CLIMATE CHANGE
32/2026

Final report

Climate and environmental impact of nuclear power – Short Version

by:

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Abstract: Climate and environmental impact of nuclear power – Short Version

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 emissions. Different lifecycle chains are covering different countries and regions for the baseline year 2020 and a projection year 2030. The study 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. The greenhouse gas emissions of nuclear energy are at a comparably low level to those of renewable energies. Due to long construction times and high investment costs, it is nevertheless not a quick or cost-effective option for significantly reducing the energy system's greenhouse gas emissions.

Kurzbeschreibung: Klima- und Umweltwirkungen der Kernenergie – Kurzfassung

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 Vergleich 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 Treibhausgasemissionen 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 Treibhausgasemissionen des Energiesystems dar.

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Summary

This report presents a short version of (Pistner et al., 2025). 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, it assesses the role of nuclear energy in this transformation process to greenhouse gas emission neutrality from several perspectives.

The global situation of nuclear energy can be characterized by the following numbers: By mid-2024, 31 countries operated nuclear power plants. Global nuclear operating capacity has remained at a relatively constant level of around 370 GW in 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. By contrast, renewable energies supplied one third of global electricity in 2024, and their share continues to rise strongly in all global regions.

We first examine the role of nuclear energy for achieving climate targets in five different integrated assessment models for future energy production. In all models, the development of renewable energy is key for achieving net-zero targets (with a share in electricity in 2050 of 70-100%), while the role of nuclear remains rather limited (at a share in electricity of 0-9%).

To further analyse, how realistic the assumptions of these global scenarios are, a comprehensive bottom-up analysis was performed that assessed countries’ plans and programs for nuclear power until 2050. In a baseline scenario, nuclear capacities will reach a level close to the current situation by 2050, while in an ambitious scenario, capacities would be 24% (around 100 GW) higher. Therefore, even the ambitious scenario only shows a rather limited growth and will not lead to a “renaissance” of nuclear energy.

This contrast sharply with the 'Declaration to Triple Nuclear Energy by 2050’ announced at COP 28 in Dubai, which projects a global installed nuclear capacity of 1,160 GW by 2050. To achieve this, 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. The capacity development path envisaged by this pledge far exceeds the ambitious scenario of our bottom-up analysis, as well as the projected capacity increases in all the recent global climate scenarios analysed.

Climate change itself constitutes a further limiting factor for nuclear energy. Climate change impacts on nuclear power plants are not hypothetical, reactor output reductions and temporary shutdowns linked to climate-induced conditions have already occurred multiple times. Existing and planned nuclear installations are increasingly exposed to rising global temperatures, extreme weather hazards, sea level rise and changes in precipitation. This will increasingly affect the reliability of electricity production from nuclear power plants.

When analyzing a system perspective of nuclear power in future energy scenarios, the basic premise is a power system primarily based on renewable electricity. These sources feature an intermittent production of electricity depending on weather conditions and time of day. Therefore, flexibility is required to meet load demands at all times.

The flexibility of a power plant is determined by its ability to operate in partial load and further technical parameters. Load-following operation of nuclear power plants is possible within limits but reduces the load factor and thus leads to a poorer economic efficiency. Since nuclear power plants are the most capital-intensive power plants, they are not suitable for integrating highly fluctuating feed-in in a system with a high share of renewable electricity. Proposed alternative use cases for nuclear power 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.

Furthermore, two issues related to time scales are relevant. Nuclear power plants exhibit construction times of eight year and beyond, with a well-documented record of unexpected delays. Onshore wind and large-scale photovoltaic projects deliver in less than five years. In addition, while wind and photovoltaics are typically designed for about 25 years of operation, nuclear power plants are today 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.

One of the central parts of (Pistner et al., 2025) is a comprehensive life cycle assessment (LCA) of nuclear power. The scope of the study covers the extraction of uranium, its use in nuclear power plants and its final disposal. The main process stages are analysed and the material and energy resources used and the emissions released are balanced for each stage. The environmental impacts—in particular the GHG emissions—for the generation of 1 kWh of electricity from nuclear energy is calculated. The methodology of the study is based on the environmental impacts of 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).

Different processes in the nuclear life cycle chain may take place in different regions or countries of the world. 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. Overall, 40 life cycle chains are analysed based on data for the baseline year 2020. For a projection year 2030 in selected process chains relative reductions in the greenhouse gas emission factors for concrete, steel and electricity are assumed. In addition, selected parameters in the life cycle chains were adopted to values expected for the projection year 2030.

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, a few life cycle chains show also higher GWP values up to a total GWP of 21 g CO_2eq/kWh. The total GWP is typically dominated by the impact of uranium mining, followed by the impact of nuclear power plant infrastructure and operation, enrichment and conversion. 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. 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 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.

In addition to life cycle emissions, the study discusses exemplary environmental impacts of severe accidents. The assessment shows, that accidents in nuclear power plants do have significant impact on the overall environmental impact of nuclear power. 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 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.

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. Proliferation is not to be seen 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.

In addition to the life cycle emission analysis, this report also provides an assessment of the life cycle costs (LCC) and greenhouse gas (GHG) abatement costs of electricity from new nuclear power plants, comparing them with those of renewable energies and hard coal. To this end, the study quantifies the Levelised Cost of Electricity (LCOE) for recently completed and ongoing construction projects, taking into account the respective investment and capital costs. End-of-life costs were also considered, which is a crucial distinction often missing in previous analyses.

In 2020, new nuclear power plants exhibited LCOE significantly higher than most renewable energy sources, with ranges for Europe (15.0-19.2 ct/kWh) and North America (15.6-16.3 ct/kWh) being considerably above the global values for onshore wind (2.4-7.7 ct/kWh with a weighted average of 3.6 ct/kWh), offshore wind (6.1-17.1 ct/kWh with a weighted average of 7.8 ct/kWh), and photovoltaics (4.6-14.8 ct/kWh with a weighted average of 5.3 ct/kWh). While hard coal LCOE under favourable conditions stood at 7.3 ct/kWh in North America and at 4.9 ct/kWh globally, many renewables were already more cost-effective. Consequently, nuclear energy's GHG abatement costs were high (e.g., 102-158 €/t CO_2eq in Europe), whereas renewables frequently demonstrated even negative abatement costs, meaning they were cheaper than coal while reducing GHG emissions.

Projections for 2030 indicate this economic disparity will even increase. LCOE for conventional nuclear power plants are expected to rise significantly to 26.1-36.2 ct/kWh. Small Modular Reactors (SMRs), based on real project data, are forecast to be costly, at ranges from 19.3-43.9 ct/kWh, far exceeding all renewables. Wind and photovoltaics have seen strong technological learning and benefited from economies of scale already between 2020 and 2025. Following a conservate mindset and assuming no further cost reductions beyond that, the LCOE for onshore wind lies at 2.0-6.2 ct/kWh, for offshore wind at 3.7-11.8 ct/kWh, and photovoltaics at 2.6-10.8 ct/kWh, thereby significantly outperforming nuclear power. Nuclear energy's GHG abatement costs are projected to escalate further, ranging from 196 to 527 €/t CO_2eq, while renewables largely retain cost-effective or negative abatement costs.

The presented results are confirmed by other recent scientific studies ((Bowyer, 2024); (Kost et al. 2024); (Lazard, 2024)). A key driver for nuclear energy's high costs is capital expenditure, forming 80% to 85% of total LCOE. This is predominantly due to immense initial investments and exceptionally long construction times, which drastically inflate financing costs. No significant potential for cost reduction is foreseen for nuclear power. Instead, a 'negative learning curve' can be observed, implying that costs will rise especially due to rising material costs (e.g., concrete) and increasing complexity. Despite optimistic claims, SMRs up to now have not proven to be economically competitive with existing renewable technologies, as actual project costs far exceed the manufacturers' original estimates.

In conclusion, new nuclear power plants are consistently more expensive than most renewable energy sources. Their high capital costs, compounded by lengthy construction timescales, make nuclear power a costly and slow option for reducing greenhouse gases. Given these factors, new nuclear power plants are expected to be prohibitively expensive and will come into operation too late to deliver significant reductions in greenhouse gases, which are essential for meeting existing climate targets.

Zusammenfassung

Dieser Bericht bildet eine Kurzfassung von (Pistner et al., 2025). 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.

Die globale Situation der Kernenergie wird durch die folgenden Zahlen beschrieben: 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 Kernkraft erzeugt. Dieser Anteil ist seit seinem Höchststand von 17% im Jahr 1996 stetig zurückgegangen. 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.

Zunächst untersuchen wir die Rolle der Kernenergie für die Erreichung der Klimaziele in fünf verschiedenen integrierten Bewertungsmodellen für die zukünftige Energieerzeugung. In allen Modellen ist die Entwicklung erneuerbarer Energien der Schlüssel zur Erreichung der Netto-Null-Ziele (mit einem Anteil am Stromverbrauch von 70-100% im Jahr 2050), während die Rolle der Kernenergie eher begrenzt bleibt (mit einem Anteil am Stromverbrauch von 0-9%).

Um weiter zu analysieren, wie realistisch die Annahmen dieser globalen Szenarien sind, wurde eine umfassende Bottom-up-Analyse durchgeführt, in der die Pläne und Programme der Länder für die Kernenergie bis 2050 ausgewertet wurden. In einem Basisszenario werden die Kernkraftwerkskapazitäten bis 2050 ein Niveau erreichen, das nahe am aktuellen Wert liegt, während sie in einem ambitionierten Szenario um 24% (rund 100 GW) steigen würden. Daher zeigt selbst das ambitionierte Szenario nur ein eher begrenztes Wachstum und wird nicht zu einer „Renaissance” der Kernenergie führen.

Dies steht in starkem Kontrast zu der auf der COP 28 in Dubai verkündeten „Erklärung zur Verdreifachung der Kernenergie bis 2050“, die eine weltweit installierte Kernkraftwerkskapazität von 1.160 GW bis 2050 vorsieht. Um dies zu erreichen, müsste 25 Jahre lang jedes Jahr im Durchschnitt mehr neue Kapazität hinzukommen, wie es beim historischen Maximum im Jahr 1985 der Fall war. Der dieser Erklärung zugrunde liegende Ausbaupfad übertrifft bei weitem das ambitionierte Szenario unserer Bottom-up-Analyse sowie die prognostizierten Kapazitätssteigerungen in allen analysierten aktuellen globalen Szenarien.

Der Klimawandel selbst stellt einen weiteren begrenzenden Faktor für die Kernenergie dar. Die Auswirkungen des Klimawandels auf Kernkraftwerke sind nicht hypothetisch, denn es kam bereits mehrfach zu klimabedingten Leistungsreduzierungen und vorübergehenden Abschaltungen von Reaktoren. Bestehende und geplante Kernkraftwerke sind steigenden globalen Temperaturen, extremen Wetterereignissen, dem Anstieg des Meeresspiegels und Veränderungen der Niederschlagsmengen ausgesetzt. Dies wird die Zuverlässigkeit der Stromerzeugung aus Kernkraftwerken zunehmend beeinträchtigen.

Bei einer Analyse der Systemverträglichkeit der Kernenergie in zukünftigen Energieszenarien geht man grundsätzlich von einem Stromsystem aus, das in erster Linie auf erneuerbaren Energien basiert. Diese Energiequellen zeichnen sich durch eine intermittierende Stromerzeugung aus, die von den Wetterbedingungen und der Tageszeit abhängt. Daher ist Flexibilität erforderlich, um den Lastbedarf jederzeit decken zu können.

Die Flexibilität eines Kraftwerks wird durch seine Fähigkeit zum Teillastbetrieb und weitere technische Parameter bestimmt. Der lastfolgefähige Betrieb von Kernkraftwerken ist innerhalb

bestimmter Grenzen möglich, verringert jedoch den Lastfaktor und führt somit zu einer schlechteren Wirtschaftlichkeit. Da Kernkraftwerke die kapitalintensivsten Kraftwerke sind, eignen sie sich nicht für die Integration stark schwankender Einspeisungen in ein System mit einem hohen Anteil an erneuerbarem Strom. Vorgeschlagene alternative Anwendungsfälle für Kernenergie wie Wasserstoffproduktion, Fernwärme und Entsalzung ändern nichts an dieser allgemeinen Einschätzung. Diese Anwendungen können zwar in bestimmten Fällen die Wirtschaftlichkeit des Lastfaktors verbessern, bleiben jedoch in ihrem Umfang marginal und sind in einigen Fällen hinsichtlich ihrer Reife spekulativ.

Darüber hinaus sind zeitliche Aspekte relevant. Kernkraftwerke weisen Bauzeiten von acht Jahren und mehr auf, wobei es immer wieder zu unerwarteten Verzögerungen kommt. Onshore-Windkraft- und groß angelegte Photovoltaikprojekte können in weniger als fünf Jahren realisiert werden. Während Windkraft- und Photovoltaikanlagen in der Regel für eine Betriebsdauer von etwa 25 Jahren ausgelegt sind, werden Kernkraftwerke heute für eine Betriebsdauer von 60 Jahren ausgelegt. Auf den ersten Blick mag dies wie ein Vorteil erscheinen, auf Systemebene könnte es jedoch ein Nachteil sein: Aufgrund ihrer kürzeren Lebensdauer können Windkraft- und Photovoltaikanlagen zwei Innovationszyklen durchlaufen und so von einer höheren Effizienz profitieren.

Einer der zentralen Bestandteile von (Pistner et al., 2025) ist eine umfassende Lebenszyklusanalyse (LCA) der Kernenergie. Der Umfang der Analyse umfasst die Gewinnung von Uran, seine Verwendung in Kernkraftwerken und seine Endlagerung. Die wichtigsten Prozessstufen werden analysiert und die eingesetzten Material- und Energieressourcen sowie die freigesetzten Emissionen für jede Stufe bilanziert. Die Umweltauswirkungen – insbesondere die Treibhausgasemissionen (THG) – für die Erzeugung von 1 kWh Strom aus Kernenergie werden berechnet. Die Methodik der Studie basiert auf den Umweltauswirkungen einzelner Lebenszyklusmodule und der Aggregation der Emissionen dieser Module über den gesamten Lebenszyklus. Grundsätzlich orientiert sich die Methodik an den Vorgaben der EU-Kommission für den Umweltfußabdruck von Produkten (PEF) sowie den internationalen Normen für die Lebenszyklusanalyse (DIN EN ISO 14040 und DIN EN ISO 14044) und den Product Carbon Footprint (PCF).

Verschiedene Prozesse in der nuklearen Lebenszykluskette können in unterschiedlichen Regionen oder Ländern der Welt stattfinden. Für alle Prozessschritte definieren wir daher das jeweilige Land, in dem dieser Prozess für eine bestimmte Lebenszykluskette stattfindet. Da für einige Schritte nur eine begrenzte Anzahl von Anlagen existiert, werden diese spezifischen Module in mehreren Lebenszyklusketten verwendet. Insgesamt werden 40 Lebenszyklusketten auf der Grundlage von Daten für das Basisjahr 2020 analysiert. Für ein Prognosejahr 2030 werden in ausgewählten Prozessketten relative Reduktionen der Treibhausgasemissionsfaktoren für Beton, Stahl und Strom angenommen. Darüber hinaus wurden ausgewählte Parameter in den Lebenszyklusketten auf Werte angepasst, die für das Prognosejahr 2030 erwartet werden.

Der typische Bereich der Treibhausgasemissionen aus den Lebenszyklusketten für das Basisjahr 2020 umfasst Werte von 5-15 g CO_2eq/kWh. Nur sehr wenige Lebenszyklusketten mit außergewöhnlich guten Eingabeparametern weisen Treibhausgasemissionen unter 5 g CO_2eq/kWh auf, einige wenige Lebenszyklusketten weisen auch höhere Treibhausgasemissionen bis zu einem Wert von 21 g CO_2eq/kWh auf. Die Treibhausgasemissionen werden in der Regel durch die Auswirkungen des Uranabbaus dominiert, gefolgt von den Auswirkungen aus Bau und Betrieb von Kernkraftwerken, der Anreicherung und der Umwandlung. Innerhalb der verschiedenen Regionen, die von den Lebenszyklusketten abgedeckt werden, weisen die entsprechenden Werte der Treibhausgasemissionen einzelner Ketten im Vergleich zu einer Standardkette eine große Streuung auf. Der typische Bereich der Treibhausgasemissionen aus den Lebenszyklusketten für das Prognosejahr 2030 umfasst Werte von 4,8 bis 14,2 g

CO_2eq/kWh, die spezifische Reduzierung gegenüber dem Basisjahr 2020 beträgt 4,4 bis 13,4 % der Treibhausgasemissionen und unterscheidet sich damit nicht grundlegend vom Basisjahr 2020.

Neben den Emissionen während des Lebenszyklus werden in der Studie auch beispielhafte Umweltauswirkungen schwerer Unfälle behandelt. Die Bewertung zeigt, dass Unfälle in Kernkraftwerken einen erheblichen Einfluss auf die Gesamtumweltbelastung durch Kernenergie haben können. Nach schweren Unfällen in Kernkraftwerken müssen möglicherweise Hunderttausende Menschen evakuiert und umgesiedelt werden, der Landverlust aufgrund radioaktiver Kontamination nach einem schweren Unfall kann den Landverlust durch den normalen Betrieb um den Faktor 2 bis 10 erhöhen, und es fallen sehr große Mengen an schwach radioaktiven Abfällen an. 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.

Die Analyse befasst sich 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. Proliferation ist nicht als deterministisches Ergebnis zu betrachten, sondern vielmehr 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.

In Ergänzung zur Lebenszyklus-Emissionsanalyse enthält dieser Bericht auch eine Bewertung der Lebenszykluskosten (LCC) und der THG-Vermeidungskosten neuer Kernkraftwerke im Vergleich zu erneuerbaren Energien und Steinkohle. Zu diesem Zweck quantifiziert die Studie die Stromgestehungskosten (LCOE) für laufende und kürzlich abgeschlossene Bauprojekte unter Berücksichtigung der jeweiligen Investitions- und Kapitalkosten. Darüber hinaus wurden auch „soziale Kosten“ (z. B. Kosten für den Nachbetrieb, die Stilllegung und die Endlagerung) berücksichtigt; dabei handelt es sich um einen wichtigen Aspekt, der in früheren Analysen oft außer Acht gelassen wurde. Unter Berücksichtigung des gesamten Lebenszyklus wurden die LCOE sowohl für das Basisjahr 2020 als auch für die Zukunftsprognose für 2030 berechnet.

Im Jahr 2020 wiesen neue Kernkraftwerke deutlich höhere LCOE auf als die meisten erneuerbaren Energiequellen, wobei die Bandbreiten für Europa (15,0–19,2 ct/kWh) und Nordamerika (15,6–16,3 ct/kWh) erheblich über denen für Onshore-Windenergie (2,4-7,7 ct/kWh mit einem gewichteten Durchschnitt von 3,6 ct/kWh), Offshore-Windenergie (6,1–17,1 ct/kWh mit einem gewichteten Durchschnitt von 7,8 ct/kWh) und Photovoltaik (4,6–14,8 ct/kWh mit einem gewichteten Durchschnitt von 5,3 ct/kWh) lagen. Während die LCOE für Steinkohle unter günstigen Bedingungen in Nordamerika bei 7,3 ct/kWh und weltweit bei 4,9 ct/kWh lagen, waren viele erneuerbare Energien bereits kostengünstiger. Dementsprechend waren auch die THG-Vermeidungskosten der Kernenergie hoch (z. B. 102–158 €/t CO_2eq in Europa), während erneuerbare Energien häufig sogar negative Vermeidungskosten aufwiesen, d. h. sie waren billiger als Kohle und reduzierten gleichzeitig die Emissionen.

Die Projektionen für 2030 deuten darauf hin, dass sich diese wirtschaftliche Ungleichheit sogar noch verstärken wird. Die LCOE für konventionelle Kernkraftwerke werden voraussichtlich deutlich auf 26,1 bis 36,2 ct/kWh steigen. Kleine modulare Reaktoren (SMR) werden auf der Grundlage realer Projektdaten voraussichtlich mit 19,3 bis 43,9 ct/kWh sehr kostenintensiv sein und damit alle erneuerbaren Energien weit übertreffen. Wind- und Photovoltaik haben zwischen 2020 und 2025 einen starken technologischen Lernprozess durchlaufen und bereits von Skaleneffekten profitiert. Unter konservativer Betrachtung und ohne Annahme weiterer Kostensenkungen liegen die LCOE für Onshore-Windenergie bei 2,0–6,2 ct/kWh, für Offshore-Windenergie bei 3,7–11,8 ct/kWh und für Photovoltaik bei 2,6–10,8 ct/kWh und damit deutlich unter denen der Kernenergie. Die THG-Vermeidungskosten der Kernenergie werden voraussichtlich weiter steigen und zwischen 196 und 527 €/t CO_2eq liegen, während erneuerbare Energien weitgehend kosteneffiziente oder negative Vermeidungskosten beibehalten.

Die vorgestellten Ergebnisse werden durch andere aktuelle wissenschaftliche Studien bestätigt ((Bowyer, 2024) ; (Kost et al. 2024) ;(Lazard, 2024)).

Ein wesentlicher Faktor für die hohen Kosten der Kernenergie sind die Investitionsausgaben, die 80% bis 85% der gesamten Stromgestehungskosten ausmachen. Dies ist vor allem auf die erheblichen Anfangsinvestitionen und die außergewöhnlich langen Bauzeiten von typischerweise 10 bis 18 Jahren zurückzuführen, die die Finanzierungskosten beträchtlich erhöhen.

Für die Kernenergie ist kein nennenswertes Potenzial für Kostensenkungen zu erwarten. Stattdessen ist eine „negative Lernkurve“ zu beobachten, d.h. die Kosten werden insbesondere aufgrund steigender Materialkosten (z.B. Beton) und zunehmender Komplexität weiter steigen. Trotz optimistischer Behauptungen haben sich SMRs gegenüber bestehenden Technologien für erneuerbare Energien als wirtschaftlich nicht wettbewerbsfähig erwiesen, da die tatsächlichen Projektkosten die ursprünglichen Schätzungen der Hersteller bei weitem übersteigen.

Zusammenfassend kann festgestellt werden, dass neue Kernkraftwerke durchweg teurer sind als die meisten erneuerbaren Energiequellen. Ihre hohen Kapitalkosten, verbunden mit langen Bauzeiten, machen die Kernenergie zu einer kostenintensiven und langsamen Option zur Reduzierung von Treibhausgasen. Angesichts dieser Faktoren ist davon auszugehen, dass neue Kernkraftwerke prohibitiv teuer sein und zu spät in Betrieb gehen werden, um signifikante Reduktionen der Treibhausgase zu erzielen, die für die Erreichung der bestehenden Klimaziele unerlässlich sind.

1 Key Messages

1. **GHG emissions from nuclear energy are rather moderate and comparable to those of renewable electricity generation.** The analysis of the GHG emissions associated with the generation of 1 kWh of electricity from nuclear energy spans values of 5-15 g CO_2eq/kWh for the baseline year 2020. The results are typically dominated by the impact of uranium mining, followed by the impact of nuclear power plant infrastructure and operation, enrichment and conversion. For the projection year 2030 the GHG emissions are expected to be in the range of 4.8-14.2 g CO_2eq/kWh and is thus not fundamentally different from the baseline year 2020.
2. **Climate change itself constitutes an important limiting factor for nuclear energy.** Existing and planned nuclear installations are increasingly exposed to rising global temperatures, extreme weather hazards, changes in precipitation and sea level rise. This will increasingly affect the reliability of electricity production from nuclear power plants.
3. **Nuclear power plants lack the flexibility needed to complement intermittent renewables like wind and solar.** Renewable energy sources – mainly wind and solar – produce electricity intermittently, depending on weather conditions and the time of day. Flexibility is therefore required in future power systems with a high proportion of renewable energies. Given the large unit size, long lead times, and limited technical flexibility 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). There is also an economic mismatch: high flexibility comes with low capacity utilization rates and thus higher life cycle costs.
4. **In terms of life cycle costs, new nuclear power plants are consistently more expensive than most renewable energy sources.** The life cycle costs ranges for Europe (15.0-19.2 ct/kWh) and North America (15.6-16.3 ct/kWh) being considerably above the global values for onshore wind, offshore wind, and photovoltaics (with a weighted average of 3.6 ct/kWh, 7.8 ct/kWh and 5.3 ct/kWh respectively). Nuclears high capital costs, compounded by lengthy construction timescales, make nuclear power a costly option for reducing greenhouse gases. Consequently, nuclear energy's GHG abatement costs (e.g., 102-158 €/t CO_2eq in Europe) are significantly higher than for renewables. Projections for 2030 indicate this economic disparity will even increase.
5. **Given all these factors, new nuclear power plants are expected to be prohibitively expensive and will come into operation too late to deliver significant reductions in greenhouse gases, which are essential for meeting existing climate targets.** This contrast sharply with the 'Declaration to Triple Nuclear Energy by 2050' announced at COP 28 in Dubai. Our assessment is confirmed by integrated assessment models for future energy production, showing that the development of renewable energy is key for achieving net-zero targets (with a share in electricity in 2050 of 70-100%), while the role of nuclear remains rather limited (at a share in electricity of 0-9%).

2 Introduction

This report summarizes the results of (Pistner et al., 2025). 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, (Pistner et al., 2025) assesses the role of nuclear energy in this transformation process to greenhouse gas emission neutrality from several perspectives.

We 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, and compare them with a bottom-up analysis of the existing fleet of nuclear power plants and national programs for the future development of nuclear power up to the year 2050, see chapter 3. We further discuss the impact of climate change on the long-term use of nuclear power, compare chapter 4 and the possible role of nuclear power in future energy systems from a system perspective, compare chapter 5.

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 with a clear focus on the global warming potential (GWP) of nuclear power, compare chapter 6. 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 for severe accidents in nuclear power plants and for proliferation aspects related to the nuclear fuel cycle, compare chapter 7.

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 relatively 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 8 we will therefore analyse the cost of producing electricity with nuclear power by means of a life cycle costing (LCC) approach. Based on the levelized cost of electricity (LCOE) calculated, in a second step 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, compare chapter 9.

3 The future role of nuclear energy in current energy scenarios

The global situation of nuclear energy can be characterized by the following numbers: By mid-2024, 31 countries operated nuclear power plants. Global nuclear operating capacity has remained at a relatively constant level of around 370 GW in 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 in all global regions.

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 requires a transformation of the global energy system 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. We examine the role of nuclear energy in such scenarios for achieving climate targets.

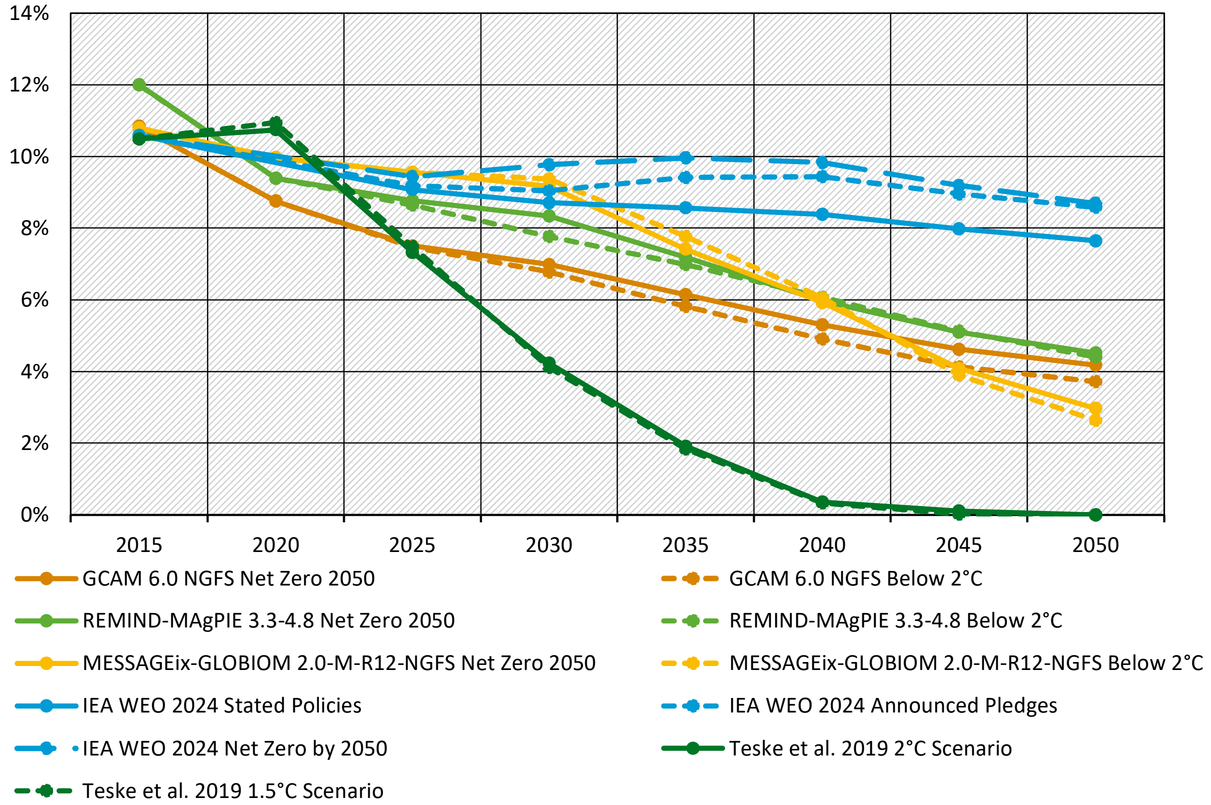
To this end, we analyse climate scenarios from five different integrated assessment models (two different climate scenarios from each model and even three scenarios from the International Energy Agency’s (IEA) World Energy Outlook). All scenarios in all models project a decline in the share of nuclear 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 (Figure 1). In these same scenarios, renewable energies increase to between 88 and 97% by 2050. Only IEA’s World Energy Outlook projects lower shares of renewable energies ranging from 70% to 85% depending on the scenario. (Figure 2).

Thus, in all models and scenarios, the development of renewable energies is key for achieving net-zero targets, the role of nuclear energy on the contrary remains 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 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.

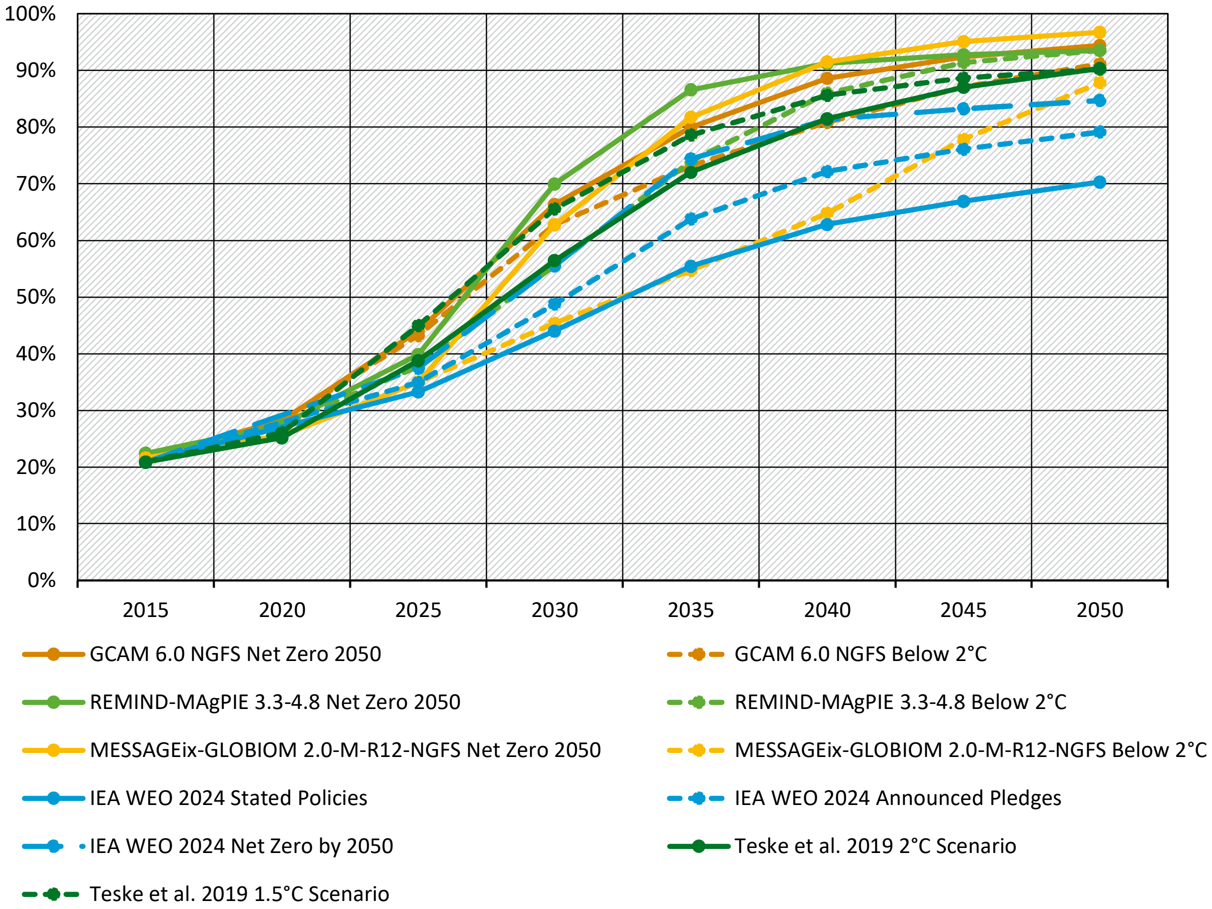
Modelling results also differ with regard to the development of installed nuclear capacities until 2050. While the MESSAGEix-GLOBIOM modellers project a decrease in capacities of 29-44%, the REMIND-MAgPIE modellers foresee a rather limited increase of 8-27% and GCAM modellers between 11-53%. The IEA World Energy Outlook is the exception with a very strong nuclear capacity increase by 170% for the “Net Zero by 2050” scenario, in contract to an increase of only 70% in the “Stated Policies” scenario which models the actual country policies (Figure 3).

Figure 1 Share of nuclear energy in electricity generation (world) in the scenarios analysed



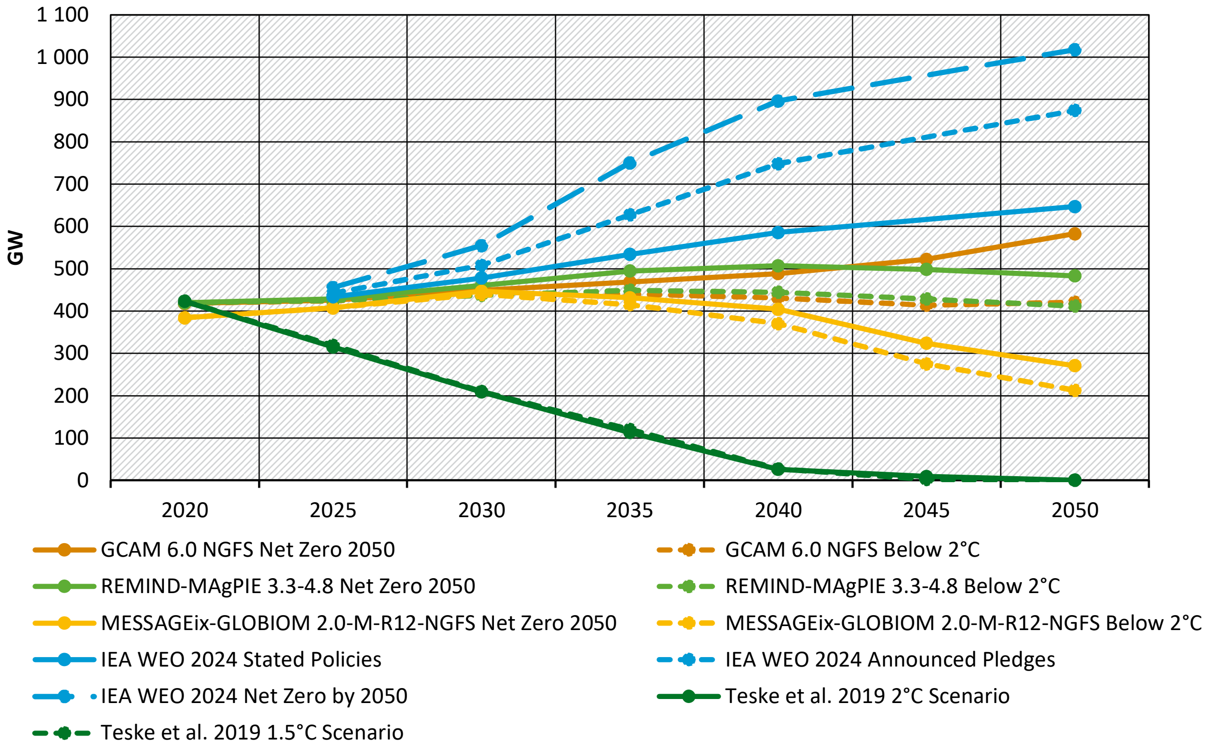
Source: (Richterss et al., 2024), (Teske, 2019), (International Energy Agency [IEA], 2024); own illustration, Öko-Institut e.V.

Figure 2 Share of non-biomass renewable energy in electricity generation (world) in the scenarios analysed



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

Figure 3 **Installed capacity of nuclear reactors (world) in the scenarios analysed**



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

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 analyse how realistic the assumptions of these global scenarios are, a comprehensive bottom-up analysis was performed that assessed countries' plans and programs regarding decommissioning, lifetime extensions and new construction of nuclear power plants until 2050. This research results in a baseline scenario and an ambitious scenario for nuclear capacity development, with the ambitious scenario including relatively optimistic plans by governments that may not be fully implemented, see Figure 4.

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.

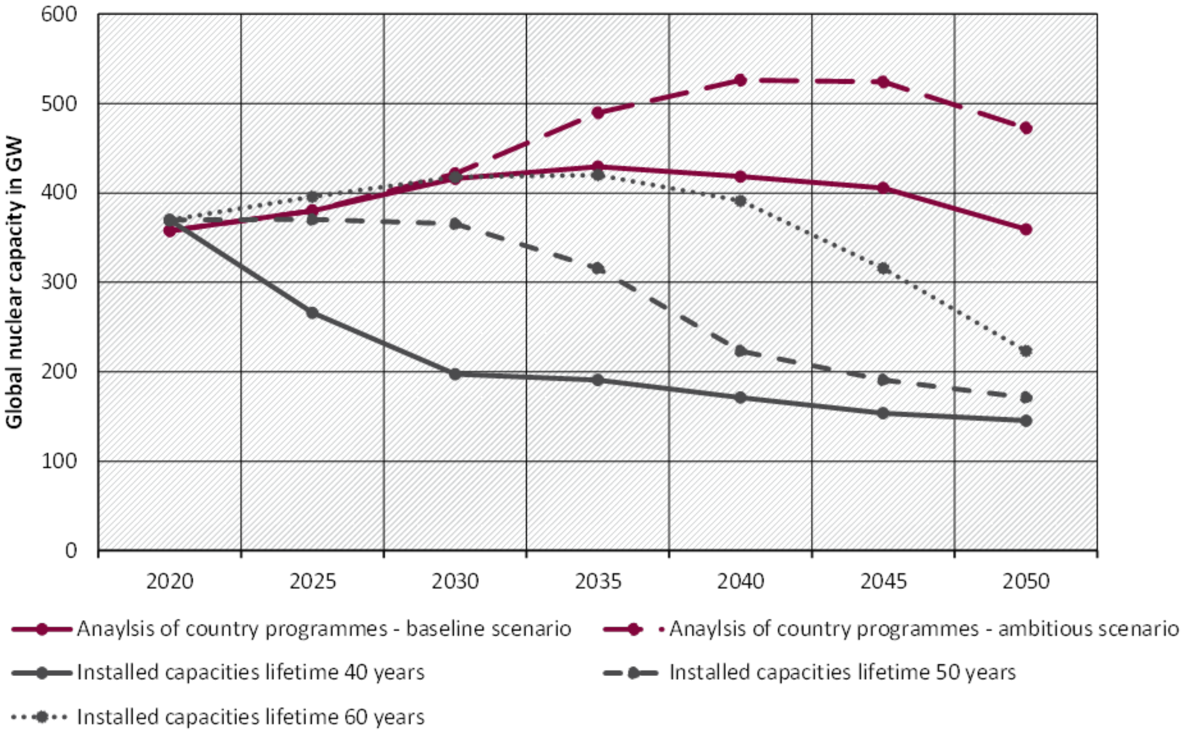
At COP 28 in Dubai French president Emmanuel Macron and US Special Envoy for Climate John Kerry announced that more than 20 countries launched the 'Declaration to Triple Nuclear Energy by 2050'. This declaration is related to an analysis of the Nuclear Energy Agency indicating a global installed net electrical capacity of 1.160 GW capacity to be operational by 2050, compared to around 370 GW today, see Figure 5. Assuming a very high lifetime of sixty years for all nuclear reactors in operation - which exceeds the currently licensed lifetime in many countries - 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, see Figure 6. 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 by 2050 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. The different contribution of nuclear versus renewable energy to total electricity generation in 2050 in the scenarios analysed is illustrated in Figure 7.

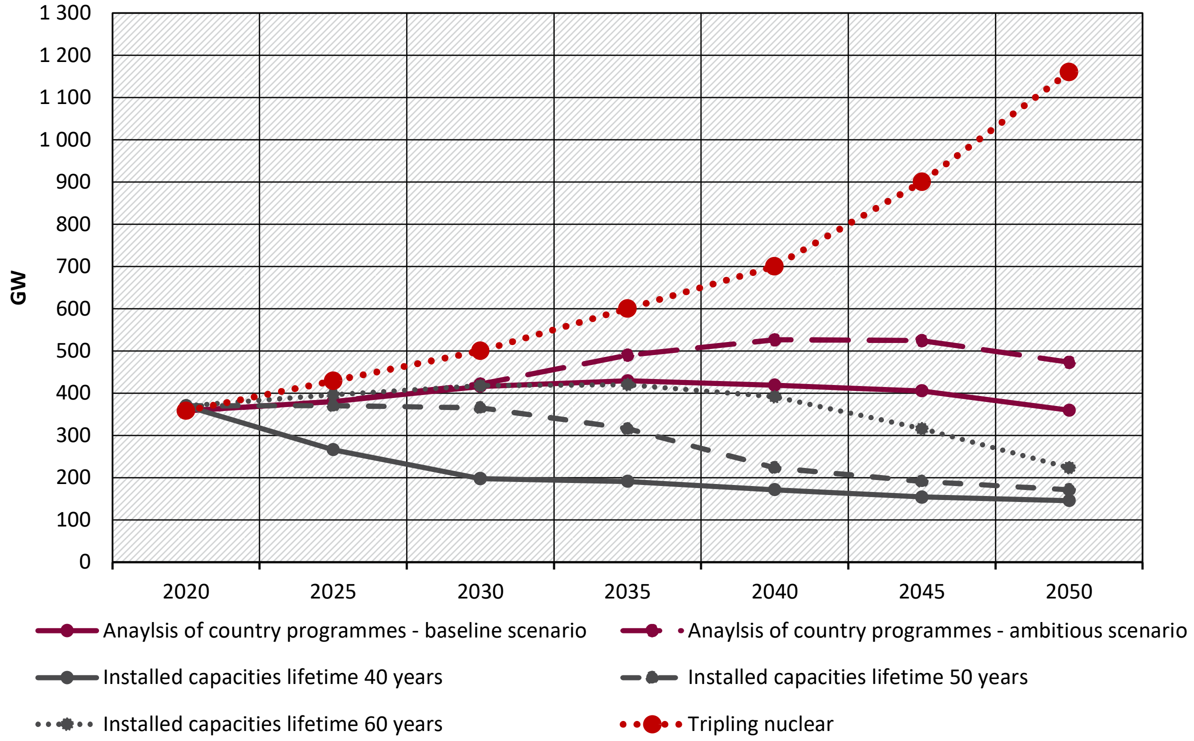
Even with high levels of nuclear energy production, scenarios with low shares of renewable energy miss the climate targets. Therefore, building up renewable energy is the crucial and primary driver to achieve climate targets.

Figure 4 **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)**



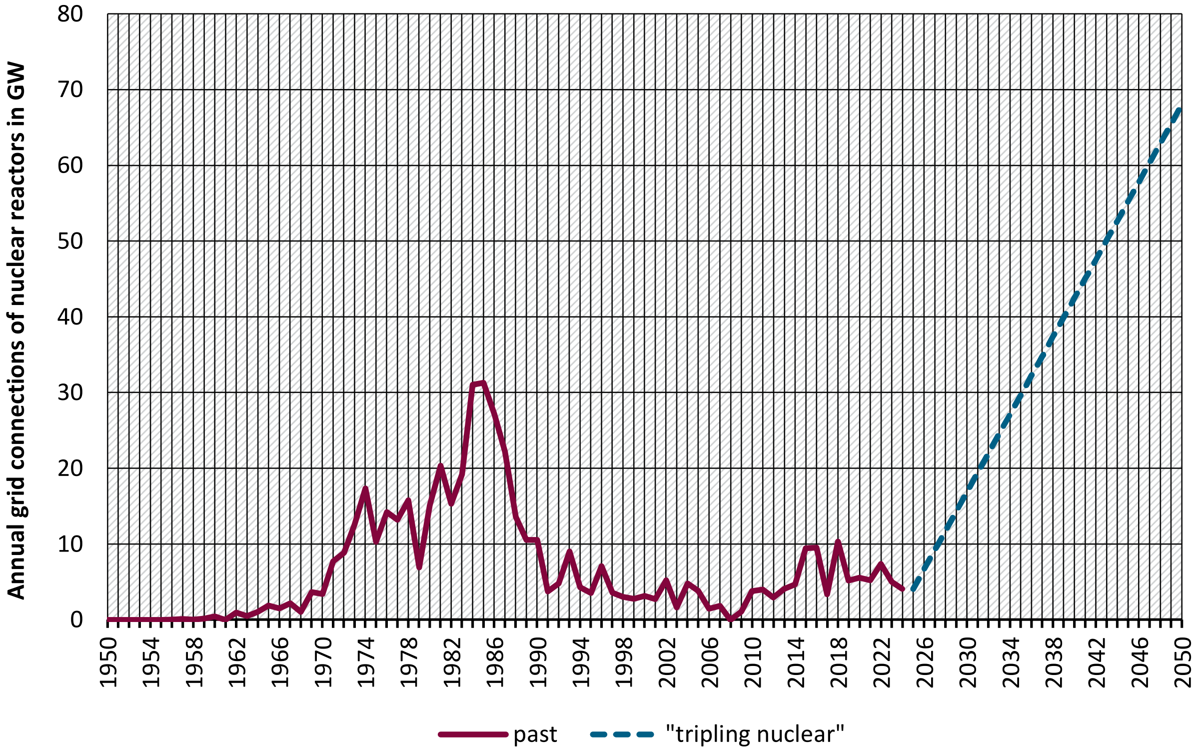
Source: data: (International Atomic Energy Agency [IAEA], 2025), own calculation; own illustration, Öko-Institut e.V.

Figure 5 **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**



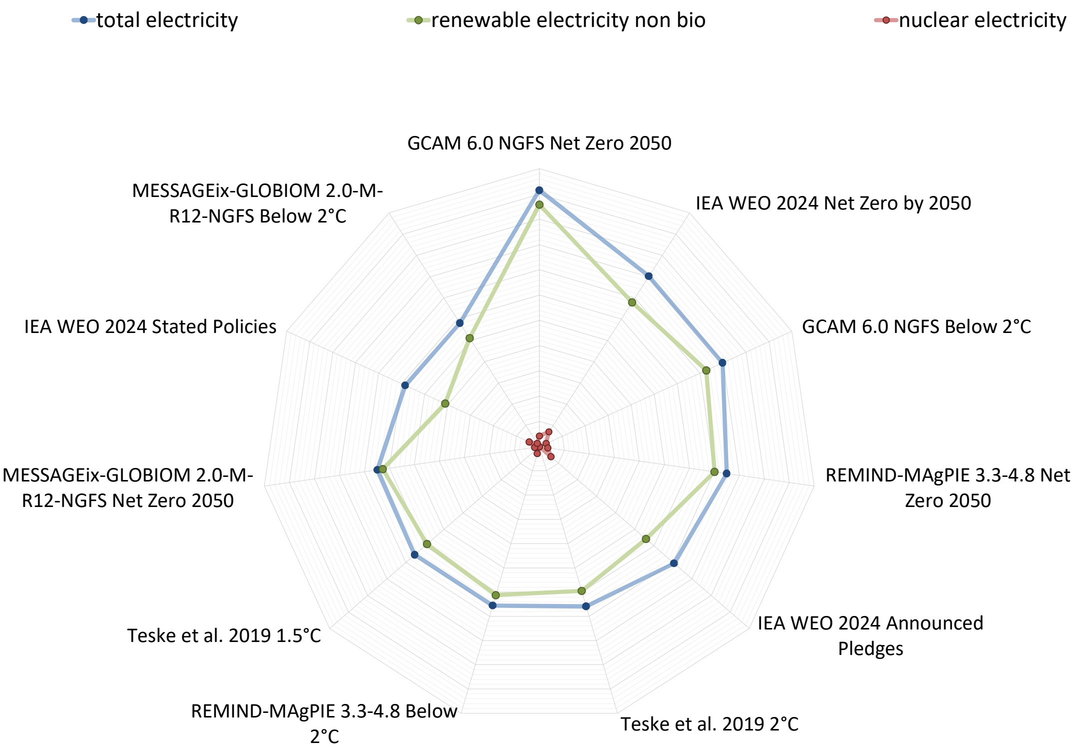
Source: data: (IAEA, 2025), (OECD Nuclear Energy Agency [NEA], 2023), own calculation; own illustration, Öko-Institut e.V.

Figure 6 **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.

Figure 7 **World nuclear electricity and renewable electricity in 2050 in comparison with total electricity in the scenarios analysed**



Source: Öko-Institut – 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.

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 towards pro-nuclear parties:

- Levelized costs of electricity for newbuild nuclear show that nuclear is the most expensive electricity source (see chapter 8). 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 far 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$ 12 to 30 billion per reactor[1]. 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.

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[1] 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.

- 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. 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 and countries have to choose between dependency on Russia or high uncertainties related to the costs and final construction period with Western suppliers.

- 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.

- 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.

4 Climate change impacts on nuclear energy

Climate change itself constitutes a further limiting factor for nuclear energy. Existing and planned nuclear installations are increasingly exposed to rising global temperatures, extreme weather hazards, sea level rise and changes in precipitation due to global warming. This will increasingly affect the reliability of electricity production from 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, and adaptation or resilience to climate change has not been part of the planning.

Higher ambient temperatures reduce the efficiency of nuclear power plants. Inland reactors located at rivers face growing risks from lack of water for cooling due to droughts and heat waves in summer periods, and production has to be reduced or stopped. This reduces the power generation and economic potential as well as reliability of supply of inland nuclear plants. 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 many plants at the same time. Therefore, the risk for energy security is significant. 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 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, and during a heat wave in 2019 two reactors had to shut down in France. 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. Future water competition and scarcity is a potential disruptive production factor for nuclear plants recently built in the Middle East, North Africa and Southeast Asia.

Higher water temperatures at coastal sites 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. For example, France experienced disruptions at its nuclear plants at Gravelines and Paluel sites due to large swarms of jellyfish clogging the cooling systems.

Coastal nuclear power plants will be exposed to more severe storms with extreme water levels and stronger tidal waves. Multiple systems failure (such as simultaneously occurring 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) is a typical feature occurring of severe storms, which are more difficult to manage than problems with one component only. Therefore, extreme storms can cause high risks for nuclear plants. Coastal sites are vulnerable to sea-level rise, coastal flooding and coastal erosion. 41% of nuclear power plants are located at coasts and more than 100 reactors are only a few metres above sea level (IAEA, 2022). According to (IAEA, 2022), 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.

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. 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. 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).

These climate change impacts on nuclear power plants 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. Table 1 provides on overview of the impacts of climate change on nuclear energy generation.

Table 1 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

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

- The power generation potential of the existing and future reactor fleet will be reduced. Outages and operational disruptions will occur more frequently and at more nuclear sites which will threaten security of supply.
- 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.

- 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.

5 A system perspective on the role of nuclear power in future energy scenarios

When analyzing the system perspective of nuclear power in future energy scenarios, the basic premise is a power system primarily based on renewable electricity, i.e., chiefly wind and solar. These energy sources feature an intermittent production of electricity depending on weather conditions and time of day. Therefore, flexibility is required to meet load demands at all times.

From a merely technical perspective, 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. Load-following operation of nuclear power plants is possible within limits which, however, goes along with higher tear and wear and thus higher costs. This also induces increased downtime due to maintenance. Part load operation also reduces the load factor and thus leads to a poorer economic efficiency. Since nuclear power plants are the most capital-intensive power plants, they are not suitable for integrating highly fluctuating renewable electricity feed-in in a system with a high share of renewable electricity.

When looking at historical data on operation of nuclear power plants, it can in fact be concluded that load-following operation is possible with the lower limit mostly being the minimum load. 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 that can be provided by nuclear power plants but is required for the integration of renewable electricity in a system with a high share of renewables.

Overall, there are two important ways of interaction between renewables and nuclear power:

- On the one hand, nuclear power plants could – within their technical limitations – 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.

Traditional energy planning usually focused on determining the number of baseload, intermediate, or peaking units required to meet future energy demands. However, with the increasing integration of variable renewable energy sources like solar and wind, a new planning paradigm prevails. In the old planning approach, 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. If non-dispatchable renewable-based generation is considered, the size of load that needs to be supplied from conventional sources shrinks significantly. This means that the optimal share of baseload generation capacity (such as nuclear power) declines rapidly. While there is no role for baseload nuclear capacities in a renewable-based electricity system, flexibility is required over different time periods and for different tasks.

Available flexibility options to back up photovoltaic 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 demand side management options, electrolysis, and finally flexibility imports. In the case of long dark doldrums or seasonal variations, backup options are reduced to dispatchable power plants, electrolysis, or flexibility imports.

Proposed alternative use cases for nuclear power 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.

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. While nuclear power plants exhibit construction times of 8 years and significantly 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 today 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.

6 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 global warming potential (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 process steps in the nuclear life cycle and the definitions of system boundaries and investigation framework, impact categories and data sources and methods to as used in (Pistner et al., 2025).

6.1 Process steps in the nuclear life cycle

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 "yellowcake". 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.

In uranium conversion, uranium hexafluoride (UF_6) as a precursor for uranium enrichment is then produced from the yellowcake. UF_6 is produced on an industrial scale using "wet" and "dry" conversion processes. In wet conversion, uranium ore concentrate is first dissolved in heated nitric acid to form uranylnitrate. 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.

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 of the fuel 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. The uranium hexafluoride coming from the conversion step is enriched by means of gas centrifuges.

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). 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 fuel assemblies are manufactured specifically and individually for the various reactors and differ in their technical design.

Mixed oxide fuel elements (MOX fuel elements) 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 nuclear fuel is then used in NPPs to produce electricity. Of the NPPs in operation and under construction, the large majority is of PWR type (pressurized water reactors using light water for cooling and moderation). Overall, PWRs are the clearly dominant NPP type today and in the foreseeable future, therefore we focus our analysis on NPPs on water-cooled reactors of the PWR type.

The spent fuel elements continue to generate radiation and non-negligible heat due to the further decay of radionuclides in the spent fuel. 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. In dry storage facilities, the fuel assemblies are stored in sealed containers in halls and cooled by air, with no active cooling system required. As no final storage facility for high-level radioactive waste has been completed anywhere in the world until 2024, it is necessary to leave the spent fuel elements in interim storage facilities for many decades.

Some of the fuel elements used in reactors are reprocessed so that the plutonium they contain, as well as some of the uranium, in theory 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 but at the same time gives access to nuclear weapons usable material. 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. For this reason, only very few countries currently utilise this option.

A distinction must be made between low, medium and high-level radioactive waste for final disposal. As of 2024, there is no active final repository for high-level radioactive waste (HLW waste) in operation. In Finland, the Posiva repository is under construction at the Olkiluoto NPP site, which should start operation in the next years. Some countries are at an advanced planning stage (Sweden, Switzerland, USA). However, none of these countries has yet granted a licence for construction. 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. 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.

Finally, 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.

All of these process steps are taken into account in the life cycle chains analysed.

6.2 Methodology

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 are balanced for each stage. The aim is to calculate the environmental impacts—in particular the GHG emissions—for the generation of 1 kWh of electricity from nuclear energy into an electricity grid for individual modules of the life cycle chain.

The methodology of the study is based on a life cycle analysis of the environmental impacts of 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 (European Commission [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 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, nuclear power plant (NPP) construction, operation and maintenance, and all backend activities—interim storage, reprocessing (where relevant), final conditioning, and (geological) disposal. No exclusion is made for infrastructure or auxiliary systems, and decommissioning impacts are allocated to the same functional unit.

Existing LCA studies on nuclear energy, 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. The Ecoinvent life cycle assessment database of the Swiss 'Centre for Life Cycle Inventories', GEMIS (Global Emissions Model of Integrated Systems) Version 5.1 and GaBi LCA database were used for the analysis.

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.

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. Other process steps, especially the actual electricity production takes place in several countries around the world. 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.

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 are included.

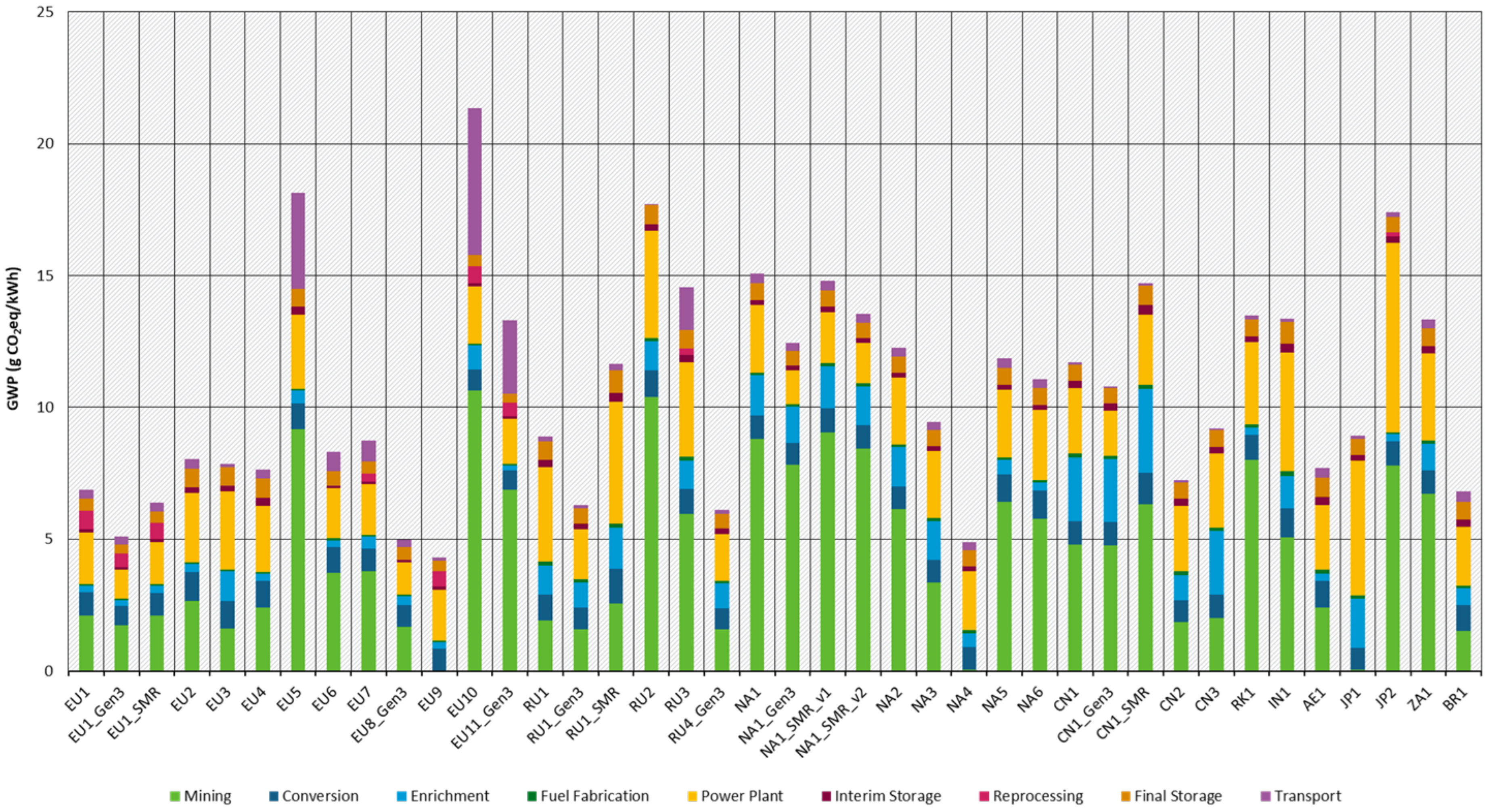
It must be noted that the actual life cycle chains are build up from single modules (like a specific mine, a specific conversion and enrichment facility, a specific NPP etc.). They do therefore not represent the real environmental impact of a specific NPP in a specific country, nor do they give a real 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.

All life cycle chains are analyzed based on data for the baseline year 2020. For a projection year 2030 in selected process chains relative reductions in the greenhouse gas emission factors for concrete, steel and electricity are assumed, which represent major inventory constituents. In addition, selected parameters in the life cycle chains were adopted to values expected for the projection year 2030. Further details on the methodological approach are given in (Pistner et al., 2025).

6.3 GHG emissions for the 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 8 for the baseline year 2020. Detailed results for the individual life cycle chains are given in (Pistner et al., 2025).

Figure 8 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 (Électricité de France [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; United Nations Economic Commission for Europe [UNECE], 2021; Wallner et al., 2011; Warner & Heath, 2012).

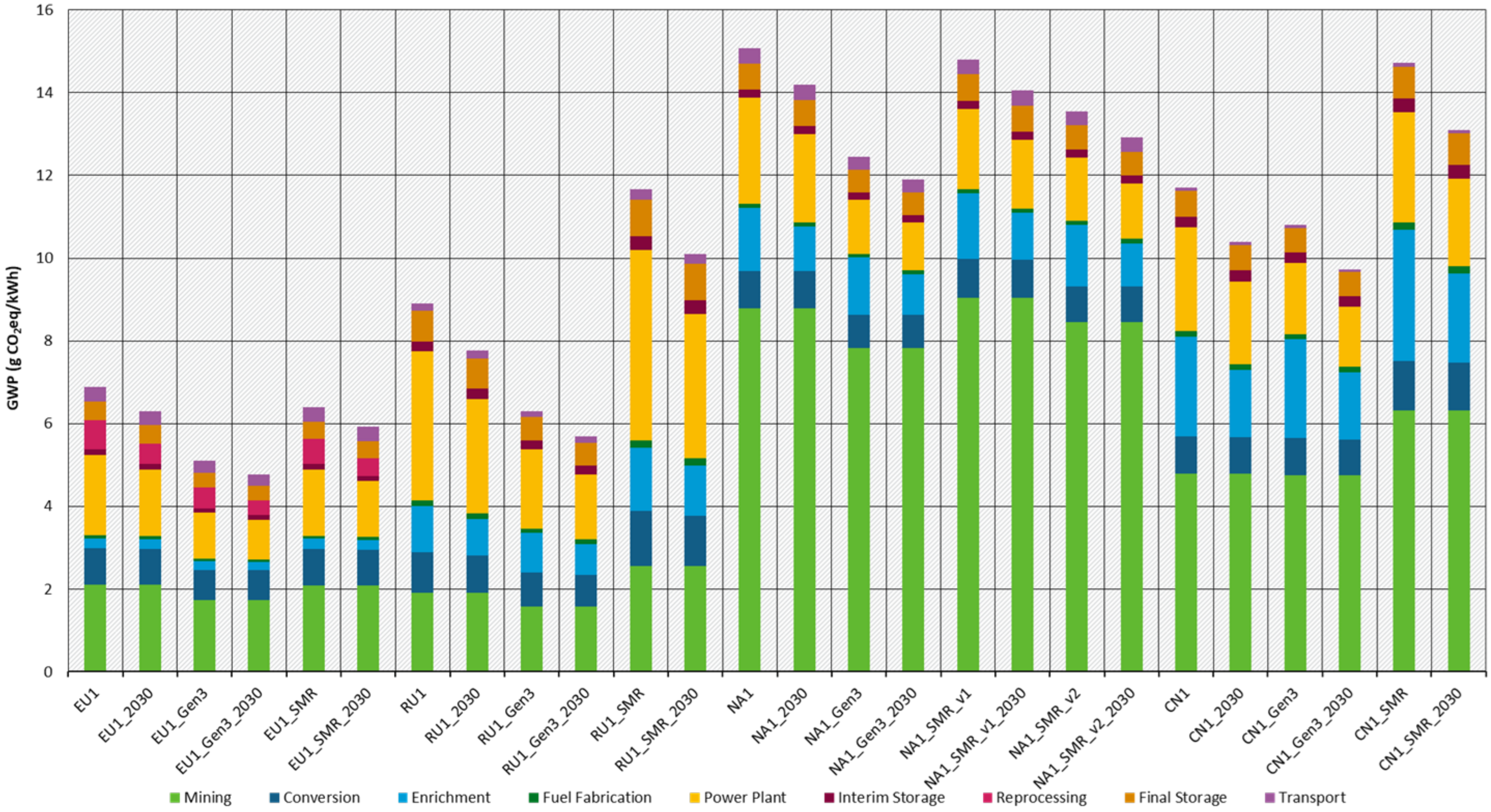
Major sensitivities explaining the broad spread in literature values are the assessment method (like economic input-output vs. process chain analysis), the input data (like the energy inputs of the various process steps) and further chosen estimates and assumptions (like plant lifetimes or load factors). 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%. 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%.

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.

6.4 GHG emissions for the projection year 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 9 for the projection year 2030, including the original values for the baseline year 2020 for comparison.

Figure 9 **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 nuclear power plants and possibly first reactors of the small modular reactor (SMR) type.

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.

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, which – on the other hand – is not to be expected for purely economic reasons.

7 Further environmental impacts of nuclear energy: severe accidents and nuclear non-proliferation

In addition to life cycle emissions, the study discusses environmental impacts of severe accidents, and the dangers related to nuclear proliferation. These are not included in the quantitative LCA due to methodological incompatibility.

7.1 Severe Accidents

The IAEA has defined the International Nuclear and Radiological Event Scale (INES), which 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. 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.

Severe nuclear accidents can lead to significant off-site consequences due to the release of large amounts of radioactivity. 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.

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.

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 of electricity generated worldwide.

While 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, wastes or costs.

A zone with strict control around Chernobyl covered an area of 2,800 km^2. Under the 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^{2}a or $1.7x10^{-3}$ m^{2}a/kWh. Considering additionally the zone with permanent control of 8100 km^2, this number would increase to 6.5 km^{2}a or $6.5x10^{-3}$ m^{2}a/kWh. 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.

The remediation work after the Fukushima Dai-ichi accident resulted in approx. 22 million m^3 of additional contaminated soil stored as low-level nuclear waste corresponding to $2.2x10^{-7}$ m^3/kWh. Compared with the 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.

Different estimates for the costs of the Chernobyl accident cover a range of US$ 20 billion 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. For Japan, this would mean additional costs of 1.2 to 7.5 cent/kWh due to the cost of the Fukushima accident.

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.

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.

7.2 Proliferation Aspects

Finally, the analysis briefly also covers the proliferation risks inherent in the nuclear fuel cycle.

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.

Only highly enriched uranium (HEU) with a uranium-235 content of > 90% in metallic form is directly suitable for nuclear weapons. LWR reactors 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.

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. 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.

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. Plutonium is produced in every reactor that uses uranium as fuel.

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 reprocessed (mechanically crushed and dissolved, followed by chemical extraction of the plutonium). In the so-called open fuel cycle with a direct final disposal of spent fuel, the plutonium is not separated and is therefore protected from access by the radiation barrier. Reprocessing provides access to separated plutonium and is therefore less proliferation-resistant.

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. Proliferation is not to be seen 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.

Due to this dual-use potential, the operation of nuclear power plants with the inherent connection to the military use of nuclear power leads to further risks for people and the environment. These aspects are difficult to quantify in terms of risk or cost, and are therefore often ignored in sustainability assessments.

8 Life cycle costing

8.1 Methodology

The calculation of the LCOE 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 centre 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) for the reviewed construction projects were initially researched and the resulting data was verified with experts ((Steigerwald et al. 2023), (Thomas, 2024)).

As a second step, the respective capital costs were determined. On this basis, the annuities were calculated using standard market discount rates (7%). Annuities are annual payments that include interest, and a pro-rata repayment of loans granted. The longer the construction time recorded or assumed for individual projects, the higher were the capital costs and the resulting annuities.

The following Table 2 summarizes the key modelling parameters for NPP construction and operation as well as the corresponding assumptions.

Table 2: Compilation of key modelling parameters and corresponding assumptions

Construction project	EPR/FIN (Olkiluoto3)	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

The costs of the downstream elements of the process chain (i.e. post-operation, decommissioning, and final disposal) are rarely, if at all, taken into account in other LCOE studies on nuclear power. Given the high level of uncertainty surrounding final storage costs, the cost data used to calculate the LCOE is based exclusively on publicly available planning data. In this respect, current planning data from Switzerland is used, which can be considered transparent with regard to its basic methodological and data-related framework conditions and assumptions.

Taking into account the whole life cycle, the levelized costs of electricity (LCOE) were calculated for both the base year 2020 as well as the future projection for 2030.

Detailed information on the methodology as well as the used key parameters, data and assumptions is given in (Pistner et al., 2025).

8.2 Baseline year 2020

Table 3 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 3: LCOE ranges (min./max.) for electricity from new nuclear power (in ct/kWh, baseline year 2020)

Construction project	EPR/FIN (Olkiluoto3)		EPR/FRA (Flamanville 3)		AP100/USA (Vogtle 3&4)	
	min.	max.	min.	max.	min.	max.
Capital costs (ct/kWh)	12.53	12.53	15.60	15.60	12.96	12.96
Operating and fuel costs (ct/kWh)	2.46	3.16	2.78	3.54	2.57	3.32
End-of-life costs (ct/kWh)	0.02	0.04	0.02	0.04	0.02	0.04
Total (ct/kWh)	**15.02**	**15.73**	**18.41**	**19.18**	**15.55**	**16.32**

Source: own compilation

The presented results are confirmed by other recent scientific studies on the LCOE of newly constructed nuclear. For example, a comparison with (Kost et al., 2024) shows good concordance in the lower end of their range (13.6 to 49.0 ct/kWh). 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. 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 in the table above 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 above is within or slightly below these Australian-contextualized values for specific European projects.

8.3 Projections 2030

Table 4 shows 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.

Table 4: **LCOE ranges (min./max.) for electricity from new nuclear power (in ct/kWh, future projection for 2030)**

Construction project	**EPR/UK (Hinkley Point C)**		**EPR/UK (Sizewell C)**		**SMR/USA (NuScale, FOAK)**		**SMR/USA (NuScale, FOAK)**		**SMR/ARG (CAREM)**	
	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Capital costs (ct/kWh)	23.24	37.88	23.68	32.54	16.65	16.65	3.07	3.07	39.91	39.91
Operating and fuel costs (ct/kWh)	2.83	3.59	2.83	3.59	2.65	3.45	2.65	3.45	2.98	3.84
End-of-life costs (ct/kWh)	0.02	0.04	0.02	0.04	0.02	0.04	0.02	0.04	0.08	0.14
Total (ct/kWh)	**26.10**	**31.51**	**26.54**	**36.17**	**19.32**	**20.14**	**5.74**	**6.56**	**42.97**	**43.89**

Source: own compilation

As the LCOE results for 2030 show, cost reduction potentials are not foreseeable for the future projection. 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[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).

8.4 Comparison with renewable and fossil power generation technologies

In this section, LCOE values resulting from a detailed analysis of costs for nuclear power plants are compared with LCOE ranges for wind, photovoltaics, and hard coal electricity generation.

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

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[2] 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.

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.

For wind (onshore and offshore), and photovoltaics, LCOE for units that came online by 2020 are available from (International Renewable Energy Agency [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.

Table 5: 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; [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

Table 5 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, 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.

On the global scale, weighted average LCOE for onshore and offshore wind declined by about 20%, and by about 30% for photovoltaics between 2020 and 2025. Current studies assume that all three technologies will experience further technological learning, but learning rates will be much lower than in the past. 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.

Still, a projection to 2030 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.

9 Greenhouse gas abatement costs

9.1 Methodology

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 1).

Equation 1: 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 detailed in chapter 6. 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 photovoltaics, life-cycle emissions are sensitive to technology choice.

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.

9.2 Baseline year 2020

Table 6 compares 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 given in chapter 8.

Renewable electricity, in favorable or average 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 10 moving further down. Nuclear power constitutes an expensive abatement option both at the lower and at the higher end.

9.3 Projections 2030

The GHG abatement costs for nuclear power range between 285 $€_{2020}$/t CO_2eq and 420 $€_{2020}$/t CO_2eq for Generation 3 nuclear power plants in Europe as well as 196 $€_{2020}$/t CO_2eq and 527 $€_{2020}$/t CO_2eq 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_2eq[3]), compare Table 7. 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, see Figure 11. 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 EUR_{2020}/tCO_2eq between GHG abatement costs of nuclear-based power generation and any of the three renewables-based technologies, even based on the 95th percentile LCOE.

Nuclear power does not constitute a cost-effective abatement option with GHG abatement costs, amounting to between 196 and 527 €/t CO_2eq, 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 chapter 8, 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.

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[3] 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 chapter 8).

Table 6: 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$_{2020}$/kWh]	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$_2$eq/kWh]	5.1[4]	12.4[4]	755.7[5]	11[6]			12[6]			48[6]		
Abatement costs [EUR$_{2020}$/tCO$_2$eq]	102 to 158	111 to 121	-	-66	-50	5	-16	6	131	-38	-29	106

Notes: [1] as calculated in chapter 8; [2] LCOE for United States as reported in (IEA, 2024), assuming no CO$_2$ pricing, high capacity factor, and domestically available coal;[3] 5th percentile, weighted average, and 95th percentile for global values as reported in Table 3; [4] as calculated in (Pistner et al., 2025) section B.3 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

Table 7: 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)

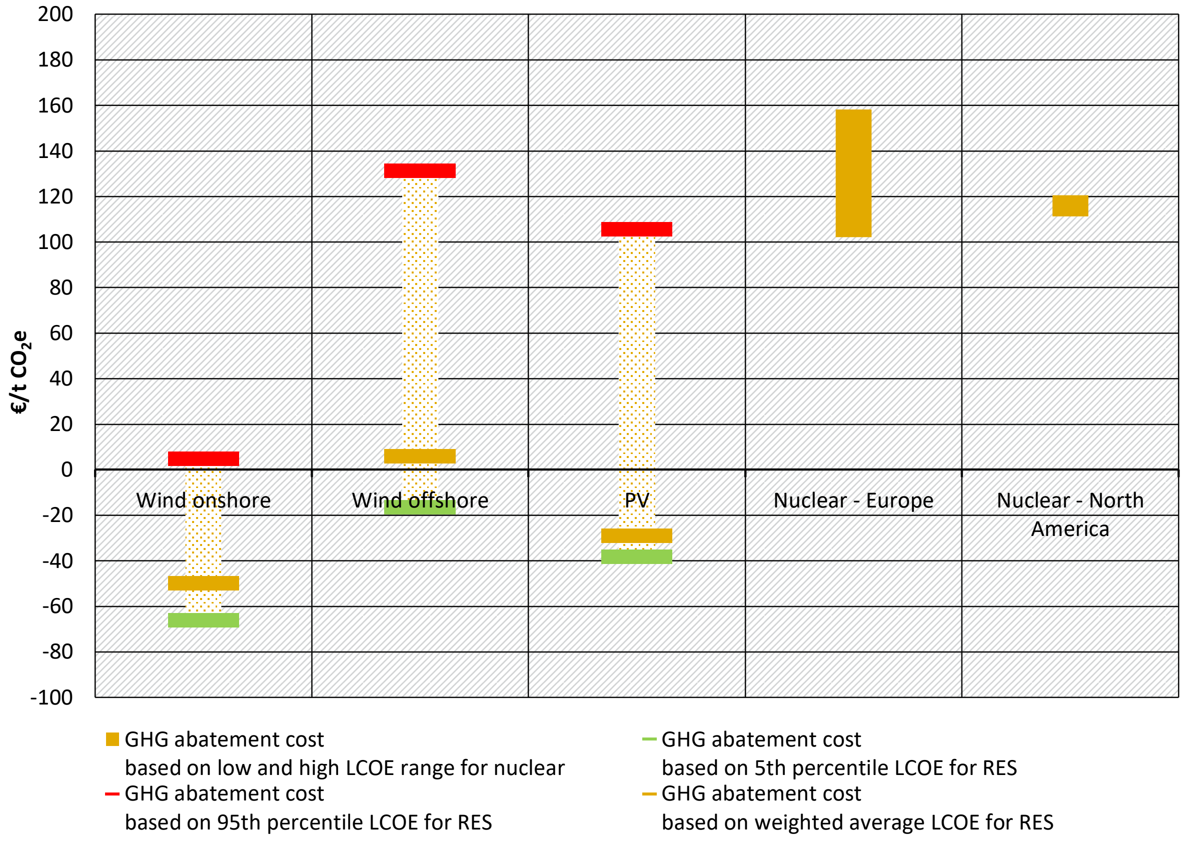
Item	Nuclear power		Hard coal	Wind onshore[3]			Wind offshore[3]			Photovoltaics[3]		
	Europe	North America		5th	Weighted average	95th	5th	Weighted average	95th	5th	Weighted average	95th
LCOE [€ct$_{2020}$/kWh]	26.1-36.2[1]	19.3-43.9[1]	4.7[2]	2.0	2.8	6.2	3.7	6.0	11.8	2.6	3.5	10.8
Life cycle GHG emissions [g CO$_2$eq/kWh]	4.8[4]	11.9[4]	755.7[5]	11[6]			12[6]			48[6]		

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
Abatement costs [EUR$_{2020}$/tCO$_2$eq]	285 to 420	196 to 527	-	-37	-26	20	-16	6	131	-38	-29	106

Notes: [1] as calculated in chapter 8; [2] LCOE for India in (IEA, 2024), assuming no CO_2 pricing, high capacity factor, domestically available coal, and low capital costs, 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 4; [4] as calculated in (Pistner et al., 2025) section B.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.

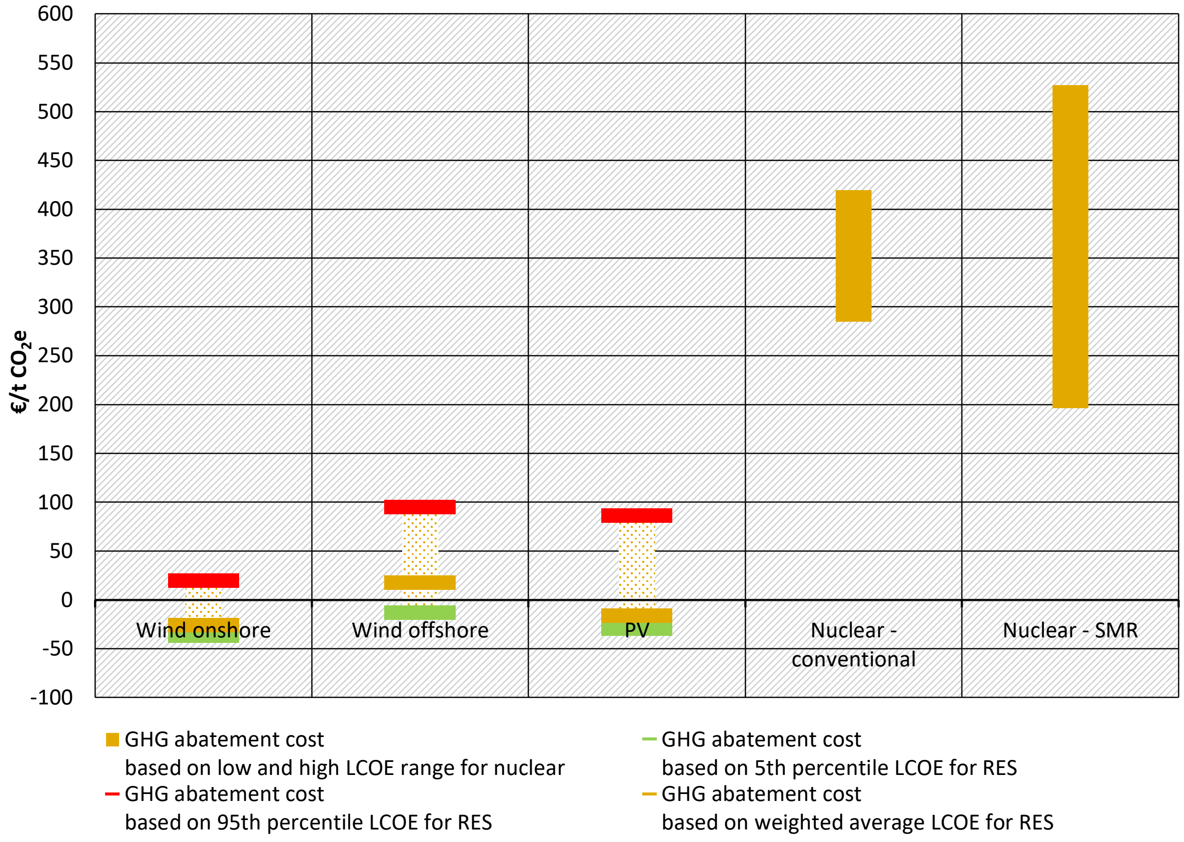
Source: own compilation

Figure 10: 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

Figure 11: 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

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