CLIMATE CHANGE
40/2019

GHG-neutral EU2050 – a scenario of an EU with net-zero greenhouse gas emissions and its implications

Full report

German Environment Agency

Umwelt Bundesamt

CLIMATE CHANGE 40/2019

Ressortforschungsplan of the Federal Ministry for the
Enviroment, Nature Conservation and Nuclear Safety

Project No. (FKZ) 3716 41 109 0

Report No. FB000147/ENG

GHG-neutral EU2050 – a scenario of an EU with net-zero greenhouse gas emissions and its implications

Full report

by

Vicki Duscha, Jakob Wachsmuth, Johannes Eckstein,
Benjamin Pfluger
Fraunhofer Institute for Systems and Innovation
Research, Karlsruhe

based on the technical annex by

Vicki Duscha, Johannes Eckstein, Andrea Herbst, Pia
Manz, Frank Marscheider-Weidemann, Benjamin Pfluger,
Patrick Plötz, Jan Steinbach, Jakob Wachsmuth
Fraunhofer Institute for Systems and Innovation Research,
Karlsruhe

Hannes Böttcher, Veit Bürger, Tilman Hesse, Margarethe
Scheffler, Kirsten Wiegmann, Wiebke Zimmer
Oeko-Institute, Freiburg

On behalf of the German Environment Agency

Imprint

Publisher
Umweltbundesamt
Wörlitzer Platz 1
06844 Dessau-Roßlau
Tel: +49 340-2103-0
Fax: +49 340-2103-2285
info@umweltbundesamt.de
Internet: www.umweltbundesamt.de

/umweltbundesamt.de
/umweltbundesamt

Report performed by:
Fraunhofer Institute for Systems and Innovation Research ISI
Breslauer Strasse 48
76139 Karlsruhe
Germany

Report completed in:
April 2019

Edited by:
Section V 1.2 Strategies and Scenarios for Climate and Energy
Guido Knoche

Publication as pdf:
http://www.umweltbundesamt.de/publikationen

ISSN 1862-4804

Dessau-Roßlau, November 2019

Abstract: GHG-neutral EU2050 – a scenario of an EU with net-zero greenhouse gas emissions and its implications

Given that the Paris Agreement has strengthened the long-term temperature goal and that it calls for a balance of greenhouse gas (GHG) emissions and sinks within the 21st century, there is the urgent need to re-assess the long-term targets of the EU and to show how the target of GHG neutrality can be reached in the EU. The aim of this study was to design a scenario called “GHG-neutral EU2050” as one way to realize a European Union with net-zero greenhouse gas emissions under further sustainability criteria. The scenario shows that a GHG-neutral EU is feasible even without the use of carbon capture and storage and with limited amounts of bioenergy. Key components of the scenario in all energy-consuming sectors (industry, buildings and transport) are a strong increase in energy efficiency as well as far-reaching electrification. These measures can reduce the final energy demand (including international transport) by about 37% and the share of electricity can be increased to almost 50%. In addition, a broad portfolio of other renewable energy options has to be exploited and substantial quantities of renewable fuels are required, which are produced from renewable electricity via electrolysis or based on biomass. Due to unavoidable GHG emissions from agriculture, industrial processes and waste treatment, achieving GHG neutrality also requires lower activity of the agricultural sector and an increased GHG sink from forestry. Besides the detailed quantitative description of a sectoral setup for all GHG-emitting sectors, the study contains a qualitative discussion of the sectoral options to reach GHG-neutrality, cross-sectoral interactions as well as the challenges associated with realizing such a scenario.

Kurzbeschreibung: THG-neutrale EU2050 – ein Szenario einer Europäischen Union mit Netto-Null Treibhausgasemissionen und seine Implikationen

Mit dem Übereinkommen von Paris hat die Weltgemeinschaft das globale, langfristige Temperaturziel verschärft. Alle Staaten streben damit gemeinsam ein Gleichgewicht zwischen Treibhausgasemissionen und -senken innerhalb des 21. Jahrhunderts an. Somit ist es auch für die EU dringend erforderlich, ihre langfristigen Ziele neu zu bewerten und aufzuzeigen, wie Treibhausgasneutralität in der EU erreicht werden kann. Ziel dieser Studie war es, ein Szenario mit dem Titel „GHG-neutral EU2050“ als eine Option zur Realisierung einer Europäischen Union mit Netto-Null Treibhausgasemissionen unter weiteren Nachhaltigkeitskriterien zu entwickeln. Das entworfene Szenario zeigt, dass eine treibhausgasneutrale EU auch ohne den Einsatz der unterirdischen Speicherung von Kohlendioxid und mit begrenzten Mengen an Bioenergie machbar ist. Wesentliche Bestandteile des Szenarios in allen energieverbrauchenden Sektoren (Industrie, Gebäude und Verkehr) sind eine starke Steigerung der Energieeffizienz sowie eine weitreichende Elektrifizierung. Durch diese Maßnahmen kann der Endenergiebedarf (einschließlich des internationalen Verkehrs) um etwa 37% gesenkt und der Anteil des Stroms auf fast 50% erhöht werden. Dennoch muss das breite Portfolio anderer Optionen für erneuerbare Energien genutzt werden, und erneuerbare Brennstoffe, die aus erneuerbarer Elektrizität durch Elektrolyse oder auf Biomassebasis hergestellt werden, werden in erheblichem Umfang benötigt. Aufgrund der unvermeidlichen Treibhausgasemissionen aus Landwirtschaft, Industrieprozessen und Abfallbehandlung sind jedoch eine geringere Aktivität des Landwirtschaftssektors und eine erhöhte Treibhausgassenke aus der Forstwirtschaft erforderlich. Neben der detaillierten quantitativen Beschreibung der sektoralen Ausgestaltung aller treibhausgasemittierenden Sektoren enthält die Studie eine qualitative Diskussion von sektoralen Spielräume zur Erreichung von Treibhausneutralität, von sektorübergreifenden Interaktionen sowie von Herausforderungen bei der Realisierung eines solchen Szenarios.

Table of content

List of figures

List of tables

List of abbreviations

Biogenic fuel	Renewable fuel based on any kind of biomass (solid, liquid, gaseous)
BTX	Benzene, toluene, and the three xylene isomers
CCS	Carbon capture and storage
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq.	GHG emission equivalent to an emission of CO_2
COP	Conference of the Parties
DAC	Direct air capture of carbon dioxide
EC	European Commission
EU	European Union (with 28 member states as of 2018)
EU-ETS	EU Emissions Trading Scheme
F-gases	Fluorinated greenhouse gases
GDP	Gross domestic product
GHG	Greenhouse gases
GHG-neutral EU2050	Name of the scenario with net-zero GHG emissions developed in this study
HDV	Heavy duty vehicle
LULUCF	Land use, land use change and forestry
NDC	Nationally Determined Contributions (in Paris-Agreement)
Novel fuel	Renewable fuel based on renewable electricity
N_2O	Nitrous oxide
PJ	Petajoule (energy measuring unit)
PtG	Power-to-Gas (any power-based gaseous fuels)
PtH	Power-to-Heat (any power-based heat including heat pumps)
PtL	Power-to-Liquid (any power-based liquid fuels)
PtX	The total of PtG, PtH and PtL
PV	Photovoltaics
Renewable fuels	The total of biogenic and novel fuels
TWh	Terawatt hours (measuring units for energy)
UBA	Umweltbundesamt
ÜvP	Übereinkommen von Paris
UNFCCC	United Nations Framework Convention on Climate Change

Summary

Introduction and objective

The EU's ratification of the Paris Agreement means that it must reconsider its current long-term greenhouse gas (GHG) mitigation target of minus 80-95% compared to 1990 levels. The Paris Agreement not only aims at keeping the temperature increase well below 2°C, and even limiting it to 1.5°C if possible, but also stipulates that a balance is to be achieved between sinks and sources of anthropogenic greenhouse gas emissions ("GHG neutrality") in the second half of the 21st century (UNFCCC 2015). The great challenge of the coming years and decades is to push the implementation of these goals globally. The development of target visions of GHG-neutral economies, the analysis of such visions and the exploration of pathways leading to the required emission trajectories are important elements of a climate policy aiming to meet the long-term mitigation targets. This is the basis for developing political strategies and policy instruments.

The aim of this study is to provide a scenario for the EU called *GHG-neutral EU2050* that balances GHG emissions and sinks for the time horizon 2050. This study's approach is based on the UBA study "Germany 2050: A Greenhouse Gas-Neutral Country" (UBA 2013). Contrary to other scenario studies, the main focus is not the quantitative analysis but also the qualitative analysis of a low-emission scenario for the EU. To this end, a detailed analysis was made of the most relevant sectors and the various technological options were compared with each other. This provided a systematic assessment of the options for a GHG-neutral EU in order to help structure the further discussions at EU level. In addition, the study integrates overarching considerations to judge whether the analyses of the various individual sectors are consistent even in the context of the very far-reaching reductions in total GHG emissions.

Approach and methodology

The methodology used to develop the scenario *GHG-neutral EU2050* followed a number of paradigms:

- **Bottom-up scenario development**: To develop GHG-neutral EU2050, the set of mitigation options in all the GHG-relevant sectors was analysed (including all energy-related emissions, but also non-energy related emissions from industry, agriculture, waste and land-use, land-use change and forestry (LULUCF)).
- **Analytical approaches**: Different analytical approaches were applied depending on the data and model availability. These included projections based on decomposition analyses, projections based on model results and full sector modelling. This heterogeneity enabled us to make the best use of the information available at the sector level, but resulted in different levels of analytical detail across sectors.
- **End-point scenario**: GHG-neutral EU2050 focuses purely on describing the situation in the year 2050 (or a year close to 2050, which is seen as an end-point). Describing the possible pathways to arrive at this end-point was not part of the project.
- **Harmonization across sectors**: Despite the bottom-up approach and the heterogeneity of the applied analytical approaches, developing a consistent scenario was one of the central objectives. Therefore, the scenario presented in this report was constructed in a recursive approach, consisting of cross-sectoral workshops, sectoral analyses, and cross-sectoral analyses of certain aspects such as biomass availability.

- **Regionally disaggregated**: While the scenario described in this report focuses on aggregated results for the EU28 (including the UK), the underlying sector models use individual Member State data whenever possible. These include, among others, differences in industry structure, use of biomass and district heating networks within the buildings sector or the electrification of railways in the transport sector.

The main data sources used for the scenario are:

- the EU's and Member States' greenhouse gas inventories from 2015 (UNFCCC 2017)
- energy balances of individual Member States as provided by Eurostat for the year 2015 (EUROSTAT 2017)
- the EU reference scenario for the European Commission (EU COM 2016) to provide a consistent data set across all Member States on the main drivers (gross domestic product (GDP), population and sector-specific drivers).

In addition, sector-specific data sets were included whenever necessary. Details on the sector-specific modelling approaches and data can be found in the separately published technical annex to this study (Duscha et al. 2019).

GHG-neutral EU2050 is based on a number of assumptions and projections concerning the development of key drivers:

- **Energy efficiency measures:** Unlike today, efficiency measures do not reduce GHG emissions in a fully decarbonised energy system, because all energy can be provided without associated CO_2 emissions. Nevertheless, energy efficiency measures do play an important role in a decarbonisation scenario, because they reduce the amount of CO_2-neutral energy that has to be provided and thus the total cost of supplying energy. Therefore, GHG-neutral EU2050 is based on ambitious efficiency assumptions in all sectors.
- **Feasibility:** GHG-neutral EU2050 focuses on feasibility under technological and certain economic constraints, e.g. the need for different qualities of cement and steel. GHG-neutral EU2050 does not rely on economic optimisation, but instead applies various analytical approaches (cf. above) and expert knowledge to find a consistent set of low-emitting technologies that fully substitutes fossil technologies. The role of policy instruments and measures, which e.g. put a sufficiently high price on carbon emissions, is not analysed within the scope of this study.
- **Consumption changes**: When choosing mitigation options, GHG-neutral EU2050focuses on measures in the areas of efficiency and consistency. Changes in the composition and level of consumption due to sufficiency measures or economic reactions to price changes resulting from the technical transformation and in particular behavioural changes are generally not considered. The scenario deviates from this guideline in those areas in which the objectives cannot be achieved by technical means alone (agriculture/food and waste management).
- **Availability of technologies:** GHG-neutral EU2050 adopts a moderately optimistic attitude with regard to the availability of technologies. Technologies are taken into account that have

at least been validated in an industrially relevant environment (TRL 5 or higher[1]). This means that highly innovative lab-scale technologies are not considered. Furthermore, technologies are also excluded that face severe limitations with regard to sustainability. This applies in particular to the construction of new nuclear power plants and the use of carbon capture and storage (CCS).

- **Biomass and electricity-based energy carriers ("renewable fuels")**: Requirements for the storability of electricity and the use of energy in non-stationary applications mean that full electrification is technically difficult or only possible at very high costs. For this reason, the study investigates the option to use *renewable fuels*, defined as either biogenic energy carriers or *novel fuels*, i.e. electricity-based energy carriers. The biomass available for energy purposes, however, is limited to waste and residual materials; cultivating energy crops and importing biomass are excluded.

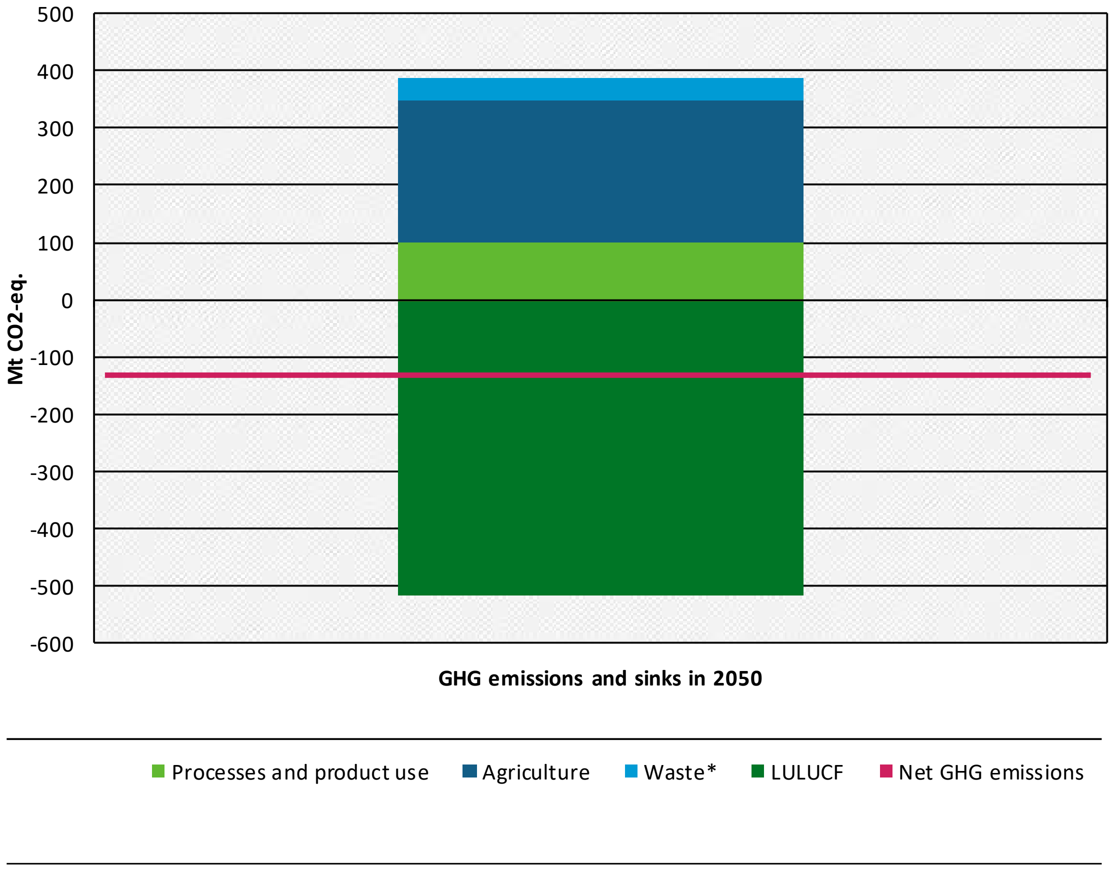
Main results

The central objective of this study is to construct a scenario for an EU with net-zero GHG emissions by 2050 under additional sustainability constraints, e.g. with regard to biomass and nuclear power. In particular, this scenario complies with the balance of GHG emissions and sinks required in Article 4 of the Paris Agreement (UNFCCC 2015) and with the target proposed in the EC's strategic vision "A clean planet for all" (EU COM 2018a).

GHG-neutral EU2050 achieves this by reducing GHG emissions across all sectors as far as technically possible, and by compensating the remaining GHG emissions with sufficient carbon sinks in the LULUCF sector. More precisely, the scenario describes a detailed viable setup across all GHG emitting sectors including agriculture, waste and international bunker fuels that is able to reduce all six Kyoto greenhouse gases to 387 Mt CO_2-eq. in the year 2050 (excluding the LULUCF sector). This corresponds to a reduction by 93% compared to 1990 levels (-92% compared to 2015). Furthermore, GHG-neutral EU2050 compensates the remaining GHG emissions by increasing the net carbon sink in the LULUCF sector to 518 Mt CO_2-eq., which is larger than the remaining GHG emissions by 131 Mt CO_2-eq. (see Figure S1).

[1] see ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf for a definition of the TRLs (technology readiness levels)

Figure S1: EU GHG emissions and sinks in GHG-neutral EU2050



* including waste incineration with energy recovery
Source: own calculation (Fraunhofer ISI and Oeko-Institute)

All energy-related GHG emissions across the energy sector, the industry sector, the transport sector, the residential sector and the services sector are mitigated, in particular by avoiding the use of fossil fuels altogether. Only 13 Mt CO_2-eq. of GHG emissions remain from the incineration of non-biogenic waste (see Table S1). To achieve this, a broad portfolio of mitigation options is applied throughout, although the focus varies in the different sectors. Details concerning the changes in energy demand and supply are presented below Table S1.

For industrial process and product use, GHG emissions of 103 Mt CO_2-eq. remain, which correspond to a reduction by only 80% compared to 1990. However, these remaining GHG emissions cannot be mitigated under the assumptions of the GHG-neutral EU2050 scenario, which are very ambitious but also consider sustainability issues other than climate change. The remaining process emissions could be reduced substantially (although not to zero), if CCS were applied when producing cement. This is not considered in detail, because the target of GHG neutrality in 2050 can be reached anyway.

Compared to 1990, the GHG reduction is even smaller in the agricultural sector, namely 55%. This reflects the unavoidable GHG emissions from land use and animal livestock. GHG-neutral EU2050 already assumes a reduction of the livestock units by 50 percent based on health considerations[2]. Any additional reduction of the remaining GHG emissions would require strengthening this already ambitious assumption even further.

[2] It is assumed that, on average, people's dietary needs meet the recommendations of the World Health Organisation, with a reduction of protein consumption to 50g/d/cap.

In the waste sector, the emissions are reduced by almost 90% by decreasing the amount of waste and changing the practices of waste disposal. Again, any additional reduction is only feasible under very strong assumptions about future waste volume. Finally, the GHG emissions from international bunker fuels are fully mitigated by switching from the use of fossil fuels to *novel fuels*, which are produced using renewable electricity only.

The LULUCF sector already represents a carbon sink today, with 318 Mt CO_2-eq. of carbon removed in 2015. However, this sink is not sufficient to offset the remaining GHG emissions in GHG-neutral EU2050. Therefore, the scenario also outlines a model for the transformation of the LULUCF sector, which enables this carbon sink to be increased to 518 Mt CO_2-eq. in 2050.

Table S1: GHG emissions of the EU in 1990, 2015 & GHG-neutral EU2050

	UNFCCC 1990 [Mt CO_2-eq.]	UNFCCC 2015 [Mt CO_2-eq.]	GHG-neutral EU2050 [Mt CO_2-eq.]	Reduction compared to 1990 [-]
Energy-related	4.351	3.371	13	-100%
Industrial processes and product use	517	377	103	-80%
Agriculture	542	429	245	-55%
Waste	236	141	26	-89%
International bunkers	180	282	0	-100%
TOTAL excl. LULUCF	**5.826**	**4.600**	**387**	**-93%**
LULUCF	-260	-318	-518	N/A
Total incl. LULUCF	**5.566**	**4.282**	**-131**	**-102%**

Source: UNFCCC 2017 and own calculation (Fraunhofer ISI and Oeko-Institute)

More details on the sectoral GHG emissions can be found in the sector descriptions in Section 5 of this study and in the separately published technical annex (Duscha et al. 2019).

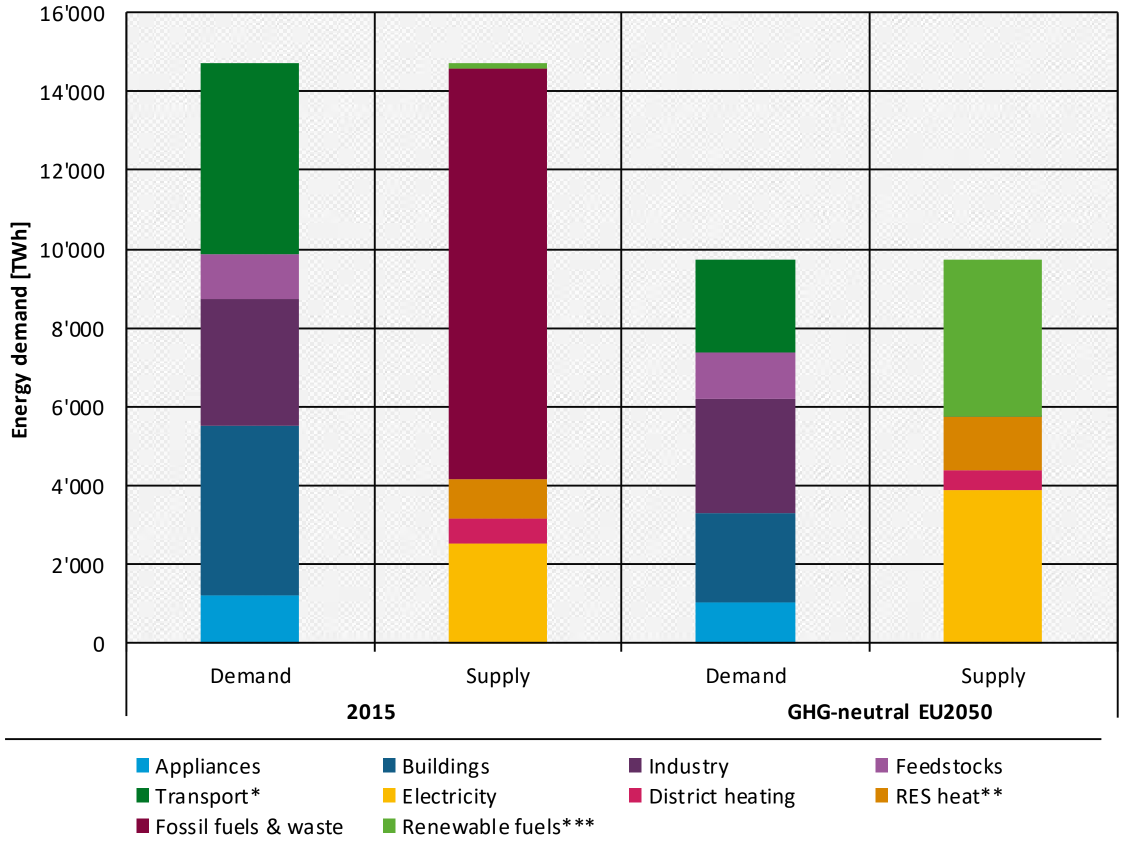
Today, energy-related GHG emissions dominate the GHG emissions of the EU, with a share of 78% in 2015. The transformation of the EU energy system is therefore key to realising a GHG-neutral EU. This means, on the one hand, limiting energy demand across all energy-consuming sectors as far as possible and, on the other hand, meeting the resulting demand with non-fossil energy carriers, in particular, renewable energy sources given the restrictions on nuclear energy and CCS described above.

In GHG-neutral EU2050, final energy demand is reduced by roughly one third, from about 14,700 TWh in 2015[3] to about 9,700 TWh in 2050 (including industrial feedstocks as well as international aviation and navigation), see Figure S2. The largest demand reductions take place in the transport and buildings sectors, with 52% and 47%, respectively, and are due to much more energy-efficient vehicles and buildings as well as strong electrification in both sectors. Incremental efficiency gains lower the energy demand of industry and appliances by 12% and

[3] Even without international navigation, the final energy demand according to EUROSTAT (2017) is about 3% lower. This mainly reflects that the official statistics contain no climate adjustment.

14%, respectively, while the non-energy demand for industrial feedstocks increases by 6% due to a slight increase in production, in particular in the chemical industry.

Figure S2: EU final energy demand in 2015 and in GHG-neutral EU2050

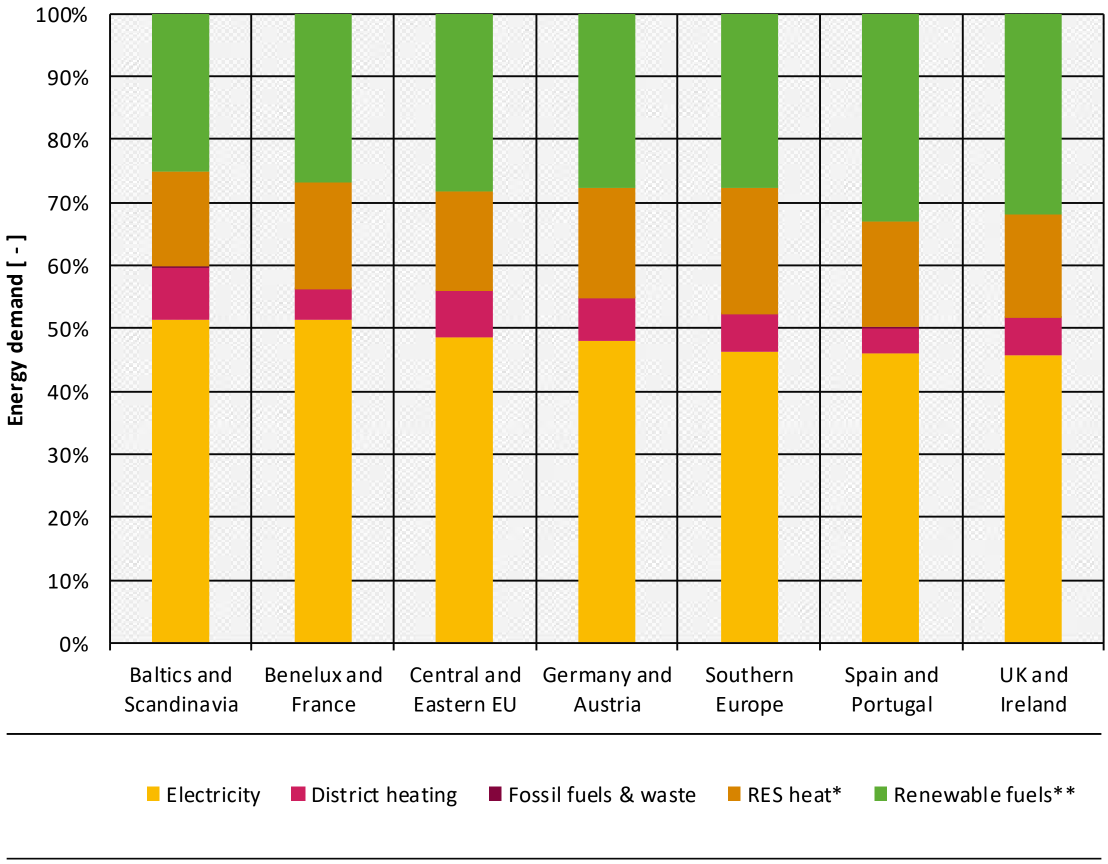


* including international aviation and navigation; ** including biomass except for biofuels in 2015; *** excluding biomass except for biofuels in 2015
Source: own calculation based on EUROSTAT (2017)

Reducing energy-related GHG emissions by 100% is further achieved by completely substituting fossil fuels, whose 2015 share in the energy mix was more than 79%, with electricity, district heat, RES heat (ambient heat, solar thermal and bioenergy) and *renewable fuels* (consisting of *novel fuels*, i.e. hydrogen and synthetic hydrocarbons, as well as biogenic fuels). The only remaining emissions are from the incineration of unavoidable non-renewable waste. Strong electrification across all energy-consuming sectors results in an increase in final electricity demand by 53% compared to 2015, and increasing its share in the energy mix from 17% to 40% (almost 50% excluding feedstocks). The use of district heat increases only slightly from 4% to 5%, while the share of RES heat doubles from 7% to 14%. The remaining demand for fuels, which mainly stems from international transport, industry and industrial feedstocks, is covered by *novel fuels*, which reach a share of 41% in 2050 (32% without feedstocks) compared to the 1% covered by biofuels in 2015.

As electricity and *renewable fuels* together cover 80% of the final energy demand in 2050, they form the backbone of energy supply in 2050. Onshore and offshore wind and solar energy in photovoltaic plants are the main sources of electricity production. The remaining nuclear power plants cover only 33 TWh of the electricity demand. There is also an additional need for *renewable fuels* of about 300 TWh for electricity generation, which are required to compensate the fluctuating electricity production from wind and solar power. 70% of these *renewable fuels* are produced (with regard to novel fuel end-use) from renewable electricity and only 30% from sustainable biomass. This means that the production of electricity and *novel fuels* is strongly interrelated. In particular, if *novel fuels* are not imported, this results in a strong increase in the total electricity demand. The GHG-neutral EU2050 scenario takes regional differences in the energy demand structure into account (see Figure S3).

Figure S3: Regional energy mixes in GHG-neutral EU2050



* including decentralised biomass use; ** excluding feedstocks
Source: own calculation based on EUROSTAT (2017)

In summary, the resulting regional energy mixes in the year 2050 no longer differ strongly because, on the one hand, there is high electrification across all sectors and regions and, on the other hand, because *renewable fuels* are needed to a certain extent in all regions for high-temperature heat and to compensate seasonal fluctuations in renewable electricity generation.

Conclusions

Since the question of how to achieve net-zero GHG emissions in the EU is a relatively new topic, this study aimed to design a scenario "GHG-neutral EU 2050" as one way to achieving a balance of GHG emissions and sinks in the EU under further sustainability criteria. The constructed scenario shows that a GHG-neutral EU is feasible even without the use of CCS and with limited amounts of bioenergy. Due to unavoidable GHG emissions from agriculture, industrial processes and waste treatment, however, achieving GHG neutrality requires lower activity of the agricultural sector and an increased GHG sink from the LULUCF sector. GHG-neutral EU2050 shows this is achievable by halving the number of animal livestock units and increasing the land use sink to more than 500 Mt CO_2 annually by dedicating larger amounts of land to forestry.

Key components of the scenario in all energy-consuming sectors (industry, buildings and transport) include a strong increase in energy efficiency as well as far-reaching electrification. In particular, this includes electrifying large parts of terrestrial freight transport and heat pumps for decentralised and centralised heating purposes. These measures can reduce final energy demand (including international transport but excluding feedstocks) by about 37% to roughly 8,500 TWh, and the share of electricity can be increased to almost 50%. In addition, a broad portfolio of other renewable energy options has to be exploited and 3,500 TWh of *renewable fuels* are required, which are produced from renewable electricity via electrolysis or based on biomass (4,750 TWh including feedstocks). If these *novel fuels* are produced domestically, this would increase electricity demand by 250%. As this may be in conflict with issues of social acceptance, imports of *novel fuels*, in particular hydrocarbons, can play a key role in realising a scenario like GHG-neutral EU2050.

The EC's Strategic Vision "A clean planet for all" outlined seven building blocks for net-zero GHG emissions in the EU, namely (1) maximise the benefits of energy efficiency, including zero-emission buildings, (2) maximise the deployment of renewables and the use of electricity to fully decarbonise Europe's energy supply, (3) clean, safe and connected mobility, (4) a competitive EU industry and the circular economy, (5) develop an adequate smart network infrastructure and inter-connections, (6) reap the full benefits of a bio-economy and create essential carbon sinks, and (7) tackle remaining CO_2 emissions with carbon capture and storage.

The key components of GHG-neutral EU2050 are generally in accordance with the first five building blocks, although the focus may vary slightly for some sectors and mitigation options. There are significant differences, however, for the final two building blocks. The sixth building block has some overlaps with the main lines of the LULUCF sector in GHG-neutral EU2050, but differs with regard to the role of bioenergy, which is strongly limited in GHG-neutral EU2050. The differences are even larger with regard to the seventh building block. While GHG-neutral EU2050 shows that a GHG-neutral EU can be realized without the use of CCS, the last building block of the EC's Strategic Vision assigns CCS a central role. A better understanding of this discrepancy is essential for deriving a reasonable long-term strategy to foster the EC's Strategic Vision. GHG-neutral EU2050 provides important insights in this regard.

Currently, the EU is on track to reach its 2020 target of reducing GHG emissions by 20% and EU regulations compatible with the 2030 target of 40% GHG reduction have come into force, although they have not yet been implemented in the Member States (EU COM 2018b). However, none of the sectors are on track to achieve the 2050 GHG reduction target of 80% to 95%. Realising GHG-neutral EU2050 will require huge efforts that go far beyond the challenges of reaching the nearer term climate targets in 2020 and 2030:

- Infrastructure developments need to be harmonised across the EU. These include electricity and gas grids, but also transport infrastructure to enable the market penetration of electric vehicles, including EU-wide catenary lines for freight transport. All of these measures require early and coordinated multilateral action to provide the necessary infrastructure.
- *Renewable fuels* supply substantial amounts of energy to the transport sector, certain parts of industry, and buildings. Therefore, efforts must be made to bring *renewable fuels* into the market. Since using biomass for their synthesis is a very limited option, there is a huge need to scale up capacities for producing and/or importing electricity-based *novel fuels*.
- Energy efficiency standards for buildings, heating systems, appliances and vehicles need to be extremely ambitious. To achieve energy intensity reductions in line with GHG-neutral EU2050, it is essential to ensure that renovations meet the highest energy performance standards and that steps are taken to accelerate renovation rates substantially. In order to

reduce demand in the transport sector, monetary and regulatory incentives must be implemented to bring about an economy "of short distances" and to increase public transport.

- Radical innovations are necessary in the industry sector, in particular concerning the production of steel and cement. Research and development in the coming decade needs to foster the development and upscaling of new zero- or low-emission processes and to enable market readiness by 2030. These new processes then need to be put into use rapidly.
- Measures to reduce the consumption of dairy and meat products are required to limit the GHG emissions of the agricultural sector. This reduction enables an increase in organic farming, afforestation and rewetting of organic soils, while limiting the dependency on imports.
- The LULUCF sinks need to be increased to offset unavoidable GHG emissions. This means that afforestation should not be counteracted by increased harvest rates. Such transitions in land use need to be well managed and consider other ecosystem services.
- Proper waste management needs to be implemented to quickly reduce landfills with their associated emissions. Recycling rates must be increased to the largest possible extent.

GHG-neutral EU2050 paints one possible picture of how to arrive at an EU with net zero GHG emissions. However, there are different options for how this can be achieved, e.g. concerning th the use of novel fuels vs. biogenic fuels and the extent of lifestyle changes vs. electrification vs. use of renewable fuels. In comparison with other scenarios, the GHG-neutral EU2050 scenario is at the very high end with regard to electrification, and even more so with regard to the use of novel fuels. This is due to the fact that the scenario focuses on the technical feasibility of net-zero GHG emissions under limited biomass availability and current sectoral demand trends. The use of novel fuels is increased even more by the fact that the scenario considers feedstocks and international shipping. Supplying such huge amounts of novel fuels will pose extensive requirements with regard to infrastructure scale-up and investments. These requirements can be significantly reduced if the remaining leeway across all energy-related sectors is exploited, in particular with regard to reducing the demand in air transportation, and implementing a circular economy to the largest possible extent, especially a cascading use of wood and chemical feedstocks. These aspects need to be explored in future research. Finally, this study focused on an EU with net-zero GHG emissions in 2050 and not on the pathways leading to this. In particular, cost considerations and infrastructure lock-ins played only a minor role. A detailed exploration of the possible pathways to reach a GHG-neutral EU also remains a task for future research.

Zusammenfassung

Einleitung und Zielsetzung

Mit der Ratifizierung des Übereinkommens von Paris (ÜvP) muss die EU ihr derzeitiges langfristiges Ziel zur Minderung aller Treibhausgasemissionen (THG-Emissionen) von minus 80-95% gegenüber 1990 überdenken. Denn das ÜvP zielt nicht nur darauf ab, den Temperaturanstieg deutlich unter 2°C zu halten und wenn möglich sogar auf 1,5°C zu begrenzen, sondern sieht auch vor, dass in der zweiten Hälfte des 21. Jahrhunderts ein Gleichgewicht zwischen Senken und Quellen anthropogener THG-Emissionen (THG-Neutralität) erreicht werden soll (UNFCCC 2015). Die große Herausforderung der kommenden Jahre und Jahrzehnte besteht darin, die Umsetzung dieser Ziele weltweit voranzutreiben. Die Entwicklung von Zielvisionen treibhausgasneutraler Volkswirtschaften, die Analyse solcher Visionen sowie die Erkundung von Entwicklungspfaden, die zu den geforderten Emissionsverläufen führen, sind wichtige Elemente einer Klimapolitik, die darauf abzielt, die langfristigen Minderungsziele zu erreichen. Dies bildet die Grundlage für die Entwicklung geeigneter politischer Strategien und Politikinstrumente.

Ziel dieser Studie ist es, ein Szenario *THG-neutrale EU2050* für den Zeithorizont 2050 vorzulegen, in welchem sich Treibhausgasemissionen und –senken ausgleichen. Der Ansatz dieser Studie baut auf der UBA-Studie „Treibhausgasneutrales Deutschland im Jahr 2050“ auf (UBA 2013). Im Gegensatz zu anderen Szenario-Studien steht neben der quantitativen auch die qualitative Analyse eines emissionsarmen Szenarios für die EU im Vordergrund. Zu diesem Zweck wurde eine detaillierte Untersuchung der wichtigsten Sektoren gemacht und die verschiedenen technologischen Optionen wurden miteinander verglichen. Auf diese Weise wurde eine systematische Bewertung der Optionen für eine THG-neutrale EU erstellt, die dazu beitragen soll, die weiteren Diskussionen auf EU-Ebene zu strukturieren. Darüber hinaus legt die Studie übergreifende Überlegungen dar, die eine Beurteilung ermöglichen sollen, ob die Analysen der verschiedenen Einzelsektoren in sich schlüssig sind, insbesondere im Kontext der sehr weitreichenden Reduzierung der gesamten THG-Emissionen.

Ansatz und Methode

Die Methodik zur Entwicklung des Szenarios *THG-neutrale EU2050* folgte einer Reihe von Paradigmen:

- **Bottom-up-Szenarioentwicklung**: Um das Szenario *THG-neutrale EU2050* zu entwickeln, wurden eine Reihe von Minderungsoptionen in allen THG-relevanten Sektoren untersucht (einschließlich aller energiebedingten Emissionen, sowie nicht-energiebezogene Emissionen aus Industrie, Landwirtschaft, Abfall sowie Landnutzung, Landnutzungsänderung und Forstwirtschaft (LULUCF)).
- **Analytische Ansätze**: Je nach Daten- und Modellverfügbarkeit wurden unterschiedliche analytische Ansätze angewandt. Dazu gehörten Projektionen auf der Grundlage von Dekompositionsanalysen, Projektionen auf der Basis von Modellergebnissen und die Modellierung ganzer Sektoren. Diese Heterogenität ermöglichte es, die auf Sektorebene verfügbaren Informationen optimal zu nutzen, führte aber auch zu unterschiedlichen analytischen Detaillierungsgraden in den einzelnen Sektoren.
- **Endpunkt-Szenario**: Das Szenario konzentriert sich ausschließlich auf die Beschreibung der Situation im Jahr 2050 (oder einem Jahr nahe 2050, das als Endpunkt betrachtet wird). Eine

Beschreibung der möglichen Pfade, die zu diesem Endpunkt führen, war nicht Teil des Projekts.

- **Sektorübergreifende Harmonisierung**: Trotz des Bottom-up-Ansatzes und der Heterogenität der angewandten analytischen Ansätze war es eine der zentralen Zielsetzungen, ein konsistentes Szenario zu entwickeln. Daher wurde das in diesem Bericht vorgestellte Szenario in einem rekursiven Ansatz erstellt, der aus sektorübergreifenden Workshops, sektoralen Analysen und sektorübergreifenden Analysen bestimmter Aspekte wie der Verfügbarkeit von Biomasse besteht.
- **Regionale Disaggregation**: Während sich das in diesem Bericht dargestellte Szenario auf aggregierte Ergebnisse für die EU28 (einschließlich des Vereinigten Königreichs) konzentriert, verwenden die zugrundeliegenden Branchenmodelle soweit möglich Daten der einzelnen Mitgliedstaaten. Dazu gehören unter anderem Unterschiede in der Branchenstruktur, die Nutzung von Biomasse und Fernwärmenetzen im Gebäudebereich oder die Elektrifizierung der Bahn im Verkehrsbereich.

Die wichtigsten Datenquellen für das Szenario sind:

- die THG-Inventare der EU und der Mitgliedstaaten ab 2015 (UNFCCC 2017)
- die Energiebilanzen der einzelnen Mitgliedstaaten gemäß den Angaben von Eurostat für das Jahr 2015 (EUROSTAT 2017)
- die EU-Referenzszenarien für die Europäische Kommission (EU KOM 2016), um einen konsistenten Datensatz über die wichtigsten Treiber (Bruttoinlandsprodukt (BIP), Bevölkerung und sektorspezifische Treiber in allen Mitgliedstaaten bereitzustellen.

Darüber hinaus wurden bei Bedarf branchenspezifische Datensätze integriert. Einzelheiten zu den sektorspezifischen Modellierungsansätzen und Daten finden sich im separat veröffentlichten technischen Anhang zu dieser Studie (Duscha et al. 2019).

Das Szenario *THG-neutrale EU2050* basiert auf einer Reihe von Annahmen und Projektionen für die Entwicklung der zentralen Treiber:

- **Energieeffizienzmaßnahmen:** Im Gegensatz zu heute werden die THG-Emissionen in einem vollständig dekarbonisierten Energiesystem von Effizienzmaßnahmen nicht reduziert, weil die gesamte Energie ohne damit verbundene CO_2-Emissionen bereitgestellt werden kann. Dennoch spielen Energieeffizienzmaßnahmen in einem Dekarbonisierungsszenario eine wichtige Rolle, da sie die Menge an CO_2-neutraler Energie, die bereitgestellt werden muss, und damit die Gesamtkosten der Energieversorgung reduzieren. Deshalb basiert das Szenario *THG-neutrale EU2050* auf ambitionierten Effizienzannahmen in allen Sektoren.
- **Machbarkeit:** Das Szenario *THG-neutrale EU2050* konzentriert sich auf die Machbarkeit unter technologischen und bestimmten wirtschaftlichen Zwängen, z. B. den Bedarf an unterschiedlichen Qualitäten von Zement und Stahl. Das Szenario *THG-neutrale EU2050* beruht daher nicht auf wirtschaftlicher Optimierung, sondern verwendet unterschiedliche analytische Ansätze (siehe oben) und Expertenwissen, um ein konsistentes Set an

emissionsarmen Technologien zur vollständigen Substitution fossiler Technologien zu finden. Die Rolle von politischen Instrumenten und Maßnahmen, die z. B. einen ausreichend hohen Preis für Kohlenstoffemissionen setzen, wird im Rahmen dieser Studie nicht betrachtet.

- **Änderungen des Verbrauchs**: Bei der Auswahl von Minderungsoptionen liegt der Fokus des Szenarios auf Maßnahmen in den Bereichen Effizienz und Konsistenz. Änderungen der Zusammenstellung und des Verbrauchsniveaus durch Suffizienz-Maßnahmen oder wirtschaftliche Reaktionen auf Preisänderungen, die sich aus der technischen Transformation und insbesondere Verhaltensänderungen ergeben, werden weitgehend nicht berücksichtigt. Das Szenario weicht von dieser Richtlinie in den Bereichen ab, in denen die Ziele nicht allein durch technische Mittel erreicht werden können (Landwirtschaft/Lebensmittel und Abfallwirtschaft).

- **Verfügbarkeit von Technologien:** Das Szenario *THG-neutrale EU2050* zeigt eine moderat optimistische Einstellung gegenüber der Verfügbarkeit von Technologien. Technologien werden berücksichtigt, die zumindest in einem industriell relevanten Umfeld validiert wurden (TRL5 oder höher [4]). Dies bedeutet, dass hoch innovative Technologien im Labormaßstab nicht berücksichtigt werden. Darüber hinaus werden auch Technologien ausgeschlossen, die in Bezug auf Nachhaltigkeit erhebliche Einschränkungen aufweisen. Dies gilt insbesondere für den Bau neuer Kernkraftwerke und den Einsatz von CO_2-Abscheidung und -Speicherung (CCS).

- **Biomasse und strombezogene Energieträger (erneuerbare Brennstoffe)**: Die Anforderungen an die Speicherfähigkeit von Strom und die Energienutzung in nicht-stationären Anwendungen führen dazu, dass die vollständige Elektrifizierung technisch schwierig oder nur mit sehr hohen Kosten möglich ist. Aus diesem Grund untersucht die Studie die Möglichkeit zur Verwendung *erneuerbarer Brennstoffe*, d.h. biogener Energieträger oder *neuartiger Brennstoffe*, d.h. strombasierte Energieträger. Die für Energiezwecke verfügbare Biomasse beschränkt sich jedoch auf Abfälle und Reststoffe; der Anbau von Energiepflanzen und der Import von Biomasse sind ausgeschlossen.

Hauptergebnisse

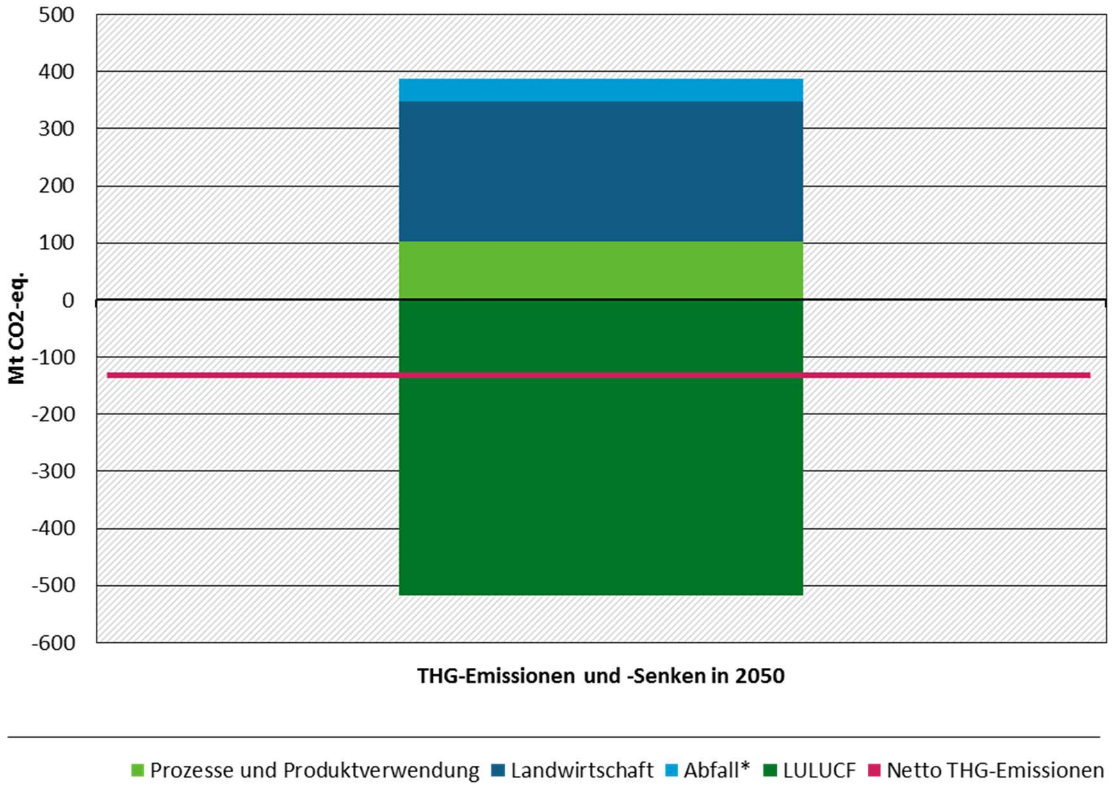
Die zentrale Zielsetzung dieser Studie ist es, ein Szenario für eine EU mit Netto-Null-THG-Emissionen bis 2050 unter zusätzlichen Nachhaltigkeitseinschränkungen, z. B. in Bezug auf Biomasse und Kernkraft, zu erstellen. Insbesondere entspricht das Szenario dem in Artikel 4 des ÜvP (UNFCCC 2015) geforderten Ausgleich der THG-Emissionen und –Senken und dem in der strategischen Vision der EU-Kommission „Ein sauberer Planet für alle" vorgeschlagenen Ziel (EU KOM 2018a).

Das Szenario *THG-neutrale EU2050* erreicht dieses Ziel, indem es die THG-Emissionen über alle Sektoren hinweg soweit wie technisch möglich reduziert, und die verbleibenden THG-Emissionen durch ausreichende CO_2-Senken im LULUCF-Sektor ausgleicht. Genauer gesagt, beschreibt das Szenario eine detaillierte, tragfähige Struktur in allen THG-Emissionssektoren einschließlich Landwirtschaft, Abfall und internationalen Bunkertreibstoffen, die in der Lage ist,

[4] siehe ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf für eine Definition von TRLs (technology readiness levels)

alle sechs Kyoto-Treibhausgasgase bis zum Jahr 2050 auf 387 Mio. t CO_2-Äquivalent (ohne den LULUCF-Sektor) zu reduzieren. Dies entspricht eine Minderung um 93% gegenüber dem Stand von 1990 (-92% gegenüber 2015). Darüber hinaus kompensiert das Szenario die verbleibenden THG-Emissionen, indem es die Netto-CO_2-Senke im LULUCF-Sektor auf 518 Mio. t CO_2-Äq. erhöht. Damit können im LULUCF-Sektor mit rund 131 Mio. t CO_2-Äq. mehr festgelegt werden als die verbleibenden THG-Emissionen (siehe Abbildung S4).

Abbildung S4: THG-Emissionen und -Senken in der EU im Szenario *THG-neutrale EU2050*



* einschließlich Abfallverbrennung mit Energierückgewinnung
Quelle: eigene Berechnung (Fraunhofer ISI und Öko-Institut)

Alle energiebedingten THG-Emissionen im Energiesektor, im Industriesektor, im Verkehrssektor, im Haushaltssektor und im Dienstleistungssektor werden weitestgehend reduziert, insbesondere durch die vollständige Vermeidung der Verwendung fossiler Brennstoffe. Es bleiben nur noch THG-Emissionen von 13 Mio. t CO_2-Äq., die aus der Verbrennung nichtbiogener Abfälle stammen (siehe Table S1). Um dies zu erreichen, wird ein breites Portfolio von Minderungsoptionen eingesetzt, wobei der Fokus in den verschiedenen Sektoren unterschiedlich ist. Einzelheiten zu den Veränderungen in Energiebedarf und –angebot sind in Tabelle S2 dargestellt.

Für die industrielle Prozess- und Produktnutzung verbleiben THG-Emissionen von 103 Mio. t CO_2-Äq., was einer Reduktion um nur 80% gegenüber 1990 entspricht. Die verbleibenden THG-Emissionen können jedoch nicht unter den Annahmen vom Szenario *THG-neutrale EU2050* gemindert werden, die sehr ambitioniert sind, aber auch weitere Nachhaltigkeitskriterien als den Klimawandel berücksichtigen. Die verbleibenden Prozessemissionen könnten erheblich reduziert werden (wenn auch nicht auf Null), wenn CCS bei der Zementherstellung eingesetzt würde. Dies wird nicht im Detail berücksichtigt, weil das Ziel der THG-Neutralität im Jahr 2050 ohnehin erreicht werden kann.

Im Vergleich zu 1990, ist die THG-Minderung in der Landwirtschaft noch geringer, nämlich 55%. Dies spiegelt die unvermeidbaren THG-Emissionen aus der Landnutzung und der Tierhaltung wider. Das Szenario *THG-neutrale EU2050* geht bereits von einer Halbierung der Großvieheinheiten aus ernährungswissenschaftlichen Gründen aus[5]. Jede weitere Reduzierung der verbleibenden THG-Emissionen würde eine weitere Verschärfung dieser ohnehin ehrgeizigen Annahme erfordern.

Im Abfallsektor werden die Emissionen um fast 90% reduziert, indem die Abfallmengen verringert und die Verfahren der Abfallentsorgung geändert werden. Auch hier ist eine zusätzliche Reduzierung nur unter sehr starken Annahmen über das zukünftige Abfallaufkommen möglich. Schließlich werden die Treibhausgasemissionen aus internationalen Bunkertreibstoffen vollständig gemindert, indem die Umstellung von fossilen Brennstoffen auf *neuartige Brennstoffe* vollzogen wird, die ausschließlich mit erneuerbarem Strom hergestellt werden.

Der LULUCF-Sektor stellt bereits heute eine CO_2-Senke dar, mit einer jährlichen Abscheidung von 318 Mio. t CO_2-Äq. im Jahr 2015. Diese Senke wäre jedoch nicht ausreichend, um alle verbleibenden THG-Emissionen im Szenario *THG-neutrale EU2050* auszugleichen. Daher stellt das Szenario auch ein Modell für die Umwandlung des LULUCF-Sektors dar, mit dem die Treibhausgassenke auf 518 Mio. t CO_2-Äq. in 2050 erweitert werden kann.

Tabelle S2: THG Emissionen der EU in den Jahren 1990, 2015 & im Szenario *THG-neutrale EU2050*

	UNFCCC 1990 [Mio. t CO_2-Äq.]	UNFCCC 2015 [Mio. t CO_2-Äq.]	THG-neutrale EU2050 [Mio. t CO_2-Äq.]	Minderung gegenüber 1990 [-]
Energiebedingt	4.351	3.371	13	-100%
Industrielle Prozesse und Produktnutzung	517	377	103	-80%
Landwirtschaft	542	429	245	-55%
Abfall	236	141	26	-89%
Internationale Bunker	180	282	0	-100%
SUMME ohne LULUCF	**5.826**	**4.600**	**387**	**-93%**
LULUCF	-260	-318	-518	N/A
SUMME mit LULUCF	**5.566**	**4.282**	**-131**	**-102%**

Quelle: UNFCCC 2017 und eigene Berechnung (Fraunhofer ISI und Öko-Institut)

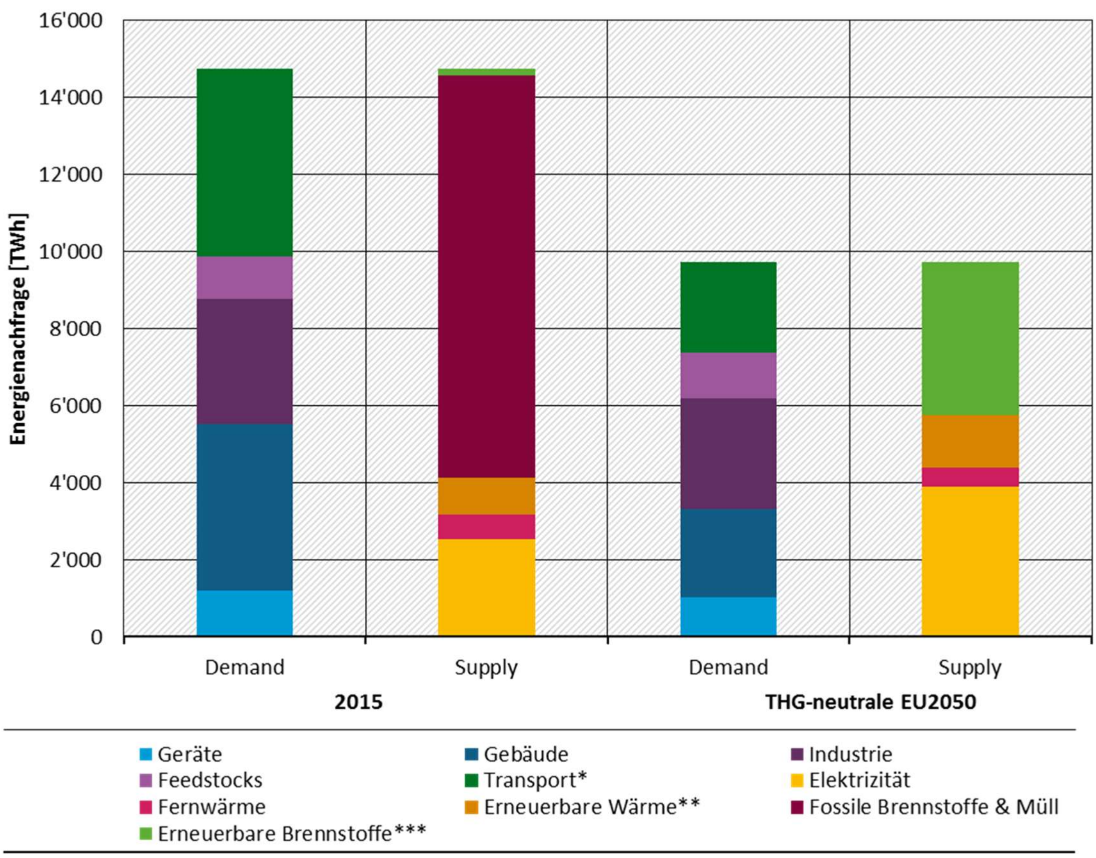
Weitere Einzelheiten zu den sektoralen THG-Emissionen finden sich in den Branchenbeschreibungen im Abschnitt 5 dieser Studie und im separat veröffentlichten technischen Anhang (Duscha et al. 2019).

[5] Es wird angenommen, dass der menschliche Ernährungsbedarf im Durchschnitt den Empfehlungen der Weltgesundheitsorganisation entspricht, mit einer Reduzierung des Pro-Kopf-Proteinverbrauchs auf 50g/Tag.

Heute dominieren die energiebedingten THG-Emissionen die gesamten Treibhausgasemissionen der EU mit einem Anteil von 78% im Jahr 2015. Die Transformation des EU-Energiesystems ist daher der Schlüssel zur Realisierung einer THG-neutralen EU. Das bedeutet einerseits, den Energiebedarf über alle energieverbrauchenden Sektoren hinweg so weit wie möglich zu begrenzen und andererseits den daraus resultierenden Bedarf mit nichtfossilen Energieträgern zu decken, insbesondere mit erneuerbaren Energieträgern unter Berücksichtigung der oben genannten Einschränkungen bei Kernenergie und CCS.

Im Szenario *THG-neutrale EU2050* wird der Endenergiebedarf um rund ein Drittel verringert, von ungefähr 14.700 TWh im Jahr 2015[6] auf circa 9.700 TWh im Jahr 2050 (einschließlich des nicht-energetischen Primärenergieverbrauchs sowie internationaler Luft- und Schifffahrt), siehe Abbildung S5. Die größten Nachfragerückgänge finden im Verkehrs- und Gebäudesektor mit 52% bzw. 47% statt und sind auf wesentlich energieeffizientere Fahrzeuge und Gebäude sowie eine starke Elektrifizierung in beiden Bereichen zurückzuführen. Allmähliche Effizienzsteigerungen senken den Energiebedarf von Industrie und Geräten um 12% bzw. 14%, während sich der Nichtenergetische Primärenergiebedarf für industrielle Rohstoffen aufgrund eines leichten Produktionsanstiegs, insbesondere in der Chemie, sogar um 6% erhöht.

Abbildung S5: Endenergiebedarf der EU im Jahr 2015 und im Szenario *THG-neutrale EU2050*



* einschließlich internationaler Luft- und Schifffahrt; ** einschließlich Biomasse mit Ausnahme von Biokraftstoffen in 2015; *** ausschließlich Biomasse mit Ausnahme von Biokraftstoffen in 2015
Quelle: eigene Berechnung auf Basis von EUROSTAT (2017)

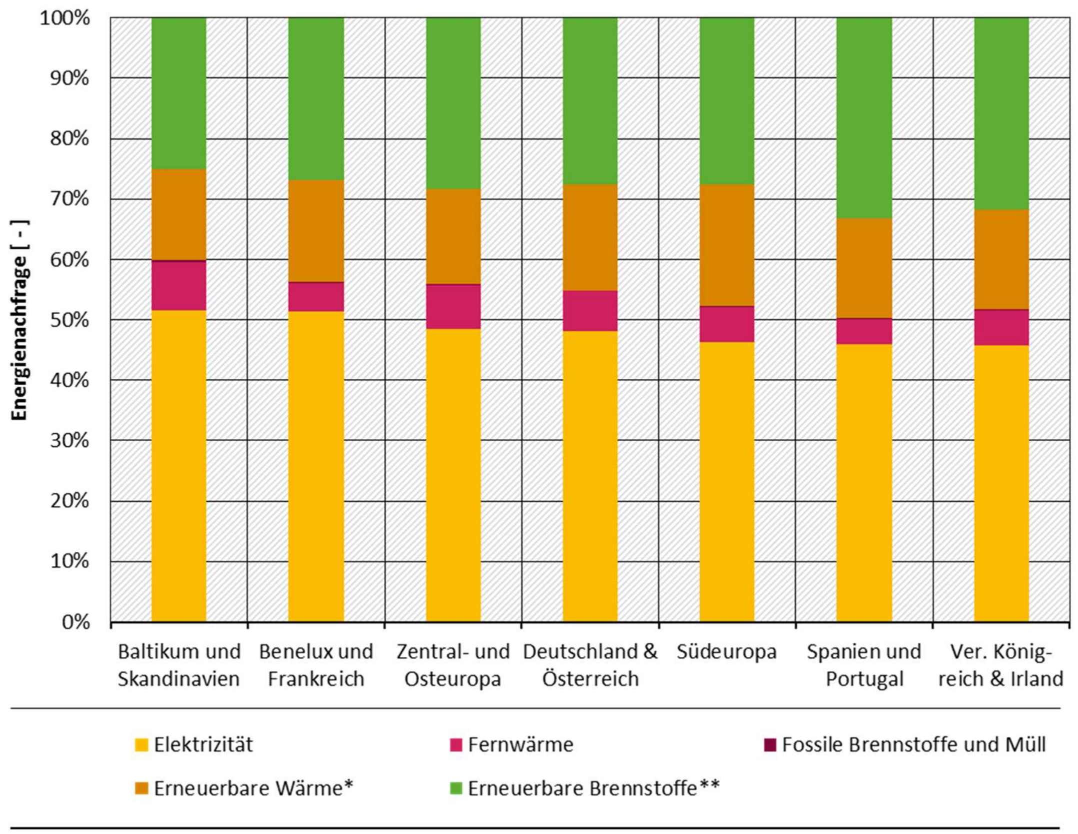
Die Reduzierung der energiebedingten THG-Emissionen um 100% wird ferner durch die vollständige Substitution fossiler Brennstoffe, deren Anteil am Energiemix im Jahr 2015 mehr als 79% betrug, durch Strom, Fernwärme, EE-Wärme (Umgebungswärme, Solarthermie und

[6] Auch ohne internationale Schifffahrt ist der Endenergiebedarf nach EUROSTAT (2017) um etwa 3% niedriger. Dies ist vor allem dadurch begründet, dass die offizielle Statistik keine Klimakorrektur enthält.

Bioenergie) und *erneuerbare Brennstoffe* (bestehend aus *neuartigen Brennstoffen*, d.h. Wasserstoff und synthetischen Kohlenwasserstoffen, sowie biogenen Brennstoffen) erreicht. Die einzigen verbleibenden Emissionen stammen aus der Verbrennung unvermeidlicher, nicht erneuerbarer Abfälle. Die starke Elektrifizierung über alle energieverbrauchenden Sektoren hinweg führt zu einem Anstieg des Endstrombedarfs um 53% gegenüber 2015 und erhöht damit seinen Anteil am Energiemix von 17% auf 40% (fast 50% ohne Rohstoffe). Die Fernwärmenutzung erhöht sich nur geringfügig von 4% auf 5%, während sich der Anteil der EE-Wärme von 7% auf 14% verdoppelt. Der verbleibende Kraftstoffbedarf, der hauptsächlich aus dem internationalen Verkehr, der Industrie und den industriellen Rohstoffen stammt, wird durch *neuartige Brennstoffe* gedeckt, die 2050 einen Anteil von 41% erreichen (32% ohne Rohstoffe) verglichen mit 1%, die 2015 durch Biokraftstoffe gedeckt wurden.

Da Strom und erneuerbare Brennstoffe zusammen 80% des Endenergiebedarfs im Jahr 2050 decken, bilden sie das Rückgrat der Energieversorgung im Jahr 2050. Hauptenergiequellen für die Stromerzeugung sind Onshore- und Offshore-Windkraftanlagen sowie die Solarenergie aus Photovoltaikanlagen. Die verbleibenden Kernkraftwerke liefern nur 33 TWh des Strombedarfs. Darüber hinaus besteht ein zusätzlicher Bedarf an *erneuerbaren Brennstoffen* von rund 300 TWh für die Stromerzeugung, um die schwankende Stromerzeugung aus Wind- und Sonnenenergie auszugleichen. 70% dieser *erneuerbaren Brennstoffen* werden (im Bezug auf den Endenergiebedarf) aus erneuerbarem Strom und nur 30% aus nachhaltiger Biomasse hergestellt. Das bedeutet, dass die Produktion von Strom und *neuartigen Brennstoffen* stark miteinander verbunden ist. Insbesondere wenn keine *neuartigen Brennstoffe* importiert werden, führt dies zu einem starken Anstieg des gesamten Strombedarfs. Das Szenario *THG-neutrale EU2050* berücksichtigt regionale Unterschiede in der Struktur des Energiebedarfs (siehe Abbildung S6).

Abbildung S6: Regionaler Energiemix im Szenario *THG-neutrale EU2050*



* einschließlich dezentraler Biomassenutzung; ** ohne nicht-energetischen Primärenergiebedarf
Quelle: eigene Berechnung auf Basis von EUROSTAT (2017)

Zusammenfassend zeigt sich, dass sich die resultierenden regionalen Energiemixe im Jahr 2050 nicht mehr stark unterscheiden, da es einerseits eine hohe Elektrifizierung in allen Sektoren und Regionen gibt und andererseits *erneuerbare Brennstoffe* in allen Regionen für Teile der Hochtemperaturwärme und zum Ausgleich saisonaler Schwankungen bei der erneuerbaren Stromerzeugung benötigt werden.

Schlussfolgerungen

Da die Frage, wie eine EU mit Netto-Null-THG-Emissionen gestaltet werden kann, ein relativ neues Thema ist, zielte diese Studie darauf ab, ein Szenario *THG-neutrale EU2050* zu entwerfen, wie ein Ausgleich der THG-Emissionen und -Senken in der EU unter weiteren Nachhaltigkeitskriterien herzustellen ist. Das erstellte Szenario zeigt, dass eine THG-neutrale EU auch ohne den Einsatz von CCS und mit begrenzten Mengen an Bioenergie erreichbar ist. Aufgrund der unvermeidbaren THG-Emissionen aus Landwirtschaft, Industrieprozessen und Abfallbehandlung erfordert die THG-Neutralität jedoch eine geringere Aktivität des Agrarsektors und eine erhöhte THG-Senke im LULUCF-Sektor. Das Szenario *THG-neutrale EU2050* zeigt, dass dies durch die Halbierung der Großvieheinheiten und durch die Erhöhung der Landnutzungssenke auf mehr als 500 Mio. t CO_2 über die Bereitstellung größerer Landflächen für die Forstwirtschaft machbar ist.

Wesentliche Bestandteile des Szenarios in allen energieverbrauchenden Sektoren (Industrie, Gebäude und Verkehr) sind eine starke Steigerung der Energieeffizienz sowie eine weitreichende Elektrifizierung. Dazu gehört insbesondere die Elektrifizierung großer Teile des Straßenverkehrssektors und Wärmepumpen für die dezentrale und die zentrale Wärmebereitstellung. Durch diese Maßnahmen kann der Endenergiebedarf (einschließlich des internationalen Verkehrs) um etwa 37 % auf circa 8.500 TWh gesenkt, und der Anteil des Stroms auf fast 50 % erhöht werden. Darüber hinaus muss ein breites Portfolio anderer erneuerbarer Energieoptionen ausgenutzt werden, und es werden *erneuerbare Brennstoffe* in einer Größenordnung von 3.500 TWh benötigt, die aus erneuerbarem Strom durch Elektrolyse oder auf Biomassebasis hergestellt werden (4.750 TWh einschließlich nicht-energetischem Primärenergiebedarf). Wenn diese *neuartigen Brennstoffe* im Inland produziert werden, würde dies den Strombedarf um 250 % erhöhen. Da dies im Widerspruch zu Fragen der sozialen Akzeptanz stehen kann, kann die Einfuhr *neuartiger Kraftstoffe*, insbesondere in Form von Kohlenwasserstoffen, eine Schlüsselrolle bei der Realisierung eines Szenarios wie *THG-neutrale EU2050* spielen.

Die strategische Vision der Europäischen Kommission "Ein sauberer Planet für alle" beschreibt sieben Bausteine für Netto-Null-Treibhausgasemissionen in der EU: (1) Maximierung der Nutzung von Energieeffizienz, einschließlich Nullemissionsgebäude, (2) Maximale Nutzung von erneuerbaren Energien und von Strom für die vollständige Dekarbonisierung der Energieversorgung Europas, (3) saubere, sichere und vernetzte Mobilität, (4) eine wettbewerbsfähige EU-Industrie und eine Kreislaufwirtschaft, (5) Entwicklung einer adäquaten intelligenten Netzinfrastruktur und von Netzverbindungen, (6) Vollen Nutzen aus der Bioökonomie ziehen und essentielle CO_2-Senken schaffen, und (7) Beseitigung der verbleibenden CO_2-Emissionen durch CO_2-Abscheidung und Speicherung.

Die ersten fünf Bausteine entsprechen im Allgemeinen den Schlüsselkomponenten vom Szenario *THG-neutrale EU2050*, wobei der Fokus in einigen Sektoren und Minderungsoptionen etwas unterschiedlich sein kann. Für die beiden letztgenannten Bausteine gibt es jedoch erhebliche Unterschiede. Der sechste Baustein überschneidet sich teilweise mit den Hauptlinien des LULUCF-Sektors in *THG-neutrale EU2050*, unterscheidet sich aber im Hinblick auf die Rolle von Bioenergie, die in *THG-neutrale EU2050* stark eingeschränkt ist. Die Unterschiede sind noch größer hinsichtlich des siebten Bausteins. Während das Szenario *THG-neutrale EU2050* zeigt, dass eine THG-neutrale EU ohne den Einsatz von CCS realisiert werden kann, weist der letzte Baustein der strategischen Vision der EU-Kommission CCS eine zentrale Rolle zu. Ein besseres Verständnis dieser Diskrepanz wird für die Ableitung einer sinnvollen langfristigen Strategie zur Förderung der strategischen Vision der EU-Kommission von wesentlicher Bedeutung sein. Das Szenario *THG-neutrale EU2050* liefert diesbezüglich wichtige Erkenntnisse.

Derzeit ist die EU auf dem besten Weg, ihr Ziel für 2020, die THG-Emissionen um 20% zu senken, zu erreichen und es sind EU-Direktiven in Kraft getreten, die mit dem für 2030 angestrebten Ziel einer THG-Minderung von 40% vereinbar sind, auch wenn sie in den Mitgliedstaaten noch nicht umgesetzt wurden (EU KOM 2018b). Keiner der Sektoren ist jedoch auf dem Weg, das THG-Reduktionsziel von 80 bis 95% für 2050 zu erreichen. Die Realisierung des Szenarios *THG-neutrale EU2050* erfordert enorme Anstrengungen, die weit über die Herausforderungen bei der Erreichung von den kurzfristigen Klimazielen in 2020 und 2030 hinausgehen:

- Die Infrastrukturentwicklung muss EU-weit harmonisiert werden. Dazu gehören Strom- und Gasnetze, aber auch die Verkehrsinfrastruktur, welche die Marktdurchdringung von Elektrofahrzeugen ermöglicht, einschließlich EU-weiter Oberleitungen für den Güterverkehr. Alle diese Maßnahmen erfordern ein frühzeitiges und abgestimmtes multilaterales Vorgehen, um die erforderliche Infrastruktur bereitzustellen.

- *Erneuerbare Brennstoffe* liefern erhebliche Mengen an Energie für den Verkehr, bestimmte Industriezweige und Gebäude. Deshalb müssen Anstrengungen unternommen werden, *erneuerbare Brennstoffe* auf den Markt zu bringen. Da die Nutzung von Biomasse für ihre Synthese eine sehr begrenzte Option ist, besteht ein großer Bedarf an Kapazitätserweiterungen für die Herstellung und/oder den Import von strombasierten *neuartigen Brennstoffen*.

- Die Energieeffizienzstandards für Gebäude, Heizungsanlagen, Geräte und Fahrzeuge müssen äußerst ambitioniert sein. Um eine Reduzierung der Energieintensität zu erlangen, die dem Szenario *THG-neutrale EU2050* entspricht, ist es unerlässlich sicherzustellen, dass Sanierungen den höchsten Gebäudeeffizienzstandards entsprechen und dass Maßnahmen ergriffen werden, um die Sanierungsrate erheblich zu vergrößern. Um die Nachfrage im Verkehrssektor zu senken, müssen monetäre und regulatorische Anreize für eine Wirtschaft der kurzen Wege und für die erhöhte Nutzung des öffentlichen Verkehrs geschaffen werden.

- In der Industrie sind radikale Innovationen notwendig, insbesondere bei der Stahl- und Zementherstellung. In den kommenden zehn Jahren müssen neue emissionsfreie oder emissionsarme Prozesse entwickelt, hochskaliert und gefördert werden, um deren Marktreife bis 2030 zu ermöglichen. Diese neuen Prozesse müssen dann schnell in der Industrie ausgerollt werden.

- Maßnahmen zur Reduzierung des Verbrauchs von Milch- und Fleischprodukten sind erforderlich, um die THG-Emissionen der Landwirtschaft zu begrenzen. Diese Reduzierung ermöglicht eine Zunahme des ökologischen Landbaus, der Aufforstung und der Wiedervernässung von organischen Böden bei gleichzeitiger Begrenzung der Importabhängigkeit.

- Die LULUCF-Senken müssen erhöht werden, um die unvermeidlichen THG-Emissionen auszugleichen. Das bedeutet, dass eine Aufforstung nicht mit höheren Erntequoten einhergehen darf. Solche Übergänge in der Landnutzung müssen gut gesteuert und dabei andere Ökosystemleistungen berücksichtigt werden.
- Eine Abfallwirtschaft muss eingeführt werden, welche die Deponierung und die damit verbundenen Emissionen schnell reduziert. Die Recyclingquoten müssen so weit wie möglich erhöht werden.

Das Szenario *THG-neutrale EU2050* zeichnet ein konkretes Bild einer EU mit Netto-Null-THG-Emissionen. Dennoch besteht in Bezug auf bestimmte Aspekte des Szenarios ein erheblicher Spielraum, unter anderem bei der Verwendung *neuartiger Brennstoffe* vs. biogener Kraftstoffe und bei dem Ausmaß der Lebensstiländerungen vs. Elektrifizierung vs. Einsatz erneuerbarer Brennstoffe. Im Vergleich zu anderen Szenarien liegt das Szenario bei der Elektrifizierung am äußersten Rand, und noch mehr bei der Verwendung *neuartiger Brennstoffe*. Dies ist darauf zurückzuführen, dass sich das Szenario auf die technische Machbarkeit von Netto-Null-THG-Emissionen bei begrenzter Biomasseverfügbarkeit und den aktuellen Trends für die sektoralen Anforderungen konzentriert. Der Einsatz *neuartiger Brennstoffe* wird noch verstärkt durch die Tatsache, dass das Szenario den nicht-energetischen Primärenergiebedarf der Industrie und den internationalen Transport berücksichtigt. Die Bereitstellung so großer Mengen an *neuartigen Brennstoffen* wird hohe Anforderungen an Infrastrukturausbau und -investitionen stellen. Diese Anforderungen können erheblich reduziert werden, wenn der verbleibende Spielraum in allen energiebezogenen Sektoren voll ausgenutzt wird, insbesondere im Hinblick auf eine Verringerung der Nachfrage im Luftverkehr, und die weitestgehende Umsetzung einer Kreislaufwirtschaft, insbesondere eine Kaskadennutzung von Holz und chemischen Grundstoffen. Diese Aspekte sollten in zukünftiger Forschung weiter untersucht werden. Schließlich lag das Augenmerk dieser Studie auf eine EU mit Netto-Null-Treibhausgasemissionen im Jahr 2050 und (fast) gar nicht auf den Pfaden, die zu diesem Ziel führen könnten. Insbesondere Kostenüberlegungen und *Infrastruktur-Lock-Ins* haben nur eine untergeordnete Rolle gespielt. Eine detaillierte Untersuchung der möglichen Pfade zur Erreichung einer TGH-neutralen EU bleibt auch eine Aufgabe für die zukünftige Forschung.

1 Introduction – towards a GHG-neutral EU in 2050

With the EU's ratification of the Paris Agreement, its current long-term greenhouse gas (GHG) mitigation target of minus 80-95% compared to 1990 needs to be reconsidered, as the Paris Agreement not only aims at holding the temperature increase well below 2°C, if possible even limit it to 1.5°C, but also stipulates that a balance between sinks and sources of anthropogenic greenhouse gas emissions ("GHG neutrality") is to be achieved in the second half of the 21st century (UNFCCC 2015). To tackle the target of net decarbonisation, the European Commission (EC) has recently published its Strategic Vision "A clean planet for all" (EU COM 2018a), which calls for net-zero GHG emissions in the EU in 2050 and describes central building blocks to achieve this target.

At the national level, some European countries have carried out initial analyses investigating the goal of a GHG-neutral economy comprehensively and in detail. More recent work on Germany includes the Federal Environment Agency's (UBA) "Germany 2050: a Greenhouse-Gas Neutral Country" project (UBA 2013) and the Climate Protection Scenarios 2050 commissioned by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (Öko-Institute & Fraunhofer ISI 2015), which also includes an investigation of a pathway towards a 95% reduction in emissions relative to 1990 in Germany.

Other pioneering works have been the analyses initiated by non-governmental organisations, such as the "Pathways to deep decarbonisation" in which decarbonisation pathways (with a focus on the energy system) are investigated for various countries worldwide (see e.g. Virdis et al. 2010) or the "energy [r]evolution" studies initiated by Greenpeace (cf. Greenpeace 2013), which also create scenarios with 100% renewable energy supply for various countries and regions. Similar work is also available for other European countries, see. e.g. the Energy Scenario for Sweden 2050 (Gustavsson et al. 2011) and the Polish scenario study "2050.pl – the journey to the low-emission future" (Bukowski. et al. 2013).

In general, the comparison with older work on comparable objectives (e.g. the EC's Energy Roadmap 2050 (EU COM 2011)) makes clear that due to very dynamic technological and economic environments, the specification of strategies towards GHG neutrality can change considerably in a comparatively short period of time.

Most of the studies available so far focus on one country or one region (e.g. Scandinavia) without systematically investigating the feedback with other countries. However, this plays an important role especially in Europe's technically, economically and politically highly interconnected structures. Very recent exceptions are the scenario analysis underlying the EU Commission's Strategic Vision "A clean planet for all" (EU COM 2018b) and the study "Net-Zero by 2050: From Whether to How" (Climact 2018). Before, there were only the EU Energy [r]evolution study (Greenpeace 2013) as well as the EU low carbon roadmap and the EU Energy Roadmap 2050 (EU COM 2011). These studies formed the starting points for the development of a low-emission future scenarios for the EU. However, they lagged behind the depth of analysis that is achieved in more recent scenario studies. Additionally, some of these studies were prepared on the basis of data and knowledge that can no longer be considered up to date in some key areas (above all with regard to renewable energies, storage and flexibility options, electric mobility, efficiency technologies, grid infrastructures, but also nuclear energy and CCS).

Summarizing, there are only a few very recent studies on strategies for a GHG-neutral EU as a whole that outline a comprehensive picture of a GHG-neutral EU and can be used as a basis for further political processes and decisions. In addition, current studies such as the Climate Protection Scenario 2050 (Öko-Institut & Fraunhofer 2015) show that it is very relevant whether climate policy is geared towards an 80% or 95% GHG emission reduction target and whether the target under consideration is interpreted as an end point or whether the reduction has to go beyond the scenario in the later future.

The aim of this study is to provide a scenario GHG-neutral EU2050 for an EU with net-zero GHG emissions in 2050, based on the UBA study "Germany 2050: A Greenhouse Gas Neutral Country" (UBA 2013). Contrary to the other scenario studies, the focus is not mainly on the quantitative analysis but also on the qualitative analysis of a low emission scenario for the EU. To this end, the most relevant sectors were subject to a detailed analysis and the various corresponding technological options were compared with each other. In this way, the options for a GHG-neutral EU have been assessed systematically in order to help structure the further discussions at EU level. This is important in view of the fact that in many areas it is not yet possible from a technological point of view to make a definite decision which options will be the most advantageous. At the same time, this assessment of scenario spaces, taking GHG-neutrality as a goal, makes it possible to exclude pathways that do not lead to the achievement of a GHG-neutral EU in the longer term. In addition, the study contains integrated overall considerations that enable to judge whether the analyses of the various individual sectors are consistent even in the context of the very far-reaching reductions in total GHG emissions.

The following Section 2 presents lessons learnt from climate protection scenarios for the development of the scenario GHG-neutral EU2050. In Section 3, the approach, the methodology and the modelling paradigms of the scenario GHG-neutral EU2050 are described. Section 4 provides an overview of the scenario Low-Carbon-Europe 2050, which describes the remaining GHG emissions and sinks in the year 2050 as well as the corresponding energy demand and supply. Section 5 summarizes the results for each sector (energy supply, transport, industry, feedstocks, buildings and appliances, waste and wastewater, agriculture as well as land use, land use change and forestry) by describing the sectoral setup foreseen by the scenario GHG-neutral EU2050 and comparing it to today's situation. The corresponding full sector reports are part of the technical annex published separately (Duscha et al. 2019). Section 6 gives an overview of the main challenges presented in the scenario to all sectors. Section 8 summarizes and concludes.

2 Lessons learnt from climate protection scenarios

As a first step to develop the scenario GHG-neutral EU2050, the range of existing scenarios has been carefully analyzed (Matthes et al. 2019). The analysis covered long-term baseline scenarios and long-term emission reduction scenarios for ambitious climate policy targets with a modelling horizon of 2050. The focus was set on scenarios for the EU, but climate protection scenarios for selected member states were also included, namely Germany, Italy, Sweden and Poland. Besides a general overview, this analysis served to identify important aspects for the development of the scenario GHG-neutral EU2050 and provides the context of the scenario developed within this project. The key lessons learned from the comparative analysis are summarized in the following paragraphs.

In general, there is a very limited number of scenarios that approach the goal of net-zero GHG emissions for the EU or one of its member states. Therefore, a scenario reaching this goal will provide further insights compared to other scenarios already published for the EU. This is particularly relevant for the partially unavoidable non-energy-related emission sources in agriculture, waste and possible emission sinks in the land use sector. It is also important for the transport and industry sector, where the majority of scenarios does not reach a complete mitigation of GHG emissions.

To provide a meaningful reference for the discussions under the Paris Agreement - i.e. aiming at net-zero GHG emissions around mid-century - the scenario needs to cover all sectors and relevant GHGs. This includes in particular methane and N_2O emissions from agriculture, where technological reduction options are limited and a significant amount of emissions will remain. It further needs to include the aviation and shipping sector, for which direct use of electricity is a mitigation option only to a limited extent and other options are needed such as GHG-neutral synthetic fuels or biofuels. Due to the persistence of the emission source, waste treatment is equally important to address, though emission levels are significantly lower compared to other sectors. The scenario also needs to include an assessment of sinks from land-use, land-use change and forestry.

While the strategy to mitigate GHG seems to be rather clear for some sectors, e.g. the electricity and transport sector, scenarios for other sectors, e.g. industry, still vary significantly, which indicates that different mitigation strategies may be possible. Focusing on these sectors with yet undecided mitigation strategies and assessing the different key strategies during the scenario development, taking into account interlinkages between sectors along with the European perspective can be a key contribution of the scenario GHG-neutral EU2050.

The assumptions made in the modelling process determine to a large extent the solution space and the final scenario. Underlying assumptions (e.g. use of CCS/exclusion of CCS, use of biomass, assumptions on main drivers such as GDP, production) should therefore be described transparently and well-argued.

The use of synthetic fuels in the transport and other sectors depends strongly on supply options of synthetic fuels. In contrast to the direct use of electricity, synthetic fuels production requires not only significantly higher electricity supplies, but also GHG-neutral carbon sources if it goes beyond the use of hydrogen. These challenges also need to be addressed transparently.

These lessons learnt provide the context for the approach and the methodology of the development of the scenario GHG-neutral EU2050 described in the next section.

3 Approach and methodology: scenario analysis for a GHG-neutral EU in 2050

3.1 Scenario development

The scenario GHG-neutral EU2050 describes a very ambitious climate protection scenario for the EU for the year 2050. The methodology for development of the scenario follows a number of paradigms.

Bottom-up scenario development: For the development of the scenario, the solution space in all GHG-relevant sectors was analysed (including all energy-related emissions, but also non-energy related emissions from industry, agriculture, waste and land-use, land-use change and forestry (LULUCF)). This bottom-up approach allowed to provide a detailed perspective on the individual sectors. At the same time, it results in a heterogeneity of analytical approaches taken between the different sectors.

Analytical approaches: Three analytical approaches can be distinguished:

- Tier 1 - projections based on decomposition analyses: The approach requiring the least data and time is a decomposition analysis of existing scenarios on the EU level. It is based on the identification of the most important drivers and the quantification of their effects on emissions. Based on projections of those drivers, future GHG emissions can be derived. Important drivers are in particular GDP, population, energy efficiency indicators or CO_2-intensity indicators. If values at EU level are not available, data for an individual MS can be adapted to derive EU-wide figures.
- Tier 2 - projections based on model results: More data and time intensive is the use of already existing model results to project an EU-wide scenario. Models and scenarios developed in the past can be used as a data base. In aggregated form, information on those scenarios can be used to develop a new scenario based on important drivers.
- Tier 3 - full modelling: Most resource intensive is the application of a detailed EU-wide bottom-up, techno-economic sector model. These models typically are partial-equilibrium optimization models, i.e. they provide a cost-optimal solution for the sector under certain conditions for the sectoral activity, technology costs and the sectoral GHG emissions.

Within this study, all three tiers have been applied, depending on the data and model availability. This heterogeneity of approaches on the one hand allowed to make best use of the information already available at the sector level (i.e. using models where they were available and suitable for the analysis) and not restricting the depth of analysis based on sectors for which the data base is least detailed. On the other hand, the approach also results in differences in the level of detail when analysing different sectors, enabling to answer certain questions for one sector, but not for all sectors and/or the scenario in general.

End-point scenario: The scenario purely focuses on the description of the situation in the year 2050 (or a year close to 2050 which is seen as an end-point) as a development of a pathway towards this endpoint was not part of the project. This setting has two implications for the scenario development:

- First, the definition of the target was as ambitious as possible as it shall not be seen as an interim target, but as a final target. Basis for the definition of the target is the 2015 Paris Agreement, which in particular calls for a global balance of GHG emission and sinks in the second half of the 21st century. Consequently this EU scenario is to reach a reduction of all six Kyoto greenhouse gases by 90 – 95% compared to 1990 levels by 2050 over all sectors including agriculture, waste and international bunker fuels, excluding the LULUCF sector. The remaining emissions are consequently to be compensated by a sufficiently large net-carbon sink from the LULUCF sector in order to reach net-zero GHG emissions in the EU.
- Second, the underlying sector models - independent of the level of detail used for the analysis – need to build on respective pathways to derive the endpoint in 2050. This approach ensures that - despite the assumptions on the transformation of the economy being highly ambitious - the final scenario considers technological restrictions and path dependencies. In some sectors, due to using pathways in the scenario development small residual quantities of fossil fuels were still part of the sector results (e.g. due to lifetime considerations). These residual quantities were in the end switched to *novel fuels* (independent of the type of fossil fuel) to derive at a fossil-fuel free energy mix.

Harmonization between sectors: Despite the bottom-up approach and the heterogeneity of the analytical approaches applied, it was one of the central points to develop a consistent scenario. Therefore, the scenario presented in this report was developed in three steps: first, a number of assumptions was made at the overall level and translated into assumptions for the different sectors. Those assumptions reduced the solution space for the scenario. In a second step, a scenario was specified for individual sectors. The scenario built on the assumptions from Step 1, including empirical experience from scenario development. In the third step, interaction between sectors, e.g. the demand for *novel fuels* or biomass was analysed from an overall perspective enabling to find a harmonized scenario over all sectors despite the bottom-up approach taken in the development.

Sector-coupling: A specific focus was put on sector-coupling, more specifically the use of electricity or electricity-based fuels in demand-side sectors. First, demand-side sector scenarios were developed in a way to use as much direct electricity as possible to limit the amount of *novel fuels* needed within the scenario. Second, demand for electricity-based fuels was collected from the demand-side sectors, but it was not decided on a sector level what type of electricity-based fuel that would be. Instead, the demand was subsumed under *novel fuels*. Part of the scenario development was to analyse these *novel fuels* in more detail, i.e. what types of fuels could be used over all sectors, how much electricity is needed for the production of the *novel fuels* and which share of *novel fuels* needs to be imported from outside of the EU.

Regionally disaggregated: While the scenario focuses only on aggregate results for the EU 28 (including the UK), the underlying sector models make use of individual Member State countries' data whenever possible. This allowed the integration of country-specifics in the scenario development that could have been lost otherwise, e.g. if the scenario was purely based on average EU 28 data sets. This includes, among others, differences in industry structure, use of biomass and district heating networks within the buildings sector or electrification of railways in the transport sector.

Details on the sector-specific modelling approaches can be found in the separately published technical annex to this study (Duscha et al. 2019).

3.2 Data sources

The main data sources used for the scenario are:

- the EU's and Member States' greenhouse gas inventories from 2015 (UNFCCC 2017)
- energy balances by individual Member States as provided by Eurostat for the year 2015 (EUROSTAT 2017)
- the EU reference scenarios for the European Commissions (EU COM 2016) for a consistent data set over all Member States on main drivers (gross domestic product (GDP), population and sector-specific drivers).

In addition, sector-specific data sets were included whenever necessary. They are listed in the technical annex (Duscha et al. 2019).

3.3 Main assumptions

The scenario GHG-neutral EU 2050 builds on a number of assumptions and projections of key drivers. As a general starting point, it is assumed that societal lifestyles and consumption patterns mainly follow current trends and develop according to the projections in the EU reference scenario 2016 (EU COM 2016), respectively. This, however, does not exclude that related societal demands are satisfied in a different way, e.g. the demand for mobility via different modes of transport. Furthermore, there are some limitations to continue current trends being not compatible with the target of net-zero GHG emissions, i.e. diets with a high share of meat products. With regard to such limitations, the scenario includes certain sufficiency considerations. The overall picture of the socio-economic conditions in the EU assumed for the year 2050 is described in the following, while some sectoral specifics can be found in the technical annex (Duscha et al. 2019).

Population and economic development

Projections for population are taken from the EU reference scenario 2016. Between 2015 and 2050 population in the EU increases from 505.5 m to 522.4 m. This is an increase of 4%. Similarly, the assumptions on the economic development follow the 2016 reference scenario. Accordingly, GDP rises from approx. 13.4 trillion € in 2015 to 22.5 trillion € in 2050. Total gross value added at EU level rises by 78%. The economic structure remains almost unchanged compared to 2015, with a slight shift towards the service sector. A positive development of gross value added can nevertheless be found in all major industrial sectors. For the chemical industry, it is 54%, for iron and steel 16% and for non-metallic minerals 43% (change 2010-2050).

Energy efficiency measures

Unlike today, efficiency measures do not reduce GHG emissions in a fully decarbonised energy system, as all energy can be provided without associated CO_2 emissions. Nevertheless, energy efficiency measures do play an important role in a decarbonisation scenario: they limit the amount of energy that has to be provided CO_2-neutral and thus the costs. Therefore, the scenario GHG-neutral EU2050 is based on ambitious efficiency assumptions in all sectors.

Feasibility: GHG-neutral EU2050 focuses on feasibility under technological and certain economic constraints, e.g. the need for different qualities of cement and steel. It does not rely on economic optimisation, but instead applies various analytical approaches (cf. above) and expert knowledge to find a consistent set of low-emitting technologies that fully substitutes fossil technologies. The role of policy instruments and measures, which e.g. put a sufficiently high price on carbon emissions, is not analysed within the scope of this study.

Consumption changes: When choosing mitigation options, the focus of the scenario GHG-neutral EU2050 is on measures in the areas of efficiency and consistency. Changes in the composition and level of consumption due to sufficiency measures or economic reactions to price changes resulting from the technical transformation and in particular behavioural changes are largely not considered. The scenario deviates from this rule in those areas in which the achievement of objectives cannot be achieved by technical means alone (agriculture/food and waste management).

Availability of technologies

The scenario GHG-neutral EU 2050 adopts a moderately optimistic attitude with regard to the availability of technologies. Technologies that have at least been validated in an industrially relevant environment are taken into account (TRL5 or higher[7]). In turn, highly innovative lab-scale technologies are not considered. Further, technologies that face severe limitations with regard to sustainability are excluded. This applies in particular to the following technologies:

- **Nuclear power:** Construction of new nuclear power plants is excluded. It seems difficult to exclude the use of nuclear power per se at EU level. However, it can be argued that building nuclear power plants fulfilling the latest safety standards is not a competitive alternative to other power generation technologies in view of the current levelized costs of electricity. The scenario assumes that although there will be no new construction of nuclear power plants in the future, the existing power plants will continue to be operated until the end of their technical lifetime and that power plants that are already under construction will also be completed and used until the end of their lifetime. As a result, a total of 4.1 GW of nuclear power plants are still in operation in 2050.

- **CCS:** The large-scale use of carbon capture and storage technologies (CCS) is excluded. CCS is a central component of most 2°C and 1.5°C compatible scenarios (cf. Duscha et al. 2018). The technology is particularly relevant in the industrial sector, because it enables process emissions to be stored without major changes of the economy's structure nor of the production processes, and in combination with biomass (BECCS) to generate negative emissions. However, it should be borne in mind that, on the one hand, CCS cannot be applied to all emission sources – it requires large point sources, sectors such as transport are therefore unsuitable – and, on the other hand, it does not necessarily lead to a complete reduction in the emissions of a process, among other things because of technological limitations in capturing emissions as well as leakages in transport and storage of CO_2. Moreover, it seems difficult to justify allowing CCS only in individual areas (e.g. as BECCS or in industry) and excluding it in other areas. Finally, storage capabilities for CO_2 are limited, which poses a limitation to the application of CCS over time. For these reasons, the scenario GHG-neutral EU 2050 tries to achieve net-zero GHG emissions without the large-scale use of CCS. If the remaining unavoidable GHG emissions cannot be compensated by the LULUCF sink, a moderate use of CCS in industry will be considered.

[7] see ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf for a definition of the TRLs (technology readiness levels)

Biomass availability and use

The use of biomass in a decarbonisation scenario is ambivalent. On the one hand, biomass is a renewable and storable form of energy whose provision uses significantly less energy than the production of synthetic renewable energy carriers such as gases produced using renewable electricity. On the other hand, the use of biomass can be problematic due to unsustainable land use and competing demands in particular for nutrition.

The biomass available for energy purposes is therefore limited to waste and residual materials. In contrast, cultivation of energy crops and the import of biomass from non-EU countries are excluded. The use of bioenergy follows a clear hierarchy: the use as a raw material, in particular for the construction sector and the chemical industry are to be preferred. Furthermore, the use of biomass in countries where it has historically been used heavily for heat generation (Scandinavia, Eastern Europe) is taken into account. Liquid manure is used in biogas plants for the supply of electricity and, if necessary, heat. In the scenario GHG-neutral EU 2050, the fuels produced from bioenergy are subsumed together with electricity-based energy carriers in a category called *novel fuels*. By contrast, the use of biofuels in air transport is excluded. More details about the assumptions with regard to biomass can be found in the technical annex (Duscha et al. 2019).

Biomass and electricity-based energy carriers ("renewable fuels"): Requirements for the storability of electricity and the use of energy in non-stationary applications result in the fact that a full electrification is technically difficult or only possible with very high costs. For this reason, the option to use *renewable fuels*, meaning either biogenic energy carriers or *novel fuels*, i.e. electricity-based energy carriers,

is investigated in this study. It must be taken into account - and presented accordingly - that the use of both hydrogen and electricity-based hydrocarbons has advantages and disadvantages. The most obvious disadvantage of hydrogen is the necessary infrastructure, which is associated with additional costs, especially if it is to be used on a larger scale (i.e. not only in the form of local networks at individual industrial sites or for refuelling trucks). On the other hand, electricity-based hydrocarbons can use the existing gas and oil infrastructures, but their production is significantly less efficient than that of hydrogen and thus more costly. Moreover, electricity-based hydrocarbons also require CO_2 as an input, i.e. CO_2 from biogenic sources or CO_2 previously filtered from the air (direct air capture).

Energy supply

Apart from the limited inclusion of nuclear energy described above, the consideration of electricity supply is based on the available technical potentials for renewable electricity at an acceptable cost. The required non-fluctuating electricity generation is estimated based on model-based analysis of the future European electricity supply, which account for the fluctuations in demand and supply. For district heat, currently no detailed analysis for a completely renewable supply of the EU is available. The shares of different energy carriers are therefore based on estimations of potentials and explorative model runs to take into account the seasonable changes in demand and supply.

Carbon availability and import of electricity, hydrogen and electricity-based hydrocarbons

In a largely decarbonised world, it is an important question which carbon sources (CO_2-neutral carbon) are available for the generation of electricity-based hydrocarbons. This study assumes that an import of pure CO_2 is not allowed. As a remedy for this problem, import of electricity (for the production of hydrogen or synthetic hydrocarbons), hydrogen and synthetic hydrocarbons is not excluded. In this regard, no specific level of imports is chosen. Instead, the range resulting from a complete domestic production of electricity-based *novel fuels* in the EU to a complete import from Non-EU countries except for local hydrogen production is presented. The extent to which CO_2 from industrial processes can be used is also examined.

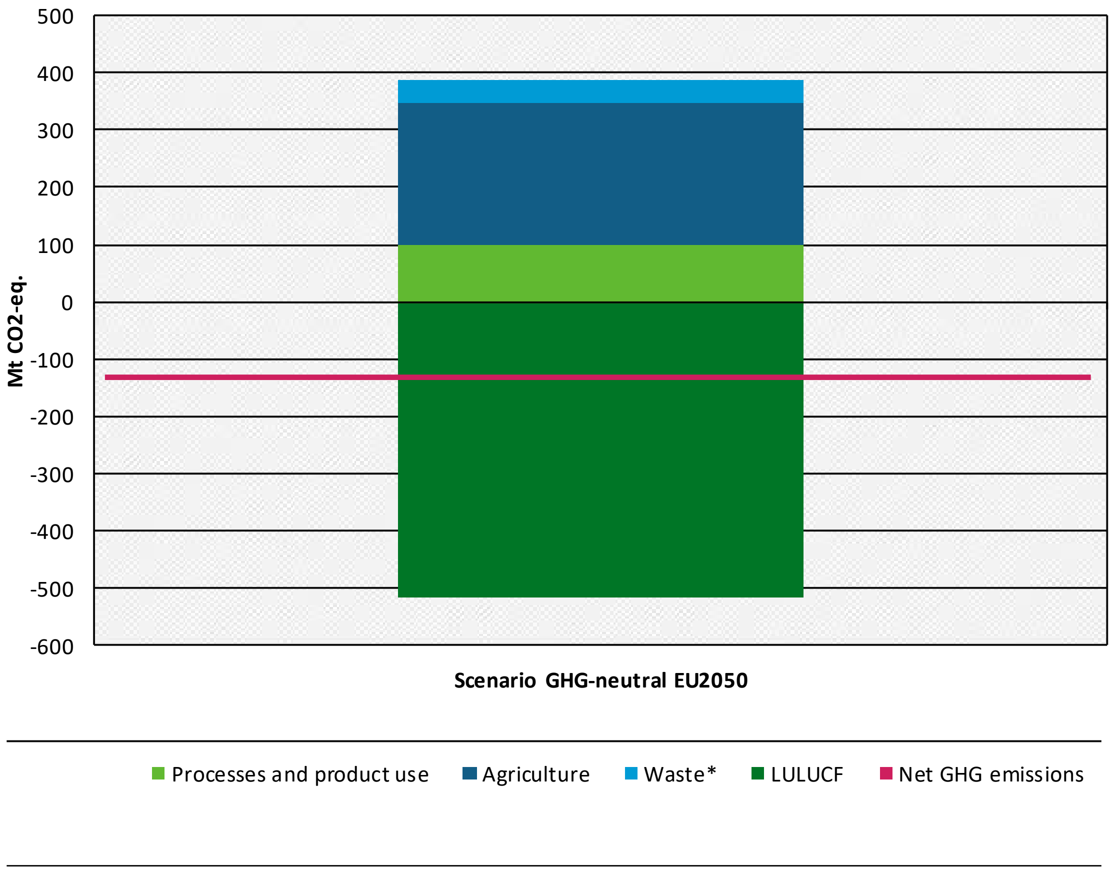
Natural and artificial CO_2 sinks

No artificial CO_2 sinks from so-balled negative emission technologies such as enhanced weathering and soil carbon sequestration are considered in this study, while the potential for additional natural sinks is investigated in the LULUCF sector and exploited tom compensate for non-avoidable emissions in other sectors.

4 GHG-neutral EU 2050: GHG emissions and energy use in the year 2050

The scenario GHG-neutral EU2050 describes a detailed sectoral setup for all GHG emitting sectors including agriculture, waste and international bunker fuels, by which a reduction of all six Kyoto GHGs to 387 Mt CO_2-eq. in the year 2050 (excluding the LULUCF sector) is achieved. This corresponds to a reduction by 93% compared to 1990 levels (-92% compared to 2015). The remaining GHG emissions are compensated by increasing the net-carbon sink from the LULUCF sector to of 518 Mt CO_2-eq., which is larger than the remaining GHG emissions by 131 Mt CO_2-eq. (see Figure 1).

Figure 1: EU GHG emissions and sinks in the scenario GHG-neutral EU2050



* including waste incineration with energy recovery
Source: own calculation (Fraunhofer ISI and Oeko-Institute)

All energy-related GHG emissions across the energy sector, the industry sector, the transport sector, the residential sector and the commercial sector are mitigated, in particular by avoiding the use of fossil fuels altogether. Only 6 Mt CO_2-eq. of GHG emission from the incineration of non-biogenic waste remain (see Table). To this end, a broad portfolio of mitigation options is applied throughout, with different focus in the various sectors. Details on the changes of the energy demand and supply are presented below Table .

For industrial process and product use, there remain GHG emissions of 103 Mt CO_2-eq., which corresponds to a reduction by only 80% compared to 1990. However, the remaining GHG emissions cannot be mitigated under the assumptions of the scenario GHG-neutral EU 2050, which are very ambitious but also mindful of sustainability issues other than climate change. The remaining process emissions could be substantially reduced (though not to zero), if CCS was applied in the production of cement. This is not considered in detail, as the target of GHG neutrality in 2050 can be reached anyway.

In the agricultural sector, the GHG reduction compared to 1990 is even lower, namely 55%. This reflects that there are unavoidable GHG emissions from land use and animal livestock. The scenario GHG-neutral EU2050 already assumes a reduction of the livestock units by half based on health considerations[8]. A further reduction of the remaining GHG emissions would require to strengthen this ambitious assumption even further.

In the waste sector, the emissions are reduced by 86% by reducing the waste amounts and changing the practices of waste disposal. Also here, a further reduction is feasible only under very strong assumptions about future waste amounts. Finally, GHG emissions from international bunker fuels are again fully mitigated by switching from the use of fossil fuels to *novel fuels*, which are produced by using renewable electricity only.

The LULUCF sector presents a carbon sink already today, with an annual removal of carbon of 318 Mt CO_2-eq. in 2015. However, this sink would not be fully sufficient to compensate for the remaining GHG emission in the scenario GHG-neutral EU2050. Therefore, the scenario also provides a setup for the transformation of the LULUCF sector, which enables to increase this carbon sink to 518 Mt CO_2-eq. in 2050.

Table 1: GHG emissions of the EU in 1990, 2015 & the scenario GHG-neutral EU 2050

	UNFCCC 1990 [Mt CO_2-eq.]	UNFCCC 2015 [Mt CO_2-eq.]	GHG-neutral EU 2050 [Mt CO_2-eq.]	Reduction compared to 1990 [-]
Energy-related	4.351	3.371	6	-99.9%
Industrial processes and product use	517	377	103	-80%
Agriculture	542	429	245	-55%
Waste	236	141	33	-86%
International bunkers	180	282	0	-100%
TOTAL excl. LULUCF	**5,826**	**4,600**	**387**	**-93%**
Land Use, Land-Use Change and Forestry	-260	-318	-518	N/A
Total incl. LULUCF	**5,566**	**4,282**	**-131**	**-102%**

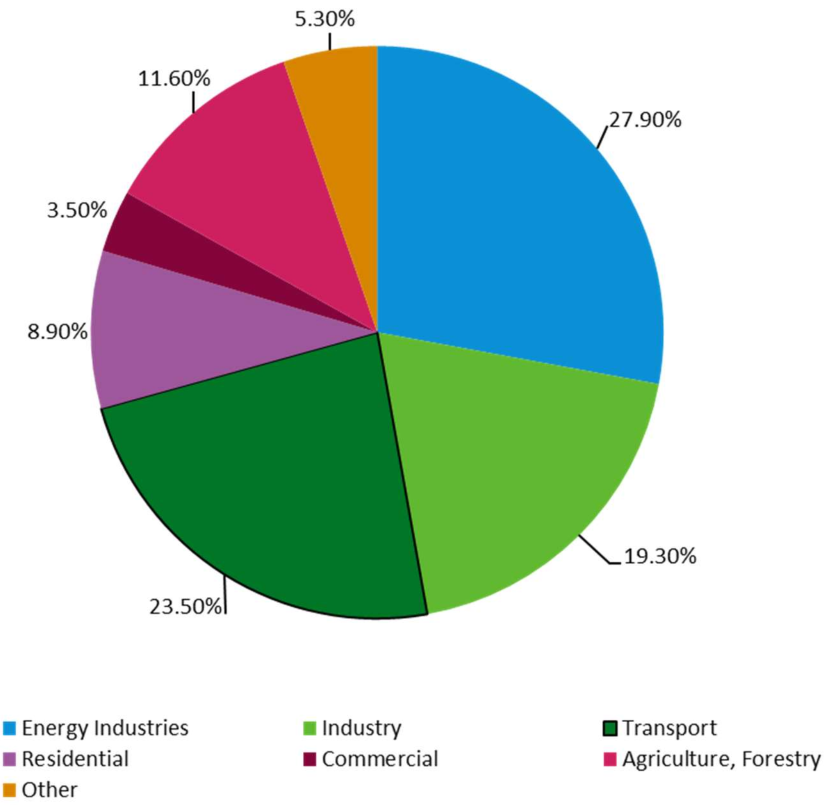
Source: UNFCCC 2017 and own calculation (Fraunhofer ISI and Oeko-Institute)

The total remaining gross GHG emissions are, of course, in strong contrast to the EU's GHG emissions in 2015 of 4.6 Gt CO_2-eq. This, however, also applies to the distributions among sectors. Today, the energy-related GHG emissions dominate the GHG emissions of the EU, with a share of 78% in 2015, with the largest shares in the energy industries and the transport sector, see Figure 2. The transformation of the EU energy system is therefore key to the realization of a GHG-neutral EU. This means on the one hand to limit energy demand across all energy-consuming sectors as far as possible and on the other hand to meet the resulting demand by a

[8] It is assumed that people's dietary on average meets the recommendations of the World Health Organisation, with a reduction of protein consumption to 50g/d/cap.

supply with non-fossil energy carriers, in particular from renewable energy sources, given the restrictions on nuclear energy and CCS described in Section 3.3.

Figure 2: GHG Emissions of the EU-28 in 2015

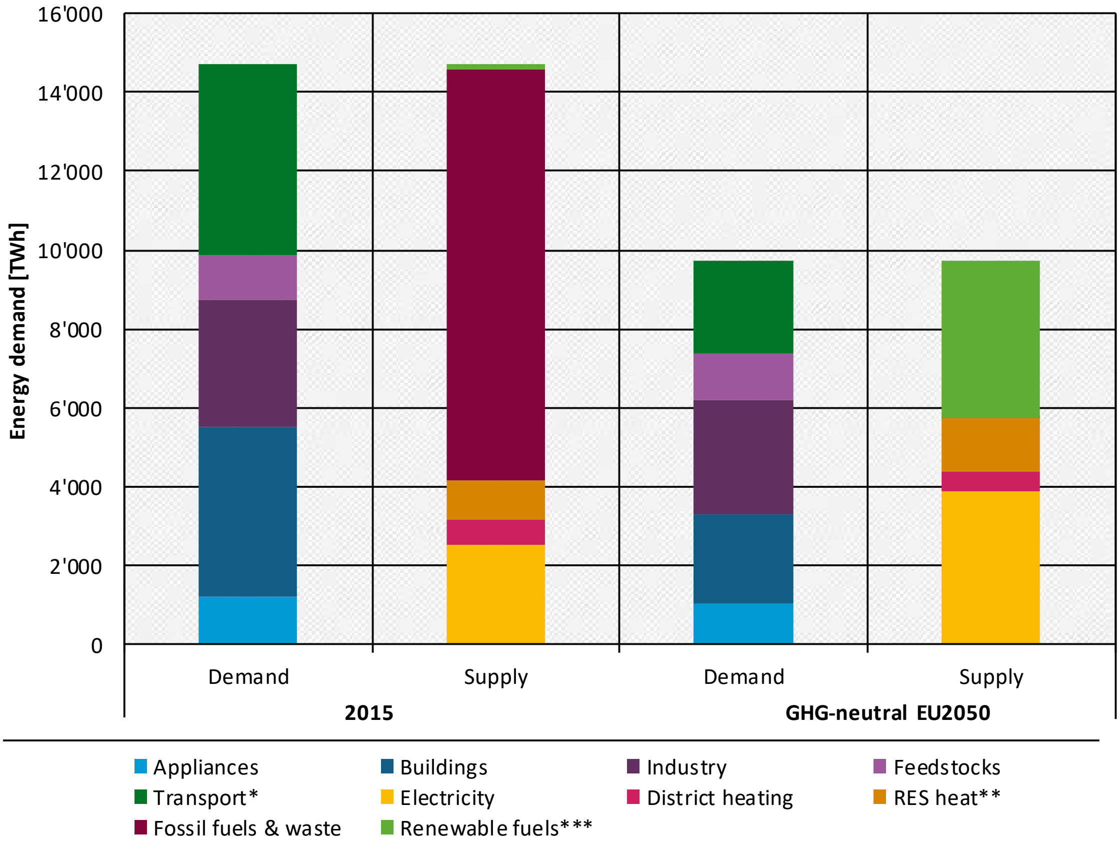


Excluding LULUCF (Land Use, Land – Use Change and Forestry) emissions and international maritime, including international aviation and indirect CO_2. Source: European Environment Agency (EEA), June 2017.

In the scenario GHG-neutral EU2050, the final energy demand is reduced by roughly one third, from about 14,700 TWh in 2015[9] to about 9,700 TWh in 2050 (including industrial feedstocks as well as international aviation and navigation), see Figure 3. The largest demand reductions take place in the transport and in the buildings sectors with 52% and 47% respectively, resulting from much more energy-efficient vehicles and buildings as well as a strong electrification in both sectors. Incremental efficiency gains lead a reduction of the energy demand of industry and appliances by 12% and 14% respectively, while the non-energy demand for industrial feedstocks even increases by 6% due to a slight increase in production, in particular in the chemical industry.

[9] Even without international navigation, the final energy demand according to EUROSTAT (2017) has been about 3% lower. This mainly reflects that the official statistics contains no climate adjustment.

Figure 3: EU final energy demand in 2015 and in the scenario GHG-neutral EU2050



* including international aviation and navigation; ** including biomass use in industry in 2015; *** biofuels in 2015
Source: own calculation based on EUROSTAT (2017)

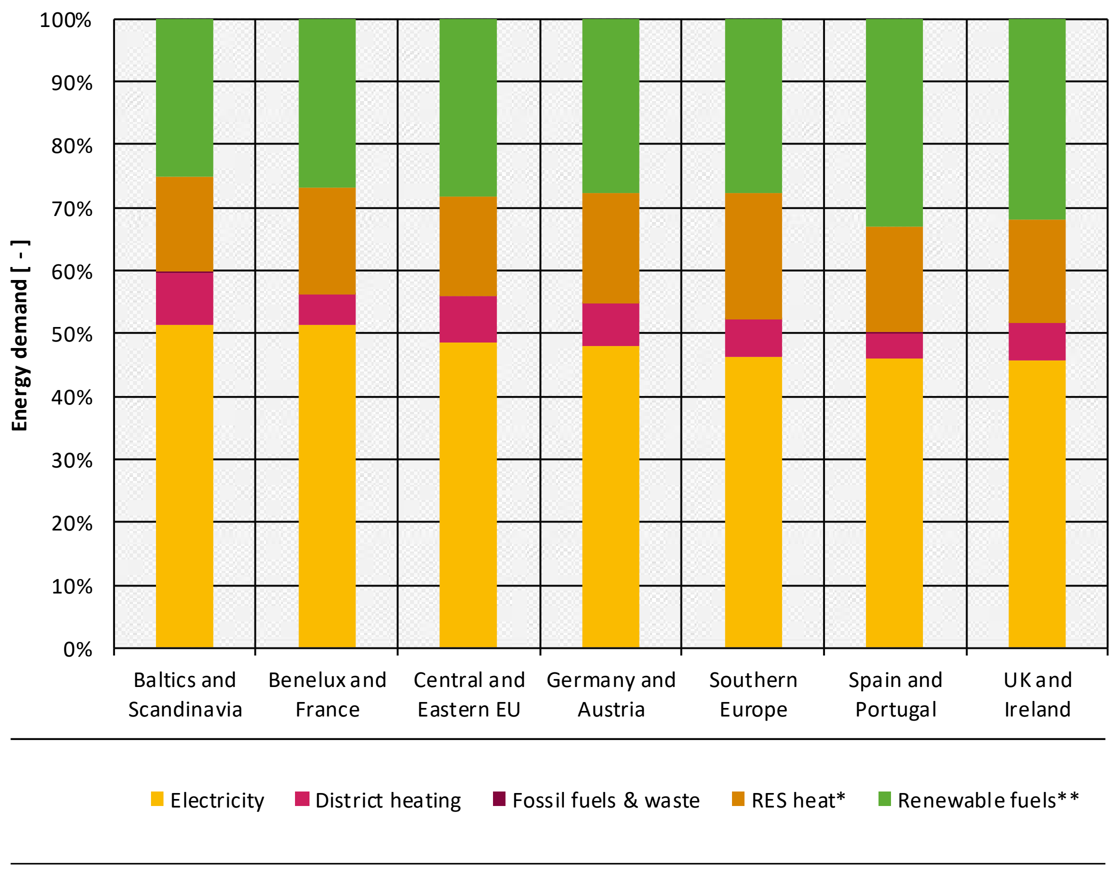
The reduction of energy-related GHG emissions by 99% is further achieved by substituting fossil fuels, whose share in the energy mix was larger than 79% in 2015, completely with electricity, district heat, RES heat (ambient heat, solar thermal and bioenergy) and *novel fuels* (hydrogen, synthetic hydrocarbons and biofuels) so that emissions only remain from the incineration of unavoidable non-renewable waste. The strong electrification across all energy-consuming sectors results in a strong increase of final electricity demand by 53% compared to 2015, thereby increasing its share in the energy mix from 17% to 40% (almost 50% excluding feedstocks). The use of district heat only slighty increase from 4% to 5%, while the share of RES heat doubles from 7% to 14%. The remaining demand for fuels, which mainly stems from international transport, industry and industrial feedstocks, is covered by *novel fuels*, reaching a share of 41% in 2050 (32% without feedstocks) compared to 1% covered by biofuels in 2015.

The scenario GHG-neutral EU 2050 applies rather strict sustainability criteria for the use of bioenergy. The biomass used for energy purposes predominantly comes from residues of agriculture and forestry. In total, the gross consumption of bioenergy amounts to 1,062 TWh, which corresponds to roughly two thirds of the gross consumption in 2015 of 1,584 TWh. In the scenario, the bioenergy is used almost completely to produce *novel fuels*, which are used as industrial feedstock and in centralized electricity and heat generation. Only a minor share of 39 TWh is still used for decentral heat supply (in Northern and Eastern European countries with high availability of wood) and none is used in the transport sector.

As electricity and *novel fuels* together cover 80% of the final energy demand in 2050, they form the backbone of energy supply in 2050. Main energy sources for electricity production are onshore and offshore wind energy as well as solar energy in photovoltaic plants. The remaining nuclear power plants cover only 33 TWh of the electricity demand. There is also an additional need for *novel fuels* of about 300 TWh for electricity generation required to compensate for the fluctuating electricity production from wind and solar power. *Novel fuels* in turn are produced to a large share of about 70% (with regard to novel fuel end use) from renewable electricity and only to a share of 30% from sustainable biomass. This means that the production of electricity and *novel fuels* is strongly interrelated. In particular, if *novel fuels* are not imported, this results in an increase of the total electricity demand in the order of 250% compared to 2015.

The scenario GHG-neutral EU2050 takes regional differences in the energy demand structure into account (see Figure 4). The electricity share is always in the order of 50% of the total final energy demand (excluding feedstocks and international transport), with the highest share in Scandinavia due to the large and cheap hydropower potentials and an accordingly adapted industrial structure. The district heating share ranges from 4% and 8%, with the highest share also in Scandinavia. Fossil fuels and non-renewable waste play a marginal role across all regions. The RES heat share varies between 15% and 20%, with the highest share in Southern Europe due to the higher solar energy potentials. Finally, the renewable fuel share ranges from 25% and 33%, with the highest share on the Iberian Peninsula due to its important role in international freight transport. In summary, the resulting regional energy mixes in the year 2050 do not differ strongly anymore for two reasons: On the one hand, there is a high level of electrification across all sectors and regions and on the other hand, because *renewable fuels* are needed to a certain extent in all regions for high-temperature heat and to compensate for seasonal fluctuations. Accordingly, the following more detailed description of the sectoral results will not focus on the regional differences but provide an overview for the EU as a whole.

Figure 4: Regional final energy mixes in the scenario GHG-neutral EU2050



Source: own calculation based on EUROSTAT (2017)

5 The scenario GHG-neutral EU2050 by sector

This section presents the sectoral setups, mitigation options and the resulting changes of GHG emissions of the scenario GHG-neutral EU2050, whereas more details on the individual sectors are given in the technical annex (Duscha et al. 2019). As usual under the UNFCCC protocol, GHG emissions from the generation of electricity and centralized heat are accounted for in the energy sector.

5.1 Energy supply

In the scenario GHG-neutral EU 2050, the central production of electricity and heat is free of GHG emissions, except for 4 Mt CO_2-eq. from the incineration of non-biogenic waste. Furthermore, the production of *novel fuels* is assumed to be completely based on renewable electricity and thus also without any GHG emissions, given that the CO_2 used in its production is GHG-neutral. Since fossil fuels are not used anymore, current emissions from petroleum refining and other energy industries such as the manufacture of solid fuels are fully mitigated, too. Table 2 gives an overview of historic and present day emissions, of which in total 99.5% are mitigated GHG-neutral EU2050.

Table 2: GHG emissions of EU energy industries in 1990, 2015 and in GHG-neutral EU 2050

	UNFCCC 1990 [Mt CO_2-eq.]	UNFCCC 2015 [Mt CO_2-eq.]	GHG-neutral EU 2050 [Mt CO_2-eq.]
Electricity & heat supply	1,439	1,075	4
Petroleum refining	123	116	0
Other energy industries	116	54	0
TOTAL	**1,678**	**1,245**	**8**
change vs. 1990		-26%	-99.5%

Source: UNFCCC (2017) and own calculation (Fraunhofer ISI)

All energy used in the scenario GHG-neutral EU2050 is either local renewable energy, such as solar thermal energy or biomass, or is supplied by the energy sector through district heating, electricity or novel fuels. The compositions of these three will be summarized in the following in ascending order of their share of final energy consumption.

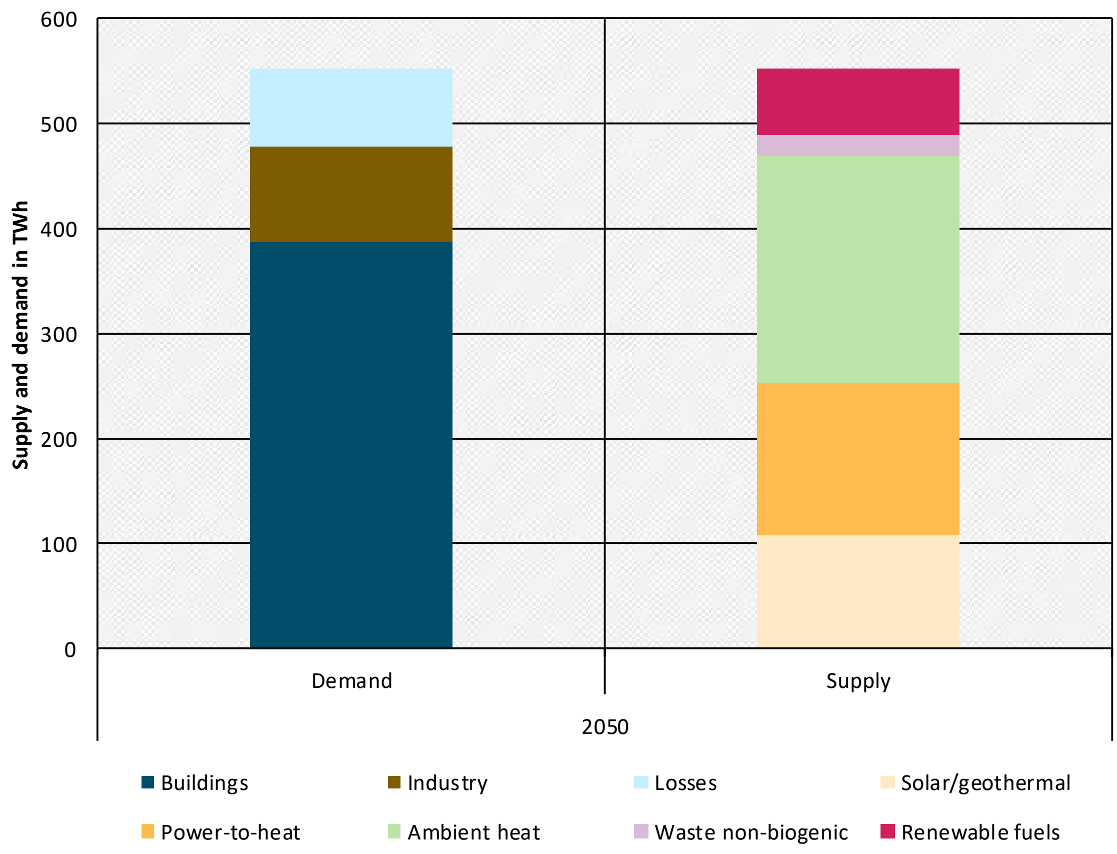
5.1.1 District heating

District heating plays an important role in the decarbonisation of the heat supply. The benefit of district heating is twofold: Firstly, it allows for an easier and cheaper integration of certain technological options. Heat storages, especially seasonal storages, are less costly at large scales, and they are critical for realising large share of solar energy on the supply side. The supply side can also profit from the economies of scale and from being situated close to, but not directly within densely populated areas. Secondly, heat grids allow for a smoother change during the transformation process. Heat grids initially supplied by gas can be switched to higher shares of renewable sources gradually. Steering the transformation by policy measures for a number of heat grids is less complicated then addressing a similar change in numerous individual heating systems.

The district heating demand, shown in Figure 5 encompasses two demands: *Buildings*, consisting of heat demand for both households and the tertiary sector, as well as *Industry* demand, which includes demand for the industry buildings as well as certain process heats at low temperature levels. Occurring losses are slightly higher compared to today due to the use of seasonal storages.

The district heat supply shows drastic changes from today's systems dominated by fossil fuels and waste firing. Fossil fuels are not burned at all anymore and non-renewable waste covers only 4% of the demand in the scenario GHG-neutral EU2050. 20% of generation come from local renewable sources, i.e. solar and geothermal energy. The remaining part of supply comes from electricity, either directly through Power-to-heat (PtH), i.e. heat pumps and electrode boilers, or indirectly through *renewable fuels*. While PtH has the advantage of a higher system efficiency, it is subject to the timely availability of RES or limited by the availability of heat storage systems. *Renewable fuels,* which are mostly generated from electricity in the scenario, show a substantially lower system efficiency due to the losses in the conversion from electricity to the fuel. However, they can be stored almost without losses for long times.

Figure 5: District heating by demand and energy source in the scenario GHG-neutral EU2050



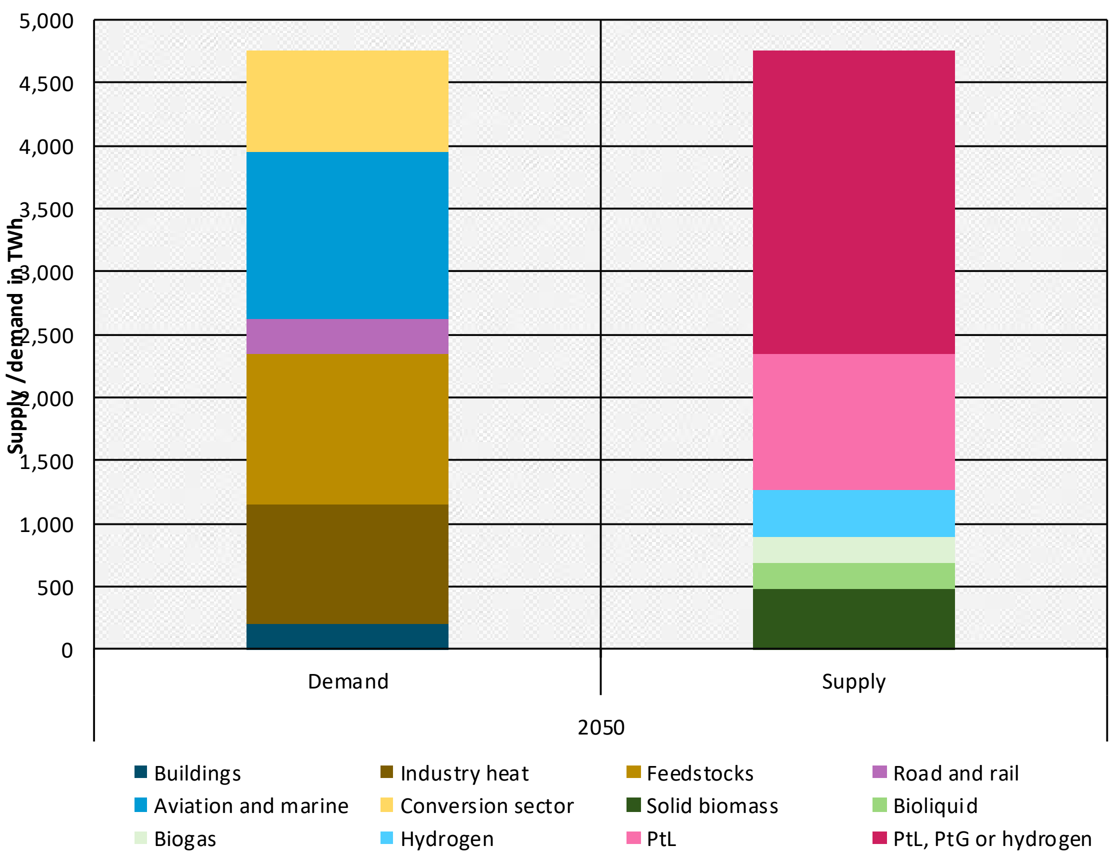
Source: own calculations (Fraunhofer ISI) and Eurostat (2017)

5.1.2 Renewable fuels

Renewable fuels are central part of the energy balance of the scenario GHG-neutral EU 2050. In the definition used in this study, *renewable fuels* encompasses not only material energy carriers generated from electricity, such as hydrogen or synthetic hydrocarbons, but also biogenic energy sources and theirs derivatives not directly used locally. This categorisation is based on the observation that for many applications a material energy carrier is needed, but for the applications it makes little or no difference whether the fuel comes from biogenic sources or from the conversion of electricity. In some areas either hydrogen or hydrocarbons could be used. However, for a range of other applications, a carbon-based fuel is necessary. The use of bioenergy follows a clear hierarchy in the scenario: the use as a raw material, in particular for the construction sector and the chemical industry are to be preferred.

Figure 6 shows the composition of energy demand and supply for *renewable fuels*. Demand from heat in buildings shrinks substantially compared to today making up for only 5% of the *renewable fuel* demand in the scenario GHG-neutral EU2050. The demand from the industry is much higher, reaching almost 1,000 TWh for industry process heat and almost another 1,200 TWh for feedstocks. Overall, the industry sector is responsible for 45% of *renewable fuel* demand. The demand from the transport sector is largely driven by aviation and marine. Road and rail transport in turn amount to only about 6% of *renewable fuel* demand. The conversion sector uses another 800 TWh for peak gas turbines and district heating.

Figure 6: Renewable fuels in the scenario GHG-neutral EU2050 by demand and source



Source: own calculations (Fraunhofer ISI)

It should be noted that we distinguish between different categories of *renewable fuels, namely*

- from biogenic sources (biomass, biogas, bioliquid)
- hydrogen,
- PtL and
- PtL, PtG or hydrogen.

The last category accommodates for the ambivalences and uncertainties of the *novel fuel* balance. While for example *hydrogen* refers to the use of hydrogen specifically – as opposed to hydrocarbons–, "PtL, PtG or hydrogen" means that basically any GHG-neutral fuel could be used.[10] 501 TWh come from biomass that is not used locally for heating, 208 TWh come from biogas and 212 TWh in liquid from form agricultural residues. When applying the hierarchy described above, almost all biogenic sources are used as a feedstock in the chemical industry. Hydrogen is relevant in two industry processes, namely steel and ammonia production. In aviation and navigation, power-to-liquid is required totaling about 1.300 TWh. Overall, the demand for biogenic or electricity based hydrocarbons totals about 2,400 TWh. The remaining demand for renewable fuels of 2,000 TWh could be supplied by hydrogen or liquid or gaseous hydrocarbons; which energy carriers could and should be used is beyond the scope of this study.

5.1.3 Electricity

Virtually all energy carriers used in the scenario GHG-neutral EU2050 stem from renewable sources: they are either the direct or indirect use of electricity generated from renewable sources, local renewable heat such as solar thermal, or of biogenic origin. As biogenic sources contribute only a small part to energy supply due to their limited potential, electricity and energy carriers derived from electricity make up for the vast majority of total energy supply in the scenario GHG-neutral EU 2050.

Figure 7 shows the composition of demand and supply for electricity. The demand side is divided in two components: The bottom parts are the direct use of electricity: Buildings, referring to heat pumps and other PtH applications in buildings, and appliances and lighting create an electricity demand of 1,567 TWh, with an additional demand of 117 TWh for PtH in district heating. Industry consumes additional 1,535 TWh for process heat and mechanical energy. Road and rail contribute a demand of 761 TWh. Overall, losses account for 358 TWh. Consequentially, electricity consumption of all demands besides novel fuel production amount to 4,338 TWh.

If all unspecified novel fuels (PtL, PtG or hydrogen) from the previous section would be implemented in the form of hydrogen, the minimum electricity demand for the generation of novel fuels would be 5,315 TWh. If all unspecified novel fuels would be hydrocarbons, this would lead to another 980 TWh of electricity demand, due to the losses in the additional conversion processes and the energy demand for generating CO_2-neutral carbon. Hence, depending on the composition of the novel fuels, the electricity demand for their production varies between 5,315 and 6,296 TWh in the scenario GHG-neutral EU2050.

The supply side is dominated by generation renewable energy sources. The three nuclear reactors currently under construction contribute only 33 TWh, even when running almost continuously; all currently running reactors are assumed to be decommissioned before 2050. All electricity demand besides the generation of synthetic hydrocarbon is covered by electricity generation from RES in Europe. 300 TWh of power generation come from peak gas turbines using *novel fuels*. Overall, the scenario requires a minimum RES production in Europe of 4,006 TWh. The remaining up to 6,296 TWh for the production of novel fuels could be generated in the EU or in other countries.

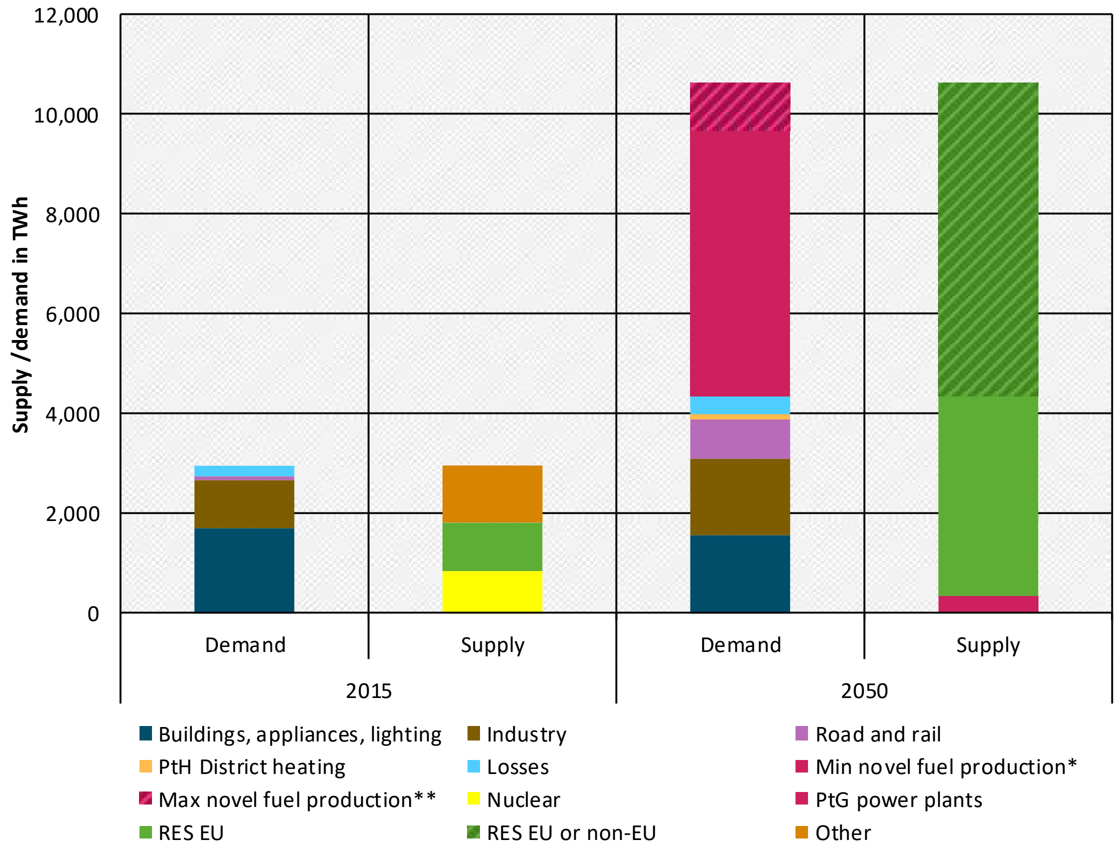
What combination of production sites inside or outside the EU should be used for *novel fuel* production depends on a variety of factors not considered here in detail. However, the EU's RES potential alone would be sufficient to cover even the upper value of RES demand; this is true

[10] Of course, that does not mean that a fuel switch would be possible after the application has been installed, but that technological options exist to supply the demand from a range of fuels.

even when only wind, solar and hydropower are taken into account (see also technical annex, Duscha et al. 2019)). Whether there is public acceptance for such an extensive utilization of RES in Europe or in other places is beyond the scope of this scenario.

Figure 7: Electricity in 2015 and in the scenario GHG-neutral EU2050 by demand and source

*



* Minimum electricity demand for novel fuel production, if hydrogen is used for all unspecified novel fuel demand

** Maximum electricity demand for novel fuel production, if hydrocarbons are used for all unspecified novel fuel demand

Source: own calculations (Fraunhofer ISI) and Eurostat (2017)

5.2 Transport

Currently, the transport sector is responsible for roughly 25% of EU's GHG emissions, or 1.182 Mt CO_2-eq including international bunkers. In contrast to all other sectors, transport has seen an increase in emissions since 1990, which was caused by an increase in transport activity. In general, the sector is divided into aviation, navigation, road and rail transport.

Within Europe, transport accounts for 3.5 trillion tonne kilometres (tkm) of freight transport and 6.6 trillion passenger kilometres (pkm) of personal mobility. In both cases, roads are the main mode of transport (50% in freight and 80% of passengers). Navigation is the second most important mode for freight (36%), but plays no major role for passengers. In contrast, air traffic is responsible for nearly 10% of passenger transport. Railways serve 12% of the demand in freight and 7% in passengers.

GHG emissions are not equally distributed among the different modes. Currently, emissions from road transport account for 73%, while navigation and aviation both come up to 13% and rail transport adds the remaining 1%. Since 1990, the development in the different sectors from

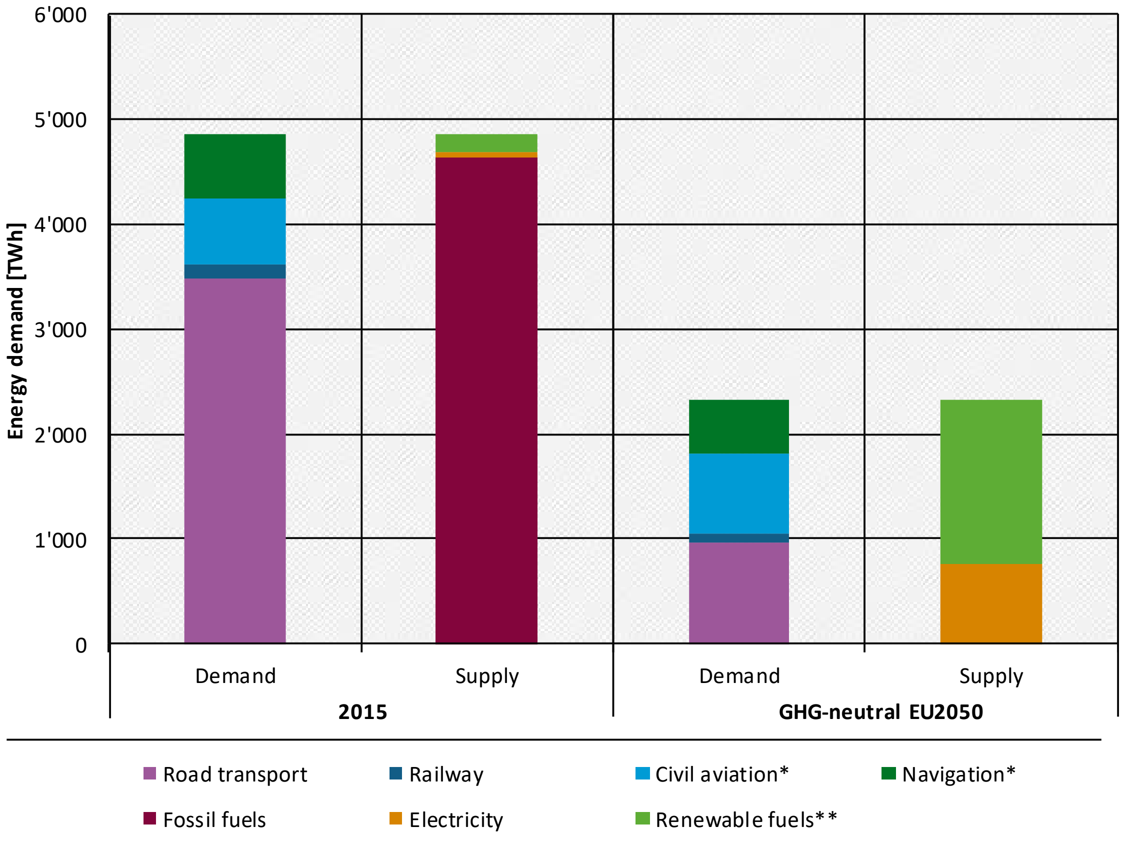
1990 to 2015 has been different, with emissions from rail transport cut in half and those from aviation doubling in this time period. Road and navigation have seen an increase of 20%.

The scenario GHG-neutral EU2050 sees the transport sector completely GHG-emission free in 2050, despite the fact that transport activity continues to grow. This is achieved in three steps: Energy demand is roughly cut in half by efficiency measures, electrification is put in place where feasible, and the remaining energy is replaced by *novel fuels*. Figure 8 gives an overview of the energy demand of the transport sector in 2050.

Transport activity on roads rises by 30% for passengers and 50% for freight until 2050. 75% will be driven electrically, with an almost fully electrified passenger traffic but also an EU-wide installation of catenary lines on the central routes for freight traffic. On routes with less frequent freight traffic, heavy duty vehicles switch to *novel fuels*, may it be renewable hydrogen, methane or methanol. Due to the strong electrification, total final energy demand drops by 70%. This is the most dramatic change by 2050 seen for the transport sector.

Rail transport activity increases by 57% and 69% for passenger and freight transport, respectively, with an increasing share of transport on electrified networks, depending on the member state. Accompanied by a 20% increase in fuel efficiency, the small remaining share of rail transport uses *novel fuels*. Aviation sees a strong increase in efficiency of 40%, so that the doubling of passenger transport activity only leads to an increase of 15% in energy demand. This is the only transport sub-sector with increasing demand. International navigation triples and intra-EU navigation increases by 25%. There is an enormous gain in efficiency of 69%. Both, aviation and navigation, rely entirely on *novel fuels*.

Figure 8: Final energy demand of EU transport in 2015 and the scenario GHG-neutral EU2050



* including international bunker fuels; ** including biofuels in 2015
Source: own calculation

By these ambitious measures, the energy demand in the transport sector drops by 52% in 2050 according to the scenario GHG-neutral EU 2050. Nevertheless, the demand by the transport sector for *novel fuels* of 1,591 TWh is substantial, making up two thirds of its total energy demand. However, one has to keep in mind that due to the higher overall efficiency of electric vehicles, a significantly higher transport activity can be achieved with the same amount of energy. Since all fossil fuels are replaced by either electricity or *novel fuels*, this sector is completely free of GHG emissions in 2050. Table 3 gives an overview of historical and present day emissions, all of which are mitigated in the scenario GHG-neutral EU2050.

Table 3: GHG emissions of EU transport in 1990, 2015 & in GHG-neutral EU2050

	UNFCCC 1990 [Mt CO_2-eq.]	UNFCCC 2015 [Mt CO_2-eq.]	GHG-neutral EU2050 [Mt CO_2-eq.]
Road	723	864	0
Railway	14	7	0
Domestic aviation	14	15	0
Domestic navigation	30	20	0
International bunkers	180	282	0
Total	**962**	**1,187**	**0**
change vs. 1990		+23%	-100%

Source: UNFCCC (2017) and own calculation (Fraunhofer ISI and Oeko-Institute)

5.3 Industry

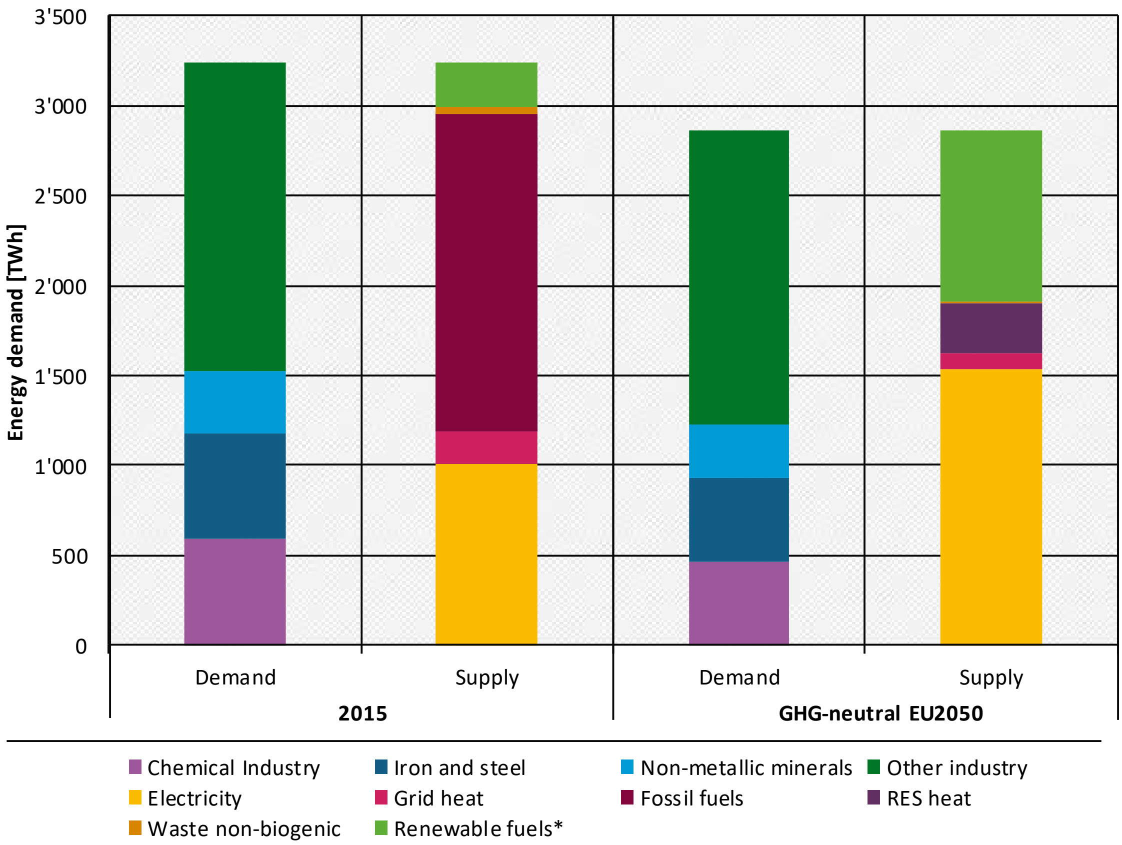
Currently, the industry sector is responsible for 3,240 TWh of final energy demand, which corresponds to 25% of the overall total (in 2015). Main energy carriers are natural gas, electricity, coal and oil. These are not only used for meeting the energy demand, but partly also directly in processes. In total, the industry was responsible for 861 Mt CO_2-eq. or about 20% of GHG emissions in the EU in 2015 (UNFCCC 2017). The process-related emissions amounted to 377 Mt CO_2-eq in 2015. The major GHG is CO_2 with 721 Mt CO_2 in 2015, but there are also 120 Mt CO_2 of F-gases emitted during the industrial production or later use of the products. He shares of CH_4 and N_2O are comparably much smaller.

The most energy-intensive sectors and those that use the lowest share of renewable energy sources are the iron and steel industry, the production and processing of non-metallic minerals and the chemical sector. Of these, the production of iron and steel (29% of total industry demand), cement clinker (25%), lime and calcination (7%) and production of ammonia (5%) are the largest contributors. In terms of direct emissions, 23% are from steam or hot water, 45% from firing other types of furnaces and 21% from process related emissions, which are especially difficult to mitigate.

The scenario GHG-neutral EU2050 achieves a reduction of total industry emissions by 87% compared to 2015, which is equivalent to 92% compared to 1990. Due to these diverse sources and pathways of emissions in this sector, many different actions are required to reduce emissions. In the scenario GHG-neutral EU2050, total energy demand is reduced by 12% in the year 2050. In addition, all energy-related GHG emissions are mitigated in 2050 except for about 2 Mt CO_2 resulting from the incineration of non-renewable waste. Electricity, ambient heat and *renewable fuels* replace coal, oil, natural gas and other fossil fuels. The demand for electricity increases by 50% while the demand for district heating is roughly cut in half. See Figure 9 for an overview of the energy demand.

The iron and steel industry sees a radical switch in production processes, away from blast oxygen furnaces to hydrogen-based direct reduction of steel and scrap-based electric arc furnaces. Diffusion of new kinds of low-carbon cements as well as recycling reduces GHG emissions in the sector of non-metallic minerals. In the chemical sector, alternative synthesis starting from hydrogen and methanol is in widespread use. This transition is discussed in more detail in the following subsection. In total, 94 Mt CO_2 of process-related, direct CO_2 emissions remain in 2050 in the industry sector. Cement and lime production are the most difficult to decarbonize, with 77 Mt CO_2 direct emissions remaining in 2050. Table 4 lists the current as well as the remaining emissions.

Figure 9: Final energy demand of the EU industry sector in the year 2015 and in the scenario GHG-neutral EU2050



* *Novel fuels* includes all kinds of biomass as well as fuels produced by Power-to-X technologies based on RES electricity
Source: own calculation (Fraunhofer ISI)

Mainly through the use of its products, the industry sector is responsible for the vast majority of the fluorinated GHG emissions (so called F-gases). The emission of F-gases in the EU has increased from 72 Mt CO_2-eq. in 1990 to 121 Mt CO_2-eq. in 2015. This is mainly due to the use of substitutes for ozone depleting substances (ODS), with a share of over 90% in 2015. The scenario GHG-neutral EU2050 assumes that the technical options to avoid the relevant substitutes for ODS will be applied to the largest extent and the emission of F-gases will also be limited in all other applications. This leads to a reduction of F-gas emissions to 10 Mt CO_2-eq., which corresponds to a reduction by 87% compared to 1990 (92% compared to 2010).

The technological changes in the scenario GHG-neutral EU2050 are ambitious. In some cases, they require that technologies and even production plants are replaced before they reach their ordinary end-of-life, which increases investment needs and costs. But these changes are necessary in order to reach the reduction of GHG emissions of 92% compared to 1990 seen feasible for the industry sector by the scenario GHG-neutral EU2050.

Table 4: GHG emissions of EU industry sector in 1990, 2015 & in GHG-neutral EU2050

Sub-sector	UNFCCC 1990 [Mt CO_2-eq.]	UNFCCC 2015 [Mt CO_2-eq.]	GHG-neutral EU2050 [Mt CO_2-eq.]
Iron and steel	280	168	1
Chemical Industry	325	128	15
Non-metallic minerals	277	192	77
Other industry	477	372	12
Total	**1,359**	**861**	**105**
change vs. 1990		**-37%**	**-92%**

Source: UNFCCC (2017) and own calculation (Fraunhofer ISI)

5.4 Feedstocks in the chemical industry

In the chemical industry, fossil fuels are used as energy source but also as a resource or feedstock to create a whole fleet of materials. Currently, the petrochemical industry uses 84 million tonnes of fossil-fuel-based feedstocks. Roughly one third of this is naphtha. Other important sources are natural gas and coal. At the moment, only 8% of feedstocks come from renewable sources, mainly biogenic fuels.

In a GHG-neutral scenario, this raw material has to be replaced by carbon from renewable sources, as it will eventually be freed to the atmosphere. Alternative substances to supply this demand of carbon come from the biological material from forests, agricultural residues, biowaste, biogenic end-of-life products or CO_2 from biogenic sources. Equally, some CO_2 will still be emitted from waste incineration and cement production, which can also be an input to the chemical industry.

While the number of final products from the chemical industry is very large, there is only a limited number of intermediate or platform products, which serve as the starting point to synthesize all downstream products. Table 5 lists the production levels of the most important platform chemicals in the scenario GHG-neutral EU 2050 and the required carbon input. Based on this, it is estimated that the future demand for carbon in the chemical industry is at roughly 57 million tonnes.

In the scenario GHG-neutral EU 2050, it is necessary to exploit all the options to use domestic raw materials for the chemical industry as much as possible. There are a lot of technical solutions, projects and concepts already prepared to make chemical synthesis and processes more energy and CO_2 efficient. This includes the use of biogas, biowaste, bio-based resources and all other renewable carbon sources as well. This will require to pursue a circular economy approach to a much higher extent than today. In particular, products should be regarded as valuable renewable carbon carriers that should be recycled after use and then reused as raw materials. The remaining demands has to come from conventional pathways with *renewable fuels* as sustainable input either produced domestically or imported from non-EU countries.

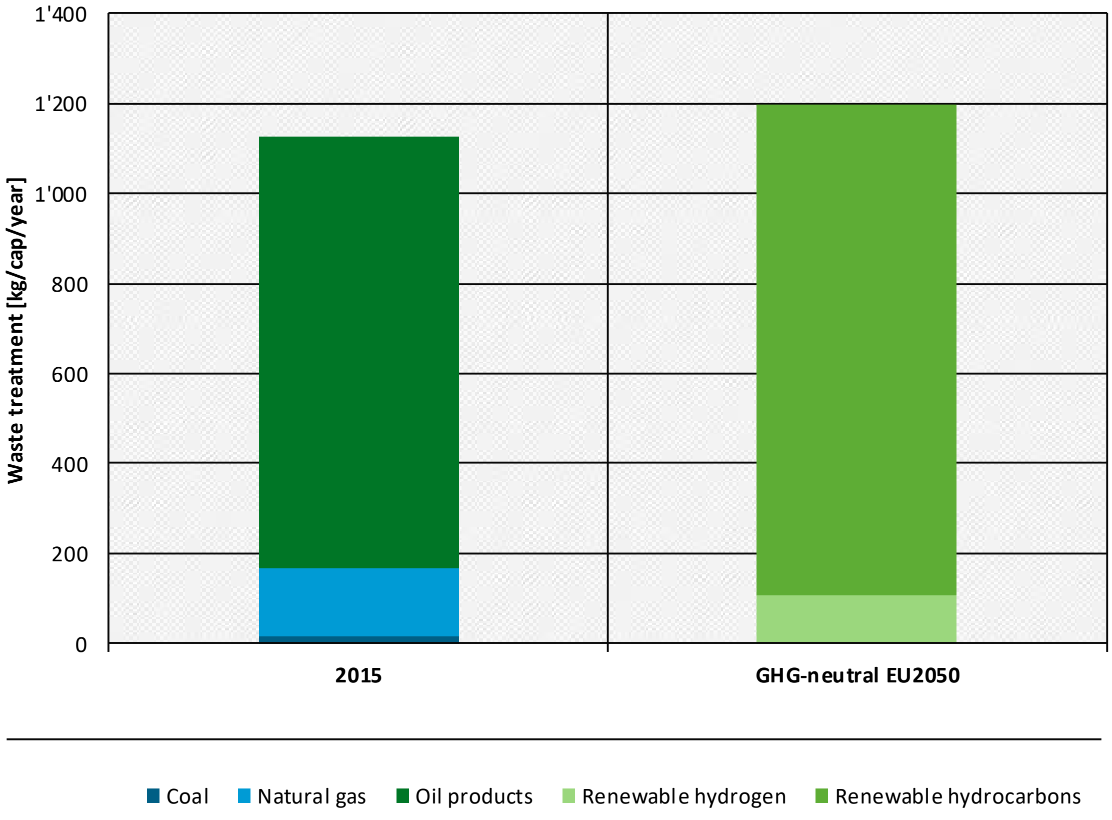
Table 5: Production of platform chemicals in GHG-neutral EU 2050 & their carbon input

Chemical	GHG-neutral EU2050 production [Mt]	GHG-neutral EU2050 carbon input [Mt]
Ammonia	19.2	0.0
Propylene	13.1	11.2
Ethylene	18.4	15.8
BTX	10.0	8.5
Other chemicals*	N/A	21.5
TOTAL	**N/A**	**57**

* The carbon input for the remaining chemicals was estimated based on today's relation to the listed platform chemicals.
Sources: Own calculation (Fraunhofer ISI) based on Bazzanella et al. (2018), Wagemann (2017)

The *renewable fuel* demand (including both biogenic and synthetic fuels) corresponding to the 57 million ton of carbon is estimated to be 114 TWh primary energy of hydrogen (for ammonia production) and 1,084 TWh of hydrocarbons (see Figure 10). This is a small increase with regard to the 1,077 TWh of fossil feedstocks in industry in 2015 (see EUROSTAT 2018), which reflects the assumed increase of production units but also a slight increase of conversion losses.

Figure 10: Feedstock demand of the EU chemical industry in the year 2015 and in the scenario GHG-neutral EU2050



* Renewable hydrocarbons include all kinds of biomass as well as fuels produced based on RES electricity
Source: own calculation (Fraunhofer ISI)

5.5 Buildings and appliances

The energy demand of buildings is determined from space heating, the demand for hot water, cooling and ventilation. In addition, this section looks at the energy demand and the emissions from appliances in households and the tertiary sector.

In 2015, a total of 5,515 TWh were used in this sector. Space heating accounts for the largest share (64%), while hot water (14%) and appliances (22%) are the other larger consumers. Space ventilation and cooling both use less than 1% of the total. 40% of the energy consumed in the EU is in the building sector (without appliances), while appliances in households and the service sector turn account for 42% of the electricity demand.

The appliances of the residential and service sector are relatively easy to decarbonize by 2050. By ending the use of natural gas as energy carrier to stoves, all appliances use electricity as energy. In addition, the scenario GHG-neutral EU2050 sees a wide-spread use of LED for lighting, which reduces energy demand in this subsector by 77%. The demand in ICT devices goes up, driven by an increase in demand of 30% in households. For other appliances, the energy demand is seen to decrease, which is achieved by strengthening the Ecodesign Directive. Overall, this leads to a reduction in demand from 1,198 TWh in 2015 to 1,025 TWh in 2050 (-14%) for appliances, see Figure 11.

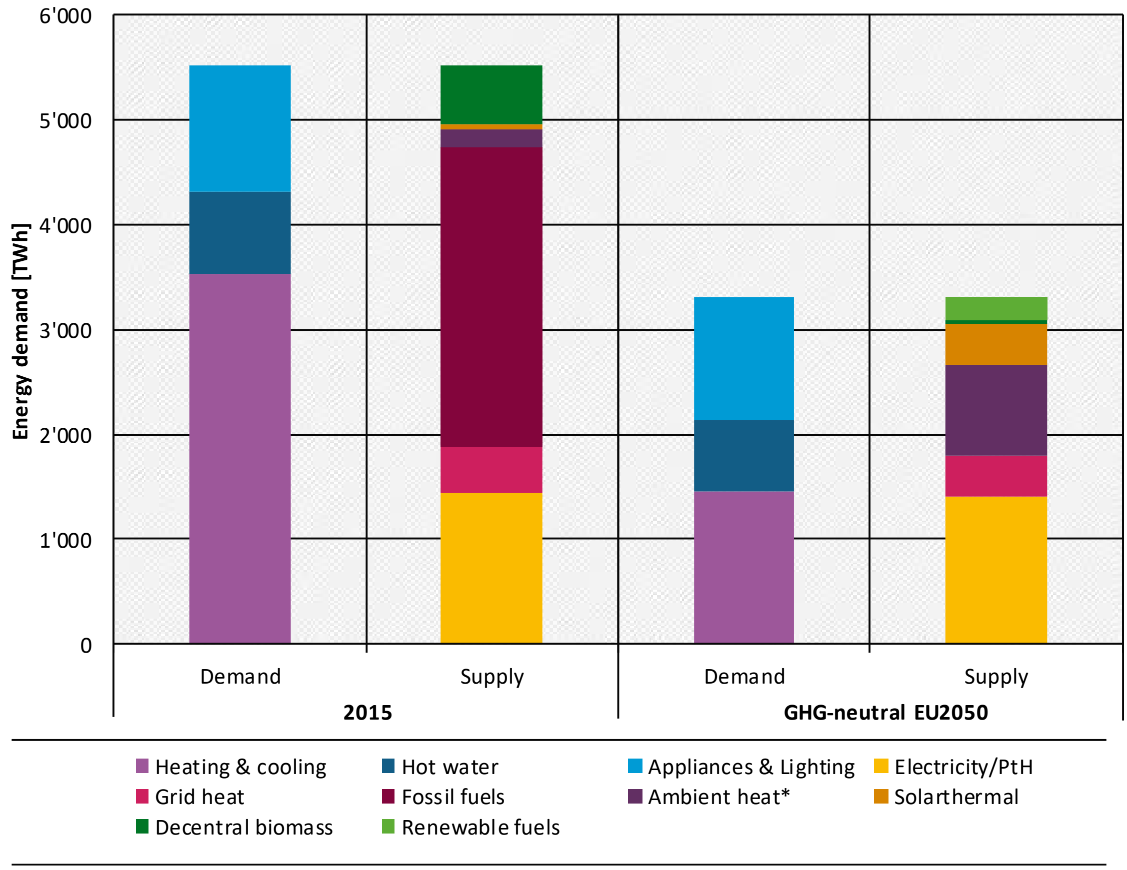
In buildings, the demand for cooling is seen to remain constant while that of ventilation increases from 9 TWh in 2015 by a factor of almost 16 to 152 TWh in 2050. This development is driven by the high share of buildings with high energy standards in 2050. Since cooling and ventilation are both electrically driven, there are again no direct emissions anymore. The situation is more complex for space heating and hot water. The energy demand for hot water is reduced by 13% in 2050, while a reduction of 59% can be achieved for space heating. Both sub-sectors see a major shift in the distribution of energy carriers away from fossil fuels, which are no longer used in 2050, towards renewable sources.

For space heating (1,443 TWh total demand), the scenario GHG-neutral EU2050 sees the strongest increase in solar thermal energy (25 TWh to 198 TWh) and heat pumps (33 TWh to 114 TWh electricity demand). District heating and electricity both reduce their absolute numbers. The decentral use of biomass for heating purposes, as is wide-spread in Northern and Eastern Europe today, is substantially reduced from 528 TWh to only 39 TWh to make the biomass available for other purposes including grid heat. The remaining demand is met by *renewable fuels*, which cover 230 TWh or 16% of the demand in 2050 (see Section 5.1.2).

The energy demand for hot water is seen at 674 TWh by the scenario GHG-neutral EU2050. Half of this will be supplied by renewable sources (heat pumps, solar thermal and biomass). The strongest increase is again seen in solar thermal energy (26 TWh to 130 TWh) and heat pumps (23 TWh to 159 TWh). The need for electricity increases by 20%, driven by the increase in heat pumps. District heating sees an increase of 50% to a share of 18% in 2050. *Renewable fuels* will be used to meet close to 10% of the demand.

In total, there is a large increase of electricity demand for heating and cooling of buildings. However, this is compensated by the decrease of the electricity demand for appliances and lighting, so that the total electricity demand of buildings including appliances does not change a lot (see Figure 11).

Figure 11: Final energy demand of the EU buildings & appliances sector in the year 2015 and in the scenario GHG-neutral EU2050



* ambient heat includes the electricity used in heat pumps

Source: own calculation (Fraunhofer ISI and Oeko-Institute)

The CO_2 emissions of the buildings and appliances sector in the EU amounted to 636 Mt CO_2 in 2015 (UNFCCC 2017), with 620 Mt CO_2-eq. coming from the energy demand of buildings. The direct emissions almost completely result from heating and cooling of buildings (512 Mt CO_2). Due to the complete replacement of fossil fuels, these emissions are fully mitigated in the scenario GHG-neutral EU2050 (see Table 6).

Table 6: GHG emissions of buildings and appliances in the EU in 1990, 2015 & scenario GHG-neutral EU 2050

Sub-sector	UNFCCC 1990 [Mt CO_2-eq.]	UNFCCC 2015 [Mt CO_2-eq.]	GHG-neutral EU2050 [Mt CO_2-eq.]
Space heating & cooling	N/A	512	0
Hot water	N/A	108	0
Appliances	N/A	17	0
Total	**831**	**636**	**0**
change vs. 1990		-23%	-100%

Source: own calculation (Fraunhofer ISI) based on UNFCCC (2017)

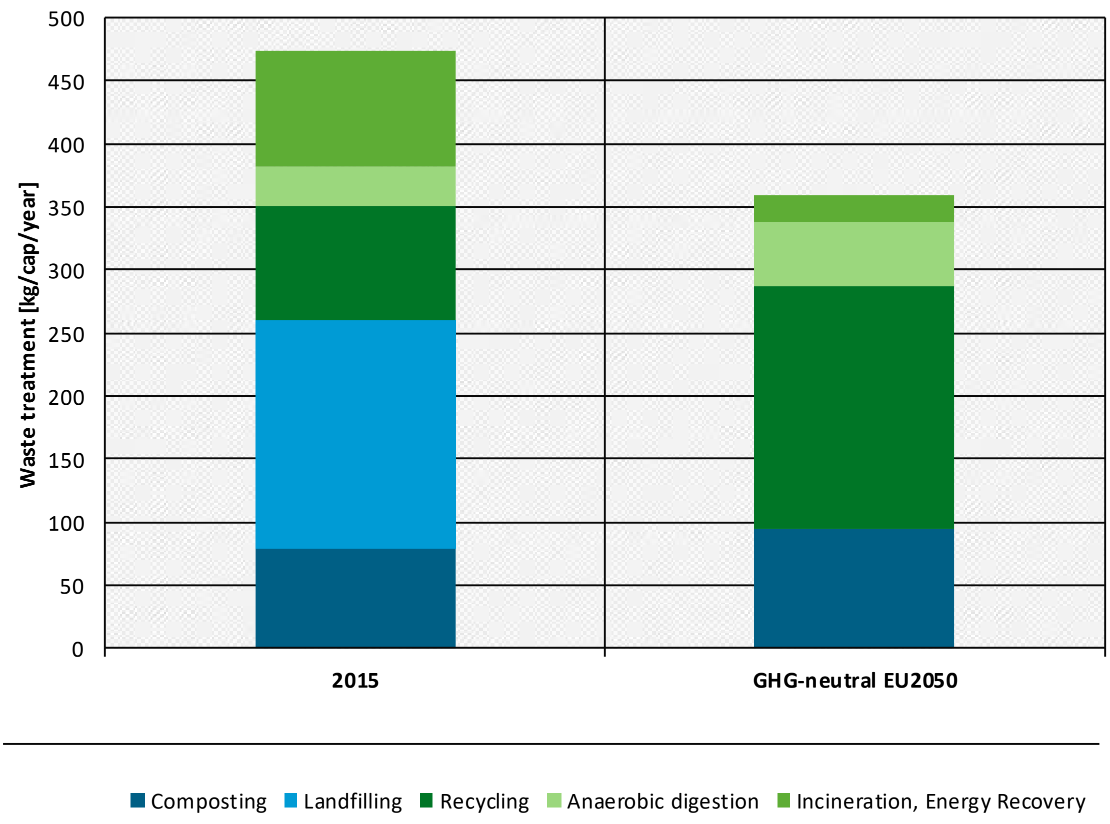
5.6 Waste and wastewater

The scenario GHG-neutral EU2050 projects that GHG emissions from waste and wastewater cannot be completely mitigated in 2050. Compared to 1990, a reduction by 89% is achieved. This reduction in emissions is mainly driven by a reduction of waste, an early stop in landfilling and an increase in recycling.

In 2015, GHG emissions from the waste sector contributed with 3% to EU total emissions (without LULUCF). Since 1990, total emissions from the waste sector decreased by 42% from 240 Mt in 1990 to 138 Mt in 2015. Taken into account emissions from waste incineration with energy recovery (which are reported under the energy sector) emissions decreased only by 26% from 255 Mt CO2 eq. to 189 Mt. CO2 eq. between 1990 and 2015 because the amount of waste incinerated increased.

As an overall driver, the generation of waste is reduced by 25% per capita in the year 2050 compared to 1990, see Figure 12. In addition, recycling rates of plastic, paper and textiles increase to 90%. In order to reduce the emissions of nitrous oxide, the scenario also assumes that the protein consumption is reduced to 50g per capita and day. In addition, food waste is reduced by 70%.

Figure 12: Waste treatment in the EU per capita according to UNFCCC inventory data for the year 2015 and assumptions for GHG-neutral EU2050



Source: UNFCCC (2017), own calculation (Oeko-Institute)

The current decreasing trend in landfilling continues, so that no more waste will be disposed of in landfills in 2050. This transition is assumed to happen early in the scenario GHG-neutral EU2050, so that landfilling is reduced to 10% in 2030. However, a certain amount of GHG emissions from existing landfills remains even in 2050 (15.1 Mt CO2-eq.), despite measures to recover landfill gas (see Table 7 for an overview). This is a reduction of 92% compared to 1990, but is still the largest source of GHG emissions in the waste sector in 2050 (39%). The remaining direct emissions come either from biological waste treatment (5.2 Mt CO_2-eq. or 14%) or waste water treatment (5.3 Mt CO_2-eq. or 14%). The scenario sees a wide distribution of aerobic wastewater treatment, which reduces GHG emissions compared with anaerobic processing.

Some waste will remain in 2050 and not be recycled, so waste incineration will still be necessary to a certain degree. This leads to emissions of 12.7 Mt CO2-eq., or 33% of the remaining emissions. This is the second largest source of emissions in the waste sector after emissions emanating from existing landfills. It includes the incineration of waste with energy recovery, which is part of energy-related emissions under the UNFCCC and, accordingly, attributed to this category in Section 4.

Table 7: GHG emissions in the waste sector until 2050 in Mt CO_2-eq.

Category	UNFCCC 1990 [Mt CO_2-eq.]	UNFCCC 2015 [Mt CO_2-eq.]	GHG-neutral EU2050 [Mt CO_2-eq.]
Landfilled	191.6	99.8	15.1
Waste incineration*	20.8	54.9	12.7
Waste water treatment	42.2	27.2	5.3
Biological waste treatment	0.7	7.3	5.2
Total	**255.5**	**189.1**	**38.4**
change vs. 1990		-26%	-85%

* including the incineration of waste with energy recovery, which is part of energy-related emissions under the UNFCCC
Source: own calculation (Oeko-Institute) based on UNFCCC (2017)

5.7 Agriculture

In 2015, the agricultural sector was responsible for 10% of GHG emissions of the EU (436.7 Mt CO_2-eq.). The level of agricultural emissions is mainly influenced by the agricultural area, the management of agricultural soils, and animal husbandry, especially husbandry of ruminant livestock.. Soils emit CO_2 and N_2O depending on the underlying surface material and nitrogen input. The livestock emits CH_4 during enteric fermentation while manure management is responsible for emissions of N_2O and also CH_4.

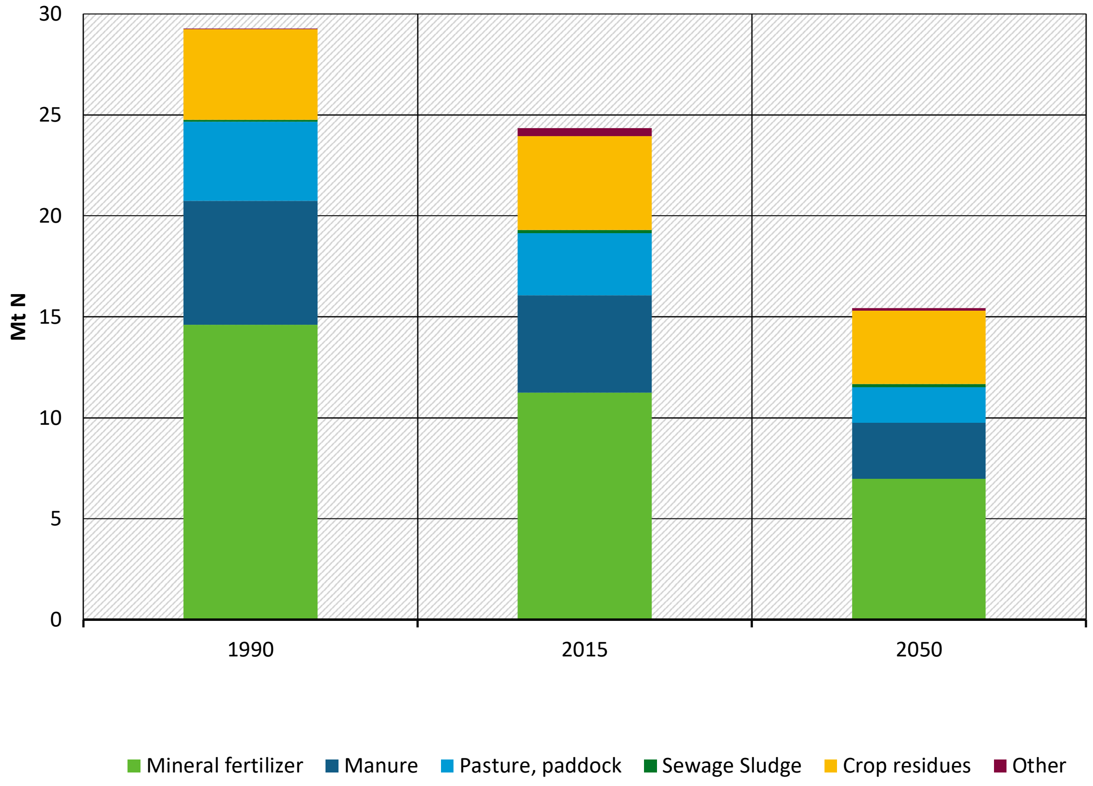
A reduction of 95% compared to 1990 is not possible without abandoning production and reducing livestock numbers. The scenario GHG-neutral EU 2050 achieves a reduction of 55% compared to 2015. Table 8 gives an overview of results for 2050.

The boundary conditions of the agricultural sector are partly given by the result of the LULUCF model (see subsection 5.8). It prescribes that the agricultural area will be reduced by 11%. This includes rewetting 50% of organic soils currently used for agricultural purposes.

The scenario GHG-neutral EU makes detailed assumptions on the reduction of livestock depending on different conditions in the member states. In total, it comes to a reduction of 42% in livestock numbers in 2050. This reduction in livestock numbers is compatible with the recommendations on healthy diets from EAT–Lancet Commission (Willett et al. 2019). Organic farming is increased to 20% (from 6% in 2015). The nitrogen surplus is limited to 30kg of nitrogen per hectare in all Member States, which represents a drastic reduction against 1990 and today. Slurry management will be implemented in 80% of farms.

Nitrogen input to agricultural soils is reduced by 37% compared to 2015 by limiting the nitrogen surplus and expanding organic farming. This leads to a reduction of 27% of GHG emissions from agricultural soils compared to 2015, see Figure 13.

Figure 13: Nitrogen input to agricultural soils in 1990, 2015 and in GHG-neutral EU2050



Source: UNFCCC (2017), own calculation (Oeko-Institute)

The emissions from enteric fermentation are directly determined by livestock numbers and go down by 42% compared to 2015. Manure management is also influenced by technical improvements and emissions therefore drop by 65% compared by 2015.

By the sum of all those measures, the emissions in the agricultural sector drop from 548.3 Mt CO_2 in 1990 to 244.5 Mt CO_2 - or by 55% - in 2050.

Table 8: GHG emissions in the agricultural sector until 2050 in Mt CO_2-eq.

Category	GHG missions 1990 [Mt CO_2-eq.]	GHG missions 2015 [Mt CO_2-eq.]	GHG emissions 2050 [Mt CO_2-eq.]
Enteric fermentation	246.7	192.2	112.2
Manure management	83.3	65.7	22.5
Agricultural soils	196.8	163.4	101.5
Other	20.9	15.4	8.7
Total	**548.3**	**436.7**	**244.5**
change vs. 1990		-20%	-55%

Source: own calculation (Oeko-Institute) based on UNFCCC (2017)

5.8 LULUCF

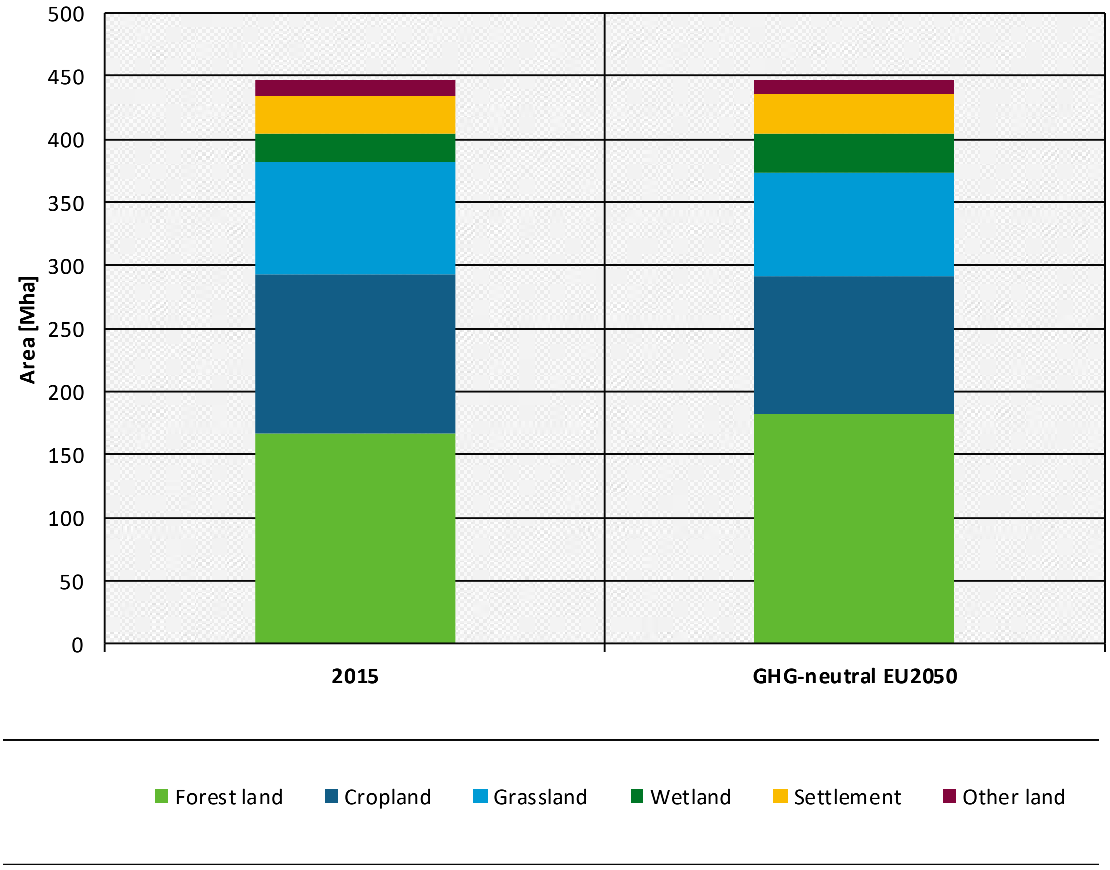
What sets the LULUCF sector (land use, land use change and forestry) apart from all others is the fact that it can serve as source or sink of GHG. In general, forests store more carbon than they emit. Settlements, grassland, cropland and wetlands are sources of GHG. The scenario GHG-neutral EU2050 additionally considers harvested wood products, which remove carbon from the system as long as they are used.

While the total area is naturally constant (448 Mha), changes in the distribution of land among the sectors determine whether LULUCF is an overall emitter of GHG or not. But the redistribution of land cannot be planned independently of the agricultural sector. Equally, biomass requirements need to be taken into account. These two limitations constrain the freedom to act in the LULUCF sector.

Despite these constraints, the scenario GHG-neutral EU2050 strengthens the status of the LULUCF sector as a GHG sink by the year 2050. Figure 14 gives the area of each sub-sector while Table 9 lists the corresponding emissions.

The main driver of change is the increase in the share of forests from 37.2% in 2015 to 40.7% in 2050 at the expense of cropland and grassland. This enhances the effectiveness of forests as carbon sink by 18.6%. The use of harvested wood products also increases in 2050 and negative emissions from this sub-sector increase from 26.2 MtCO_2 to 36.5 MtCO_2.

Figure 14: Area of main LULUCF sectors in 2015 and in the scenario GHG-neutral EU2050



Source: own calculation (Oeko-Institute)

Grassland and cropland on organic soils present just a small fraction of the respective total area (2.7% and 1.3%), but are responsible for a much larger share of emissions. 54.5% of cropland emissions come from organic soils. Grassland on mineral soil alone is a sink of emissions and only that on organic soils turns it into a source. In the scenario GHG-neutral EU, half of the land (grass, crop and forest) on organic soils is transformed and mostly to wetlands, increasing the total share of wetlands from 5.4% in 2015 to 7.1% in 2050. This reduces emissions from grassland and cropland effectively.

By these measures in the different sub-sectors, the effect of LULUCF as net emissions sink is increased by 58.5% in 2050 from removing 326.6 Mt CO_2 in 2015 to 517.7 Mt CO_2 in 2050.

Table 9: Emissions of main LULUCF sectors in 2015 and 2050 in Mt CO_2

Sub-sector	Emissions 1990 (Mt CO_2)	Emissions 2015 (Mt CO_2)	Emissions 2050 (Mt CO_2)
Forest land	-396	-427	-506
Cropland	79	58	22
Grassland	27	1	-29
Wetland	18	14.5	16
Settlement	39	47	17
Other land	4	0	-1
Harvested wood products	-31	-29	-37
Total	**-260**	**-327**	**-518**
change vs. 1990		-67	-258

Source: UNFCCC (2017) and own calculation (Oeko-Institute)

6 Sectoral leeway and cross-sectoral interactions of a GHG-neutral European Union

The scenario GHG-neutral EU2050 mainly describes one option for a sectoral setup of a European Union with net-zero GHG emissions, with the exception of the energy supply sector, where the leeway with regard to the production of renewable electricity and the import of renewable fuels is made explicit. In this section, the leeway in defining a sectoral setup is discussed also for the other sectors. Moreover, cross-sectoral interactions and the resulting synergies and trade-offs in the realization of a GHG-neutral EU are described.

6.1 Sectoral solution spaces

A way to determine the leeway with regard to the sectoral setup of a GHG-neutral EU is by comparison with other scenarios with a reduction of gross GHG emissions in a similar order of magnitude. Of course, the differences between the scenarios come about not randomly or solely because of different methods but rather because of different underlying assumptions on future technologies, consumption patterns and the overall organization of the economy. In the following, the corresponding ranges of mitigation levers in scenarios with a GHG reduction by more than 90% compared to 1990 are assessed (called full decarbonisation scenarios here). The sectors whose GHG emissions are essentially caused by their use of energy have been assessed by an index decomposition analysis, which enables the attribution of GHG emission reductions to certain key levers such as sectoral activity changes, energy efficiency, electrification and use of renewable energies. The details of the methodology are described in the technical annex (Duscha et al. 2019). The non-energy related sectors cannot be analysed by means of a decomposition analysis. Here, the assumptions and results of the scenario GHG-neutral EU2050 are directly compared with those of other scenarios.

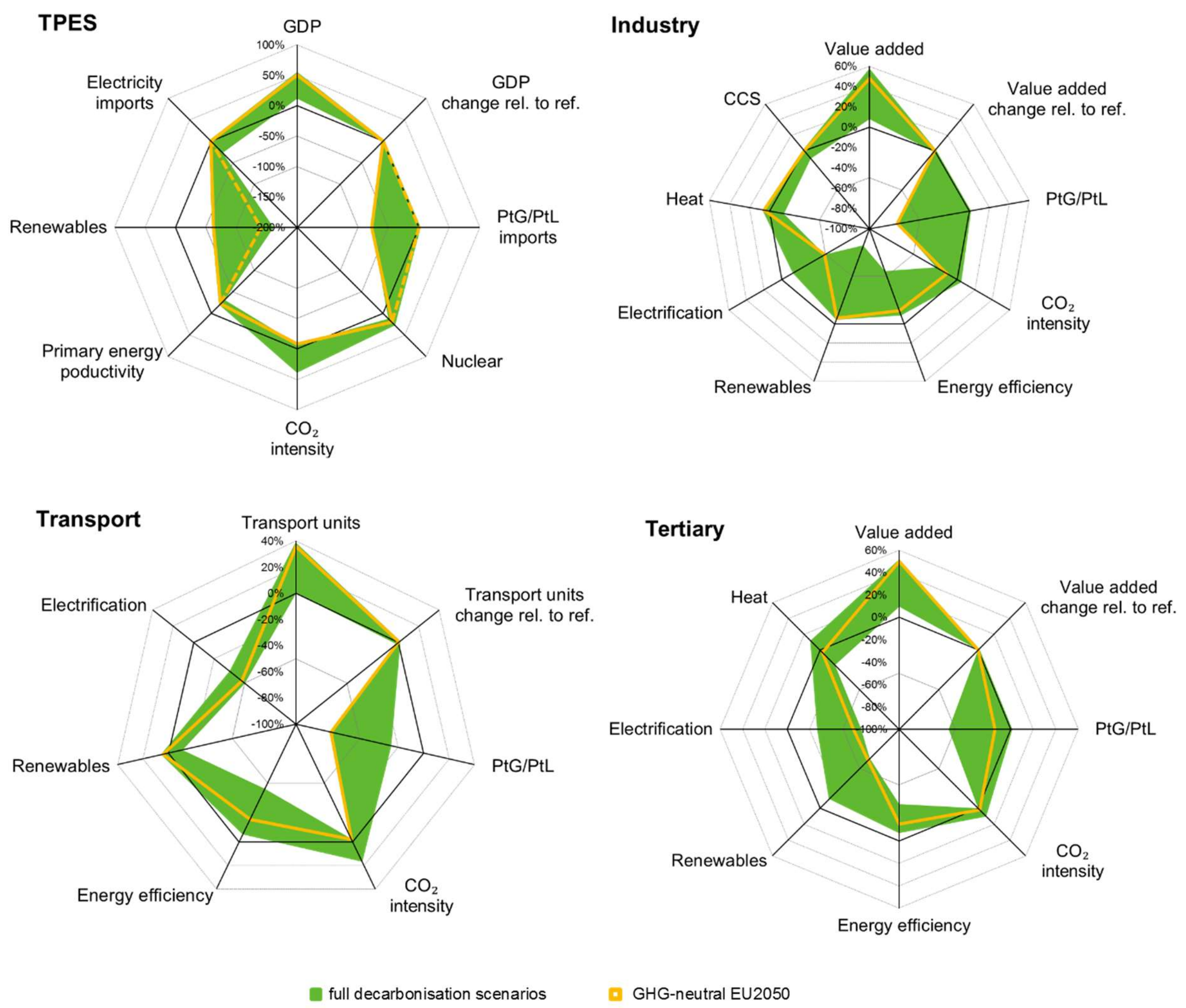
The leeway of the sectoral setups of full decarbonisation scenarios can be summarized as follows:

- With regard to the total primary energy supply, the full decarbonisation scenarios show few alternatives on how to decarbonise total primary energy supply: as they all assume strongly limited use of nuclear power and CCS, renewable energies contribute the vast share of the emission reduction. However, there is large leeway with regard to a possible import of novel fuels, which is made explicit by the scenario GHG-neutral EU2050
- In the power sector, there is little leeway for the decarbonisation, since electricity is provided from renewable sources to a very large extent. However, the necessary amount also strongly depends on whether novel fuels are imported or produced within the EU. Moreover, the power sector decarbonisation is determined by any remaining fossil power and the role of nuclear energy. In this regard, the scenario GHG-neutral EU2050 marks the 100% RES case.
- In the industrial sector, there is some leeway with regard to the shares of the levers electrification, energy efficiency, novel fuels, biogenic fuels and CCS. The scenario GHG-neutral EU2050 is at the upper end with regard to electrification and use of novel fuels, given that CCS is excluded and the use of biogenic fuels is strongly limited.

- In the transport sector, there is substantial leeway with regard to the combination of the levers electrification, energy efficiency, novel fuels and biogenic fuels, but also with regard to a reduction of transport demand. The scenario GHG-neutral EU2050 does not make use of such a demand reduction. It is at the upper end with regard to electrification and use of novel fuels, given that the use of biogenic fuels in transport is excluded and electrification of heavy-duty vehicles via catenary lines is strongly employed.
- In the residential sector, there is certain leeway with regard to the combination of the levers electrification, energy efficiency, district heating and direct use of renewables (solar and ambient heat). The scenario GHG-neutral EU2050 is at the upper end with regard to electrification and the direct use of renewables. Some scenarios assume a higher annual rate of renovations which leads to a stronger reduction of emissions through energy efficiency.
- In the tertiary sector, there is some leeway similar to the leeway in the residential sector. In particular, the scenario GHG-neutral EU2050 is at the upper end with regard to electrification and the direct use of renewables, while some scenarios assume a higher annual rate of renovations with regard to the energy efficiency lever.
- The effect of the driving forces is quite high for all sectors, while there is almost no contribution of a change of the sectoral activity relative to the reference case. This shows that the existing full decarbonisation scenarios mostly do not build on a reduction of activity based on sufficiency in the energy-related sectors. This also applies to the scenario GHG-neutral EU2050.
- Most full decarbonisation scenarios reach a similar reduction of GHG emissions in the agricultural sector. Central to those scenarios, in particular GHG-neutral EU2050, is the reduced consumption of dairy and meat products. Without the reduced consumption, there remain more agricultural GHG emissions to be compensated by carbon sinks.
- In the LULUCF, the share of forests increases in all full decarbonisation scenarios, in particular GHG-neutral EU2050, which strengthens the role of the LULUCF sector as a carbon sink. Central to this is the transformation of agricultural land that has been freed up to permanent other classes, mainly forests, with a focus on reducing the use of organic soils.

A quantitative impression of the impacts of the different energy-related levers is presented in Figure 15 for a representative set of sectors. More detailed descriptions of the results for all sectors can be found in the technical annex (Duscha et al. 2019).

Figure 15: Contributions of different emission levers to the total emission reduction by 2050[11]



Source: Own representation, based on data from Matthes et al. 2019 and Duscha et al. 2019.
TPES = total primary energy supply; ref. = reference scenario; PtG/PtL = Power-to-gas/Power-to-liquid
Dotted lines show the variant of a production of novel fuels within the EU.

6.2 Cross-sectoral interactions

While there is some leeway with regard to the combination of the various levers in most of the sectors (see Section 6.1), the exact choices of the contributions of each of the mitigation levers are not independent, as they rather influence one another. These cross-sectoral interactions complement the sectoral leeway of each sector. These interactions have been assessed based on expert knowledge. The assessment has been split into two parts: on the one hand, the interaction between demand for novel fuels, biomass supply and the land use carbon sink; on the other hand, interrelations of the demand for novel fuels, energy efficiency and sufficiency levers have been discussed. The following points give a summary of the expert knowledge about sectoral interactions concerning the sectoral interactions related to the use of novel fuels, biomass and land use:

- Framework conditions for the use of biogenic resources are given by the animal stock of the agricultural sector as well as the land use shares of woodland, wetland and agricultural land.

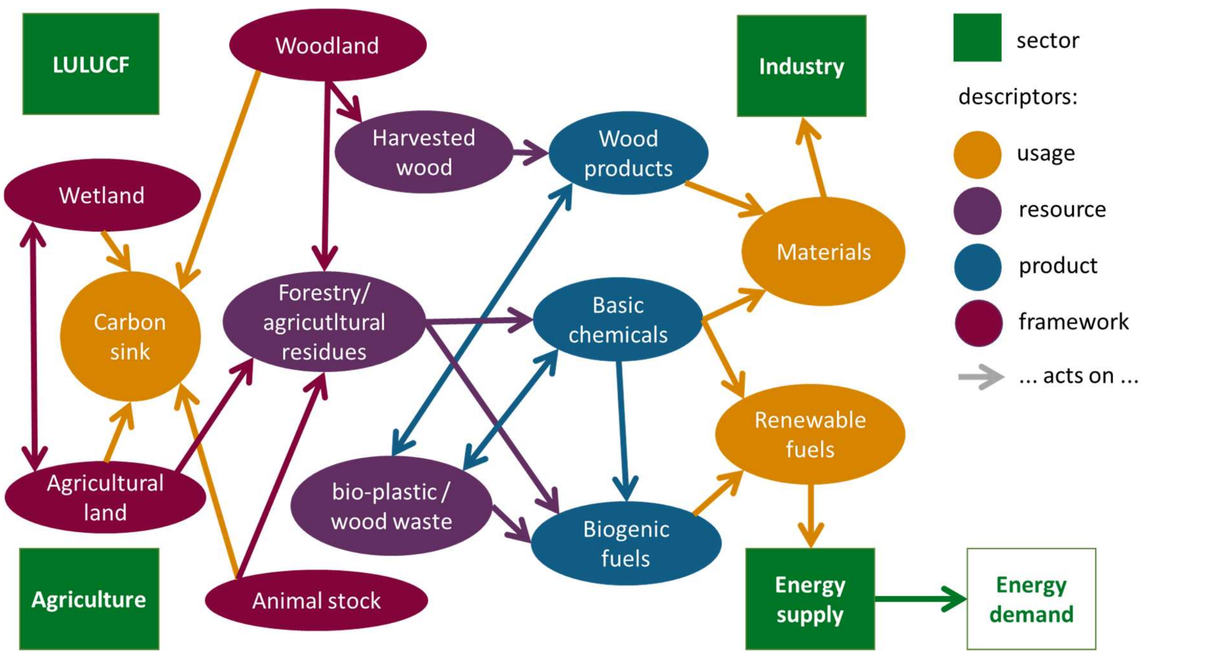
[11] The methodology used tends to underrate activity changes and energy efficiency in comparison with other levers, in particular for those scenarios with the highest overall ambition (see Duscha et al. 2019).

These land uses are in direct competition. The land use splitting also has a direct impact on the natural carbon sink. While an increase of woodlands and wetlands serves as an additional carbon sink, the animal stock (in particular bovinal) entails additional non-CO2 emissions, which have to be compensated by carbon sinks.

- As the carbon sink needs to be restored and increased, the use of biogenic products is strongly limited. Therefore, the use of biogenic products should follow a cascading approach. Harvested wood of high quality is meant to be used as a material in the industry sector mainly, neither as a feedstock for basic chemicals nor as an energy carrier.
- Forestry and agricultural residues (including manure) can be a major input to meet the feedstock demand for basic chemicals. If there is a surplus of those residues, they can also be used for energy purposes directly, in particular to produce renewable fuels. Bio-plastics waste and wood waste should be recycled if possible, but at the end of their lifetime can serve to produce renewable fuels as well.
- The cascading use of biogenic resources enables an optimized use, thereby reducing the need for novels fuels as a feedstock for basic chemicals and for energy purposes.

Figure 16 presents a graphical overview of the interactions (as arrows) of the different sectors (in boxes) within the scope of different descriptors (in ovals) related to the use of novel fuels, biomass and land use.

Figure 16: Graphical representation of the interactions between sectors with a focus on novel fuels, biomass and land use

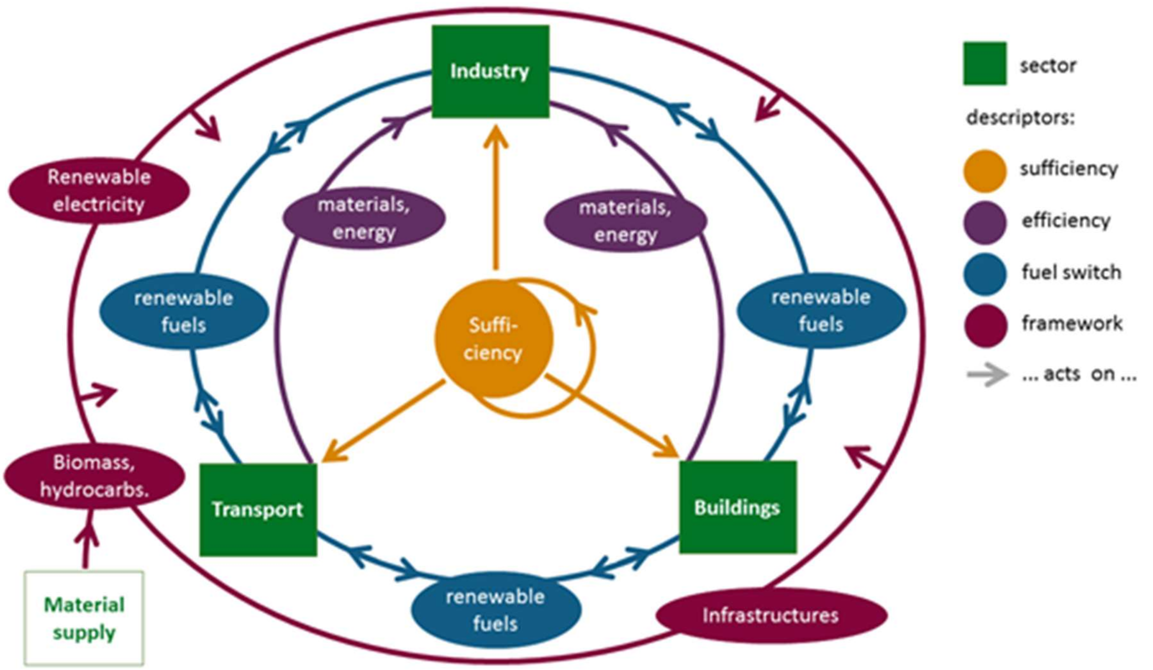


Source: Own representation (Fraunhofer ISI)

The expert knowledge about the sectoral interactions concerning the use of energy are summarized below. Figure 17 presents a graphical overview of the interactions (as arrows) of the different sectors (in boxes) within the scope of different descriptors (in ovals) with a focus on novel fuels vs. energy efficiency vs. sufficiency.

- While the energy efficiency improvements in the different sectors require separate technologies and policies, buildings and transport could stimulate industrial material and energy efficiency increases and process changes because of their dependent nature. E.g., an increase in energy-efficient renovation activity would stimulate an increase in demand of material, which could be covered by low-carbon cements if the correct incentives are set.
- The availability of novel fuels to one sector could increase its use in others and influence the transformation to alternative technologies. In turn, prices for novel fuels could increase if all sectors increase their demand. This affects all relevant sectors. The exact implications require a detailed modelling study.
- Sufficiency measures are a powerful lever on the transformation of all sectors. This lever influences all sectoral descriptors as well as the characteristics of the larger scale concept of a circular economy. Whether or not sufficient behaviour in one sector implies similar changes in another sector and how to foster these changes requires further investigation.
- The availability of energy infrastructures and renewable energies are overarching levers required for the transition in the different sectors. The investment into infrastructures requires detailed assessment to prevent technological lock-ins.
- Biomass or other sources of carbon are necessary to synthesize novel hydrocarbons. This closely links the discussion presented here to that of biomass and the land use sink presented above.

Figure 17: Graphical representation of the interactions between sectors with a focus on novel fuels vs. energy efficiency vs. sufficiency



Source: Own representation (Fraunhofer ISI) based on workshop discussion.

6.3 Conclusion on sectoral leeway and cross-sectoral interactions

In summary, the scenario GHG-neutral EU2050 is at the extreme end with regard to electrification but even more with regard to the use of novel fuels in comparison with other scenarios. This is due to the fact that the scenario focuses on the technical feasibility of net-zero GHG emissions under limited biomass availability and current trends for sectoral demands. The use of novel fuels is even more increased by the fact that the scenario includes a consideration of feedstocks and international shipping. The supply with such huge amounts of novel fuels will pose tremendous requirements with regard to infrastructure scale up and investment. These requirements can be significantly reduced, if the remaining leeway across all energy-related sectors is exploited, in particular with regard to a reduction of demand in air transportation, and a circular economy is implemented to the largest extent possible, in particular a cascading use of wood and chemical feedstocks. These aspects need to be explored in future research.

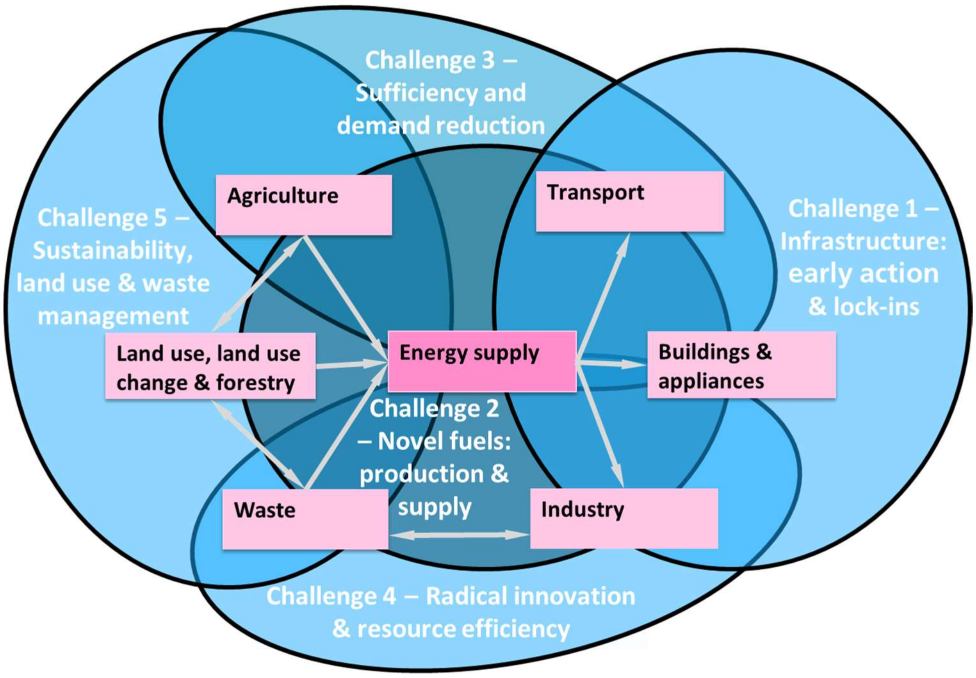
7 Major challenges towards a GHG-neutral European Union

The scenario GHG-neutral EU 2050 shows in general that GHG-neutrality even on a European scale is technically feasible. The analysis discloses that changes of lifestyles can be limited to – however, substantial – changes of food consumption patterns. There is also some leeway with regard to the relation of limiting sectoral activities, increasing energy efficiency, implementing a circular economy, and consuming renewable energy. Furthermore, other studies have shown that the realisation of net-zero GHG emissions can be beneficial from a socio-economic point of view, in particular for economic growth (see e.g. EU COM 2018b). Nevertheless, the necessary transformation to realize any kind of such a scenario is tremendous. The transformation includes overcoming certain challenges that go far beyond the obstacles in reaching the near-term climate targets. In the following, a closer indicative look at relevant challenges is taken in order to provide insights in ways to tackle them. Therefore a special emphasis is put on those challenges that occur when moving from 80% GHG reduction to net-zero GHG emissions based on the bottom-up sector analyses and the sector experts' experience. This discussion is structured with a cross-sectoral perspective and also takes into account the most important sectoral interactions. The discussion reflects both challenges related to the realisation of the particular scenario GHG-neutral EU2050 but also more general issues with regard to achieving net-zero GHG emissions. The discussion is subsumed under the following issues:

1. Infrastructure: early action and lock-ins
2. *Novel fuels*: production and supply
3. Sufficiency and demand reduction
4. Radical innovation and resource efficiency
5. Sustainability, land use and waste management

Both these clusters of key challenges when moving from 80% GHG reduction to net-zero GHG emissions and the cross-sectoral interactions are visualized in Figure 18.

Figure 18: Overview of key challenges to realize a GHG-neutral EU by 2050



Source: own representation (Fraunhofer ISI)

7.1 Infrastructure – early action and lock-ins

The reduction of GHG emissions by 80% already requires huge efforts in energy-related sectors. However, such a lower level of ambition allows to leave certain hard-to-mitigate subsectors largely untouched, in particular aviation and international shipping, buildings under monumental protection, as well as process-related emissions in the steel and cement sector. However, reaching net-zero emissions requires to tackle also these subsectors. Accordingly, the scenario GHG-neutral EU2050 envisages radical changes to energy supply, transport systems, industrial production systems as well as the building stocks in the time horizon until 2050. Furthermore, the realisation of net-zero GHG emissions requires certain distinct decisions about the chosen pathway, e.g. with regard to making use of CCS or not. Here, the scenario GHG-neutral EU2050 takes the route of a 100% RES pathway with limited use of biomass.

With regard to energy supply, the current growth rates of RES in Europe are not in line with the necessities of GHG-neutral EU2050. Although the exact mix or location of the RES plants is not determined in this study, the order of magnitude can be estimated: Let us assume that of the almost 4,000 TWh RES electricity necessary in the EU – meaning that most novel fuels production takes place outside Europe – 2,000 TWh will be from wind and 1,000 TWh from solar. Let us further assume that wind will have an average of 3,500 full-load hours, and solar 1,200 full-load hours. That would require an installed capacity of 571 GW wind energy and 833 GW photovoltaics. For reaching and maintain these capacities, gross installations need to reach 22.9 GW/a for wind energy and 33 GW/a for photovoltaics[12]. If the novel fuel production would be completely in Europe, these values would increase to 40 and 49 GW/a, correspondingly. Even without the additional electricity demand for novel fuel production, securing public acceptance for such an expansion remains to be challenging.

In the transport sector, the high proportion of electrified road vehicles requires EU-wide harmonised infrastructure development, both for cars in the form of charging infrastructure and for heavy-duty transport in the form of overhead lines. Ambitious fuel economy standards for all classes of vehicles are another crucial instrument driving the transformation of the transport sector in the scenario. In the EU, standards for passenger cars and light-duty vehicles are currently not in line with those applied in the scenario GHG-neutral EU2050, and the recently agreed standards for heavy duty vehicles are not sufficiently stringent, either.

In the buildings sector, the final energy demand for space heating is reduced by about 50% in the scenario GHG-neutral EU2050. This requires a progression of building energy standards (for new buildings as well as refurbished ones) that is very ambitious (on average -20% every 5 years). In order to limit electricity demand as in the scenario GHG-neutral EU2050, the energy consumption of appliances, lighting and cooking also has to be reduced substantially. This can be achieved by intensifying the current policies on an ongoing basis, in particular minimum energy performance standards. In addition, improved labelling also contributes to more energy-conscious buildings and purchasing behavior.

A crucial cross-sectoral issue is the electrification of all energy-consuming sectors. An important prerequisite is the extension of the electricity grid in parallel with the expansion of renewable electricity generation. This applies both to the national grids (on both transmission and distribution levels) and also the interconnectors between the member states. The latter is particularly important to enable a cost-efficient expansion of the supply with renewable energies. The scenario GHG-neutral EU2050 envisages a use of hydrogen mainly in regional industry clusters. This requires building local hydrogen pipelines for interconnection. However,

[12] Assumed Lifetime of wind solar power plants is 25 years.

hydrogen could also be used as a complimenting fuel in the transport sector and/or fed into the gas grids to a certain extent. This would require an EU-wide harmonization of the gas infrastructure.

Furthermore, the gas infrastructure plays an important role in the realization of a scenario like GHG-neutral EU 2050. While the consumption of natural gas has to be phased out to the largest possible extent, the supply with renewable gases becomes key to ensure the supply with residual fuels. To this end, the European gas infrastructure needs to be adapted, as the production and import of electricity-based fuels can be expected to lead to new import routes. In addition, there is a trade-off between introducing ambitious demand-side mitigation options and using more synthetic renewable fuels. This suggests a vast range of the remaining demand for renewable fuels, which entails challenges to keep the gas infrastructure economically viable. Hence, early policy action is necessary to avoid possible lock-ins with regard to the gas infrastructure (cf. UBA 2019).

In general, it is necessary to set incentives towards a net-zero emissions economy as early as possible, as wrong investment decisions taken in the coming decade may already lead to carbon lock-ins in the year 2050, e.g. in the building stock and industrial production plants.

7.2 Novel fuels: production and supply

In spite of a high level of electrification in the scenario GHG-neutral EU2050, there remains a demand for gaseous and/or liquid energy carriers in all energy-consuming sectors, with extent and type depending on the sector, as well as for feedstocks. In scenarios with 80% GHG emission reduction, these remaining fuels can still be met by fossil fuels to a certain extent. To mitigate all energy-related GHG emissions, however, this demand has to be covered by *renewable fuels*, which are either biogenic or generated from renewable electricity, like RES-methane, hydrocarbons from PtL or PtX synthesis or hydrogen. Currently, biomass is the most important RES in industry, transport and buildings. However, sustainable biomass potentials are limited, in particular when the demand for biomass of other sectors such as agriculture and the construction sector is taken into account. Therefore, RES-electricity based *novel fuels* play an important role in all sectors. A carbon-neutral electricity generation is thus a central prerequisite.

When assuming a growth of transport activity based on standard projections, a particularly high share of *novel fuels* is necessary in the transport sector, supplying roughly two thirds of the energy (see Figure 6). Due to ambitious efficiency measures, the energy demand for navigation decreases, despite rising activity. In aviation, the efficiency increase cannot outweigh the rise in activity. Since a direct use of electricity seems impossible from today's perspective, both subsectors depend entirely on *novel fuels* to meet their energy demand in the scenario GHG-neutral EU2050. For road transport, the scenario GHG-neutral EU2050 assumes an increase in the market penetration of electric vehicles and electric trucks from just a few percent today to 75% in stock in 2050. Nevertheless, in this scenario there remains a significant need for *novel fuels* for road transport, too. As it will be difficult and expensive to produce such large amounts of *novel fuels*, these findings call for addressing options to limit transport activity, too, in particular in aviation and international shipping.

In the industry sector, the scenario GHG-neutral EU2050 also assumes an increased direct use of electricity, but depending on the subsector, *novel fuels* will play an important role to meet the energy demand. The iron and steel industry stands out, using hydrogen to meet roughly 50% of the energy demand. A certain amount of *novel fuels* is used in every sector, led by the production of non-metallic mineral products (cement and lime among others) and the chemistry industry.

In the latter, it is also important to replace fossil carbon feedstocks by renewable sources. Here, hydrogen and CO_2 may serve as feedstock to produce platform chemicals.

For the building sector, the scenario GHG-neutral EU2050 is more cautious about the use of *novel fuels*. Other RES options like solar thermal or ambient heat are available to decarbonize this sector. Still, *novel fuels* play an important role and supply about 10% of the energy for space heating hot water in this scenario GHG-neutral EU2050. Finally, *novel fuels* are also necessary to some extent for fuelling power plants that compensate for the fluctuations of fluctuating RES electricity generation from wind and PV plants.

The energy needed to produce all kinds of *novel fuels* will be a key driver for electricity demand. The use of hydrogen is generally more efficient because losses during the synthesis of hydrocarbons and for supplying CO_2 are avoided and moreover because the use of hydrogen in fuel cells is also more effective than burning hydrocarbons in combustion engines. However, transporting hydrogen has higher infrastructure requirements. Nevertheless, given the large amounts of *novel fuels* present in the scenario GHG-neutral EU2050, the utilization of the infrastructure can be expected to be high, which limits the additional infrastructure costs. In total, these arguments, hence, suggest that maximizing the share of hydrogen in the *novel fuels* is favourable.

In spite of that, there remains a need for hydrocarbons in certain sectors, in particular in maritime and air transport as well as in chemical industry. To achieve GHG neutrality, all carbon used in energy carriers and feedstocks needs to be renewable except in the cement sector and in the small remaining share of non-renewable waste. Renewable carbon sources are both biomass and direct air capture (DAC); for the amounts needed in this scenario, the overwhelming majority will have to come from DAC. There is no use in separating these two sources once the carbon has been feed into the energy and/or material cycle.

While it is hardly possible to re-capture the carbon in decentral applications like in the transport sector, it is beneficial to re-capture the emitted CO_2 in the centralized industrial processes, as this requires usually less effort than DAC and is therefore cheaper. Capture rates of up to 90% are feasible already today (see Hermann et al. 2014). The captured CO_2 can be used to produce renewable hydrocarbons based on renewable hydrogen. To organize the production of the hydrocarbons in an effective way, it can be useful to pool the captured CO_2. To this end, an infrastructure for transporting CO_2 that connects regional industrial production clusters is necessary. One option for this is to convert gas pipelines not used anymore due to the lower demand for gas (see Trinomics 2018). If the production of novel fuels should take place outside of Europe, the CO_2 would have to be transported to those sites. Nevertheless, carbon losses require an additional input of carbon here, too. This can again come from DAC or biomass. Moreover, since the CO_2 from biogenic sources is limited as explained above and capture is only meaningful in centralized processes, there remains a large demand for hydrocarbons based on DAC of CO_2. In particular, this applies to all *novel fuels* used in aviation and navigation, due to the fact that the use of biomass for these applications has been excluded for sustainability reasons in the scenario GHG-neutral EU2050.

It should be pointed out here that there is a sufficient technical potential to provide renewable electricity for the production of all the *novel fuels* in the EU, with levelized costs of electricity (LCOE) generation in the not unreasonable order of 100 EUR/MWh. Nevertheless, the land use requirements are extensive and are likely to result in issues with social acceptance of a RES expansion in the necessary magnitude. Therefore, the import of *novel fuels* is an important option to take into account. For hydrogen, however, the transport is rather expensive so that a production within the EU could be favourable. For hydrocarbons, transport is cheap and the high additional electricity demand for DAC of the required CO_2 can be met much easier in regions with lower LCOEs of RES power generation, such as Northern Africa (cf. UBA 2016).

Nonetheless, the costs of *novel fuels* will be another obstacle. Even under optimistic technologic advancements, the fuels will cost a multiple of their fossil counterparts. At least in next decades, even a very high carbon price will not be sufficient to incentivise demand for *novel fuels*. Furthermore, in order to prevent carbon leakage, any attempt for large scale diffusion of *novel fuels* in the industry sector requires international coordination; otherwise, companies using *novel fuels* will be disadvantaged to their international competitors using fossil fuels. This is, however, true for aspects of decarbonisation as well.

7.3 Sufficiency and demand reduction

In many areas, the scenario GHG-neutral EU2050 uses assumptions on the activity levels or demands for certain services or goods. For reasons of comparability and to prove the feasibility, these assumptions have been based mainly on the standard projections for the EU, in particular for the energy-related sectors. Only in the agricultural sector, demand changes are shown to be necessary in any case to achieve net-zero GHG emissions due to unavoidable non-CO_2 emissions. In the other sector, however, the standard projections for sectoral activities may also not apply anymore, when a pathway towards net-zero emissions is fostered by the society. This is often directly or indirectly linked to questions of sufficiency, i.e. changes in behaviour, in particular consumption patterns, which ultimately lead to a reduction of GHG emissions.

The agricultural changes are strongly linked to food consumption patterns. An increase in organic farming along with a reduction of livestock not only reduces emissions but also the availability of meat and dairy products on the market. An internationalisation of food production by increasing imports would counteract the goal of reducing emissions globally, making changes in consumption patterns unavoidable. A detailed analysis discloses that traditional dietary habits need to be changed substantially in many EU MS (see the technical annex Duscha et al. 2019 for details). In particular, the climate-friendly diets are also not in line with today's nutritional recommendations, especially concerning milk consumption. Therefore, the official recommendations urgently need to be revised. However, it must also be emphasized that most MS already have national recommendations for meat consumption at hand that are in line with the principles of a climate-friendly diet. As consumption is significantly higher than the existing national recommendations today, there does not seem to be a clear link between dietary recommendations and consumption levels in reality. For the introduction of political instruments on the demand side, this means that besides an expansion of information and education, instruments of price control should also be introduced. These considerations are closely linked to emissions from the waste sector, which partly also depend on the reduction of protein intake. Further, related to this is the reduction of food waste. Therefore, a strong reduction of emissions in agriculture and food sector demand for a change not only of consumption patterns but also of dietaries.

The final energy demand of passenger transport is strongly driven by an increase in transport activity, resulting in a large demand for novel fuels, in particular for aviation. As the supply with novel fuels comes with large challenges and also certain side-effects (see Section 7.2), this demand should be limited by reducing the amount of flights where possible and providing smart mobility systems. The same applies to freight transport, where regional economic cycles would reduce the necessary mileage. However, this requires additional regulatory support by e.g. additional certification or financial incentives for regional production. The motorised distance per passenger may also be reduced by a shift to non-motorised modes or to public transport. But passenger car mobility will only drop if the supply of alternative services is improved and the relative costs fall significantly. A more pronounced shift of freight from road to rail transport also reduces final energy demand.

Industrial production is determined by the demand for certain products, which gives a far-reaching lever to regulation. In addition to a direct reduction, an increase in recycling of different materials or in material efficiency would help in achieving net-zero GHG emissions by limiting the extent of radical innovations and renewable fuels needed.

The housing sector faces future challenges that strongly depend on the regional circumstances. In areas with decreasing population, the per capita floor area may increase dramatically whereas increases in population extent the pressure on the housing market. As a consequence, the energy needed per person for space heating may change dramatically if no counter-measures are taken. Due to the regional differences, this challenge is to be tackled by local authorities in particular. A sufficiency-based reduction of living area per capita in cities will not only reduce the burden for climate mitigation but also help to cope with an increasing urban population.

The changes in the agricultural sector, hence, require sufficiency measures that support a societal change towards lifestyles that are more sustainable, in particular a substantially lower meat consumption, which is more in line with the official guidelines for a healthier food consumption. Also in the other sectors, the challenges will be substantially smaller if demand reductions are achieved. Such a societal transformation cannot be steered from the political side. However, it can be governed by various measures such as incentives, e.g. better information of consumers about positive health impacts, but also regulations, e.g. internalisation of external costs.

7.4 Radical innovations and resource efficiency

The scenario GHG-neutral EU2050 mostly builds on technologies that are available today, since radical innovations are per se not predictable. However, there are close-to-mature technologies and concepts discussed to date which are very likely to be necessary to reduce GHG emissions to net-zero instead of only 80% reduction. Furthermore, they may open up opportunities to mitigate emissions that seem unavoidable today. In order to achieve timely a comprehensive diffusion of the necessary innovations, the required technologies have to be ready for diffusion by 2030 at the latest. Therefore, substantial research, development and innovation activities need to take place in the coming decade.

In the industry, where energy-intensive processes have been optimised over the past decades, incremental progress of energy efficiency by improvements of the different processes is an important pillar of the industrial decarbonisation. However, much more deep emission cuts are necessary. Those require substantial changes in the iron and steel, cement and chemicals industries in addition to the support for RES and energy efficiency. In the steel sector, the mature but not common process of direct reduction offers the option of a fuel switch to hydrogen in order to mitigate emissions completely. In the cement sector, there currently seem to be no option for a full decarbonisation, but new types of processes enable to produce new kinds of clinker leading to cement with a much lower carbon-footprint. The carbon supply to the chemical industry as feedstock needs to be singled out since carbon itself cannot be replaced as a feedstock, but will need to come from renewable sources. Here, innovations that increase the rate of carbon that can be sequestered could play an important role.

For all these radical innovations, pilot and demonstration plants need to be built to prepare for market introduction. It might easily take ten years for new processes in the materials industry to progress from lab-scale to market. Certification processes such as those needed for new cement types can prolong the time taken even more. Consequently, the current policy mix needs to be adjusted to effectively support R&D activities directed at the GHG-neutrality of all subsectors. The following roll-out will pose additional challenges due to the difficulties in replacing well-established production routes.

A rather cross-cutting issue in industry is a necessary increase of resource efficiency. In the iron and steel industry, an increase of scrap availability is necessary.[13] In the cement industry, re-carbonating cement products have to enter the market in order to reduce clinker production, and limited concrete recycling that allows replacing limestone is assumed to take place in the scenario GHG-neutral EU2050. In the chemical industry, waste plastics will also increasingly become a source of renewable carbon, when plastics is increasingly produced with renewable fuels as a feedstock (see Section 5.4). Similar considerations apply to the construction sector and the energy industry as well and also affect the waste sector, as this is linked to increasing recycling rates. The issue of resource efficiency is not only important for achieving GHG-neutrality but also to make use of limited resources in a sustainable way. In particular, the new technologies used for mitigation contain various kinds of rare elements, whose use should be limited as far as possible (cf. UBA 2013). Therefore, the choice of mitigation options should take into account considerations on resource efficiency. In general, this requires a circular economy approach. Products have to be considered as carriers of valuable resources that should be recycled after use and then reused as raw materials.

7.5 Sustainability, land use and waste management

The agricultural and land use sectors come under increasing pressure to respond to different and partly contrasting demands. Besides the necessary reduction of GHG emissions to meet climate protection targets, other environmental goals also need to be considered, i.e. concerning water quality or biodiversity.

The transition seen by the scenario GHG-neutral EU2050 in the LULUCF sector itself can already be taken as a major challenge, where contrasting interests limit the options of change by land conversion. The transformation of cropland to wetland and forest reduces the production of agricultural goods in the EU. A similar reduction is expected from the conversion of farming practices to organic farming. In order to avoid an increase of imports of agricultural goods, demand side measures to increase efficiency and promote sufficiency need to be taken.

The newly established forests from former crop- and grasslands will not immediately provide the same amount or quality of biomass and timber as existing forests. The use of biomass for energy purposes is limited in the scenario GHG-neutral EU2050 and harvest amounts are kept constant. However, the demand for carbon by the chemical industry will need to be met from renewable sources, one of which could be an increased use of biomass. This need for biomass therefore needs to be managed well in order to avert negative effects on soil, water, landscape and biodiversity while minimizing the competition with timber and food supply.

The agricultural sector has little room for innovations. Currently, nitrification inhibitors are already in use in parts of the world. The scenario GHG-neutral EU2050 does not consider them because of potential environmental impacts and the missing evidence for a lasting reduction effect. Similarly, feed additives to reduce CH_4 emissions from enteric fermentation are not considered because of restrictions regarding animal welfare and food safety. However, by improving these innovations or developing similar but sustainable alternatives, the agricultural GHG emissions could be further reduced by the year 2050. However, the reduction of animal

[13] This does not mean that scrap to other world regions should be excluded, as emission reductions in steel production are necessary around the globe.

stocks is necessary to a certain extent in any case, in order to free up land resources for the increase of natural carbon sinks.

The reduction of CH_4 emissions from landfills strongly depends on a fast reduction of waste disposal on landfills. Until the year 2030 only 10 % of municipal waste can be landfilled to achieve the reduction target in 2050. The technical mitigation options to reduce emissions from the waste sector are available and already in place in countries like Germany. The implementation is therefore primarily dependent on strengthening the political targets, adaptation of implementation strategies and costs. More detailed considerations of the pathways show that changing the current waste management practices in the next years has an impact on emissions in 2050 (see the Technical Annex by Duscha et al. 2019). The differences of 5 – 8 Mt CO2-eq. may be small in comparison to the current high total emissions in the EU. However, for reaching the final target of -95% in 2050 also these small amounts of emission reductions are relevant.

7.6 Further challenges – pathways towards GHG-neutrality

The scenario GHG-neutral EU2050 provides one concrete picture of an EU with net-zero GHG emissions. Recently, other studies have also provided scenarios that show the feasibility of net-zero GHG emissions in the EU, in particular the scenario analysis in the In-depth Analysis underlying the EU Commission's Strategic Vision "A clean planet for all" (EU COM 2018b) and the study "Net-Zero by 2050: From Whether to How" (Climact 2018). While the scenarios differ in certain aspects, e.g. with regard to the use of bioenergy and CCS, they agree in the vast majority of regards, in particular with regard to the necessity to reduce energy-related emissions to a minimum and to make use of natural carbon sinks to compensate for unavoidable GHG emissions. Moreover, the clusters of challenges described in this section mainly apply to all these scenarios. Hence, the identified challenges with regard to infrastructures, novel fuels, radical innovations, sufficiency and land use will need to be addressed by upcoming political debates on climate policy being compatible with the Paris Agreement in any case.

However, it is necessary to look not only at the end point of a GHG-neutral EU but also to assess in detail the pathways connecting the status of today with that end point. The end point developed in this study has taken into account the techno-economic lock-ins resulting from the current pathways to a certain extent, but cost considerations have played a minor role in the selection of the setup. The focus here was on the technical feasibility of a GHG-neutral EU under sustainability restrictions. When looking at the pathways, however, considerations of societal costs and acceptability have to be addressed thoroughly. This may result in some of the challenges turning out to be even greater, but some may also turn out to be smaller than expected, in particular when long-term economic benefits and also the multiple other benefits, e.g. with regard to health and comfort, can be shown to be expectable.

8 Conclusions

Given that the Paris Agreement (UNFCCC 2015) has strengthened the long-term temperature goal and that it calls for a balance of GHG emissions and sinks within the 21st century, there is a strong need to re-assess the long-term targets of the EU and to point out how the target of GHG neutrality can be reached in the EU.

Since the question of how to design an EU with net-zero GHG emissions is a rather new topic that has not been too much explored, the aim of this study has been to design the scenario GHG-neutral EU2050 as one particular way to achieve a balance of GHG emissions and sinks in the EU under further sustainability criteria, i.e. without the use of CCS and only limited amounts of bioenergy. Due to unavoidable GHG emissions from agriculture, industrial processes and waste treatment, however, a lower activity of the agricultural sector and an increased GHG sink from the LULUCF sector is necessary. In the scenario GHG-neutral EU2050, this is shown to be achievable, in particular by halving the number of animal livestock units and by increasing the land use sink to more than 500 Mt CO_2 annually due to a higher share of land being dedicated to forestry.

Key ingredients of the scenario in all energy-consuming sectors (industry, buildings and transport) are a strong increase of energy efficiency as well as a far-reaching electrification. In particular, this includes the electrification of large parts of terrestrial freight transport and heat pumps for decentral and central heating purposes. By these measures, the final energy demand (including international transport) can be reduced by about 37% to roughly 8,500 TWh and the share of electricity can be increased to almost 50%. Nevertheless, the broad portfolio of other renewable energy options has to be exploited and *renewable fuels*, which are produced from renewable electricity via electrolysis or based on biomass, are required in the substantial order of 3,500 TWh (4,750 TWh including feedstocks). If the *novel fuels* generated from electricity were to be produced domestically, this would result in a drastic increase of the electricity demand in the order of 250% compared to 2015. As this may be in conflict with issues of social acceptance, the import of *novel fuels*, in particular hydrocarbons, can play a key role for the realization of a scenario such as GHG-neutral EUGHG-neutral EU2050.

The EC's Strategic Vision "A clean planet for all" has come up with seven building blocks for net-zero GHG emissions in the EU, namely (1) maximise the benefits of energy efficiency, including zero emission buildings, (2) maximise deployment of renewables and use of electricity to fully decarbonise Europe's energy supply, (3) clean, safe and connected mobility, (4) a competitive EU industry and the circular economy, (5) develop an adequate smart network infrastructure and inter-connections, (6) reap the full benefits of bio-economy and create essential carbon sinks, and (7) tackle remaining CO_2 emissions with carbon capture and storage.

The first five building blocks are generally in accordance with the key ingredients of the scenario GHG-neutral EU2050, although the focus may be a bit different for some sectors and mitigation options. For the latter two building blocks, however, there are significant differences to the scenario GHG-neutral EU2050. The sixth building block has also some overlap with the main lines of the LULUCF sector in the scenario GHG-neutral EU2050 but differs with regard to the role of bioenergy, which is strongly limited in the scenario GHG-neutral EU2050. The differences are even larger with regard to the seventh building block. While the scenario GHG-neutral EU2050 shows that a GHG-neutral EU can be realized without the use of CCS, the last building block of the EC's Strategic Vision gives CCS a central role. A better understanding of this discrepancy will be essential for deriving a reasonable long-term strategy to foster the EC's Strategic Vision. The scenario GHG-neutral EU2050 provides important insights in this regard.

Currently, the EU is on track to reach its 2020 target of reducing GHG emissions by 20% and EU regulations compatible with the 2030 target of 40% GHG reduction have come into force, though not implemented in the Member States yet (EU COM 2018b). Anyway, all sectors are not yet on track for reaching the current GHG reduction target of 80% to 95% by 2050. The realisation of the scenario GHG-neutral EU2050 requires huge efforts that go far beyond the challenges of reaching the nearer term climate targets in 2020 and 2030:

- Infrastructure developments need to be harmonised across the EU. This includes electricity and gas grids but also the transport infrastructure to enable market penetration of electric vehicles, including EU-wide catenary lines for freight transport. All of these measures require early and coordinated multilateral action to provide the necessary infrastructure.
- *Renewable fuels* supply substantial amounts of energy to the transport sector, certain parts of industry and buildings. Therefore, efforts must be made to bring *renewable fuels* into the market. Since using biomass for their synthesis is a very limited option, there is a huge need for scale up of capacities for producing and/or importing electricity-based *novel fuels*.
- Energy efficiency standards for buildings, heating, appliances and vehicles need to be extremely ambitious. To achieve energy intensity reductions in line with the scenario GHG-neutral EU2050, it is essential to ensure that renovations meet the highest energy performance standards and that steps are taken to accelerate renovation rates substantially. In order to reduce demand in the transport sector, monetary and regulatory incentives for an economy of short distances and increased public transport must be implemented.
- Radical innovations are necessary in the industry sector, in particular the steel sector and the cement sector. Research and development in the coming decade needs to foster the development and upscaling of new zero- or low-emission processes and to enable market readiness by 2030. These new processes then need to be put into use rapidly.
- Measures to reduce the consumption of dairy and meat products are required to limit GHG emissions of the agricultural sector. This enables an increase in organic farming, afforestation and rewetting of organic soils while limiting the dependency on imports.
- The LULUCF sinks needs to be increased to compensate for unavoidable GHG emissions. This means that afforestation should not be counteracted by increasing harvest rates. Such transitions in land use need to be well managed and account for other ecosystem services.
- Waste management needs to be implemented to quickly reduce landfilling with the related emissions. Recycling rates need to increase to the largest possible extent.

The scenario GHG-neutral EU2050 provides one concrete picture of an EU with net-zero GHG emissions. Nevertheless, there is substantial leeway with regard to certain aspects of the scenario, among others the use of novel fuels vs. biogenic fuels and the extent of lifestyle changes vs. electrification vs. use of renewable fuels. In comparison with other scenarios, the scenario GHG-neutral EU2050 is at the extreme end with regard to electrification but even more with regard to the use of novel fuels. This is due to the fact that the scenario focuses on the technical feasibility of net-zero GHG emissions under limited biomass availability and current trends for sectoral demands. The use of novel fuels is even more increased by the fact that the scenario includes a consideration of feedstocks and international shipping. The supply with such huge amounts of novel fuels will pose tremendous requirements with regard to infrastructure scale up and investment. These requirements can be significantly reduced, if the remaining leeway across all energy-related sectors is exploited, in particular with regard to a reduction of demand in air transportation, and a circular economy is implemented to the largest extent possible, in particular a cascading use of wood and chemical feedstocks. These aspects need to be explored in future research. Finally, this study has focused on an EU with net-zero GHG emissions in 2050 and (almost) did not look at the pathways that lead to this target. In particular, cost considerations and infrastructure lock-ins have played only a minor role. A detailed exploration of the pathways to reach the target of a GHG-neutral EU also remains a task for future research.

9 List of references

Bukowski, M.; Gaska, J.; Jackl, F.; Kassenberg, A.; Pankowiec, A.; Sniegocki, A. et al. (2013): 2050.pl the journey to the low-emission future. Available online at http://np2050.pl/files/pliki/raport_low-emission_poland_2050.pdf, last accessed 19 October 2017.

Climact (2018): Net-Zero by 2050: From Whether to How. Commissioned by the European Climate Foundation. Online available at: https://europeanclimate.org/a-net-zero-emissions-european-society-by-2050-is-within-reach-but-getting-there-starts-today/, last accessed 27 Feb 2019.

Duscha V.; Denishchenkova, A.; Wachsmuth, J. (2018): Achievability of the Paris Agreement targets in the EU: Demand-side reduction potentials in a carbon budget perspective. Climate Policy. https://doi.org/10.1080/14693062.2018.1471385

Duscha V.; Wachsmuth, J.; Eckstein, Herbst, A.; Manz, P.; Marscheider-Weidemann, F.; Pfluger, B.; Steinbach, J.; Böttcher, H.; Bürger, V.; Hesse, T.; Scheffler, M.; Wiegmann, K.; Zimmer, W. (2019): GHG-neutral EU2050, technical annex. Climate Change 40/2019. ISSN 1862-4804, Dessau-Roßlau, November 2019.

EEA (2017): European Environment Agency, Mobility and Transport – Statistical pocketbook 2017, June 2017.

EU COM (2011a): A Roadmap for moving to a competitive low carbon economy in 2050. Text 52011DC0112. Brussels

EU COM (2011b): Energy Roadmap 2050. Impact Assessment. Part 2/2. SEC(2011) 1565. Available online at https://ec.europa.eu/energy/sites/ener/files/documents/sec_2011_1565_part2.pdf, last accessed 10 March 2018.

EU COM (2016): European Commission, "EU Reference Scenario 2016. Energy, transport and GHG emissions. Trends to 2050". Online available at: https://ec.europa.eu/energy/en/data-analysis/energy-modelling, last accessed 27 Feb 2019.

EU COM (2018a): European Commission, "COM(2018) 773. A Clean Planet for all. A Eu-ropean strategic long-term vision for a prosperous, modern, competitive and climate neutral economy.," Brussels, Belgium, 2018.

EU COM (2018b): European Commission, "In-Depth Analysis in Support of the Commission Communication COM(2018) 773," Brussels, Belgium, 2018.

EUROSTAT (2017): Energy balance sheets — 2015 data — 2017 edition. ISBN: 978-92-79-69844-6. DOI 10.2785/032728. Online available at: https://ec.europa.eu/eurostat/documents/3217494/8113778/KS-EN-17-001-EN-N.pdf/99cc20f1-cb11-4886-80f9-43ce0ab7823c, last accessed 22 Dec 2018.

Greenpeace (2010): Energy [R]evolution 2010. A sustainable world energy outlook. Available at http://www.greenpeace.org/international/en/publications/reports/Energy-Revolution-A-Sustainable-World-Energy-Outlook/, last accessed 22 Nov 2017.

Greenpeace (2015): Energy [R]evolution. A sustainable world energy outlook 2015. Available at http://www.greenpeace.org/international/en/publications/Campaign-reports/Climate-Reports/Energy-Revolution-2015/, last accessed 22 Nov 2017.

Gustavsson, M.; Särnholm, E.; Stigson, P.; Zetterberg, L. (2011): Energy Scenario for Sweden 2050. Based on Renewable Energy Technologies and Sources. Available online at http://www.wwf.se/source.php/1409709/Energy%20Scenario%20for%20Sweden%202050_bakgrundsrapport%20IVL_sep%202011.pdf, last accessed 19 October 2017.

Hermann, H., Emele, L., & Loreck, C. (2014): Prüfung der klimapolitischen Konsistenz und der Kosten von Methanisierungsstrategien. Study. Öko-Institut, Berlin. Online available at: https://www.oeko.de/oekodoc/2005/2014-021-de.pdf, last accessed 27 May 2018.

IEA (International Energy Agency) (2016): World Energy Outlook 2016. Paris. Available at https://www.iea.org/bookshop/720-World_Energy_Outlook_2016, last accessed 22 Nov 2017.

IEA (2018): World Energy Outlook 2018: OECD Publishing. Online verfügbar unter: https://www.iea.org/weo2018/, zuletzt geprüft am 08.02.2019.

Intergovernmental Panel on Climate Change - IPCC (2006): 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). IGES, Japan.

Matthes, F. C.; Blanck, R.; Greiner, B.; Zimmer, W. (2018): The Vision Scenario for the European Union. 2017 Update for the EU-28. Report for the Greens/EFA Group in the European Parliament. Available online at https://www.oeko.de/fileadmin/oekodoc/Vision_Scenario__EU-28-Report_2017.pdf, last accessed 10 March 2018.

Matthes, F., Greiner, B., Duscha, V., Wachsmuth, J. (2019): Low Carbon Europe 2050: Decomposition analysis of long-term projections for the European Union and selected member States. Interim report. Climate Change 28/2019. ISSN 1862-4804, Dessau-Roßlau, Juli 2019.

Öko-Institut & Fraunhofer ISI (2015): Klimaschutzszenario 2050: 2. Endbericht. Studie im Auftrag des Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit. Available online at http://www.isi.fraunhofer.de/isi-wAssets/docs/x/de/projekte/Bericht_Runde_2.pdf, last accessed 19 October 2017.

Ruiz, P.; Sgobbi, A.; Nijs, W.; Thiel, C.; Longa, F.D.; Kober, T.; Elbersen, B.; Hengeveld, G. (2015): The JRC-EU-TIMES model. Bioenergy potentials for EU and neighbouring countries. EUR 27575 EN, EU, Luxembourg. Online available at: https://setis.ec.europa.eu/sites/default/files/reports/biomass_potentials_in_europe.pdf

Trinomics (2018): "Study on Bringing TEN-E and The CEF In Line with Our COP-21 Climate Goals". Online available at: http://www.trinomics.eu/wp-content/uploads/2018/04/Final-report-Gas-study-SD-Group-EP-22-02-2018.pdf, last accessed 3 May 2018

UBA (2013): Germany in 2050 – a greenhouse gas-neutral country. German Environment Agency (UBA), Dessau-Roßlau, Germany. Online available at: https://www.umweltbundesamt.de/publikationen/germany-2050-a-greenhouse-gas-neutral-country

UBA (2016): Klimaschutz und regenerativ erzeugte chemische Energieträger – Infrastruktur und Systemanpassung zur Versorgung mit regenerativen chemischen Energieträgern aus in- und ausländischen regenerativen Energien. Climate Change 08/2016. ISSN 1862-4359, Dessau-Roßlau, Februar 2016

UBA (2019): Gas Roadmap for the Energy Transition - A Sustainable Climate Contribution of the Gas Sector. Climate Change 12/2019. ISSN 1862-4359, Dessau-Roßlau, April 2019.

UNFCCC (2015). Paris Agreement. http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf, last accessed 10 October 2017.

UNFCCC (2017): Annex I Party GHG Inventory submissions. https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/submissions/national-inventory-submissions-2017, last accessed 16 Oct 2018

Virdis, M. R.; Gaeta, M.; De Cian, E.; Parrado, R.; Martini, C.; Tommasino, M. C. et al. (2015): Pathways to deep decarbonization in Italy. Available online at http://deepdecarbonization.org/wp-content/uploads/2015/09/DDPP_ITA.pdf, last accessed 19 October 2017.

Wachsmuth, J.; Schaeffer, M.; Hare, B. (2018) The EU long-term strategy to reduce GHG emissions in light of the Paris Agreement and the IPCC Special Report on 1.5°C. Working Paper Sustainability and Innovation No. S 22/2018. Available at https://www.isi.fraunhofer.de/content/dam/isi/dokumente/sustainability-innovation/2018/WP22-2018_The_EU_long-term_strategy_to_reduce_GHG_emissions_WAJ.pdf

Willett, Walter, Johan Rockström, Brent Loken, Marco Springmann, Tim Lang, Sonja Vermeulen, Tara Garnett, et al. (2019): „Food in the Anthropocene: The EAT–Lancet Commission on Healthy Diets from Sustainable Food Systems". The Lancet 393 (10170): 447–92. https://doi.org/10.1016/S0140-6736(18)31788-4.