TRANSNET BW

ENERGY SYSTEM 2050

Towards a decarbonised Europe

CONTENTS

ABSTRACT

Climate change is one of the major global challenges of our time. According to the World Meteorological Organization there is a 50% probability that global temperatures will increase by 1.5°C as soon as 2026. At the same time, we are facing a paradigm shift triggered by the Russian war on Ukraine. The vulnerability of our energy and resource supply has become particularly obvious this spring. The high energy prices are having a dramatic impact on society and the economy, on top of the already difficult economic situation due to the pandemic.

To address these challenges, the role of the European Union is of utmost importance. With these political uncertainties and the impact of climate change, time is running out. The transition to clean energy has already brought about tremendous changes in our society and economy, while at the same time fostering the development of new technologies. However, if we do not reduce our emissions quickly enough in Europe and worldwide, tipping points will occur in the Earth system. This will cause feedback loops of irreversible increases in global temperatures, leaving catastrophic consequences in their wake.

This confirms the need for planning ambitious actions, which this study supports. To present a clear vision of the future of the energy system and create a basis for discussions, TransnetBW has published the study Energy System 2050 - towards a decarbonised Europe. The study considers European climate neutrality in 2050 as a target scenario and uses a detailed model to compare two cost optimal paths to reach the ambitious goals. The first path relies on a global market with gas imports from outside the EU, and the other develops an increasingly energy resilient Europe. The results show in detailed analyses how to achieve climate neutrality by 2050 by taking measures in each sector – renewables, heating, transport, industry and particularly the electricity and gas grids. The main outcomes are as follows:

/ **The energy transition can only be implemented efficiently if it is planned and performed jointly at European level.** The energy transition gives Europe the chance to become significantly more independent of energy imports. The EU27 will need an installed power plant capacity of around 3,500 to 4,000 GW. To achieve this goal, we need to start building this capacity today.

/ **Electricity must be understood in a new way.** The concept of "demand determines generation" can no longer be applied to an energy system with variable renewables. In the future, temporal flexibility must be guaranteed through storage facilities and demand management in all connected sectors.

/ **Electricity and gas infrastructure as the backbone for the energy transition**. Cross-border energy trading is becoming increasingly important. Therefore, a massive expansion of 2.8 times the current electrical grid is necessary. By contrast, the development of the hydrogen and gas system is dependent on the path taken for the energy system.

The energy transition is not a national task – it must be implemented across national borders. Therefore, TransnetBW does not limit the energy transition to its own control area or Germany but examines it for the European Union and beyond. We hope that the new study will provide a basis for going beyond national strategies to begin the international planning of a "European energy transition thought through to the end".

EXECUTIVE SUMMARY

TWO SCENARIOS TO EUROPE'S CLIMATE NEUTRALITY

In this study we assume that the European Green Deal is established, which means that Europe's energy system must become climate-neutral by 2050. To achieve this goal, we present two central scenarios, Global Markets (GM) and Energy Resilient Europe (ERE), which consider different developments in boundary conditions for climate neutral hydrogen production and availability. The modelling covers most European countries and considers almost all energy demand from the electricity, heating, transport, and industry sectors. The electricity sector is the first to reach full decarbonisation. Already in 2040, the share of emissions from the power sector is negligible small. The heating and transport sectors experience a linear decline of emissions over the period. However, decarbonisation of the industry sector is more challenging and cost-intensive than other sectors. It should be noted that this study does not cover the complete decarbonisation of the international transport sector (aviation and navigation). Therefore, additional steps are needed for complete climate neutrality. These steps include producing and importing climate-neutral hydrogen or climate-neutral synthetic hydrocarbons.

ELECTRIFICATION LEADS TO A GROWING DEMAND FOR ELECTRICITY

A fundamental transformation of the energy system is necessary to achieve a reduction in energy-related greenhouse gas emissions in Europe. This comprises the expansion of renewable energies such as wind energy and photovoltaics in the electricity sector, the partial electrification of the heating and transport sectors and the development of demand for power-to-X technologies to produce hydrogen or other synthetic hydrocarbons. Sector coupling will lead to a strong increase in electricity demand. In the European Union, we expect the total electricity demand to increase between 2020 and 2050 from approximately 2,491 TWh to 5,190 TWh (GM) and 5,833 TWh (ERE). Up to 18% of this will be needed for the electrification of the heating and transport sectors, and up to 32% will be needed for power-to-X applications. In our scenarios, Germany is the largest consumer of electricity with 937 TWh (GM) to 1,087 TWh (ERE).

Flexibility of electricity demand for an innovative power system. To build a sustainable and cost-efficient system, flexible consumers and storage facilities must integrate electricity generation from variable renewables. The heating, transport and gas sectors have enormous potential for demand side management and for storing electricity, heat, and gaseous energy sources. By coupling the sectors, flexibility in electricity demand can be substantially increased. For example, batteries of electric vehicles can be charged when renewable energies are abundant, and discharged in shortage situations to provide electricity. We observe that missing flexibility to and from the transport sector calls for alternative flexibility options, which are characterised by much higher cost. It appears that V2G and DSM may play a relevant role in efficient future energy systems. To tap at least a share of this potential, a forward-looking policy framework and market incentives need to be established. In addition, we also see stationary battery storages with a capacity of up to 161 GW in 2050 in the EU27. Through these flexible consumers and storages, the maximum simultaneous electricity demand in the EU27 will increase more than three times from today up to 1,508 GW (GM) and 1,745 GW (ERE). Of this, a total of 934 GW (GM) to 1,114 GW (ERE) is flexible demand (battery storages, pumped hydro storages, 50% BEV demand, electrolysers, heat pumps, resistive heaters). This flexibility corresponds to 62% to 64% of total the total demand. The largest flexibility comes from power-to-gas with 24% (GM) to 31% (ERE) of the total demand. The smart charging of electric cars accounts for 16%. Battery storages and pumped hydro storages have a share of around 11%. The flexibility ratio differs depending on the available technologies in each country. In Germany, the maximum simultaneous electricity demand increases from around 80 GW in 2020 up to 302 GW in 2050 (ERE) with a 54% share of flexibility. Due to this high flexibility, the electricity generation of renewable energies can be integrated effectively.

MASSIVE EXPANSION OF WIND AND PHOTOVOLTAIC NECESSARY

The foundation for a climate-neutral energy system is the expansion of renewable energies in the electricity sector. Onshore and offshore wind turbines as well as rooftop photovoltaic power stations and utility-scale photovoltaic farms need to be expanded drastically going forward. We considered the impact of onshore wind expansion on people (acceptance) and environment (species protection) by limiting the land use to a maximum of 5% per country. For the EU27 countries, we calculated that the installed wind power capacity needs to be expanded from 177 GW in 2020 to 844 GW (GM) and 969 GW (ERE), or up to 5.5 times more. From a linear perspective, we therefore need an expansion rate of at least 23 to 27 GW/year from today to 2050. At the same time, the installed capacity of photovoltaic systems needs to increase from 139 GW in 2020 to 2,136 GW (GM) and 2,462 GW (ERE) in 2050. This is up to 17.8 times more than today, with an expansion rate of at least 69 to 80 GW/year. This makes PV the most important energy source in our scenarios.

The potential of renewables impacts the energy mix on a national level. There will be strong regional variations in wind and PV generation due to specific local meteorological conditions in Europe. Italy and the Iberian Peninsula will predominantly generate electricity from PV (over 75% of power generation), whereas the British Isles, Denmark and the Netherlands will largely use wind turbines (over 70% of power generation). Wind and PV generation will be more balanced in large electricity producers like France, Germany, and Poland. In addition, hydropower plants will be used for electricity generation and seasonal storage, especially in Scandinavia (44.6 GW storage capacity) and the Alpine countries (29.7 GW storage capacity).

GROWING INTEGRATION OF THE EUROPEAN ENERGY MARKETS

To balance out temporary and regional variations in supply and demand, and connect solar and wind generation locations with high-load centres, the electricity grid interconnection capacity in the EU27 needs to almost triple to 200 GW. This is fairly consistent across both scenarios. As a result, international electricity trade will also triple (gross electricity trade in 2050 of around 1,600 TWh). Germany, which imports around 14% of its electricity demand (132 TWh to 165 TWh) and Italy, which imports around 24% (104 TWh to 129 TWh) are the largest net importers in absolute terms. The largest net exporters are France, which exports around 9% of electricity generation (91 TWh to 111 TWh) and Denmark, which exports around 32% (57 TWh to 78 TWh). The energy market in Denmark is optimised for about 40 GW to 60 GW of wind turbines. During peak times of electricity generation from renewables, Denmark exports more than 50% of domestic electricity generation to Germany and other countries. As a country with considerable electricity generation from photovoltaics, France uses demand management for load shifting and other flexibility options such as stationary battery storages, which have an installed capacity of 38 GW (ERE) to 47 GW (GM). Around 9% of electricity generation is temporarily stored.

HYDROGEN AS BASIS FOR EUROPEAN INDUSTRY AND FUELS FOR THE TRANSPORT SECTOR

Hydrogen will play a key role for the climate neutral energy system in 2050. It will be intensively used as an energy carrier or feedstock in industrial processes and as a fuel for the transportation sector. In addition, hydrogen will be used as input for the synthesis of hydrogen derivatives such as synthetic hydrocarbons. In the GM scenario, 57% of hydrogen production takes place in Europe, while the remaining 43% is imported via hydrogen pipelines from countries outside the EU27 (such as North Africa, via Spain or Italy). By contrast, in the ERE scenario, 100% of the hydrogen production is in Europe. This means that depending on the scenario, 376 GW (GM) to 560 GW (ERE) of electrolyser generation capacity and 150 GW (GM) to 219 GW (ERE) of hydrogen grid interconnector capacity will be needed in the EU27 by 2050. In all modelled regions, including the UK, we calculated an electrolyser capacity of up to 660 GW (ERE). Poland, Spain, and France have a total of 205 GW (GM) and 268 GW (ERE) electrolyser capacity, which is approximately half of the electrolysis capabilities in the EU27. In the ERE scenario, the capacities are almost double in Germany (up to 60 GW) and Denmark (up to 33 GW) compared to the GM scenario, due to the lack of imports from outside the EU.

Development of a European hydrogen market. According to the ERE scenario, the following EU27 countries are the leading exporters of hydrogen: Denmark (25 TWh), Poland (84 TWh), Greece (25 TWh) and the Netherlands (39 TWh). In Spain, hydrogen is mainly used locally to produce synthetic gases and fuels. On the other hand, Italy imports 70% (ERE) to 95% (GM) of its hydrogen demand, and Germany 34% (ERE) to 80% (GM). In the ERE scenario, imports are from other European countries and in the GM scenario, also from outside of Europe.

EUROPE WILL BECOME SIGNIFICANTLY MORE INDEPENDENT OF IMPORTED ENERGY CARRIERS

As a result of the increasing electrification of the energy system and the expansion of renewable power plants, the energy transition results in fewer imported energy carriers. Comparing our study results for 2050 with 2020 values, we observe that the demand for oil is around 72% lower. Demand for gas is between 63% and 83% lower depending on the scenario. Synthetic energy carriers partly cover this demand. In the ERE scenario, 72 TWh of synthetic oils are imported to the EU. The EU could import this oil from the USA or Canada, for example. The emissions resulting from the use of natural gas or mineral oil are compensated by direct air capture and carbon capture and storage.

GRID ANALYSIS SHOWS MASSIVE CONGESTIONS THROUGHOUT EUROPE

The grid infrastructure planned today in the Ten-Year Network Development Plan is just the first step of the grid expansion requirement for a successful energy transition. The planned grid for 2035 does not meet the large transmission requirements of the 2050 scenario in any of the countries considered. The system will be critically affected by grid congestions throughout Europe. The power supply system in 2050 requires a further development of the transmission grid. Italy, for example, has significant congestions due to high energy flows between the northern and southern parts of the country. In France, there are substantial congestions from the southwest towards the northeast. These are due to the large PV feed-ins.

A study of Germany shows the substantial need for grid expansion. The grid confirmed in the German NEP 2035, Version 2021, shows heavy congestions when confronted with the 2050 scenario. The length of the German extra-high voltage AC reference grid is approximately 36,000 km, of which around 55% has unacceptable grid congestions, particularly in the north-south direction. For a better understanding of the most critical tasks for the transmission grid, we analysed different situations. These included a strong wind and high load situation on a January evening with a north-south transit flow, and a sunny high load situation with a south-north transit in July at midday.

EXTENSIVE DEVELOPMENT OF THE ELECTRICAL GRID IN EUROPE NECESSARY

Despite the numerous planned and ongoing enhancements in the TYNDP, AC grid expansion measures will reach their technically reasonable limits. It is thus not effective to manage overloads by extending the AC grid only. This is mainly due to the increasing distances between the sources of renewable generation and future load centres. To meet this need in an efficient and targeted manner, we see an interconnected and power flow optimising European HVDC overlay grid as the best solution. In addition, the interconnection of offshore wind farms, regardless of national borders, offers greater potential for efficiently increasing offshore wind integration to meet long distance transmission needs.

AS AN ELECTRICITY IMPORTER AND ELECTRICITY HUB OF EUROPE, TRANSNETBW'S CONTROL AREA NEEDS A RELIABLE HIGH-PERFORMANCE GRID

In the future, Baden-Württemberg, a state in southwest Germany and the control area of TransnetBW, will increasingly need to import electricity from other German states or from abroad. Less than half of the electricity demand will be generated locally by 2050. In addition, Baden-Württemberg serves as an important hub between Germany and Austria, Switzerland, and France. Therefore, a reliable and high-performance electricity grid integration is essential for our future energy system.

Additional HVDC links in TransnetBW's target grid. In order to reduce the extensive overloads in the grid, we identified three additional north-south connections, one west-east connection, and interconnectors to France and Switzerland as well as the confirmed HVDC connections (SuedLink and Ultranet). Due to further technical developments, we assume HVDC cables with a rated voltage of 800 kV and current of 2,300 A to be ready for operation in 2050. Therefore, the rated power of the HVDC links increases to 3.5 GW. As a result, Baden-Württemberg's HVDC converter capacity will amount to 18 GW, including the capacity to France and Switzerland.

Further expansion of the AC grid needed. The AC measures planned by TransnetBW for 2035 confirmed in the German NEP 2021 are necessary for the energy economic developments until 2050. Furthermore, over 830 kilometres of TransnetBW's extra-high voltage AC grid, which is over 25% of the transmission circuits, must be additionally reinforced.

DIGITALISATION AND INNOVATION TO CREATE A SMART ELECTRICITY GRID

Besides making electricity demand more flexible through sector coupling and use of storages, innovative electrical equipment enables an optimised utilisation of the electricity grid. HVDC converter stations and phase-shifting transformers allow a higher degree of utilisation of the future grid through the targeted control of power flows. Weather-dependent dynamic line rating will facilitate a significant increase in grid utilisation, thanks to real-time measurement of weather conditions. Combining these power flow optimising measures results in huge potential for shifting power flows from overloaded circuits. If these measures are applied to the German grid, the congestions seen in the reference grid will decline by around 25% without any further grid expansion.

INCREASING NEED FOR SYSTEM INERTIA & IMPORTANCE OF GRID FORMING INVERTERS

System splits are the main challenge for frequency stability within the ENTSO-E Continental Europe Synchronous Area. Potential active power imbalance in case of a system split corresponds to the active power transmission before a system split. In Germany, this potential active power imbalance increases significantly between 2035 and 2050, leading to an increasing need for system inertia. Also, the widespread installation of grid-forming inverters (instead of grid-following inverters) is necessary to protect the power system from blackout in case of severe system splits.

INCREASING NEED FOR STATIC AND DYNAMIC REACTIVE POWER COMPENSATION TO GUARANTEE VOLTAGE STABILITY

Increasing trade in electricity, accompanied by higher utilisation of the electricity grids, leads to massive power flows through the AC transmission systems. These widespread power flows result in a substantial need for overexcited reactive power, which is more than 2.5 times higher in 2050 than 2035 as calculated in the German NEP. Therefore, we highly recommend new reactive power compensation (for example, new compensation devices such as capacitors and STATCOM) to guarantee voltage stability and thus a stable, secure energy supply.

1.0

INTRODUCTION

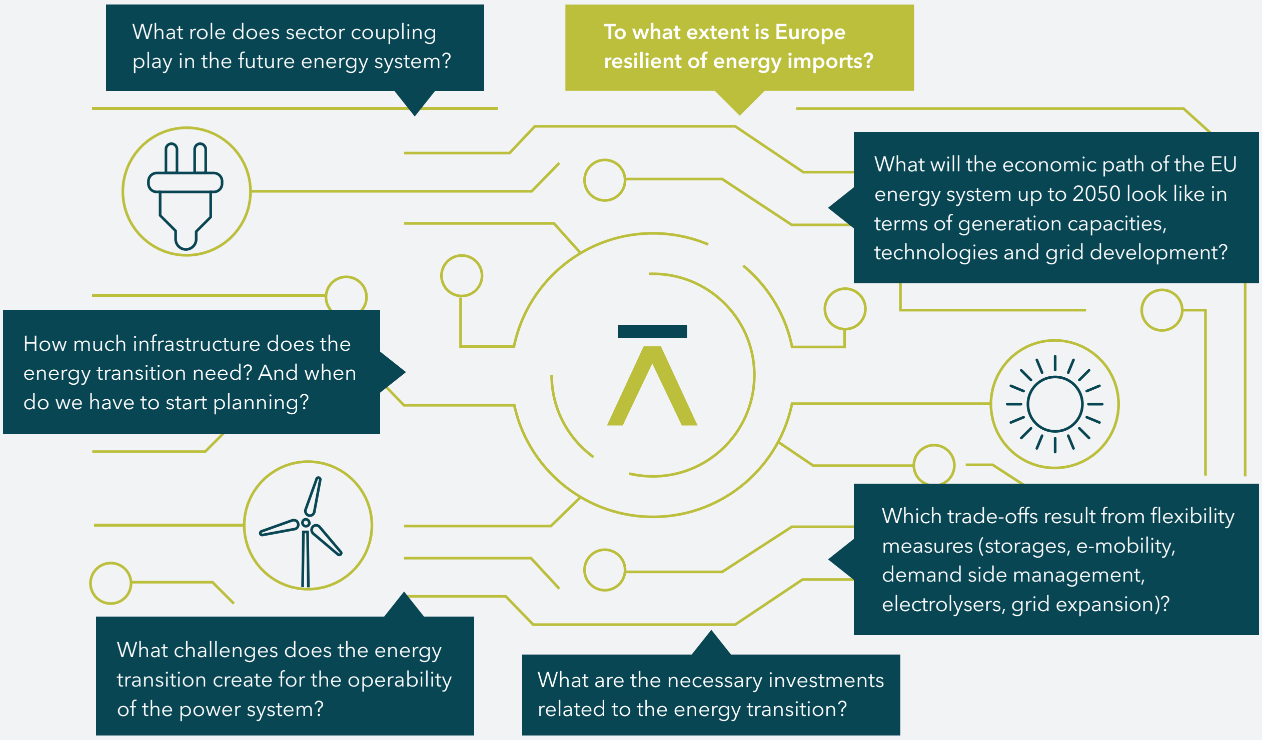
1.1 MOTIVATION

The **European Green Deal** sets out the framework for achieving a sustainable economy in the EU. Europe is aiming for a climate-neutral energy system in 2050. Some countries are even planning to be climate neutral before 2050. For example, Germany decided on a stricter climate protection law in 2021 to achieve climate neutrality by 2045. In this context, the electricity grid plays a key role in enabling the energy transition and the development of the future energy system. It is exactly this electricity grid that connects renewable energy sources and the consumers of tomorrow. However, planning a sustainable and efficient power grid is a costly and time-consuming process. Moreover, the power system is becoming increasingly complex, due to the growing interaction of the power sector with other energy sectors, as well as the more active role of decentral actors (prosumers). With this in mind, we want to find out which challenges for the transmission grid are included in the energy transition and climate protection goals and what we must do to meet them. Topologies, technologies, markets, and system operation principles will change. It is our aim and ambition to understand the impact of these changes on the future European Energy System and ultimately to plan a demand-oriented electricity grid infrastructure. With the study *Energy System 2050 – towards a **decarbonised** Europe* we want to provide perspectives for Europe's energy transition and a basis for this discussion.

EUROPEAN GREEN DEAL
The European Green Deal is a package of initiatives and measures approved by the European Commission in 2020 that aims to make Europe a climate-resilient society by 2050. The measures include reduction of greenhouse gas emissions as well as investments in research and innovation. The Green Deal includes several climate actions such as the New EU Strategy on Climate Adaptation and the 2030 Climate Target Plan.

DECARBONISATION
In the energy system, decarbonisation refers to the reduction of use of energy sources based on hydrocarbons such as oil, coal or natural gas.

The main questions we aim to investigate are summarised in the following figure:



What role does sector coupling play in the future energy system?

To what extent is Europe resilient of energy imports?

What will the economic path of the EU energy system up to 2050 look like in terms of generation capacities, technologies and grid development?

How much infrastructure does the energy transition need? And when do we have to start planning?

Which trade-offs result from flexibility measures (storages, e-mobility, demand side management, electrolysers, grid expansion)?

What challenges does the energy transition create for the operability of the power system?

What are the necessary investments related to the energy transition?

FIGURE 1:
What will the future energy system look like?

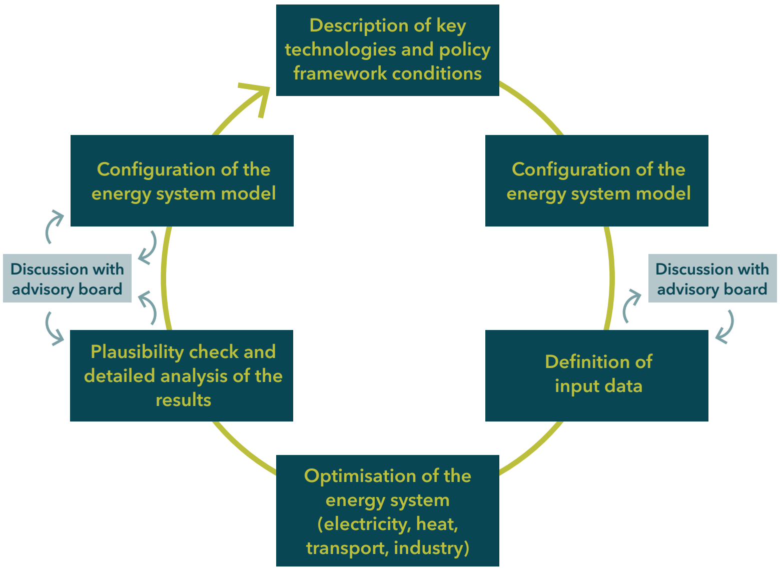
1.2 OBJECTIVES AND PROCEDURE

With a focus on Germany and based on the climate protection goals at the time (90% CO2 reduction in Germany), we presented a realistic picture of the future energy system in our study "Electricity Grid 2050" (published in April 2020). We developed this picture of the future by applying comprehensive, high-quality data in scientific models and have achieved robust results. However, we did not want to stop there. We wanted to define our vision for the energy system in 2050 even more precisely and think further ahead.

We pursued this mission in our new study. Our main objectives were to model a scenario of full climate neutrality and to extend our approach to a European level. We also know that developments in the energy system until 2050 are prone to a high degree of uncertainty. We believe that the future role of green hydrogen including its derivatives is still not clear and needs to be studied by means of more than one single scenario. In this study, we present two main scenarios, which consider different possible developments for boundary conditions regarding green hydrogen production and availability. We show the impact of such boundary conditions on the future location and capacities of electrolysers within Europe as well as on the required transport infrastructure for power and gas. To test the uncertainty of some crucial parameters and challenge the robustness of the results, we also performed a series of additional sensitivity analyses.

We also examined many scientific sources for defining the input data and developed our models accordingly. As in the previous study, we developed our target picture of the future energy system in iterative and evolving drafts. The following figure (Figure 2) schematically shows the iterative procedure. In each draft, the key technologies and the policy framework conditions were defined, and the energy system model (ESM) was configured accordingly. Next, we determined the input data for modelling. These come from several external sources and were provided by our experts in each discipline. Then, we optimised the energy system including the electricity, gas, heat, and industry sectors (in a one-to-three-hour resolution). In the next step, we analysed and assessed the results together with our steering committee and the external advisory board. We went through this process several times, allowing us to repeatedly check and adjust various sensitive parameters. The process results in a robust and resilient pathway for the energy system that is conclusive from an expert point of view.

FIGURE 2:
Iterative procedure to the target vision for the energy system.



Based on this result for the energy system, we further disaggregated our data in the process of regionalisation. This gave us a detailed view of the distribution of producers and demands in Europe. Subsequently, a highly detailed simulation of grid utilisation was carried out. Grid congestions in Central Europe were identified and grid measures were defined for the future grid of TransnetBW. Along with grid development, we also conducted an evaluation of the operability of the future power system in terms of frequency and voltage stability.

Due to the high complexity and expenditure, regionalisation and grid development was only carried out for one scenario of the energy system. Our goal was to determine the need for grid expansion “at the lower end“. Nevertheless, the main messages of the chapter on grid development can be transferred from one scenario to another.
Some relevant aspects for the design of the future energy system are outside the

1.3 LIMITS OF THE METHODOLOGY

scope of this study and are not considered in the scenario modelling. Below, we summarise what is covered by the results of the study and what is not:

Figure 3:
Limits of the methodology.

What is covered in this study ✓

- Pan-European energy systems in a one-hour time resolution that work for an average weather year (2012)
- Macro-economic cost-optimised paths towards a climate-neutral energy system
- The role of sector coupling and flexibility options in the future energy system
- A regionalised view of the European energy supply and consumption
- An evaluation of the robustness of the cost-optimized energy system to specific parameters through a sensitivity analysis
- An assessment of the future grid utilisation and needs in Central Europe
- TransnetBW's target grid for achieving the energy transition
- An evaluation of the needs for a stable system operation in 2050

What is not covered ✗

- A generation adequacy analysis and so a full dimensioning of balancing power (such as thermal power plants)
- A detailed consideration of individual country targets
- A consideration of optimal investment strategies for individual stakeholders
- Specific locations of power plants
- The complete decarbonisation of the international/global transport sector
- Model endogenous optimisation of industry demand (assumptions source-based)
- An evaluation of market design options

NOTE ON GENERATION ADEQUACY ANALYSIS
This type of analysis is primarily used to design a power system that guarantees electricity demand in all situations, even in exceptional ones. Therefore, a variety of extreme weather years and unplanned unavailability must be analysed.

1.4 ADVISORY BOARD

Europe still has a long way to go until 2050. From today's perspective, there are many different approaches to achieve climate neutrality. That is why we have set up an advisory board consisting of European scientists, political representatives, and experts. Our ideas and solutions were constantly challenged. Questions, suggestions, and discussions among the advisory board have enriched our knowledge and greatly improved the quality of the study. Our cooperation with the advisory board provided us with a wide range of information on political, scientific, and technical aspects.

The advisory board was assembled as follows:

- Ralph Bahke (ONTRAS Gastransport)
- Katrin Flinspach (terranets bw GmbH)
- Prof. Dr. Veit Hagenmeyer (Karlsruhe Institute of Technology)
- Prof. Dr. Dogan Keles (Technical University of Denmark)
- Dr. Martin Konermann (Netze BW GmbH)
- Dr. Felix Christian Matthes (Öko-Institut e.V.)
- Helmfried Meinel (Ministry of Environment, Climate Protection and the Energy Sector Baden-Württemberg) (until 2021)
- Dr. Michael Münter (Ministry of Environment, Climate Protection and the Energy Sector Baden-Württemberg)
- Leonardo Meeus (Florence School of Regulation)
- Dr. Philipp Ostrowicz (Copenhagen School of Energy Infrastructure)

We would like to thank the members of the advisory board for the interesting and constructive discussions and their competent advice during the preparation of the study. TransnetBW is fully responsible for the results of this study.

2.0

ENERGY SYSTEM MODELLING

2.1 SCENARIOS

Below, we describe the scenario settings within the framework of this study. First, we describe the assumptions that apply to all scenarios. Second, we present the main constraints that apply to the two central scenarios, Global Markets (GM) and Energy Resilient Europe (ERE), in 2.1.2 and 2.1.3 respectively. Finally, in 2.1.4 we present an overview of the sensitivities.

2.1.1 COMMON SCENARIO ASSUMPTIONS

All modelled scenarios assume the same carbon dioxide (CO2) reduction path towards 2050. Such a reduction path is based on the European Green Deal (EC 2021). The European Climate Law prescribes the goal set out in the European Green Deal for Europe's economy and society to become climate-neutral by 2050. The law also stipulates the intermediate target of reducing net greenhouse gas emissions at least 55% by 2030, compared to 1990 levels. Climate neutrality by 2050 means achieving net zero greenhouse gas emissions for EU countries. The model assumes a linear decrease of CO2 emissions between 2030 and 2050. Finally, we decided to avoid setting individual country targets for CO2 emissions. Instead, we propose an EU-wide CO2 constraint. This means that the model can be used to determine the investment decisions with minimal energy system cost. In addition, **perfect market conditions** are assumed, so real-world market dynamics are not considered. With regard to the power plant and energy transport infrastructure, existing system components in the first year of the simulation have been considered (MaStR 2021) (IRENASTAT 2021) (OPSD 2020) (ENTSOG 2015) (diw 2017).

PERFECT MARKET CONDITIONS
Under perfect market conditions, we ssume that each energy system agent has complete information (past, present, and future) about cost. In addition, we assume that the market is not distorted by any kind of regulation or subsidy.

Unless otherwise specified, cost assumptions and the techno-economic parameters of technologies only vary over time (for more details see Appendix). For the European countries, no geographic differentiation is made for those parameters. This also applies for fossil and synthetic energy carriers such as natural gas, coal, oil products and hydrogen. For hydrogen imports from outside the model region (EU), a yearly import price based on several external sources has been assumed (Hampp 2021) (Langfristszenarien 2021) (GasForClimate 2021). The interest rate (7%) for investments is assumed to be constant over time and space.

To consider social acceptance and environmental protection, the land use for onshore wind expansion was limited to a maximum of 5% for every modelled region. An additional sensitivity analysis was performed to evaluate an even lower level of acceptance for onshore wind. All scenarios – except for a single dedicated sensitivity – have been calculated based on the complete meteorological year 2012. This year, which can be considered as a typical meteorological year from a historical perspective at European level, is also used as a reference meteorological year for the German Grid Development Plan. Details about the input data used in the ESM optimisations can be found in Chapter 2.2.3.

2.1.2 GLOBAL MARKETS SCENARIO

The Global Markets scenario (GM) is one of the two main scenarios of this study. Due to the original setting of the study, this scenario has been selected as the basis for the sensitivity analyses and the grid development analyses described in Chapter 3.0.

The basis of the scenario is that hydrogen can be freely traded on the global market without significant political boundaries or restrictions, while an optimistic development of investment cost for renewables and electrolysers is assumed.

Hydrogen transport is assumed to occur via pipeline from non-EU countries close to European borders (such as North Africa and Eastern Europe). Accordingly, costs for hydrogen transport via pipeline are estimated to be lower than for intercontinental transport via shipping. Additional details about the used techno-economic assumptions can be found in the Appendix.

In this scenario, the hydrogen price is estimated to range from 82 €/MWh in 2030 to 55 €/MWh in 2050. The estimated costs are within the range of values found in the available literature. The study "Langfristszenarien" (Langfristszenarien 2021) estimates high costs for hydrogen in 2050 (81 €/MWh), while a recent scientific study estimates much lower costs (40 - 46 €/MWh) (Hampp 2021).

NOTE ON H_2 IMPORT COST
Under the assumption that renewables will continue reducing their cost, we expect that local hydrogen production cost, such as in North Africa via PV and electrolysis, may fall to approximately 40 €/MWh in 2050. Further assuming the dedicated construction of a large-scale hydrogen pipeline from North Africa to Europe's borders (such as Spain or Italy), additional 15 €/MWh should be added to allow for hydrogen transport. The expected hydrogen cost at Europe's borders would amount to 55 €/MWh. Further transport costs within Europe are calculated endogenously by the model, so that final supply cost for imported hydrogen in Central Europe would be higher.

In addition, the **55 €/MWh** applied in the GM scenario only includes transport costs up to the model boundaries (Europe's borders). All H_2 pipelines within the model boundaries are modelled and calculated, and included separately in the cost optimisation function. So, in the model, transporting hydrogen from North Africa to Germany would be more expensive than 55 €/MWh.
Also, in this scenario the maximally installable electrolyser capacity for Europe is limited to 450 GW in 2050. This value as a fixed upper limit was based on the EU hydrogen strategy. The detailed results of this scenario are presented in 2.3.1.

2.1.3 ENERGY RESILIENT EUROPE SCENARIO

The Energy Resilient Europe (ERE) scenario is the second central scenario of this study. This scenario describes a situation where energy imports from outside Europe – particularly hydrogen – are less economically competitive than in the GM scenario, or where trade partners outside Europe are less willing to cooperate than in the GM scenario. In this scenario, we assume that hydrogen is imported to Europe via shipping. Additional details on techno-economic assumptions can be found in the Appendix.

In this case, it is assumed that no limitation applies to the installable electrolyser capacity in Europe. All other model assumptions remain unchanged. The results will show that in this scenario Europe will reach a higher degree of energy resilience than in the GM scenario (2.3.1).

2.1.4 SENSITIVITY ANALYSES

The central scenarios describe two of many possible developments of the European energy system until 2050. Other pathways towards climate neutrality are possible. Moreover, some of the key input parameters are prone to a relatively large degree of uncertainty. A recognised method to test the robustness of the results of a scenario is by performing sensitivity analyses. Within the framework of sensitivities, key parameters or drivers of the model are varied within a certain range. The main advantage of sensitivities is the variation of a single parameter, so that the impact on the results can be analysed individually. This is important due to the complexity of energy systems. Sensitivity analyses cannot be interpreted as fully independent scenarios; they must always relate to a reference scenario. Accordingly, we do not rank or value sensitivity analyses in terms of probability of occurrence. Sensitivities also help avoid possible model artifacts (for example, due to issues related to the linear optimisation methodology).

All sensitivities assume the Global Markets scenario as the reference scenario. However, the core messages from the sensitivities can also be applied to the Energy Resilient Europe scenario. We focussed on the following sensitivities:

BUILDING RENOVATION RATE
This indicator refers to the percentage of buildings which undergo a renovation within one year. To calculate the corresponding heat demand reduction, the building renovation rate must be multiplied by the renovation efficiency, the average heat demand reduction after a conducted renovation measure.

/ Low Building Renovation Rate (HEAT).
The central scenarios assume moderate **renovation rates** (1.9% per year after 2030, coupled with a renovation efficiency of up to 57%), particularly when compared with dedicated studies (UBA 2021) (agora 2021). This sensitivity assumes lower values for both renovation rates and renovation efficiency of 1.1% per year and 35% respectively. The main purpose of this sensitivity is to determine the additional amount of renewable energy needed to meet the higher heat demand.

SMART CHARGING
Smart charging refers to a charging system in which electric vehicles, charging stations, and charging operators share common data. In the context of energy system optimisation, we assume that electric vehicles use such a system for charging batteries, which helps minimise energy system costs under the consideration of future driving profiles.

VEHICLE TO GRID (V2G)
Vehicle to Grid describes a system in which electric vehicles, such as battery electric vehicles (BEV), plug-in hybrids (PHEV), or hydrogen fuel cell electric vehicles (FCEV), communicate with the power grid by feeding power back into the grid.

/ Inflexible Mobility (V2G/DSM).
The central scenarios assume that a certain share of private electric cars (25% of the total fleet) is willing to contribute to the flexibility of the power system through **smart charging** and **vehicle-to-grid (V2G).** For example, the resulting flexibility potential for Germany is around 100 GW in 2050, even considering the limited availability of vehicles over time. However, it is questionable whether private individuals are willing to help stabilise the power system this way. Here, too, a regulatory framework should be created to determine what type and level of economic incentives are sufficient to mobilise this flexibility potential. For this reason, this sensitivity analyses the impact of the lack of such flexibility for the energy system. In this case no smart charging and no vehicle-to-grid are considered.

/ Low RES Expansion Acceptance (WIND).
The acceptance of the energy transition towards climate neutrality is high among the population. However, when citizens are directly affected, the acceptance of wind turbines often decreases. Within the framework of this sensitivity, we reduce the land availability for wind onshore to a maximum of 2% of the total area in each of the model regions.

/ Extreme Meteorological Year (WY96).
The meteorological data of the year 2012 have been used for both central scenarios. In this sensitivity, we examine the robustness of the results based on a variation of the meteorological data. The focus of the evaluation is the capacity of required balancing flexibility and thermal power plants. For this analysis, we chose the year 1996, which was characterised by low yield of PV and wind, as well as a pronounced "**dark doldrums**" for about 10 days in January.

DARK DOLDRUMS
Dark doldrums is a term used to describe a period of time in which little to no energy can be generated with the use of wind and solar power. Dark doldrums events are common in the North of Europe from October to February, typically 50 to 150 hours per year.

/ Nuclear Renaissance (NUCLEAR).
In the central scenarios, we assume that new nuclear plants can be only built in countries with operational nuclear power plants in 2020. Further, in the GM and ERE scenario we assume a substantial reduction of nuclear power plant capacity in Europe until 2050 (11 GW in France, 42 GW in the EU). In this sensitivity, we take the global ambition scenario of the Ten-Year Network development Plan (TYNDP) 2022 as a basis (102 GW nuclear plants in the EU in 2050) and allow for the phase-in of nuclear plants in countries that currently do not publicly support a nuclear phase-out.

/ Limiting grid expansion (ACDC).
In this sensitivity, we examine the potential impact of limiting power grid development to the planned expansion projects until 2035 only. In the results, we highlight the differences in comparison with the reference scenarios.

2.2 THE ENERGY SYSTEM MODEL

In this section, we briefly describe our energy system model and its fundamental features. In addition, we present the main input data required by the ESM and additional key boundary conditions related to the scenario setting.

2.2.1 PYPSA

Within the framework of this study, the ESM PyPSA has been used (Brown 2018). PyPSA stands for "Python for Power System Analysis" and is an open-source toolbox for simulating and optimising complex energy systems. The adopted model version is PyPSA-Eur-Sec (PyPSA 2022). This version optimises the future European energy system under consideration of sector coupling. Supply and demand in the following sectors are considered as well as the power sector: transportation, heating, biomass, and industry including industrial feedstock. A list of all technologies included in the model is documented in the Appendix. All relevant CO2 emitters are considered, except waste management, agriculture, international aviation, and international navigation. For the latter, we assume that additional synthetic fuels will be produced in non-European countries in regions with good conditions for renewables and imported into Europe.

In addition, we extended the basic model by adding features to help answer research questions related to the focus of the current study. The main developments include the consideration of concurrent alternative technologies in the private road transport sector and their endogenous optimisation, a more detailed characterisation and diversification of wind power, photovoltaics, and conventional technologies.

The optimisation procedure aims at minimising the sum of operational expenditures (OPEX) as well as capital expenditures (CAPEX) for capacity expansion of all technologies and for each model region within the year of analysis. The model takes on the perspective of a central system planner, which minimises macroeconomic expenditures under consideration of given boundary conditions (for more details, see 2.2.3). Accordingly, the economic competitiveness of single power plants (such as balancing power plants) is not explicitly considered. This means that the model may decide to invest in unprofitable power plants (or any other energy system component) if it is beneficial from the energy system point of view. The model further assumes perfect market conditions, so there is no consideration of real market mechanisms.

The energy system model is applicable for the long-term planning of the European energy system as a whole, with consideration to sector coupling. The model addresses the role of flexibility options such as power and gas grids, energy storage and key technologies such as electrolysers, and heat pumps including e-mobility. The model results deliver recommendations not only for 2050, but also for a cost-optimised path towards climate-neutrality.

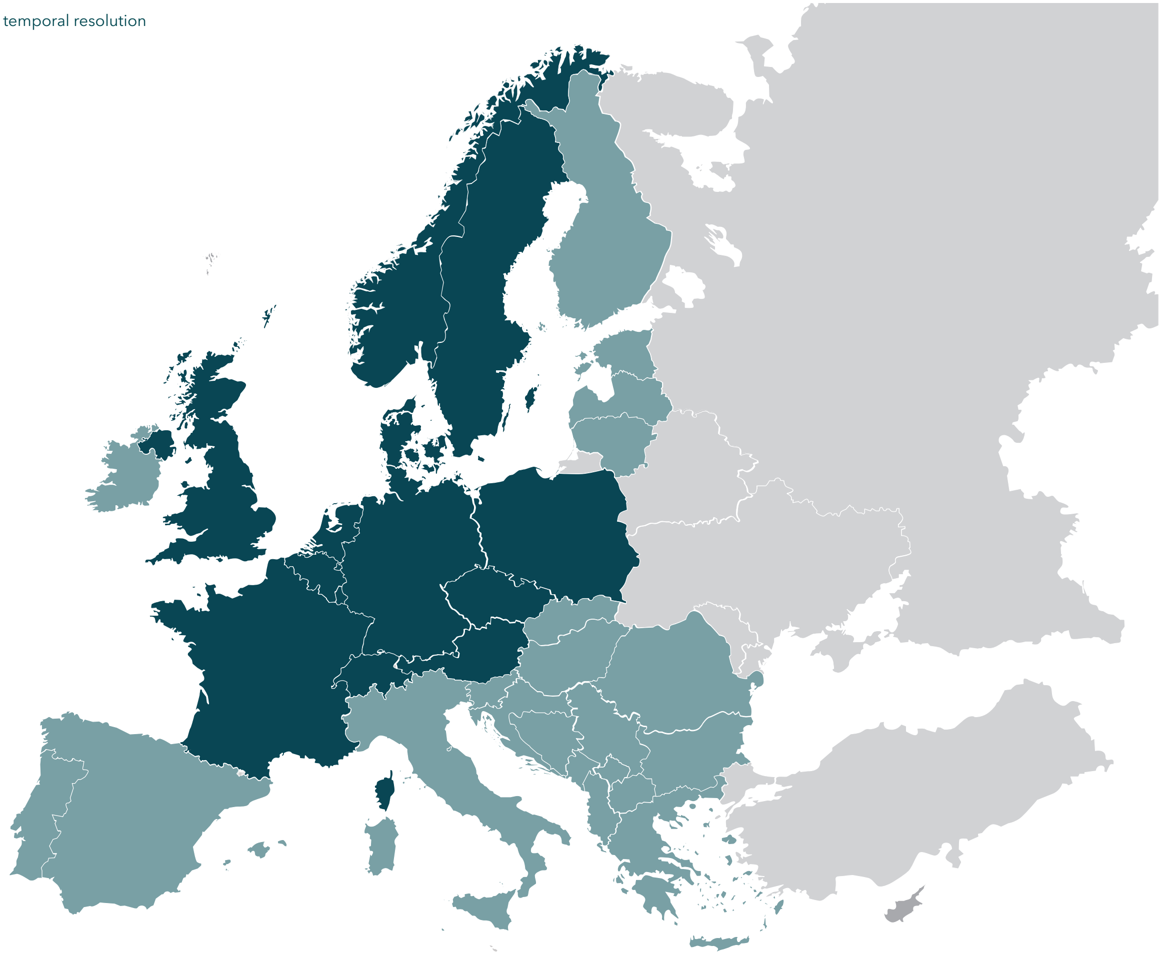
2.2.2 REGIONAL AND TEMPORAL RESOLUTION

COPPER PLATE
It is assumed that there are no grid congestions within a market area and thus homogeneous electricity prices. The grid expansion required for this purpose is then determined and planned in a subsequent step.

The geographical focus of the present study is limited to the territory of European Network of Transmission System Operators (ENTSO-E), excluding Iceland, Turkey, and Cyprus. The smallest spatial entity of the model is defined by national states. The development of the transmission grid within national states is therefore not covered (**copper plate** approach). An exception is the subdivision of Denmark East and West, to consider the separation of the continental European interconnected grid and the Nordic synchronous area. In addition, the Balearic Islands and Sardinia have been modeled as separate regions in the ESM. Figure 4 shows the modelled regions.

FIGURE 4:
Modelled regions in Europe including temporal resolution for each country.

■ 1h-time-res.
▨ 3h-time-res.



MYOPIC APPROACH
In concrete terms, myopic approaches assume limited knowledge about the future, which means that optimisation in each year is based only on the results of the previous year and the constraints of the current expansion phase. For this reason, myopic models are well suited to simulate decisions under real economic conditions.

NOTE ON "HIGH COMPLEXITY" COUNTRIES
Countries with a high energy transition, a complex grid infrastructure and high storage capacities. The one-hour resolution is especially important for storage management.

Model runs are carried out in the period between 2020 and 2050 with 10-year time steps. The optimisation approach is **myopic** , that is without foresight regarding the future. To find a compromise between result accuracy and computational time, we apply an iterative optimisation procedure: first, whole-EU consideration in three-hour resolution and second, one-hour resolution for selected EU countries with a "**high complexity**" in Central Europe. The high time resolution and the consideration of a complete meteorological year (8,760 hours) allow us to capture the typical daily and seasonal power production patterns for wind and photovoltaics.

2.2.3 INPUT AND OUTPUT DATA

The open-source model version of PyPSA-Eur-Sec uses only publicly available datasets and includes calculation routines to prepare the data for modelling. TransnetBW has reviewed all datasets of this version and replaced a large part of the datasets. Different datasets that were used in the process are as follows:

/ Internal datasets include datasets of TransnetBW that are not publicly available. These refer to data for the power sector (such as power plant data and power grid data).

/ Open-source datasets are based on publicly available sources (studies and data from the Federal Statistical Office). It should be noted that the input data are based on public datasets, which were further processed by expert teams at TransnetBW (such as gas grid data, development of transport demand, and transformation of the industrial sector).

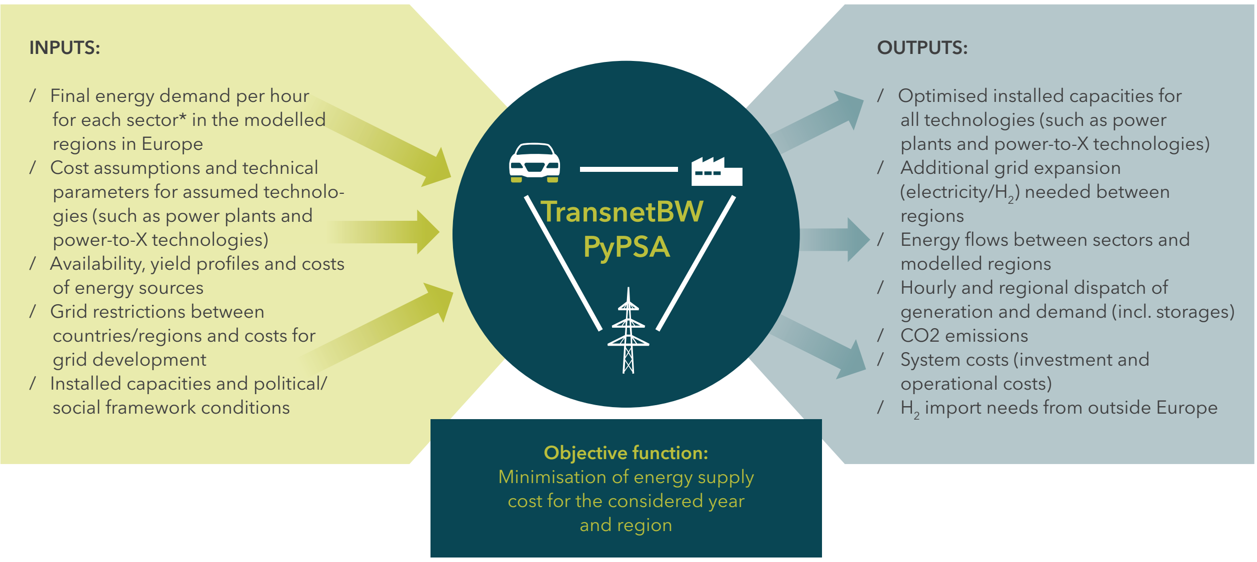


FIGURE 5:
Summary of inputs and outputs of the energy system model (TransnetBW PyPSA).

As shown in Figure 5, the main inputs of the model are:
/ European Climate and energy policy goals
/ The existing energy infrastructure (power plant and energy storage fleet, transport infrastructure for electrical power and natural gas, vehicle fleet)
/ **Final energy consumption** per hour for each sector in the modelled regions in Europe
/ Potentials, availability and yield profiles for each renewable technology and model region
/ Technical and economic parameters of technologies for conversion, storage, and transport of energy (power plants, power-to-X technologies, etc.)
/ Grid restrictions between model regions and costs for grid development

NOTE ON FINAL ENERGY CONSUMPTION MOBILITY
The final energy consumption for private mobility (cars) is a result rather than a model input. The reason is that this share of the mobility sector is optimised. The optimisation takes place among a series of drives (BEV, PHEV, FCEV, CNG, ICE), each characterised by a specific energy consumption.

The key results of the optimisation are:
- Installed capacities for all energy system components (such as power plants, power-to-X technologies, and e-mobility) as well as their hourly dispatch and operation for each year and each model region
- Energy flows and imports/exports between modelled regions and sectors
- Grid expansion between model regions (power, natural gas, hydrogen) as well as energy flows (whole year in one-hour or three-hour time resolution) between sectors and model regions
- CO2 emissions investment and operational cost

Capacities and Potentials

The sources for the evaluation of existing capacities as well as future renewable potentials are as follows:
- For the first year of simulation (2020), we use the Core Energy Market Data Register (Marktstammdatenregister) (MaStR 2021) for Germany. For European countries, we utilise the Irena Database (IRENASTAT 2021).
- Between 2030 and 2050, the model optimises the capacities of wind and PV in each region. In addition, we set lower and upper boundaries for each technology and country:
  - Lower boundaries are set to capacities of existing plants with consideration of their technical lifetimes. In addition, data from the 2019 German Grid Development Plan (**NEP, Netzentwicklungsplan**) (German TSOs 2019) and 2020 TYNDP (ENTSO-E 2020) are used for Germany and other European countries respectively.
  - Upper boundaries, the potentials of wind and PV in terms of maximally installable capacities, are set by the available land area in each model region (CLC 2018). In addition, user-defined maximum boundaries can be set for dedicated sensitivities, such as social acceptance.

NETZENTWICKLUNGSPLAN (NEP)

Following the European Single Market Directive, all European TSOs must create national Grid Development Plans. The basis of the German "Netzentwicklungsplan Strom" (NEP) is the Energy Authority Law (EnWG). The grid development plan defines the future transmission requirements for energy between various starting and end points in a period of 10 to 15 years. It thus does not yet include actual route corridor plans of the federal states' planning authorities. The last NEP was created in 2021 focussing on 2035 (NEP 2021)

Meteodata

Meteodata and corresponding normalised renewables generation profiles are derived from the Atlite PyPSA-package (Atlite 2020). Atlite is the lightweight version of Aarhus RES Atlas for converting weather data to power system data. Within this package, meteodata are available in hourly resolution and for several years with a geographic resolution of 30 km x 30 km. The data are then aggregated for the modelled regions and transformed to normalised power generation yields.

For the main scenarios and most of the sensitivities, we assumed the meteorological conditions of 2012 for the entire modelling period without considering the potential impact of climate change. The year 2012 can be regarded as a typical meteorological year due to the following characteristics:
- Average full load hours of PV all over Europe
- Average full load hours wind power in Germany, rather high in Southern Europe
- Average to partly colder temperature profiles
- The coldest week was very cold, which should be considered in the context of power plant investments.

In addition, in a dedicated sensitivity, we examine the impact of selecting a different historical year characterised by low renewables availability (1996).

Techno-Economic Assumptions

Model results are very sensitive to even relatively small differences in technical and economic assumptions. On the other hand, the cost development of single technologies is typically characterised by a high degree of uncertainty. Given these premises, in the preparatory stage of this study, we conducted a comprehensive review of existing literature. Furthermore, we developed an approach to assess possible capital expenditures (CAPEX) developments of key technologies from 2020 to 2050. Technologies examined in detail are PV, wind onshore, wind offshore, Li-Ion batteries, low-temperature electrolysers, as well as

Fischer-Tropsch and Sabatier reactors. The approach is based on the learning curve method (Samadi 2011). Operation and maintenance expenditures (OPEX) are typically expressed as share of investment per year. The OPEX values and efficiency trends are based on the literature. More details about the method and results can be found in the Appendix.

Prices for energy carriers such as hard coal, lignite, natural gas, and oil are assumed to vary over time. No geographical differentiation among model regions has been considered. The prices have been derived from a literature review (ENTSO-E 2020) (DLR 2020) (FZJ 2020) (LUT 2018) (agora 2021).

Prices for hydrogen imports from outside the modeling region were assessed, considering learning curves for renewables and electrolysers. In addition, costs for hydrogen transport were considered (GasForClimate 2021). The assumptions are within the range of values found in the literature. The study "Langfristszenarien" (Langfristszenarien 2021) assumes high costs for hydrogen in 2050 (81 €/MWh), while a recent scientific study assumes much lower costs (40 - 46 €/MWh) (Hampp 2021). Within the framework of the study, 55 €/MWh has been assumed for 2050 in the Global Markets scenario. With the goal of not importing hydrogen from outside Europe, the price has been set to 81 €/MWh for the Energy Resilient Europe scenario.

Storage Potentials

Regarding storages, we make the following assumptions:

/ Hydropower potential in Europe is fully exploited. Data about existing plants are taken from (Geth 2015) (EIA 2014) (PyPSA 2022) and TransnetBW's internal database.

/ Hydrogen underground storage potential is limited by the geographical availability of suitable geologic formations (Caglayan 2020).

/ No limitation for Li-Ion battery storages. Possible bottlenecks due to potential lack of raw materials are not considered.

Energy Infrastructure

Data about existing thermal power plants – including information about decommissioning - are taken from TransnetBW's internal database as well as from the open power system database (OPSD 2020). The model optimises the future need for thermal power plants in the years after 2020.

We assume that there will be a phase-out of coal-fired power plants by 2038 in Germany. For other European countries, an explicit coal phase-out is not set; rather, the main driving force for reducing coal consumption is the decreasing CO2 emissions budget towards 2050.

Concerning carbon sequestration technologies, **DAC** is allowed without any geographical restrictions, provided this technology is economically competitive. **CCS** is allowed in all modelled regions, except Germany.

The cross-border trading capacities for electricity are equivalent to the specifications in the **ENTSO-E GridKit** for the period 2020-2035. This information is supplemented by data from TransnetBW's internal database.

The international gas grid and gas storages are fixed at the 2020 level (ENTSOG 2015) (diw 2017). After 2030, there is also the option of repurposing a share of the existing gas grid into a hydrogen grid (GasForClimate 2021). In order not to further increase the complexity of the model, specific CAPEX for new hydrogen pipelines are assumed to be independent of capacity. Instead, an average value has been adopted.

DAC

Direct air capture (DAC) technologies extract CO2 directly from the atmosphere. The CO2 can be permanently stored in deep geological formations (achieving negative emissions or carbon capture) or it can be used, for example in food processing or in combination with hydrogen to produce synthetic fuels (Direct Air Capture – Analysis - IEA).

CCS (CARBON CAPTURE AND STORAGE)

Carbon capture and storage, sometimes also CCUS (Carbon Capture, Utilisation and Storage) refers to a suite of technologies that can play an important and diverse role in meeting global energy and climate goals. CCUS involves the capture of CO2 from large point sources, including power generation or industrial facilities that use either fossil fuels or biomass for fuel. The CO2 can also be captured directly from the atmosphere. If not being used on-site, the captured CO2 is compressed and transported by pipeline, ship, rail or truck to be used in a range of applications, or injected into deep geological formations (including depleted oil and gas reservoirs or saline formations) which trap the CO2 for permanent storage (About CCUS – Analysis - IEA).

NOTE ON USED ENTSO-E GRIDKIT

In the version of the GridKit used in this study, following in 2021 developed links are missing: Celtic DC Link (FR-IE), SI-HU Link, PL-LT Link and FR-LU Link.

SYNGAS
Syngas is a fuel gas mixture consisting primarily of hydrogen, carbon monoxide, and very often some carbon dioxide. The name comes from its use as intermediates in creating synthetic natural gas (SNG) and for producing ammonia or methanol.

COMBINED HEAT AND POWER
Combined heat and power (CHP) is the simultaneous conversion of primary energy into mechanical or electrical energy and usable heat within a thermodynamic process. The heat produced in parallel with electricity generation is used for heating and hot water supply or for industrial processes. The use of cogeneration reduces the energy input and carbon dioxide emissions. (Federal Environment Agency, 2020)

PROTON-EXCHANGE MEMBRANE FUEL CELLS (PEMFC)
Also known as polymer electrolyte membrane fuel cells, PEMFCs are a type of fuel cell being developed mainly for transport applications, as well as for stationary fuel cell applications and portable fuel cell applications. Their distinguishing features include lower temperature/pressure ranges (50 to 100 °C) and a special proton-conducting polymer electrolyte membrane. PEMFCs generate electricity and operate on the opposite principle to PEM electrolysis, which consumes electricity.

Electricity Sector

The energy system model encompasses all main technologies for power generation. These include thermal power plants such as coal power plants, gas turbines, combined cycles, and nuclear power plants. The use of **syngas** in gas turbines is possible. In addition, **combined heat and power (CHP)** plants fed by coal, gas or biomass are considered.

Regarding renewables, wind power (onshore and offshore), photovoltaics and hydropower are considered. For onshore wind, a technological differentiation in four classes is considered. Such differentiation is based on wind power potentials in the model regions. PV is classified as utility scale and rooftop plants. For rooftop, separate techno-economic conditions apply: their investment cost is higher than for utility scale PV, but interest rates are lower (see Appendix, Table 10). To some extent, this allows for the lower return on investment expected by private investors in this market segment. Neither floating offshore wind nor floating PV are covered in this study.

In addition, different hydropower plants are considered: reservoirs, pumped hydro storages and run-of-river plants.

Two battery storage technologies are included in the energy system model beside hydro storages. These are utility scale batteries and electric car batteries. The availability of the latter is constrained by the scenario settings. Fuel cells are another option for power generation.

Heat Sector

The ESM includes the following technologies for modelling the heat sector: boilers fed by biomass, natural gas, syngas, oil and coal, air-source and ground-source heat pumps, solar thermal, heating rods, CHP plants and **proton exchange membrane fuel cells (PEMFC)**. An overview of the technologies in the model is given in the Appendix. The technology parameters and costs are based on a systematic literature review (dena 2018) (DEA 2020) (acatech 2018).

The model assumes that the heat sector operates in a system-supporting mode. This means that heat storages allow a certain degree of demand side management (DSM). In the heat sector, hot water storage tanks are available for DSM. It is assumed that heat can be stored for up to 180 days in central regions and 3 days in decentralised regions.

For heat pumps, the energy system model distinguishes between air-source heat pumps in urban regions and ground-source heat pumps in rural regions. The model can freely optimise the capacity of the heat pumps. The coefficient of performance is calculated using hourly weather data.

Transport Sector

The transport sector in the energy system model includes road, rail, national water transport and aviation. International aviation and navigation are not included. Depending on the subsector, different technological options are available to the model. We consider the road transport sector in detail, particularly the private road sector. For the latter, the following vehicles are modelled: conventional internal combustion engines (ICE), compressed natural gas (CNG) cars, hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), and fuel cell electric vehicles (FCEV). Each car drive is characterised by its own techno-economic parameters such as investment and operational cost, efficiency, and lifetime. ICE cars can be fueled by either fossil or synthetically produced oil. The same applies to CNG cars. The share of the private road transport sector in the years studied is optimised by the model.

However, no optimisation takes place for the remaining transport subsectors. Instead, the share of conventional and alternative drives is given as an input to the model.

NOTE ON MOBILITY DSM
DSM in the mobility sector means that within each model region car batteries are assumed to act as an energy-system-supporting virtual storage. We assume that each electric car in 2050 has a charging capacity of 11 kW and a storage capacity of 50 kWh. We also assume that at 5:00 AM, the state of charge of the battery storage must be at least 75%.

The private road sector is also assumed to play an important role as an additional flexibility option in future energy systems. Two types of flexibility are considered: **demand side management** (DSM) and vehicle-to-grid (V2G). Depending on vehicles' availability and minimum battery state of charge in the early morning hours, the grid is assumed to have control over the storage function to minimise overall energy system cost. However, this assumption represents a system that is not in place - from neither a technical nor regulatory point of view. Therefore, we assume that DSM only applies to a limited share of electric cars (50%). V2G is an additional flexibility measure. In this case, we assume that a share of the electric car fleet can feed power to the grid when it is required. Here the same limiting factors as for DSM apply. In the current modelling assumption, no incentives are provided to car owners to participate in flexibility measures.

Industry sector

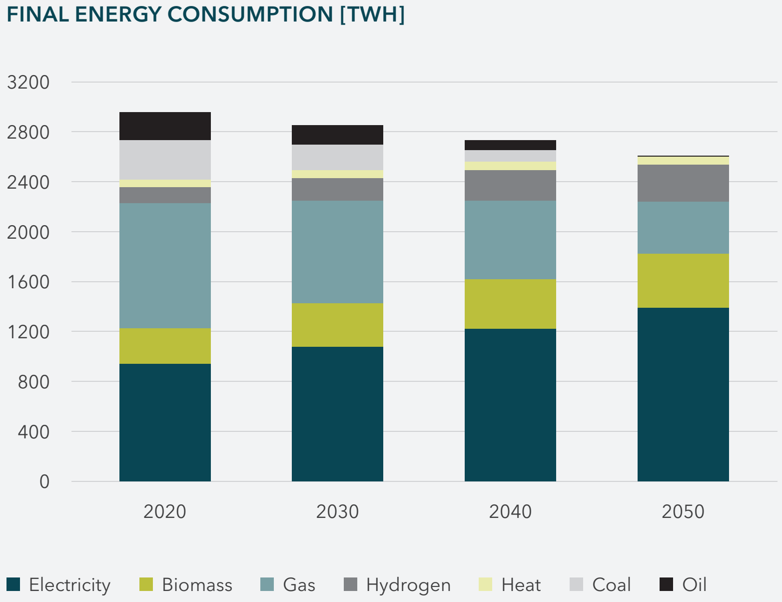
The following industries are considered in the ESM: iron and steel, non-ferrous metals, chemical industry, non-metallic mineral products, pulp, paper and printing, food, beverages and tobacco, transport equipment, machinery equipment, textiles and leather, as well as wood and wood products.

For the steel and paper industry and other industrial sectors, the energetic and feedstock demands are fixed within a scenario, so no optimisation takes place. In the case of the chemical industry, the final energy consumption is an input, while the usage of feedstock (such as imported fossil or synthetic fuels, hydrogen and Fischer-Tropsch products) is an optimised model result.

The development the industrial energy demand as well as its breakdown by energy carriers is a model input. The values are based on a meta-analysis of different available studies (such as dena Leitstudie). An overview of the final demand breakdown by energy carrier is given in Figure 6. According to the setting, the share of electricity increases from approximately 29% in 2020 to 53% in 2050. The share of biomass slightly increases from 9% to 17% in the same time span, while gas declines drastically from 1,063 TWh/year (36%) in 2020 to 421 TWh/year (16%) in 2050. The overall demand just slightly decreases from 2,988 TWh/year in 2020 to 2,604 TWh/year in 2050.

FIGURE 6:
Modelled final energy consumption of the industry sector, EU27, 2020 to 2050.

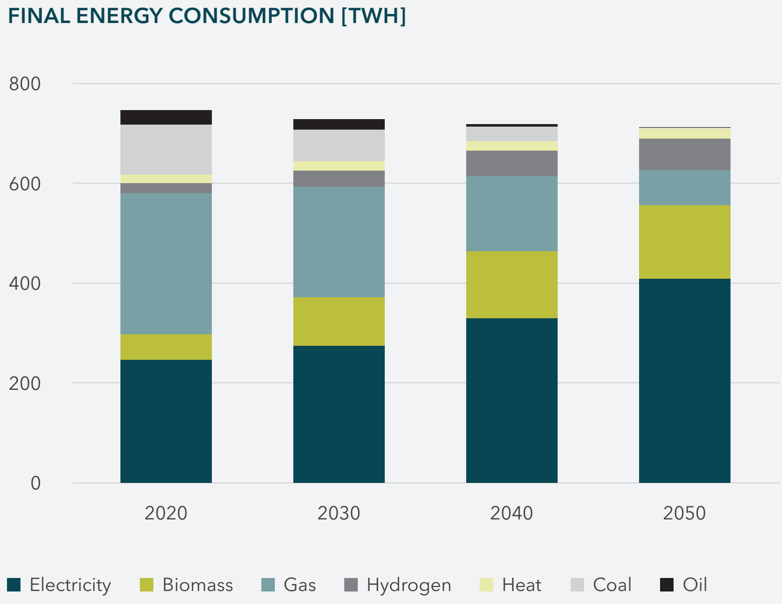
NOTE ON FINAL ENERGY CONSUMPTION
For oil and gas, only the energetically used energy share is represented.



Industry sector - Germany

In comparison to other sectors, total energy consumption in the German industry sector is assumed to remain relatively stable over the years, declining slightly from 744 TWh to 710 TWh, as shown in Figure 7. However, the energy mix is a result of the optimisation of all modelled sectors (and not an input). Indeed, we see no difference between the ERE and GM scenarios. The most obvious development is the increase in direct electricity use from 246 TWh in 2020 to 408 TWh in 2050, or 33% to 57% of the total energy consumption. Another noticeable increase can be seen in the share of biomass. It becomes the second most important energy source for German industry in 2050 with an energy use of 149 TWh or 20% of the total demand. Hydrogen plays an importan role in the industry sector, too. It contributes 62 TWh to the total energy demand in 2050. In contrast, the share of fossil fuels, especially gas and coal, falls dramatically. Gas decreases from 281 TWh in 2020 to 69 TWh in 2050, and oil completely disappears at the end of the studied period.

FIGURE 7:
Modelled final energy consumption of the industry sector, Germany, 2020 to 2050.



Demand Development

Electricity Sector

The development of electricity demand in each model region is partly defined exogenously and partly optimised by the model. The development of **conventional electricity demand** is a model input based on scenario C of the German NEP, 2019 version (German TSOs 2019). Values after 2035 are extrapolated until 2050. The same trend as for Germany is assumed for the other European countries. In 2020, conventional electricity demand amounted to 461 TWh/year in Germany and 2,739 TWh/year in the complete model region. In 2050, these values drop to 404 TWh/year and 2,599 TWh/year.

NOTE ON CONVENTIONAL ELECTRICITY DEMAND
For classical electricity demand, we assume a decrease due to increasing efficiencies. Such decrease is based on the scenario C of the German NEP, 2019 version (German TSOs 2019). We additionally subtract the electricity demand for heat generation from the conventional electricity demand, as this is optimised endogenously by the model.

Transmission **grid losses** are calculated as a share (5.5%, empirical value) of constant electricity demand (classical and industry). Distribution grid losses are not explicitly accounted for in the model, but included in conventional electricity demand.

GRID LOSSES
The term grid losses refers to the total energy that is lost during the transmission or transformation of electricity. Grid losses are the differences between the metered energy feed-in and consumption over all grid access points.

Mobility Sector

The data for current mobility demand is derived from aggregated transport demand and daily profiles. As a central reference for the base year calibration in the transport sector, a dataset from the Joint Research Center (JRC) is used. This includes other demand sectors besides the transport sector, including the industrial sector in the EU-28 (JRC-IDEES 2018). This database includes transport demand (in pkm or tkm) and energy demand by energy source, transport mode and country.

In addition, data from the German Federal Highway Research Institute (PyPSA 2022) (BASt 2018) have been used for the definition of daily demand profiles in the road transport sector. It is further assumed that differences between seasons are negligible and that profiles are representative for all countries.
The main data source for the mobility demand development until 2050 is the EU Reference Scenario 2020 for traffic forecasts (EC 2021).

Heat Sector

Germany's energy policy target includes a 20% reduction of final energy consumption for heat supply compared to 2008, which corresponds to an efficiency increase of 1.84% per year. In PyPSA, we define the reduction of heat demand (useful energy), while the reduction of final energy consumption for heat supply is a model result. The current heat demand per region and sector, as well as the current technology stock, are based on the European JRC-IDEES database "Integrated Database of the European Energy Sector" (JRC-IDEES 2018). The heat consumption profiles per region and sector are based on the EU study "Hotmaps 2050 - Heating & Cooling outlook until 2050" (hotmaps 2020).

Future development of heat demand (thermal insulation, efficiency) is assumed according to the BCG and Prognos study "Climate paths for Germany" (prognos 2018). In both central scenarios as well as in most of the sensitivities, an average heat demand reduction of 1.08% per year has been assumed for Germany. This value is based on an assumed renovation rate of 1.9% per year and a renovation efficiency of 57%. A more pessimistic scenario is considered in the sensitivity "Low Building Renovation Rate".

2.3 OUR FUTURE VISION OF EUROPE IN TWO SCENARIOS

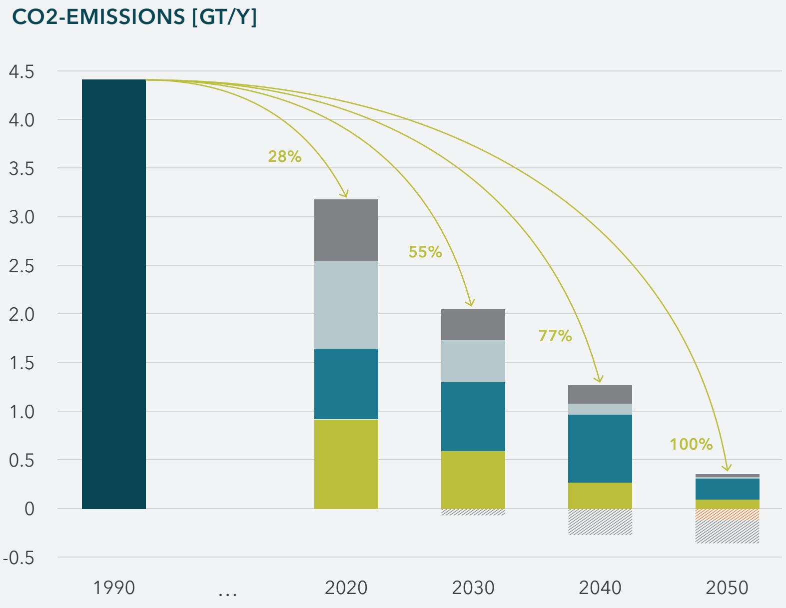
In this chapter, we present the main results of the energy system modelling. First, the results of the two central scenarios are presented, compared, and critically discussed (2.3.1). In the subsequent section, the key findings of the sensitivity analyses are described (2.3.2). In Chapter 2.3.3, we describe the results of the main scenarios with a focus on Germany.

2.3.1 RESULTS OF CENTRAL SCENARIOS (EU27)

Compared to the reference year, in which the total CO2 emissions in Europe amounted to 4.4 Gt, a reduction target of 55% by 2030 and **climate neutrality** by 2050 will be achieved in accordance with the EU Green Deal (Figure 8).

NOTE ON ESM ASSUMPTION ON CLIMATE NEUTRALITY
In the ESM, the CO2 emission reduction path has been set as an input (upper limit) in each of the modeled years, while the model optimises the allocation of the share of emissions among concurring energy sectors. The CO2 emission upper limit has been set at EU level. A linear reduction of CO2 emissions is assumed between 2030 and 2050 for both scenarios.

FIGURE 8:
European CO2 reduction pathway, GM and ERE scenario, 1990 to 2050.



■ Heating
■ Electricity
■ Industry
■ Transport
■ Total Emissions
▨ DAC
▨ Industry CC

NOTE ON MODELLED SECTORS
The complete decarbonisation of the intercontinental transport sector (aviation and navigation) is not modelled in this study (see Chapter 2.2.3).

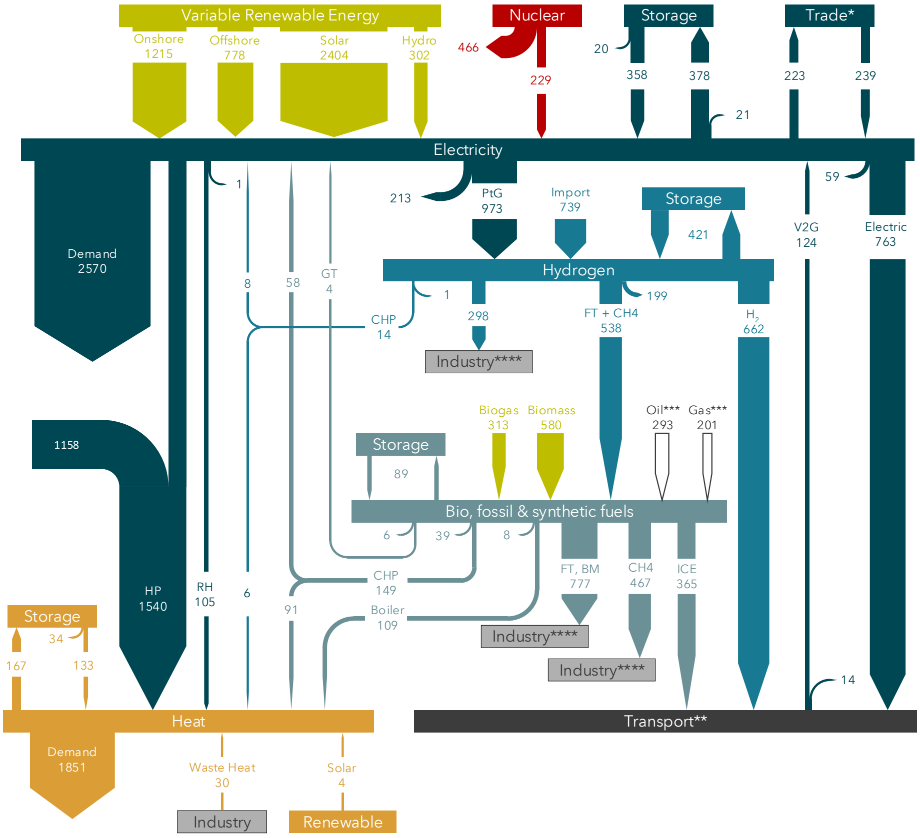
NOTE ON INDUSTRIAL CC
Industrial carbon capture and DAC are used to balance remaining CO2 emissions in the energy system. As explained in 2.2.3, the industrial energy demand as well as its breakdown by energy carriers is a model input. The values are based on a meta-analysis of available studies (dena Leitstudie)

The reduction of CO2 emissions occurs in all **modelled sectors**, which are heating, electricity, industry and transport. The electricity sector is the first to reach full decarbonisation. Already in 2040, the share of emissions in the power sector is almost negligible (0.12 Gt/year, 3.6%). The heating and transport sectors experience a linear decline of emissions throughout the period. Decarbonisation of the industry sector appears relatively challenging and more cost-intensive than for other sectors. In 2020, industry gross emissions account for 0.74 Gt/year (22.3%), but in 2040 they still reach 0.70 Gt/year, which is approximately 55% of the total gross (positive) emissions. In 2050, industry still emits 0.22 Gt/year of CO2, which is equivalent to 61% of the total gross emissions, followed by transport with 0.10 Gt/year (27.5%), heating with 0.1 Gt/year (8.0%) and electricity with 0.01 Gt/year (3.4%). Negative emissions play an increasing role starting from 2030. **Industrial carbon capture** (CC) is the only negative emission technology used in 2030 (- 0.07 Gt/year) and 2040 (- 0.27 Gt/year), while in 2050 an additional contribution is made by direct air capture (DAC, - 0.12 Gt/year).

Energy flows

Figure 9 depicts the energy flows of the Global Markets (GM) scenario in 2050. The horizontal boxes represent the different sectors. For the sake of simplicity, the sector for gas, oil, biomass and other energy carriers, which can be roughly described as “fuels“, is divided into bio, fossil & synthetic fuels. The sectors are linked together via conversion technologies such as CHP or PtG. Typically, when analysing only one sector, such as the electricity sector, these links are referred to as generation technologies or generation capacities. However, in the context of an energy system, the term link is often used, as it better describes the coupled aspect of the system. For some categories, such as biomass, we have simplified the definition by excluding the underlying agricultural sector and treating it as an import into our flow diagram. While generation technologies (links) are shown vertically, losses are pictured as curved arrows, which are aligned horizontally and not connected to other entities.

FIGURE 9:
Energy flow diagram, GM scenario, EU27, 2050.



CH4	Methane (fossil or synthetic)
CHP	Combined Heat and Power
FCEV	Fuel Cell Electric Vehicle
FT	Fischer-Tropsch product
HP	Heat Pump
ICE	Internal Combustion Engine
PtG	Power-to-Gas
RH	Resistive Heater
V2G	Vehicle-to-Grid

* The trade also contains 100 TWh transit flows across non-EU27 regions like Switzerland and UK , e. g. power transmitted from Germany to Italy via Switzerland is accounted twice. First as export, then as import.

** The emission reduction of international transport is outside the scope of this study and has been only taken partially into account. Therefore, all fossil based fuel demand of the international transport is not shown.

*** Even in a fully decarbonised energy system, small amounts of fossil energy carriers are used. Their emissions are fully captured by existing Carbon Capture technologies or encountered with negative emissions.

**** "Industry" contains energetic as well as feedstock usage. Fossil feedstock is not represented in this chart as its respective CO_2 content is not released into the atmosphere. Hence, all fossil based feedstock flows are excluded.

In general: Energy flows below 1 TWh are not depicted. Therefore, small imbalances between inputs and outputs may occur.

The energy flow diagram shows how the electricity sector is dominated by VRE power generation. It is backed up by electricity storages, trade, generation from hydrogen and other fuels and, in certain countries, nuclear power. In terms of renewable energy, biomass comes from the bio, fossil and synthetic fuels sector through the CHP link. Also, there is co-generation of power and heat via the hydrogen CHP link. The biggest share of the load is shown as the demand. It consists of conventional electricity demand, new industry appliances, grid losses and the electricity demand from DAC. Electricity demand in the heat and transport sectors is roughly equal to the demand by electrolysers (PtG). Finally, gas-fired turbines provide a small amount of energy to the system. They are fed by a mixture of bio, synthetic and fossil gas. The CO2 emissions of all fossil energy carriers are countered with either DAC, CCS or negative emissions such as biomass CCS. Hence, the depicted energy system remains carbon neutral.

The hydrogen sector is shown adjacent to the electricity sector because of the strong interconnection through the PtG link. While the largest share of hydrogen supply in the EU comes from electrolysis, significant amounts of hydrogen are still imported. We assumed a cost competitive import price in the GM scenario, which will be most likely achieved by pipeline-based imports. Demand for hydrogen fluctuates less, but storage usage is greater than other sectors. This can be explained by the role that electrolysis plays in the energy system: it is a flexible load that can be used to counterbalance varying VRE generation. Due to the large capacity of installed storage, the energy system benefits from its flexibility. Similar high flexibility is provided by electricity storages, which are realised by **Pumped Hydro Storage (PHS)** and batteries. To a lesser extent, additional flexibility is provided by heat storages in the heat sector, and gas storages in the gas sector for storing the surplus generation of syngas, for example. Although it is not depicted as a storage, the combination of electric transport and V2G has similar capabilities. Here, surplus electricity can be stored in the batteries of electric vehicles, which later feed the power back to the electricity grid.

PUMPED HYDRO STORAGE (PHS):
Pumped hydro storage is a type of hydroelectric energy storage. It is a configuration of two water reservoirs at different elevations that can generate power as water moves down from one to the other (discharge), passing through a turbine. The system also requires power as it pumps water back into the upper reservoir (recharge). PHS acts like a giant battery, because it can store power and then release it when needed. (EERE 2022)

Next, the combined sector of bio, fossil and synthetic fuels is shown. On the input side, a variety of sources deliver energy to this sector. Biogas and biomass are the renewable energy carriers for this sector. While these could also be imported from outside the EU, the energy system model always chooses not to, because of the high costs. Oil and gas are also fed into the energy system, while counterbalancing their CO2 emissions to keep the system carbon neutral. Beside fossil and biogenic fuels, synthetic methane and oils are also present. In the GM scenario, these are all produced in the EU by methanisation processes or Fischer-Tropsch synthesis. Comparing the sizes of the outputs in this sector, it is clear that the feed-in to electricity and heat is comparatively low. Most of the demand for these energy carriers comes from the industry sector and some from the transport sector.

From a purely technical perspective, synthetic fuels could replace fossil fuels by means of current conversion technologies. This would need upstream processes like electricity-to-hydrogen and hydrogen-to-methanisation conversions. While our energy system still includes this route, it is not an economical way to cover all energy demands. It is far more economically feasible to utilise energy in its primal form where possible, to minimise losses and eliminate the need for additional industrial facilities. Therefore, direct electrification of industry processes, heating appliances, and transportation needs are dominant in the electricity sector, as they make direct use of energy. They use the power generated by VRE and nuclear plants. In the next section, hydrogen is intensively used in industry and transport. Only one additional conversion process is necessary. The last section consists of synthetic or carbon neutral fossil fuels, the most expensive in this chain. Small amounts are still present because they provide flexibility to the system and serve some loads which are not flexible in terms of alternative energy carriers.

The next energy flow diagram visualises the results of the Energy Resilient Europe (ERE) scenario for the year 2050. The demands of industry and transport remain the same, and the end use of electricity and heat is very similar. The major difference is the stronger interconnection between the electricity and hydrogen sectors, which compensates for significantly lower hydrogen imports. The remaining 9 TWh of imports are from non-EU27 European countries, not the global market. Further downstream, fuel imports are different from the GM scenario, and the direct import of synthetic oil is noticeable. As a result, with the higher capacity of PtG, additional VRE and nuclear generation can be observed in the electricity sector. Also, there is more import than export of electricity to and from non-EU countries. In total, this leads to substantially lower energy imports from outside the EU.

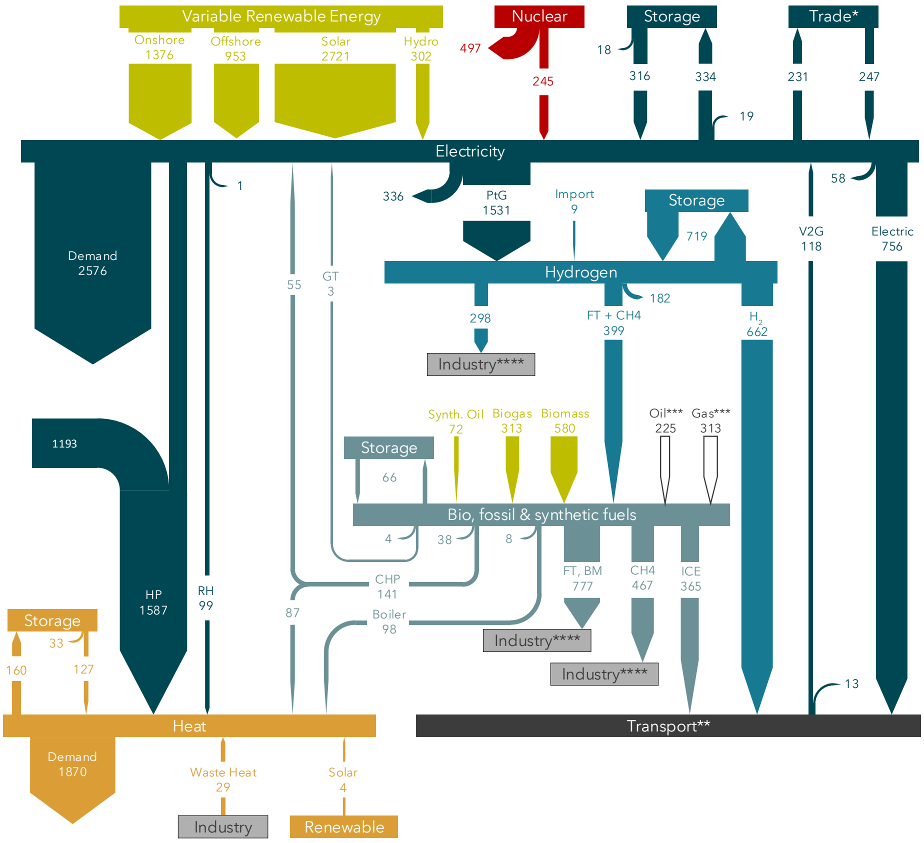


FIGURE 10:
Energy flow diagram, ERE scenario, EU27, 2050.

CH4	Methane (fossil or synthetic)
CHP	Combined Heat and Power
FCEV	Fuel Cell Electric Vehicle
FT	Fischer-Tropsch product
HP	Heat Pump
ICE	Internal Combustion Engine
PtG	Power-to-Gas
RH	Resistive Heater
V2G	Vehicle-to-Grid

* The trade also contains 113 TWh transit flows across non-EU27 regions like Switzerland and UK, e. g. power transmitted from Germany to Italy via Switzerland is accounted twice. First as export, then as import.

** The emission reduction of international transport is outside the scope of this study and has been only taken partially into account. Therefore, all fossil based fuel demand of the international transport is not shown.

*** Even in a fully decarbonised energy system, small amounts of fossil energy carriers are used. Their emissions are fully captured by existing Carbon Capture technologies or encountered with negative emissions.

**** "Industry" contains energetic as well as feedstock usage. Fossil feedstock is not represented in this chart as its respective CO_2 content is not released into the atmosphere. Hence, all fossil based feedstock flows are excluded.

In general: Energy flows below 1 TWh are not depicted. Therefore, small imbalances between inputs and outputs may occur.

One of the minor but notable changes is the absence of hydrogen electrification. While electrification of hydrogen seemed cost effective in the GM scenario, the higher cost of hydrogen reduces it to zero. At the same time, hydrogen storage nearly doubles, while electricity storage is slightly reduced. This can be explained by the stronger interconnection between the electricity and hydrogen sectors. Much higher electrolysis capabilities allow for more effective hydrogen storage to balance electricity generation fluctuations. Although there is no direct feedback link from hydrogen to electricity, PtG enables a better utilisation of VRE generation.

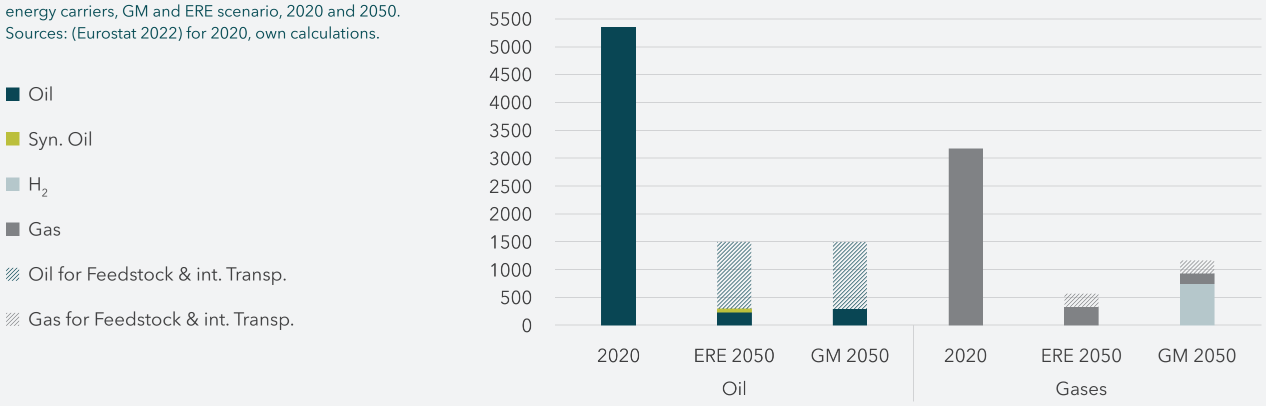
If we look further downstream, we notice less processing of hydrogen to higher quality products. The energy resilience of hydrogen results in higher costs, which affects the competitiveness of hydrogen-based fuels produced in the EU. This occurs in the fuels sector with a shift of energy carriers. Synthetic oil imports replace some parts of the pure fossil oil. This avoids CO2 emissions, which the system is now able to allocate somewhere else. We can observe a higher use of fossil gas, which is of higher energetic value than fossil oil, but has roughly the same CO2 emissions.

Comparison of energy imports

As we have shown, demand for oils and gases will decrease significantly due to the energy transition. To visualise the extent of decrease, the following figure compares the demand of the EU27 in 2020 with the demand in 2050, optimised in the model. Hydrogen produced in the EU is not shown here.

FIGURE 11:
Natural energy carriers produced in EU and imported energy carriers, GM and ERE scenario, 2020 and 2050. Sources: (Eurostat 2022) for 2020, own calculations.

EU-PRODUCED NATURAL AND EU-IMPORTED ENERGY CARRIERS [TWH/Y]



NOTE ON DEMAND IN 2020
The 2020 demand of the EU27 is not exactly comparable with the model results; rather, it represents the extent of demand. Only part of the demand of intercontinental transport was considered. Therefore, additional demand for hydrogen or synthetic fuels in 2050 is expected.

Comparing our study results for 2050 with the 2020 values, we observe that oil demand is over 72% lower and gas demand is between 63% (GM) and 83% (ERE) lower, depending on the scenario. This shows that Europe will become significantly more independent of energy carriers as a result of the energy transition. In the GM scenario, we observe the use of mineral oil, natural gas and imported hydrogen. The ERE scenario shows how the EU is becoming more energy resilient through a large reduction in imported hydrogen. Therefore, the demand for natural gas rises to 313 TWh, which is still significantly below the amount of natural gas that can be produced in the EU (2020: >480 TWh). In conclusion, in the ERE scenario, natural gas will probably not have to be imported from non-EU countries. To compensate for lower production of synthetic fuels and higher CO2 emissions from natural gas, 72 TWh of synthetic oils are imported to the EU. It is conceivable that this oil could be imported from the USA or Canada, for example. The emissions from mineral oil and natural gas are compensated by CCS and DAC.

Primary energy consumption
The reduction of CO2 emissions is the main driver for a deep transformation process throughout the energy system. This development is accompanied by a reduction in primary energy consumption, as shown in Figure 12. The data for 2020 for the EU27 are based on the Eurostat database (Eurostat 2022). The figures for 2050 are model results for the GM scenario and the ERE scenario.

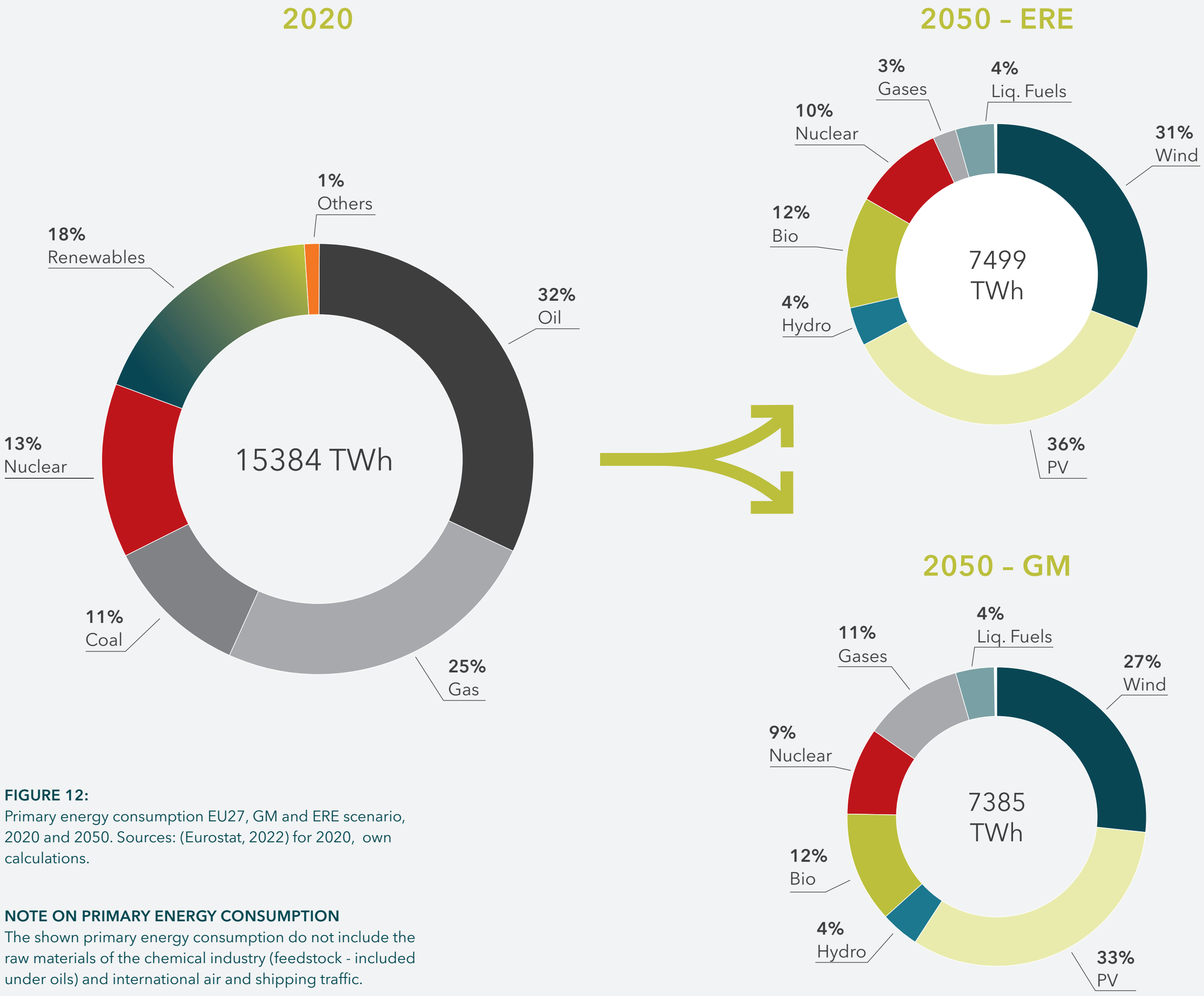


FIGURE 12:
Primary energy consumption EU27, GM and ERE scenario, 2020 and 2050. Sources: (Eurostat, 2022) for 2020, own calculations.

NOTE ON PRIMARY ENERGY CONSUMPTION
The shown primary energy consumption do not include the raw materials of the chemical industry (feedstock - included under oils) and international air and shipping traffic.

In the period from 2020 to 2050, the energy content of all energy sources used in Europe directly or for conversion into energy carriers will be roughly halved. Indeed, primary energy consumption will decline from 15,384 TWh/year in 2020 to around 7,500 – 7,390 TWh/year in 2050. Consumption is significantly reduced due to lower losses during energy conversion and a decrease in final energy consumption. The key drivers for the consumption decrease are building retrofits and increasing efficiency gains from electrification in the heating and transport sectors, with the growth of heat pumps and electric mobility.

The expansion of renewables, particularly PV and wind power, plays a key role in the reduction of primary energy consumption. In the GM scenario, the renewable energy share increases from 18% in 2020 to around 76% in 2050. This value may appear low in relation to the climate neutrality goals. However, the GM scenario results show that minimum cost of supply is also achieved with energy imports from outside Europe, including gases such as green hydrogen, synthetic gases, fossil gases and biogases as well as green e-fuels. The share of gases and synthetic fuels produced in Europe is included in renewables and not shown separately. The small remaining share of European fossil fuel extraction accounted for by gases and synthetic fuels is not considered, while DAC and CCS offset its CO2 emissions. Nuclear power accounts for an additional 9% to 10%.

A comparison of the values of the two main scenarios for 2050 shows that a significant shift occurs when the cost for hydrogen imports becomes more expensive (note that the assumption for H_2 import cost is 55 €/MWh in the GM scenario and 81€/MWh in the ERE scenario). In the ERE scenario, the reduction of H_2 imports is noticeable in the decrease in gases (from 810 TWh/year in GM to 292 TWh/year in ERE, which is a reduction of roughly 64%). This is compensated by a pronounced increase of both wind (+ 17%) and photovoltaics (+ 13%). There is also a moderate increase in nuclear power (+ 7%). The other contributions and total primary energy consumption remain roughly constant. In the ERE scenario, the renewable energy share increases to 83%, with a relative increase of around 7% in comparison to the GM scenario.

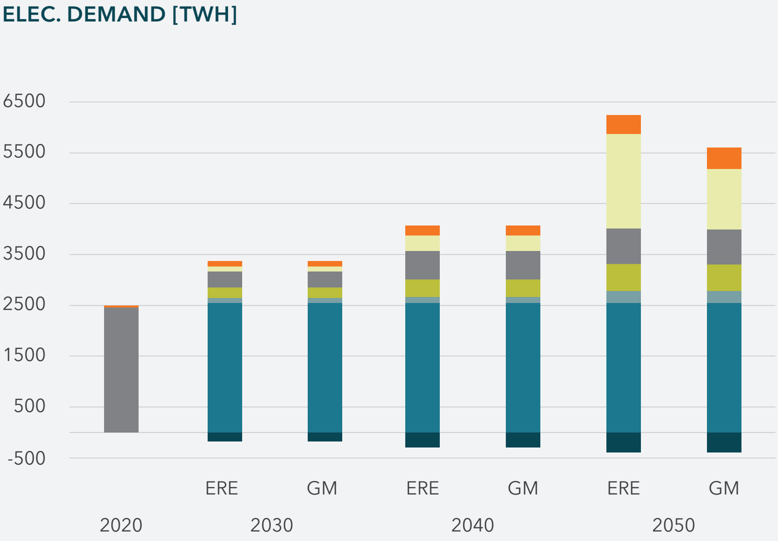
Electricity

As mentioned, the decline in primary energy consumption goes hand in hand with the increase in electricity demand, as shown in Figure 13. Total electricity demand between 2020 and 2050 increases from approximately 2,491 TWh/year to 5,190 TWh/year (GM) and 5,833 TWh/year (ERE). This growth is mainly driven by e-mobility (370 TWh/year in 2030 in both scenarios, 690 TWh/year in 2050 in both scenarios) and power-to-X technologies (90 TWh/year in 2030 in both scenarios, 1,190 TWh/year (GM) and 1,870 TWh/year (ERE) in 2050). Among power-to-X technologies, electrolysers have the largest share. Therefore, power-to-X is the key driver for the differences between the GM and ERE scenarios. The main reason behind the increase of power-to-X power consumption is additional hydrogen production in the EU to replace the more costly non-EU H_2 imports. The additional electrolysers in Europe cause higher power consumption. Such an effect is also noticeable in the following figures for installed capacities and corresponding electricity generation (Figure 14 and Figure 15).

The overall increase is also due to electrification of the heat sector by heat pumps (110 TWh/year in 2030, 240 TWh/year in 2050, with minor differences between the two scenarios) as well as **new industry processes** (200 TWh/year in 2030, 530 TWh/year in 2050, also with negligible differences between GM and ERE). The increase in total demand is partly compensated by a decrease in conventional demand due to efficiency gains. This is around 390 TWh/year in 2050.

NEW INDUSTRY PROCESSES
„New industry" includes the sum of changes in demand of all sectors relative to the base year. The following sectors are considered: iron and steel, nonferrous metals, alumina production, aluminium production, other nonferrous metals, chemical industry, pharmaceuticals, non-metallic mineral products, cement, ceramics, glass production, pulp, paper and printing, printing and media reproduction, food and beverages, vehicle construction, mechanical engineering, textiles and leather, wood and wood products.

FIGURE 13:
Net electricity demand EU27, GM and ERE scenario, 2020 to 2050. Sources: (Eurostat 2022) for 2020, own calculations.



🟧 Storage
🟨 Power-to-X
⬜ E-Mobility
🟩 New Industry Applications
🟦 Heat
🟦 Conventional
⬛ Net Electricity Demand
⬛ Efficiency

The maximum simultaneous electricity demand in the EU27 will increase more than 3 times from today up to 1,508 GW in the GM scenario and 1,745 GW in the ERE scenario. Flexible consumers account for 62% to 64% of the total demand in the specific situations at the end of March 2050, at midday (see Table 1). This flexibility ratio differs depending on the available technologies in the countries. The largest flexibility comes from power-to-gas with 24% (GM) to 31% (ERE) of the total demand. The smart charging of electric cars accounts for 16%. Battery storages and pumped hydro storages have a share of around 11%."

TABLE 1:
Maximum simultaneous electricity demand in the EU27, GM and ERE scenario.

Scenario	**ERE**	**GM**
Date	2050-03-28, 12 pm	2050-03-29, 1 pm
Inflexible demand	631 GW	574 GW
Flexible demand	1,114 GW	934 GW
of which power-to-gas	544 GW	363 GW
of which storages	181 GW	193 GW
of which smart charging BEVs	285 GW	237 GW
of which power-to-heat	104 GW	141 GW
Total	1,745 GW	1,508 GW
Flexibility share	64%	62%

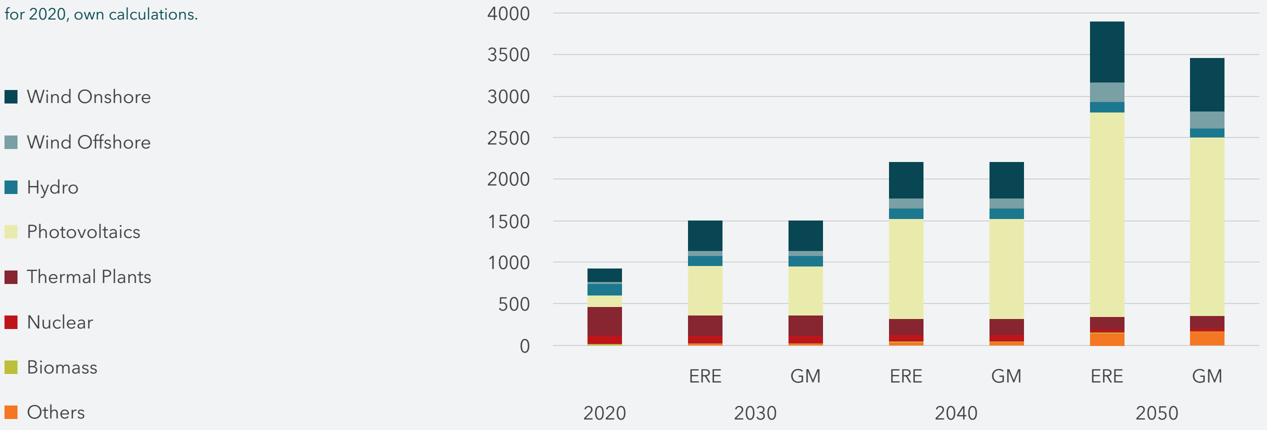
NOTE ON FLEXIBILE/INFLEXIBLE DEMAND
The inflexible demand includes 50% BEV-demand, conventional electricity demand, electricity road freight, grid losses, new industry electricity. The flexible demand includes battery storages, pumped hydro storages, 50% BEV-demand, elektrolysers, heat pumps, resistive heaters and helmeth.

As expected, there is a massive rollout of renewables, bringing installed power plant capacity in the EU27 up to almost 3,500 GW (Figure 14). While the installed power plant capacity in 2020 amounted to approximately 920 GW, it is expected to grow to roughly 1,500 GW by 2030. The largest increase in installed capacity is for PV. In the GM scenario, the results show a PV installed capacity of 2,135 GW in 2050. For such development, an average installation rate of 67.2 GW/year would be necessary in the EU27. The expansion of wind is also substantial, although less pronounced than PV. Onshore wind increases to 681 GW (average installation rate of 16.4 GW/year), while offshore wind reaches 167 GW (average installation rate of 6.2 GW/year).

At the same time, the capacity of conventional power plants decreases from 337 GW in 2020 to 154 GW in 2050, after reaching a peak in 2030 (245 GW). The same applies to nuclear power plants, which decline from 106 GW in 2020 to 33 GW in 2050.

FIGURE 14:
Electricity generation capacity EU27, GM and ERE scenario, 2020 to 2050. Sources: (Eurostat 2022) for 2020, own calculations.

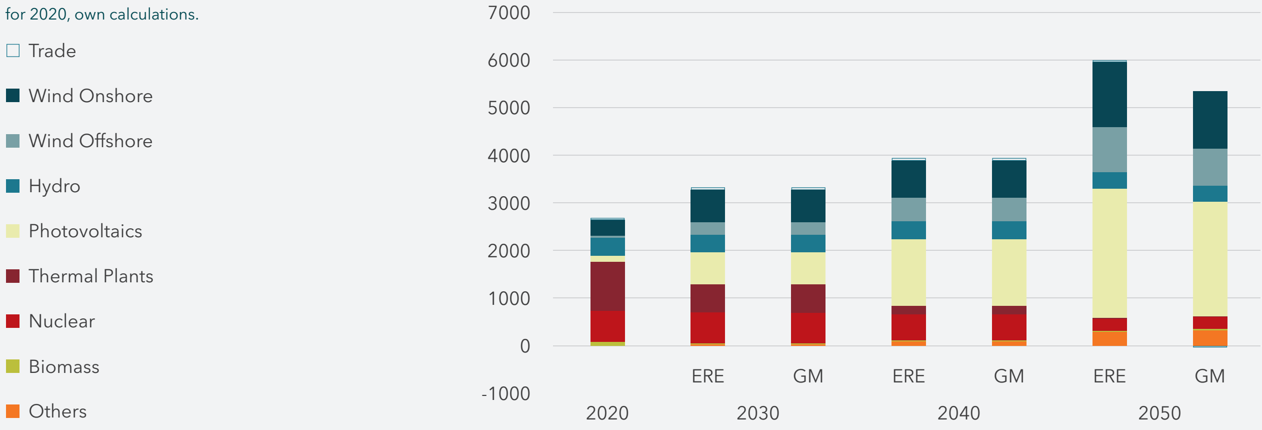
GENERATION CAPACITY [GW]



An overview of power generation and trade in the EU27 in the considered time span (A015) shows that electricity generation will roughly double. In 2020 power generation amounted to 2,670 TWh/year, but the values for 2050 will rise to 5,990 TWh/year and 5,340 TWh/year.

FIGURE 15:
Annual electricity generation EU27, GM and ERE scenario, 2020 to 2050. Sources: (Eurostat 2022) for 2020, own calculations.

GENERATION INCL. TRADE [TWH]



As we have shown, renewable energy forms the basis for the electricity sector in 2050. In contrast to conventional fossil-based generation technologies, land use is a critical property of PV and wind plants. Therefore, it is necessary to measure the use of available potential, as well as the capacities needed.

The bar chart in Figure 16 shows the PV capacities of both scenarios in comparison. In addition, the total available potential is visualised by red dots. PV is present in two forms in the model: as rooftop PV modules and utility scale plants in agricultural areas. In terms of potential, six countries stand out: France, Spain, Germany, Poland, UK and Italy. For both scenarios, France, Spain and Italy make use of nearly all available locations of PV. Their geographical location in Europe, the availability of suitable areas and the meteorological conditions lead to an overall high usage of PV, independently of the scenario.

CAPACITY [GW]

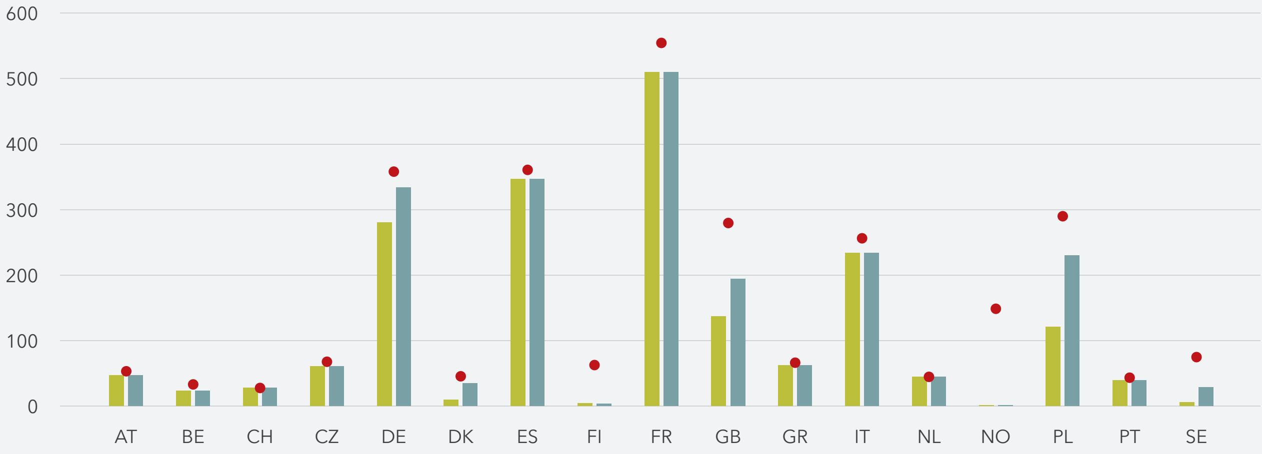


FIGURE 16:
Utilisation of PV potentials EU27, GM and ERE scenario, 2050.

In contrast to this pronounced expansion of PV, the situation in Poland, Great Britain and Germany is different. These countries respond with a higher utilisation of PV potential in the ERE scenario than in the GM scenario. We can think of it as a merit order of expansion. Countries with high PV utilisation in both scenarios provide cost effective generation of carbon neutral electricity in the European context. If the demand for electricity rises, as in the ERE scenario, Germany, Great Britain and Poland are the next best choices for additional PV generators. Unused potential in the Scandinavian countries can also be utilised. In comparison to other countries, generation and provision of electricity is more expensive in Europe. This is due to the meteorological profile and the necessary grid expansion.

Although we focussed only on countries with major PV potentials, the conclusions also apply to countries with lower potentials. In addition to PV, this type of analysis can also be made for onshore and offshore wind plants. The associated bar charts are shown in Figure 17 and Figure 18.

France, Poland, Great Britain and Germany each have over 100 GW of onshore wind turbines in 2050. France utilises approximately 50% of its onshore potential, while Poland and Great Britain make use of nearly every suitable onshore region. When we compare GM with ERE, we can observe that France and Germany show significant changes in their onshore utilisation, while many other countries show nearly no sensitivity. This seems to be independent of the degree of potential utilisation.

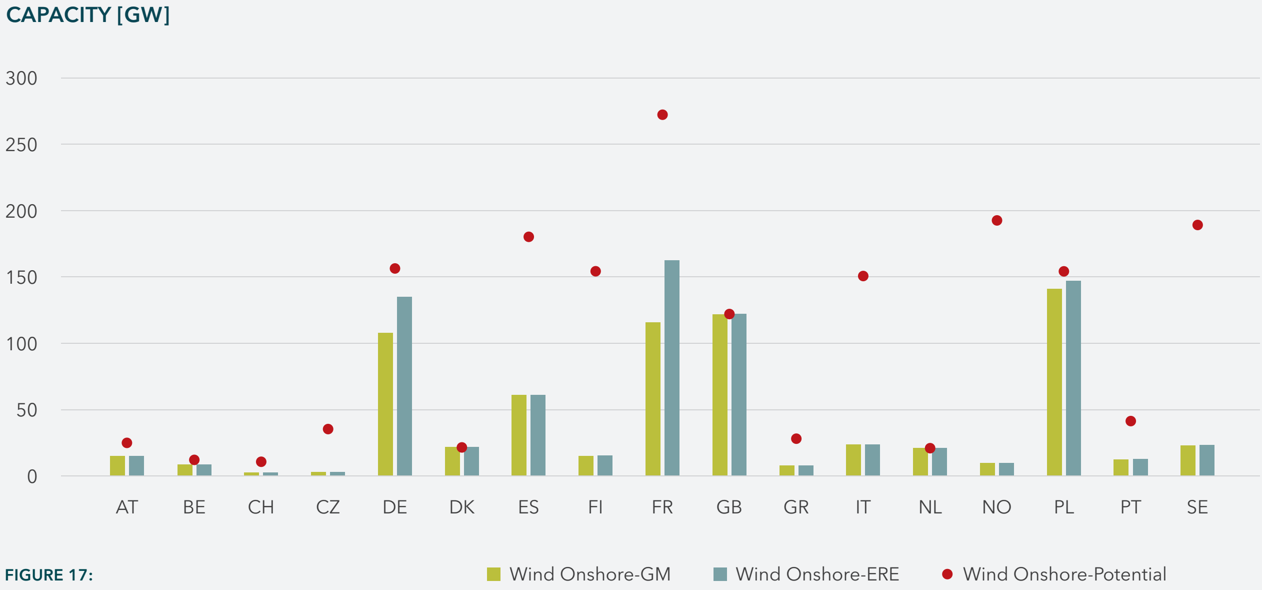


FIGURE 17:
Utilisation of wind onshore potentials EU27, GM and ERE scenario, 2050.

Figure 18 also shows the installed capacities across both scenarios. The potential for offshore wind generators is marked by red dots. Germany, the Netherlands and Great Britain have the highest installed capacities, closely followed by Denmark, which has similar capacities, at least for the ERE scenario. In terms of the previously described “next best approach“, Denmark and the Netherlands may provide the additional electricity for the higher power-to-gas demand in the ERE scenario. In comparison to PV and onshore wind, offshore power plants are not as different in our two main scenarios.

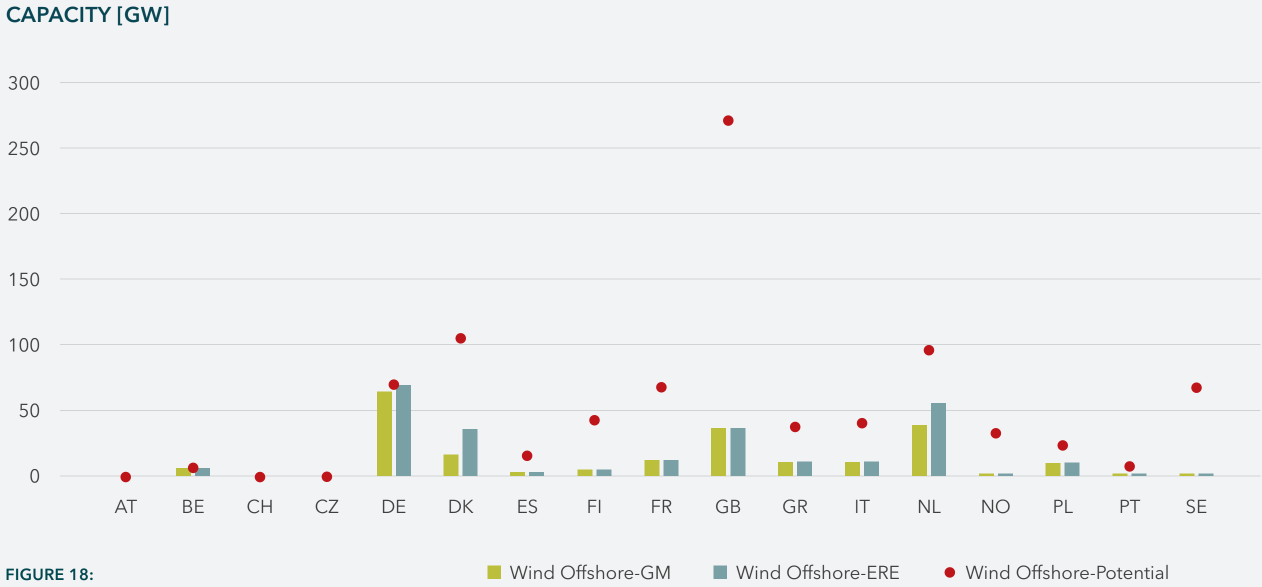


FIGURE 18:
Utilisation of wind offshore potentials EU27, GM and ERE scenario, 2050.

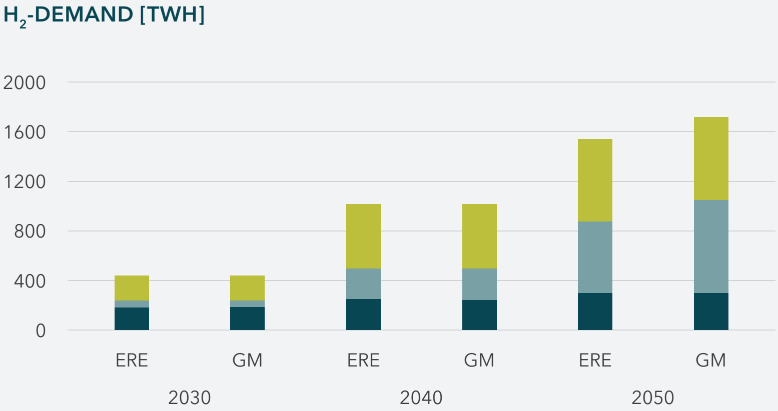
Hydrogen
The analysis of the power sector has shown the increasing role of sector coupling and green hydrogen for the energy system. In this section, we describe the production and demand of hydrogen for the EU27 in the two main scenarios.

Hydrogen will mainly be used as energy carrier or feedstock in a number of industrial processes, and as a fuel in the transportation sector. In addition, hydrogen may be used as input for the synthesis of hydrogen derivatives such as syngas and fuels, as well as for reconversion to power. The usage of hydrogen in the heat sector is allowed in the model, but this does not seem to be a competitive option given the techno-economic conditions.

In general, there is potential for hydrogen use in sectors where process emissions cannot be avoided by using electricity, or where it is more economical (if this is technically possible). Examples of hydrogen utilisation in industrial processes are found in the steel and chemical industries. The iron and steel industries account for about 60% of the total industrial hydrogen demand and the chemicals industry for 40%.

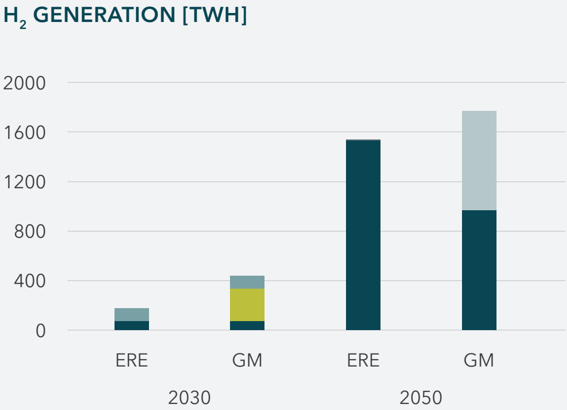
While hydrogen demand amounts to 438 TWh/year in both scenarios in 2030, in 2050 the overall hydrogen demand amounts to 1,710 TWh/year in the GM scenario and 1,540 TWh/year in the ERE scenario (Figure 19). In 2030 and 2040, the results of the two scenarios are identical. In both years, hydrogen demand is divided almost equally between industry (184 TWh/year) and the transport sector (198 TWh/year), with a minor share for the production of synfuels (56 TWh/year). A differentiation is visible in 2050. In this year, there is higher hydrogen demand in the GM scenario. This is not surprising, as this scenario has relatively optimistic expectations for green hydrogen imports. In the GM scenario, the overall hydrogen demand is higher due to a larger amount of hydrogen derivatives (synthetic fuels/gases).

FIGURE 19:
Hydrogen demand EU27, GM and ERE scenario, 2030 to 2050.



The differences between the ERE and GM scenarios can be better understood by looking at the hydrogen generation structure (Figure 20). In 2030 and 2040, steam methane reforming (SMR) with or without carbon capture (CC) remains an important hydrogen generation technology. The share of electrolysers increases over time, reaching its maximum in 2050. In 2030 and 2040 the scenarios hardly differ, but in 2050 there is a substantial difference. In the GM scenario, 57% of hydrogen is produced in Europe, while the remaining 43% is imported from countries outside Europe. By contrast, in the ERE scenario, 100% of the hydrogen production is in Europe. The reason behind this shift is the higher hydrogen import price in the ERE scenario. The small negative value for "Import (EU)" in the GM scenario in 2050 is the EU27 export to other European countries.

FIGURE 20:
Hydrogen generation and import EU27, GM and ERE scenario, 2030 and 2050.



Accordingly, the installed electrolyser capacity also differs between the two scenarios. While the capacity of electrolysers in the EU27 is similar (24.8 GW in 2030 and 121.8 GW in 2040), in 2050 the installed capacity of electrolysers ranges between 376 GW in the GM scenario and 560 GW in the ERE scenario. The average full load hours of electrolysers in 2050 are around 2,700 h/year in the ERE scenario and slightly under 2,600 in the GM scenario.

Figure 21 shows the installed capacities of electrolysers for both scenarios in the year 2050. In the GM scenario, Poland, Spain and France have a total of 200 GW electrolyser capacity (and over 260 GW in ERE), which is approximately half of the total capacity in the EU27. Some countries have a similar electrolysis capacity in both scenarios. Bulgaria and Greece are such examples. On the other hand, Germany, Denmark, France, Poland and Romania react with high sensitivity to the increased demand for hydrogen electrolysis.

ELECTROLYSER CAPACITY [GW]

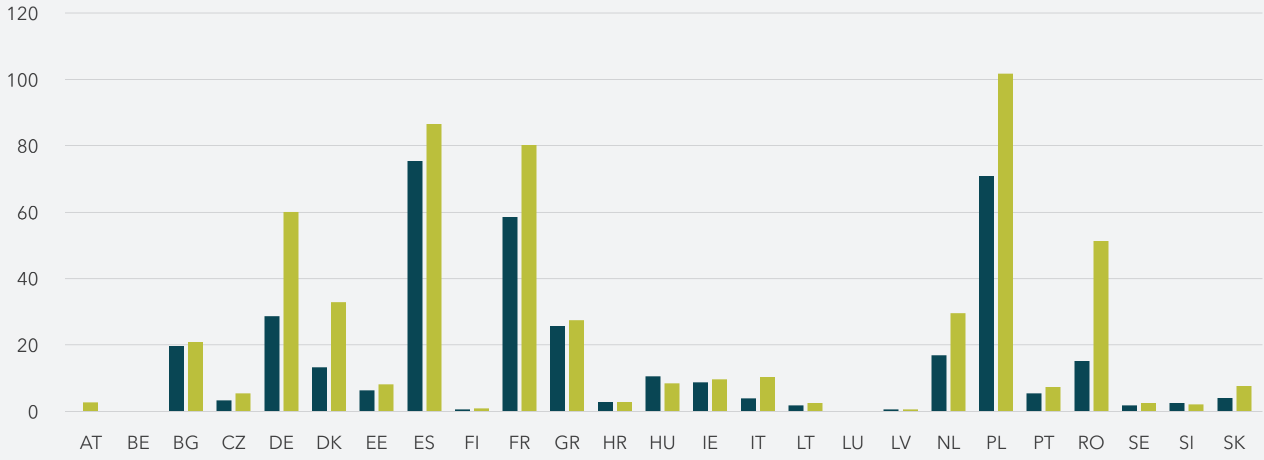


FIGURE 21:
Electrolyser capacity per country, GM and ERE scenario, 2050.

There is a correlation between the expansion of variable renewables and electrolysers. The countries that expand renewables in the ERE scenario also invest more in electrolyser capacity. However, this correlation seems not to be true for the demand of hydrogen. Figure 22 shows the hydrogen demand per country in 2050 for both scenarios. Although Germany doubles its electrolyser capacity from 29 GW in GM to 60 GW in ERE, its demand for hydrogen drops from 400 TWh to 300 TWh. The higher cost of hydrogen in ERE influences its utilisation in the downstream sectors, which can differ greatly between countries. Another example can be seen in Poland. Although electrolyser capacity increases in the ERE scenario, demand remains the same. Therefore, while the generation of hydrogen via electrolysis strongly correlates with higher local VRE capacities, demand for hydrogen is not regionally coupled to its production. This phenomenon shows the importance of integrated modelling of all related energy sectors for an interconnected Europe, as the differing structures of the coupled sectors can behave very differently from country to country.

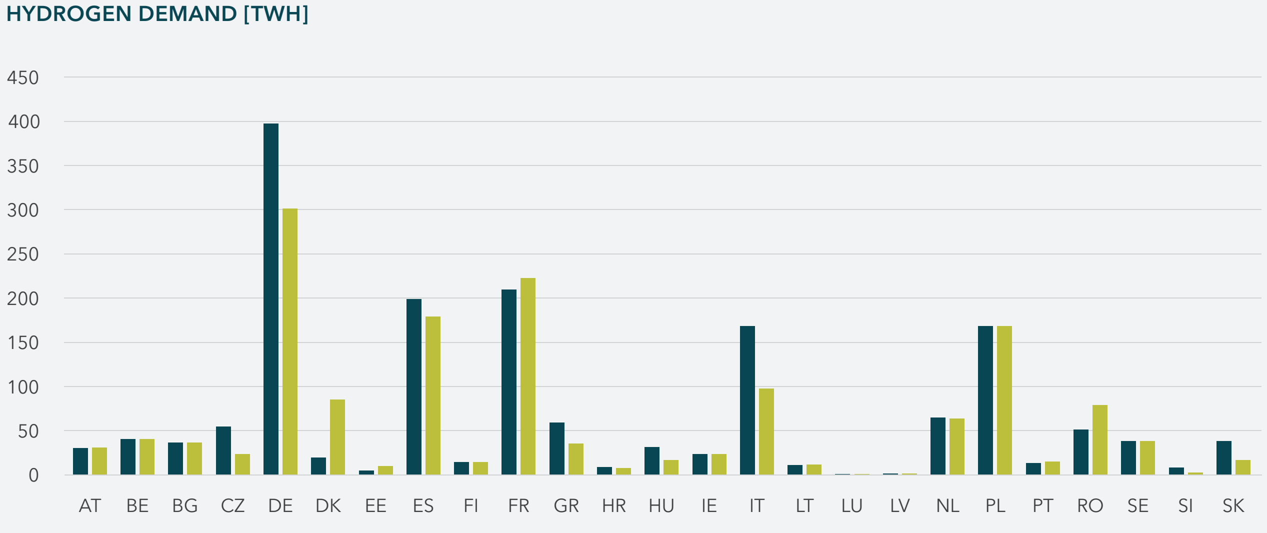
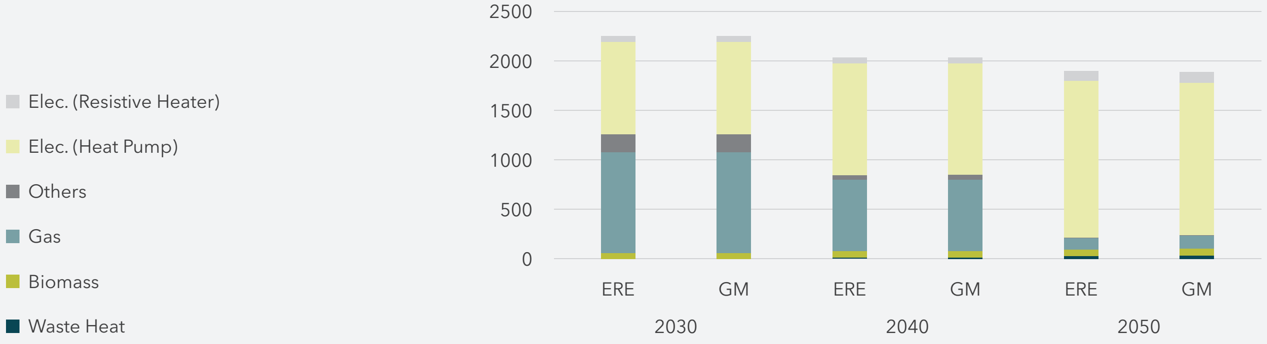


FIGURE 22:
Hydrogen demand per country, GM and ERE scenario, 2050.

Heating Sector

An analysis of heat supply by technology is presented in Figure 23. The total heat demand slightly decreases from 2,254 TWh/year in 2030 to approximately 1,900 TWh/year in 2050 in both scenarios. In the heating sector, there is a trend to direct electrification, which increases from 988 TWh/year (43.8%) in 2030 to 1,686 – 1,644 TWh/year (88.6% - 87.2%) in 2050. During this period, gas boilers are almost completely replaced by heat pumps and resistive heaters. We also observe a moderate increase of biomass.

FIGURE 23:
Heat supply EU27, GM and ERE scenario, 2030 to 2050.



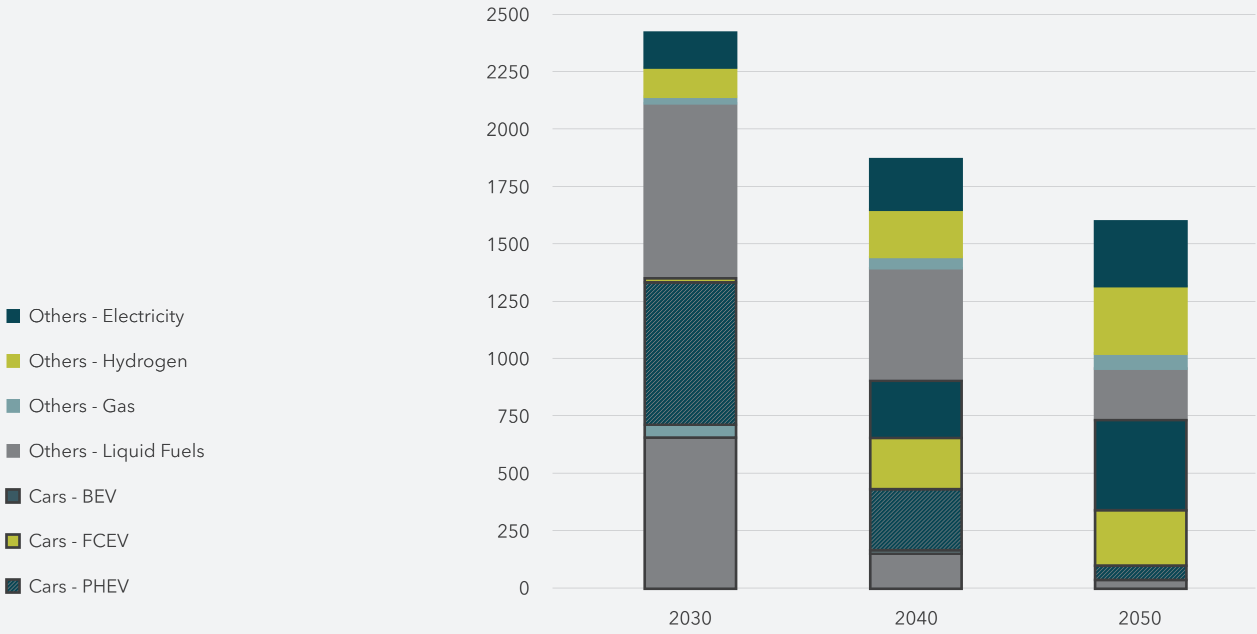
Transport Sector

Increased energy efficiency leads to a decrease in final energy consumption across all sectors. In a comparison of the sectors, the largest decrease can be seen in the transport sector. The energy demand for transport purposes is expected to decline by about 33% between 2030 and 2050, as shown in Figure 24.

The most significant reduction is expected in the road passenger sector. In the EU27, the energy demand for cars almost halves between 2030 and 2050 (1,350 TWh/year in 2030, 730 TWh/year in 2050). This trend is explained by the increasing role of e-mobility and the related high efficiency of the electric engines. In the remaining transport subsectors (domestic aviation, domestic navigation, rail and road freight), there is only a moderate change in demand.

FIGURE 24:
Energy demand for the transport sector, EU27, GM and ERE scenario, 2030 to 2050.

FINAL ENERGY DEMAND FOR TRANSPORT [TWH]



The breakdown of the private road passenger sector (cars) by technology is also shown in Figure 24. According to techno-economic assumptions, in 2030 there will be a drastic reduction of conventional internal combustion engines (ICE), which are mainly substituted by plug-in hybrid electric vehicles (PHEV). In addition, compressed natural gas (CNG) motors will fuel 4.2% of cars. The share of PHEV declines in the following years, amounting to only 8.2% in 2050. After 2040, ICE vehicles almost completely disappear, and the dominating technologies are battery electric vehicles (54.5%) and fuel cell electric vehicles (FCEV, 33.0%). The latter are mainly used for medium and long-distances.

Expansion of interconnector grid capacity

In this subsection, we present and compare the results of the power grid and hydrogen grid in the two main scenarios. Figure 25 shows that there is a substantial expansion of the interconnector power grid (both AC and DC) between 2030 and 2050. The thickness of the links indicates the absolute capacity of the interconnector grid connections, while the colour indicates the capacity expansion between 2030 and 2050.

Maximal interconnector grid expansion occurs between France and Spain, as well as between Germany and Austria (both 9 GW). However, expansion occurs in all considered regions, particularly in central continental Europe and Spain, Italy and UK.

The need for enhanced infrastructural links is driven by the carbon neutrality goals and the subsequent massive expansion of renewables. Figure 25 also shows the distribution of power generation and gross electricity demand in the considered model regions. In 2050, renewable energy technologies cover nearly 100% of power demand, a minor share of nuclear power plants. Balancing power plants are important for the security of supply in critical hours, when low availability of renewables is coupled with high loads. However, the energy delivered from balancing power plants throughout the year is marginal. More details about such critical situations will be described later in this chapter.

The figure also shows that regional renewable potentials play a major role in defining the optimal share of renewables and annual power yield. PV resources are relatively well distributed among regions of comparable latitude, while wind power resources are concentrated in the region around the North Sea. PV is dominant in southern European countries including France, Hungary and the Czech Republic. Onshore wind has larger shares in Central Europe and Greece, while offshore has larger shares in the countries around the North Sea and the Baltic Sea. Finally, as expected, hydropower remains important in Alpine countries such Switzerland and Austria, as well as Scandinavian countries. Nuclear power plants are spread throughout France, UK, Czech Republic, Poland, and other South-East European countries.

In 2050, the sum of the international electricity interconnector capacities in the EU27 amounts to 200 GW in the GM scenario and 196 GW in the ERE scenario.

We can also observe that power trade occurs among European countries, as generation exceeds power demand in some countries, while other countries rely on imports. Such figures are only annual values and it should be stressed that each country has to rely on imports in particular situations, while exporting a share of the domestic production in other situations. Looking at the annual values, Germany and Italy are the largest power importers, while France, the Netherlands, Poland, Spain, and other South-East European countries have a positive annual power balance. More details on power trade among countries are given later in Figure 27.

Finally, in the figures for power, there is a shift towards additional VRE produced in the EU in the ERE scenario, in contrast to the GM scenario, as discussed previously (see Figure 16 - Figure 18).

With regard to the hydrogen interconnector grid, the difference between GM and ERE is much more pronounced than for the electricity interconnector grid (Figure 26). In the GM scenario, the hydrogen pipeline network is well developed in Central Europe, but pipelines to the Iberian Peninsula, Great Britain, and South European countries are less developed. The international hydrogen interconnection capacity in this case is 150 GW. The situation changes in the ERE scenario, where an international hydrogen interconnection capacity of 219 GW is expected in 2050. This is due to additional reinforcement of the interconnector grid in Central Europe, and the substantial development of a pan-European hydrogen interconnector grid. In the ERE scenario, there are interconnections between France and Spain, Great Britain and its continental neighbours, as well as Italy and South Eastern European countries. The graphs also show that electrolysers are the only hydrogen production technology in 2050 in Europe. Countries such as Germany, Italy, Belgium, Austria, Czech Republic and Hungary rely on hydrogen imports in the GM scenario. On the contrary, in the ERE scenario, hydrogen is produced in the EU, so that hydrogen trade only occurs among European states. Countries such as Denmark, Poland, Netherlands, and Romania become net hydrogen exporters, while Germany reduces its relative dependency on imports. In some countries, such as Spain, hydrogen is partially used locally for production of synfuels. In this case, not hydrogen but its follow-on products (synthetic oil and methane) are exported.

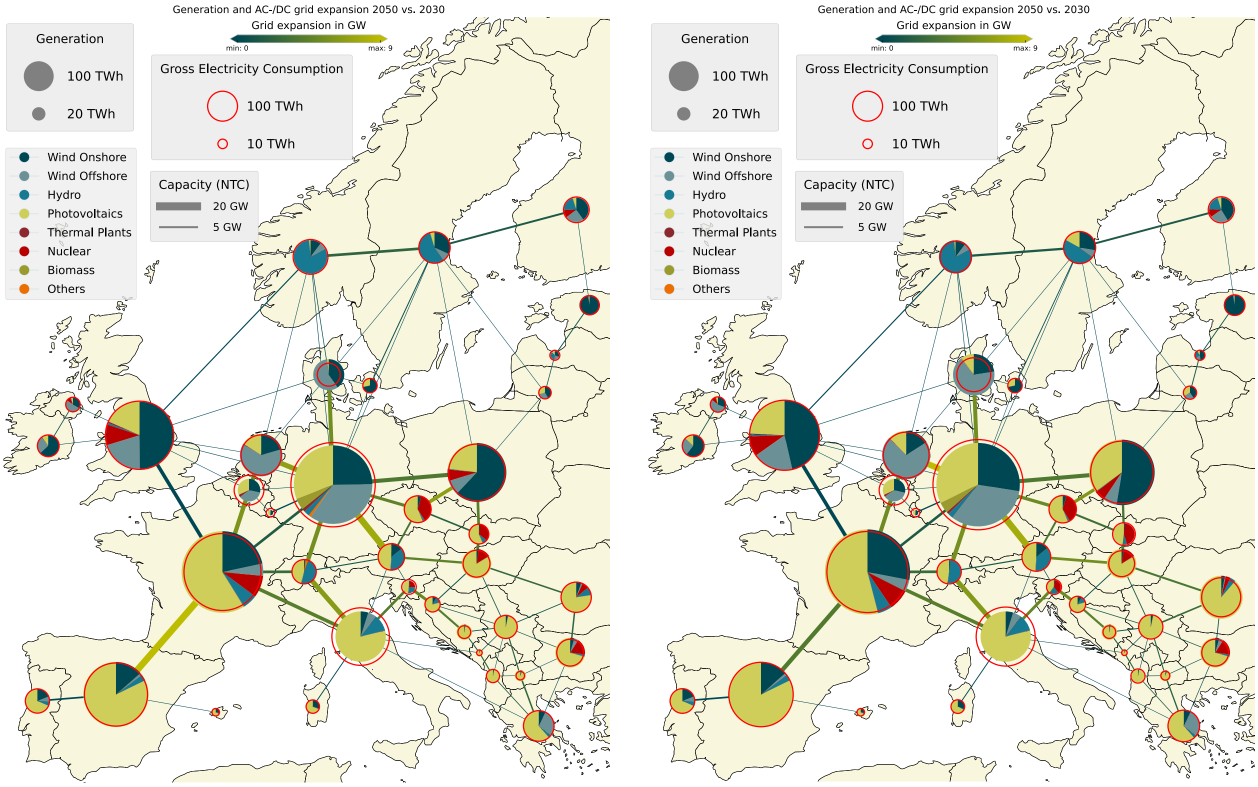


FIGURE 25:
Electricity generation, demand and AC/DC interconnector grid expansion, GM scenario (left) and ERE scenario (right), 2050.

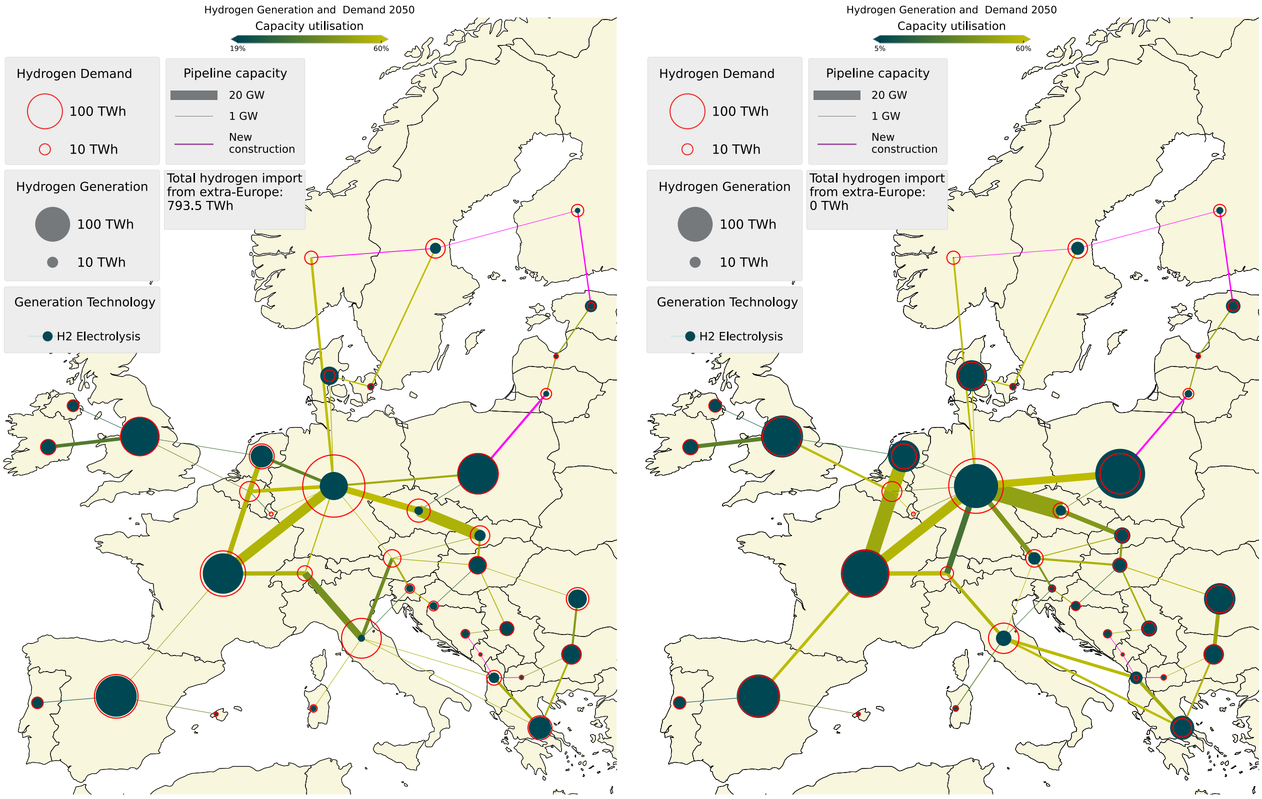


FIGURE 26:
Hydrogen generation, demand and interconnector grid expansion, GM scenario (left) and ERE scenario (right), 2050.

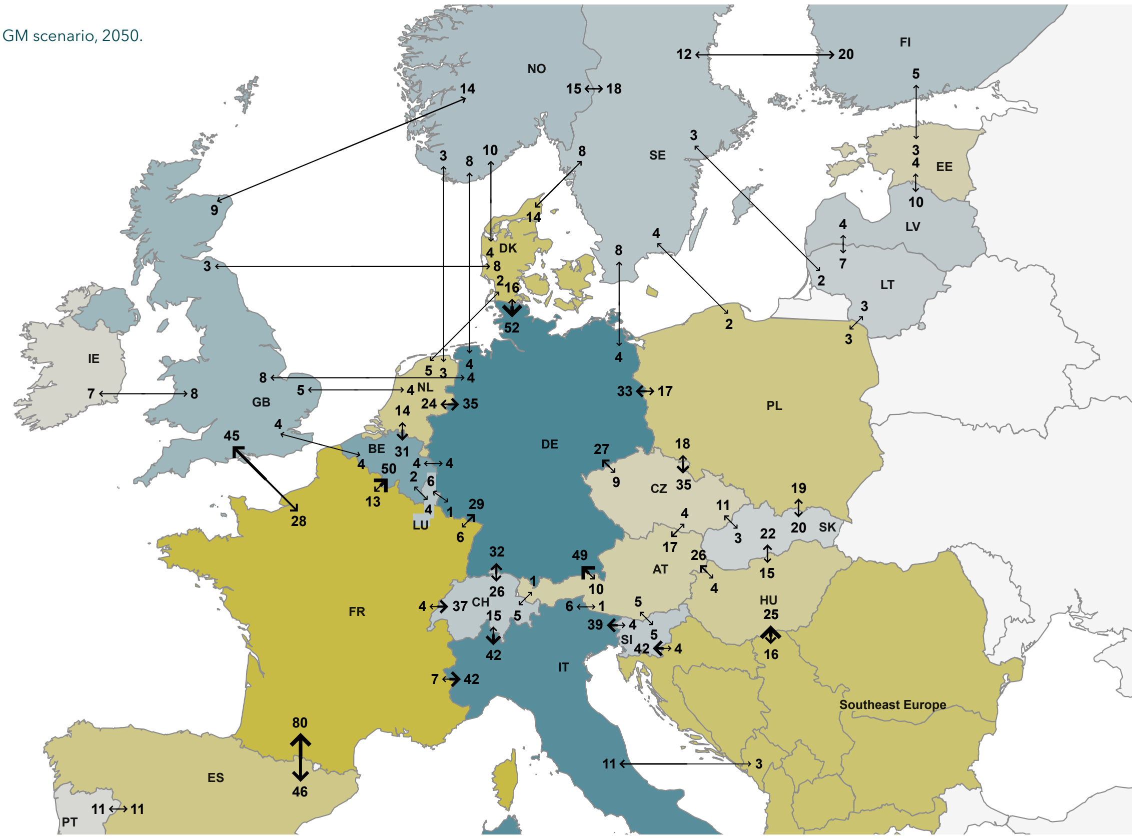
As the graphs show, the European power system in 2050 is deeply interconnected. Significant power transits occur between EU27 and non-EU27 countries (see also item "Trade" in Figure 9 and Figure 10). Power transits across countries are defined by the sum of minimum time steps between imports and exports. According to this methodology, larger transits occur through Switzerland (approximately 60 TWh/year), Great Britain (approximately 20 TWh/year) and Serbia (approximately 15 TWh/year). These figures differ just slightly between the two scenarios. The transits amount to around 100 TWh/year in the GM scenario and 113 TWh/year in the ERE scenario. It should be noted that the methodology does not consider transits across two or more non-EU27 countries, such as transits from Sweden (EU27) over Norway and Great Britain (non-EU27) to Ireland (EU27). Accordingly, the number presented in Appendix, Table 12 may underestimate total European transits. However, we assume that the methodology is suitable for identifying major transits and that the underestimation is acceptably low. Additional details can be found in the Appendix.

Finally, we look at the annual power trade among European countries (Figure 27, GM scenario and Figure 28, ERE scenario). The graph shows the annual sum of bilateral power trade between countries in both directions. The colour of the countries indicates whether a country is a net importer or net exporter.

In the GM scenario, Germany and Italy are the largest net importers in absolute terms (132 TWh/year and 104 TWh/year, respectively). The largest net exporter is France (111 TWh/year). The largest power flows are as follows:

/ Spain → France (80 TWh/year)
/ Austria → Germany (49 TWh/year)
/ France → Great Britain (45 TWh/year)
/ France → Italy (42 TWh/year)
/ Switzerland → Italy (42 TWh/year)
/ South-East Europe → Slovenia (42 TWh/year)

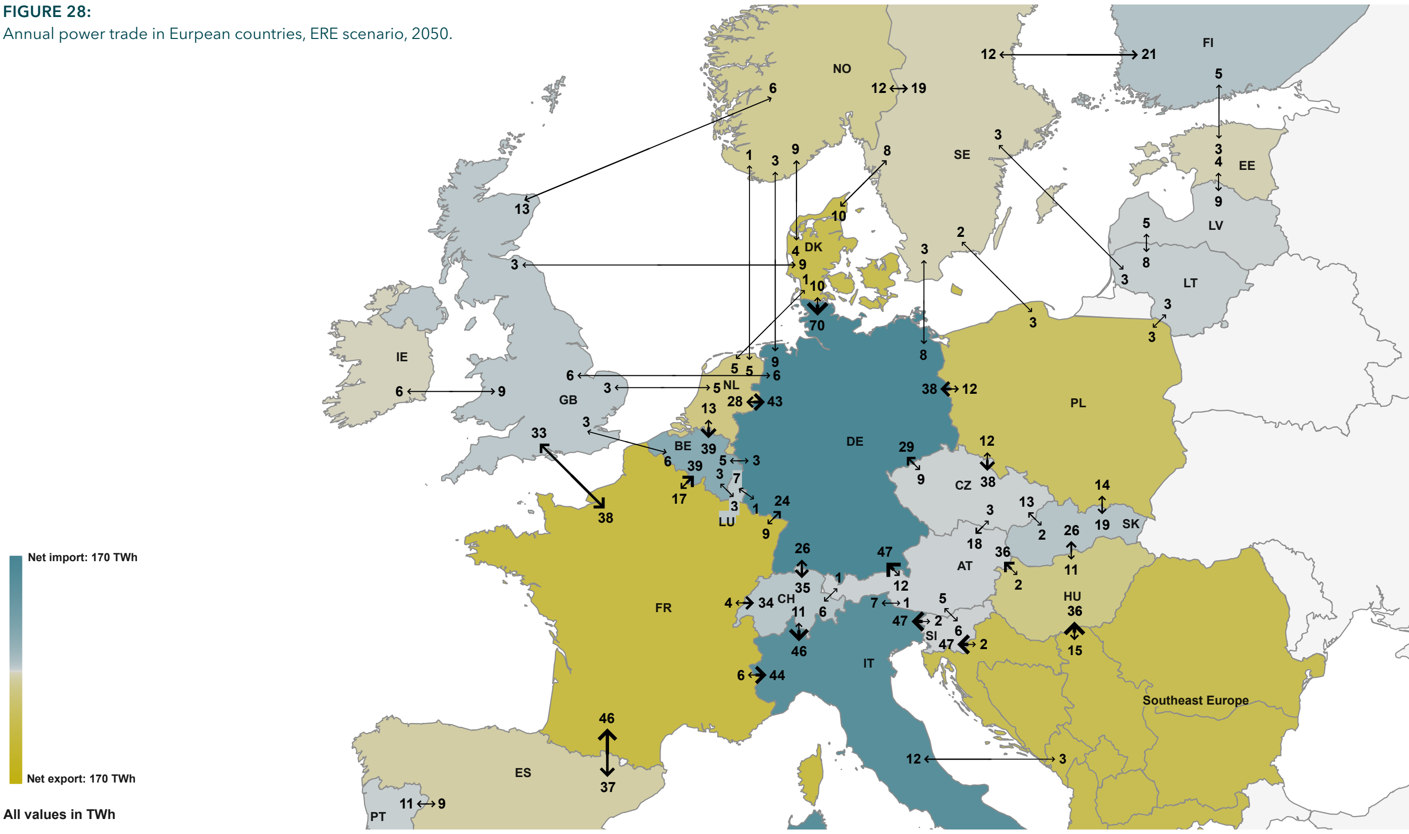
FIGURE 27:
Annual power trade in Eurpean countries, GM scenario, 2050.



In the ERE scenario, the import/export balance of most of the countries remains constant. Germany and Italy remain the two largest European power importers (165 TWh/year and 129 TWh/year, respectively).

South-East Europe (75 TWh/year) and Denmark (61 TWh/year) emerge as major exporters besides France, Netherlands and Poland. The majority of the largest flows in the GM scenario are the same in the ERE scenario, but the flow from Spain through France to Great Britain is reduced. This is mainly due to the additional PV expansion of PV in Great Britain in this scenario. There is an additional expansion of PV in Denmark, which leads to an increase in power exports from Denmark to Germany (70 TWh/year gross export).

FIGURE 28:
Annual power trade in Eurpean countries, ERE scenario, 2050.



All values in TWh

Critical week in January 2050

To show how the EU27 countries interact with each other in our model, we summarise demand and power generation for one week in January and July 2050 (GM scenario) in the following figures (Figure 29 to Figure 33). For the January week, we present the figures for Germany, which needs very high electricity imports in the selected week, and Denmark, which is a wind-dominated country. For the July week, we present France as a PV-dominated country.

We want to highlight that the results presented below are not intended to replace an adequacy study (see Chapter 1.3 Limits of the methodology). Nevertheless, we believe that the results help simplify the paradigm shift required to reach climate neutrality. Our aim is to describe the role of renewables and flexibility options, and highlight the paramount importance of international grids and cooperation among countries in challenging situations.

First, we discuss the analysis of load patterns for Germany (Figure 29). We identify the conventional load at the bottom of the diagram, which shows the typical day/night cycles. As is currently the case, peak demand of conventional load is at noon and the early evening hours during working days, while lower peaks occur during the weekend.

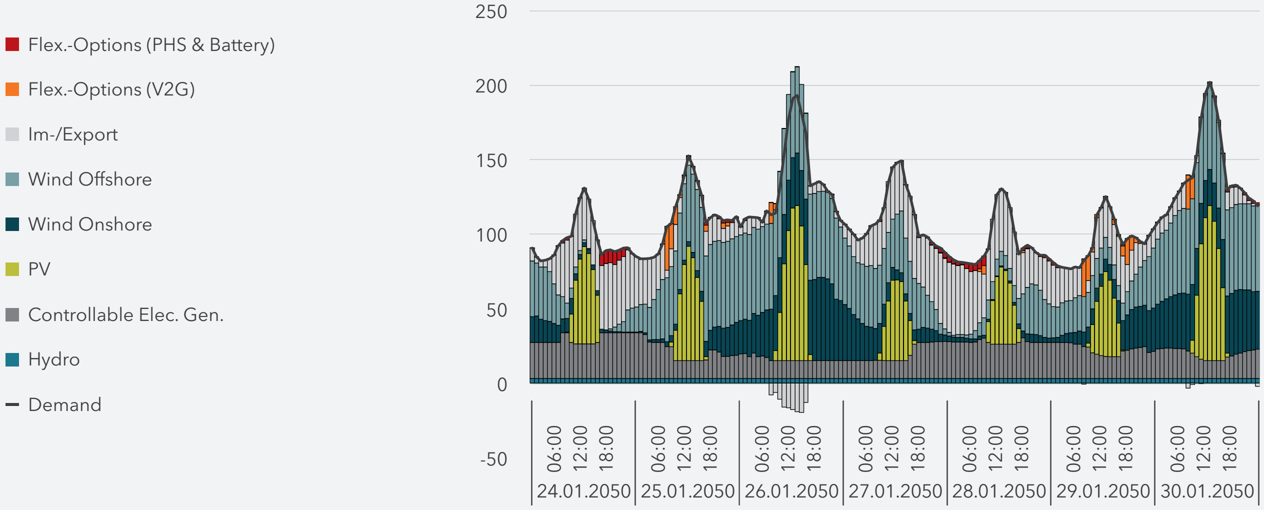
We can observe a total of four additional loads: e-mobility, power-to-X, industrial load and storages. Except for pumped hydro storage, which is already a factor, all other loads derive from the increase of electrification in other energy sectors. Electrification is a constant load in many industry processes (such as steel), while power-to-X and e-mobility are flexible demands.

In particular, **e-mobility** has daily peaks, while power-to-X seems to react more smoothly. The reason for this behaviour has to be investigated in the electricity generation patterns (Figure 30). Unlike today, in 2050 the load is defined by the current availability of renewable energies and reacts flexibly to different meteorological conditions. We observe that e-mobility peaks in the demand diagram correlate with PV power generation, while power-to-X technologies reach their maximum in situations of very high wind and PV power generation. During the third day, the abundant availability of RES leads to the charging of other storages as well as power exports to neighbouring countries.

NOTE ON FLEXIBILITY E-MOBILIY
Due to the status of the model, a detailed analysis of interaction between transport and distribution grid is not possible, so that a detailed analysis of the flexibility potential of e-mobility is still pending.

FIGURE 29:
Electricity generation and trade, Germany, GM scenario, January 2050.

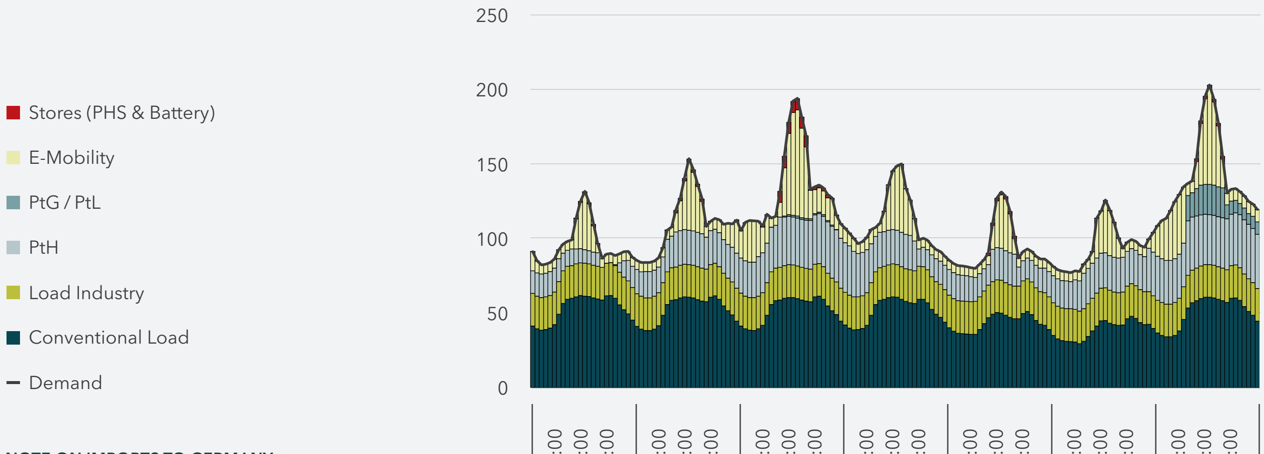
ELECTRICITY GENERATION & TRADE [GW]



By contrast, there are also situations with negligible RES power generation. This is the case in the evening hours of the first day shown in Figure 30. In this case, a series of measures must be taken to guarantee the supply. First, controllable electricity generation plants (must-run biomass power plants and gas turbines) run at maximum power, while PHS and batteries are discharged. The remaining gap is covered by power imports. It is important to stress that such imports result from the optimisation of the European power and energy system, not from the consideration of Germany as a stand-alone country. This means that in this critical situation for Germany, a number of neighbouring countries can export a share of their power generation, which is still cost-effective, given the assumptions.

FIGURE 30:
Electricity demand, Germany, GM scenario, January 2050.

ELECTRICITY DEMAND [GW]



NOTE ON IMPORTS TO GERMANY
A detailed description of one import situation to Germany can be found in Chapter 2.3.3.

The diagram for Denmark in the same week shows a completely different situation (Figure 31). Due to excellent power potentials for both onshore and offshore wind, Danish electricity generation exceeds the load most of the week. The outstanding availability of wind from the 3rd to the 4th and 7th days is used mainly for hydrogen production (Figure 32) and for power exports. We can also observe how the wind conditions here allow for a continuous production of electricity almost regardless of day and night cycles. Due to the significantly lower capacity of e-mobility in Denmark, there is very little difference between the load before and after DSM.

FIGURE 31:
Electricity generation and trade, Denmark, GM scenario, January 2050.

ELECTRICITY GENERATION & TRADE [GW]

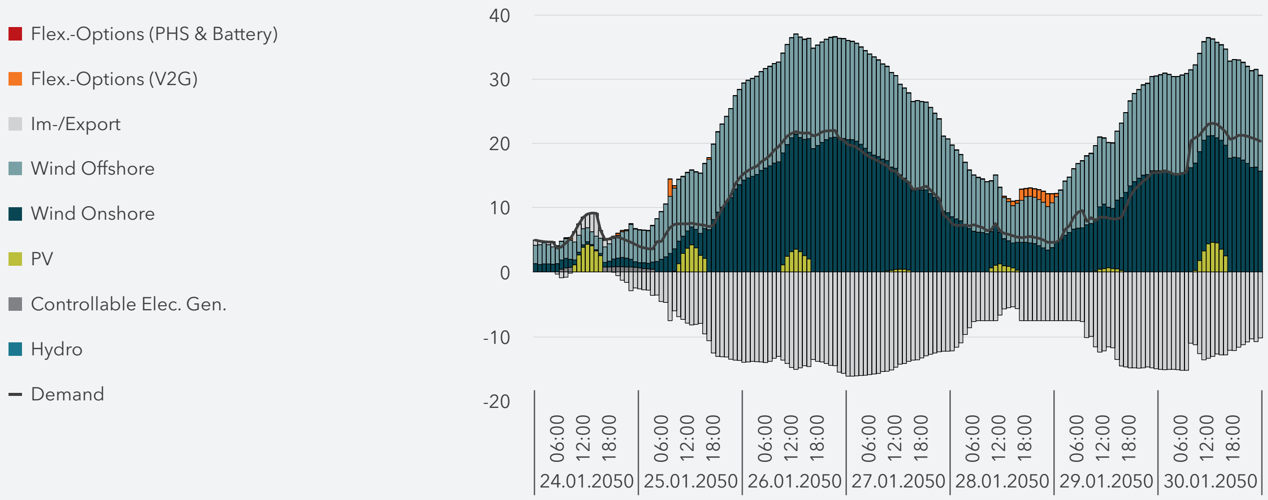
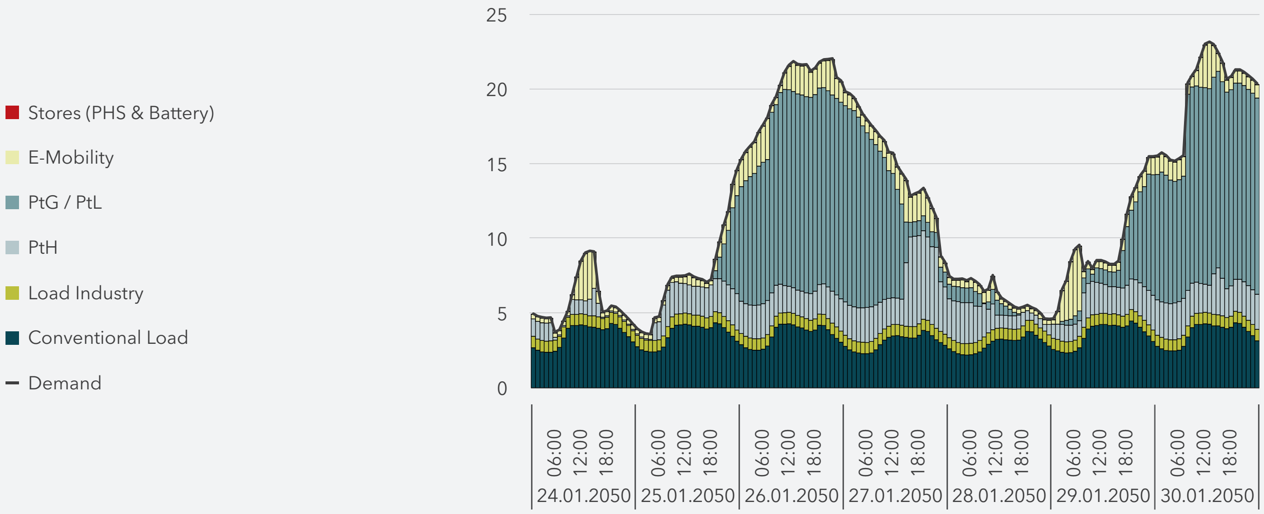


FIGURE 32:
Electricity demand, Denmark, GM scenario, January 2050.

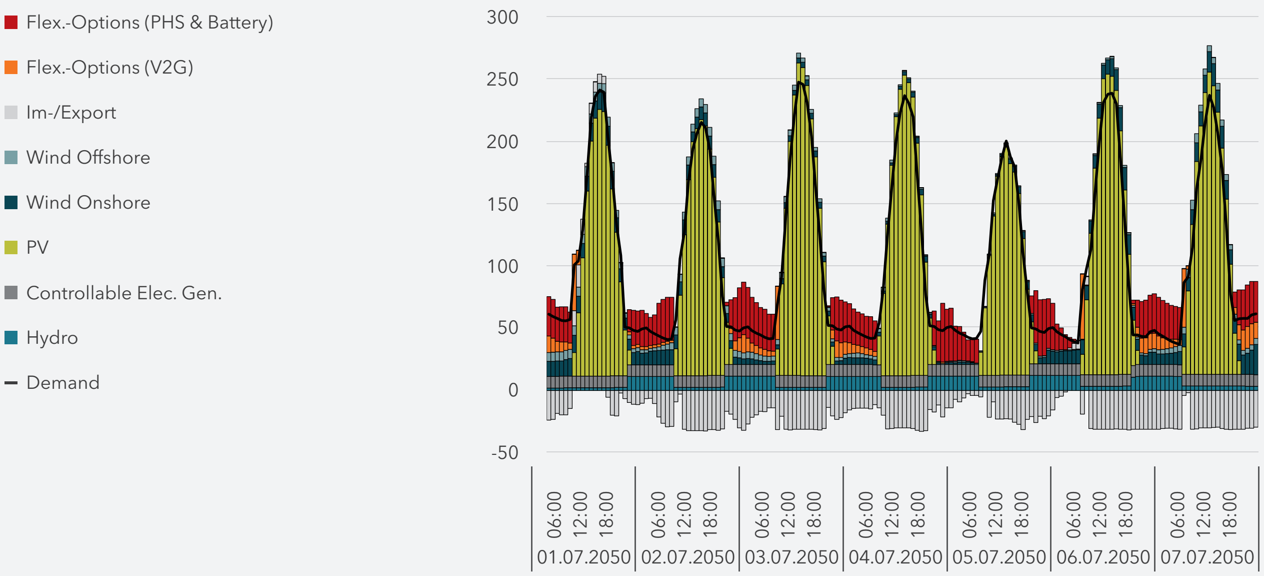
ELECTRICITY DEMAND [GW]



Looking into another European example in July in France (see Figure 33), pronounced PV peaks and a minor share of controllable electricity generation (nuclear power) characterises the power production. We can see an extreme day and night cycle in electricity production due to PV. To use this electricity effectively and balance the rapidly changing production cycle, battery storages are profitable here. Around noon, large stationary batteries are charged, while discharging occurs during the evening and even at night. It is interesting to note that battery discharge is also partially used for power export (for example to Germany).

FIGURE 33:
Electricity generation and trade, France,
GM scenario, July 2050.

ELECTRICITY GENERATION & TRADE [GW]



2.3.2 RESULTS OF SENSITIVITY ANALYSIS

The following figures present the key outcomes of the sensitivity analyses, which have been performed in addition to the two main scenarios. The GM scenario served as the basis for the calculation. However, the conclusions can also be applied to the ERE scenario. The scenario setting for all sensitivities has been described in Chapter 2.1.4. The differences between the ERE and GM scenarios have been discussed in the previous section; here, we will focus on the additional scenarios.

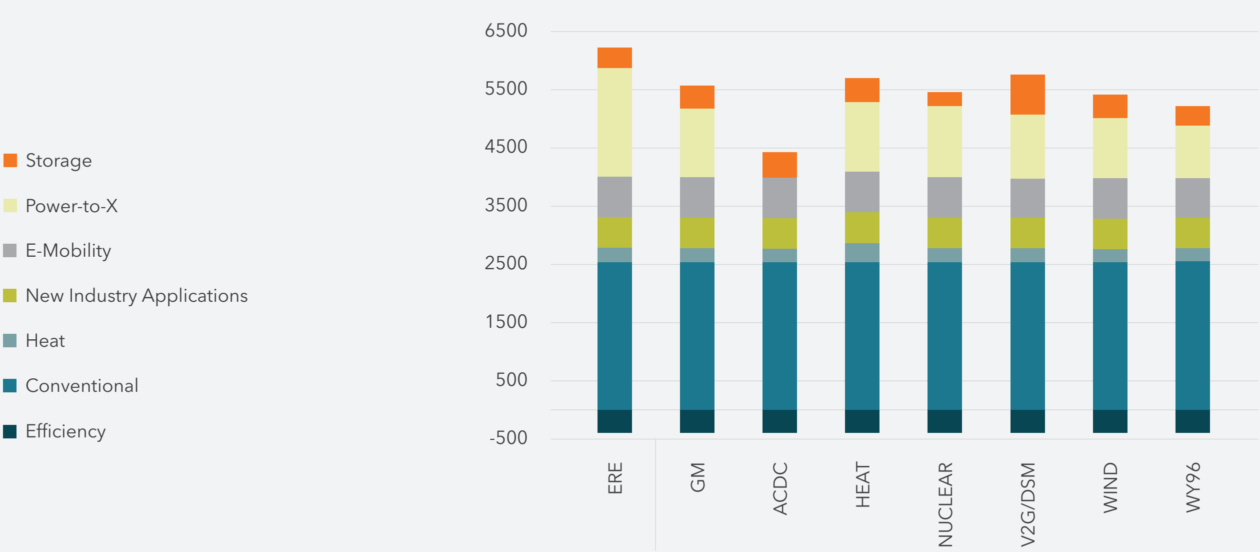
In all sensitivities, total electricity demand values range from 4,850 TWh/year to 5,833 TWh/year (ERE). Most sensitivities have similar values as in the GM scenario.

Conventional electricity demand and demand savings due to efficiency remain constant in the sensitivities. The same applies to the demand for new industry applications, which are not subjected to optimisation. As expected, power demand for heating purposes is higher in the Low Building Renovation Rate (HEAT) sensitivity. In this case, additional power demand amounts to approximately 90 TWh/year in 2050 for EU27. Additional demand for e-mobility remains constant in all sensitivities, except for inflexible mobility (V2G/DSM). In this case, the additional demand is approximately 30 TWh/year lower than in the main scenarios.

The largest variation among the sensitivities in absolute terms is the additional demand for PtX applications. Its value is highest in the ERE scenario, mainly driven by the additional electrolysers in Europe. The two lowest values for PtX are in the Low RES Expansion Acceptance (WIND) sensitivity and the extreme weather year (WY96) sensitivity. It is interesting to note that the latter sensitivity is also characterised by low wind power yield (-220 TWh in comparison to the GM scenario).

FIGURE 34:
Electricity demand sensitivity analyses, EU27, 2050.

ELEC. DEMAND [TWH]

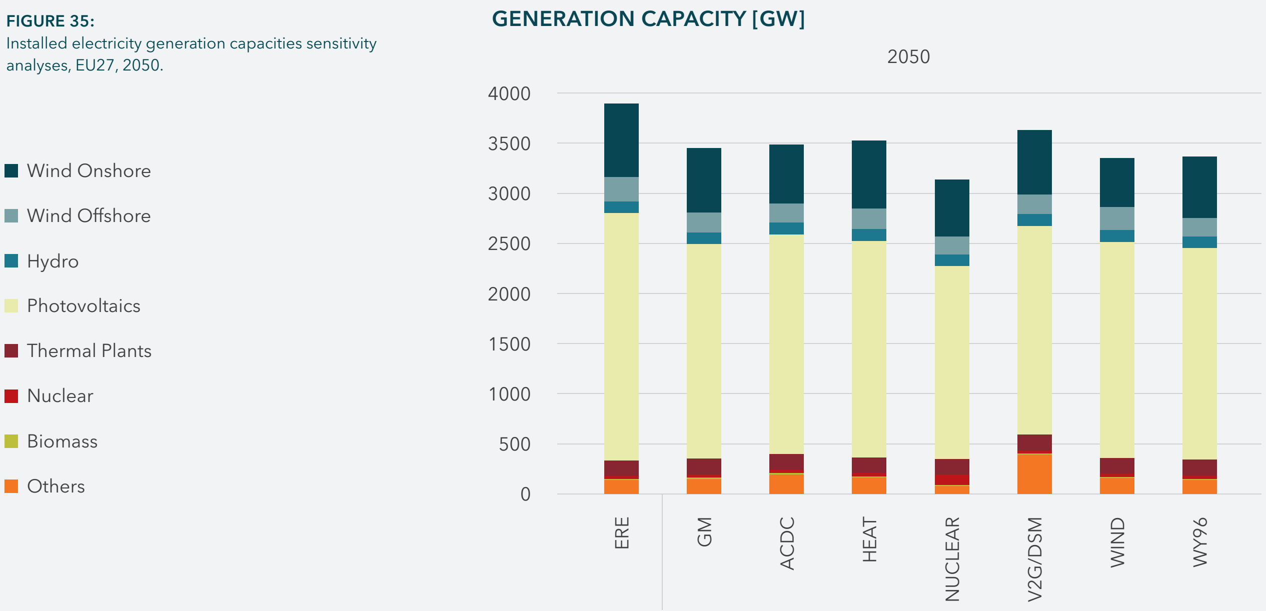


A similar picture is painted by the analysis of the installed capacity of power plants and annual electricity generation (Figure 35 and Figure 36). With regard to installed capacity, the trend is similar to the electricity demand figures. The installed capacity is highest in the ERE scenario (3,895 GW), driven in particular by PV, while the lowest value is in the NUCLEAR sensitivity (3,140 GW). The reduced capacities in the NUCLEAR scenario are wind power (-99 GW), PV (-217 GW) and stationary storages (-67 GW). A pronounced reduction of wind power capacity can also be observed in the sensitivities of WIND (-122 GW) and WY96 (-51 GW). It has to be stressed that in the WIND scenario a shift occurs between onshore and offshore wind (+34 GW). However, such shift is not sufficient to compensate for the missing onshore wind energy. Finally, in this scenario, a gap of approximately 185 TWh/year VRE remains.

In the limiting grid expansion (ACDC) sensitivity, there is a partial technological shift between PV and wind power. In this sensitivity, the installed PV capacity is 54 GW higher than in the GM scenario, while the wind capacity drops by about 72 GW. Most of this reduction is caused by onshore wind (61 GW). This underlines the importance of power grid development in regions with abundant wind resources.

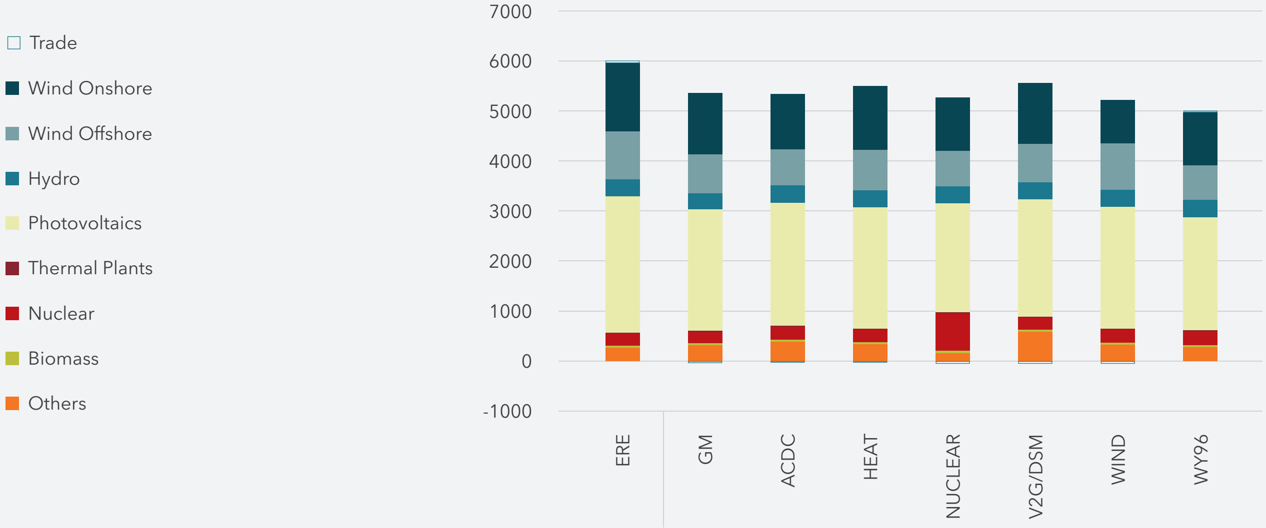
There is also a noticeable increase of stationary storages in the V2G/DSM sensitivity (+236 GW). In this case, the missing flexibility to and from the transport sector calls for alternative flexibility options, which have higher costs. Therefore, it appears that V2G and DSM may play a significant role in efficient future energy systems. To this aim, a forward-looking policy framework may be needed to tap at least some of this potential.

FIGURE 35:
Installed electricity generation capacities sensitivity analyses, EU27, 2050.



As expected, in the NUCLEAR sensitivity, there is a significant expansion of nuclear power (519 TWh/year) (Figure 36). This is much more visible than in the previous figures, with a 72 GW increase compared to the GM scenario. This is clearly due to the base-load operation mode of nuclear plants. The equivalent full load hours are approximately 7,000 h/year over all scenarios and sensitivities. Finally, it can be noted that net power trade with non-EU27 countries plays a relatively small role (+/- 30 TWh/year) in all sensitivities.

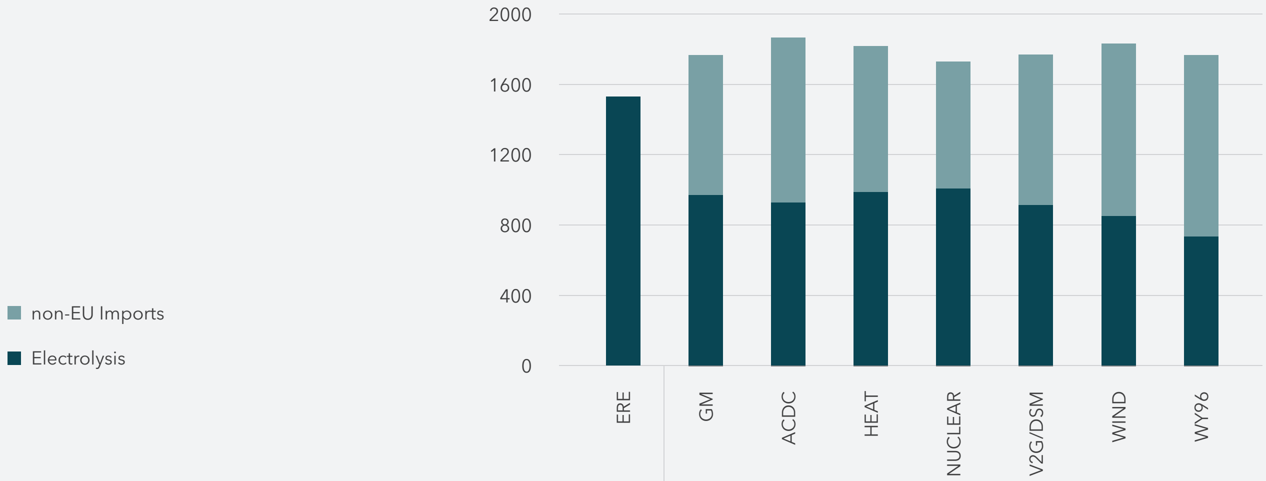
FIGURE 36:
Electricity generation including trade sensitivity analyses, EU27, 2050.



For a better interpretation of the results, it is worth looking at hydrogen generation trends across the sensitivities (Figure 37). The hydrogen demand varies from 1,540 TWh/year in the ERE scenario to 1,810 TWh/year in the ACDC sensitivity. The highest value in the ACDC sensitivity is explained by the fact that freezing power grid expansion after 2035 cannot be compensated completely by alternatives in the electricity sector (such as greater exploitation of PV as a well distributed technology with more stationary batteries). Therefore, alternative measures are needed, such as increased usage of hydrogen and its derivatives.

Except for the ERE scenario, which is characterised by a substantially different setting (high cost of hydrogen imports from non-EU regions), hydrogen generation in 2050 consists of an almost 50-50% share of EU27 generation and non-EU27 imports. The sensitivities with the lowest domestic hydrogen production are WIND and WY96. In those two cases, the import share from non-EU countries increases to 56% and to 61%, respectively.

FIGURE 37:
Hydrogen generation sensitivity analyses, EU27, 2050.

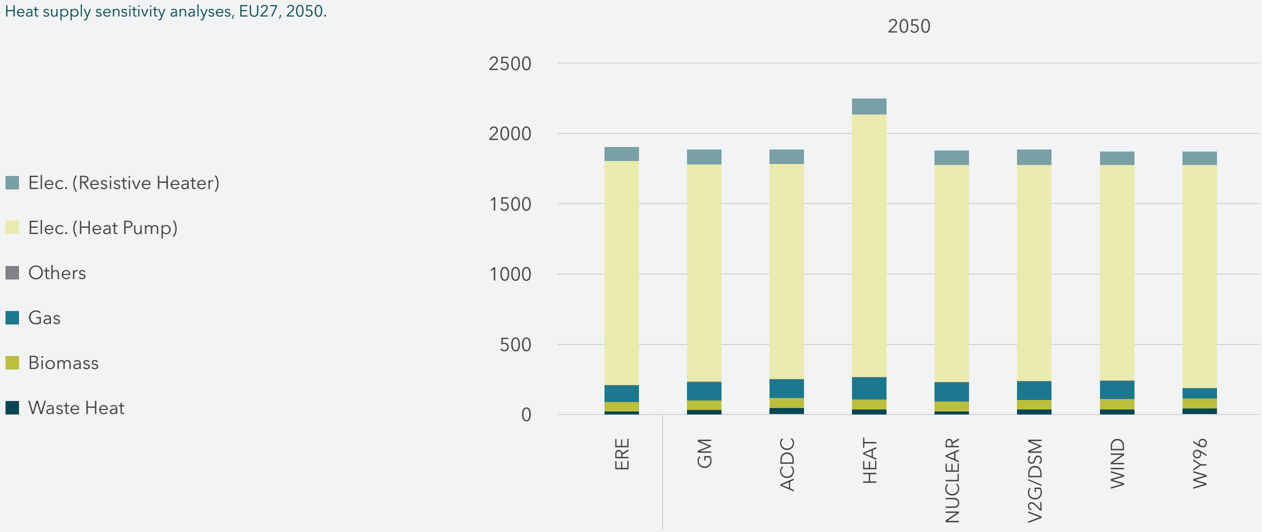


Regarding hydrogen usage, the amounts of hydrogen used in the industry and transport sectors remain the same. The relevant differentiation among the sensitivities is the amount of hydrogen used for the production of hydrogen derivatives such as synthetic hydrocarbons through Fischer-Tropsch synthesis and methanation. The highest values for synfuel production can be found in the ACDC, WIND and HEAT sensitivities (approx. 770 TWh/year in the three cases).

For the heat sector, the breakdown of heat supply in the sensitivities is shown below (Figure 38). Here, the shares of technologies remain practically unchanged. As expected, the only major difference is the increased heat demand in the HEAT sensitivity. In this case, the heat demand is 21% higher than in the GM scenario. In absolute terms, this means an increase of 323 TWh/year. The additional demand is almost completely absorbed by the expansion of heat pumps.

FIGURE 38:
Heat supply sensitivity analyses, EU27, 2050.

HEAT SUPPLY [TWH]



Finally, we compare the grid development for electricity and hydrogen among the sensitivities (Figure 39). First, we observe that a considerable power grid expansion is required in all sensitivities. In 2020 the EU27 interconnection capacity amounted to 70 GW, but in 2050 it is approximately 200 GW in all sensitivities, except for the ACDC sensitivity, where grid expansion has been exogenously limited in our model. Second, an unexpected result is that grid expansion is needed in almost equal measure in all scenarios and sensitivities. Such an expansion demand seems to be non-sensitive to the expansion of the hydrogen pipeline grid, for example between the ERE and GM scenarios, and the NUCLEAR sensitivity.

As expected, there is a more extensive development of the hydrogen grid in the ERE scenario (219 GW of interconnection capacity), where almost all hydrogen is produced in Europe and electrolysers are distributed across the continent (see also 2.3.1 and Figure 26 for more information). The hydrogen grid expansion is lowest in the NUCLEAR sensitivity (137 GW).

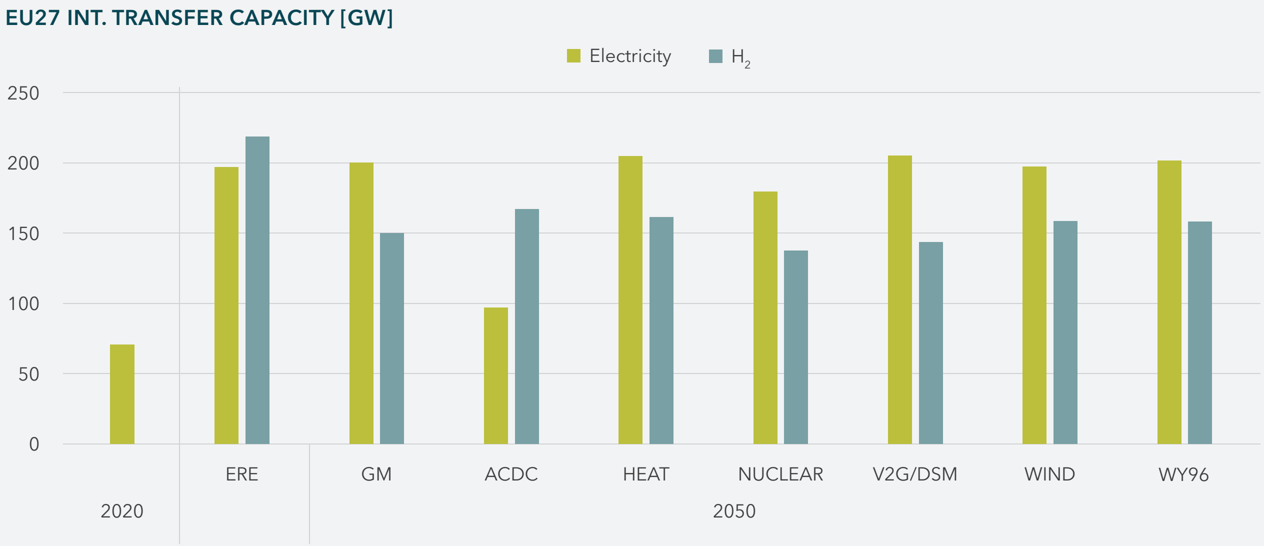


FIGURE 39:
Comparison of electricity and hydrogen interconnector grid expansion sensitivity analyses, EU27, 2050.

Conclusions

Within several sensitivity analyses based on the GM scenario settings, it has been proved that key results, such as RES capacities and the required grid expansion for power and hydrogen, do not change drastically if the model assumes a global market for hydrogen and its derivatives. We can conclude that results for the main indicators are robust, at least on the EU27 level. The ACDC sensitivity is characterised by a hampered expansion of the power grid, which results in higher costs of hydrogen imports from non-EU countries. The HEAT sensitivity shows a rather pessimistic scenario regarding building renovation rate. In this case, lagging efficiency measures are reflected in a higher need for heat pumps and renewables, thus putting additional pressure on land use. The NUCLEAR sensitivity assumes the operation of a significant nuclear power plant fleet in some European countries, based on the current TYNDP scenarios. This scenario should not be understood as a technological or economical preference, but simply as a "what if" analysis. In addition is to mention, that for nuclear – as for every technology - no detailed technological and environmental impact assessment has been done in our study. The main result of this analysis is that the expansion of nuclear power leads to less expansion of wind and PV. In a further sensitivity (V2G/DSM) we assessed the impact of complete lack of flexibility in the transport sector to the power sector. In this case, neither vehicle-to-grid nor smart charging are considered. We observe that missing flexibility to and from the transport sector calls for alternative flexibility options, which are characterised by higher cost. Therefore, it appears that V2G and DSM may play a relevant role in efficient future energy systems. To this aim, a forward-looking policy framework may be put in place to tap at least a share of this potential. Within the framework of the WIND sensitivity, we reduce the land availability for onshore wind to a maximum of 2% of the total area in each of the model regions to indirectly consider a lower acceptance of the energy transition towards climate neutrality among the population. In this case, the missing energy from onshore wind is balanced by a mix of increased offshore wind and PV capacity as well as by higher hydrogen imports from non-EU countries. Finally, in the WY96 sensitivity we examine the robustness of the results based on a variation of the meteorological data. For this analysis, we chose the year 1996, which was characterised by low yield of PV and wind as well as a pronounced "dark doldrums" for about 10 days in January. This sensitivity is characterised by low wind power yield (-220 TWh in comparison to the GM scenario), which results in low power demand – mainly driven by lower requirements by power-to-X applications in Europe. The WIND and WY96 sensitivities are characterised by the lowest domestic hydrogen production among all other sensitivities. In those two cases, the hydrogen import share from non-EU countries increases to 56% and to 61%, respectively from the 45% in the GM scenario. It is also worth noting that a considerable power grid expansion is required in all sensitivities, except for the ACDC sensitivity, where grid expansion has been exogenously limited. Such an expansion of the power grid seems to be non-sensitive to the expansion of the hydrogen pipeline grid, between the ERE and GM scenarios.

2.4 DEEP-DIVE TO GERMANY

It is expected that primary energy consumption in Germany will go through a structural transition in the coming 30 years. Currently, fossil fuels are still the major energy sources and responsible for nearly 80% of total energy consumption. This amounted to 3,387 TWh in the year 2021 (see Figure 40). The most important energy carrier was oil, followed by gas, mainly due to their use in the industry sector. Hard coal, lignite und nuclear energy, covering 24% of total primary energy consumption, are mainly used for electricity generation. Renewable energy has reached a share of 16% to become the third most important energy carrier in Germany.

In both scenarios, total energy consumption will be reduced dramatically. This is results from rising efficiency and, more importantly, the fuel switch due to widespread electrification in the heating, transport and industry sectors. The key difference between the scenarios is the role of gas in the future energy system. In the GM scenario, gases, mainly renewable gases, still have a notable share of 23%. However, in the ERE scenario, they contribute only 11% to energy consumption, as the import of gases from outside Europe is very limited. In the ERE scenario, the reduced import of gases is largely substituted by the expansion of renewables in Germany.

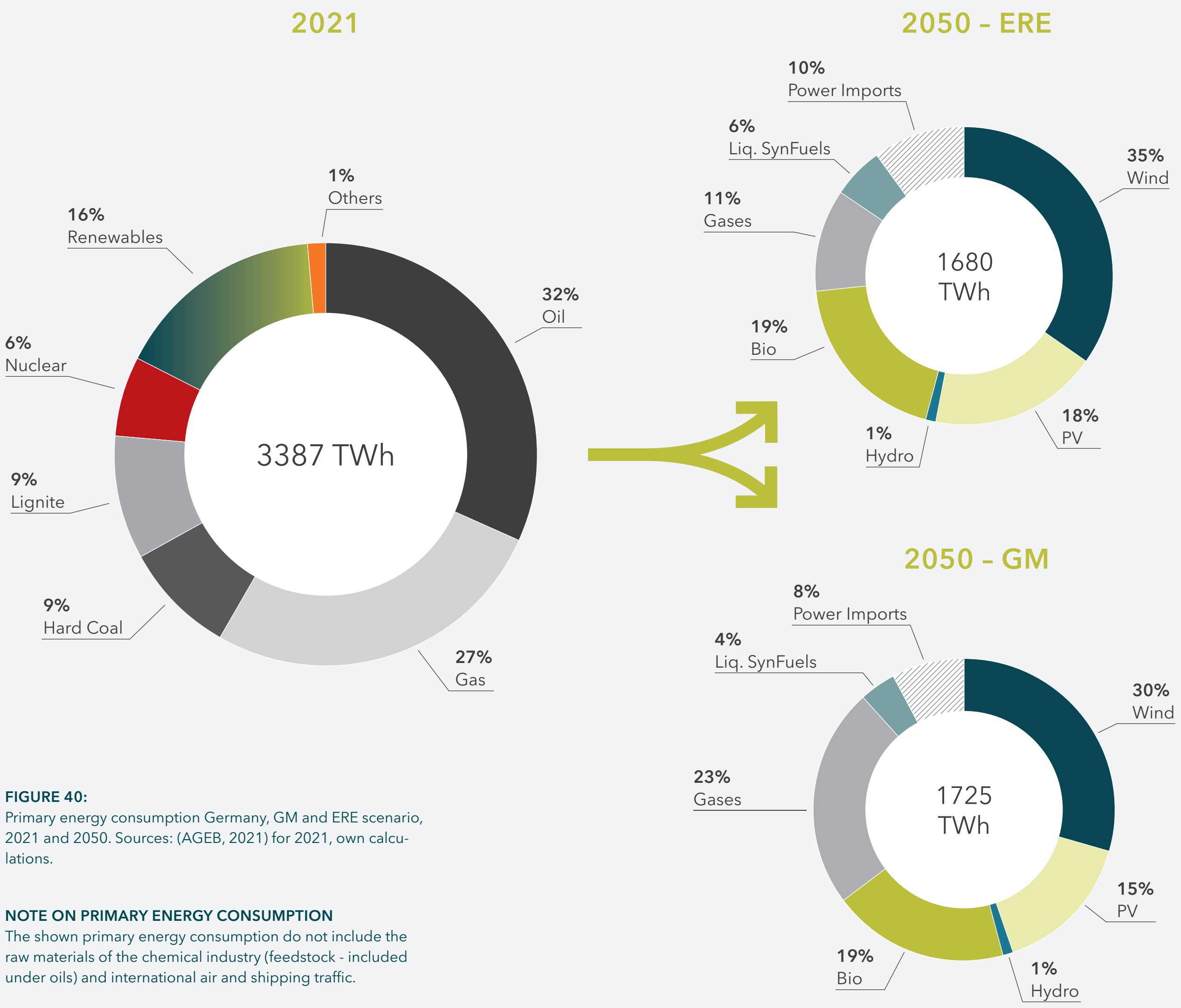
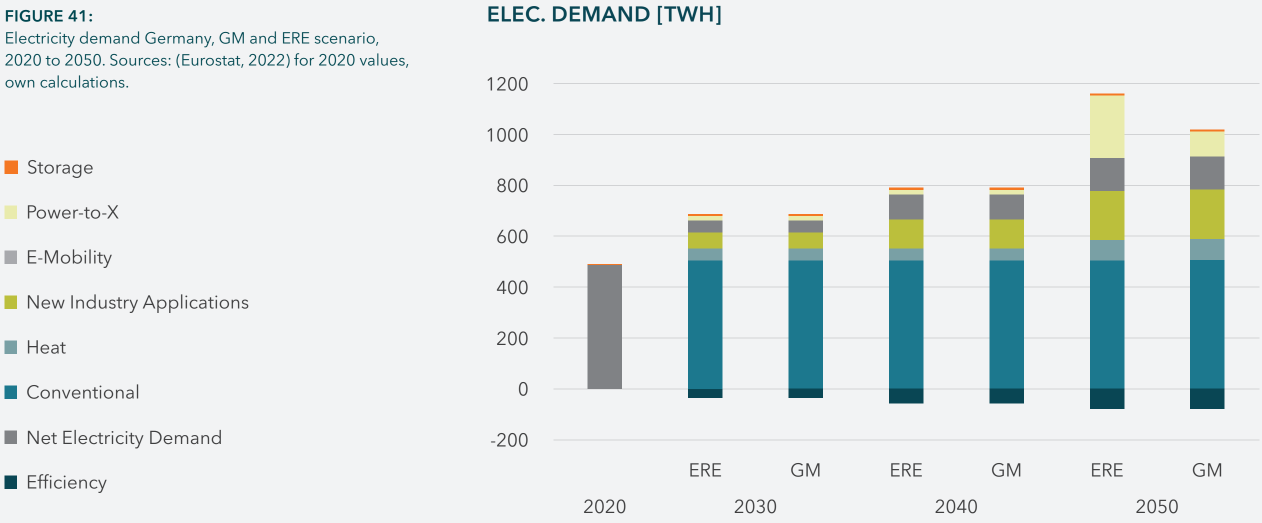


FIGURE 40:
Primary energy consumption Germany, GM and ERE scenario, 2021 and 2050. Sources: (AGEB, 2021) for 2021, own calculations.

NOTE ON PRIMARY ENERGY CONSUMPTION
The shown primary energy consumption do not include the raw materials of the chemical industry (feedstock - included under oils) and international air and shipping traffic.

The development of electricity demand in Germany in Figure 41 is similar to the trend in Europe. From a 2020 perspective, we expect electricity demand to double by 2050. Until 2040, the GM and ERE scenarios are comparable, in terms of both total demand and the share of different types of demand. In 2050, the total demand in the ERE scenario (1,087 TWh/year) is much higher than in the GM scenario (937 TWh/year), primarily due to the more intensive use of power-to-X technologies, mostly for the domestic generation of hydrogen. Independent of the scenarios, new applications in the industrial sector are becoming more prominent. Their demand for electrical energy increases from 32 TWh/year in 2030 to 193 TWh/year in 2050. Efficiency gains and additional conventional demand balance each other out, which results in a constant demand (507 TWh/year) over the modelling period in both scenarios.

FIGURE 41:
Electricity demand Germany, GM and ERE scenario, 2020 to 2050. Sources: (Eurostat, 2022) for 2020 values, own calculations.



The maximum simultaneous electricity demand in Germany will increase more than 3 times from today (in 2020 around 80 GW) up to 248 GW in the GM scenario and 302 GW in the ERE scenario. Flexible consumers have a total share of 50% to 54% in specific situations at March 2050, midday (see Table 2). In the ERE scenario, the largest flexibility comes from power-to-gas with 20% of the total demand. With less power-to-gas capacity in the GM scenario, smart charging of electric vehicles with 14% and controlled heat generation with 20% have the largest share of total demand."

TABLE 2:
Maximum simultaneous electricity demand in Germany, GM and ERE scenario.T

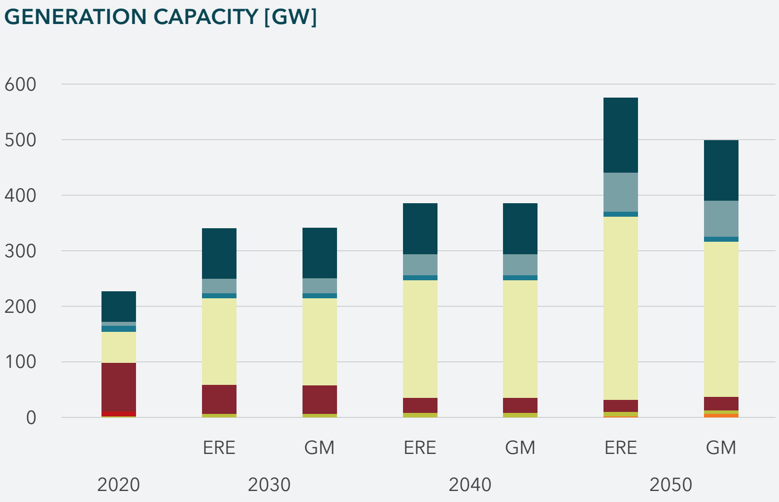
Scenario	**ERE**	**GM**
Date	2050-03-28, 12 pm	2050-03-07, 12 pm
Inflexible demand	138 GW	124 GW
Flexible demand	164 GW	124 GW
of which power-to-gas	60 GW	29 GW
of which storages	9 GW	9 GW
of which smart charging BEVs	50 GW	35 GW
of which power-to-heat	45 GW	51 GW
Total	302 GW	248 GW
Flexibility share	54%	50%

NOTE ON FLEXIBILE/INFLEXIBLE DEMAND
The inflexible demand includes 50% BEV-demand, conventional electricity demand, electricity road freight, grid losses, new industry electricity. The flexible demand includes battery storages, pumped hydro storages, 50% BEV-demand, elektrolysers, heat pumps, resistive heaters and helmeth.

Starting from 2020, generation capacity will more than double by 2050. In this context, we see a decrease in the capacity of thermal plants and a strong increase in renewables. The generation capacities in Germany are expected to increase the most during the last ten years of the modelled period. The development in Figure 42 is aligned with the capacity expansion of photovoltaics, which becomes the generation technology with the highest capacity after 2030. The higher need for hydrogen production in 2050 in the ERE scenario is also reflected in the noticeable generation capacity. The main differences to the GM scenario are onshore wind and photovoltaics. In accordance with the climate targets, the capacity of thermal plants is reduced to a minimum. This is primarily for the security of supply and based on renewable gas. Nuclear will only be operated in 2020.

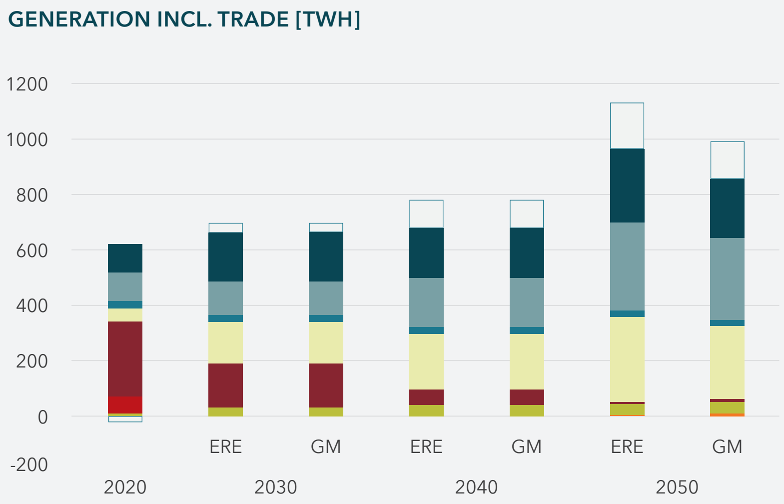
Until 2040, both scenarios show the same development in the generation capacity, which increases from 340 GW to 385 GW. In 2050, the capacity in the ERE scenario amounts to 576 GW, whereas in the GM scenario it is 498 GW.

FIGURE 42:
Installed capacity for electricity generation in Germany, GM and ERE scenario, 2020 to 2050. Sources: (Eurostat, 2022) for 2020 values, own calculations.



Electricity generation in Germany will rise dramaticallly compared to 2020. At the same time, the share of thermal power plants decreases and in 2050 generation from renewables meets almost all of the electricity demand. The pattern of electricity generation in both scenarios is similar to that of electricity demand and generation capacity. From 2030 to 2040, total generation is identical in both scenarios, increasing slightly from 658 TWh to 672 TWh. In 2050, higher capacity in the ERE scenario results in total generation of 959 TWh, which is 107 TWh higher than the GM scenario. Despite the very different capacities of onshore, offshore and photovoltaics, all contribute to generation with fairly balanced shares. Another major difference to 2020 is that Germany must increase its import steadily to cover domestic electricity demand. This rises from 32 TWh in 2030 to 166 TWh (ERE) and 132 TWh (GM) in 2050, respectively.

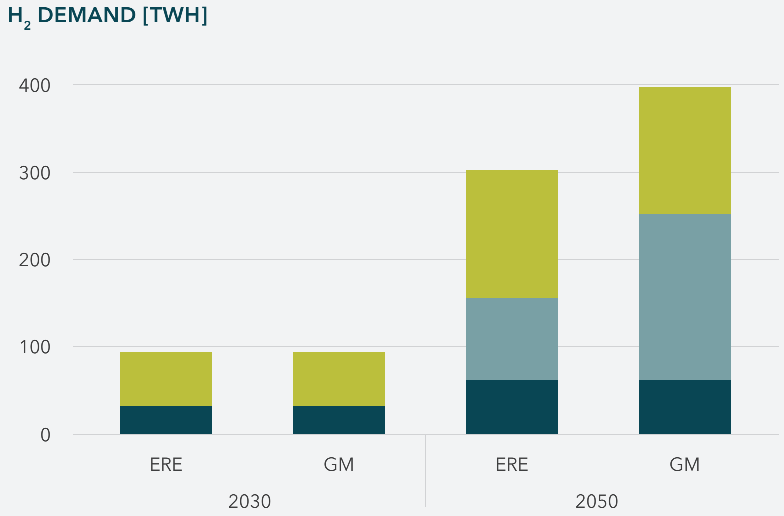
FIGURE 43:
Annual electricity generation incl. trade in Germany, GM and ERE scenario, 2020 to 2050. Sources: (Eurostat, 2022) for 2020 values, own calculations.



Hydrogen
An extended utilisation of hydrogen in Germany is expected by 2050, as shown in Figure 44. In 2030, in both scenarios, the total demand for hydrogen is 94 TWh, of which around two thirds comes from the transport sector, and the remaining third in the industry sector. In 2050, the total demand for hydrogen increases to 302 TWh in the ERE scenario and 398 TWh in the GM scenario. The **difference between scenarios** is due to its use in generating synthetic fuels and gases (94 TWh hydrogen in the ERE scenario and 190 TWh in the GM scenario). The direct use of hydrogen in the transportation sector and industry sector is an exogenous input and independent of scenarios. We assumed 146 TWh and 62 TWh demand for hydrogen in these sectors in 2050.

NOTE ON DIFFERENCE GM/ERE HYDROGEN DEMAND
For a detailed analysis of the different hydrogen demands in the GM and ERE scenarios, see European analysis in Chapter 2.3.1.

FIGURE 44:
Hydrogen demand in Germany, GM and ERE scenario, 2030 and 2050.

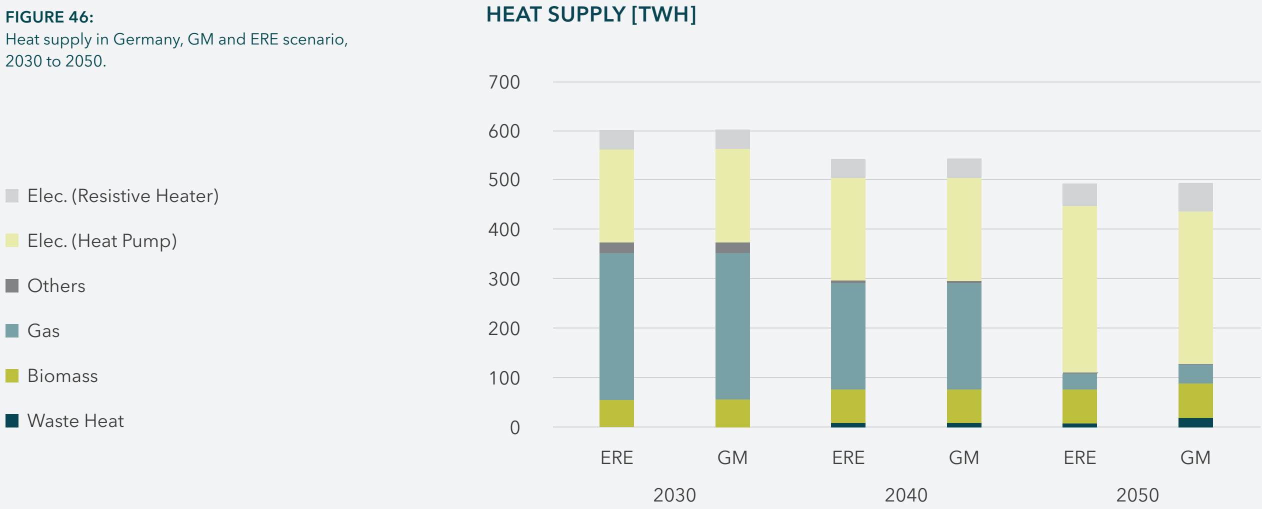


Up to 2030, the domestic demand for hydrogen in Germany is mainly covered by SMR. Only a minor share is provided by electrolysis. A systematic change is expected by 2050, when electrolysers will mainly be used for hydrogen production. This domestic production amounts to 200 TWh in the ERE scenario and 82 TWh in the GM scenario. Imports play an important role in the GM scenario: a total of 320 TWh are imported from outside Europe. The possibility of importing non-European hydrogen enables the higher demand in this scenario. In the ERE scenario, imports are only from European countries such as Denmark (see Chapter 2.3.1).

FIGURE 45:
Hydrogen generation and import in Germany, GM and ERE scenario, 2030 and 2050.

Heating sector
We also expect a high electrification rate in the heating sector due to limited alternative options for CO2 reduction. Due to efficiency improvement in the building sector, in both scenarios total heat supply decreases from 602 TWh in 2030 to 493 TWh in 2050, shown in Figure 46. In 2030, gas still dominates in the heating sector in Germany with 298 TWh, followed by heat pumps with 190 TWh. In 2050, gas can largely be replaced by heat pumps, which generate a total of 338 TWh in 2050. The use of biomass and resistive heaters is nearly constant over the years, with a slight increase in the GM scenario in 2050.

FIGURE 46:
Heat supply in Germany, GM and ERE scenario, 2030 to 2050.



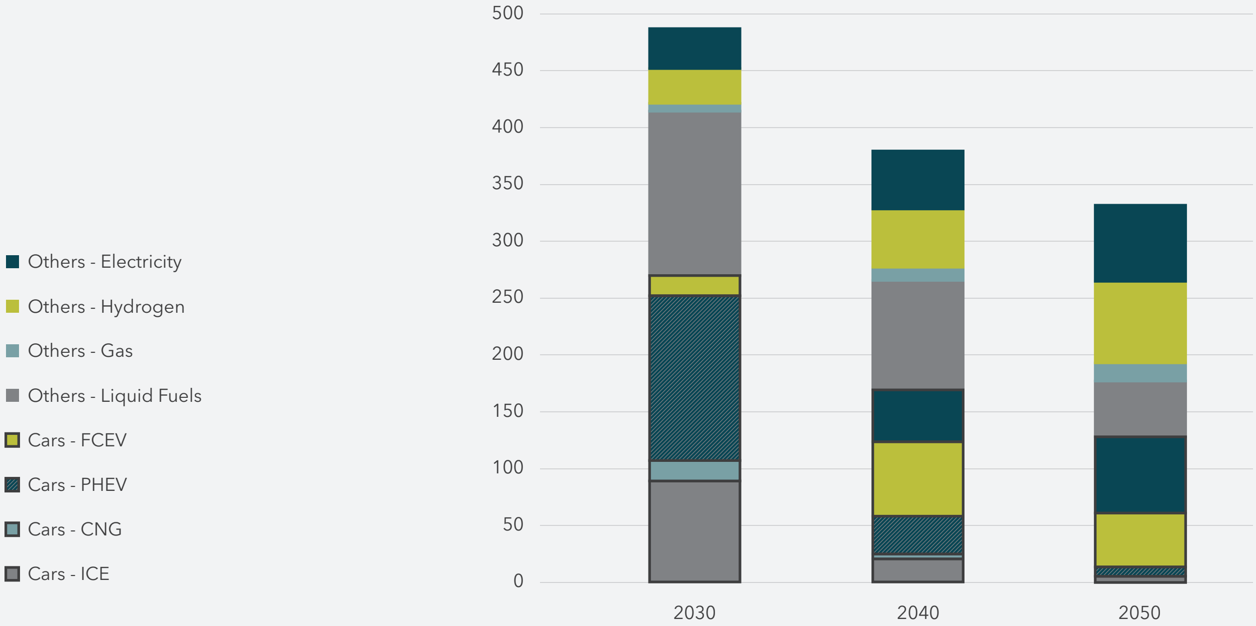
Transport sector

Energy consumption in the German transport sector is expected to decline substantially by 2050. This is mainly due to the road passenger sector, with energy demand decreasing from 271 TWh in 2030 to 128 TWh in 2050, as shown in Figure 47. Furthermore, currently dominant ICE technology is first replaced by PHEV, and then by BEV and FCEV. Electric vehicles account for an energy demand of 115 TWh in 2050, and ICE decreases from 89 TWh in 2030 to only 5 TWh in 2050.

For other transportation purposes such as freight, liquid fuels are the main transitional technology until 2030, similar to PHEV for the road passenger sector. The demand for liquid fuels is progressively replaced and their energy use declines from 144 TWh in 2030 to 49 TWh in 2050. Therefore, electricity and hydrogen become increasingly important. Their energy uses rises from 35 and 31 TWh in 2030 to 67 and 71 TWh in 2050, respectively.

FIGURE 47:
Energy consumption in transport sector in Germany, GM and ERE scenario, 2030 to 2050.

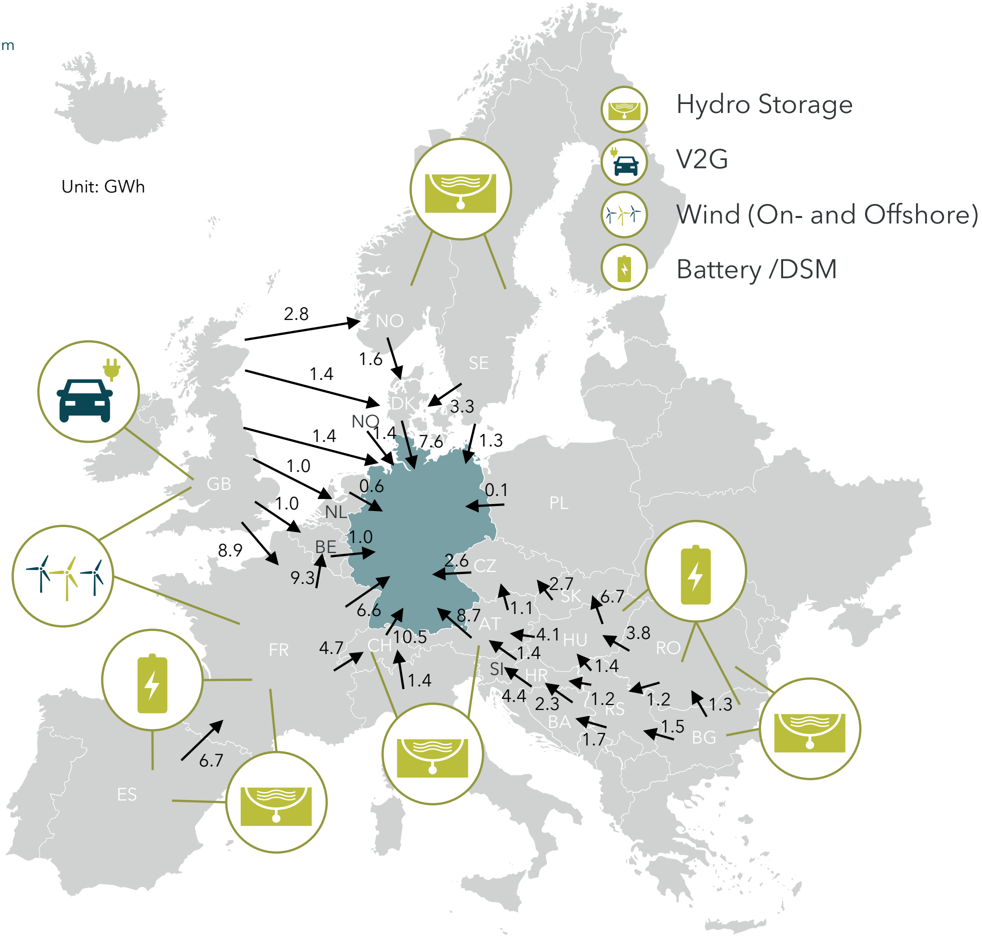
FINAL ENERGY DEMAND FOR TRANSPORT [TWH]



Critical Week in January 2050

In Figure 29 and Figure 30, we looked at a critical week, during which Germany must meet up to half of its electricity demand with imports. It is worth investigating the power trade situation in the hour with the highest import, 7:00 pm on 24 January. During this hour, Germany imports from all neighbouring countries. Furthermore, we can observe energy flows from almost all directions to central Europe, especially to Germany. The largest import contributions are from Austria and Switzerland, primarily with hydro storage. Denmark acts as a transit country for hydropower from Scandinavian countries to Germany. France exports to Germany with a major contribution of battery storage and wind energy. On the other hand, it allows a substantial transit energy flow from Spain and Great Britain to other central European countries, particularly Germany and the Netherlands.

FIGURE 48:
Import to Germany, GM Scenario, 7:00 pm on 24 January 2050.



2.5 REGIONALISATION OF RESULTS

The results of the ESM show that interconnection and cooperation are needed in Europe to transport carbon neutral electricity to the future load centres from regions that are geographically and meteorologically suitable for renewable power generation. However, the spatial resolution of energy system models only allows for simulations on countries or regions of equivalent size, as the complexity of such models reach their computational limits. This level of detail may be sufficient for determining national targets and guiding policies. However, it lacks the necessary depth for resolving technological challenges such as the transport demand in national grids.

Therefore, model results need to be further spatially disaggregated. This can be done by integrating statistical data, which are usually available in much higher spatial resolution. Also, market data such as power plant locations can be used to further enrich the data set with spatial information.

The methodology and results of this disaggregation will be discussed in the following two subsections. This spatially enhanced data set will then be used to conduct sophisticated technical analyses of the national and European levels. Referring to the initial methodology of this study, the Global Markets scenario has been chosen as the basis for the following analysis.

2.5.1 METHOD OF REGIONALISATION

For an adequate regionalisation of the model results, we used a twofold approach:

/ Scaling based on regional and sectoral models of higher spatial resolution
/ Adaption of existing scenario data from regulatory processes

VARIABLE RENEWABLE ENERGY (VRE)
VREs are electricity generation technologies whose primary energy source varies over time and cannot easily be stored. VRE sources include solar, wind, ocean, and some hydropower generation technologies. (National Renewable Energy Laboratory 2015)

Variable Renewable Energy (VRE) sources and new flexible demand appliances play a central role in the future energy system. Their temporal and regional profiles have a significant impact on electricity transportation needs. We used the models and data from two projects conducted by the *Forschungsstelle für Energiewirtschaft e. V.* (FfE), “eXtremOS“ (FfE 2021) and “Versorgungssicherheit 2021“ (not publicly available).

The spatial distribution of the following model data is calculated using the models and data from the projects mentioned above: onshore and offshore wind generators, solar rooftop and utility panels, conventional electricity load, load of new electricity appliances in the industry sector, electricity demand of transportation, grid losses, electric heating technologies such as heat pumps and resistive heaters, and the consumption and generation of battery storages.

NUTS3
The NUTS classification (nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU and the UK for the purpose of:
the collection, development and harmonisation of European regional statistics; socio-economic analyses of the regions; framing of EU regional policies. (EUROSTAT, 2022)

While the model consortium of these projects can enhance spatial and temporal aspects of the ESM results, only the information on spatial distribution has been used here. Based on data availability and level of detail, we have chosen to use **NUTS3 regions** as the target spatial resolution. These regional clusters are defined for all European nations and roughly correspond to municipalities, provinces, or districts.

GIS
A geographic information system (GIS) is a computer system for capturing, storing, checking, and displaying data related to positions on Earth’s surface. GIS can show many kinds of data on one map, such as streets, buildings, and vegetation. (National Geographic 2022)

As an illustration of the method, the example of onshore wind generators is given below. First, a **GIS** based analysis was conducted to identify suitable locations with expansion potential. Nature reserves, settlements, infrastructure, and regional buffer zones were excluded. Then, wind farm models were used to classify suitable areas. Typical technical characteristics of wind powered generators such as the type of turbine, its dispatch characteristics, and the height of the system were considered. Also, additional weather data from European weather models were used. With this information, a hypothetical wind power generation capacity was calculated per region. Regions with especially low electricity yields were then excluded in case of insufficient profitability. For the regionalisation of the model results, a distinction between existing and invested plants must be made. Using publicly available data such as existing locations and wind turbine specifications, we allocated existing plants to the previously quantified potential areas. Next, we added the additional investment proposed by the model. For a more realistic result, we calculated the expansion considering two indicators: “existing plants“ and “generation potential“ in each region. A ratio between these expansion indicators was defined over the 10-year steps of the ESM. For the year 2030, we assumed 50% of the newly built plants to scale with the existing capacity per area (disregarding other technical characteristics). The remaining new plants were then distributed based on the potential electricity yield. This approach ensures a more realistic expansion, which is not only driven by the hypothetical electricity yield of an area.

A similar approach was used for the other technologies, both VRE sources and demand side technologies. In each case, specialised models were used together with statistical and meteorological data of high spatial resolution. The results were then used to downscale the ESM results to the NUTS3 regional resolution. While this approach would also allow for spatially diverse generation profiles, only the regional information was used. This is due to further technical restrictions. The creation of regional differences in the generation profiles would inevitably lead to deviations in the overall generation profile, which then would deviate from the model results. For the further analysis of grid stability, a 100% consistent model result is necessary. This cannot be achieved with reshaped generation and load profiles.

For conventional technologies, or technologies that can be built on old conventional sites, we used a different approach. The technologies we included were coal, lignite, natural gas and biomass power plants, pumped hydro storages, run of river plants and hydro reservoirs. We used internal data from the German Grid Development Plan 2021, scenario B2040 (German TSOs 2022), which forecasts the central European grid topology in the year 2040 including its power plant sites. On this basis, we manually adapted the grid topology to the system configuration of the ESM results.

ELECTROLYSER
An electrolyser is a system that uses electricity to break water into hydrogen and oxygen in a process called electrolysis. Through electrolysis, the electrolyser system creates hydrogen gas. The oxygen that's left over is released into the atmosphere or can be captured or stored to supply other industrial processes or even medical gases in some cases. (Cummins 2020)

SYNTHETIC NATURAL GAS (SNG)
SNG describes a variety of natural gas alternatives that are as close as possible in composition and properties to natural gas. SNG can be derived from coal, (waste) biomass or synthesized using renewable energy. (MAN-ES 2022)

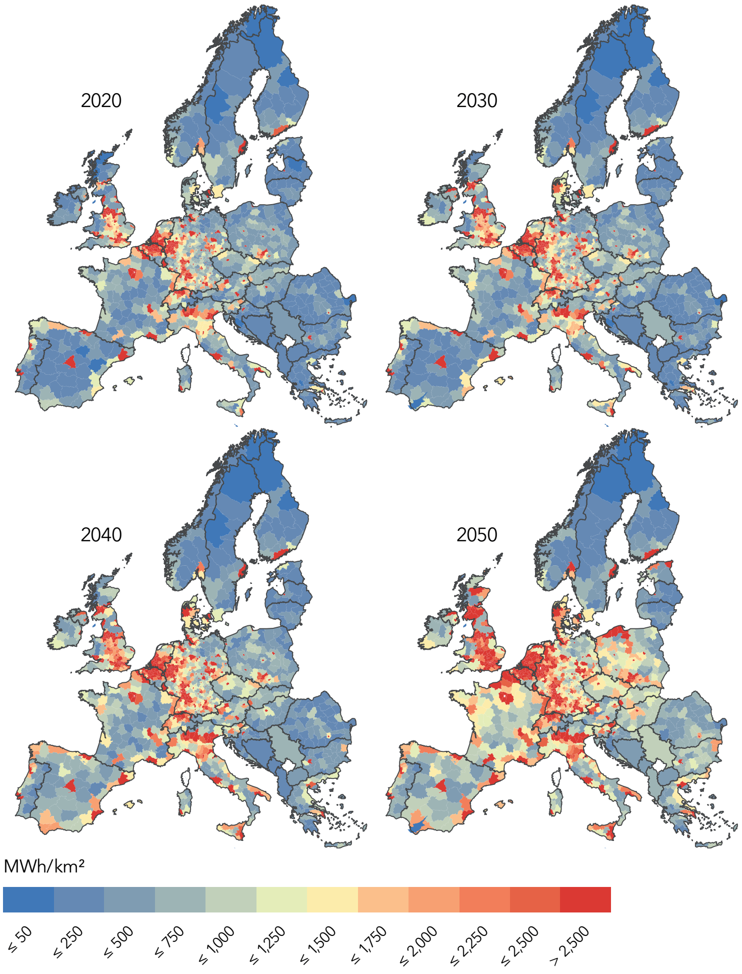
Finally, power-to-gas appliances were regionalised. We distinguished between hydrogen production via **electrolysers** and **synthetic natural gas (SNG)** production. We further assume that hydrogen production will be predominant in regions with high surplus renewable generation. The electrolyser expansion data from the model results is therefore scaled according to the amount of surplus renewable generation of each NUTS3 region. A different approach was used for the synthesis of SNG. The underlying process needs a source of carbon. Because we assume syngas will be exclusively green in 2050, we allocated the SNG sites near biomass plants, which can provide green carbon.

2.5.2 RESULTS FOR REGIONALISED EUROPE

This chapter will present selected insights into the Global Markets scenario in the year 2050, which highlight the regional aspects of our vision. As described in the previous section, all results are calculated and visualised on NUTS3 level.

FIGURE 49:
Total yearly electricity demand for EU27, GM scenario, 2020 to 2050.

TOTAL ELECTRICITY DEMAND

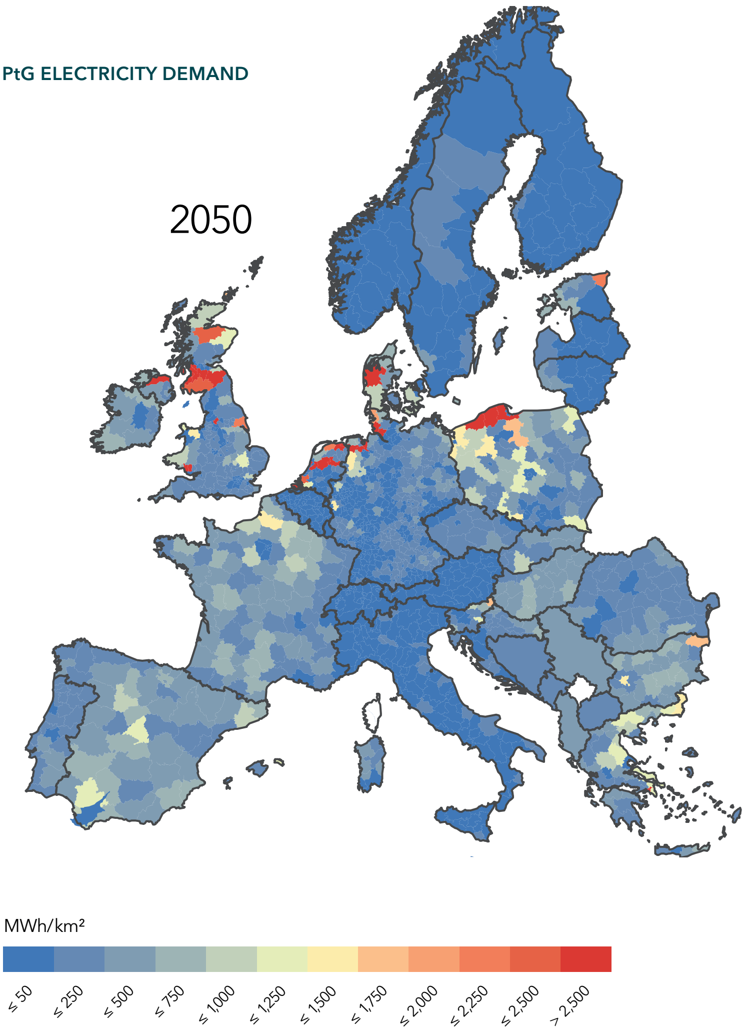


Administrative Boundaries: Europe: © OpenStreetMap Contributors | Germany: © GeoBasis-DE / BKG 2017 | Generalization: FfE e.V.

One of the key results of the regionalisation process is the regional distribution of the total (yearly) electricity demand shown in Figure 49. The ESM estimates that sector coupling technologies will play a dominant role in the energy system, which not only leads to a higher overall electricity demand, but also changes its regional profile. In 2020, we can clearly identify the capitals of Europe as well as some additional regions with high industry density. Over the decades, existing hotspots remain, but new high-density areas develop as well. This can be observed at locations near the sea, where abundant offshore wind energy is available. Some notable regions are northern England, Scotland, northern France, Denmark, northern Germany, and northern Poland. These new high-density load centres resulted from an integrated planning of the energy system. Our future energy system relies heavily on power-to-gas commodities like hydrogen. To reduce the load in the heavily utilised electricity grid and to use existing infrastructures for gas or other fuels, it is advisable to produce these products in regions where local electricity is readily available and transport them in their gaseous or fluid forms. Accordingly, conversion infrastructure is allocated to regions with a large surplus of renewable energy. Offshore wind farms are the main drivers for these regions, which serve as the main landing points for the power generated offshore. The regional distribution of power-to-gas facilities is shown in Figure 50. We can clearly identify the correlation between newly formed high-density load centres and the demand of power-to-gas facilities.

FIGURE 50:
Yearly electricity demand of power-to-gas facilities, GM scenario, 2050.

PtG ELECTRICITY DEMAND

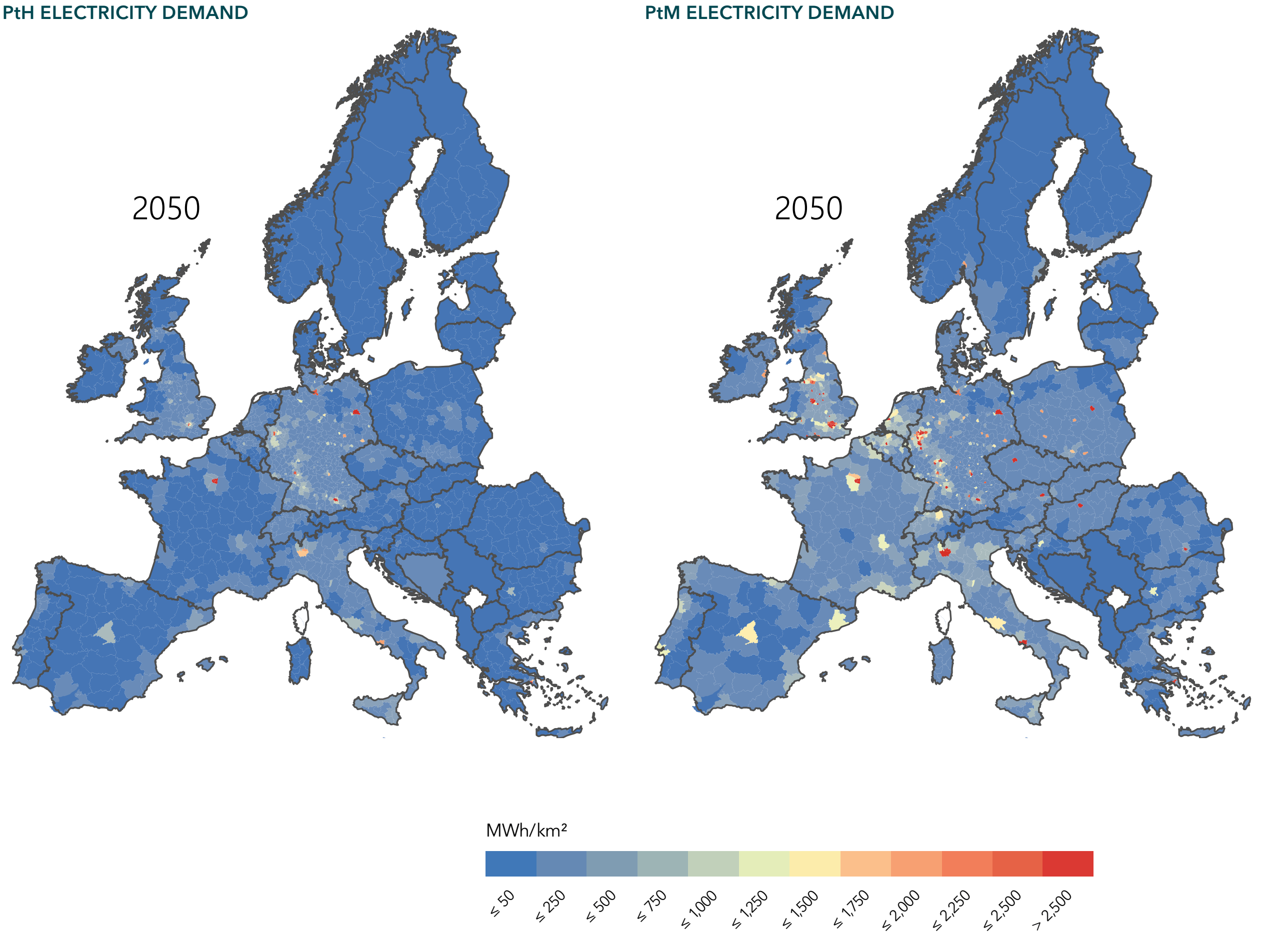


Administrative Boundaries: Europe: © OpenStreetMap Contributors | Germany: © GeoBasis-DE / BKG 2017 | Generalization: FfE e.V.

In addition to the newly formed high-density load centres, numerous low-density areas increase their demand. These are found in France, Spain, Poland, Czech Republic, and Greece. This effect is also driven by power-to-gas appliances. In contrast to the high-density areas, the newly formed medium-density demand areas depend more on mainland VRE such as solar and onshore wind plants, which are more widely distributed throughout these countries.

While power-to-gas plants have the greatest effect, power consumption is also driven by the remaining sectors, mobility and heating. Figure 51 shows the effect of those sectors. Both sectors have a similar regional profile. Big cities are visible as medium to high-density areas and rural regions have a slightly increased demand for power.

FIGURE 51:
Yearly electricity demand of power-to-heat (left) and power-to-mobility (right), GM scenario, 2050.

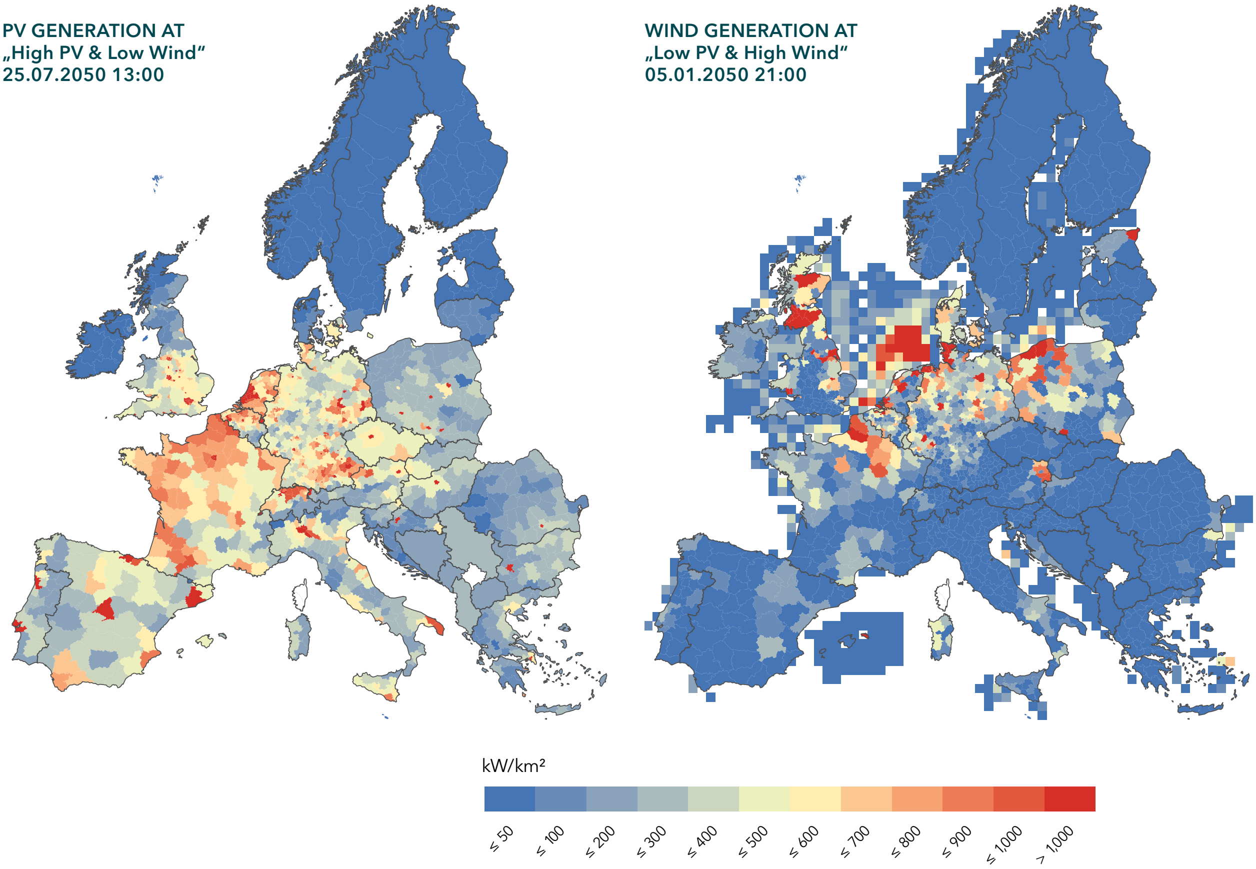


Administrative Boundaries: Europe: © OpenStreetMap Contributors | Germany: © GeoBasis-DE / BKG 2017 | Generalization: FfE e.V.

From the perspective of power delivery, distances between generation and load are crucial. Because our vision of the future incorporates a significant number of VRE sources, focussing on installed capacities alone is not sufficient. As the time of day and weather conditions determine the availability of generation, it is more useful to study single situations of high system stress (in terms of power transport).

Figure 52 shows the broad profile of regional differences. The map on the left depicts an hour with very high solar power generation, which is combined with rather low wind generation. Solar power is a vital component of the power system. In terms of regional distribution, we note that although solar power is present all over Europe, generation capacity varies greatly within countries. This is especially true for Germany and to some extent for France, Italy, Spain, and Austria.

FIGURE 52:
High solar generation (left) and high wind generation (right), GM scenario, 2050.



PV GENERATION AT
„High PV & Low Wind“
25.07.2050 13:00

WIND GENERATION AT
„Low PV & High Wind“
05.01.2050 21:00

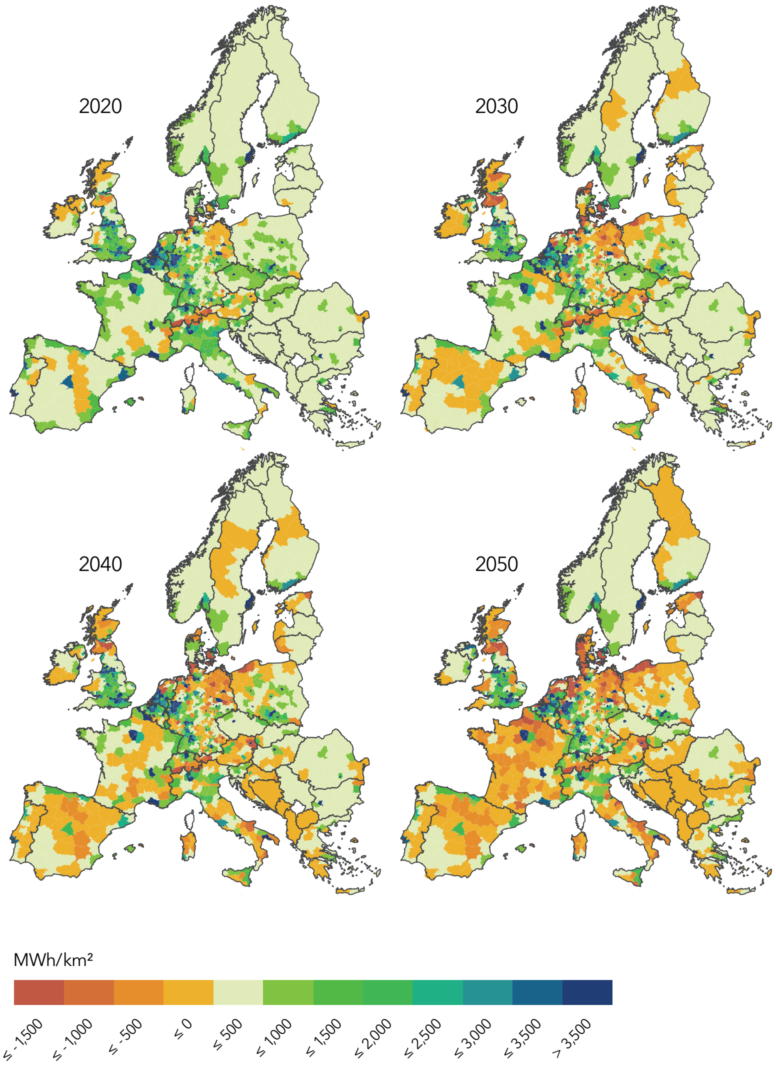
Administrative Boundaries: Europe: © OpenStreetMap Contributors | Germany: © GeoBasis-DE / BKG 2017 | Generalization: FfE e.V.

The map on the right in Figure 52 shows the opposite pattern: wind power generation is high and solar low. In contrast to the solar profile, areas of wind generation are highly clustered around offshore generation sites in the North Sea and in the coastal regions of Poland, Germany, Denmark, the Netherlands, and North-East France. This inevitably leads to additional international differences. While Figure 52 shows only the extreme values of this meteorologically driven phenomenon, similar profiles are likely to occur on multiple occasions per year. Our model results show that system stress is faced with demand flexibility and grid expansion. These two situations illustrate how differently wind and PV are distributed in Europe, thus demonstrating the benefits of planning an interconnected Europe.

Highlighting the extent of system stress, Figure 53 shows the development of the residual load over the course of the years. Today, the residual load is mostly positive, as the power system still consists of a combination of VRE and conventional plants. Led by the decreasing carbon budget, northern and southern regions of Europe switch from positive to negative residual load, which is clearly visible in 2030 and later. While a positive residual load indicates that additional power generation is needed, a negative residual load indicates that surplus energy is available. This energy must be either stored (temporal flexibility) or transported to a region with demand (spatial flexibility).

FIGURE 53:
Development of the residual load in EU27, GM scenario, 2020 to 2050.

RESIDUAL LOAD



Administrative Boundaries: Europe: © OpenStreetMap Contributors | Germany: © GeoBasis-DE / BKG 2017 | Generalization: FfE e.V.

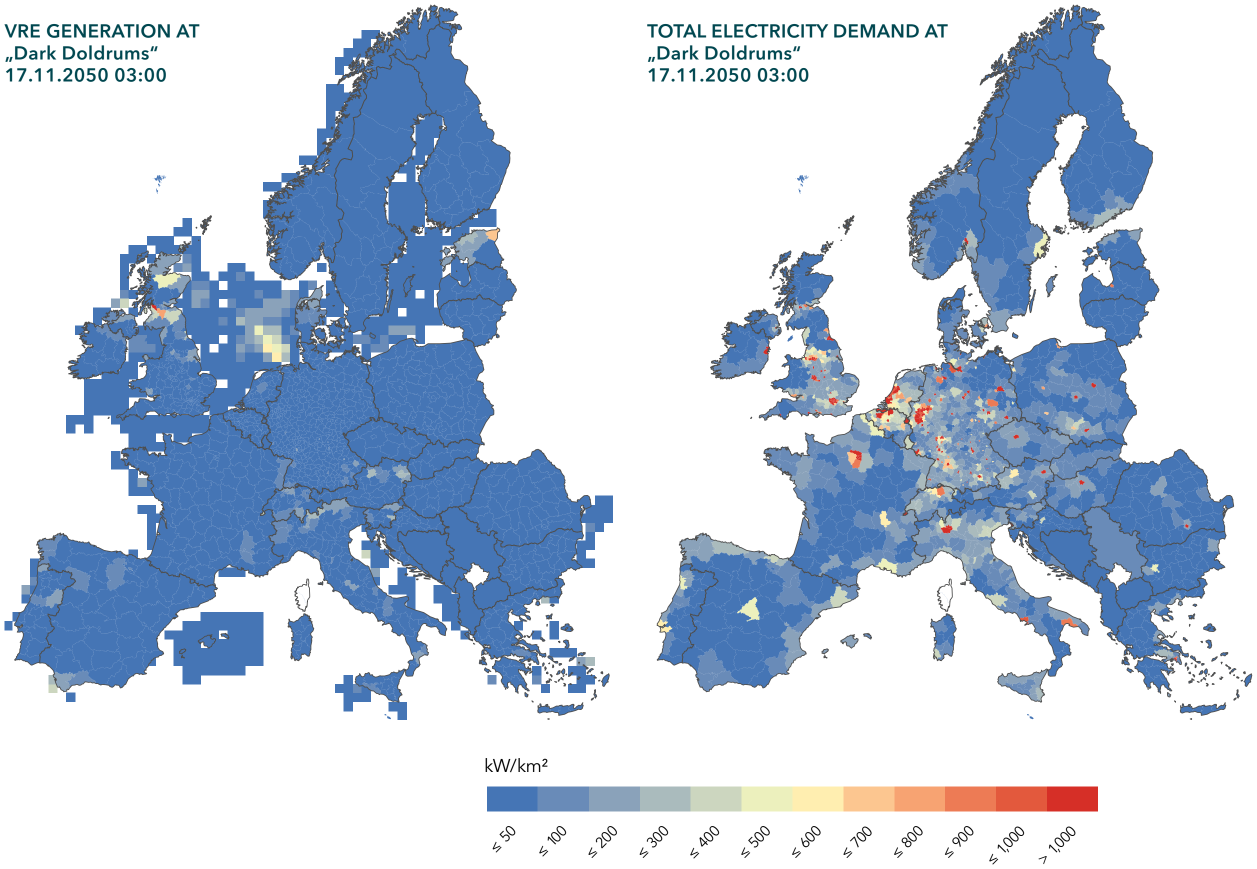
To depict the residual load, we transferred the generation of offshore wind farms to their corresponding feed-in points on land. Hence, regions with surplus energy at the northern coasts obtain the wind power from offshore plants, as well as onshore plants. Between 2030 and 2050, VRE expands from northern and southern regions towards central parts of Europe. This is due to the potential differences. Roughly, we can assume high solar potentials in the south, decreasing further towards the north, and vice versa for wind. This pattern does not apply to rooftop solar panels, which form high-density solar generation in big cities, as the number of roofs is high and the distances to the loads are short.

While some countries such as Spain and Italy seem to have a balance of regions with positive and negative residual load in 2050, other countries such as Denmark, the Netherlands and France have mostly negative residual loads. Like the stress highlighted in Figure 52, the distribution of the residual load indicates the need for a robust transport grid. Imbalances inside a country can be managed with storages, demand flexibility and the transport grid, while imbalances on international levels can only be managed with an effective, interconnected transport grid in Europe.

In terms of absolute numbers, we can clearly identify a significant rise in demand and transportation needs all over Europe. The issues we currently face such as the growing need for congestion management are only a fraction of the challenges that are still ahead of us. The changes in 2020 to 2030 and beyond indicate that we need to increase our rate of adaption.

Our analyses focussed on the stress induced by the regional differences of VRE sources. Nevertheless, we should also emphasise the challenges of the availability of VRE. Critical situations, like a cold day with high heating demand but low wind and solar generation, put the system under extreme pressure. Figure 54 shows the system reaction to such a weather situation in the year 2050.

FIGURE 54:
VRE generation (left) and electricity demand (right) during low VRE phase, GM scenario, 2050.



VRE GENERATION AT
„Dark Doldrums“
17.11.2050 03:00

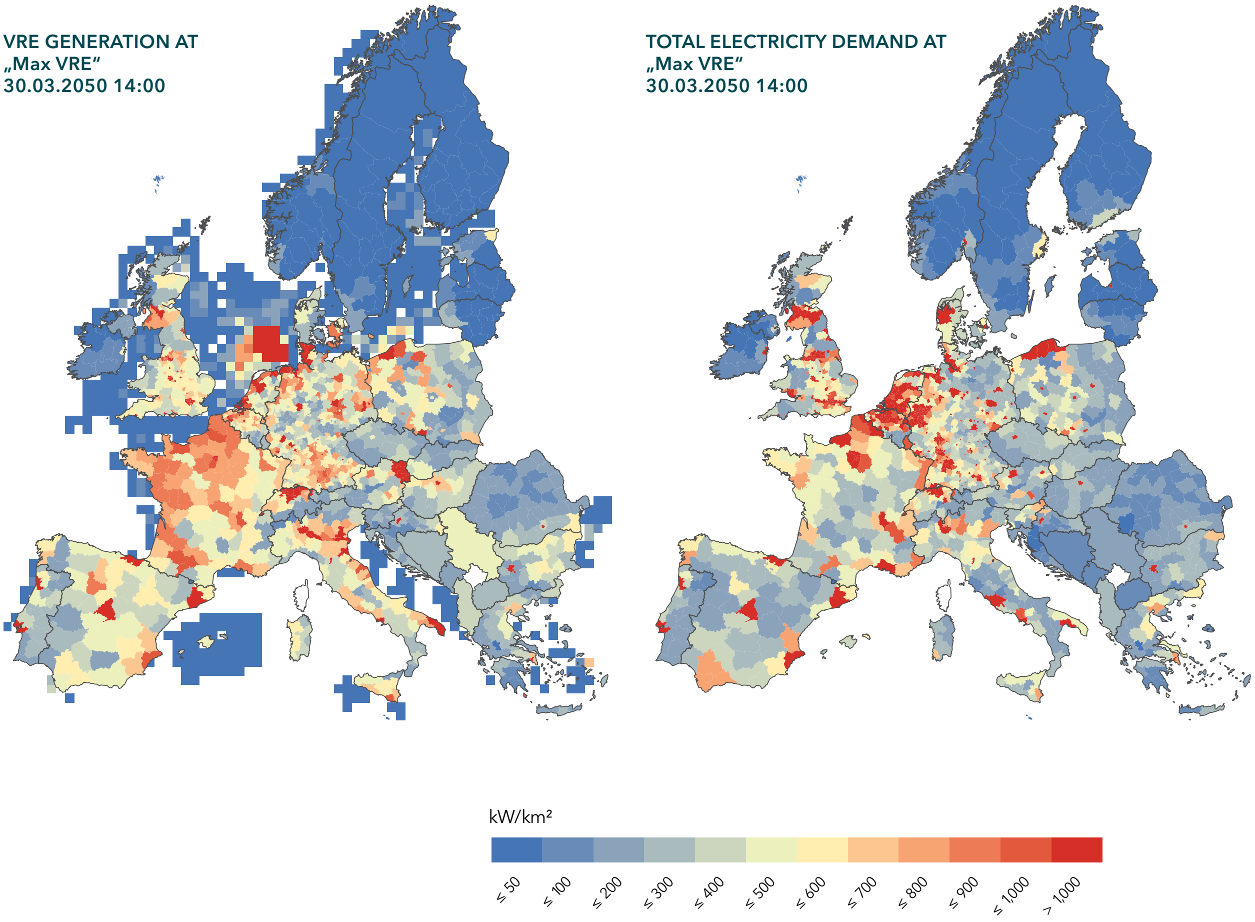
TOTAL ELECTRICITY DEMAND AT
„Dark Doldrums“
17.11.2050 03:00

Administrative Boundaries: Europe: © OpenStreetMap Contributors | Germany: © GeoBasis-DE / BKG 2017 | Generalization: FfE e.V.

The generation from VRE sources is pictured on the left map. This situation occurs in the winter, very early in the morning, in the hours before sunrise. Those are the typical hours when battery electric vehicles are charging, and heating systems are active. Also, some industry processes and power-to-gas plants would normally run overnight. However, the map on the right in Figure 54 shows that the demand is relatively low. There are still some hotspots in densely populated areas, but the system proves to be flexible enough.

In contrast to the very low VRE generation status, there is a point during the year when maximum VRE generation occurs over all regions. Then, not even neighbouring countries are available for the "disposal" of surplus energy. Again, the flexibility of the demand side is the key to stability, as shown in Figure 55.

FIGURE 55:
VRE generation (left) and electricity demand (right) during high VRE phase, GM scenario, 2050.



VRE GENERATION AT „Max VRE“ 30.03.2050 14:00

TOTAL ELECTRICITY DEMAND AT „Max VRE“ 30.03.2050 14:00

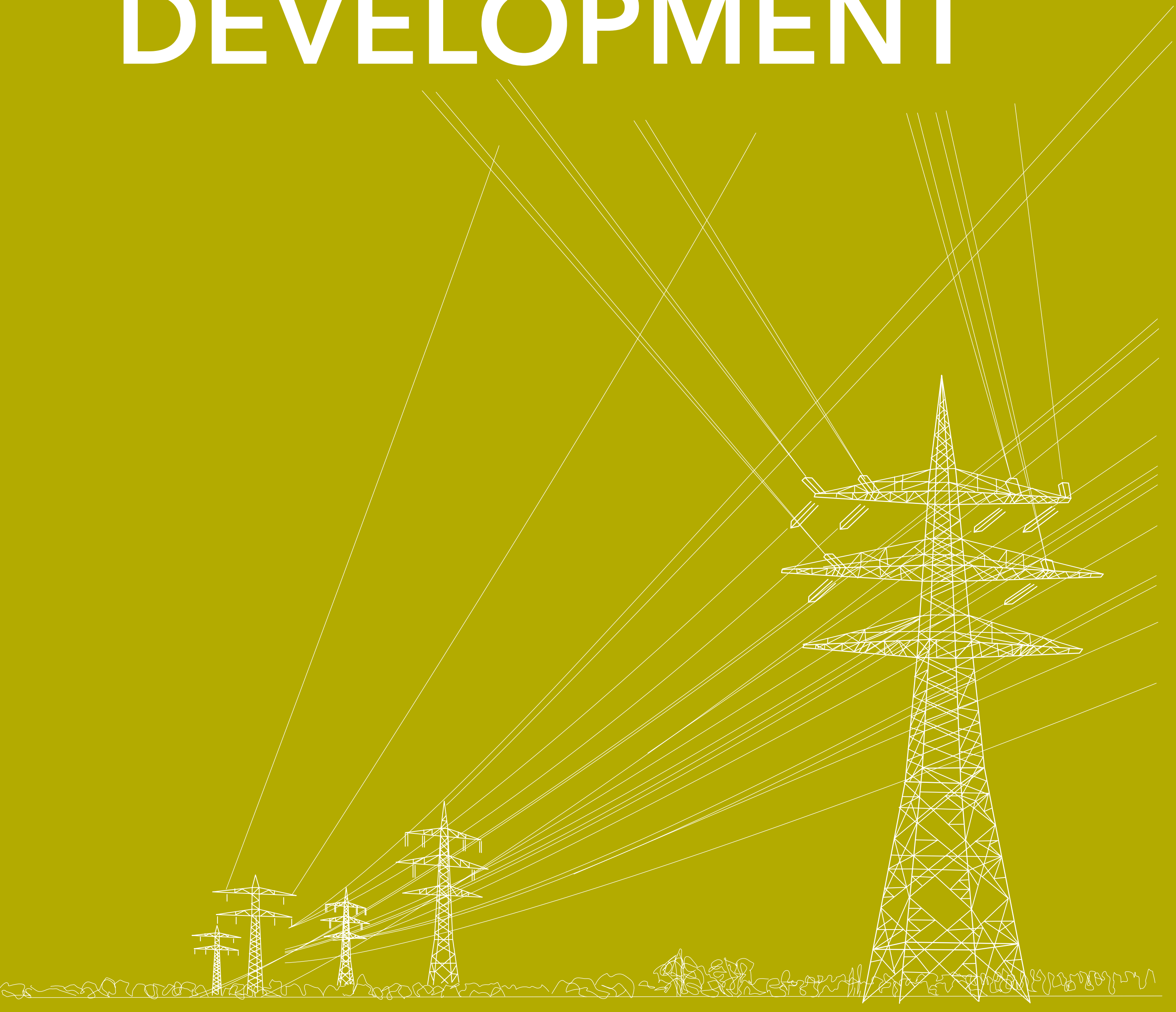
Administrative Boundaries: Europe: © OpenStreetMap Contributors | Germany: © GeoBasis-DE / BKG 2017 | Generalization: FfE e.V.

Power generation from wind and solar plants is simultaneously available over all European regions (left). The regional pattern roughly matches the electricity demand, pictured on the right. This demonstrates that despite the integrated planning approach, where the expansion of power-to-gas plants is completely driven by grid compatibility, increased power still needs to be transported throughout Europe to reach units with flexible demand.

In summary, the Global Markets scenario pictures a European continent where topological and meteorological synergies connect via sector coupling and international cooperation in the form of market coupling. The challenges are visible on two dimensions: intranational flexibility and international trade. The drivers are clearly the spatial distribution of VRE potentials and the additional demand resulting from sector coupling. Except for power-to-gas plants, these generation potentials and electricity demands remain bound to their geographical location. From the perspective of the energy system, temporal flexibility must be provided through storages and demand flexibility of all interconnected sectors, coupled with an effective power grid, which serves as a backbone. To stay cost efficient, grid friendly expansion of new loads must be considered. Also, if feasible, energy transport via other energy carriers should be used intensively.

3.0

GRID DEVELOPMENT



3.1 GRID UTILISATION & DEVELOPMENT

As several national und European legislative packages have shown, political decision-makers are determined to achieve a carbon-neutral energy system as soon as possible. The energy transition comes with profound changes in the generation structure in the electricity sector, thus creating new and challenging tasks for the transmission grid. While a speedy implementation is welcomed, adapting the infrastructure to the new demands takes time. Therefore, it is important to quickly determine a transmission grid to meet the expected needs. This is what we will discuss in the following chapters, based on the Global Markets scenario described in Chapter 2.3.1.

We will carry out grid analyses for the year 2050 and evaluate the utilisation of the extra-high voltage grid based on outage simulations. First, Chapter 3.1.1 introduces the methodology used. Then, we present the initial situation in the European transmission grid without additional grid extension measures in 3.1.2. In 3.1.3 we focus on the initial grid utilisation in Germany. Next, we explain how congestions can already be reduced by optimising power flows (3.1.4). Finally, Chapters 3.1.5 and 3.1.6 present the necessary measures developed in the HVDC and HVAC transmission grid to solve overloads. Together, these measures result in the target grid presented in Chapter 3.1.7. This is the transmission grid envisioned by TransnetBW for 2050.

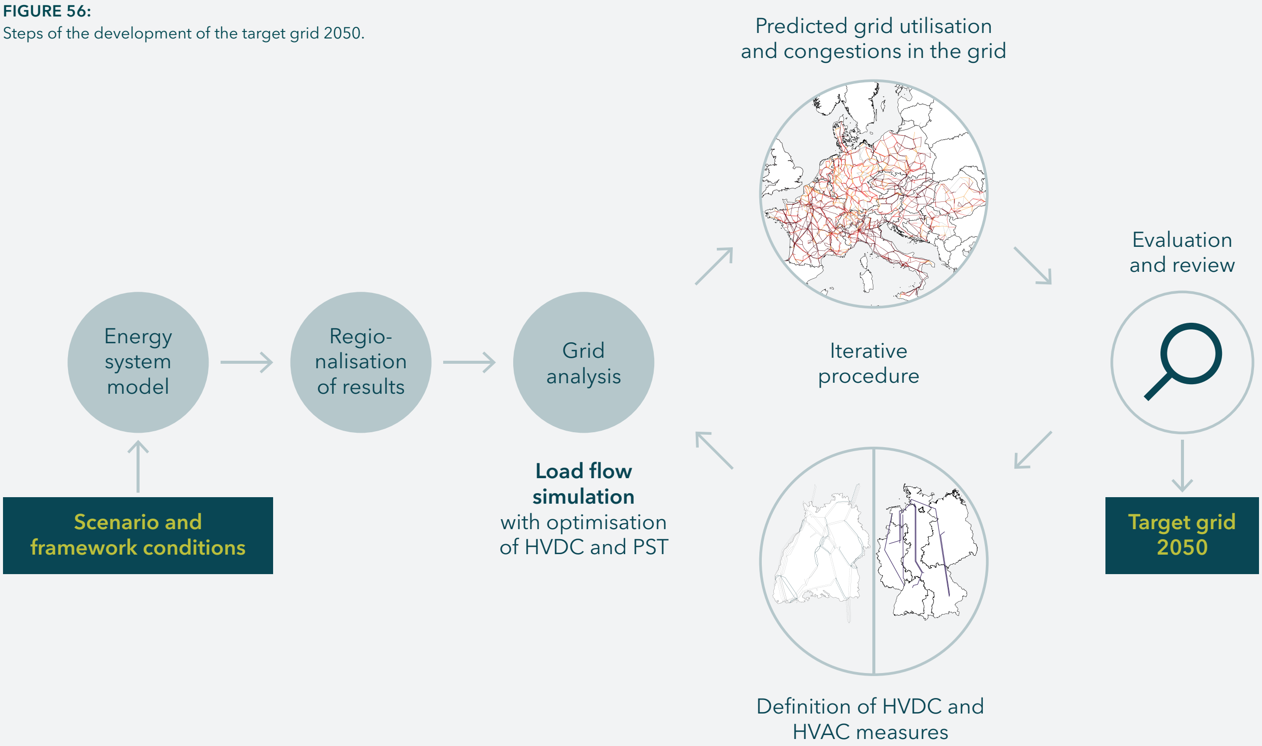
3.1.1 METHODOLOGY FOR THE DEVELOPMENT OF THE ELECTRICAL GRID 2050

According to the **planning principles of the four German transmission system operators**, the (n-1) criteria must be observed when planning the extra-high voltage grid (German TSOs, 2020). If the utilisation of the grid equipment exceeds 100%, this is reported as a grid congestion or overload.

Figure 56 shows the steps from the definition of the framework conditions to the definition of necessary grid expansion measures for the 2050 grid. In the following, the iterative procedure is described in detail.

PLANNING PRINCIPLES OF GERMAN TSOs
Initially published by the four TSOs in 2012, this publication is continuously updated to align with framework conditions for network planning. Technical and economic principles of grid expansion planning are described to transparently present the underlying methodology and needs.

FIGURE 56:
Steps of the development of the target grid 2050.



Based on the energy system optimisation for 2050 (see Chapter 2.3) and the regionalisation of the results for the electricity supply system (see Chapter 2.5), the grid analysis simulates the hourly load of the extra-high voltage grid and identifies grid congestions. The next step is to define grid construction measures to eliminate congestions and validate their effectiveness. The aim is to fulfil the transmission function, while meeting the requirements of the power supply system in 2050. The result of the proposed portfolio of measures is the plan for the 2050 grid. To define the measures, the NOVA principle, which is also valid in other planning processes like the German NEP, is applied. This procedure minimises the impact on the public and the environment by evaluating if grid congestions can also be solved by optimising or enhancing the grid instead of building new lines.

For grid optimisation, **weather-dependent dynamic line rating (DLR)** is generally applied. This method is also used for planning in the German NEP. Active elements for power flow control in the transmission grid, such as **phase-shifting transformers (PST)** or controllable **high voltage direct current (HVDC)** transmission links, are used for further optimisation. The possibility of higher utilisation of individual circuits in (n-1) cases with up to 4,000 A is also being examined on a case-by-case basis.

For grid enhancement, existing grid elements are replaced by more powerful components. Transmission capacity can thus be increased, for example, by using **high-temperature conductors (HT/HTLS conductors)** or by installing new circuits on existing routes.

If these measures do not relieve congestions, as the final step the grid can be expanded. For this purpose, new lines, new substations or HVDC transmission links for long-distance transmission can be planned.

In our grid analysis, we focussed on the TransnetBW transmission grid and designed countermeasures to cope with overloads on these circuits. However, since our grid is in the heart of Europe, it connects regions of high wind or PV generation and the Alpine hydro-storages. Furthermore, Baden-Württemberg will be strongly dependent on imports. Hence, further long-distance transmission links are evaluated and planned, which necessarily include possible connecting points outside Baden-Württemberg.

This is also the case for interconnectors from Baden-Württemberg to neighbouring countries. For interconnectors to other German TSO or between other European countries, no additional measures are implemented beyond the ones described in 3.1.2. The grid development process is based on the results of the energy system model including congestions in the grid. However, it does not necessarily implement the additional transmission capacity identified by the energy system model into certain measures in the grid (see Figure 25).

Overloads of transformers within the transmission grid or to the distribution grid are out of the scope of this study. Therefore, countermeasures are not proposed here, and these overloads are not considered in the OLE calculation. This is also the case for possible topological restrictions due to an insufficient short-circuit resistance at substations. For investigations into these issues and the development of necessary measures, further studies with detailed regional concepts will be needed.

WEATHER-DEPENDENT DYNAMIC LINE RATING (DLR)
The transmission capacity of the power grid varies depending on the season and weather. With colder temperatures and cooling by wind, more power can be transmitted than on hot summer days. With the help of weather dependent DLR, it is possible to increase the load of the electrical grid significantly. Using live measurement data, the maximum power flows acceptable under the current weather conditions can be calculated precisely, so that the sag of the conductor lines remains within the technical specifications.

PHASE-SHIFTING TRANSFORMER (PST)
Grid equipment which is a specific form of a transformer. The phase-shifting transformer enables control of power flows in the alternating current grid.

HIGH VOLTAGE DIRECT CURRENT (HVDC)
In contrast with the more common alternating current (AC) systems, HVDC transmission links use direct current (DC) for the transmission of electrical power.

HIGH-TEMPERATURE CONDUCTOR (HT/HTL)
Line conductor that, due to the materials used, can function at a higher operating temperature than traditional aluminium/steel conductors (> 80°C). HT conductors offer a higher current capacity with comparable cross section and geometry. These are available as thermal resistant aluminium (TAL) conductors with a maximum operating temperature of up to 150°C.

3.1.2 ANALYSIS OF THE INITIAL SITUATION

REFERENCE GRID
The reference grid is the assumed expansion status of the electricity grid as the starting point for the grid calculations.

Reference Grid

The starting point of our grid analysis is the preparation of a reference grid, which represents the initial situation for the extra-high voltage grid in 2050. It is derived from the dataset used by the four German TSOs in the German NEP 2021. Hence, it includes several additional measures beyond the existing transmission grid.

/ The reference for the German grid includes all measures that are being implemented as well as those recently confirmed by the national regulatory authority (NRA) in the current German NEP 2021 (Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen, 2022).

/ The European grid is based on the TYNDP 2020 (ENTSO-E, 2021). It includes all projects with a status that is more advanced than "under consideration", unless not confirmed by the German NRA (based on a cost-benefit-analysis according to the German NEP). Additionally, for relevant foreign areas adjacent to the German TSOs grids (observability area), information about the development until 2035 was exchanged with these TSOs within the German NEP process.

/ All congestions within substations that limit the connected circuit's full transmission capacity were assumed to be relieved throughout the German transmission grid by 2050, hence enabling currents up to 3,600 A.

HVDC Reference Grid

The transport of electricity with high voltages is possible at low cost using three-phase current (AC) technology. This technology is particularly relevant in regions where there are many substations to supply the distribution grid, or where regionally generated electricity is integrated.

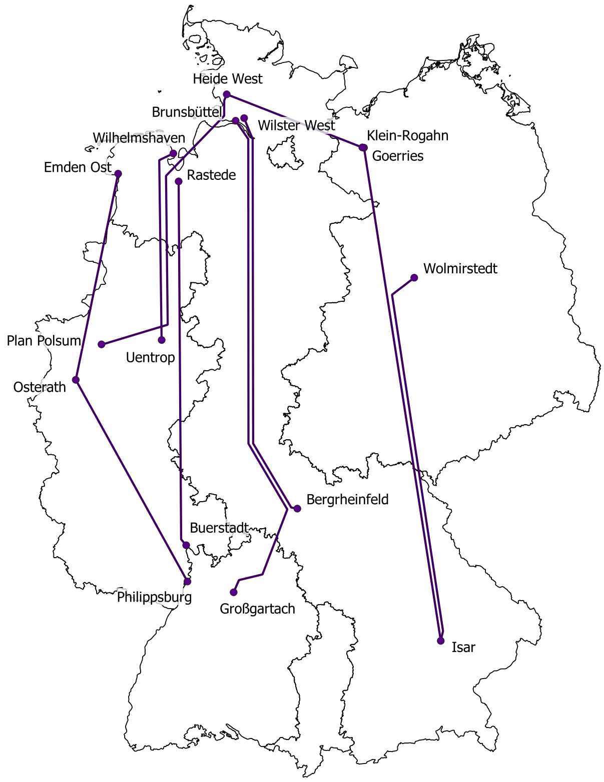
For long distance transmission, HVDC technology offers many advantages compared to AC technology. It has lower grid losses than transmission with three-phase current. In addition, HVDC converter stations offer additional flexibility for the electricity grid. Power flows can be controlled in a targeted manner by adjusting the HVDC converter station. This enables higher system security and stability. HVDC transmission lines can also be constructed underground using cable technology without the need for large compensation systems. The disadvantage of HVDC transmission links is the comparatively high cost. This is due to the necessary converter stations that connect the HVDC transmission lines to the AC grid. For this reason, the technology's economic advantage of low grid losses only takes effect in the overall costing when bridging long distances. For Germany, this means the north-south links, which connect power generation areas in the north that have a surplus of electricity with load centres in the south.

HVDC transmission links can also be used to transport power from south to north when there is high solar radiation and little wind. These links thus play a major role in the planning of the TransnetBW transmission grid. They allow Baden-Württemberg to be connected to distant power generation centres, making them essential for the security of supply of the TransnetBW control area.

MULTI-TERMINAL-HVDC
Today's HVDC-links are mainly designed as point-to-point connections. This is due to the technical challenge of switching off direct current, which is a substantially needed development for fully meshed DC-grids. Multi-terminal links represent an intermediate state with very few, but more than two directly connected converters.

The German HVDC reference grid consists of ten connections within four corridors in a north-south-direction. Three connections end in Baden-Württemberg or close to it, three in Bavaria, three in North-Rhine-Westphalia, and one in Mecklenburg-Vorpommern. Some of them are designed as **multi-terminal HVDC-links**, which adds flexibility through intermediate stations. As per law, all but one will be realised as underground cable. Usually, the connections have a rating of 2 GW, and the use of 525 kV HVDC cable technology is planned. Furthermore, several HVDC onshore and offshore interconnectors are planned or already in operation. These are also part of the reference grid but not shown in Figure 57. The connections shown illustrate the reference grid, but do not represent the planned routes.

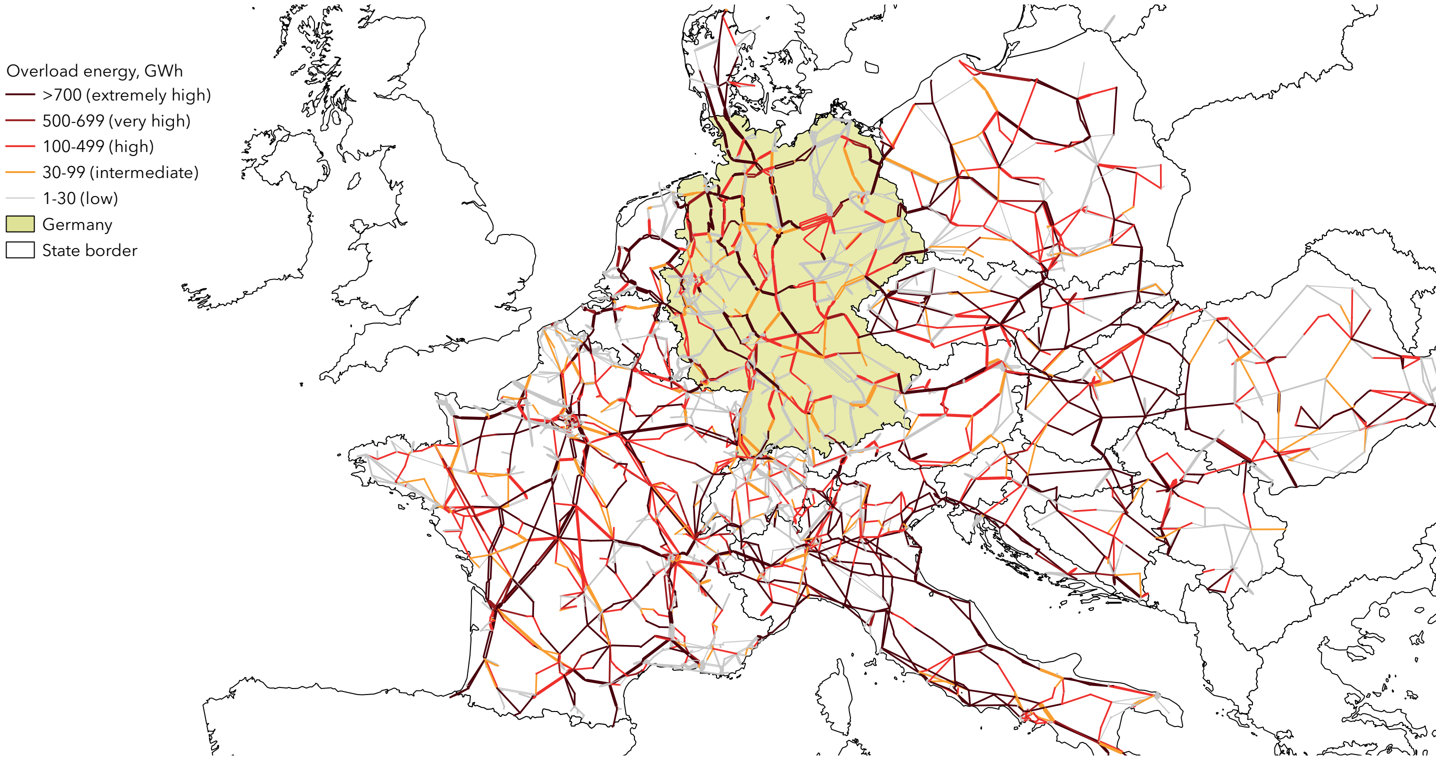
FIGURE 57:
HVDC Reference grid according to the German NEP 2021.



OVERLOAD ENERGY
The overload energy is calculated for each individual circuit from the sum of the hourly power that cannot be transmitted in the (n-1) case due to an overload.

Utilisation of the extra-high voltage grid
To evaluate grid capacity, non-transportable energy (**overload energy (OLE)**) is determined in the (n-1) case. A circuit with a high value of OLE is often overloaded to a large extent. Circuits that are less frequently overloaded have a lower value. Figure 58 shows the circuits in the reference grid with their respective overload energy in the year under review. HVDC connections are not shown, as these do not register any overloads due to their controllability.

FIGURE 58:
Overload energy (non-transportable energy) in (n-1) case in the reference grid, GM scenario, 2050.

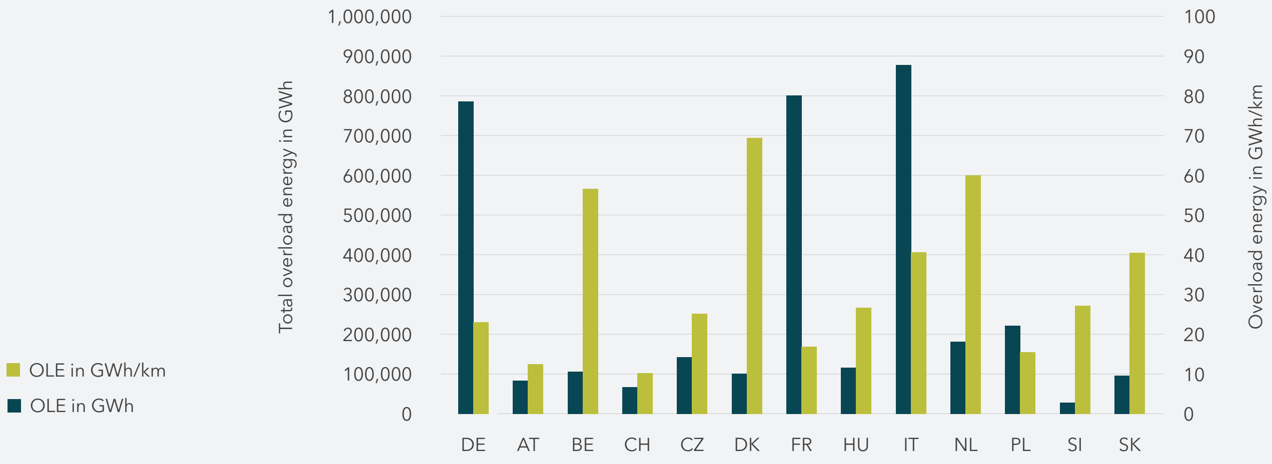


The figure provides an overview of critical overloaded sections or regions in the transmission grid. As the figure shows, the grid infrastructure planned in the reference grid is not sufficient to meet the large transmission requirements of the scenario for 2050 in any country. Italy, for example, has substantial congestions due to high energy flows between the northern and southern part of the country. In France, there are major congestions from the southwest towards the northeast. These are due to the high PV feed-ins (see Chapter 2.5).

To compare the dimension of overload in the national transmission grids, we standardised OLE values by dividing them by the total length of the corresponding extra-high voltage transmission grid (Figure 59). Since the national transmission grids are modelled in less detail when further away from Germany, only selected countries are shown. It is important to note, however, that OLE is sensitive to the specific grid structure (such as average circuit length) so this only provides a rough comparison.

To use a common data base, the grid data are derived from the ENTSO-E factsheet 2018 (ENTSO-E, 2019). Hence, grid projects that were put into operation since then and projects planned until 2050 are not included. Nevertheless, the figure suggests the additional transmission demand in the scenario under consideration.

FIGURE 59:
Standardised overload energy for selected countries, GM scenario, 2050.



As Figure 59 shows, the standardised OLE differs significantly between the countries. While the absolute OLE is highest in countries with a long transmission grid, like Germany, France and Italy, the standardised OLE paints a different picture. Especially the wind dominated North Sea coastal countries such as Belgium, Denmark or the Netherlands are faced with high relative grid congestions. This is also the case for PV-dominated countries such as Slovenia and Slovakia, which are faced with transits due to their location between central Europe and PV-dominated Eastern Europe and the Balkan countries. Italy, as a PV-dominated and partly importing country, also has very high OLE values. Here, a significantly higher transport between the load centres in the south and northern Italy is expected. Also, it can be seen in Figure 58 that even in countries with a lower average standardised OLE there are routes that need substantial reinforcements. For example, the axis in an east-west direction in Austria, or the north-south direction to Spain in France are such routes. The high variability and geographical distribution of renewable power generation plants and consumers lead to large-scale overloads in all countries.

3.1.3 GRID UTILISATION IN GERMANY

This is also the case for Germany. Firstly, although the standardised OLE is in the middle range, it indicates a significant need for grid enhancements. Secondly, it must be considered that the German reference grid includes all measures identified in the last German NEP 2021 (2035).

Figure 60 provides a closer look at the drivers for additional transmission demand in Germany until 2050. It shows the electricity demand and generation from renewable energy sources (wind and photovoltaics) in regions in Germany for the year 2050.

FIGURE 60:
Renewable generation and demand for electricity in different regions in Germany (annual quantities), GM scenario, 2050.

- 🟦 Wind energy offshore
- 🟦 Wind energy onshore
- 🟨 Photovoltaics
- 🟥 Electricity demand incl. PtG

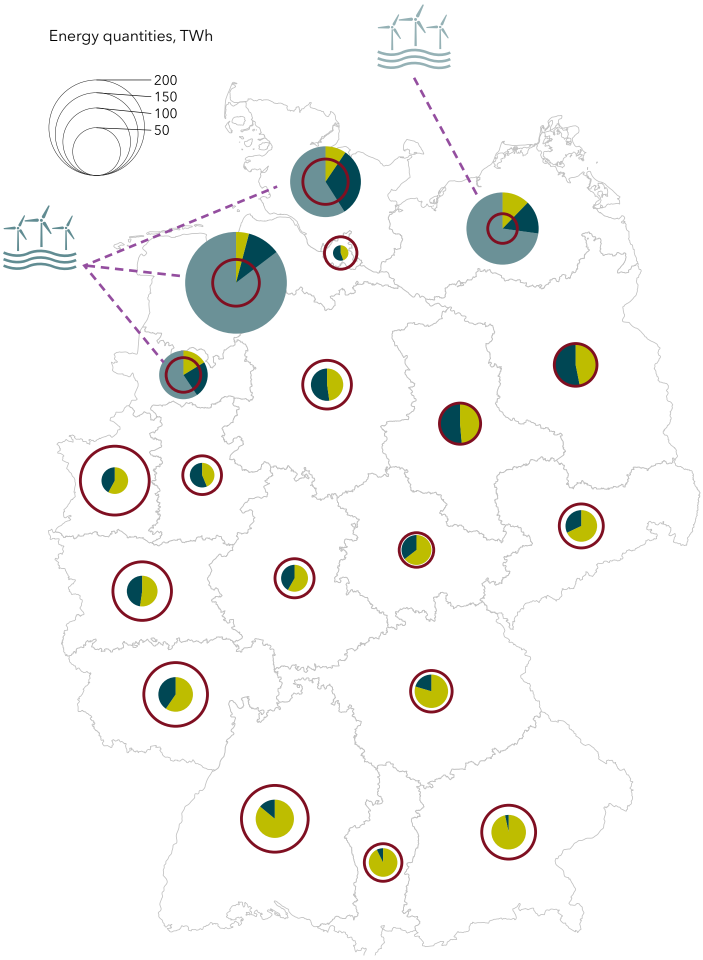


Figure 60 illustrates that, due to the high potential for the expansion of wind energy in the North Sea, the feed-in considerably exceeds the regional demand, especially in Lower Saxony and Schleswig-Holstein. These regions are particularly suitable for the localisation of electrolysers to store the surplus renewable energy and thus reduce the need for grid extension (see Chapter 2.5). The demand shown in Figure 60 includes the demand of power-to-X facilities.

In contrast, the west of Germany and the southern states of Bavaria and Baden-Württemberg have a large electricity deficit. This results in a very large transmission requirement from northwest to west and south Germany, which leads to widespread critical overloads in the electricity grid. Moreover, the electricity deficit varies significantly over time. The large installed capacity of 300 GW photovoltaics in Germany also results in a renewable surplus in the south, but only in sunny daytime hours. For this reason, a few power-to-X facilities are also located in the south, and power flows from south to north or west can also result in overloading of the transmission grid.

These explanations are not only applicable to overloads in the German transmission grid, but also to those in other countries with large coastal areas and remote load centres, such as France. As shown in Figure 58, it is not possible to transport and distribute electricity from renewable energies in Germany without reinforcing the transmission grid.

Evaluation of selected power flow situations

To gain a better understanding of the utilisation of the German transmission grid and develop appropriate countermeasures, we evaluated the effects of characteristic power demand and power generation situations on grid utilisation. Critical situations were identified based on a comparison of electricity generation from renewable energies, electricity demand and cross border power exchanges in Germany. The following results are the maximum utilisation of power circuits in the (n-1) case.

Situation 1: Strong wind and high load situation with north-south transit flows in January 2050, in the evening

TABLE 3:
Strong wind and high load situation with north-south transit flows, GM scenario, January 2050 evening.

P_{MAX}
Maximum power generation or demand for electricity in 2050 – to be distinguished from installed capacity.

Key figures	Power	P/P_{MAX}
DE offshore wind, feed-in	58.0 GW	100%
DE onshore wind, feed-in	106.7 GW	98%
DE photovoltaics, feed-in	0.0 GW	0%
DE electricity demand	172.4 GW	71%

FREQUENCY OF THE STRONG WIND AND HIGH LOAD SITUATION
In more than 450 hours of the year 2050, mainly in the winter months, similar strong wind and high load situations will occur, resulting in corresponding extreme situations for the transmission grid.

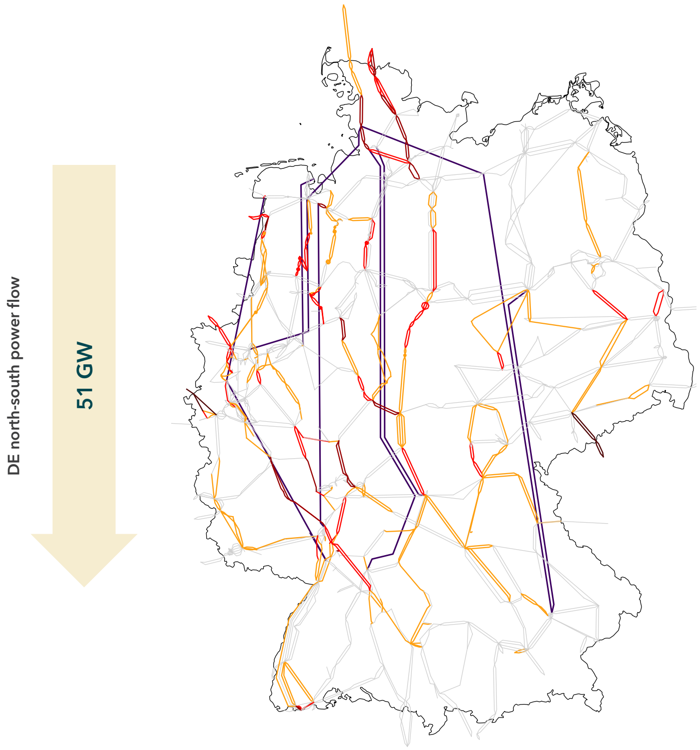
In this **situation**, the feed-in from offshore wind power plants in the coastal regions of Poland, Germany, Denmark, the Netherlands, and north-east France reaches the maximum values. In Germany, the maximum power generated by offshore wind energy, amounting to 58.0 GW, is reached. At the same time, the combination of high electricity demand and extremely low regional electricity generation by photovoltaics leads to an extreme shortfall of electricity in southern countries such as Spain and Italy. Hence, there is a strong need for transporting surplus energy in the north-south direction.

The resulting utilisation of the German transmission grid in the (n-1) case can be seen in Figure 61.

FIGURE 61:
Utilisation of the extra-high voltage grid in (n-1) case in the reference grid in the strong wind and high load situation with north-south transit flows, GM scenario, January 2050 evening.

Utilisation in (n-1) case in %
- — >260
- — 180-260
- — 140-180
- — 105-140
- — 0-105

- — HVDC (controllable)
- ☐ State border



As shown in Figure 61, the high transport demand causes congestion on circuits in a north-south direction. In addition to the internal power flows from the connection points of offshore wind to the load centres in the west and south of Germany, there are significant imports on the northern borders of Germany. Here, Germany imports 35.5 GW in total. Over 90% of this is provided by neighbouring coastal countries: Denmark, the Netherlands, Poland, and Great Britain. As electricity generation and total demand in Germany are well balanced, the 35 GW is transported further to Austria, Switzerland, France, and the Czech Republic, resulting in the strong north-south **transit flows** throughout the German transmission grid.

TRANSIT FLOW
Transit flows are the transmission of electricity through a dedicated grid area. Transits are the balance of imports and exports of this grid area.

Looking at the utilisation of the German transmission grid, these transit flows can be clearly identified. The maximum import from the Netherlands and Denmark, combined with the large export to Switzerland and the Czech Republic, causes 140% overload of the interconnectors on the respective borders. The planned German internal HVDC transmission lines are used to capacity with 20.4 GW. Nevertheless, in this situation the transmission grid lacks sufficient transport capacity, so the north-south and north-west AC transmission lines are overloaded.

Situation 2: Sunny high load situation with south-north transit flow in July 2050, midday

On the other hand, the expansion of generation capacities of photovoltaics in the southern areas of Europe increases the power flows in the opposite direction – from south to north. Especially in the sunny hours with little wind in the north, regional congestions in the transmission grid may occur.

TABLE 4:
Sunny high load situation with south-north transit flow, GM scenario, July 2050 midday.

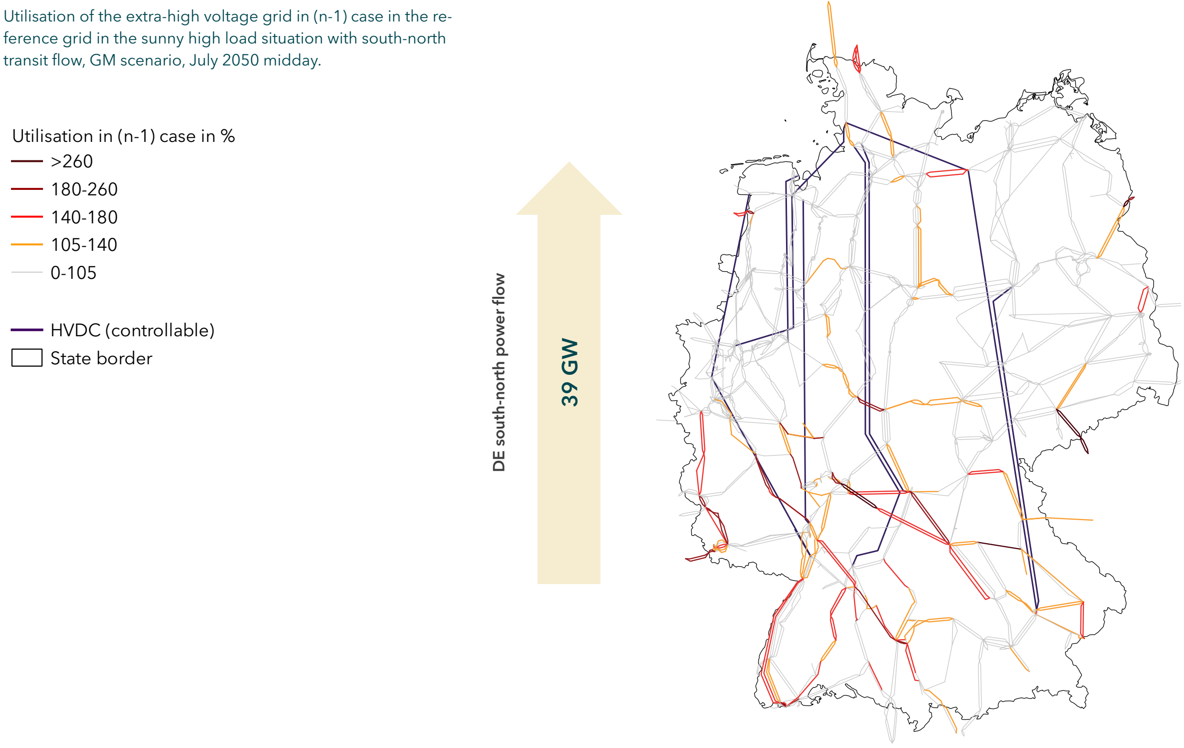
Key figures	**Power**	P/P_{MAX}
DE offshore wind, feed-in	8.3 GW	14%
DE onshore wind, feed-in	2.6 GW	2%
DE photovoltaics, feed-in	156.3 GW	88%
DE electricity demand	178.4 GW	74%

FREQUENCY OF THE SUNNY HIGH LOAD SITUATION
The selected situation is representative for more than 300 hours of the year 2050.

In the considered **situation**, due to the high level of solar radiation, the total generation in France, Italy, Austria and in the Balkan region exceeds the total demand for electricity. This coincides with a deficit of electricity in the Netherlands, Germany, Poland and the Scandinavian countries because of high demand and low wind power generation. Looking at the frequency of this situation during the year, we can see that this characteristic power demand and power generation pattern also occurs in spring and autumn, not only in summer.

As a result, in this situation Germany imports a total 42.6 GW of power from France, Switzerland, Austria, and the Czech Republic. 31.4 GW are transit flows through Germany to the northern borders. The congestions that results can be seen in Figure 62 below.

FIGURE 62:
Utilisation of the extra-high voltage grid in (n-1) case in the reference grid in the sunny high load situation with south-north transit flow, GM scenario, July 2050 midday.



Compared to the high wind situation, line utilisation in the southern states of Bavaria and Baden-Württemberg is more critical in the low wind situation. The AC lines from the southern borders towards load centres in North Rhine Westphalia, Hesse and Rhineland Palatinate are extremely overloaded. In the northern part of Germany, only single overloaded AC circuits occur. Also in this case, a major role is played by the planned internal HVDC transmission links, which overlay the AC transmission grid to relieve widespread congestions.

Situation 3:
Low RES generation with west-east transit flow in July 2050, early morning

The following is an overview of changes in the direction of power flows across Europe when there is no extreme generation from wind power plants or photovoltaics.

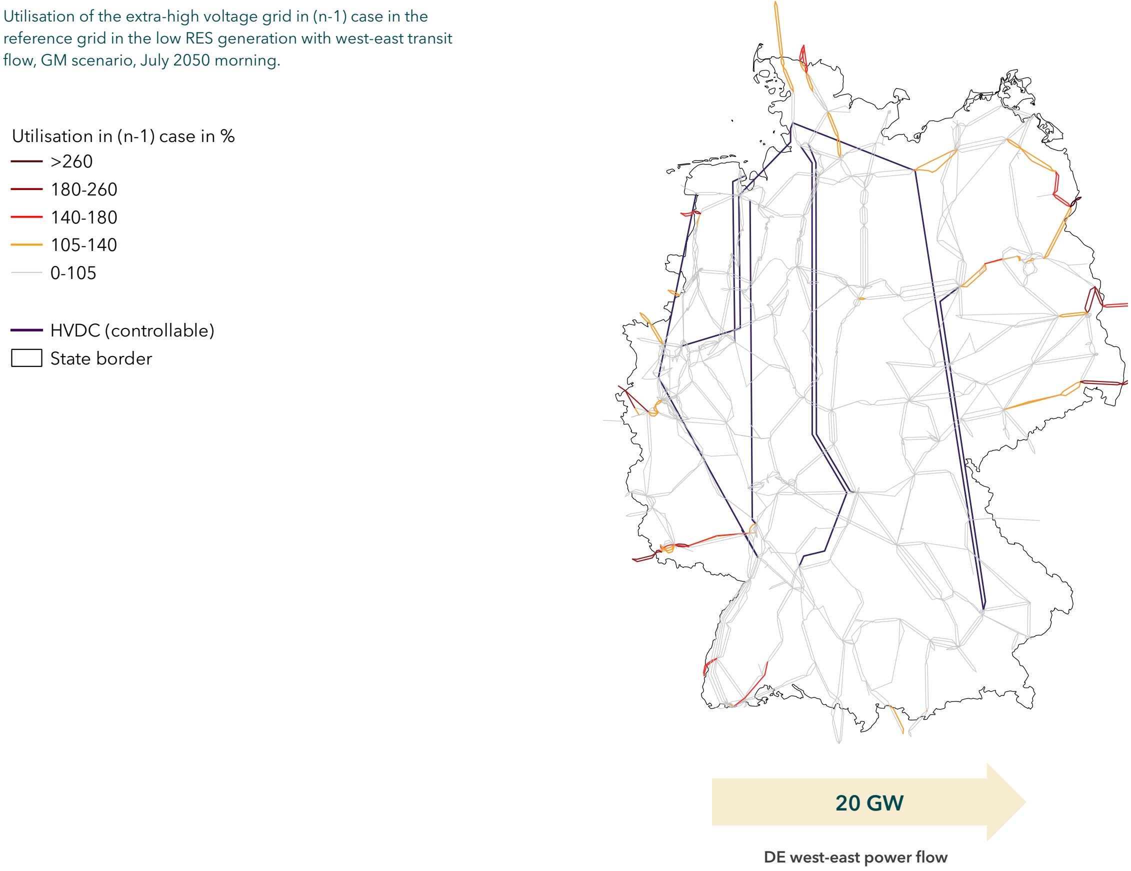
TABLE 5:
Low RES generation with west-east transit flow, GM scenario, July 2050 morning.

Key figures	Power	P/P_{MAX}
DE offshore wind, feed-in	23.9 GW	41%
DE onshore wind, feed-in	22.1 GW	20%
DE photovoltaics, feed-in	24.8 GW	14%
DE electricity demand	101.3 GW	42%

FREQUENCY OF WEST-EAST OR EAST-WEST TRANSIT FLOW SITUATIONS
The situation with low RES generation and transit flows in the west-east or east-west transit flows is representative for more than 400 hours of the year 2050.

Due to low feed-in from onshore wind power plants and photovoltaics, Germany and some eastern countries such as Poland are highly dependent on imports from other countries. The electricity deficit in Germany amounts to 28.4 GW. In this **situation** the main electricity suppliers are France, Netherlands, Belgium, and Denmark, with over 60 GW generated power from offshore wind power plants. The resulting transport demand in the west-east direction leads to high imports on Germany's western borders and transit flows of 17.6 GW towards Poland. The (n-1)-utilisation of the German transmission grid is shown in Figure 63.

FIGURE 63:
Utilisation of the extra-high voltage grid in (n-1) case in the reference grid in the low RES generation with west-east transit flow, GM scenario, July 2050 morning.



The line utilisation in the German transmission grid is much less critical in this situation compared to the above situations of high north-south transit flows. As a result of the high cross-border flows, the main critical congestions occur on the lines connecting Germany with the Netherlands, France, Denmark, and Poland. Regarding the interconnectors, this situation shows that the exchange capacities on the German borders in the reference grid are not sufficient for the cross-border exchanges expected in 2050. Since the potential for further AC reinforcements in the existing routes is limited, new cross-border transmission corridors must be evaluated.

It is important to stress that there are a wide variety of other critical situations during the year, resulting in major overloads in the transmission grid. These could not be clearly assigned to one of the described power demand and generation patterns, which only represent a small selection. The analysis of each characteristic situation is crucial for developing appropriate counter-measures on specific transmission lines to reduce grid congestions.

3.1.4 GRID OPTIMISATION

For grid optimisation, several measures were applied as follows:

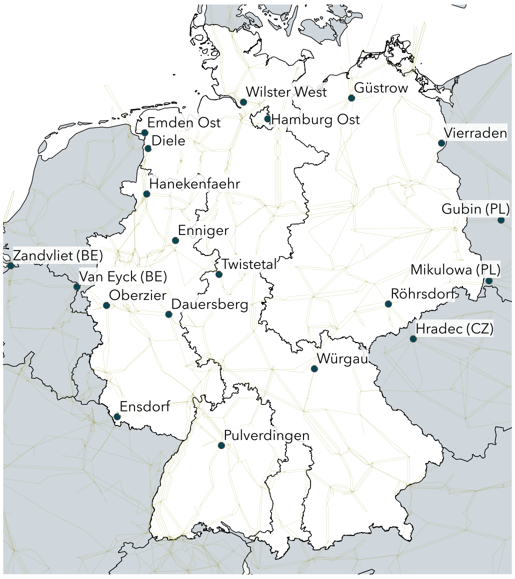
/ Weather-dependent dynamic line rating (DLR): DLR is a method that is also used for planning in the German NEP, further described in the planning principles of the four German TSOs. It is generally applied on the circuits of the German transmission grid, allowing utilisation of up to 150% of the rated current. Generally, within the control area of TransnetBW, the maximum allowed current is limited to 3,600 A to account for voltage stability problems (see Chapter 3.2.2).

/ The possibility of higher utilisation of individual circuits in (n-1) cases with up to 4,000 A is also being examined on a case-by-case basis.

/ Active elements for power flow control in the transmission grid, such as phase-shifting transformers (PST) or controllable HVDC transmission links, provide further optimisation.

While hourly DLR has already been implemented in the planning processes, its implementation in the grid operational processes is much more complex. Therefore, it has not yet been used for interconnectors, neither in planning nor in operational processes. Since DLR is an effective means of relieving grid congestions, we assumed this optimisation measure to be in operation in 2050, not only within the German grid but also on the interconnectors from Baden-Württemberg to Austria, France, and Switzerland.

FIGURE 64:
Locations of Phase Shifting Transformers included in the study.

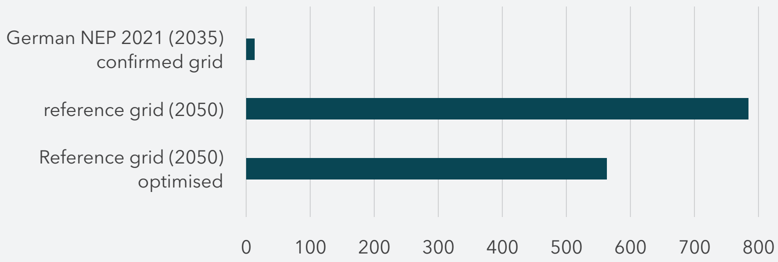


The OLE calculation can also depict the degree of overload in national transmission grids, for example by comparing total OLE to the corresponding value in the national development plan. Doing so for Germany, we see an immense increase from 19 TWh (confirmed grid in the German NEP 2021) to 785 TWh (reference grid 2050) (see Figure 65). This grid shows heavy overloads when confronted with the scenario for 2050 – highlighting the need for comprehensive grid extensions. The length of the German extra-high voltage AC-reference grid is approximately 36,000 km, of which around 55% shows unacceptable grid congestions, particularly in the north-south direction.

Figure 64 shows all PST that are used to control the power flows within the German grid on interconnectors and to reduce loop flows through neighbouring countries. Together with the controllable HVDC links of the reference grid they supply a huge potential of shifting power flows from overloaded circuits to reduce congestions. If applied to the congestions in the reference grid, OLE is reduced by around 25% without additional grid extension (Figure 65). However, this approach is only reasonable if there are circuits situated nearby with free capacity. Another disadvantage in the long run is that this shift means a detour for the power flow, resulting in higher grid losses.

FIGURE 65:
Overload energy in the German transmission grid after optimising power-flows, German NEP 2021 and GM scenario.

OVERLOAD ENERGY IN TWH



3.1.5 HVDC MEASURES FOR 2050

The aim of the grid analysis is to develop long-term grid concepts to reduce grid congestions efficiently and economically, which are expected because of changes in the energy system. In the future, the energy supply in Baden-Württemberg will increasingly depend on imports from other German states, as well as from other European countries. Located in Europe's centre, Baden-Württemberg is in a strategic position to ensure security of supply by linking itself to regions of high wind as well as high solar potential and the Alpine region. Power flows not only transit other states and countries on their way to Baden-Württemberg, but also transit through this state. This is a contribution to a secure and cost-efficient energy supply for Baden-Württemberg, Germany, and Europe.

These challenges require an efficient electricity grid. However, despite the numerous planned and ongoing enhancements, AC grid expansion measures will reach their technically reasonable limits. It is thus not effective to handle overloads by extending the AC grid only. This is mainly due to the increasing distances between the sources of renewable generation and load centres. As the reference grid's overloads show, further long distance transmission capacity is urgently needed. HVDC technology meets this need in an efficient and targeted manner. The advantages described in Chapter 3.1.2 are likely to become even more significant due to technical improvements. It is expected that increased conductor size and voltage levels will reduce the losses in extruded **HVDC cables** by two thirds until 2050 (ENTSO-E, 2019). Based on this, we assume HVDC cable with a rated voltage of 800 kV and current of 2,300 A to be system tested and ready for operation in 2050. Therefore, the rated power of a standard HVDC link increases to 3.5 GW (deduction of expected losses for inverter and cable included). Following the German grid planning principles, in case of failure the loss of power

EXTRUDED CABLE
In contrast to longer established MI (mass impregnated) cables, the younger technology of extruded cables offers lower weight, higher current carrying capabilities and lower environmental impact, thus making it the preferred technology for underground transmission. It is the most frequently used technology for HVAC and HVDC underground cables in recent transmission links and further development towards higher transmission capabilities and reliability can be expected.

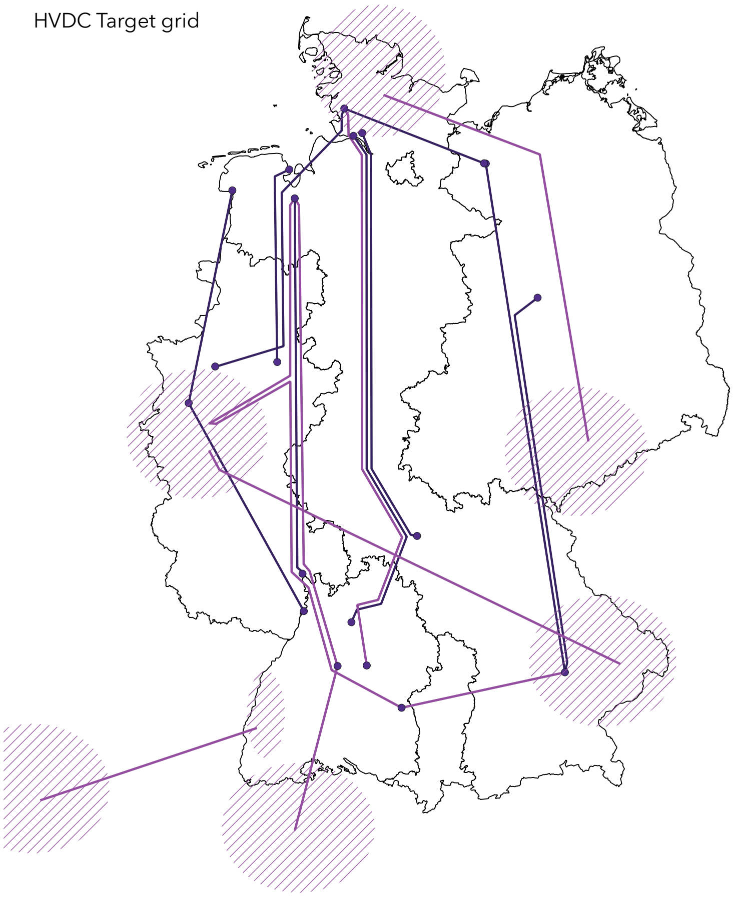
METALLIC RETURN CONDUCTOR

A bipolar HVDC connection consists of two conductors operated at nominal voltage in opposite polarity. A metallic return conductor (MR) is basically a third conductor. If voltage and current ratings are chosen adequately, the HVDC connection can still be operated with full or half the transmission capacity in (n-1) cases (e.g. cable faults) by using the MR. This switching can be realized automatically without interruption in most cases, thus significantly reducing the impact on the power transmission system.

is to be limited to a maximum of 2 GW. This requirement can be met by adding **a metallic return conductor**. By this means, the HVDC link can still be operated with half the power in case of failure on one cable. Thanks to this development, the required area for HVDC cable routes will drop significantly as the power rating increases. According to the current German legal constraints, HVDC links are to be realised as underground cable.

FIGURE 66:
HVDC target grid in 2050.

— 2 GW
— 3.5 GW



NOTE ON SHADED CIRCLES

The shaded circles indicate grid connecting points that are not the responsibility of TransnetBW, as well as points that could not be established for this study due to complex planning and coordination. For the subsequent modelling, provisional locations were determined for the HVDC converters. Shaded circles are deliberately drawn overlapping national borders as, with regard to the overloads seen on the interconnectors, an extension could be reasonable.

Figure 66 shows the additional HVDC links identified in this study to solve grid congestions in the control area of TransnetBW, thus enabling power exchange to adjacent regions. To meet the high transmission demand, several connections must be added linking Baden-Württemberg (load centre and connection to France, Switzerland, and Austria) and north Germany (wind power generation centre and connection to the countries around the North Sea such as Denmark). The suggested projects are also based on existing or planned projects in the German NEP, the TYNDP or previous studies.

Particularly in the north-south direction, these HVDC connections help to relieve congestions significantly. This can be illustrated by looking at the utilisation of the added HVDC link Lower Saxony (Rastede) - Baden-Württemberg (Point south of Stuttgart). In 5,500 of 8,760 hours of the year, the connection is used to capacity for transporting power to the south – or in the opposite direction.

The measures set out in this study are not intended to solve congestions in other TSO control areas. Grid connection points are only set outside Baden-Württemberg when they are part of a link to Baden-Württemberg. However, because of the heavy overloads, it was necessary to anticipate the construction of two possible HVDC links outside Baden-Württemberg to determine countermeasures in the TransnetBW AC grid based on reliable and realistic grid utilisation.
The additional 3.5 GW connections are as follows:

- *Internal German DC links:*
  - Lower Saxony (Rastede) - Baden-Württemberg (Point south of Stuttgart)
  - Schleswig-Holstein (Heide) - Baden-Württemberg (Altbach)
  - Lower Saxony (Rastede) – North-Rhine-Westphalia (Ruhr area) - Baden-Württemberg (Dellmensingen) – Bavaria (East of Munich) (designed as Multi-Terminal HVDC)
- *DC-Interconnector links:*
  - Baden-Württemberg (Rhine Valley) – France (Burgundy)
  - Baden-Württemberg (Point south of Stuttgart) – Switzerland (around Mettlen) (designed as Multi-Terminal HVDC with Rastede – Point south of Stuttgart)
- *Internal German DC links outside Baden-Württemberg:*
  - North-Rhine-Westphalia (border area to the Netherlands) - Bavaria (border area to Austria)
  - Schleswig-Holstein (border area to Denmark) – Saxony (border area to Czech Republic)

NOTE ON LINKS OUTSIDE BADEN-WÜRTTEMBERG
The aim of the study was not to plan measures outside the TransnetBW area, but a meaningful optimisation of the grid utilisation and definition of a target grid for TransnetBW is only reasonable if there are no excessive congestions in the rest of the German grid.

The total HVDC capacity of the converter stations in Baden-Württemberg, including the capacity of the two confirmed connections Ultranet and SuedLink, amounts to 18 GW. It should be noted that the total capacity of cables to and from Baden-Württemberg is higher, but due to the installation of the multi-terminal converters, the power is limited to the input and output capacity of the specific converter station.

Considerations for future developments and challenges
HVDC technology is likely to gain increasing ground due to the high utilisation of the AC grid and the limited suitability of AC lines for long-distance transmission. Furthermore, it offers the controllability of power flows, which additionally helps to reduce overloads, as Chapter 3.1.4 has shown.

The number of currently planned HVDC connections in the European transmission grid illustrates that the HVDC overlay grid is not a future possibility, but already taking shape. However, national and international technical and regulatory hurdles must be overcome to form a European overlay grid and to benefit from it. Support for research and development and pilot projects is crucial in the process.

Today's HVDC links are mainly designed as point-to-point connections. Technical challenges involve the development of all equipment needed to establish a fully meshed HVDC grid. Even though semi-meshed structures such as multi-terminal connections are already possible, many steps are needed until equipment such as DC circuit breakers are fully system tested and ready for widespread use. Another important aspect is to already ensure interoperability today, to account for the future interconnection between existing point-to-point connections. If these requirements are met, a fully meshed HVDC grid offers several advantages:

/ By combining two point-to-point connections one converter less is needed, thus reducing converter costs.

/ In case of a failure on a connection, this part can be switched off while power flows through other connections, unless their transmission capacity is exhausted.
/ In conjunction with its controllability, a meshed HVDC grid can deal with strongly fluctuating power flows and bypass grid congestions.

Existing regulatory challenges involve a continuous common European grid planning as well as difficulties by establishing a HVDC offshore grid. As this study demonstrates, an economically optimised European energy system comes with longer transmission distances between power plants and consumers. This requires efficient European grid planning processes with a strong mandate by national stakeholders. Regarding a HVDC offshore grid, the objective is to establish a regulatory framework that allows for the simultaneous use and development of offshore cables as grid connections of offshore wind farms and interconnectors. Such a framework could offer the following benefits:

/ Offshore wind farms are usually connected via one exclusive grid connection. In case of a failure the farm must be switched off. For wind farms near national borders, the most efficient way to establish a redundant connection could be a link to a neighbouring foreign farm.

/ The connection of offshore wind farms enables the realisation of synergy effects, as less connections to the onshore grid are needed. This is due to the different wind infeed within the area covered.

/ By connecting offshore wind farms and using connections as interconnectors, power flows can be optimised to reduce onshore grid congestions and improve European prosperity.

/ As Chapter 3.1.2 and Chapter 3.1.3 outline, more interconnectors are needed. Particularly the North Sea coastal countries are faced with heavy overloads. Accounting for public acceptance, the realisation of offshore interconnectors by connecting offshore wind farms could help to meet the additional transmission demand. However, particularly in the Wadden Sea, the environmental impacts must be considered.

3.1.6 HVAC MEASURES FOR 2050

To develop the 2050 grid, the addition of several Gigawatts of power flow controlling HVDC transmission links, defined in Section 3.1.5, will be combined with regional AC grid expansion measures in Baden-Württemberg.

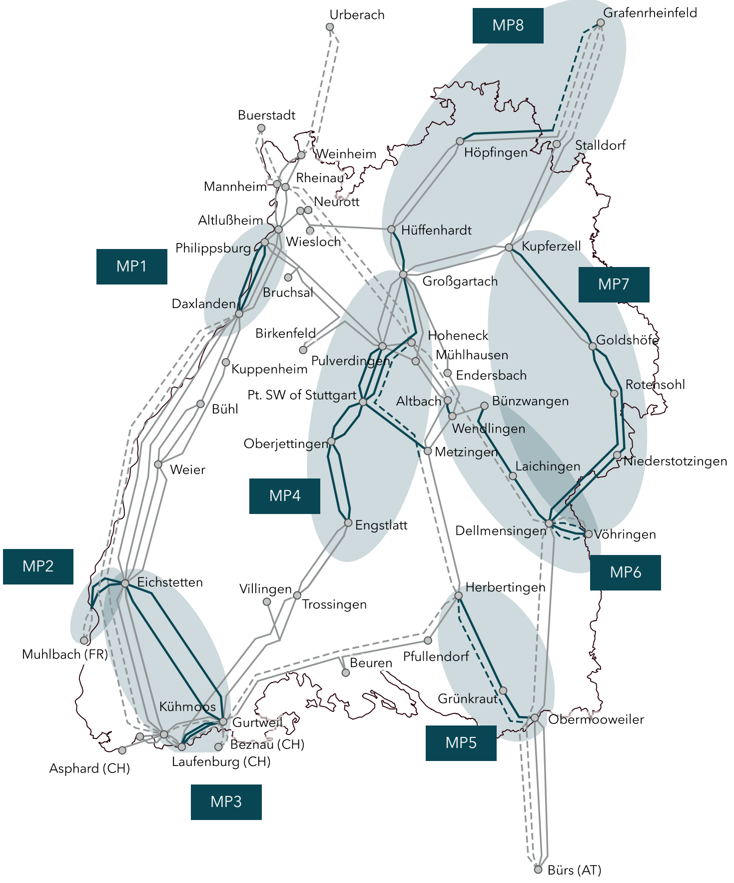
In the following, the additional AC measures to cope with expected congestions in the TransnetBW electricity grid are presented. Packages of measures are regionally clustered. It is assumed that the planning principles of the four German transmission system operators will be observed, as well as the NOVA principle explained above. Therefore, the expansion measures were identified after grid optimisation, using planned power flow controlling equipment (PSTs, HVDCs), evaluating topological measures and considering weather-dependent DLR. As described in Section 3.1.4, all congestions within substations are assumed to be relieved until 2050. Hence, possible necessary enhancements in the substations or even additional switchgears are not further defined in the packages of measures.

Electricity lines in the extra-high voltage grid in Baden-Württemberg, which are not owned by TransnetBW, are considered when defining the target grid. Critical congestions on these electrical elements will be relieved using grid optimisation measures or reactivating projects from the German NEP.

Overload energy is evaluated to assess critical overloads in the grid. In the case of minor overloads (overload energy less than 30 GWh per year and circuit), it is assumed that these overloads can be relieved sensibly by means of redispatch – curbing power plant output. This threshold is based on the criteria used by the German NRA (Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen, 2022). It should also be noted that changes in neighbouring grid structures can weaken, shift, or increase the overloads shown here. For this reason, alternative solutions are being developed for these packages of measures. These alternative solutions are not fully presented in this study and will only be applied once meaningful long-term concepts have been developed together with neighbouring transmission system operators. This section provides an overview of the measures identified in this study for the target grid in 2050. The proposed measures are not intended to be the only possible solution for the year 2050. Rather we propose a solution which, under the assumptions made, meets the expected requirements of the energy system in 2050 and is appropriate and sensible from a grid planning perspective.

Figure 67 provides an overview of the identified packages of measures (MP) in Baden-Württemberg.

FIGURE 67:
Overview of the identified packages of measures in Baden-Württemberg (AC).



/ MP1: NORTHERN BADEN

MP1-01: Daxlanden – Philippsburg

To reduce critical overload on the lines leading to the well-developed route along the Rhine, reinforcement of line conductors of the existing 380 kV circuits between Daxlanden and Philippsburg is necessary to allow for operation with 4,000 A. Application of DLR is an optimisation measure to further reduce overload energy. Measures will be necessary on both conductors, each with a length of 33 km.

/ MP2: AC INTERCONNECTOR TO FRANCE

MP2-01: Eichstetten - Muhlbach (FR)
To meet the high transmission demand between TransnetBW and France, we suggest a new HVDC connection, as described in 3.1.5, which is capable of transporting most of the energy. The existing 380 kV interconnector from Eichstetten to Muhlbach (FR) can be relieved of most of the critical overload energy by application of DLR and operation with 4,000 A.

As can be seen in Figure 68, some overload energy on the interconnector remains. Since power-flows in the border triangle are sensitive to grid extensions and power-flow control measures of the neighbouring TSO, this remaining challenge should be addressed in multilateral grid planning studies, which will be carried out for this region soon.

/ MP3: UPPER RHINE

The circuits in this area connect the grids of Germany, France, and Switzerland, thus forming an important transit axis that transports energy from the north towards Switzerland and Italy. In critical situations, the expected high north-south power flows cause the overload of existing circuits. On the 380 kV interconnectors to Switzerland, DLR is used for grid optimisation, which increases transmission capacity between TransnetBW, Amprion and the Swiss control area.

MP3-01: Eichstetten – Gurtweil
The measure consists of the upgrade of the voltage level between Eichstetten and Gurtweil substations from 220 kV to 380 kV. This enhancement, which requires new towers, will significantly increase transmission capacity in this area and thus reduce overload energy. The length of each new 380 kV circuit amounts to 72 km each. Measure MP3-01 was part of MP6 in the previous Electricity Grid 2050 study.

MP3-02: Gurtweil – Laufenburg (CH)
The voltage level of circuits between Gurtweil and Laufenburg (CH) substations is upgraded from 220 kV to 380 kV. New transmission circuits and new towers are required on a length of 22 km. DLR is used for grid optimisation. Measure MP3-02 was part of MP6 in the previous Electricity Grid 2050 study.

/ MP4: CENTRAL NECKAR REGION

The Middle Neckar region is characterised by a very high demand for energy. The circuits in this area are mainly used to supply the Stuttgart area and to transit electrical energy from the northeast to the south. The existing circuits from the substation in Großgartach (Leingarten) to the south and further into the Middle Neckar region lack the capacity for the expected transmission tasks, resulting in overloads in critical grid situations.

The Western bypass is a part of the first line commissioned in 1930 connecting the Rhenish coal-mining district with the Alpine hydro-storages. In a joint grid enhancement measure, TransnetBW and Amprion intend to replace the 220 kV line with a more powerful 380 kV line to reduce overloads along the Neckar valley. This will strengthen the grid to the south and west of Stuttgart, thus diverting power flows. In combination with another line replacement, the measure spans from Großgartach in the north to Hoheneck, further to a new substation "Point Southwest of Stuttgart" and turning east to join the existing 380 kV line at Point Rommelsbach and finally the substation at Metzingen. Below, only the resulting topology in TransnetBW's grid is described in detail.

As the suggested HVDC connections to Rastede and Switzerland are provisionally connected to the substation of Point Southwest of Stuttgart, an enhanced grid near the DC converters helps to distribute incoming energy.

MP4-01: Großgartach – Hoheneck
An existing 220 kV line is replaced by a 380 kV line over 65 km, allowing for a new circuit from Großgartach to around Hoheneck. The measure is a modification of measure P306 from Großgartach to Pulverdingen in the German NEP 2021.

MP4-02: Western bypass, Hoheneck – Point Southwest of Stuttgart
The first part of the Western bypass is the enhancement of a 29 km line between Hoheneck and Point Southwest of Stuttgart with two new 380 kV circuits. In combination with MP3-01, the line owned by TransnetBW is used for a direct connection between the substations of Großgartach and Point Southwest of Stuttgart.

MP4-03: Western bypass, Point Southwest of Stuttgart - Point Rommelsbach – Metzingen
In the second section, replacement of the existing line over a length of 62 km enables a new 380 kV circuit from Point Southwest of Stuttgart to Point Rommelsbach. An additional 3 km of a new 380 kV parallel line may be needed to connect the circuit to the substation at Metzingen, thus enabling an important 380 kV connection in the east-west direction south of Stuttgart.

MP4-04: Pulverdingen – Point Southwest of Stuttgart
Both circuits between Pulverdingen and Point Southwest of Stuttgart – originally leading from Pulverdingen to Oberjettingen – will be replaced with conductors allowing for operation with 3,600 A. The exchange of conductors will take place on 28 km of each line.

MP4-05: Point Southwest of Stuttgart – Oberjettingen
Both circuits between Pt. SW of Stuttgart and Oberjettingen – originally leading from Pulverdingen to Oberjettingen – will be replaced with conductors allowing for operation with 4,000 A. The exchange of conductors will take place on 18 km of each line.

MP4-06: Oberjettingen – Engstlatt
Both circuits between Oberjettingen and Engstlatt will be replaced with conductors allowing for operation with 4,000 A. The exchange of conductors will take place on 34 km of each line.

/ MP5: UPPER SWABIA

MP5-01: Herbertingen – Grünkraut
To prepare the connections to the Austrian region of Vorarlberg, which has numerous pumped storage power plants, for the expected transmission demand in 2050, new circuits capable of 3,600 A and corresponding towers between Herbertingen and Grünkraut must be installed.

During TransnetBW grid enhancement on this route, the parallel 220 kV circuit, operated by Amprion, could also be upgraded to 380 kV. This measure corresponds to a proposal in a former German NEP, P52 M94a.

MP5-02: Grünkraut – Point Neuravensburg – Obermooweiler
Even though the southern part of the route from Herbertingen to Obermooweiler features slightly higher transmission capacity, this circuit should also be replaced on new towers, allowing for operation with 3,600 A due to high demand. The distance between Herbertingen and Grünkraut is 41 km, while Grünkraut to Obermooweiler amounts to another 18 km. Grid optimisation with DLR on all circuits leading to Austria is also assumed.

/ MP6: ACROSS THE ALB TO ULM

Power flow analysis for the year 2050, applied to selected situations in 3.1.2 reveals diagonal flows through Baden-Württemberg. Together with the suggested HVDC links and the corresponding provisionally placed DC converters connected to the substation at Dellmensingen, the transmission circuits leading from the Middle Neckar Region to Dellmensingen and Bavarian Swabia become more significant.

MP6-01: Altbach – Wendlingen

The transmission capacity on the circuit from Altbach to Wendlingen can be increased by replacing the conductors allowing for operation with 4,000 A. It can further be optimised by applying DLR.

MP6-02: Bünzwangen – Laichingen

The existing circuits between Bünzwangen and Laichingen substations must be replaced with conductors that are capable of 3,600 A. The distance from Bünzwangen to Laichingen is 46 km.

MP6-03: Laichingen – Dellmensingen

The existing circuits between Laichingen and Dellmensingen substations must be replaced with conductors that are capable of 3,600 A. The length of these lines amounts to 24 km.

MP6-04: Interconnector to Vöhringen (Amprion)

To ensure the secure long-term transport of the power infeed from the new HVDC transmission link, an additional circuit is required between the substations at Dellmensingen and Vöhringen. This will be realised by a new construction in the existing route and installation of an additional circuit. A length of 17 km, the same as the other interconnectors can be assumed.

/ MP7: EASTERN ALB

The extra-high voltage grid in northeast Baden-Württemberg between Dellmensingen and Kupferzell, also known as the "East Ring", is a main transit axis for north-south-power flows. It provides a parallel route to the highly utilised Middle Neckar Region. Furthermore, it is connected to the grid nodes with direct connection to the neighbouring control areas, where there is high demand for energy exchange in 2050.

Several of the circuits with rather weak transmission capacity will have to be enhanced. These measures are summarised in measure package MP7. Measures in MP7 have already been identified as measures in the German NEP 2021, as P304 and P305.

MP7-01: Kupferzell – Goldshöfe

An additional 55 km circuit between Kupferzell and Goldshöfe needs to be installed on existing towers. Through this measure, two parallel circuits from Kupferzell to Dellmensingen are created.

MP7-02: Goldshöfe – Rotensohl / Goldshöfe - Niederstotzingen

To provide higher transmission capacity, existing 20 km and 47 km circuits from Goldshöfe are to be replaced with lines capable of 3,600 A, which also require new towers.

MP7-03: Niederstotzingen - Dellmensingen / Rotensohl – Dellmensingen

The 380 kV circuits leading to Dellmensingen with lengths of 41 km and 67 km are to be replaced with lines capable of 3,600 A, which also require new towers.

/ MP8: NORTHERN WÜRTTEMBERG AND FRANCONIA

One of the most important transit and transport axes for supplying the urban and industrial centre around Stuttgart is in the northeast of Baden-Württemberg. Due to higher north-south power flows via the Grafenrheinfeld to Großgartach (Leingarten), further congestions are expected on these circuits in 2050 despite the implementation of the measures planned in the German NEP 2021 (P48).

MP8-01: Großgartach – Hüffenhardt
Between Großgartach and Hüffenhardt, an additional 380 kV circuit is required. The additional circuit will be 19 km long. This measure was identified in German NEP 2021 as P303, but not permitted.

MP8-02: Höpfingen – Grafenrheinfeld (TenneT)
From Grafenrheinfeld via Rittershausen to Höpfingen, with a length of 42 km, the installation of a new circuit on the existing transmission towers will be required to realise an additional 380 kV circuit. The measure was identified as P332 in German NEP 2021, but has not been approved yet.

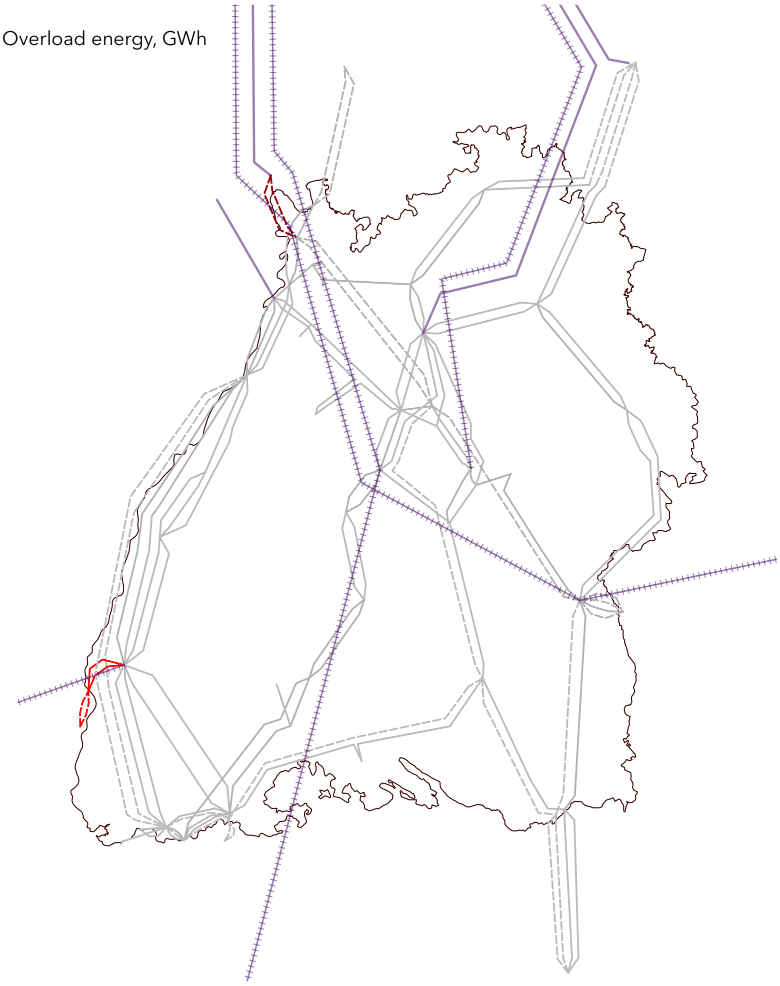
3.1.7 TARGET GRID

After implementation of all packages of measures, no critical overloads in the TransnetBW grid remain, as shown in Figure 68, except for the TransnetBW-France AC interconnector (see MP2).

FIGURE 68:
Overload energy for the target grid of TransnetBW, GM scenario, 2050.

— >700 (extremely high)
— 500-699 (very high)
— 100-499 (high)
— 30-99 (intermediate)
— 1-30 (low)
- - - External circuits

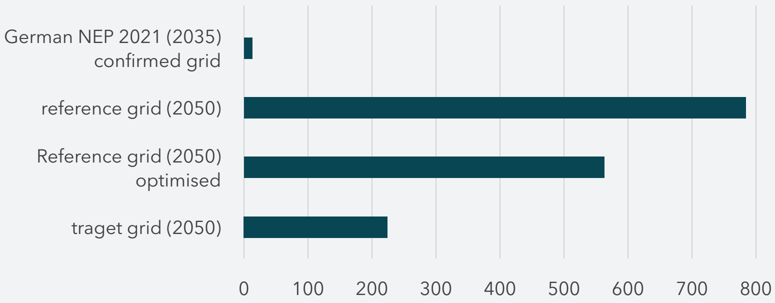
— HVDC (controllable)
┼┼┼ HVDC expansion grid



The target grid for Baden-Württemberg comprises a total HVDC capacity of 14.5 GW to other German states and further HVDC interconnectors to France and Switzerland with 3.5 GW each. All AC measures planned by TransnetBW for 2035 and confirmed in the German NEP 2021 have proven to be necessary in 2050, too. Furthermore, additional 830 kilometres of TransnetBW's extra-high voltage AC grid, and thus over 25% of the transmission circuits, need to be reinforced.

FIGURE 69:
Remaining overload energy in the German transmission grid in consideration of the target grid 2050 for Baden-Württemberg, German NEP 2021 and GM scenario.

OVERLOAD ENERGY IN TWH



The HVDC and AC measures also lead to a significant reduction of overload energy in the German transmission grid of around 60% compared to the optimised reference grid (Figure 69). The focus of this study was to develop a target grid for TransnetBW only. Hence, the remaining congestions within the German transmission grid and on interconnectors and possible countermeasures need to be evaluated by the responsible TSO.

Alternative planning options for the target grid
As transmission system operator, TransnetBW operates and plans the grid to ensure security of supply according to the (n-1) criteria. For this purpose, independent single component outages are evaluated in grid planning and grid operation, ensuring that an outage of electrical equipment does not result in a critical violation of technical limits. In addition, the simultaneous unavailability of several electrical components must be controlled to some extent. In this way, congestions are to be regionally limited to avoid major supra-regional outages. The failure of multiple linkage transmission routes (also called common mode failure) would lead to a simultaneous outage of several circuits.

With the planning of the proposed target grid 2050, the connecting lines between the control areas of TransnetBW (Baden-Württemberg) and TenneT (Bavaria) will be realised by a multiple linkage transmission route with a total of four 380 kV circuits. Thus, a failure of the route would lead to an outage of all four circuits. In certain power flow situations, this could endanger the security of supply in Baden-Württemberg and Germany. For this reason, alternative planning options are being examined for the MP8 package of measures. An additional connector between Baden-Württemberg (Goldshöfe) and Bavaria (Raitersaich) is planned for this purpose. This will relieve the existing transit lines to Bavaria and guarantee a higher system security, avoiding a maximum occupancy of the multiple linkage transmission route.

Since this connector would be a new construction in a new route, an expansion is not reasonable at the current stage. However, possible changes in neighbouring grid structures could increase structural congestion and affect the transport of electricity along the axis between TransnetBW and TenneT. Therefore, the necessity for additional connecting routes depends on the expansion plans of neighbouring transmission system operators.

3.2 OPERABILITY OF THE POWER SYSTEM

To ensure the stable operation of the interconnected power system in 2050, system stability aspects are of utmost importance. Therefore, a short overview of two stability aspects, frequency stability and voltage stability, is given in the following.

3.2.1 FREQUENCY STABILITY ASPECTS

FREQUENCY
Power systems are operated with alternating current (AC) at a certain frequency. The
ENTSO-E Continental Europe Synchronous Area is operated with a nominal frequency of 50 Hz. In general, the frequency within a power system is an indicator of the balance between generation and load. If the frequency drops/rises, it indicates a load higher/lower than the generation.

POWER SYSTEM INERTIA
Power system inertia is the instantaneous active power reserve in the system, today mainly provided by synchronous machines of conventional power plants. In case of an active power imbalance, the inertia defines the rate of change of frequency in the system, until the active power control becomes active.

GRID-FOLLOWING INVERTER
State-of-the-art control concept of inverters connected to the grid (e.g. wind power plants, photovoltaic, STATCOM). The main control target of grid-following inverters is to maximise active power infeed coming from the primary energy source (e.g. wind power).

According to (Kundur, et al., 2004) "Frequency stability refers to the ability of a power system to maintain steady **frequency** following a severe system upset resulting in a significant imbalance between generation and load. It depends on the ability to maintain/restore equilibrium between system generation and load, with minimum unintentional loss of load. Instability that may result occurs in the form of sustained frequency swings leading to tripping of generating units and/or loads."

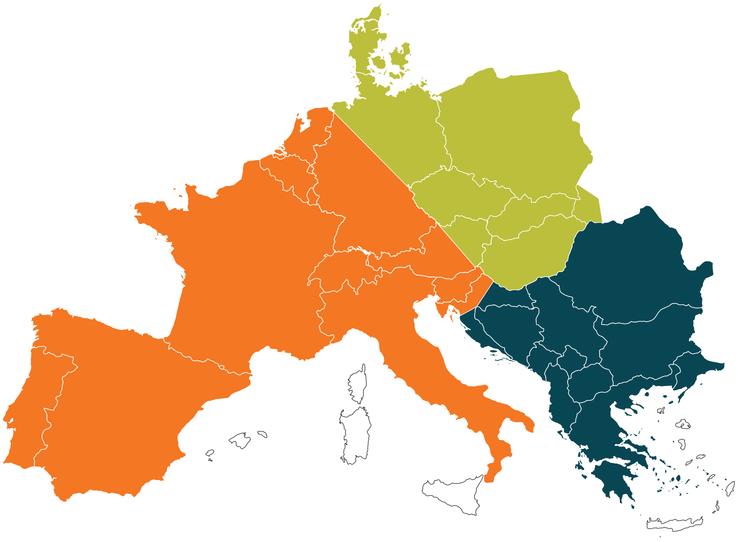
Today, power systems all over the world are affected by decreasing **power system inertia** caused by increasing infeed of non-synchronous renewable generation, in particular wind and photovoltaics, based on **grid-following inverters** . In small synchronous areas temporary low system inertia already affects system stability during normal operation. In contrast, this has not been the case in big synchronous areas like the ENTSO-E Continental Europe Synchronous Area. Low inertia in parts of the synchronous area is not an issue during normal interconnected system operation when active power imbalances typically do not exceed the design incident of 3 GW. However, in case of an unintentional system split dividing the interconnected power system into two or more asynchronous islands, low inertia combined with high active power imbalances (more than the design incident of 3 GW) can have a significant impact on frequency stability due to the resulting high rate of change of frequency (RoCoF).

Thus, system splits are the most severe system disturbances, challenging frequency stability within the ENTSO-E Continental Europe Synchronous Area.

A system split occurs if an incident results in cascade tripping of transmission lines, dividing the interconnected power system into two or more asynchronous islands. The time and location of the split is unpredictable. Nevertheless, typically the risk of a system split increases for a highly loaded AC transmission system with long distance power transmission. In Germany, as part of the Continental Europe Synchronous Area, the transmission capacities from north to south are increasing continuously to satisfy transmission demand, caused by the increasing wind power infeed in the north and market needs. These increasing transmission capacities lead to increasing potential active power imbalances because of a system split.

As shown in Figure 70 a severe system split divided the ENTSO-E Continental Europe Synchronous Area into three separate islands in 2006 (ENTSO-E, 2007). The active power imbalance of the over-frequency island in the northeast (Area 2) amounted to approximately 10 GW. Today, due to the increased transits from north to south, such a system split could result in an active power imbalance of up to approximately 25 GW.

FIGURE 70:
System Split in 2006 (ENTSO-E, 2007)



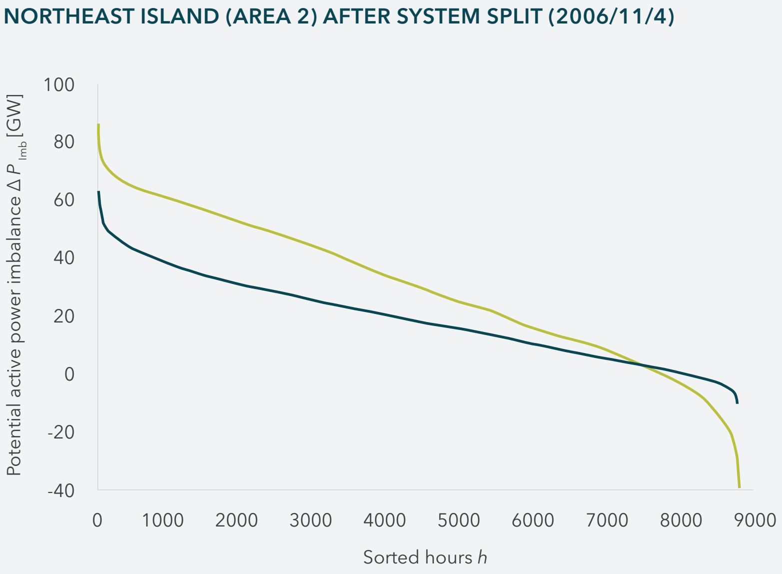
🟧 Area 1 under-frequency

🟩 Area 2 over-frequency

⬛ Area 3 under-frequency

Figure 71 shows the hourly potential active power imbalance ΔP_{Imb} (sorted in descending order), if applying the same system split for 2035 (German grid development plan 2021) and 2050 (this study). It clearly shows that the potential active power imbalance continues to rise significantly.

FIGURE 71:
Potential active power imbalance in 2050 (GM scenario) compared to 2035 (German NEP 2021).



— 2050 (ES2050)

— 2035 (NEP2021 B2035)

In the 2021 German grid development plan, the system needs for frequency stability were determined for the first time (German TSOs, 2021). The main result was the increasing need for system inertia to stay within the permitted frequency range and to limit the rate of change of frequency (RoCoF) in case of severe system splits. The demonstrated increase in potential active power imbalances up to 2050 shows that the system inertia need will not remain the same after 2035 but will increase. These results, once again, underline the urgency to act.

Besides the need for system inertia, more stringent requirements for limited frequency sensitive mode (the main control scheme of the system defence plan) are needed as well as the massive installation of **grid-forming inverters** (instead of the state-of the-art grid-following inverters), to prevent the power system from black out in case of severe system splits.

GRID-FORMING INVERTERS
New control concept of inverters, able to stabilise the power system like synchronous machines. Therefore, the main control target of grid-forming inverters is to react according to the system needs (e.g. provision of inertia).

3.2.2 VOLTAGE STABILITY ASPECTS

Every electrical line connected to alternating voltage produces **reactive power** depending on the current flowing through the line. Only at the **natural power** of the line, no reactive power is consumed. If the transmitted power is lower than the natural power, the transmission line is underexcited and the voltage of the grid increases. However, if the transmitted power is higher than the natural power, the power line is overexcited, which leads to decreasing voltage. To keep the voltage within the given limits and guarantee a stable operation, it is necessary to compensate the reactive power consumption of the power grid.

REACTIVE POWER
Reactive power is the need for energy for the commutation of the electro-magnetic field due to alternating current. This energy cannot be used and is "stored" in the electrical system, which affects the voltage.

NATURAL POWER
At natural power, the inductive (current flowing through a coil with one winding (overhead line)) and the capacitive reactive power (condenser with high voltage at the overhead line and ground on earth) of the line is the same. This is the only bias point of a line with no voltage change over the line. There is no need for reactive compensation.

Due to the change caused by the rapidly increasing infeed of renewable energies, decreasing infeed from synchronous machines and the need for long-distance transportation of electrical power, reactive power compensation is becoming increasingly important. In the past, the synchronous machines compensated the grid in their areas, but in the future the grid will lack compensation in the high transit corridors, due to a shortage of production units with sufficient capacity for reactive power consumption.

Therefore, the high utilisation of power lines leads to a substantial demand for stationary and dynamic overexcited reactive power. In this study, the method for calculating the demand for reactive power in the German grid is based on the German NEP 2021. Depending on the utilisation of lines and transformers, the **stationary need** for reactive power is calculated, based on small areas in Germany. The method is described in the German NEP 2021. For estimating the **dynamic need** for reactive power, the difference in reactive power demand between normal condition and outage events must be considered. Because this study does not focus on demand-actuated grid development, some line congestions remain in the grid (see Chapter 3.1, high overload energy in the German transmission system). These congestions can be handled in the stationary calculation (Chapter 3.1) but not in the special outage calculation to determine the dynamic reactive power demand. Therefore, it is not possible to make a valid estimation of the dynamic need of the system due to outages. Therefore, only a qualitative estimation of dynamic reactive power development can be given.

STATIONARY NEED
The need for reactive power in an electrical system in steady state mode. It can be compensated by devices with no Q(U) control such as inductors or capacitors.

DYNAMIC NEED:
Dynamic need is the need for reactive power in an electrical system due to dynamic (or quasi dynamic) events. This can change slowly over several minutes due to changes in the market (normally at the change of hour) or rapidly due to failures like short circuits. This need must be compensated by devices with Q(U) control such as synchronous machines or STATCOM.

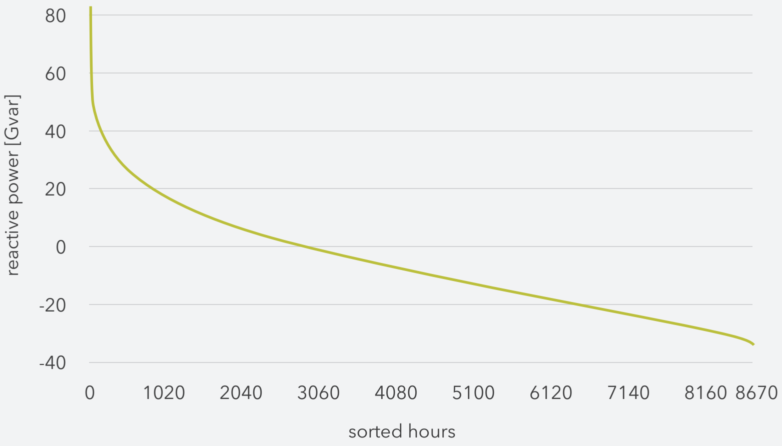
To clarify the outcome of this study, the values are aligned with the results of the German NEP 2021. In Table 6 the maximum demand for stationary reactive power in different use cases is compared for both studies and the whole of Germany.

TABLE 6:
Maximum stationary reactive power demand of the German grid, NEP 2021 and GM scenario.

	Underexcited need [Mvar]	Overexcited need [Mvar]
German NEP 2021 (2035)	30,196	29,980
Energy System 2050	34,461	82,888

Table 6 shows that the stationary underexcited reactive power need is very similar in both scenarios. This is because only a very limited AC grid extension from 2035 to 2050 is considered. Stationary underexcited reactive power depends on the capacitance between line and earth. Therefore, the length of all transmission lines is determined by the need for underexcited reactive power. New AC power lines are only planned for Baden-Württemberg after 2035, with a focus on 2050. For the rest of Germany many new DC lines are planned, but DC lines have no effect on the reactive power demand of the grid. This only leads to slightly increased needs for underexcited reactive power in 2050 compared with 2035. In contrast, the stationary overexcited need in 2050 increases by more than 2.5 times compared to German NEP 2021. This is related to the extreme utilisation of the grid. In some hours, many transmission lines are loaded with 4 kA, which leads to a very high demand for overexcited reactive power.

FIGURE 72:
Stationary reactive power demand of the German grid, GM scenario, 2050.



In Figure 47 the stationary need for reactive power during the whole year simulation is shown in descending order. The sorting of the stationary reactive power illustrates the assumption of the market that there are no grid congestions within a market area. This leads to high transits and thus highly loaded lines during many hours of the year. As a result, the German grid exhibits an overexcited behaviour for over 3000 hours per year.

In Table 7 we take a deeper look into the stationary reactive power demand in Baden-Württemberg (BW). For the analysis, the region served by TransnetBW is divided into three areas, representing the north, the southwest and the southeast.

TABLE 7:
Maximum stationary reactive power demand in the area of TransnetBW, GM scenario, 2050.

		Underexcited need [Mvar]	**Overexcited need [Mvar]**
BW north	German NEP 2021 (2035)	720	1442
	Energy System 2050	879	2063
BW southwest	German NEP 2021	880	653
	Energy System 2050	1002	2142
BW southeast	German NEP 2021	533	551
	Energy System 2050	609	1993

The results for the area served by TransnetBW are very similar to those for the whole of Germany. The stationary overexcited need (right column) increases significantly, whereas there are only slight differences in underexcited need in 2035 and 2050.

Finally, a brief outlook for the development of dynamic reactive power is given below. In this study, no outages and failures in the system were considered for the calculation of dynamic need for reactive power. However, it is obvious that failures with outages in a highly loaded grid will cause a massive voltage drop (see high overload energy in the German transmission system). When 4,000 A are flowing through the grid on several parallel transmission lines, this causes a very high demand for reactive power. If one or two lines are tripping due to a short circuit, the power from those lines commutates to the parallel lines, which are already highly loaded. Because the reactive power demand of transmission lines is proportional to the square of the current flowing through the line, the commutation causes a massive additional need for reactive power. This demand must be compensated quickly by **dynamic devices** to prevent voltage collapse.

DYNAMIC DEVICES
Dynamic devices are devices with a Q(U) controller. These can include synchronous machines, converter from Renewables or HVDC, as well as new built STATCOM.

To summarise, the main outcome of the reactive power study is the significant increase in need for stationary overexcited compensation. The results of the German NEP 2021 are not final values, but only one step towards a completely decarbonised future in Europe. The greater stationary need will also cause a massive increase in dynamic reactive power need. Therefore, many additional dynamic devices for ensuring voltage stability will be needed. Therefore, the need for dynamic devices depicted in the German NEP 2021 is also only an intermediate goal on the way to a stable and secure decarbonised energy system in Europe in 2050.

GLOSSAR

NOTION	INFORMATION
Building Renovation Rate	This indicator refers to the percentage of buildings which undergo a renovation within one year. To calculate the corresponding heat demand reduction, the building renovation rate must be multiplied by the renovation efficiency, the average heat demand reduction after a conducted renovation measure.
CCS (Carbon Capture and Storage)	Carbon capture and storage, sometimes also CCUS (Carbon Capture, Utilisation and Storage) refers to a suite of technologies that can play an important and diverse role in meeting global energy and climate goals. CCUS involves the capture of CO2 from large point sources, including power generation or industrial facilities that use either fossil fuels or biomass for fuel. The CO2 can also be captured directly from the atmosphere. If not being used on-site, the captured CO2 is compressed and transported by pipeline, ship, rail or truck to be used in a range of applications, or injected into deep geological formations (including depleted oil and gas reservoirs or saline formations) which trap the CO2 for permanent storage.
Combined heat and power	Combined heat and power (CHP) is the simultaneous conversion of primary energy into mechanical or electrical energy and usable heat within a thermodynamic process. The heat produced in parallel with electricity generation is used for heating and hot water supply or for industrial processes. The use of cogeneration reduces the energy input and carbon dioxide emissions. (Federal Environment Agency, 2020)
Copper plate	It is assumed that there are no grid congestions within a market area and thus homogeneous electricity prices. The grid expansion required for this purpose is then determined and planned in a subsequent step.
DAC	Direct air capture (DAC) technologies extract CO2 directly from the atmosphere. The CO2 can be permanently stored in deep geological formations (achieving negative emissions or carbon capture) or it can be used, for example in food processing or in combination with hydrogen to produce synthetic fuels.
Dark doldrums	Dark doldrums is a term used to describe a period of time in which little to no energy can be generated with the use of wind and solar power. Dark doldrums events are common in the North of Europe from October to February, typically 50 to 150 hours per year.
Decarbonisation	In the energy system, decarbonisation refers to the reduction of use of energy sources based on hydrocarbons such as oil, coal or natural gas.
Dynamic devices	Dynamic devices are devices with a Q(U) controller. These can include synchronous machines, converter from Renewables or HVDC, as well as new built STATCOM.
Dynamic need	Dynamic need is the need for reactive power in an electrical system due to dynamic (or quasi dynamic) events. This can change slowly over several minutes due to changes in the market (normally at the change of hour) or rapidly due to failures like short circuits. This need must be compensated by devices with Q(U) control such as synchronous machines or STATCOM.
Electrolyser	An electrolyser is a system that uses electricity to break water into hydrogen and oxygen in a process called electrolysis. Through electrolysis, the electrolyser system creates hydrogen gas. The oxygen that’s left over is released into the atmosphere or can be captured or stored to supply other industrial processes or even medical gases in some cases. (Cummins, 2020)

European Green Deal	The European Green Deal is a package of initiatives and measures approved by the European Commission in 2020 that aims to make Europe a climate-resilient society by 2050. The measures include reduction of greenhouse gas emissions as well as investments in research and innovation. The Green Deal includes several climate actions such as the New EU Strategy on Climate Adaptation and the 2030 Climate Target Plan.
Extruded Cable	In contrast to longer established MI (mass impregnated) cables, the younger technology of extruded cables offers lower weight, higher current carrying capabilities and lower environmental impact, thus making it the preferred technology for underground transmission. It is the most frequently used technology for HVAC and HVDC underground cables in recent transmission links and further development towards higher transmission capabilities and reliability can be expected.
Frequency	Power systems are operated with alternating current (AC) at a certain frequency. The ENTSO-E Continental Europe Synchronous Area is operated with a nominal frequency of 50 Hz. In general, the frequency within a power system is an indicator of the balance between generation and load. If the frequency drops/rises, it indicates a load higher/lower than the generation.
GIS	A geographic information system (GIS) is a computer system for capturing, storing, checking, and displaying data related to positions on Earth’s surface. GIS can show many kinds of data on one map, such as streets, buildings, and vegetation. (National Geographic, 2022)
Grid losses	The term grid losses refers to the total energy that is lost during the transmission or transformation of electricity. Grid losses are the differences between the metered energy feed-in and consumption over all grid access points.
Grid-Following Inverter	State-of-the-art control concept of inverters connected to the grid (e.g. wind power plants, photovoltaic, STATCOM). The main control target of grid-following inverters is to maximise active power infeed coming from the primary energy source (e.g. wind power).
Grid-Forming Inverter	New control concept of inverters, able to stabilise the power system like synchronous machines. Therefore, the main control target of grid-forming inverters is to react according to the system needs (e.g. provision of inertia).
High Voltage Direct Current (HVDC)	In contrast with the more common alternating current (AC) systems, HVDC transmission links use direct current (DC) for the transmission of electrical power.
High-Temperature Conductor (HT/HTL)	Line conductor that, due to the materials used, can function at a higher operating temperature than traditional aluminium/steel conductors (> 80°C). HT conductors offer a higher current capacity with comparable cross section and geometry. These are available as thermal resistant aluminium (TAL) conductors with a maximum operating temperature of up to 150°C.
Metallic Return Conductor	A bipolar HVDC connection consists of two conductors operated at nominal voltage in opposite polarity. A metallic return conductor (MR) is basically a third conductor. If voltage and current ratings are chosen adequately, the HVDC connection can still be operated with full or half the transmission capacity in (n-1) cases (e.g. cable faults) by using the MR. This switching can be realised automatically without interruption in most cases, thus significantly reducing the impact on the power transmission system.
Multi-Terminal-HVDC	Today’s HVDC-links are mainly designed as point-to-point connections. This is due to the technical challenge of switching off direct current, which is a substantially needed development for fully meshed DC-grids. Multi-terminal links represent an intermediate state with very few, but more than two directly connected converters.

Myopic Approach	In concrete terms, myopic approaches assume limited knowledge about the future, which means that optimisation in each year is based only on the results of the previous year and the constraints of the current expansion phase. For this reason, myopic models are well suited to simulate decisions under real economic conditions.
Natural Power	At natural power, the inductive (current flowing through a coil with one winding (overhead line)) and the capacitive reactive power (condenser with high voltage at the overhead line and ground on earth) of the line is the same. This is the only bias point of a line with no voltage change over the line. There is no need for reactive compensation.
Netzentwicklungsplan (NEP)	Following the European Single Market Directive, all European TSOs must create national Grid Development Plans. The basis of the German "Netzentwicklungsplan Strom" (NEP) is the Energy Authority Law (EnWG). The grid development plan defines the future transmission requirements for energy between various starting and end points in a period of 10 to 15 years. It thus does not yet include actual route corridor plans of the federal states' planning authorities. The last NEP was created in 2021 focussing on 2035 (NEP 2021).
New Industry Processes	„New industry" includes the sum of changes in demand of all sectors relative to the base year. The following sectors are considered: iron and steel, nonferrous metals, alumina production, aluminium production, other nonferrous metals, chemical industry, pharmaceuticals, non-metallic mineral products, cement, ceramics, glass production, pulp, paper and printing, printing and media reproduction, food and beverages, vehicle construction, mechanical engineering, textiles and leather, wood and wood products.
NUTS3	The NUTS classification (nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU and the UK for the purpose of the collection, development and harmonisation of European regional statistics; socio-economic analyses of the regions; framing of EU regional policies. (Eurostat, 2022)
Overload Energy	The overload energy is calculated for each individual circuit from the sum of the hourly power that cannot be transmitted in the (n-1) case due to an overload
Perfect Market Conditions	Under perfect market conditions, we assume that each energy system agent has complete information (past, present, and future) about cost. In addition, we assume that the market is not distorted by any kind of regulation or subsidy.
Phase-Shifting Transformer (PST)	Grid equipment which is a specific form of a transformer. The phase-shifting transformer enables control of power flows in the alternating current grid.
Planning Principles of German TSOs	Initially published by the four TSOs in 2012, this publication is continuously updated to align with framework conditions for network planning. Technical and economic principles of grid expansion planning are described to transparently present the underlying methodology and needs.
P_{MAX}	Maximum power generation or demand for electricity in 2050 – to be distinguished from installed capacity
Power System Inertia	Power system inertia is the instantaneous active power reserve in the system, today mainly provided by synchronous machines of conventional power plants. In case of an active power imbalance, the inertia defines the rate of change of frequency in the system, until the active power control becomes active.
Proton-Exchange Membrane Fuel Cell (PEMFC)	Also known as polymer electrolyte membrane fuel cells, PEMFCs are a type of fuel cell being developed mainly for transport applications, as well as for stationary fuel cell applications and portable fuel cell applications. Their distinguishing features include lower temperature/pressure ranges (50 to 100 °C) and a special proton-conducting polymer electrolyte membrane. PEMFCs generate electricity and operate on the opposite principle to PEM electrolysis, which consumes electricity.

Pumped Hydro Storage (PHS)	Pumped hydro storage is a type of hydroelectric energy storage. It is a configuration of two water reservoirs at different elevations that can generate power as water moves down from one to the other (discharge), passing through a turbine. The system also requires power as it pumps water back into the upper reservoir (recharge). PHS acts like a giant battery, because it can store power and then release it when needed. (EERE, 2022)
Reactive Power	Reactive power is the need for energy for the commutation of the electro-magnetic field due to alternating current. This energy cannot be used and is "stored" in the electrical system, which affects the voltage.
Reference Grid	The reference grid is the assumed expansion status of the electricity grid as the starting point for the grid calculations.
Smart Charging	Smart charging refers to a charging system in which electric vehicles, charging stations, and charging operators share common data. In the context of energy system optimisation, we assume that electric vehicles use such a system for charging batteries, which helps minimise energy system costs under the consideration of future driving profiles.
Stationary Need	The need for reactive power in an electrical system in steady state mode. It can be compensated by devices with no Q(U) control such as inductors or capacitors.
Syngas	Syngas is a fuel gas mixture consisting primarily of hydrogen, carbon monoxide, and very often some carbon dioxide. The name comes from its use as intermediates in creating synthetic natural gas (SNG) and for producing ammonia or methanol.
Synthetic Natural Gas (SNG)	SNG describes a variety of natural gas alternatives that are as close as possible in composition and properties to natural gas. SNG can be derived from coal, (waste) biomass or synthesized using renewable energy. (MAN-ES, 2022)
Transit Flow	Transit flows are the transmission of electricity through a dedicated grid area. Transits are the balance of imports and exports of this grid area.
Variable Renewable Energy (VRE)	VREs are electricity generation technologies whose primary energy source varies over time and cannot easily be stored. VRE sources include solar, wind, ocean, and some hydropower generation technologies. (National Renewable Energy Laboratory, 2015)
Vehicle to Grid (V2G)	Vehicle to Grid describes a system in which electric vehicles, such as battery electric vehicles (BEV), plug-in hybrids (PHEV), or hydrogen fuel cell electric vehicles (FCEV), communicate with the power grid by feeding power back into the grid.
Weather-Dependent Dynamic Line Rating (DLR)	The transmission capacity of the power grid varies depending on the season and weather. With colder temperatures and cooling by wind, more power can be transmitted than on hot summer days. With the help of weather dependent DLR, it is possible to increase the load of the electrical grid significantly. Using live measurement data, the maximum power flows acceptable under the current weather conditions can be calculated precisely, so that the sag of the conductor lines remains within the technical specifications.

LIST OF ABBREVIATIONS

ABBREVIATIONS	INFORMATION
AC	Alternating current
ACDC	Sensitivity Limiting grid expansion
BEV	Battery electric vehicle
BW	Baden-Württemberg (German Federal State)
CAPEX	Capital expenditures
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CHP	Combined heat and power
CNG	Compressed natural gas
CO2	Carbon dioxide
DLR	Dynamic line rating
DSM	Demand side management
ENTSO-E	European Network of Transmission System Operators for Electricity
ESM	Energy system model
ERE	Scenario Energy Resilient Europe
EU	European Union
FCEV	Fuel cell electric vehicle
GM	Scenario Global Markets
H_2	Hydrogen gas (or Dihydrogen)
HEAT	Sensitivity Low Building Renovation Rate
HEV	Hybrid electric vehicles
HT	High temperature
HTLS	High temperature low sag
HVDC	High voltage direct current
ICE	Conventional internal combustion engines
MP	Package of measures
NEP	German Netzentwicklungsplan (Grid Development Plan)
NRA	National regulatory authority
NUCLEAR	Sensitivity Nuclear Renaissance
OLE	Overload energy

OPEX	Operational expenditures
PHEV	Plug-in hybrid electric vehicles
P_{Imb}	Active power imbalance
Pmax	Maximum power
PST	Phase-shifting transformer
PV	Photovoltaic
PyPSA	Python for Power System Analysis
RES	Renewable energy source
RoCoF	Rate of Change of Frequency
SNG	Synthetic natural gas
TSO	Transmission System Operator
TBW	TransnetBW
TYNDP	Ten Year Network Development Plan
V2G	Vehicle-to-grid
V2G/DSM	Sensitivity inflexible mobility
VRE	Variable renewable energy
WIND	Sensitivity Low RES Expansion Acceptance
WY96	Sensitivity Extreme Meteorological Year

APPENDIX

LIST OF TECHNOLOGIES

Table 8 and Table 9 presents the complete list of the technologies included in PyPSA. Own model expansions are highlighted in bold, green.

TABLE 8:
Overview of model components, part 1.

Buses	Generators	Links	
[EU-Level]	**[EU-Level]**	**[EU-Level]**	Air-Source Heat Pumps2),3)
Atmosphere CO2	EU-Natural Gas	CO2 Ventilation	Air-Source Heat Pumps1)
CO2 Storage	EU Oil	Direct-Air-Capture	Heat Storage1),2),3)
Coal	**Green Gas Imports**	**[Regional-Level]**	Resistance Heater1),2),3)
Natural Gas	**[Regional-Level]**	Gas Turbine	Gas Boiler1),2),3)
Biogas / Biomass	Nuclear	H_2-Electrolysis	Micro-CHP1),3)
Synthetic Oil	Hydro	H_2-Fuel Cell	CHP2)
[Regional-Level]	Solar Thermal1),2),3)	H_2-Pipeline	Gas-to-Urban
Electric Power	Wind Offshore AC/DC	Batteries	Sold Biomass to Urban
Hydrogen	**Wind Onshore 1 - 4**	Sabatier-Process	Fischer-Tropsch-Synthesis
Batteries	**PV Utility and Rooftop**	High Temp. P2G (Helmeth)	**Coal Power Plant (w CCS)**
E-Mobility	**Coal**	Steam Methane Reforming	**Coal –CHP (w CCS)**
Heat1),2),3)	**Load Shedding**	E-Mobility	**Oil- und Coal Boiler**
Heat Storage1),2),3)		Vehicle-2-Grid	**Biomass-Boiler**
CHP2)		**H_2 Pipelines**	

TABLE 9:
Overview of model components, part 2.

Stores/Storages	Demand/Load
[EU-Level]	Electricity
Atmosphere CO2	Heat1),2),3)
EU Natural Gas	E-Mobility
EU Biomass	Fuel Cells Mobility
Fischer-Tropsch Synthesis	H_2 Mobility4)
[Regional-Level]	**Oils**
Battery Storages	**Biomass**
E-Mobility-Batteries	**Gas**
Heat Storages1),2),3)	**Coal**
Pumped Hydro Storage	
Reservoirs	

NOTE
1)Rural
2)Urban & Central
3)Urban & Decentral
4)In Industry

TECHNO-ECONOMIC ASSUMPTIONS

TABLE 10:
Main techno-economic assumptions, 2030 to 2050.

Technology	Unit	Parameter	2030	2040	2050
battery inverter	per unit	efficiency	0,91	0,92	0,92
battery inverter	%/year	FOM	0,49	0,70	0,90
battery inverter	EUR/kWel	investment	160	80	63
battery inverter	years	lifetime	21,00	26,00	30,00
battery storage	EUR/kWh	investment	153	76	60
battery storage	years	lifetime	21,00	26,00	30,00
biomass	per unit	efficiency	0,30	0,30	0,30
biomass	%/year	FOM	5,01	5,01	5,02
biomass	EUR/kWel	investment	3230,35	3227,08	3223,81
biomass	years	lifetime	30,00	30,00	30,00
CCGT	per unit	efficiency	0,60	0,60	0,60
CCGT	%/year	FOM	3,43	3,43	3,43
CCGT	EUR/kWel	investment	686,54	686,54	686,54
CCGT	years	lifetime	30,00	30,00	30,00
CCGT	EUR/MWhel	VOM	4,00	4,00	4,00
DAC	%/year	FOM	3,83	3,91	4,00
DAC	EUR/(tCO2/a)	investment	650,66	541,10	431,54
DAC	years	lifetime	27,00	29,00	30,00
DAC	EUR/t CO2	VOM	77,24	75,40	73,56
electrolysis	%/year	FOM	4,36	3,61	2,85
electrolysis	EUR/kWel	investment	333	230	202
electrolysis	years	lifetime	19,00	21,00	23,00
Fischer-Tropsch	per unit	efficiency	0,59	0,63	0,66
Fischer-Tropsch	%/year	FOM	7,16	8,45	9,74
Fischer-Tropsch	EUR/kWH2	investment	1141,00	994,00	846,00
Fischer-Tropsch	years	lifetime	19,00	22,00	25,00
HVAC overhead	%/year	FOM	2,00	2,00	2,00
HVAC overhead	EUR/MW/km	investment	500,00	500,00	500,00
HVAC overhead	years	lifetime	40,00	40,00	40,00
HVDC inverter pair	%/year	FOM	2,00	2,00	2,00
HVDC inverter pair	EUR/MW	investment	600000,00	600000,00	600000,00
HVDC inverter pair	years	lifetime	40,00	40,00	40,00
HVDC overhead	%/year	FOM	2,00	2,00	2,00
HVDC overhead	EUR/MW/km	investment	2000,00	2000,00	2000,00
HVDC overhead	years	lifetime	40,00	40,00	40,00
HVDC submarine	%/year	FOM	2,00	2,00	2,00
HVDC submarine	EUR/MW/km	investment	2000,00	2000,00	2000,00
HVDC submarine	years	lifetime	40,00	40,00	40,00
hydrogen storage	EUR/kWh	investment	41,57	31,29	21,00
hydrogen storage	years	lifetime	30,00	30,00	30,00
hydrogen underground storage	EUR/kWh	investment	0,03	0,03	0,03
hydrogen underground storage	years	lifetime	33,00	33,00	33,00

Technology	Unit	Parameter	2030	2040	2050
methanation	per unit	efficiency	0,86	0,88	0,90
methanation	%/year	FOM	2,13	2,21	2,30
methanation	EUR/kWMethan	investment	369,36	289,46	249,78
methanation	years	lifetime	20,00	22,00	25,00
nuclear	per unit	efficiency	0,33	0,33	0,33
nuclear	%/year	FOM	3,07	3,07	3,07
nuclear	EUR/MWhth	fuel	3,15	3,15	3,15
nuclear	EUR/kWel	investment	3259,12	3259,12	3259,12
nuclear	years	lifetime	60,00	60,00	60,00
nuclear	EUR/MWhel	VOM	2,10	2,10	2,10
OCGT	per unit	efficiency	0,40	0,40	0,40
OCGT	%/year	FOM	3,25	3,25	3,25
OCGT	EUR/kWel	investment	392,31	392,31	392,31
OCGT	years	lifetime	25,00	25,00	25,00
OCGT	EUR/MWhel	VOM	3,00	3,00	3,00
offwind	%/year	FOM	4,81	6,02	7,24
offwind	EUR/kWel	investment	1684,00	1516,00	1415,00
offwind	years	lifetime	25,00	25,00	25,00
offwind	EUR/MWhel	VOM	0,01	0,01	0,01
onwind	%/year	FOM	1,26	1,33	1,41
onwind	EUR/kWel	investment	1023,17	979,32	946,19
onwind	years	lifetime	25,00	25,00	25,00
onwind	EUR/MWhel	VOM	0,01	0,01	0,01
SMR	per unit	efficiency	0,74	0,74	0,74
SMR	%/year	FOM	7,03	7,03	7,03
SMR	EUR/kWCH4	investment	416,74	356,62	296,50
SMR	years	lifetime	25,00	25,00	25,00
SMR CCS	per unit	efficiency	0,67	0,67	0,67
SMR CCS	%/year	FOM	5,15	5,84	6,54
SMR CCS	EUR/kWCH4	investment	596,50	596,50	596,50
SMR CCS	years	lifetime	25,00	25,00	25,00
solar-rooftop	%/year	FOM	2,26	2,68	3,11
solar-rooftop	EUR/kWel	investment	784,95	660,72	536,48
solar-rooftop	years	lifetime	25,00	25,00	25,00
solar-utility	%/year	FOM	2,32	2,71	3,11
solar-utility	EUR/kWel	investment	462	357	335
solar-utility	years	lifetime	25,00	25,00	25,00
Hard Coal	€/MWh	-	12.85	14.28	16.99
Natural Gas	€/MWh	-	28.71	31.54	32.58
Oil	€/MWh	-	53.02	53.43	45.13

HYDROGEN IMPORT COST FROM NON-EU COUNTRIES

TABLE 11:
Calculation of hydrogen import cost from non-EU countries in 2050.
Note: higher values for pessimistic scenarios matches with the value taken by the study Langfristszenarien, 2021.

PV		**optimistic**	**avg (GM)**	**pessimistic (ERE)**	**Comment**
P installed	MW	100	100	100	
FLH	h/y	1960	1960	1960	e.g. MENA region
spec. Capex	€/kW	184	335	335	from LUT / TBW assumptions, 2050
interest	%	7%	7%	7%	from LUT
life time	y	40	40	40	from LUT
Annual capital cost	Mio. €/y	1,38	2,51	2,51	
spec. Opex	% inv/y	2%	2%	2%	from LUT
Sum Annual Cost PV	**Mio. €/y**	**1,7**	**3,2**	**3,2**	
Electrolysis					
P inst	MW	100	100	100	
FLH	h/y	1960	1960	1960	
Efficiency LHV	%	70%	70%	70%	assumption for 2050
H_2 prod.	GWh/y	137,2	137,2	137,2	
spec. Capex	€/kW	148	202	202	from LUT / TBW assumptions, 2050
interest	%	7%	7%	7%	
life time	y	30	30	30	
Annual capital cost	Mio. €/y	1,19	1,63	1,63	
Opex	Mio. €/y	0,52	0,71	0,71	
Sum Annual Cost	**Mio. €/y**	**1,7**	**2,3**	**2,3**	
H_2 Transport - pipeline for "optimistic" and "avg" scenario; LOHC shipping for pessimistic scenario					
Distance	km	1000	1000	-	from H_2 production region to Europe boundaries
Spec. CAPEX H_2 pipeline	€/MW/km	263	263	-	New pipeline. CAPEX: https://gas-forclimate2050.eu/sdm_downloads/extending-the-european-hydrogen-backbone/
Annual capital cost	Mio. €/y	1,33	1,33	-	
opex	Mio. €/y	0,64	0,64	-	
Sum Annual Cost H_2 pipeline	**Mio. €/y**	**2,0**	**2,0**	**-**	
Transported H_2 /year	GWh/y	137	137	-	
LCOT (Transport)	**€/MWh_H_2**	**14**	**14**	**43**	LOHC: calculated based on: https://www.ffe.de/wp-content/uploads/2022/02/et_2022_h2transport-kosten-1.pdf

$LCOH_2$		optimistic	avg (GM)	pessimistic (ERE)	
Sum Annual Costs PV+ Electrolysis	Mio. €/y	3,5	5,5	5,5	
$LCOH_2$ w/o Transport	**€/MWh_H_2**	**25**	**40**	**40**	
$LCOH_2$ incl. Transport	€c/kWh	4,0	5,5	-	
$LCOH_2$ incl. Transport	**€/MWh_H_2**	**40**	**55**	**84**	

As one can observe in Table 11, there is great uncertainty for hydrogen import cost assumptions. The range for imports is very wide (according to the used sources between 40 and approximately 90 €/MWh in 2050).

In addition, the 55 €/MWh applied in the GM scenario only includes the transport costs up to the model boundary (European borders). All H_2 pipelines within the model boundaries are modelled and calculated and are thus included separately in the cost optimisation function. In the model, transporting hydrogen from North Africa to Germany would be significantly more expensive than 55 €/MWh. Also, these are prices calculated from models, so there is no political control of prices.

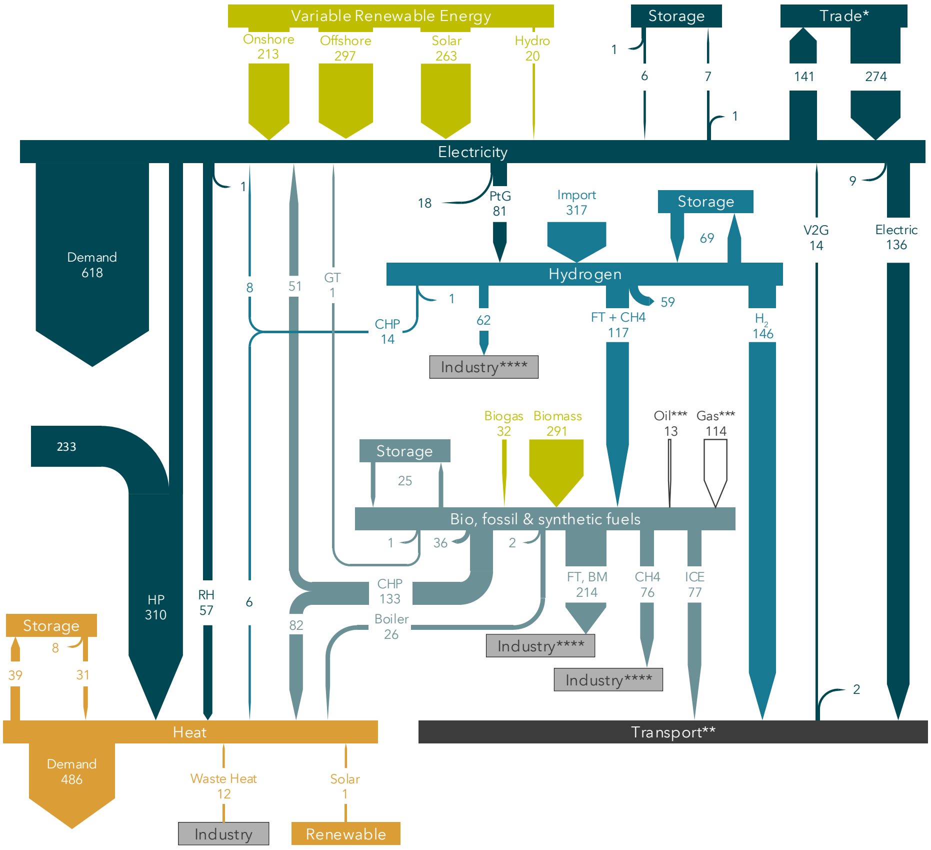
EU POWER TRANSITS

TABLE 12:
Electricity transits between EU27 and non-EU27 countries in 2050 in TWh

Country	Transit GM 2050	Transit ERE 2050
AL	0.0	0.0
BA	0.0	0.0
CH	61.2	62.2
GB	19.8	21.7
ME	0.0	0.0
MK	2.3	4.9
NO	5.2	7.3
RS	11.8	16.6
SUM	**100.4**	**112.7**

ENERGY FLOW DIAGRAMS FOR GERMANY

FIGURE 73:
Energy flow diagram, GM scenario, DE, 2050



CH4	Methane (fossil or synthetic)
CHP	Combined Heat and Power
FCEV	Fuel Cell Electric Vehicle
FT	Fischer-Tropsch product
HP	Heat Pump
ICE	Internal Combustion Engine
PtG	Power-to-Gas
RH	Resistive Heater
V2G	Vehicle-to-Grid

* The trade also contains transit flows across non-EU27 regions like Switzerland and UK, e. g. power transmitted from Germany to Italy via Switzerland is accounted twice. First as export, then as import.

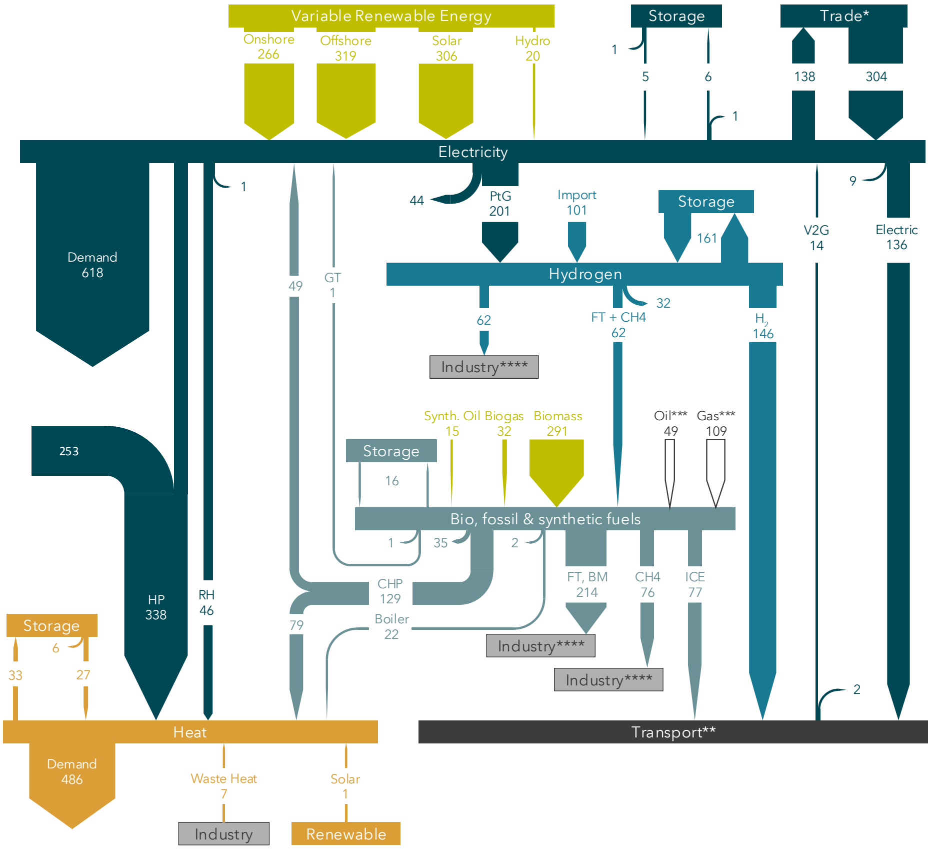
** The emission reduction of international transport is outside the scope of this study and has been only taken partially into account. Therefore, all fossil based fuel demand of the international transport is not shown.

*** Even in a fully decarbonized energy system, small amounts of fossil energy carriers are used. Their emissions are fully captured by existing Carbon Capture technologies or encountered with negative emissions.

**** „Industry" contains energetic as well as feedstock usage. Fossil feedstock is not represented in this chart as its respective CO_2 content is not released into the atmosphere. Hence, all fossil based feedstock flows are excluded.

In general: Energy flows below 1 TWh are not depicted. Therefore, small imbalances between inputs and outputs may occur.

FIGURE 74:
Energy flow diagram, ERE scenario, DE, 2050.



CH4	Methane (fossil or synthetic)
CHP	Combined Heat and Power
FCEV	Fuel Cell Electric Vehicle
FT	Fischer-Tropsch product
HP	Heat Pump
ICE	Internal Combustion Engine
PtG	Power-to-Gas
RH	Resistive Heater
V2G	Vehicle-to-Grid

* The trade also contains transit flows across non-EU27 regions like Switzerland and UK, e. g. power transmitted from Germany to Italy via Switzerland is accounted twice. First as export, then as import.

** The emission reduction of international transport is outside the scope of this study and has been only taken partially into account. Therefore, all fossil based fuel demand of the international transport is not shown.

*** Even in a fully decarbonized energy system, small amounts of fossil energy carriers are used. Their emissions are fully captured by existing Carbon Capture technologies or encountered with negative emissions.

**** „Industry“ contains energetic as well as feedstock usage. Fossil feedstock is not represented in this chart as its respective CO_2 content is not released into the atmosphere. Hence, all fossil based feedstock flows are excluded.

In general: Energy flows below 1 TWh are not depicted. Therefore, small imbalances between inputs and outputs may occur.

LITERATURE

acatech.
2018. Energiesysteme der Zukunft - Optimierungsmodell REMod-D. [Online]
Available at: https://energiesysteme-zukunft.de/fileadmin/user_upload/Publikationen/PDFs/ESYS_Materialien_Optimierungsmodell_REMod-D.pdf

AGEB.
2021. AG Energiebilanzen e.V. - Energiewirtschaft in Deutschland. [Online]
Available at: https://ag-energiebilanzen.de/

agora.
2021. agora Energiewende - Klimaneutrales Deutschland 2045, Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann. [Online]
Available at: https://www.agora-energiewende.de/veroeffentlichungen/klimaneutrales-deutschland-2045/

Atlite.
2020. Atlite: A Lightweight Python Package for Calculating Renewable Power Potentials and Time Series. [Online]
Available at: https://github.com/PyPSA/atlite

BASt.
2018. Bundesanstalt für Strassenwesen. [Online]
Available at: https://www.bast.de/DE/Home/home_node.html

Brown, T. H. J. S. D.
2018. PyPSA: Python for Power System Analysis, Journal of Open Research Software, 6(1). [Online]
Available at: arXiv:1707.09913, DOI:10.5334/jors.188

Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen.
2022. Bedarfsermittlung 2021-2035, Bestätigung Netzentwicklungsplan Strom. [Online]
Available at: https://data.netzausbau.de/2035-2021/NEP2035_Bestaetigung.pdf

Caglayan, N. W. H. U. H. J. L. M. R. P. A. K. D. S.
2020. Technical potential of salt caverns for hydrogen storage in Europe. International Journal of Hydrogen Energy, pp. Pages 6793-6805; https://doi.org/10.1016/j.ijhydene.2019.12.161.

CLC.
2018. Corine Land Cover Database. [Online]
Available at: https://land.copernicus.eu/pan-european/corine-land-cover

Cummins.
2020. Electrolyzers 101: What They Are, How They Work and Where They Fit in a Green Economy. [Online]
Available at: https://www.cummins.com/news/2020/11/16/electrolyzers-101-what-they-are-how-they-work-and-where-they-fit-green-economy

DEA.
2020. Danish Energy Agency - Technology Data. [Online]
Available at: https://ens.dk/en/our-services/projections-and-models/technology-data

dena.
2018. Dena Leitstudie. [Online]
Available at: https://www.dena.de/themen-projekte/projekte/energiesysteme/dena-leitstudie-integrierte-energiewende/

dena.
2018. dena-Leitstudie Integrierte Energiewende - Impulse für die Gestaltung des Energiesystems bis 2050. [Online]
Available at: https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9261_dena-Leitstudie_Integrierte_Energiewende_lang.pdf

diw.
2017. Deutsche Institut für Wirtschaftsforschung - Electricity, Heat, and Gas Sector Data for Modeling the German System. [Online]
Available at: https://www.diw.de/documents/publikationen/73/diw_01.c.574130.de/diw_datadoc_2017-092.pdf

DLR.
2020. MuSeKo, Multi-Sektor-Kopplung. [Online]
Available at: https://elib.dlr.de/135971/1/MuSeKo-Endbericht-2020-08-31.pdf

EC.
2021. European Commission - eu-reference-scenario-2020. [Online]
Available at: https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en

EC.
2021. European Commission; European Green Deal; European Climate Law. [Online]
Available at: https://ec.europa.eu/clima/eu-action/european-green-deal/european-climate-law_de

EERE.
2022. Office of Energy Efficiency & Renewable Energy. Pumped Storage Hydropower. [Online]
Available at: https://www.energy.gov/eere/water/pumped-storage-hydropower

EIA.
2014. Energy Information Administration - Hydro power generation: historical yearly hydro power generation per country from 2000 to 2014. [Online]
Available at: www.eia.gov/international/data/world

ENTSO-E.
2007. System Disturbance on 4 November 2006 - Final Report, s.l.: s.n.

ENTSO-E.
2019. ENTSO-E factsheet 2018. [Online]
Available at: https://www.entsoe.eu/Documents/Publications/Statistics/Factsheet/entsoe_sfs2018_web.pdf

ENTSO-E.
2019. TYNDP 2018, technologies for transmission system. [Online]
Available at: https://tyndp.entsoe.eu/tyndp2018/

ENTSO-E.
2020. TYNDP Scenarios - Europe´s Energy Future. [Online]
Available at: https://tyndp.entsoe.eu/scenarios/

ENTSO-E.
2021. TYNDP 2020. [Online]
Available at: https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/TYNDP2020/FINAL/entso-e_TYNDP2020_IoSN_Main-Report_2108.pdf

ENTSOG.
2015. TRANSMISSION CAPACITY AND SYSTEM DEVELOPMENT MAPS. pp. https://www.entsog.eu/maps#transmission-capacity-map-2015.

Eurostat.
2022. Complete Energy Balances. [Online]
Available at: https://ec.europa.eu/eurostat/cache/infographs/energy_balances

Eurostat.
2022. Complete Energy Balances. [Online]
Available at: https://ec.europa.eu/eurostat/cache/infographs/energy_balances

Eurostat.
2022. Eurostat: Nomenclature of Territorial Units for Statistics (NUTS) - Background;. [Online]
Available at: https://ec.europa.eu/eurostat/web/nuts/background

FfE.
2021. Guminski, A.; Fiedler, C.; Kigle, S.; Pellinger, C.; Dossow, P.; Ganz, K.; Jetter, F.; Kern, T.; Limmer, T.; Murmann, A.; Reinhard, J.; Schmid, T.; Schmidt-Achert, T.; von Roon, S.: eXtremOS Summary Report. [Online]
Available at: https://extremos.ffe.de/

FZJ.
2020. Forschungszentrum Jülich - WEGE FÜR DIE ENERGIEWENDE, Kosteneffiziente und klimagerechte Transformationsstrategien für das deutsche Energiesystem bis zum Jahr 2050. [Online]
Available at: https://juser.fz-juelich.de/record/877960/files/Energie_Umwelt_499.pdf

GasForClimate.
2021. A Path to 2050 - Extending the European Hydrogen Backbone - A European Hydrogen Infrfastructure Ccovering 21 Countries. [Online]
Available at: https://gasforclimate2050.eu/sdm_downloads/extending-the-european-hydrogen-backbone/

German TSOs.
2019. Netzentwicklungsplan Strom 2030, Version 2019, Zweiter Entwurf (Grid development plan for electricity 2030, version 2019, second draft). [Online]
Available at: https://www.netzentwicklungsplan.de/sites/default/files/paragraphs-files/NEP_2030_V2019_2_Ent-wurf_Teil1.pdf

German TSOs.
2020. Grundsätze für die Ausbauplanung des deutschen Übertragungsnetzes. [Online]
Available at: https://www.transnetbw.de/de/netzentwicklung/planung/netzplanungsgrundsaetze

German TSOs.
2021. Netzentwicklungsplan Strom 2035, Version 2021, Zweiter Entwurf, Begleitdokument Systemstabilität (Grid development plan for electricity 2035, version 2021, second draft, accompanying document system stability), s.l.: s.n.

German TSOs.
2022. 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH: Netzentwicklungsplan 2035 (2021). [Online]
Available at: https://www.netzentwicklungsplan.de/de/netzentwicklungsplaene/netzentwicklungsplan-2035-2021

Geth, F. e. a.
2015. An overview of large-scale stationary electricity storage plants in Europe: Current status and new developments. Renewable and Sustainable Energy Reviews, p. https://www.sciencedirect.com/science/article/abs/pii/S1364032115007923.

Hampp, J. D. M. B. T.
2021. Import options for chemical energy carriers from renewable sources to Germany. p. https://arxiv.org/pdf/2107.01092.pdf.

hotmaps.
2020. Horizon 2020 project: The open source mapping and planning tool for heating and cooling. [Online]
Available at: https://www.hotmaps-project.eu/

IRENASTAT.
2021. IRENA, International Energy Agency - Online Data Query Tool. [Online]
Available at: https://pxweb.irena.org/pxweb/en/IRENASTAT

JRC-IDEES.
2018. Joint Research Center - The JRC Integrated Database of the European Energy System. [Online]
Available at: https://data.jrc.ec.europa.eu/collection/id-0110

Kundur, P. et al.
2004. Definition and Classification of Power System Stability.

Langfristszenarien.
2021. Langfristszenarien, Fraunhofer ISI, Consentec, ifeu, TU Berlin. [Online]
Available at: https://www.langfristszenarien.de/enertile-explorer-de/

LUT.
2018. GLOBAL ENERGY SYSTEM BASED ON 100% RENEWABLE ENERGY - Energy Transition in Europe Across Power, Heat, Transport and Desalination Sectors. [Online]
Available at: https://energywatchgroup.org/wp-content/uploads/EWG-LUT_Full-Study_Energy-Transition-Europe.pdf

MAN-ES.
2022. MAN Energy Solutions. SNG - Synthetic Natural Gas. [Online]
Available at: https://www.man-es.com/discover/decarbonization-glossary---man-energy-solutions/synthetic-natural-gas

MaStR.
2021. Marktstammdatenregister, Bundesnetzagentur. [Online]
Available at: https://www.marktstammdatenregister.de/MaStR/

National Geographic.
2022. Natianal Geogrpahic Resource Library. GIS (Geographic Information System). [Online]
Available at: https://www.nationalgeographic.org/encyclopedia/geographic-information-system-gis/

National Renewable Energy Laboratory.
2015. Integrating Variable Renewable Energy into the Grid: Key Issues, https://www.nrel.gov/docs/fy15osti/63033.pdf: s.n.

OPSD.
2020. Open Power System Database. [Online]
Available at: https://open-power-system-data.org/

prognos, B. &.
2018. Klimapfade für Deutschland. [Online]
Available at: https://www.prognos.com/de/projekt/klimapfade-fuer-deutschland

PyPSA.
2022. PyPSA Eur-Sec. [Online]
Available at: https://github.com/PyPSA/pypsa-eur-sec

Samadi.
2011. The experience curve theory and its application in the field of electricity generation technologies – A literature review,. Renewable and Sustainable Energy Reviews, https://doi.org/10.1016/j.rser.2017.08.077., pp. Pages 2346-2364.

UBA.
2021. Umweltbundesamt. [Online]
Available at: https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/2021-04-26_cc_18-2021_waermewende.pdf

AUTHORS OF THE STUDY


Jonas Lotze


Dr. Massimo Moser


Philipp Sittaro

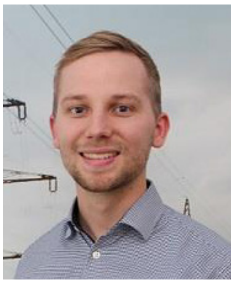

Dr. Ninghong Sun


Georgios Savvidis


Kostiantyn Troitskyi


Markus Mogel


Natnael Kidane


Christoph John


Dr. Joachim Lehner

TransnetBW GmbH
Pariser Platz
Osloer Str. 15 - 17
70173 Stuttgart

transnetbw.de

Registration Court:
Amtsgericht Stuttgart
Registration Number: HRB 740510
VAT Identification Number: DE 191008872

Executive Board:
Dr. Werner Götz (Chairman)
Michael Jesberger
Dr. Rainer Pflaum

Responsible:
Olaf Sener

Commercial Register:
Registergericht - Registration court
HRB 740510
Umsatzsteuer-ID - VAT ID
191008872

Design:
dreisatz - büro für gestaltung,
Fellbach, Germany

www.energysystem2050.net