Phase II — Pathways to 2050

A joint follow-up study by Gasunie and TenneT
of the Infrastructure Outlook 2050

DBI GUT Gas- und Umwelttechnik GmbH
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IAEW High Voltage Equipment & Grids, Digitalization & Power Economics | RWTH AACHEN UNIVERSITY
gasunie crossing borders in energy
TenneT Taking power further

Foreword

“This Phase II report confirms the need for integration of both gas and electricity networks in order to achieve the energy policy goals. It reinforces the awareness that this is a European matter. If we want the energy transition to be timely and affordable, this requires also a strong political cooperation within Europe.”

Manon van Beek

TenneT TSO B.V.

Manon van Beek

TenneT and Gasunie hereby present their study Phase II – Pathways to 2050. This study is a follow-up on the Infrastructure Outlook 2050 (IO2050) study, which contributed to a better understanding of the possibilities of a future integrated energy system for Germany and the Netherlands in the year 2050. Phase II is now bridging the gap from the year 2030 - the planning horizon of current national grid development plans - and 2050 by studying possible transition pathways. The impact of distinct future developments regarding renewable energy sources (RES) supply and energy demands on the transforming energy infrastructure is analyzed.

For this study, an integrated energy system model has been developed to determine transition pathways of the European energy infrastructure from 2030 to 2050 based on minimizing the total investment and operational costs of various technological options. Three different scenarios have been developed, building on IO 2050 and other current studies. All scenarios assume a 95% decarbonization target within the energy system and expect an ambitious growth in RES supply.
While aiming at the same decarbonization target a different impact on infrastructure can be observed in the scenarios.

Phase II study reaffirms that the coupling of the complementary energy infrastructures for electricity and gas (hydrogen and methane) is essential to integrate large scale RES in the energy system. We also see in the three studied scenarios, that a further development of the energy transmission infrastructures for electricity and gas is required beyond 2030. On the gas side a new Europe wide hydrogen grid will have to be created starting from 2030 based on re-using existing methane infrastructure.

"The further integration of the energy transmission infrastructures for electricity, hydrogen and methane plays a crucial role for future energy systems.
The Phase II report clearly demonstrates that the development of Power-to-Gas is an important aspect to enter the next phase of the energy transition and to reach the 2050 goals outlined in the European Green Deal."

Han Fennema
N.V. Nederlandse Gasunie

Han Fennema

For the three scenarios the Phase II study confirms that Power-to-Gas is a key technology for enabling the energy transition and linked to very ambitious extension plans of renewable energy sources. To foster these investments in Europe, an extension of renewable energy production capacities surpassing current national plans is required. Storage and dispatchable power plants are required as sources for flexibility to ensure a reliable, CO2-neutral demand coverage for each energy carrier. The study clearly reveals that the imports of CO2 neutral gases to Europe – i.e. green hydrogen, synthetic methane and others – will become an essential part of the energy supply in all scenarios.

The study strengthens the insight that international cooperation is key for an affordable, sustainable and reliable energy system. Increasing interdependencies of energy transmission infrastructures in Europe as cost-minimal source for flexibility require strong political cooperation and alignment within NW-Europe. Infrastructure needs to be planned timely in an integrated way to find optimal solutions for an affordable and fast energy transition. This naturally includes timely and reliable decision on the capacity and location of renewable energy production. Phase II also concludes that the coordination of investment decisions on the demand side (electric, gas-based or hybrid) with infrastructure decisions is required to avoid inefficiencies. Both in the Netherlands as well as in Germany TenneT and Gasunie together with other stakeholders continue research anticipating on large scale renewable energy production and demand in the Dutch and German energy system, and the consequences they have for infrastructure development.

Executive Summary

To achieve Paris Climate Agreement targets for CO_2 emission reduction, energy supply, energy demand and the connecting energy infrastructure must undergo a profound transition. The coupling of the complementary energy infrastructures for electricity and gas (hydrogen[1] and methane) is considered to be a key concept to integrate renewable energy sources (RES) on a large scale in the energy system and to ensure security of supply. TenneT and Gasunie have conducted the study Infrastructure Outlook 2050 (IO2050) in 2019 to understand future designs of the integrated energy system for Germany and the Netherlands in the year 2050.

Based on findings and open questions of IO2050, the follow-up study Phase II: Pathways to 2050 (Phase II) focuses on transition pathways of the energy infrastructures [2] towards an integrated European energy system. Accordingly, the study aims at increasing the general understanding of influences and interdependencies in the development of integrated energy systems. Therefore, the impact of distinct future developments regarding RES supply and energy demands on the transforming energy infrastructure is analyzed. For this purpose, an integrated energy system model is developed. The model determines transition pathways of the European energy infrastructure by minimizing the total investment and operational costs of various technological options (i.e. energy transmission infrastructures, power-to-gas (PtG) units, power plants and storages). Based on this, the study puts a special focus on the Netherlands and Germany (focus area) and covers the timeframe from 2030 to 2050 in 5 year steps.

[1] Hydrogen transmission infrastructure is developed in all scenarios, based on partial re-purposing of existing methane infrastructure.

[2] Transmission capacities are considered as simplification of the target energy transmission infrastructures as defined in national network development plans

Building on the results of IO 2050 and other latest studies, three different scenarios have been developed. All scenarios assume a 95% decarbonization target within the energy system. The scenarios vary type and amount of installed RES as well as energy demand (focus on electrification vs. focus on gas). Those scenarios represent highly ambitious developments with regard to energy supply and demand to provide further insights on the impact of challenging frameworks to the energy infrastructure in general and to the energy transmission systems in particular:

(EL & RES)	High electrification and ambitious RES
(Gas & RES+)	High gas demand and very ambitious RES
(EL & RES+)	High electrification and very ambitious RES expansion

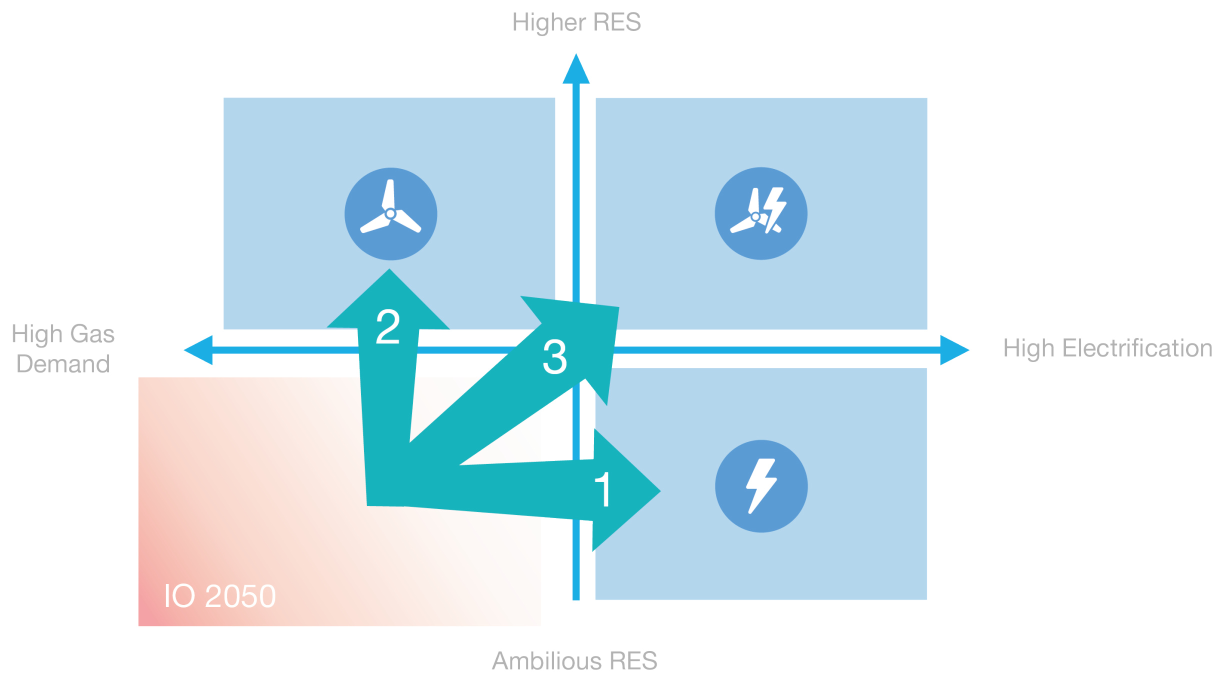

Figure 1: Developed combined scenarios

Key Insights

What do the numbers tell us?

Global imports of CO_2 neutral

gases to Europe,

i.e. green hydrogen,

synthetic methane and others,

will become an essential part of

the energy supply

in all our scenarios

Regardless of the total installed RES capacities within Europe, a complete European energy independency is not achievable in any of the scenarios. Accordingly, imports will remain an essential part of the European energy supply. However, a shift towards CO_2 neutral energy carriers, like green hydrogen and synthetic methane, is necessary to reach CO_2 emission targets.

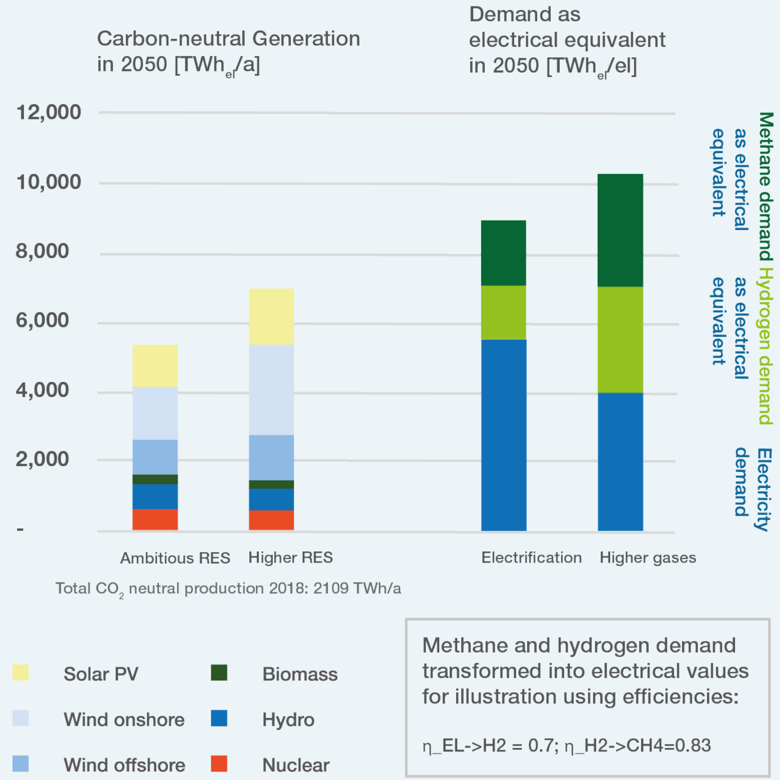

Figure 2: European supply compared with demand in 2050

Highly ambitious RES development - surpassing current accelerating national plans in Europe - is necessary to work towards CO_2 reduction targets in line with the Paris Agreement and to decrease European energy imports simultaneuously. The developed scenarios for this study underline that ambitious expansion of RES capacities in Europe is required to cover the expected growing European electricity demand. If, in addition, gas demand is to be covered by domestic RES in combination with PtG units, the expansion need for RES capacities rises even further.

Further development of the energy transmission infrastructure for electricity, hydrogen, and methane beyond 2030 is essential for the future energy system. This development needs to be planned timely in an integrated way to find optimal solutions for a faster and affordable energy transition.

Investment decisions on the demand side (electric, gas-based or hybrid) need to be coordinated with the development of the integrated energy infrastructure in order to avoid inefficiencies.

The investment decisions (i.e. location and installed capacities) of energy intensive industries and other main energy consumers have a high impact on necessary investments as well as the development of the entire integrated energy infrastructure. This needs to be incorporated when defining supportive measures for the usage of different energy carriers.

Due to the increasing total electricity demand in combination with a growing RES supply, the electricity transmission infrastructure needs to be expanded further beyond 2030. The expansion need is strongest in the scenarios with 'High Electrification' (EL & RES and EL & RES+).

In all scenarios, a high share of the final energy demand is assumed to be covered by hydrogen as energy carrier. To enable this, an EU-wide hydrogen grid needs to be developed. This can be done efficiently by refitting of existing methane transmission infrastructure.

Storages and dispatchable power plants as sources for flexibility are required to ensure a reliable, CO_2-neutral demand coverage for all hours of the year.

Power-to-Gas is a key technology for the next step in the energy transition

To further investigate the assumption on PtG capacities from IO 2050, this study is focused for the first time on the co-optimized investment and dispatch across all energy infrastructure assets. Based on the optimally coordinated dispatch of flexibility options across all energy carriers (e.g. energy transmission and batteries) electrolyser capacities reach high full load hours in the investigated scenarios. However, investment and dispatch of these units depend on the overall surplus of RES supply to the energy system. Accordingly, higher RES capacities as well as lower end-user electrification promote the installation of PtG units, which reach 110 GW in Germany and the Netherlands in scenario (Gas & RES+) in 2050.

Even in the scenario (EL & RES), PtG units may play a significant role. In this scenario CO_2 neutral hydrogen needs to be imported from sources outside of Europe. This may include sourcing it from PtG units or other means to generate CO_2 neutral hydrogen.

A smart, flexible investment in and usage of European energy infrastructure – both for electricity and gas – plays an important role for the aim of an affordable energy system.

The optimization used in the study has shown the close interaction of investment and dispatch decisions of energy transmission, conversion and storages in future energy systems. This underlines the strong interdependencies of investment and dispatch considerations in integrated energy system planning. Accordingly, an integrated framework for investment and operation strategy is essential for the successful energy transition.

The energy infrastructure is especially stressed in situations, when there is either a very high or a very low supply by domestic renewables. The applied model invests in their installation and utilizes them to their full capacity in the respective hours. Storages on the electricity site (pumped-storage and batteries) are used for short-term shifting of smaller energy volumes. For hydrogen and methane, large storage capacities were assumed in salt caverns and pore storages respectively providing flexibility especially for seasonal storage. However, for some simulated situations with very high and/or long lasting residual electricity load, investments in and the dispatch of power plants based on CO_2 neutral gases are calculated by the model – although the resulting full load hours are far below today's level (less than 1000 hours in all scenarios in 2050). In order to ensure investments in these assets, adaptions in the policy framework are required.

KEY STAKEHOLDER IMPACTS

What do we need to do?

- Prepare today for investments in energy transmission infrastructure beyond 2030! Construction of new electricity transmission infrastructure and refitting existing methane infrastructure to hydrogen are both required.
- Developments on the demand side (electric, gas or hybrid) need to be considered in combination with energy transmission grids to avoid inefficiencies. Especially energy intensive industries and other main users need to be incorporated given their impact.

- Determine desired RES development for after 2030 enabeling the decorbonization targets and allowing for acceptable levels for energy imports! This will have a profound impact on infrastructure development after 2030.
- Legal and regulatory frameworks need to facilitate and steer transition paths. First step is the implementation of an integrated system development plan. Mid-term goal could be further harmonization of regulations and markets of electricity and gas.
- Policy measures, enabling cost reduction and upscaling of PtG, shall be defined and implemented at an early stage in order to have PtG technologies well developed to meet the challenges ahead.
- International cooperation is key for an affordable, sustainable and reliable energy system. Increasing interdependencies of energy transmission infrastructures in Europe, as a cost-minimal source for flexibility, require strong political cooperation as well as alignment within Europe and also globally.

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1. Introduction

Introduction

In order to reach the goals set by the 2015 UN Climate Change Conference in Paris, CO_2 emissions in all emitting sectors need to be reduced. In energy sectors like electricity, heating, industry and transport, this can only be achieved via the use of carbon neutral energy carriers. Electricity, but also hydrogen and methane, as well as other energy carriers, can be produced in carbon neutral ways and are, therefore, considered promising energy carriers for future energy systems. Increasingly discussed and already applied options in this context are the power-to-gas concepts of producing hydrogen via electrolysis and, with some drawback regarding efficiency and cost, methane via electrolysis and subsequent methanation. The latter necessitates the provision of non-fossil CO_2. These concepts offer options of storing and transporting renewable energy and may open the path for the integration of additional renewable generation. These developments will lead to an increased coupling between the electricity, gas, heating/cooling, industrial and transport sector. The timely fashion, scope and impact of this so-called sector coupling on the necessary and optimal energy transmission infrastructure expansion and operation are not fully known and are, thus, subject to current research.

Therefore, discussions about the future sector coupling and efficient transmission system expansion intensify. As trusted advisors for future developments in the energy transition and responsible energy transmission operators, TenneT and Gasunie jointly conduct and publish a series of studies. These studies focus on future integrated enery system for electricity (EL), hydrogen (H_2) and methane (CH_4). The supply side is assumed to be dominated by RES. The energy infrastructure (transmission infrastructure, conversion and storage) acts as linking element between supply and demand. (see Figure 3).

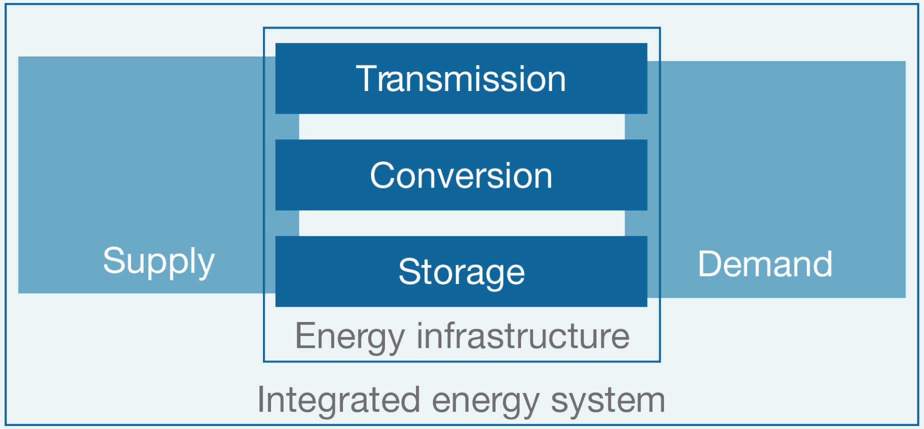


Figure 3: Definition integrated energy system

Infrastructure Outlook 2050

As one of the first steps, TenneT and Gasunie published the study Infrastructure Outlook 2050 (IO2050) in early 2019. In this study, different future integrated energy system designs for Germany and the Netherlands in the year 2050 have been investigated based on their capability to cover electricity, hydrogen and methane demands. A particular focus was set on modelling the dispatch of the transmission infrastructures for these energy carriers in combination with other flexibility options like conversion and storage. The study concluded, firstly, that an energy system based on domestic RES will rely on coupled electricity and gas grids and, secondly, that adequately located PtG units and gas storages have the potential to reduce the need for additional electricity lines.

Phase II - Pathways to 2050

The present study Phase II: Pathways to 2050 builds on the insights of the IO2050 and focuses on the necessary steps towards possible integrated energy systems, considering the cost-minimal transition of the energy infrastructure (including energy transmission infrastructure, conversion facilities, and energy storages) from 2030 to 2050, given assumed renewable capacities and demand structure of three different scenarios. While the overall aim – to increase the general understanding of influences and interdependencies in the development of future integrated energy systems – is similar to the previous study, a different innovative approach has been chosen. The present study relies on an integrated model, optimizing investment and dispatch decisions for different flexibility options in the energy infrastructure on a cost basis. With this approach, it aims at answering questions that remained unanswered in the IO2050:

- How does the expansion of RES capacities as well as the development of demand for electricity, hydrogen and methane influence the European energy system transition between 2030 and 2050?
- When, where and how many conversion and storage assets should be installed?
- How do the transmission infrastructures for electricity, hydrogen and methane need to evolve to link future supply and demand?

The remainder of this document summarizes the most important features and findings of the study. The chapter Methodology explains the overall study. The Scenario Framework Development section describes the main input data and the approach to compile it.
The chapter Integrated System Expansion Model summarizes the most important features of the developed and applied model as well as its limitations. The subsequent chapters Insights from Scenario Development and Insights from Model Calculations compile insights from the study execution. Finally, key insights and key stakeholder impacts are summarized in the Conclusion section.

2. Methodology

Methodology

The main part of this study focuses on the development and application of an integrated system expansion model with consistent input data to derive insights of general validity regarding drivers of system expansion and sector coupling.

In order to achieve this goal the study approach is subdivided into three main steps:

I. Scenario Framework Development

As input for the applied model, consistent scenarios for future energy supply from RES and demands are necessary. These scenarios need to adhere to the overall storyline of CO_2 emission reduction targets and be available in a geographical and temporal resolution, fitting to the scope of this study. During the scenario framework development existing data assumptions from available studies are compiled, checked for consistency and validity and finally used to generate three scenarios that conform to the given storyline and granularity. The three scenarios differ in the amount and distribution of

- Electricity and gas demands
- and available energy supply from RES

Additional input data, e.g. initial transmission capacities, technology parameters, import costs for energy carriers, etc. are also analyzed and compiled in this step.

II. Integrated Energy System Expansion Model

The developed model is a linear optimization model that jointly optimizes investment and dispatch decisions for units and assets in the electricity, hydrogen and methane system. The model optimizes these decisions for the European energy system. However, Germany and the Netherlands ("Focus Area") are investigated in greater detail, resulting in a higher spatial granularity than other European countries. For example, Germany is modelled in 35 regions, based on NUTS-2 regions neglecting city-states, and the Netherlands are modelled in four regions, based on NUTS-1 regions. This allows the investigation of effects on the transmission infrastructure on a detailed level for the focus area. The temporal scope covers a period of 20 years from 2030 to 2050, with time steps of five years for investment optimization and dispatch calculations.

III. Aggregation of Study Insights

Study insights arise from different parts of the study. Firstly, initial conclusions can already be derived in the scenario development phase, where fundamental relations between European RES production, consumption (end-use of different energy carriers), and required imports reveal themselves. During this phase, high-level insights regarding requirements for the infrastructure resulting from demand distributions of electricity, hydrogen and methane, necessary RES expansion and its limitations as well as insights regarding import dependency emerge. These first conclusions are summarized in the chapter First Insights from Scenario Development. Secondly, insights arise from the simulation results of the investigated scenarios. For the three scenarios, results are analyzed in detail separately and then compared to the other scenarios' results in order to derive general insights. Focus is set on evaluations that provide insights towards the study's main questions. Accordingly, especially the development of energy transmission infrastructure, sector coupling assets, storages and back-up capacities are evaluated and compared. An overview of these results is compiled in Chapter 6.

3. Scenario framework

Scenario framework

In this section, the main input data for the ensuing model application is investigated, compiled and prepared to form consistent European scenarios covering the investigated time horizon from 2030 to 2050. These investigated scenarios consist of two dimensions:

- Demand scenarios for every modelled energy carrier, region and simulated hour
- Supply scenarios for every modelled region and simulated hour

Data for these scenarios is sourced from available studies, existing scenarios and other literature. None of these studies or scenarios provides sufficient, consistent data meeting all requirements of this study. Therefore, the available data needed to be combined and modified to form consistent scenarios as presented in the following chapters[1]. Demand and supply scenarios are then combined to three framework scenarios, which form the basis for later investigations. Moreover, further input data, e.g. initial transmission capacities for electricity, hydrogen and methane and the assumed costs of expanding these capacities are presented as general input to all scenarios.

[1] The data gathered from different studies differed regarding base years, sectoral definitions, geographical resolution and CO2 reduction targets. This needed to be aligned consistently.

Demand Scenarios

Demand scenarios for this study consist of annual energy demands as well as hourly time-series for every simulated region, year and energy carrier, i.e. electricity, hydrogen and methane. Other energy carriers that are not explicitly modelled in this study, also need to be taken into account[2] in order to achieve consistent scenarios based on the same energy demand. All scenarios meet the designated CO_2 emission reduction target of 95% in 2050 and the respective reduction targets for previous years. To investigate the impact of the demand mix on the energy infrastructure, two demand scenarios are designed:

- High Electrification: In this scenario, many applications are electrified in order to increase energy efficiency. The heating sector has a high share of electric heat pumps and the transport sector is highly electrified. Nonetheless, hydrogen plays a significant role in the transport sector. Also in the industry sector, many processes are electrified. PtX technologies are applied within industrial plants in order to defossilize these processes. Some processes like chemical industry processes or steel production are also changed to hydrogen-based processes.
- High Gas Demand: In contrast to the first scenario, this scenario has a wider technology mix. Therefore, especially hydrogen but also methane as well as other renewable energy sources have a higher share in the demand mix. This applies to all sectors: the heating sector, which uses different thermal technologies, especially methane, the transport sector, where different technologies are used and, finally, the industry sector, where hydrogen and methane dominate the end-use energy demand.

[2] Other energy carriers such as liquefied, carbon neutral fuels were considered during assembling the energy demand scenarios but are not endogenously simulated in the model, based on the assumption of negligible impact on the investigated energy infrastructure.

Since no available study provided the needed data meeting all requirements, multiple studies and scenarios were combined and modified. For Germany, the dena Leitstudie[3] was used as the basis, since its scenarios electrification and technology mix, each with 95% CO_2 reduction targets, meet the requirements above. For the Netherlands the demand scenarios are based on the Dutch study Net voor de Toekomst[4], which was also used as a data basis for the IO2050. Here, the scenario *regie regionaal* is chosen as a base for the 'High Electrification' scenario, the scenario *regie nationaal* for the 'High Gas Demand' scenario. For other European countries in the outer scope of this study, the input data are based on the energy demands in the EU reference Scenario 2016[5]. Since the CO_2 reduction targets of this scenario are not as ambitious as required, an approach was developed that allows the modelling of a Europe-wide transition towards potentially CO_2 neutral energy carriers like hydrogen and methane to meet CO_2 reduction targets, while still maintaining country-specific characteristics. The trends for decarbonization of the dena study scenarios were used to adjust the energy demands of other European countries to energy demands that can reach the required CO_2 reduction targets. The scenario data from the different studies have to be modified to achieve a consistent set of input data, e.g. to consider consistent sector definitions. To further improve the input data regarding the demand for green hydrogen, further modifications for the industry and transport sector are integrated into the demand scenarios based on research during this study.

The resulting energy demands for the final simulation year 2050 are shown in Figure 4 for the focus area (Germany and the Netherlands) and compared to respective 2017 values.

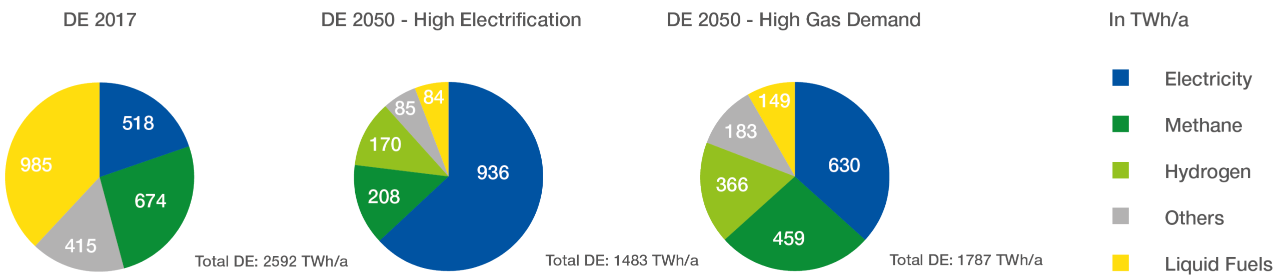


Figure 4a: Energy Demands for 2017, 'High Electrification' and 'High Gas Demand' Scenario in DE

[3] dena-Leitstudie Integrierte Energiewende, Deutsche Energie-Agentur GmbH, ewi Energy Research & Scenarios gGmbH, 2018 / [4] Net voor de Toekomst, Achtergrondrapport, CE Delft, 2017 / [5] EU reference scenario 2016 Energy, transport and GHG emissions Trends to 2050, European Commission, Energy, E3M-Lab of the Institute of Communication and Computer Systems at the National Technical university of Athens, …

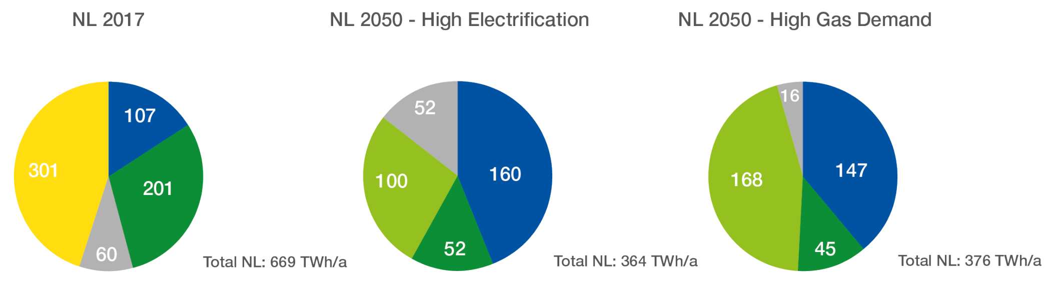


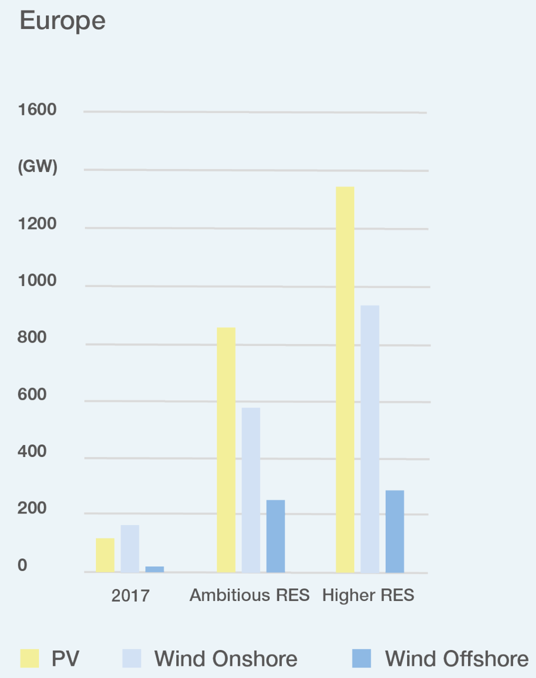
Figure 4b: Energy Demands for 2017, 'High Electrification' and 'High Gas Demand' Scenario in NL

Since Germany and the Netherlands are modelled in a higher spatial granularity, the annual energy demands are further regionalized to NUTS-2 or NUTS-1 regions respectively. Regionalization keys, e.g., inhabitants per region, employees or transportation indicators allow the consideration of regional influences and characteristics on the resulting local energy demand. Moreover, region-specific time series allow for local differences, e.g., energy demand for heating applications based on local temperature.

The scenario demand results show a substantial increase in electricity demand, especially in the 'High Electrification' scenario but also in the 'High Gas Demand' scenario. The share of gases is increasing significantly in the 'High Gas Demand' scenario, despite a decline in total methane demand. In particular, hydrogen has a significant role, especially in the 'High Gas Demand' scenario for the Netherlands. In 2017, the energy carriers electricity, hydrogen and methane, which are the focus of this study, accounted for less than 50% of the final energy sources. Especially liquid fuels like gasoline and diesel had a significant role. In contrast, by 2050, electricity, hydrogen and methane account for well over 75 % of the final energy demand.

Supply Scenarios

Analogous to demand scenarios, the model requires input regarding the supply side. This especially encompasses installed RES capacities, but also nuclear and fossil power plants, except for gas-to-power units, i.e. gas-fired power plants using methane or hydrogen, whose installed capacity is modelled endogenously. Other fossil and nuclear power plants follow a given path of planned (de-)commissioning based on TYNDP data.



Installed RES capacities are based on data of different studies to create two different scenarios:

- Ambitious RES: Already the base scenario foresees very ambitious RES expansions in order to achieve the likewise ambitious CO_2 reduction. For Germany, the RES expansion pathways of *dena Leitstudie* and TYNDP 2018 *Global Climate Action (GCA)* scenario, for the Netherlands the regie nationaal scenario from Net voor de Toekomst are chosen. For other European countries, the TYNDP GCA scenario is used and extrapolated linearly to 2050.

- Higher RES: In order to have the energetic potential for large scale conversion of RES to green gases, the second supply scenario assumes even more ambitious RES expansion. For this reason, the maximal potentials of different studies for RES expansion are assumed. For Germany and the Netherlands, the scenario relies on the maximal reasonable assumptions of IO2050, for other European countries, the potentials of the Ten Year Network Development Plan[6] scenarios and the e-Highway 2050[7] study are analyzed und utilized.

[6] TYNDP 2018 - Scenario Report, ENTSO-E, ENTSO-G, 2017 / [7] e-Highway2050, Modular Development Plan of the Pan-European Transmission System 2050, Database per country, EU 7th Framework Programme, 2015

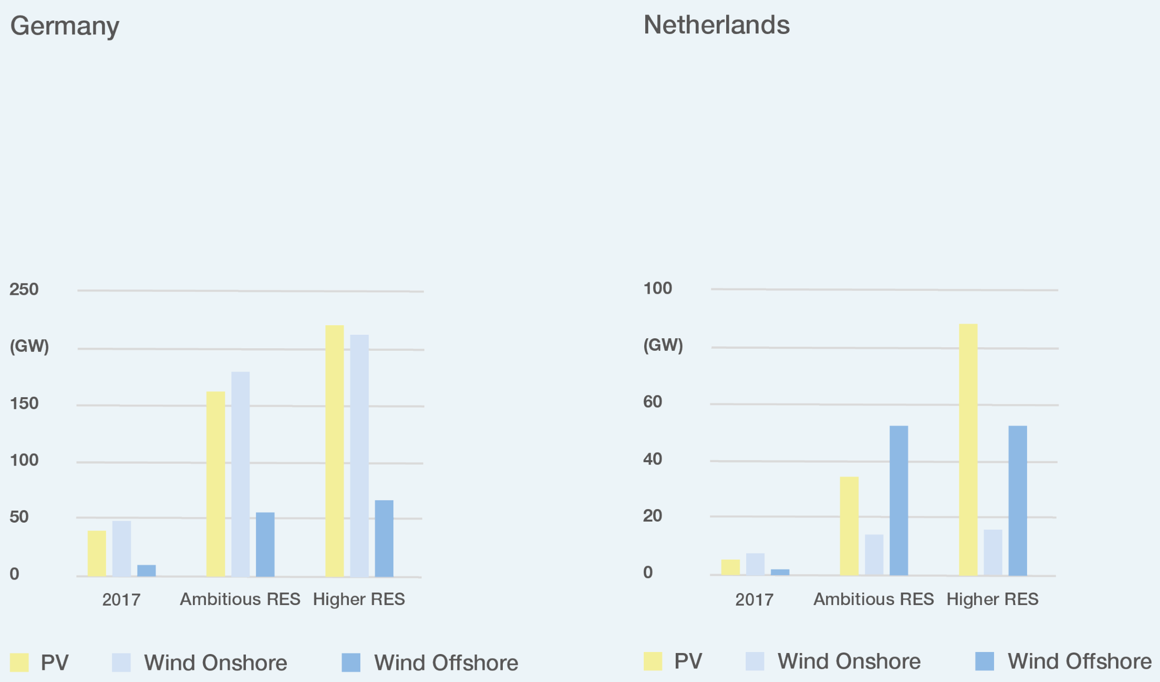


Figure 5: Installed RES capacities in DE and NL in 2050 (2017 for comparison)

Thus, both supply scenarios assume ambitious RES expansions all over Europe in order to achieve the CO_2 reduction targets. Figure 5 shows the installed RES capacities for the final simulation year 2050 for the focus area and for Europe. Historical values for 2017 are given for comparison[8].

Analogous to the demand, RES capacities are regionalized to the investigated regions, considering local conditions. Moreover, intermittent RES units are modelled with infeed time-series. These time-series are based on weather data for each region sourced from the MERRA 2 platform[9] for the meteorological year 2015 consistent to the weather based profiles for energy demand.

[8] Based on ENTSO-E Factsheet 2017 / [9] https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/

Combined Scenarios

Based on the presented demand and supply scenarios, three combined scenarios are derived. As they are already building upon the results of IO 2050 and other latest studies, those scenarios represent highly ambitious developments with regard to energy supply and demand to provide further insights on the impact of challenging frameworks to the energy infrastructure in general and to the energy transmission systems in particular:

EL & RES: RES capacities from the 'Ambitious RES' scenario are combined with efficient electrification on the demand side ('High Electrification' scenario). Electricity demand can barely be covered by domestic RES generation resulting in a low potential for the production of green gases. Focus is therefore set on the import of other energy carrier like green gases.

Gas & RES+: A change in demand structure from high electrification to a higher share of hydrogen and methane demand from the 'High Gas Demand' scenarios as well as increased RES capacities of the 'Higher RES' scenario are assumed. Lower electricity demand in combination with high RES infeed results in the highest sector coupling potential for the domestic production of green gases among the considered scenarios.

EL & RES+: Efficient electricity-based appliances and very high RES supply from the 'Higher RES' scenario reduce energy imports to Europe. Electricity demand can largely be covered by domestic RES generation resulting in large domestic sector coupling potential to produce green gases with electricity surplus from RES production that is available in many hours of the year.

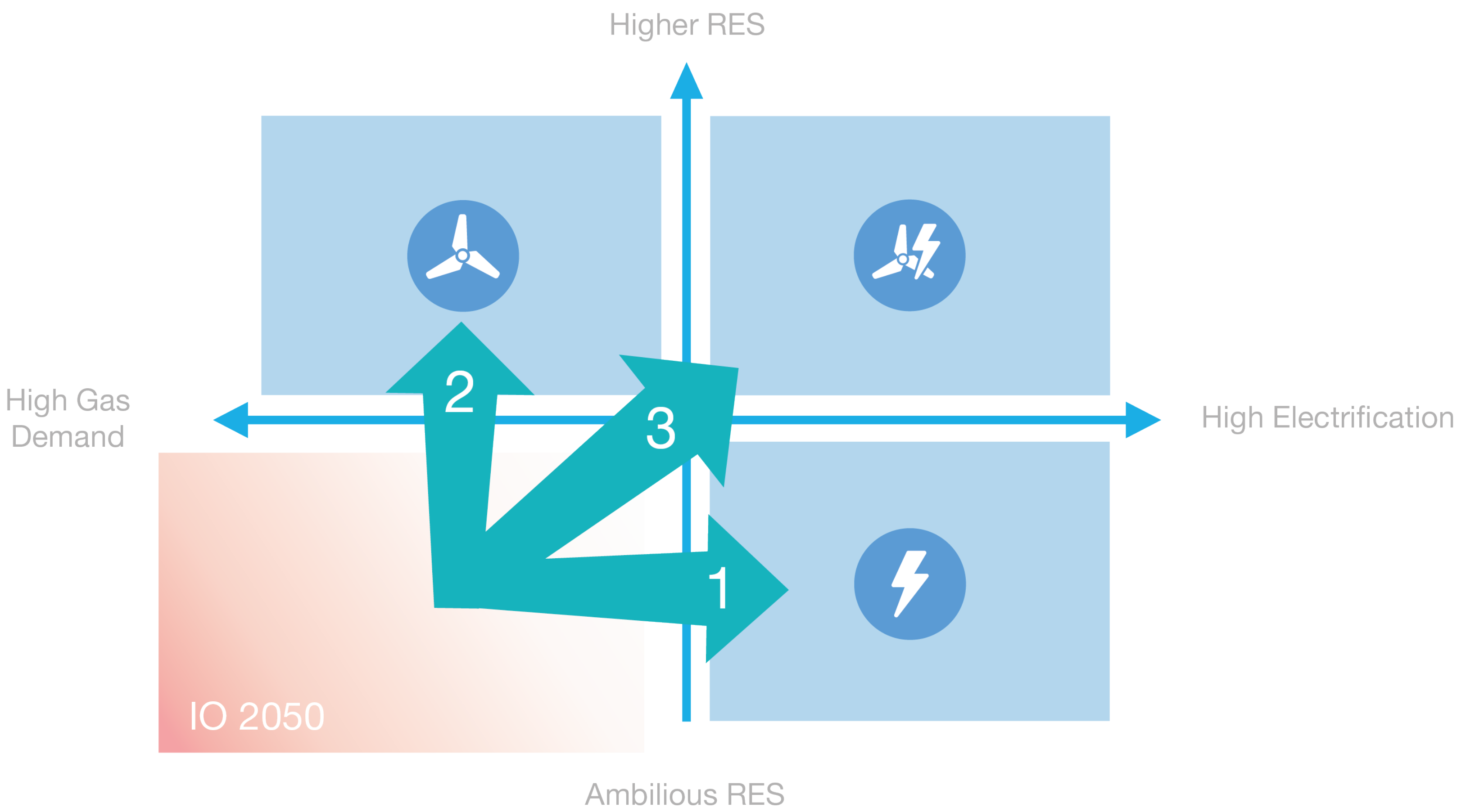


Figure 6: Developed combined scenarios

An overview of the differences of input data for energy demands and available (exogenous) generation capacities in the combined scenarios for Germany and the Netherlands for the year 2050 is given in Table 1.

			2050					
			EL & RES		Gas & RES+		EL & RES+	
			Germany	Netherlands	Germany	Netherlands	Germany	Netherlands
Energy Demands [TWh/a]	Buildings Heating	Electricity	164	23	113	15	164	23
		Hydrogen	0	6	0	61	0	6
		Methane	24	22	170	19	24	22
		Others	19	41	118	5	29	41
	Buildings Appliances	Electricity	173	66	213	66	173	66
	Industry	Electricity	490	47	217	47	490	47
		Hydrogen	37	68	163	68	37	68
		Methane	171	1	267	1	171	1
	Transport	Electricity	110	24	86	18	110	24
		Hydrogen	133	25	203	39	133	25
		Methane	13	29	21	24	13	29
		Liquid Fuels	84	0	149	0	84	0
Generation Capacities [GW]	RES	PV	165	34	218	85	218	85
		Wind Onshore	179	14	210	16	210	16
		Wind Offshore	53	53	64	53	64	53
		Biomass	10	0,5	10	0,5	10	0,5
		Run-of-River	4	0,1	4	0,1	4	0,1
	Power Plants	Nuclear	0	0	0	0	0	0
		Lignite	0	0	0	0	0	0
		Coal	0	0	0	0	0	0
		Oil	3	0	3	0	3	0
		Hydrogen	Based on Simulation Results					
		Methane						

Table 1: Scenario comparison of energy demands and generation capacities in DE and NL (2050)

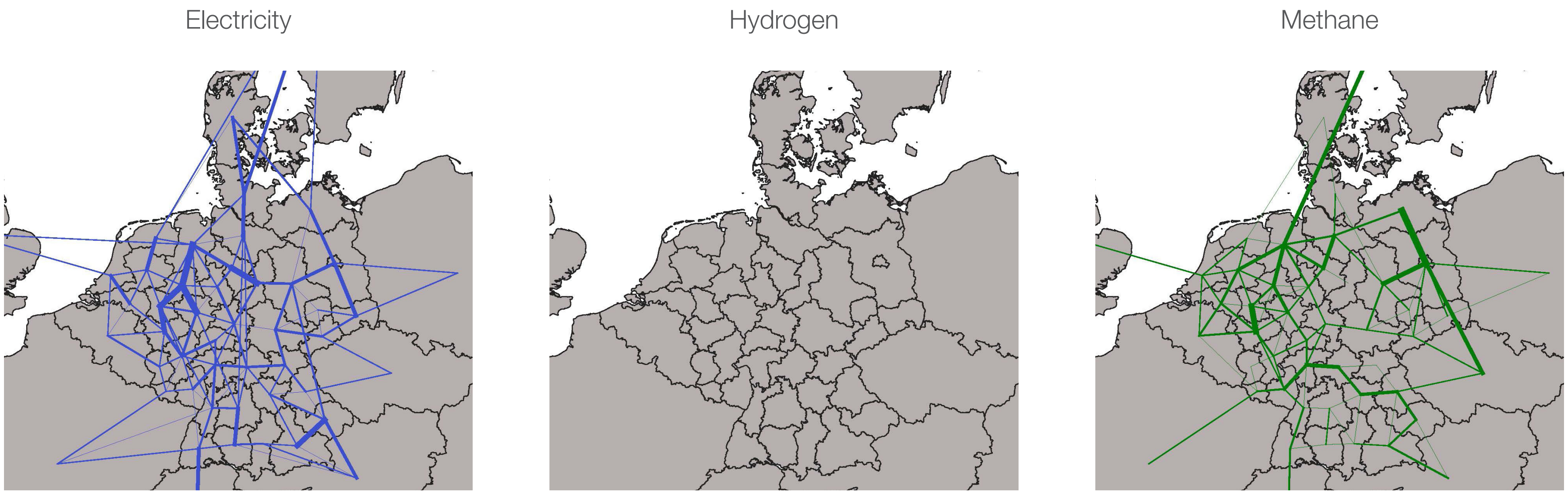


Figure 7: Assumed initial transmission capacities in 2030 for electricity, hydrogen and methan[14]

General Input

Apart from demand and supply scenarios, the model requires additional input. Most notably, this input includes initial transmission capacities between simulated regions for the first simulated year (2030) and the assumed costs for network expansion, conversion capacity, and imports of CO_2-neutral gases. This basic input is consistent for all developed scenarios. The electricity transmission capacities are approximated based on the aggregation of individual line capacities running between two considered regions including a 30% reduction of the capacities to incorporate (n-1) considerations. Interconnector capacities are sourced from the ENTSO-E Transmission System Map[10] and TYNDP 2018[11] projects to model the current planning state until 2030. For Germany, the target grid of the scenario B 2035 of the current Grid Development Plan[12] was assumed. Methane transmission capacities are approximated based on data from the ENTSO-G transparency platform[13].
For hydrogen, no initial transmission capacities are assumed for 2030. The initial assumptions are visualized in Figure 7.

[10] https://www.entsoe.eu/data/map/ / [11] https://tyndp.entsoe.eu/tyndp2018/ / [12] https://www.netzentwicklungsplan.de/en/front / [13] https://transparency.entsog.eu/

[14] Infrastructure from non-European countries is not shown in the figure

Further input includes data regarding investment costs, efficiencies and other parameters as essential input. Linearized capacity- and length-dependent investment costs for additional transmission capacities are derived from cost assumptions and data based on the German grid development plans for electricity and gas. Other investment costs are based on a respective literature review. Additionally, the developed scenarios imply a need for import possibilities of hydrogen and methane from outside the modelled region, albeit very high RES capacities in Europe are already assumed. Therefore, input data regarding today's import capacities and expected prices were investigated and used. It is assumed that imported methane is increasingly CO_2 neutral, while imported hydrogen is produced in a CO_2 neutral way from 2030 onwards, which impacts the assumed price for the respective imports. An overview of the assumed values for prices[15] and CO_2 neutral shares of the imported gases is given in Figure 8.

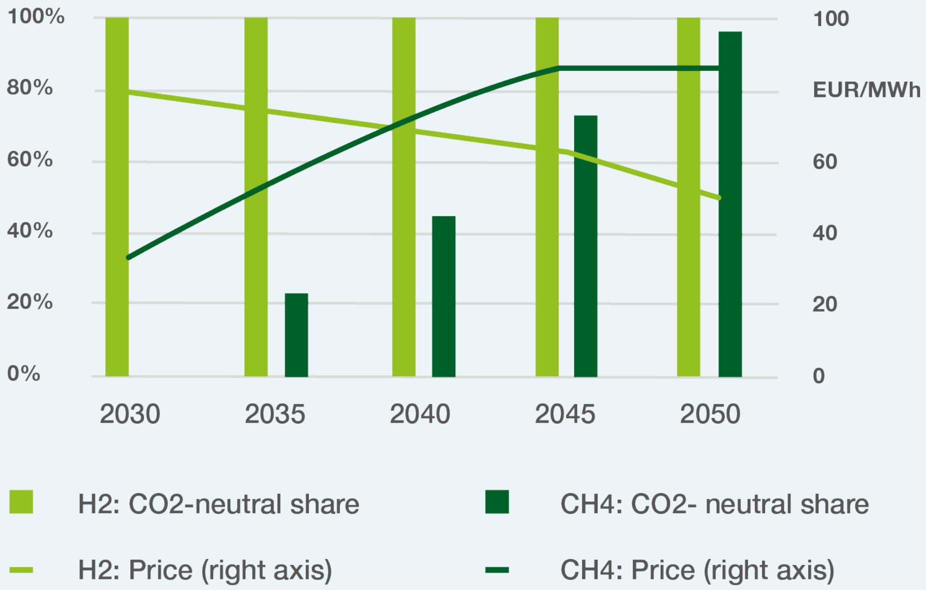


Figure 8: Assumed prices and CO_2 neutral shares of imported gases

[15] Based on own calculations and data from World Energy Outlook 2016 and Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018): The Future Cost of Electricity-Based Synthetic Fuels

4. Integrated System Expansion Model

Integrated System Expansion Model

In order to simulate the impact of different electricity, hydrogen and methane demands in combination with different supply scenarios on the development and utilization of the energy infrastructure, an integrated system expansion tool was developed. The model simulates investment and dispatch decisions regarding power plants, conversion technologies (PtG and GtP), imports, storages and energy transmission infrastructure (electricity, hydrogen and methane). In order to do so, a linear optimization problem is formulated, consisting of an objective function and constraints. The objective function minimizes total system costs, including investment costs of endogenously modelled energy infrastructure assets and operational costs arising from their respective dispatch. The formulated constraints represent restrictions confining the dispatch of these assets. In this model, the most important restrictions are demand coverage of all energy carrier demands, compliance with CO_2 restrictions as well as technical restrictions of the assets. This modelling approach allows the simulation and optimization of the energy system considering interdependencies between investment decisions in different technologies and the subsequent utility of these technologies based on their dispatch possibilities.

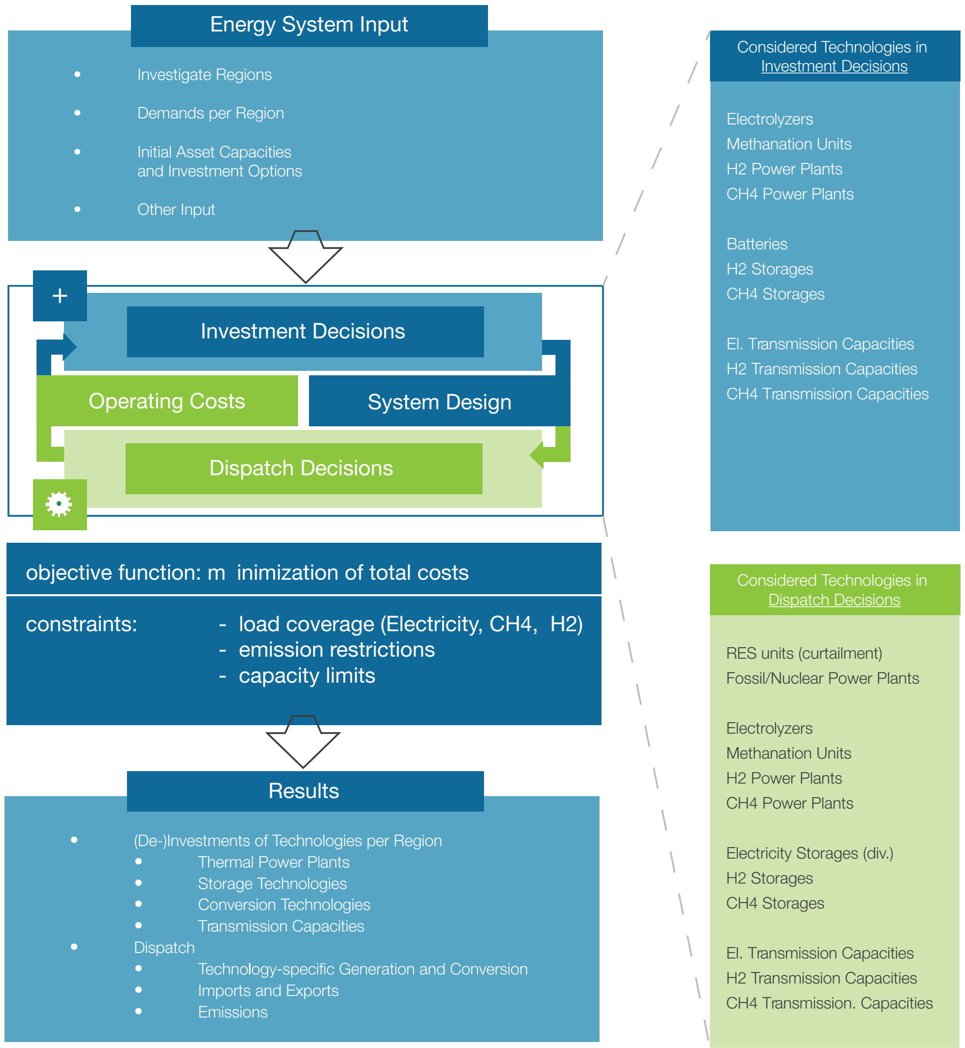


Figure 9: Overview of developed integrated system expansion model

The model uses a regional granularity, e.g., NUTS regions, countries or groups of countries, for the European energy system. The temporal scope can cover multiple decades based on representative years, e.g. in 5-year steps as was the case for the simulation runs performed in the context of the present study. Within the simulated years, the model offers the possibility to include representative weeks or all hours of the year, depending on the geographical scope and complexity of the investigated system.

The modelled regions are connected via limited transmission capacities for electricity, hydrogen and methane (analogous to the ''NTC approach" in the electricity sector) whereas transmission restrictions within regions are neglected ("copper plate"-approach). Investments into existing transmission capacities or connections between neighbouring regions are possible, allowing a simplified endogenous expansion of transmission capacities for electricity, hydrogen and methane. This allows for an approximation of necessary expansion needs for each energy carrier.

Furthermore, in every modelled region, conversion technologies like power-to-hydrogen, hydrogen-to-methane or gas-fired power plants (hydrogen or methane) are also possible investment options. This allows an approximation of the optimal degree of sector coupling in terms of infrastructural sector coupling (i.e., coupling of electricity, hydrogen and methane infrastructures).

The tool uses a linear optimization model, which aggregates power plants, conversion technologies, storages, etc. to cluster units with similar technical characteristics. Despite linearization, the resulting formulation is characterized by high complexity, in particular when covering a European geographical scope as well as a long-term time horizon. Figure 9 gives an overview of the developed model and summarizes the technologies that can be expanded endogenously in the model as well as the technologies whose dispatch is optimized in the dispatch part of the model.

The developed approach allows the investigation of various questions, providing insights, fitting to the scope and design of the model. However, necessary modelling decisions as well as necessary simplifications driven by high complexity of the investigated energy system, must be considered when interpreting the presented results. The following overview summarizes the model's main features and limitations.

Main aims of developed approach

- Investigate the impact of possible demand and supply developments on energy conversion and transport needs as well as the required infrastructure transition in the focus area of Germany and the Netherlands

Main features of developed approach

- Integrated modelling of the electricity, methane and hydrogen infrastructure
- Integrated optimization model allows combined consideration of investment and dispatch decisions considering interdependencies and trade-offs in energy system design
- Modelling pathways in 5-year steps from 2030 to 2050
- Focus on Germany and the Netherlands ("focus area") with higher spatial granularity to allow results on regional level
- Consideration of European synergies through European scope

Main limitations of developed approach

- Model simplifications for complexity reduction necessary
  - Simplified modelling for transmission capacities necessary
  - Simplified modelling for seasonal storages necessary
  - Other spatial & temporal simplifications as well as simplifications regarding level of detail of assets
- Minimization of total system cost implies macro-economic rather than business oriented view
  - Results valid for high-level indications of influencing factors in sector coupled energy systems
  - No conclusions can be made for individual units, (pipe)lines, etc.

Figure 10: Main aims, features and limitations of the developed approach

5. Insights from Scenario Development

Insights from Scenario Development

In the process of researching and developing the scenario framework for the subsequent simulations, first general insights regarding future energy systems already manifest. These insights illustrate general challenges of future energy systems as well as help to assess and better understand simulation results of this study.

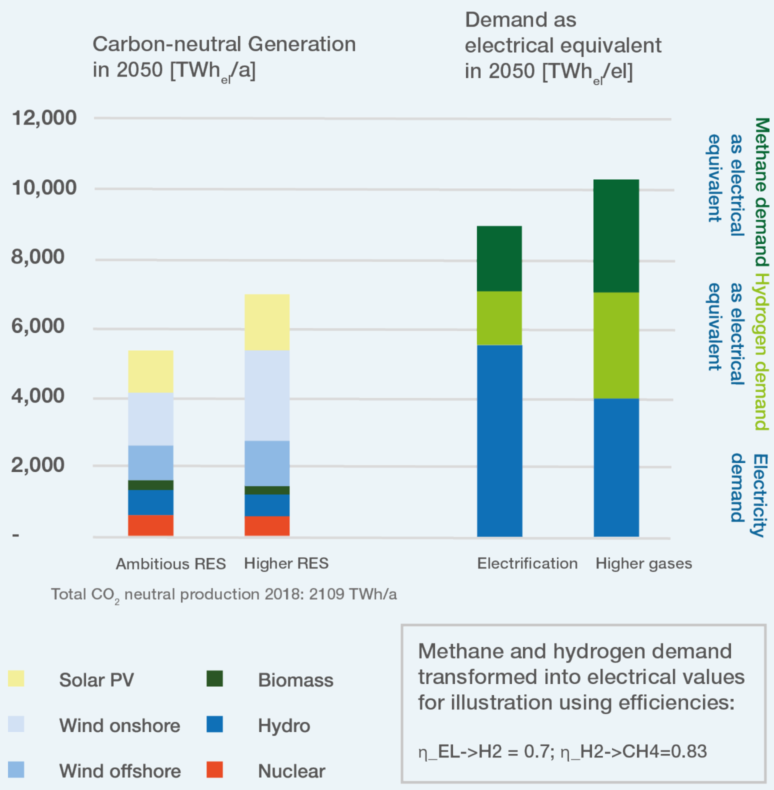


Figure 11: European supply compared with demand in 2050

Electrification of end-user applications increases efficiency and helps to avoid losses of conversion technologies, while a high gas demand may relieve the electricity infrastructure

Analyzing the two developed demand scenarios, one based on high electrification and one based on higher use of hydrogen and methane, a difference in final energy demand can be observed. This difference stems from the fact that most gas-based applications have a lower efficiency compared to electric applications, increasing the final energy demand (see figure 11).

Today, imports cover the biggest part of the demand for gases or most other fuels. If the future energy system relies more heavily on gas production from power-to-gas units, conversion losses of these units also have to be taken into account, raising the primary energy demand further.

This implies that electricity generated from RES will generally be used to cover electricity demand first. Only when RES generation cannot cover the electricity demand directly, e.g. because of limited transmission capacities, storage options or oversupply in the total system, electricity should be used to cover gas demands via power-to-gas units.

On the other hand, high electrification leads to increasing peak-loads in the electricity system, resulting in a high need for flexibility options such as transmission capacities for imports, storages or conversion assets. In contrast, a high share of gases or other alternative energy carriers reduces the stress on the electricity system at the cost of increasing the demand for primary energy due to less efficient technologies and conversion losses. In addition, the gas sector can provide substantial transport and storage capabilities to the energy system, possibly counteracting the previously mentioned disadvantages.
The trade-off between advantages and disadvantages of using different energy infrastructures for transport or storage to cover given demands is intrinsically modelled in the developed simulation approach. The results represent an overall efficient pathway to the CO_2 reduction target within the given boundaries and assumptions. Therefore, simulation results in the next chapter will give indications regarding the optimal solution of this trade-off for each scenario.

Highly ambitious RES development all over Europe is necessary to work towards CO_2 reduction targets and lower dependency on energy imports

Only the 'Higher RES' scenario towards 2050 provides sufficient RES infeed to cover the rising electricity demand through carbon-neutral sources, especially in the (EL & RES) and the (EL & RES+) scenario. This underlines the necessity of continued and increased effort to expand RES capacities in the future, when CO_2 emission reduction targets are to be met. The developed scenarios, therefore, rely on studies that assume very ambitious RES developments for the future. Nonetheless, even for these ambitious RES developments, the expected RES infeed falls short regarding the whole future energy demand. As a result, the sector coupling potential even in very ambitious scenarios is not sufficient for complete energy independence in Europe.

Imports of gaseous energy carriers will remain an essential energy source, leading to a continuing need for transmission infrastructure for molecules. Natural gas will be replaced by CO_2-neutral gases (hydrogen and methane).

Building on the last insight, one major conclusion of comparing the assumed RES capacities to the foreseen demand is that Europe will continue to depend on substantial imports of energy carriers in the future. Additionally, in order to meet tightening CO_2 emission targets, these imports will need to be CO_2 neutral to an increasing extent towards 2050. This makes potentially CO_2 neutral fuels like hydrogen and methane likely candidates as energy carriers used for import. Accordingly, an adequate infrastructure will be necessary to enable their transport. Simulation results of this study allow conclusions regarding the necessary infrastructures for hydrogen and methane. These results are presented in the next chapter.

6. Insights from Model Calculations

Insights from Model Calculations

The developed integrated system model is applied to each of the three presented scenarios described in the chapter Scenario Framework Development. Subsequently, the simulation results for every scenario, consisting of investment decisions as well as dispatch decisions for the years between 2030 and 2050, were analyzed and evaluated. In this summary, focus is put on investment decisions in sector coupling units and batteries for electricity storage as well as resulting need for investments in transmission infrastructure.

Development of power-to-gas units, especially electrolyzer units, largely depends on the available RES generation and electricity demand

With higher installed RES capacities, electrolyzer units become more advantageous to the overall system towards 2050. They are mostly installed close to offshore wind connection points. In addition, some capacities are also located near to hydrogen demand centers. In total, around 110 GW of electrolyzer capacity is installed in the (Gas & RES+) scenario inside the focus region, followed by the (EL & RES+) scenario with around 63 GW capacity. The lowest amount is installed in the (EL & RES) scenario, with around 8 GW in 2050. The regional distribution in the focus area and development from

2030 to 2050 is displayed in Figure 12. Most of the electrolyzer capacity is built between 2040 and 2050. However, in the (Gas & RES+) scenario, a higher share of H_2 end-user applications drives ramp-up of sector coupling assets already in 2035.

In the (EL & RES) scenario, installed RES capacities and therefore infeed is lower compared to the other two scenarios prohibiting frequent oversupply of RES infeed. Accordingly, the available RES generation is mostly used to cover electricity demand rather than hydrogen demand via the PtG route. This demand is, therefore, mainly sourced from imports. Full load hours of the electrolyzers in this scenario reach 1900 h in 2050. In the other two scenarios, RES capacities and infeed are higher. Additionally, in the (Gas & RES+) scenario, the electricity demand that needs to be covered, is much lower. This allows for higher amounts of available RES generation for conversion to hydrogen. Full load hours reach 4770 h in the (EL & RES+) scenario and 6690 h in the (Gas & RES+) scenario in 2050.

Methanation units are only expanded in the (Gas & RES+) scenario - to a negligible degree - where they cover an insignificant share of the methane demand in 2050. In the other scenarios, there is no indication for the advantageousness of methanation units under the given assumptions. Renewable energy is a scarce resource in all investigated scenarios. The additional efficiency losses of the methanation process are only justified in cases when sufficient RES generation is available to cover the electricity and hydrogen demand first. In the investigated scenarios, RES capacities are not sufficient to allow for large-scale methanation capacities to materialize, given the chosen assumptions on cost and efficiency.

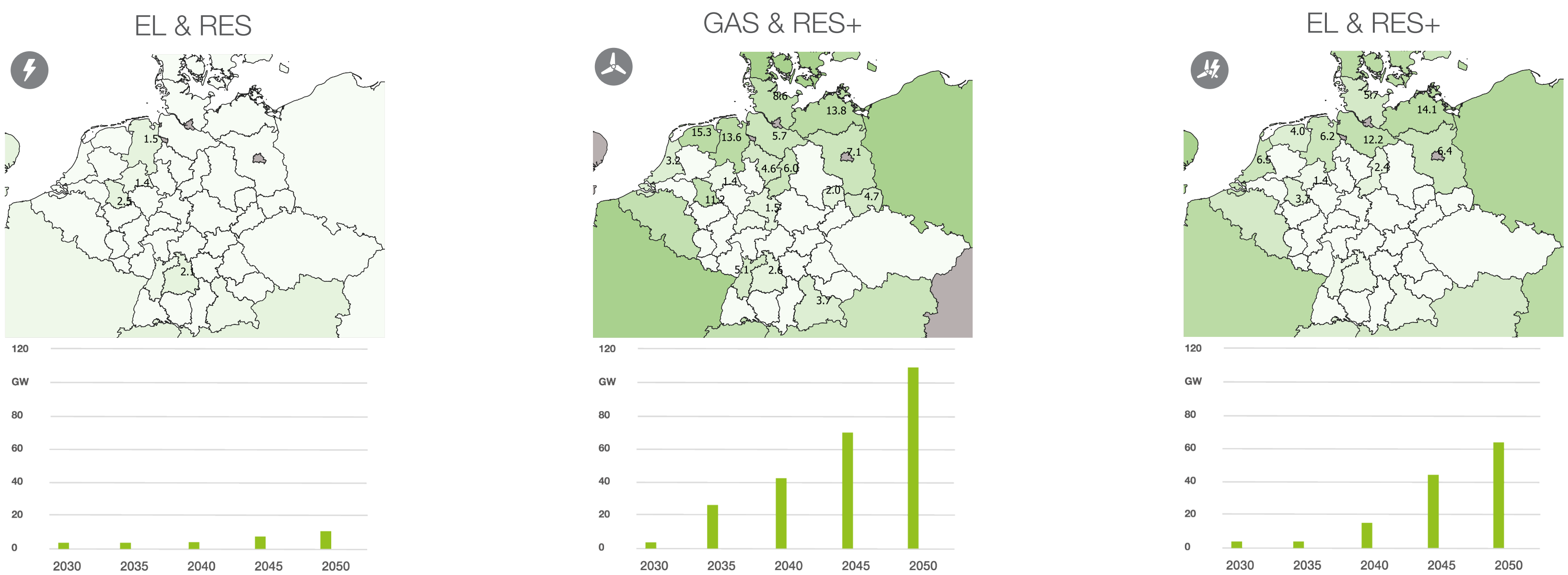


Figure 12: Installed electrolyzer capacities in GW in 2050 and development in focus area

Dispatchable power plants are necessary in all scenarios, but have very few load hours

In the investigated scenarios, significant capacities of methane-fired power plants are not decommissioned in order to provide secured capacity in high load situations. In two scenarios, the initial capacities of these power plants suffice for the most part and are not expanded. Only in the (EL & RES) scenario, where RES capacities are comparatively low, but peak-loads are strongly increasing due to high electrification, additional methane-fired power plant capacities are constructed to total 95 GW in 2050 in the focus area. In this scenario, these capacities are regularly used in winter situations to cover ordinary electricity demand (energy need), rather than only very few peak-demand situations (power need) as in the other scenarios. Accordingly, methane-fired power plants reach comparatively high full load hours of around 1050 h. This is in strong contrast to the other scenarios, where these power plants are only used rarely for peak-load situations. Here, 75 GW in the (EL & RES+) scenario and 31 GW in the (Gas & RES+) scenario of installed capacity are required by the system in the focus area in 2050. Based on the used meteorological year, these units only reach very low full load hours of less than 100 h in both 'Higher RES' scenarios in 2050. Electricity producers based on hydrogen are not expanded in the simulated scenarios, although they are modelled with comparable prices and efficiency parameters.

In many cases, the utilized methane-fired power plants are capacities from the initial power plant stack, having a cost advantage over hydrogen-fired power plants that require new investments. Furthermore, newly constructed methane-fired power plant capacities in the Import-oriented scenario benefit from the availability of high methane transmission capabilities. These units require substantial amounts of methane in very few hours for peak-load coverage. While the methane transmission capacities can provide these high transmissions, hydrogen capacities would have to be expanded via re-purposing of methane capacities or newly installed capacities. Considering the limited amount of hours, in which these capacities are required, this is not advantageous to the overall system. Modelling decisions regarding technical lifetimes of power plants, hydrogen storages and infrastructure might impact the model results regarding the expansion of hydrogen-fired power plants. More detailed modelling of these units may provide further insights regarding this topic.

In the investigated scenarios, demand side management is not considered. However, in case of low utilization of backup capacities in few hours, demand side management might be a flexibility option that allows the reduction of installed backup capacity of power plants.

Existing gas storages suffice for investigated scenarios, while electricity storages are expanded depending on scarcity of residual RES infeed

As initial storage capacities for methane and hydrogen, existing storages have been assumed. For methane, pore and aquifer storages with a working storage capacity of 246 TWh$_{CH_4}$ are assumed in the focus area. For hydrogen, existing salt cavern storages have been assumed to be converted for hydrogen storage, totaling 101 TWh$_{H_2}$ working storage capacity in the focus area (98 TWh$_{H_2}$ in Germany and 3 TWh$_{H_2}$ in the Netherlands), especially in the northern part. The simulation results show no expansion of these storage capacities until 2050, based on the chosen assumptions. The receding use of methane and the remaining high capacities of methane transmission capacities as well as the flexibility of import options assumed in this model do not necessitate additional storage capacities. For hydrogen storages, initial overall storage capacity also suffices under the given assumptions. However, further, more detailed modeling of these storages is advised for further investigations.

In the electricity sector, a significant amount of batteries is expanded in all scenarios, serving as electricity storage. The highest installed battery capacities can be observed in the (EL & RES) scenario with 18 GW (and an energy storage volume of 36 GWh), although 11 GW are already decommissioned after reaching the end of their assumed technical lifetime. These high installed capacities underline the importance of RES infeed in this scenario, which is only scarcely available. In this case, batteries are installed in order to save the available surplus electricity due to their high efficiency.

In the (EL & RES+) scenario 13 GW (26 GWh energy storage volume) of batteries are installed in the focus area in 2050.

In the (Gas & RES+) scenario the lowest capacity is installed with 7 GW (14 GWh of energy storage volume). Here, high capacities of electrolyzer units are installed, reducing the need for flexibility from battery storages. Figure 13 shows the distribution of battery capacities in the focus area in 2050, as well as their development from 2030 to 2050. Installed battery capacities are roughly the same in all scenarios, indicating that battery storage does not play a significant role for longer term storage under the installation cost assumptions that were used in the model runs. Installed battery capacities were mainly used for short-term storage of electricity. However, in this study, provision of control power was not modelled, which might be an additional application for storages.

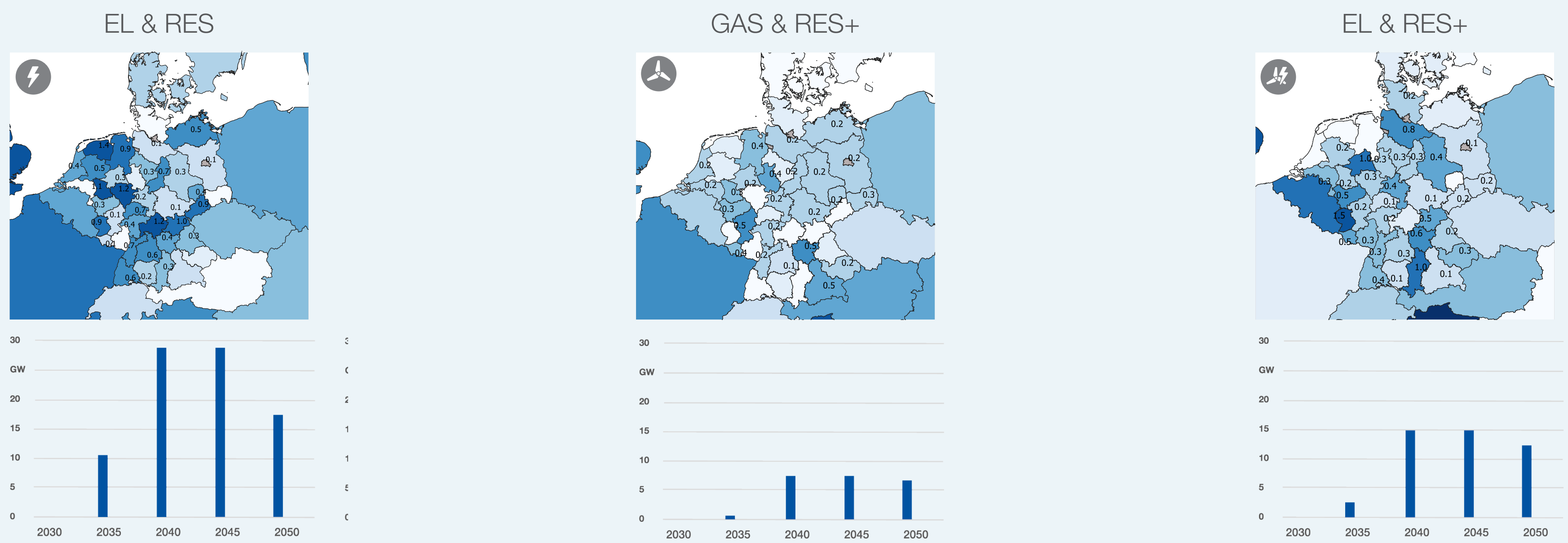


Figure 13: Installed battery capacities (power) in 2050 and development in focus area

Expansion of electricity transmission capacity as well as refitting of methane to hydrogen transmission infrastructure is necessary in all considered scenarios

In all simulated scenarios, expansion of electricity transmission capacity is advantageous in the focus area, albeit to varying degrees. In the (EL & RES+) scenario, where RES infeed and electricity demand is high, the simulation results indicate the highest need for additional transmission capacity. The biggest share of additional transmission capacity is located in the northern part of the focus area, where the installed RES capacity, especially offshore wind capacities, are highest.
In the (EL & RES) scenario, the additionally installed transmission capacities are lower than in the (EL & RES+) scenario. Here, additional capacities are located across the focus area forming North-to-South corridors.
The smallest increase of electrical transmission capacities can be observed in the (Gas & RES+) scenario. Capacities are barely increased in the focus area, and instead significant parts of the considerable RES infeed in this scenario are converted to hydrogen close to the source (cf. installed electrolyser capacity),
while the existing electricity transmission capacities suffice to supply the comparatively low electricity demand. As a result,
the demand side with high peak loads has a higher sensitivity on transmission capacity needs than installed RES capacities,
since load cannot be easily curtailed. Figure 14 illustrated the electricity transmission capacities that are installed in addition to the initial 2030 transmission capabilities in all three scenarios up to 2050.
These results base on a simplified modelling approach of electricity transmission capacities, a more detailed modelling and simulation might give further insights into the topic.

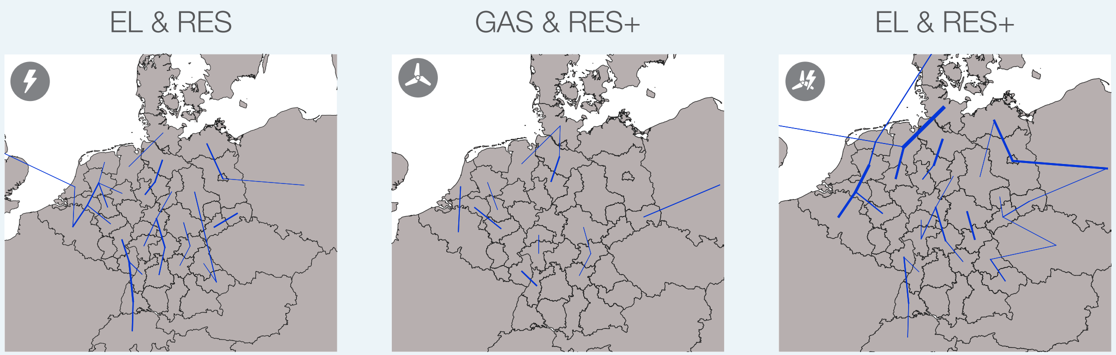


Figure 14: Expansion of electricity transmission capacities in focus area up to 2050

In contrast, methane transmission capacities are not expanded in any of the simulated scenarios. The decreasing methane demand causes lower utilization and therefore decreasing need for the existing methane transmission infrastructure. Consequently, existing capacities are refitted for hydrogen transmission, as displayed in Figure 15. Under the given assumptions, the emerging hydrogen transmission infrastructure is exclusively based on former methane infrastructure in the simulated scenarios. As these results are based on a simplified modelling of the refitting requirements, a more detailed modelling and simulation with different cost assumptions might give further insights into the topic.

Refitting methane transmission infrastructure for hydrogen transmission lowers the respective capacity for methane transmission. The resulting transmission infrastructures for all scenarios are illustrated in Figure 16. The changes of methane transmission capacities are negligible on most borders, only few transmission capacities are fully refitted for hydrogen transmission.

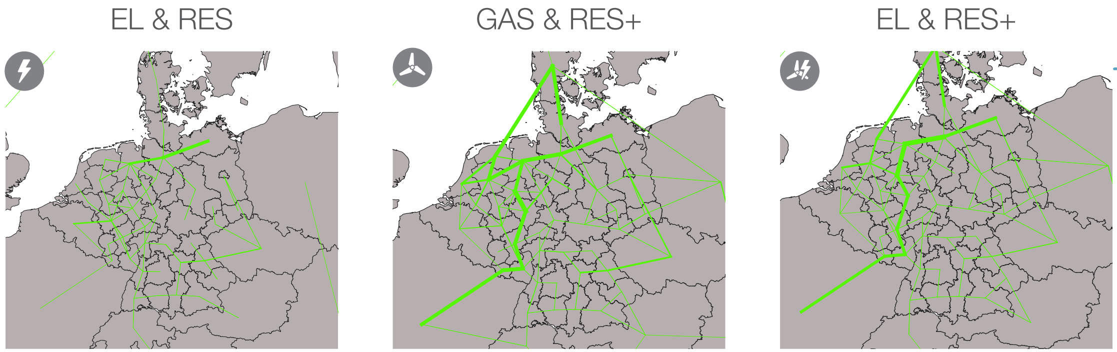


Figure 15: Development of hydrogen transmission capacities in focus area up to 2050 [16]

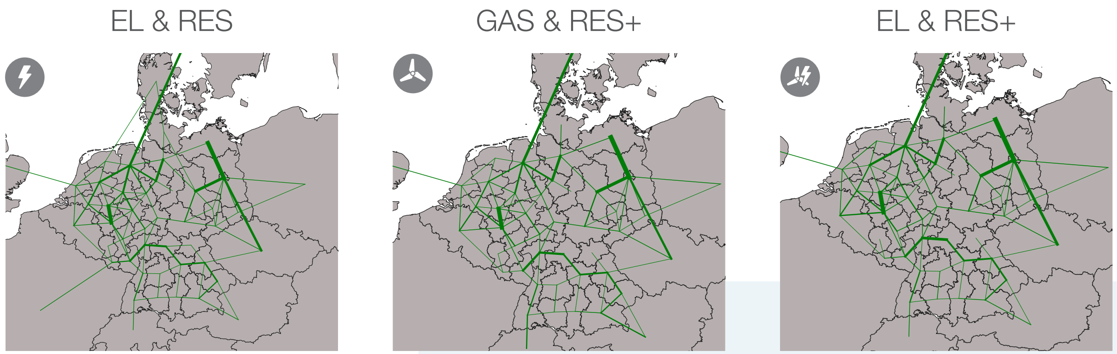
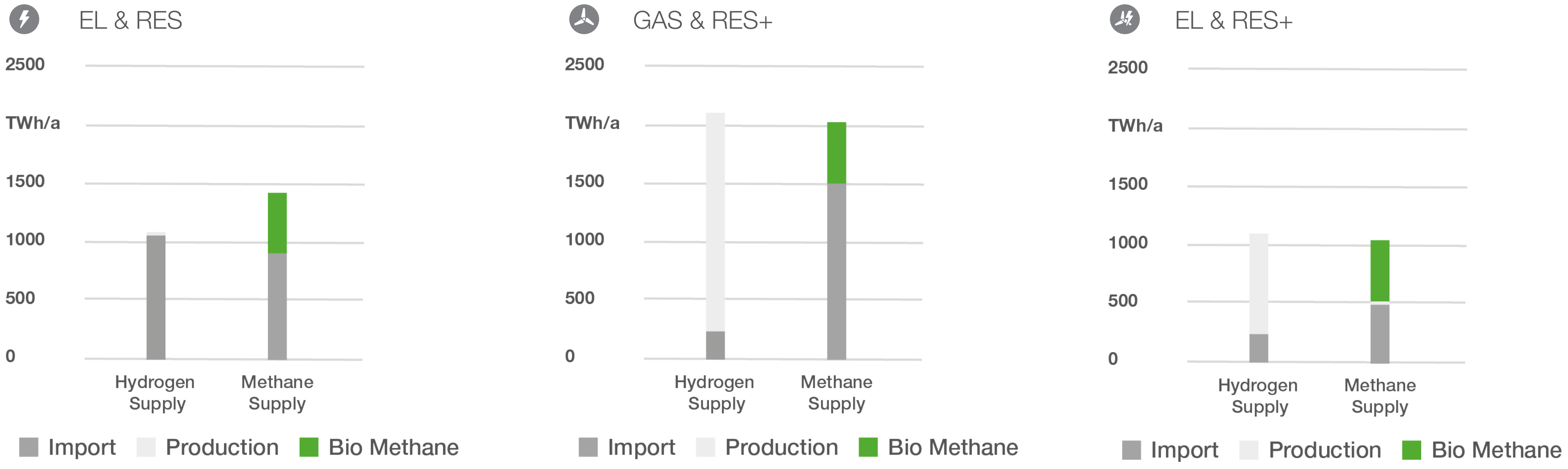


Figure 16: Remaining methane transmission capacities in focus area in 2050 [17]

High installed RES capacities and electrification in combination with PtG units decrease energy imports

[16] Infrastructure from non-European countries is not shown in the figure / [17] Infrastructure from non-European countries is not shown in the figure



Gas import share 77,6%   Gas import share 42,9%   Gas import share 36,3%

Figure 17: Hydrogen and methane sources in Europe in 2050

The installed RES capacity determines the potential for domestic production of green gases, since surplus electricity can be converted to gases. In the simulated scenarios, conversion assets mostly produce hydrogen, due to energy efficiency (in comparison to methanation), which can substitute hydrogen imports. Based on the lower efficiency, methanation units are very rarely installed by the model. Accordingly, due to the low utility of methanation units in the resulting energy system, methanation units are not expanded in the simulated scenarios. On the other hand, electrolyzers can be used considerably in scenarios with high RES infeed. Accordingly, these units are expanded to a significant extent in the respective scenarios, as highlighted previously.

The expansion and dispatch of PtG units affects the gas supply structure in the simulated scenarios. In cases, where residual RES infeed is available (i.e. in the 'Higher RES' scenarios), a significant amount of the hydrogen demand is covered with domestic production. Additionally, when residual RES infeed increases further, due to lower electricity demand (e.g. in the (Gas & RES+) scenario, the domestic production of hydrogen also increases. The remaining demand, as well as the major part of the methane demand is imported from outside Europe. Domestic production and imports of hydrogen and methane as well as resulting import dependency rates are illustrated in Figure 17 for the three considered scenarios.

Future energy systems will rely heavily on flexibility options to manage considerable positive and negative residual demands

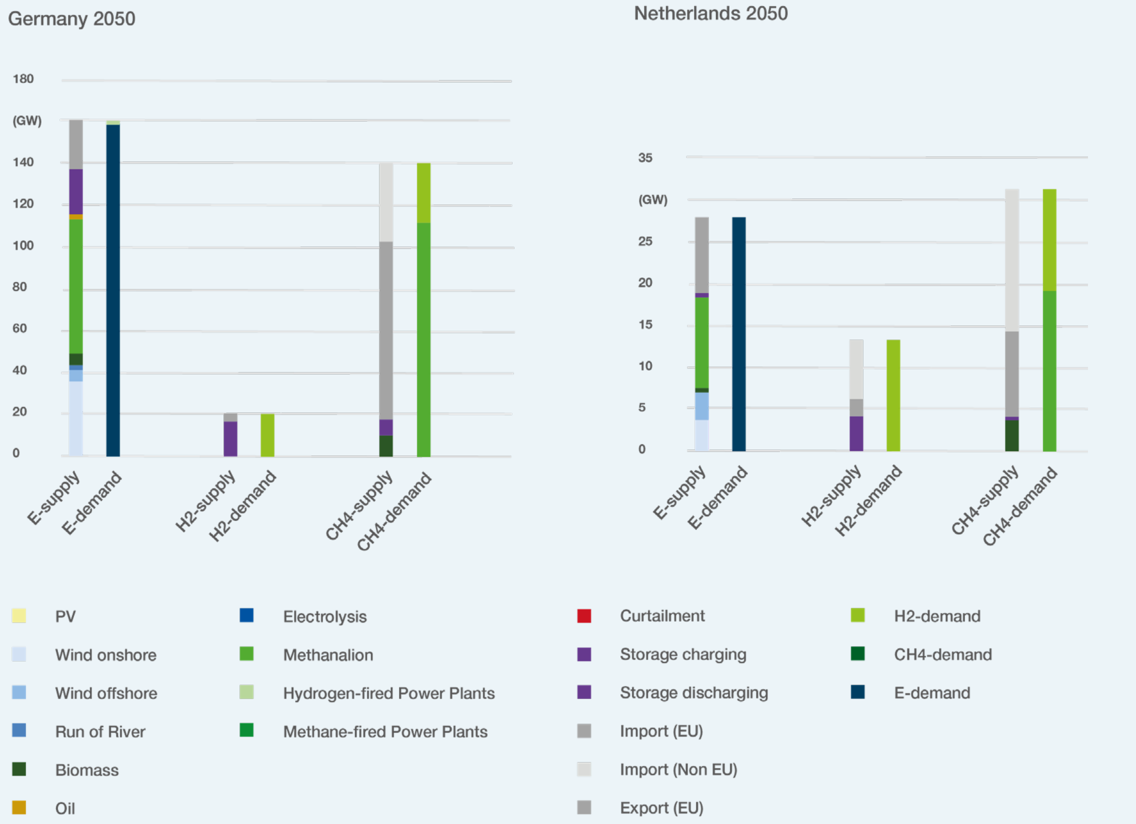


Figure 18: Dispatch in hour with high residual load in DE and NL in 2050 ('EL & RES+') scenario

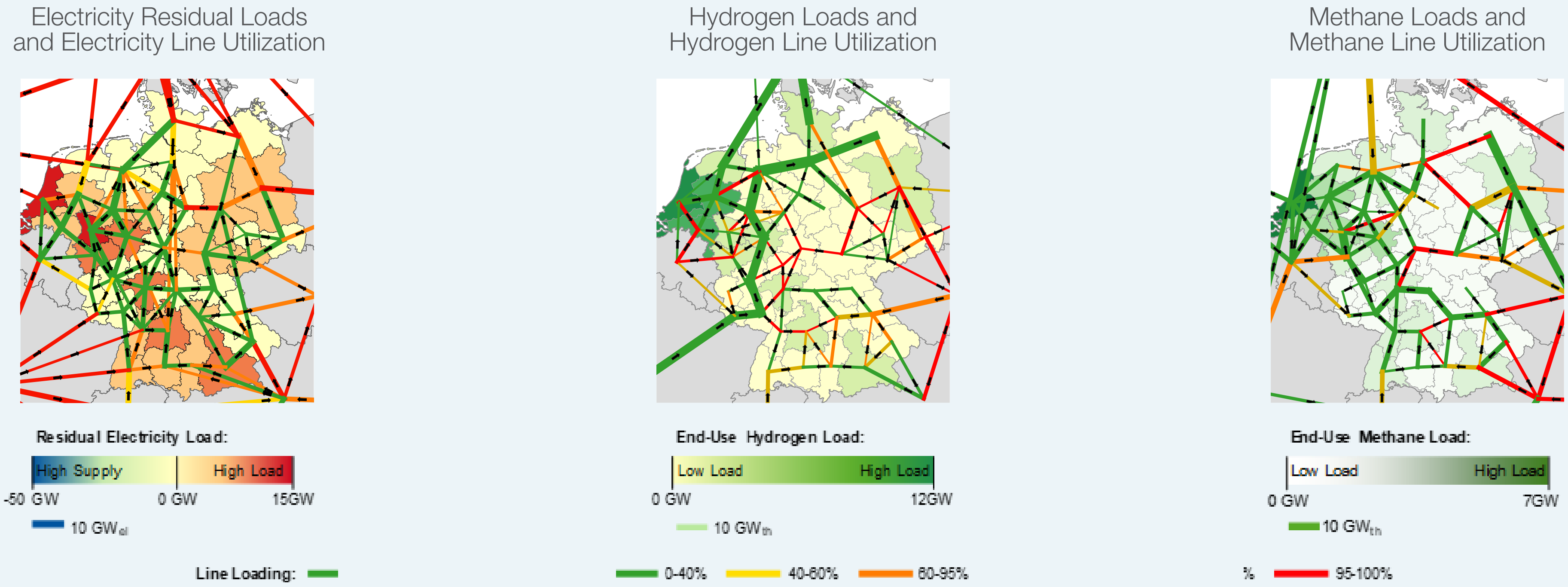


Figure 19: Dispatch in hour with high residual load in DE and NL in 2050 ('EL & RES+') scenario [18]

The applied approach optimizes the energy system in a way that allows it to cope with every critical situation included in the defined scenario. Despite high installed capacities of RES, situations with high residual loads occur, which can be challenging to the overall system. These situations manifest in times of high electricity demand for conventional electric appliances, heating and mobility in combination with low RES infeed from wind and PV units, e.g. in cold and dark winter evenings. Various flexibility options can be dispatched in these situations, however, many face limitations. Imports from neighboring countries may be limited by transmission capacities and cannot be guaranteed at all times. Electricity storages need to be charged even in longer cold periods with low RES feed-in. Finally, back-up capacities like hydrogen-fired or methane-fired power plants can be used to cover these peak-loads. However, these units also face restrictions from their respective transmission systems. Consequently, the total system needs to be designed in such a way that allows the cost minimal investment and dispatch of all assets to ensure a secure coverage of demand in the simulated scenario. An example of how the system covers a high residual load situation in the (EL & RES+) scenario is illustrated in Firgure 18 and 19. For Germany and the Netherlands, supply and demand in this hour for every simulated energy carrier is displayed, as well as the composition of each of these positions. Additionally, the effects of this demand and supply situation on the respective infrastructures are illustrated for electricity, hydrogen and methane transmission capacities.

[18] Infrastructure from non-European countries is not shown in the figure

The results underline that the system is able to cover high residual electricity loads as shown in figure 19. In order to do so, the system relies on methane-fired power plants that cover roughly 50 % of the electricity demand in this hour, complementing the comparatively low RES infeed. Storages and imports cover the remaining electricity demand. Likewise, demands in the hydrogen and methane system are also covered by storages and imports. Especially in the methane sector, a high additional demand can be observed, which is due to the dispatch of methane-fired power plants to cover the electricity demand.

Integration of RES infeed also requires flexibility. Optimization of the total system implies that, under normal conditions, RES infeed is used as efficiently as possible. Accordingly, this electricity is used to cover existing demand first. Surplus electricity is exported to other regions with remaining demand or stored in electricity storages like batteries or pumped-storages. Subsequently, remaining RES infeed that cannot be exported or stored is used in electrolyzers for hydrogen production. Lastly, curtailment of still remaining RES infeed represents the last possible option and may be efficient, if the integration of this infeed would require high additional investments in new flexibility options. For such situations, analogously to situations with high residual load, an optimal trade-off between the investments in transmission capacities, storages and PtG units and their dispatch in the resulting energy system, including the resulting need for curtailment in rare situations,

Figure 20: Dispatch in hour with high RES infeed in DE and NL in 2050 (EL & RES+) scenario

has to be made. An example of how the system integrates RES infeed a situation with high RES infeed in the EU-oriented scenario is illustrated in Figure 20 and 21. In this situation, RES supply is significantly higher than the electricity demand (displayed in blue as "E-demand") in Germany and the Netherlands (as well as in other neighboring countries). The RES surplus is used to charge electricity storages, cover electricity demand in other regions (i.e. is exported, if residual demand exists in other regions), or to operate electrolysis units. However, in this hour, RES generation is also curtailed to a significant extent, being the measure of last resort, when all other flexibility options are fully utilized.

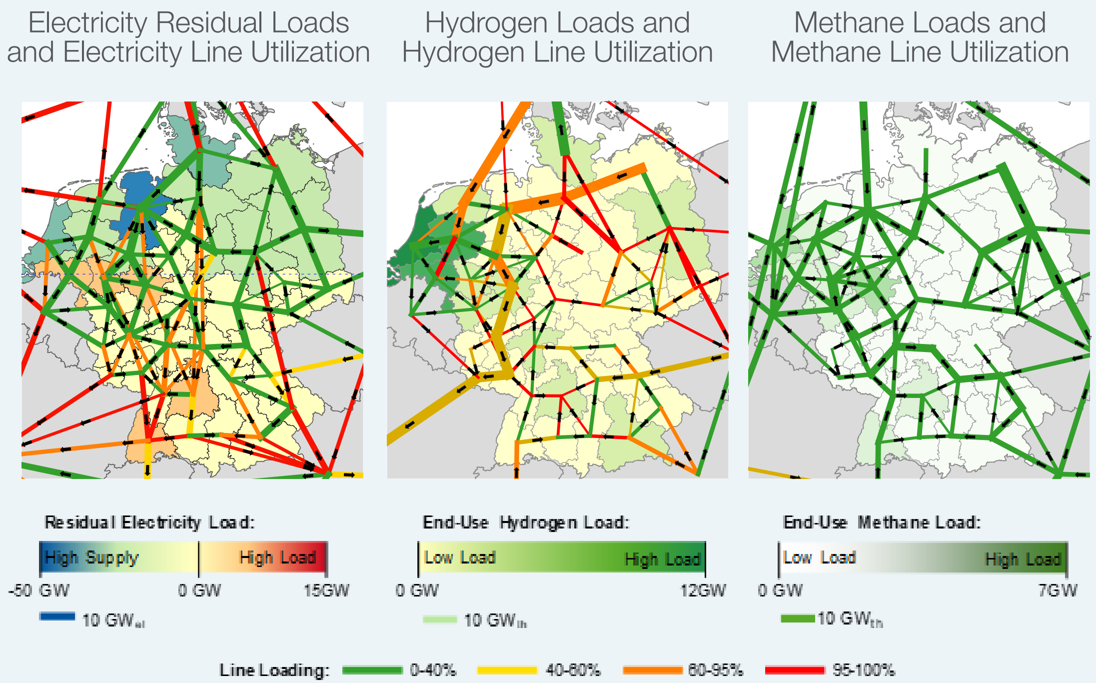


Figure 21: Dispatch in hour with high RES infeed in DE and NL in 2050 (EL & RES+) scenario [19]

[19] Infrastructure from non-European countries is not shown in the figure

7. Conclusions

Conclusion

This study aimed to increase the general understanding of influences and interdependencies in the development of integrated energy systems. In order to do so, the study focuses on following questions:

This study aimed to increase the general understanding of influences and interdependencies in the development of integrated energy systems.
In order to do so, the study focuses on following questions:

- How does the expansion of RES capacities as well as the development of demand for electricity, hydrogen and methane influence the European energy system transition between 2030 and 2050?
- When, where and how many conversion and storage assets should be installed?
- How do the transmission infrastructures for electricity, hydrogen and methane need to evolve to link future supply and demand?

The results, presented in the last two chapters, give insights towards answering these questions. Summarizing these, the key insights of this study are:

Global imports of CO_2 neutral gases to Europe, i.e. green hydrogen, synthetic methane and others, will become an essential part of the energy supply in all our scenarios

Regardless of the total installed RES capacities within Europe, a complete European energy independency is not achievable in any of the scenarios. Accordingly, imports will remain an essential part of the European energy supply. However, a shift towards CO_2 neutral energy carriers, like green hydrogen and synthetic methane, is necessary to reach CO_2 emission targets.

Highly ambitious RES development - surpassing current accelerating national plans in Europe - is necessary to work towards CO_2 reduction targets in line with the Paris Agreement and to decrease European energy imports simultaneuously. The developed scenarios for this study underline that ambitious expansion of RES capacities in Europe is required, to cover the expected growing European electricity demand. If, in addition, gas demand is to be covered by domestic RES in combination with PtG units, the expansion need for RES capacities rises even further.

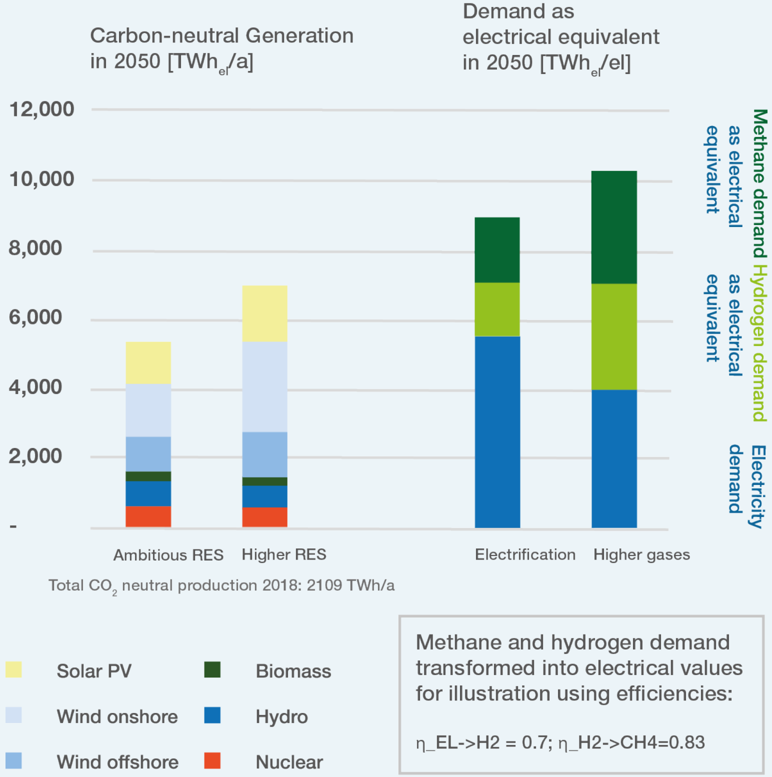


Figure 22: European supply compared with demand in 2050

Investment decisions on the demand side (electric, gas-based or hybrid) need to be coordinated with the development of the integrated energy infrastructure in order to avoid inefficiencies.

The investment decisions (i.e. location and installed capacities) of energy intensive industries and other main energy consumers have a high impact on necessary investments as well as the development of the entire integrated energy infrastructure. This needs to be incorporated when defining supportive measures for the usage of different energy carriers.

Further development of the energy transmission infrastructure for electricity, hydrogen, and methane beyond 2030 is essential for the future energy system. This development needs to be planned timely in an integrated way to find optimal solutions for a faster and affordable energy transition.

Due to the increasing total electricity demand in combination with a growing RES supply, the electricity transmission infrastructure needs to be expanded further beyond 2030. The expansion need is strongest in the scenarios with 'High Electrification' (EL & RES and EL & RES+).

In all scenarios, a high share of the final energy demand is assumed to be covered by hydrogen as energy carrier. To enable this, an EU-wide hydrogen grid needs to be developed. This can be done efficiently by refitting of existing methane transmission infrastructure.

Power-to-Gas is a key technology for the next step in the energy transition

To further investigate the assumption on PtG capacities from IO 2050, this study is focused for the first time on the co-optimized investment and dispatch across all energy infrastructure assets. Based on the optimally coordinated dispatch of flexibility options across all energy carriers (e.g. energy transmission and batteries) electrolyser capacities reach high full load hours in the investigated scenarios. However, investment and dispatch of these units depend on the overall surplus of RES supply to the energy system. Accordingly, higher RES capacities as well as lower end-user electrification promote the installation of PtG units, which reach 110 GW in Germany and the Netherlands in scenario (Gas & RES+) in 2050.

Even in the scenario (EL & RES), PtG units may play a significant role. In this scenario CO_2 neutral hydrogen needs to be imported from sources outside of Europe. This may include sourcing it from PtG units or other means to generate CO_2 neutral hydrogen.

Storages and dispatchable power plants as sources for flexibility are required to ensure a reliable, CO_2-neutral demand coverage for all hours of the year.

The energy infrastructure is especially stressed in situations, when there is either a very high or a very low supply by domestic renewables. The applied model invests in their installation and utilizes them to their full capacity in the respective hours. Storages on the electricity site (pumped-storage and batteries) are used for short-term shifting of smaller energy volumes. For hydrogen and methane, large storage capacities were assumed in salt caverns and pore storages respectively providing flexibility especially for seasonal storage. However, for some simulated situations with very high and/or long lasting residual electricity load, investments in and the dispatch of power plants based on CO_2 neutral gases are calculated by the model – although the resulting full load hours are far below today's level (less than 1000 hours in all scenarios in 2050). In order to ensure investments in these assets, adaptions in the policy framework are required.

A smart, flexible investment in and usage of European energy infrastructure – both for electricity and gas – plays an important role for the aim of an affordable energy system.

The optimization used in the study has shown the close interaction of investment and dispatch decisions of energy transmission, conversion and storages in future energy systems. This underlines the strong interdependencies of investment and dispatch considerations in integrated energy system planning. Accordingly, an integrated framework for investment and operation strategy is essential for the successful energy transition.

8. Recommendations for further work

Recommendations for further work

The execution of this study and the compilation of its results accentuated the complexity of questions relating to investigations of integrated energy systems and their development. A number of disclaimers apply and some open questions remain for continued research in this area. Recommendations for further work therefore are:

- All results presented in this study are subject to modelling assumptions related to e.g. investment and/or dispatch related costs, efficiencies, and technological availabilities. Further sensitivity analysis is recommended to enhance our insight in the interplay between electricity, gas, conversion, import, and storage infrastructure, in order to make robust statements to shape societally desired pathways to a carbon-neutral energy system in 2050.

- This study shows strong interdependencies between RES, demands for electricity, hydrogen and methane, imports, transmission capacity and power-to-gas expansion. For investigations considering the optimal expansion and allocation of RES units, infrastructure and flexibility options, we recommend modelling investment decisions in RES capacities as well as the investment decision on the demand side as endogenously determined decisions.

- In this study, the transmission (pipe)lines are modelled in a simplified way as transmission capacities between regions. Accordingly, physical power flows are not considered. For subsequent studies focusing on individual (pipe)lines, we recommend using grid models with nodal granularity considering physical power flows for electricity and gas systems.

- Analyses have shown that in addition to power-to-gas, other flexibility options can also provide important flexibility to the electricity system. We therefore recommend taking other power-to-gas options and demand side management or flexibility from district heating systems into account in subsequent studies.

- The results show that imports of green gases are necessary in all three scenarios to ensure the future energy supply with the set CO_2 targets. We therefore recommend investigating future import locations, possible import prices and the necessary infrastructure.

- This study focused on optimizing integrated investment and dispatch on cost basis. The effects of different market instruments, e.g. from capacity markets to nodal pricing were not studies in detail despite their possible (striking) effect. We therefore recommend to include a deeper analysis of the impact of market design options in future studies.

- This integrated energy system model is developed to determine transition pathways of the European energy infrastructure by minimizing the total investment and operational costs of various technological options. We are aware that these pathways have impact on the environment but since this is a system model this is not taken into account. We recommend that future studies should consider these impacts.

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The DBI Gas- und Umwelttechnik GmbH (DBI) is one of the leading German Gas institutes. DBI has long term experience and outstanding knowledge in gas technologies, research and development, innovative engineering, gas- and innovative technologies and gas strategic problems. The service portfolio includes the entire gas supply chain – from production, storage and transport down to the efficiently applied uses of renewable energy sources - and especially implementing renewable gases like hydrogen and biomethane into the existing gas infrastructure.

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With the goal of providing vital knowledge to decision-makers in politics and the private sector, the IEK-3's research activities concentrate on assessing new energy-related concepts and technologies by means of system modeling. In accordance with political frameworks, IEK-3's activities focus on developing and applying comprehensive modeling techniques for analyzing the transformational processes taking place in the supply and use of energy in Germany and beyond. The main assessment criteria are efficiency, robustness and flexibility in energy systems, as well as their economic and environmental impacts. Analyses range from isolated technical systems to national and transnational energy networks, particularly emphasizing the economy-wide integration of renewable sources via sector coupling concepts. Moreover, the integration of the national energy system into European and global supply networks is investigated, also incorporating resource availability under the evolving conditions of future energy systems.

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IAEW is part of the Faculty of Electrical Engineering and Information Technology of RWTH Aachen University. Under direction of Univ.-Prof. Dr.-Ing. A. Moser, the focus of research and industrial projects lies on the mathematical simulation, the technical and economical optimization as well as evaluation of the expansion and operation of power systems. Thereby special emphasis is placed on the markets and the generation as well as on the transmission and distribution of electrical energy. Due to many years of experience as a research institute in the field of market- , power grid- as well as system analysis, IAEW possesses detailed knowledge regarding the evaluation of market design, behaviour of market actors, grid expansion projects, power flow calculations and forecast errors of renewable energies as well as the objective interpretation of results.

crossing borders in energy

Taking power further

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Gasunie is a European gas infrastructure company. Gasunie's network is one of the largest high-pressure pipeline networks in Europe, comprising over 15,000 kilometres of pipeline in the Netherlands and northern Germany. Gasunie wants to help accelerate the transition to a CO2-neutral energy supply and believes that gas-related innovations, for instance in the form of renewable gases such as hydrogen and green gas, can make an important contribution. Both existing and new gas infrastructure play a key role here. Gasunie also plays an active part in the development of other energy infrastructure to support the energy transition, such as district heating grids. **Crossing borders in energy.**

TenneT is a leading European electricity transmission system operator (TSO) with its main activities in the Netherlands and Germany. With over 23,000 kilometres of high-voltage connections we ensure a secure supply of electricity to 41 million end-users. TenneT is one of Europe's major investors in national and cross-border grid connections on land and at sea, bringing together the Northwest European energy markets and accelerating the energy transition. We make every effort to meet the needs of society by being responsible, engaged and connected. **Taking power further**


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