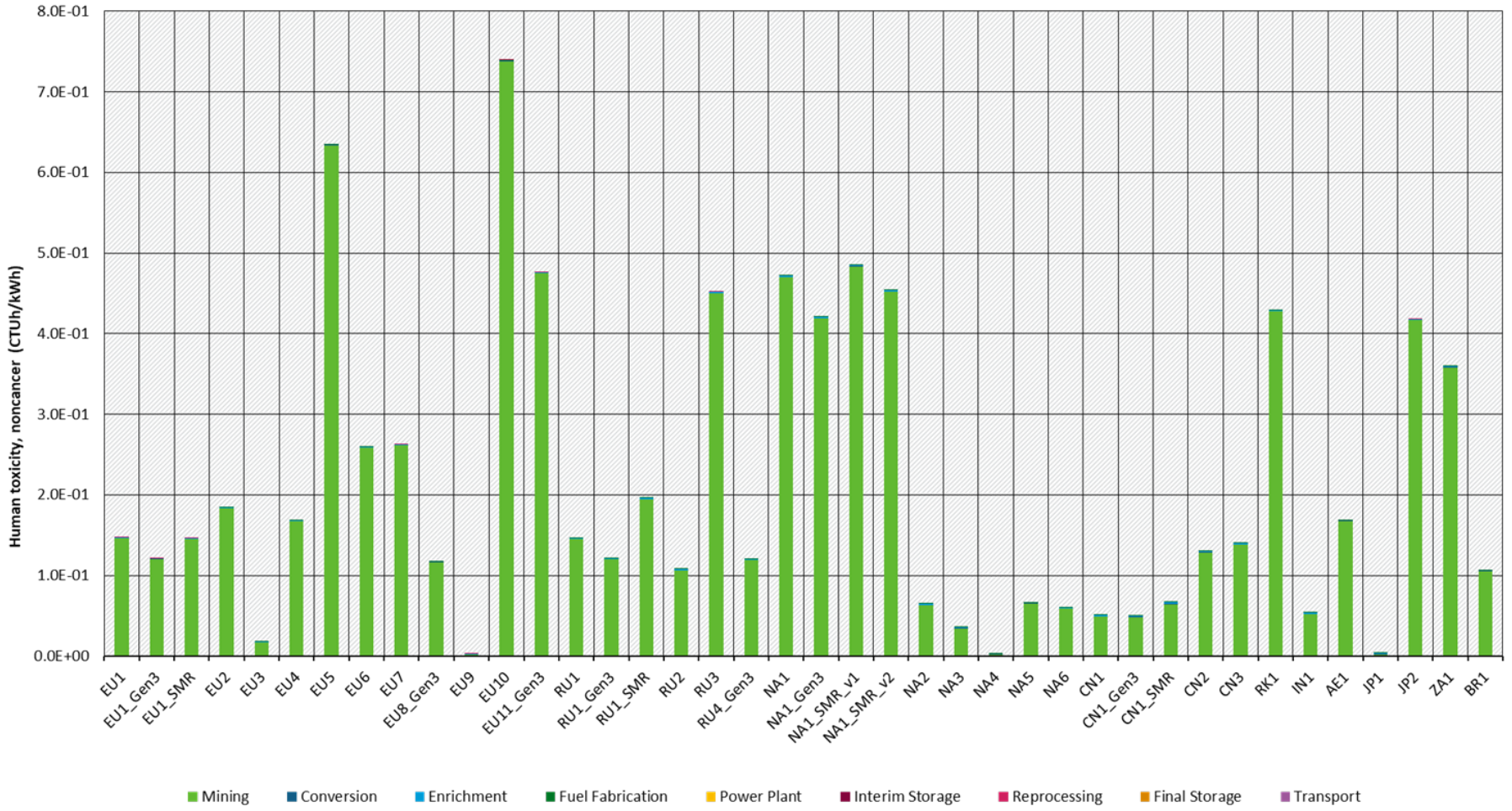
Figure 238: Breakdown of human toxicity (cancer) for life cycle chains



Sources: Öko-Institut

C.8 Human Toxicity (Noncancer)

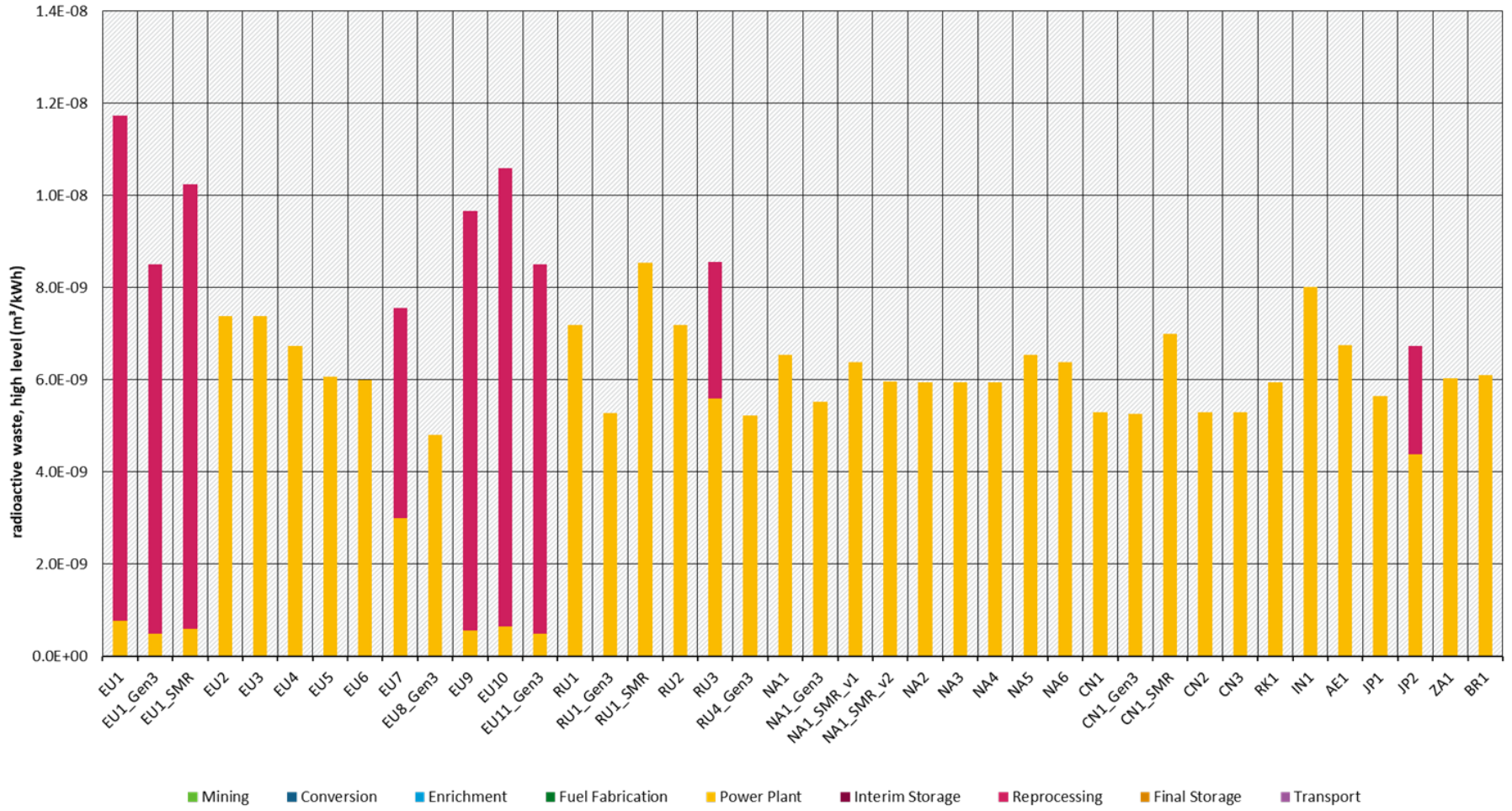
Figure 239: Breakdown of human toxicity (noncancer) for life cycle chains



Sources: Öko-Institut

C.9 High-Level Waste

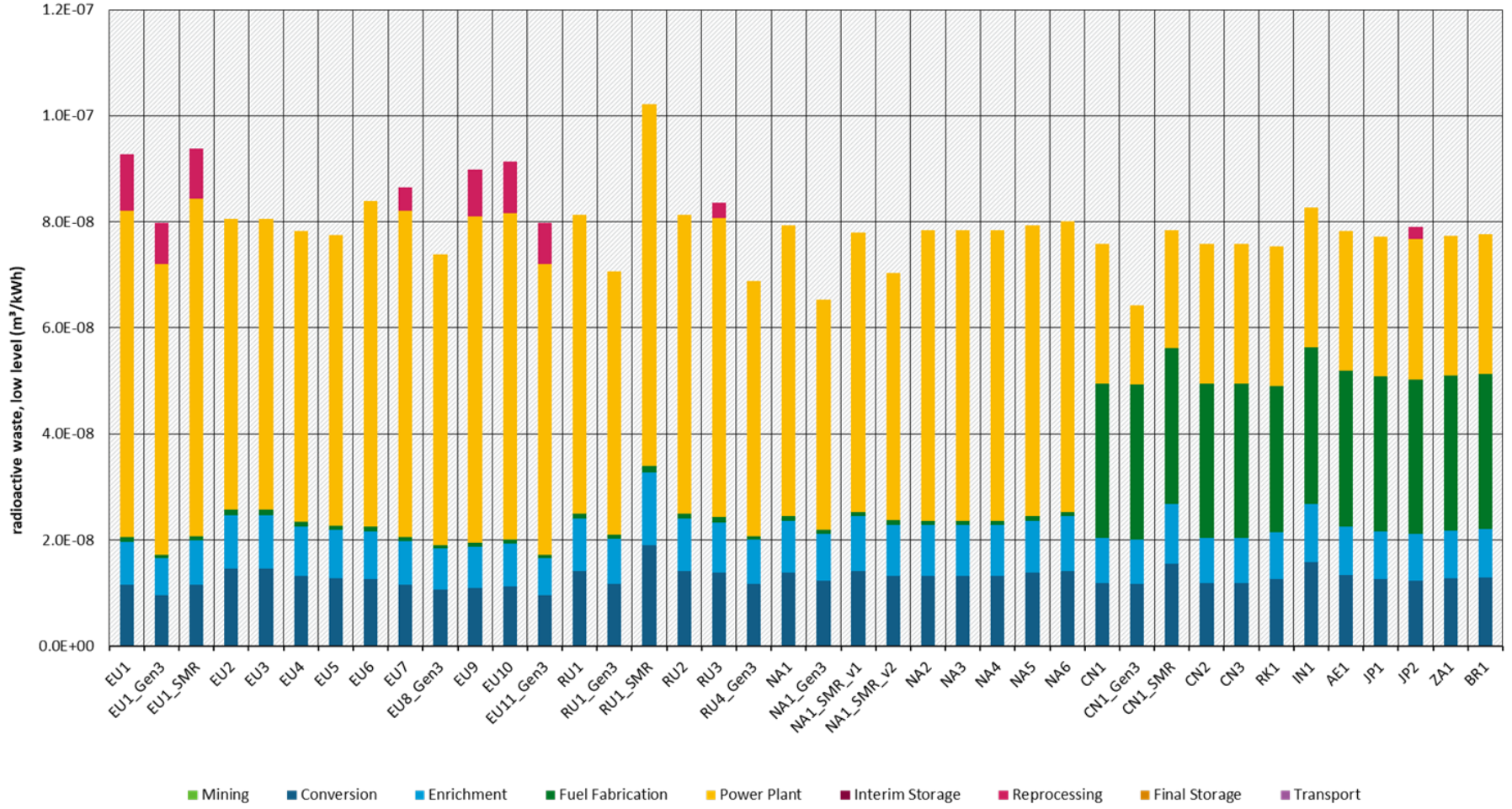
Figure 240: Breakdown of high-level radioactive waste for life cycle chains



Sources: Öko-Institut

C.10 Low-Level Waste

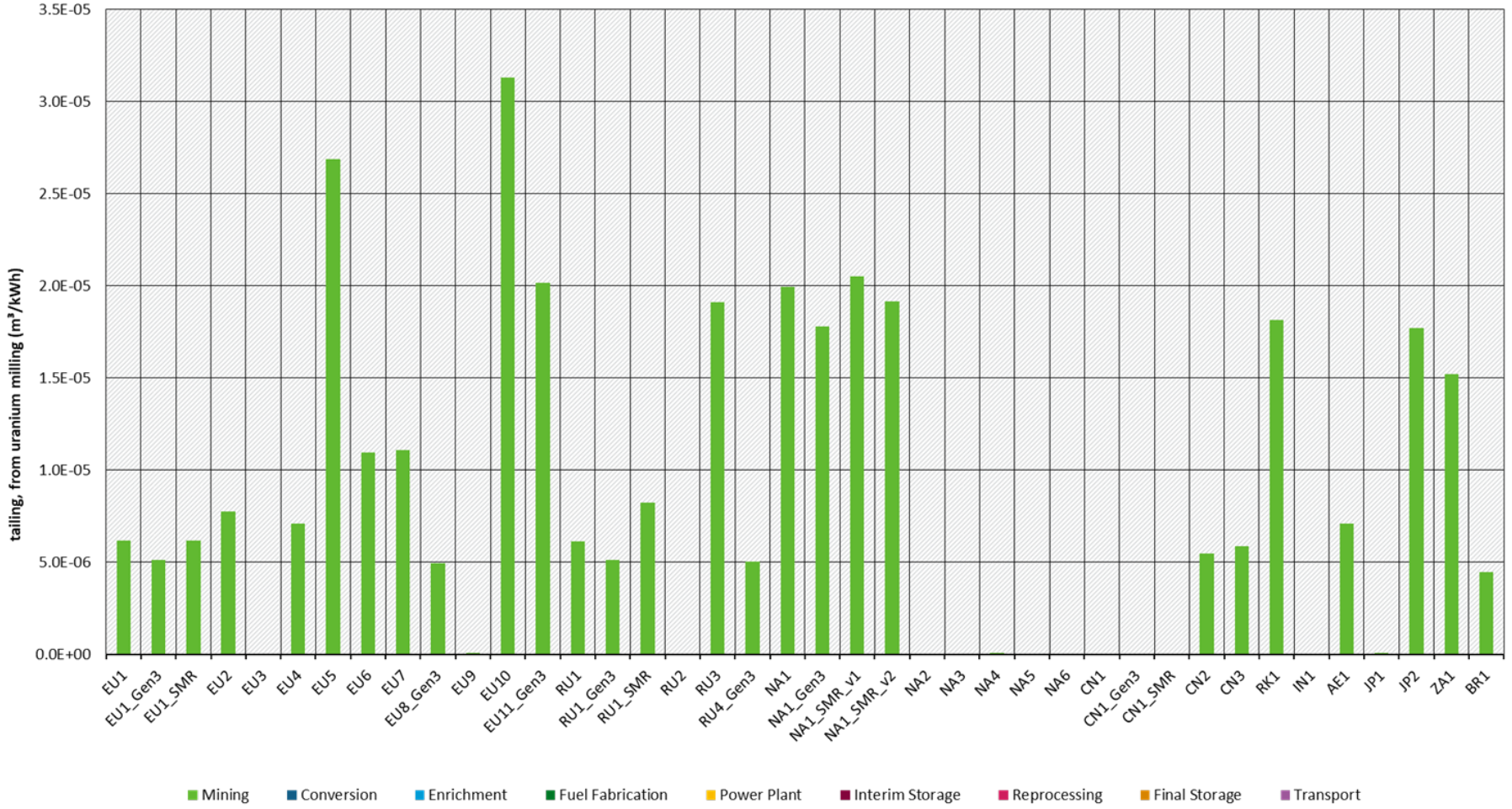
Figure 241: Breakdown of low-level radioactive waste for life cycle chains



Sources: Öko-Institut

C.11 Tailings

Figure 242: Breakdown of tailings for life cycle chains



Sources: Öko-Institut