FfE

eXtremOS

Summary Report

Modeling Kit and Scenarios for Pathways Towards a Climate Neutral Europe

eXtremOS

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Executive Summary

A prerequisite for achieving European greenhouse gas emission reduction targets in line with the goals of the Paris Agreement are deep emission cuts in all energy end-use sectors and on the energy supply-side. In practice, this means that these sectors must perform a substantial transition within the upcoming three decades. This creates a high demand for academic methods that capture this complexity and enable the evaluation of potential transformation pathways, thereby supporting informed decision making of policymakers and practitioners. Therefore, the aim of eXtremOS is to develop and apply methods which enable the simulation of consistent European socio-technical energy scenarios.

In an integrated scenario process quantitative modeling is combined with qualitative scenario construction to enable the development of socio-technical transformation pathways. The basis for the quantitative evaluation is a European data model that captures the energy carrier and application specific structure of European final energy consumption. To process this data into pathways depicting the European energy system transformation in the EU27, Norway, Switzerland and United Kingdom, a model landscape containing four demand-side and four supply-side models was developed/expanded in eXtremOS. These models enable the analysis of final consumption, energy procurement and consequently emission development for all 1348 NUTS-3 regions in Europe, in hourly resolution for the years 2017 to 2050. The models are designed to enable the linkage between quantitative modeling and qualitative scenario development. The disciplines of storytelling and quantitative simulation are combined in an integrated scenario process, which is applied to derive two consistent European socio-technical energy system scenarios: the climate protection scenario solidEU and a scenario named quEU, in which climate targets are not achieved. In addition, four extreme scenarios are constructed based on parameter variations performed within the solidEU scenario world.

The eXtremOS results show the importance of holistic European approach to energy system analysis as well as the added value gained by combining detailed demand and supply-side modeling. Purely national analyses are insufficient to capture the effects that a European energy transition has on the highly interconnected energy system, since all European countries are committed to the fight against climate change. Future analysis should take this finding into account.

Furthermore, the development and application of the integrated scenario process revealed that comparisons between scenario worlds are at the least extremely difficult. Numerous energy political studies at the European and German level however frequently compare climate protection and so-called reference scenarios and go as far as calculating cost differences to derive conclusions about additional costs of climate change. The solidEU and quEU development process, however, shows that the socio-political environment required to trigger quantitative developments leading to climate protection differ significantly from scenarios in which targets are not achieved. This suggests that comparisons between scenarios with completely different underlying drivers and assumptions are not meaningful.

1 Introduction

The aim of eXtremOS is to develop and apply methods which enable the simulation of consistent European socio-technical energy scenarios. This section explains the motivation behind the research and introduces the structure of this report.

The main objective of eXtremOS (XOS) is the development and application of methods that facilitate the investigation of the effect of extreme technological, regulatory, and social developments on the European energy system, which includes the EU27, Norway, Switzerland, and the United Kingdom (EU27+3). The focus on extreme scenarios is motivated by the idea that disruptive events are unpredictable but can have a significant impact on the future development of the energy system. Hence, potentially disruptive social, technical, and economic developments are identified and their effect on the development of the European energy system analyzed. EXtremOS selects scenarios which not only have significant impact on the European energy system but are also interesting from an analytical and academic standpoint, focusing both on understanding what is required to achieve climate targets in Europe as well as the complex interconnections between parameters necessary to model such developments.

Three aspects set eXtremOS apart from classical research in the field of energy transition and climate protection studies

1. European focus with the possibility of national analyses: purely national analyses are insufficient to capture the effects that a European energy transition has on the highly interconnected energy system. Hence, XOS assumes a European perspective on scenario generation and quantitative modeling.
2. Holistic European energy system model landscape: the XOS model landscape consists of eight interconnected models, which facilitate a high level of detail in energy demand and supply modeling. Using this model landscape, European transformation pathways are modeled in hourly resolution and at NUTS-3 level for the EU27+3.
3. The integrated scenario approach: in XOS qualitative, context scenarios and quantitative energy system modeling are combined using an integrated scenario approach. Through this, consistent scenario worlds are created in which techno-economic as well as socio-political developments are considered.

The starting point for defining and quantifying extreme scenarios is the construction of an EU-wide database which allows for the analysis of the energetic and market structure of the EU27+3 (cf. section 2). Amongst other sources, this database builds the basis for defining qualitative and quantitative scenarios (cf. section 3). In section 4 the eXtremOS model landscape is introduced. This model landscape is subsequently used to derive findings for the defined scenarios (cf. sections 5, 6 and 7).

This report is a summary of the most important methodological developments and findings gathered throughout the 3-year research project eXtremOS. Where relevant, highlight boxes at the side of each page are used to communicated key messages and/or direct the readers' attention towards the eXtremOS project website, publications, short reports, interactive data visualizations and open data which were developed in XOS.

The eXtremOS website provides further details on the aspects covered in this report as well as access to all publications, short reports, interactive data visualizations and open data developed in XOS. It is accessible at: https://extremos.ffe.de

2 Status Quo of the European Energy System

The status quo of the European energy system is characterized by regional differences in terms of energy generation and consumption. Identifying and documenting these heterogeneities is important and necessary not only to simulate future developments on a European scale but also to highlight existing challenges and potentials in the context of energy and climate policy targets. In this section, the data basis used to analyze and portray the energy system of each of the 30 eXtremOS countries is described.

2.1 Data Basis

To effectively monitor the status quo of each European country, a variety of datasets from different sources were compiled. These data can be divided into

- general data and qualitive information on key facts and figures, current topics and national targets,
- data on final energy consumption (FEC) and associated CO_2-emissions, and
- data on the electricity sector.

For the general data and qualitive information, sources from European institutions such as the European Environment Agency (EEA) [1], the International Energy Agency (IEA) [2] and the World Bank [3] were used and supplemented with country specific sources where necessary.

To fully capture the consumption side of each nation's energy system, a comprehensive methodology to create so-called application-oriented energy and emission balances for all 30 countries was developed. These balances represent the compilation of detailed status quo data on annual final energy consumption and energy-related CO_2-emissions for the four final energy sectors. As a foundation for the balances, data on final energy consumption per nation, year, energy source, sector and industry branch are obtained from the database of the statistical office of the European Union (Eurostat) [4]. These data are subsequently processed and combined with data from other sources on a sector-specific basis. To achieve a precise differentiation of applications at the lowest level of detail, mainly two studies by Fraunhofer ISI were used and blended with energy data [5], [6]. The energy-related emission balances are based on annual, country-specific emission factors from the UN National Inventory Reports (NIR) [7], which are scaled with each country's final energy consumption per energy source. The resulting application-oriented energy and emissions balances are used to analyze and display the status quo of past years for each eXtremOS country in addition to being input for the FfE model-landscape.

More detailed information regarding the methodology used to develop application-oriented balances is available HERE.

Since the value of flexibility in the context of European electricity market coupling is a central object of investigation of the eXtremOS project, another focus of the status quo description is on the power sector of each country. To fully capture the characteristics of this sector, data are provided on physical electricity generation, on the one hand, and on the electricity market and variable renewable energy source (vRES) support programs on the other. For the former, installed capacities per generator type are presented based on [8] and [9]. Furthermore, the resulting electricity generation by type is derived from the dataset "Production of electricity and derived heat by type of fuel" published in the Eurostat database [10]. To classify the integration of the individual countries into the integrated European electricity market, imported and exported electricity (cross-border physical flow) is presented on the basis of [11]. To characterize the price situation of electric consumers, the structure of customer prices for residential and industrial customers in each country is presented and compared to the European average prices based on data published by Eurostat [10]. In another segment of the country profiles, core information on national electricity markets such as average electricity prices, trading volumes and information on capacity markets and additional CO_2-pricing schemes are summarized. Lastly, current vRES costs and support schemes are presented based on various country-specific sources.

Country profile can be downloaded HERE and are further explained in the following section.

2.2 Status Quo Assessment

The described data basis is used to establish a profound understanding of the individual national energy systems in Europe. To facilitate this understanding, the eXtremOS team compiled so-called country profiles, in which core aspects of the different national energy systems are summarized and presented. These profiles are filled with the quantitative data and qualitative information described in section 2.1. The resulting documents comprise a country overview, a presentation of the current electricity sector and two pages on energy consumption and emissions by sector, energy source, and application for the most recent year of available data. In addition to the document-based profiles, an interactive web application was developed within the eXtremOS project, where users can explore all relevant data on cartographic maps, as shown in Figure 2-1.

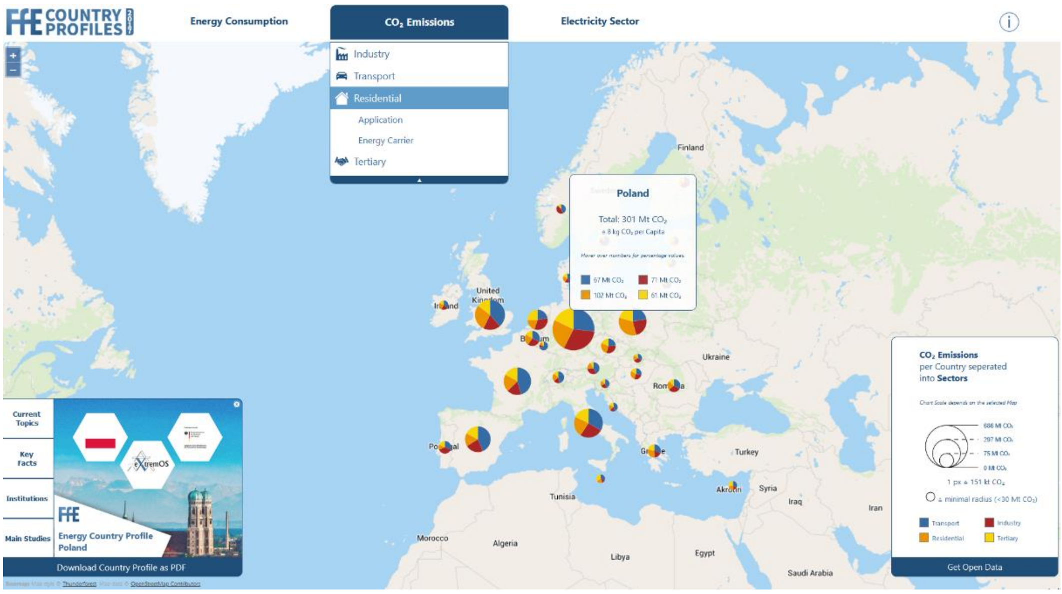


Figure 2-1: Screenshot of the interactive map application of the country profiles

The interactive web visualization of the FfE country profiles can be found HERE.

Based on the application-based energy balances the final energy consumption, for all 30 European countries for the years of 2014 to 2017 can be discussed. This is exemplified by Figure 2-2 which shows the sum of final energy consumption of all eXtremOS countries for 2017. Starting with the inner circle, the shares of applications of the total of 13,682 TWh are displayed. The largest share of final energy consumption results from mechanical energy (40 %), followed by space heating (28 %). The remaining 10 applications account for 32 % in total, with process heating >500 °C at 8 % representing the third-largest share.

Data regarding the status quo of Europe's energy system can be retrieved from the FfE open data portal

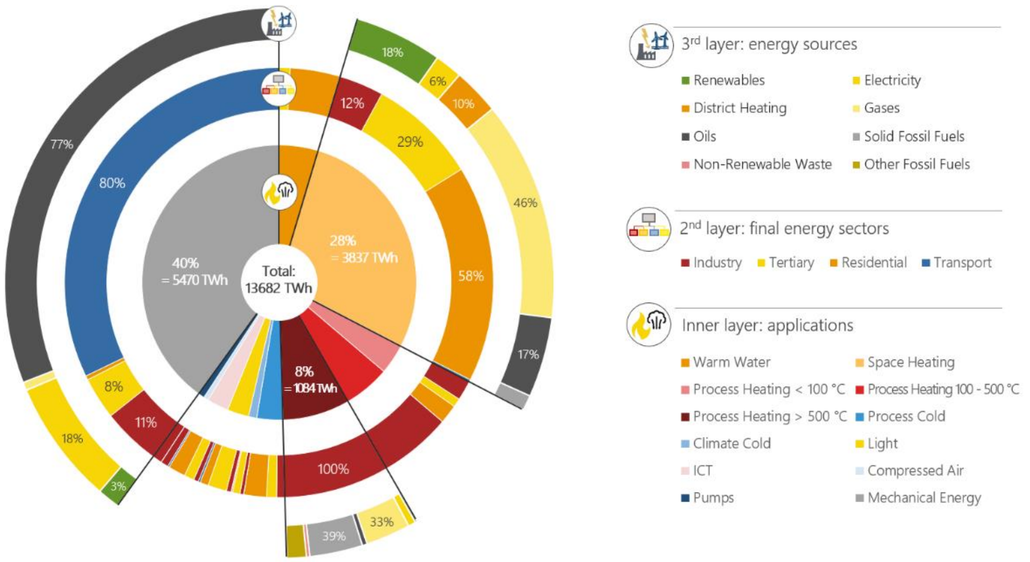


Figure 2-2: Total FEC of EU27+3 by application, sector and energy source, 2017

As the 2nd layer of the figure shows, mechanical energy is mostly consumed in the transport sector (80 %), where in turn no other application accounts for a significant share of consumption. For the application of space heating, the residential sector is responsible for more than half of the final energy consumption (58 %). Apart from space heating, warm water, process heating <100 °C, process cold, light and ICT are relevant applications in this sector. Similarly, the tertiary sector is accountable for 29 % of FEC in space heating, which in absolute terms is the largest amount of consumption for this sector. Warm water, process cold, light, ICT and mechanical energy all play a minor role in the tertiary sector. As for the industry sector, process heating constitutes the primary source of final energy consumption, where 100 % of the energy consumption in process heating >100 °C is accounted for in the industry. Space heating, process heating <100 °C and mechanical energy also represent relevant shares in this sector.

The 3rd layer of Figure 2-2 illustrates the energy sources used for the respective applications. For visualization purposes, energy sources for the three applications with the largest shares of FEC are displayed. To provide mechanical energy, mainly oil (77 %) and electricity (18 %) are consumed in the eXtremOS countries. For space heating, a variety of energy sources is used, where gas constitutes the largest share with 46 %, followed by renewables (18 %) and oil (17 %). District heating only accounts for 10 % in this application. In the case of process heating >500 °C, large shares of energy consumption are caused by solid fossil fuels (39 %) and gases (33 %).

Similar to the FEC, data from the energy-related emission balances is displayed in Figure 2-3. Again, the total values of CO_2-emissions of all eXtremOS countries are presented adding up to 3,392 million tons of CO_2 in 2017. Apart from distinguishing by applications, sectors and energy sources, we introduce a fourth layer, where CO_2-emissions directly related to FEC are contrasted to CO_2-emissions indirectly caused by the procurement of relevant energy sources.

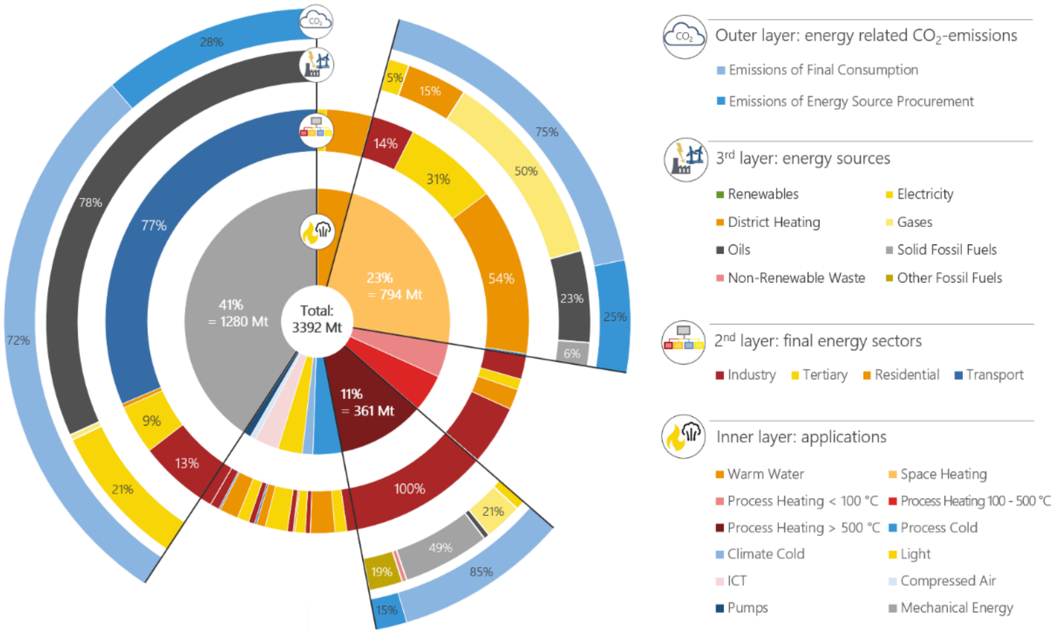


Figure 2-3: Energy-related CO_2-emissions for EU27+3, 2017

Starting with the two inner layers, the displayed shares of applications and sectors are similar to the corresponding shares of FEC. This finding implies that the mix of energy sources and thus its energy related CO_2-emissions do not vary significantly in applications and final energy sectors for the total of all eXtremOS countries. Yet, some minor differences are noteworthy. The shares of mechanical energy and process heating >500 °C, for instance, are slightly larger for CO_2-emissions than for FEC, which is the opposite for the share of space heating. As the share of renewables used in space heating is higher than for mechanical energy or process heating (see Figure 2-2), and as renewables are not contributing to energy-related CO_2-emissions, the share of emissions accountable for space heating is lower and the shares for mechanical energy and process heating are higher. Hence, some applications cause less emission than their share of FEC might imply and vice versa. A similar effect is witnessed at final energy sector level. Here, the share of total energy-related CO_2-emissions caused in the residential sector is lower than its share of total FEC by 4 %, since the share of renewables applied in this sector is high. In contrast, the share of total energy-related CO_2-emissions is slightly higher for the other sectors in comparison to their shares of total FEC.

The outer layer of Figure 2-3 shows that nearly two thirds of all energy related CO_2-emissions of the eXtremOS countries are directly linked to FEC with only 36 % being related to emissions from energy source procurement. The three exemplary applications, for which the shares of energy related emissions are visualized in the figure, show even higher shares of emissions of FEC. Hence, efficiency improvements in the procurement of energy sources and expanding renewable electricity generation can reduce energy related CO_2 emissions. However, the findings imply that replacing emission-related energy sources by zero-emission energy sources in applications linked to high shares of FEC is likely to become necessary in the future, as the direct consumption of energy sources accounts for the major share of CO_2-emissions in Europe.

Publications and further information related to the eXtremOS ad-hoc analyses are available at the xos website.

Excursus: eXtremOS Ad-hoc Analyses

In addition to specifying and analyzing the status quo of Europe's energy system, a variety of topics that were the subject of intense public debate during the three-year project duration were discussed in the format of ad-hoc analyses. The selected issues are:

- **The influence of electrification on the gas market**, where an electrification scenario is compared to a base scenario for 2030 to analyze the effect on long-range gas transports
- **The production of European steel with hydrogen**, where the increase in hydrogen consumption in case of a 100 % switch to hydrogen-based steel production is analyzed
- **The industrial on-site generation of electricity in Europe**, where the magnitude of European on-site electricity generation in industry is examined and the potential integration of industrial power plants into the spot market is discussed

The findings were published in professional media and/or challenged in conferences, thus contributing to current debates within the project duration.

As an example for the presentation of each country's electricity sector, Figure 2-4 shows an overview of the German electricity sector for 2017.

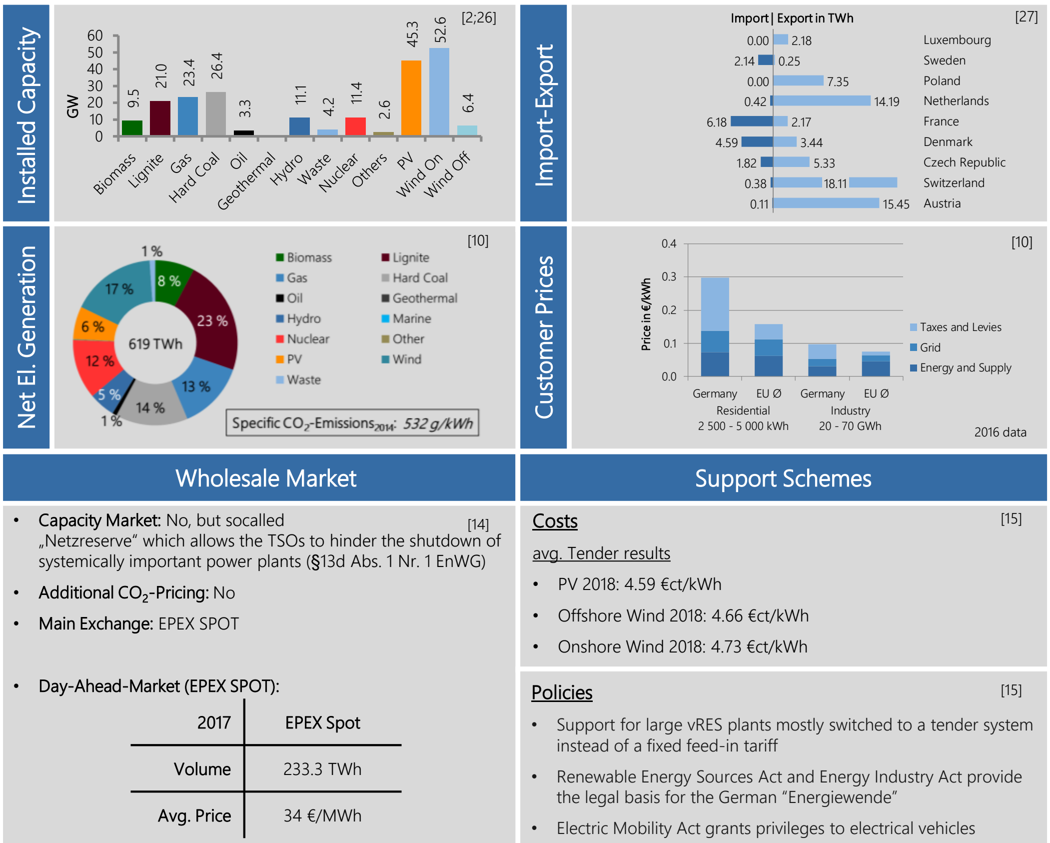


Figure 2-4: Excerpt if eXtremOS country profile for Germany, 2017

In the top left corner installed capacities and resulting net electricity generation per type are presented. The latter is still dominated by fossil generators in 2017, but the increasing expansion of wind and solar is starting to impact on this, accounting for a total of 23 % of

German electricity production. Furthermore, the resulting average emission factor of 523 gCO_2/kWh_{el} is presented. The top right corner of the graph shows the imported and exported electricity to and from Germany with its electric neighbors. Due to its geographical location, Germany is considered a transit country, importing as well as exporting large quantities, although it is a net exporter overall. The electricity tariff structure for residential and industrial customers is shown below. Only a small portion of customer prices can be attributed to actual electricity generation, especially in Germany, whereas the larger share can be attributed to taxes, levies and grid fees. Due to the scope of these price components Germany has one of the highest customer prices in Europe. The lower part of the profile presents information on each country's wholesale market structure, like information on capacity markets as well as average traded volumes and prices on the day-ahead market as well as individual vRES support schemes and policies.

To sum up, the status quo of the European energy system is well characterized by the presented data. As discussed, the magnitude of final energy consumption and CO_2-emissions poses a considerable challenge in terms of decarbonization and climate targets for Europe as a whole. This finding is underlined by the small amount of installed generation capacities of RES, which today account for 36 % of the net electricity consumption. Thus, the status quo identified for the eXtremOS countries in total offers many potentials for the development of extreme scenarios with different political objectives and disruptive technical changes.

3 Scenarios in eXtremOS

The contents of this section are a summary of the information provided in [12] and [13].

The core focus of *eXtremOS* is to analyze the effect of extreme developments on the European energy system. To identify such developments and translate them into quantitative energy system scenarios a scenario framework which facilitates the plausible quantification of these parameters is required. The quantitative values assigned to these parameters are connected to reasoning, by embedding the eXtremOS model landscape in a socio-political context [12]. For this, a scenario process is developed and implemented, in which qualitative scenario storylines are translated to quantitative input data. The disciplines of storytelling and quantitative simulation are consequently combined in a so-called integrated scenario process. To do so, the existing cross-impact balance and simulation approach (CIB&S) [14] is augmented by the so-called *From Word to Value* (FWV) procedure [15]. The resulting integrated scenario process is then applied to derive two socio-technical European energy system scenarios. These build the basis for implementing and analyzing the effect of parameter variations within these scenario worlds. The following sections provide a summary of the scenario process developed and implemented in eXtremOS. References to further reading are provided throughout the section.

3.1 Scenario Process

The aim of the eXtremOS scenario process was to derive quantitative energy system scenarios, which are embedded in a socio-political context. Figure 3-1 shows the integrated scenario process used in eXtremOS [12].

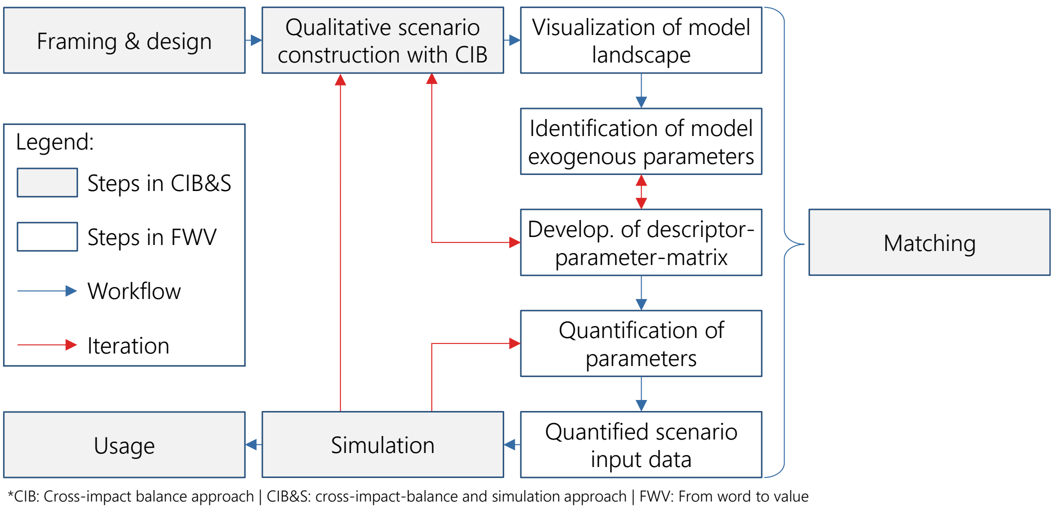


Figure 3-1: Expansion of CIB&S approach through the F*rom Word to Value* procedure[1]

The scenario process is based on the CIB&S approach (grey boxes) and entails the following steps [14]:

- Framing and design of the scenarios and process
- Qualitative (extreme) scenario development using cross impact balance (CIB) method

[1] CIB&S steps are from [14].

- Matching qualitative and quantitative scenarios
- Model-based simulation of scenarios
- Usage of scenario results

In eXtremOS the matching stage was elaborated through the FWV procedure [15], which facilitates the consistent and traceable quantification of scenario storylines. Each step in the scenario process is detailed in the following sub-sections.

3.1.1 Framing & Design

In the first step of the scenario process shown in Figure 3-1, the goal and topic, as well as geographical and temporal scopes of the scenarios are defined. Furthermore, procedural aspects are decided, such as the method for qualitative scenario creation, the models used for scenario quantification, and the design of the iterative procedure between qualitative scenario and quantitative modeling experts [12], [14].

The framing and design of the scenarios was defined between the eXtremOS project leads at FfE and the Institute for Technology Assessment and Systems Analysis (ITAS) at the Karlsruhe Institute of Technology (KIT). The aim of the scenarios in eXtremOS is to describe extreme sociopolitical, economic and energy-related developments which trigger extreme energy system transformation. Thereby a scenario is defined as extreme if it has a low probability of occurrence from today's perspective and an extreme impact on individual actors or the energy system as whole with respect to the status quo or a defined reference. Furthermore, an extreme scenario has three core components:

The Qualitative scenario construction was done by our research partners from the Institute for Technology Assessment and Systems Analysis (ITAS) at the Karlsruhe Institute of Technology (KIT)

- A consistent scenario storyline.
- A quantitative energy system scenario which is in itself consistent as well as with respect to the storyline.
- One or more so-called quantitative extreme scenario seeds, which describe an extreme development of one or more key parameters in the energy system and are embedded into the scenario framework.

The geographical scope of the storylines is Germany and its electrical neighbors.[2] The time horizon of the scenarios is 2017 to 2050.

The goal of the scenario process was to translate one or more storylines into a quantitative scenario. The qualitative part of the scenario process was designed and executed by KIT ITAS. Quantitative modeling was performed at FfE. To allow the possibility of a structured combined scenario process, qualitative scenario creation was performed using the CIB method. Quantitative modeling was performed using the FfE model landscape described in section 4. The scenario process was set out to be a loose coupling between qualitative and quantitative scenario processes. It was aimed at translating one or more storylines to quantitative scenarios, as opposed to developing storylines for a predefined quantitative modeling framework.

Semi-annual research partner meetings presented the main points of iteration between the qualitative scenario team at KIT ITAS and the quantitative modeling team at FfE. The meetings were used to exchange information about and discuss the status quo of the qualitative and

[2] All countries with existing or planned line transfer capacities to and from Germany: Austria, Switzerland, Italy, France, United Kingdom, Norway, Sweden, Belgium, Netherlands, Denmark, Poland, Czech Republic, Slovakia, Slovenia, and Hungary.

quantitative processes (e.g., exchange information about descriptors and parameters used). Ultimately, the processes of quantitative modeling and storyline development can be characterized as interdependent, but not closely coordinated. Based on the classification provided in [14], the combined scenario process in eXtremOS can be described as having a medium degree of integration.[3] This results from the fact that the qualitative and quantitative processes were linked by regular meetings, but performed by two different institutions and teams.

The aim of the integrated scenario process was to derive two holistic energy system scenarios which could serve as basis for exploring the effects of extreme parameter variations. For this purpose, the concept of extreme scenario seeds was introduced. While comparisons between different extreme scenario worlds would have been possible, core assumptions about these scenario worlds can differ significantly, raising serious doubts over the interpretability of differences. This is avoided if parameter variations are performed within a scenario world. Scenario seeds can therefore be viewed as sensitivity analyses performed based on the derived integrated scenarios. The identification and selection of extreme scenario seeds consequently builds on the results of the integrated scenario process and is therefore described in section 3.2.

3.1.2 Qualitative Scenario Construction with CIB

In step two of the scenario process, storylines based on the CIB method described in [16] are derived. At the core of CIB lies an algorithm with which the mathematical consistency of different scenarios is evaluated. In CIB, the scenario world is described through a set of descriptors which each assume different trends/futures. The interdependencies between descriptor trends are assessed based on literature review and/or expert interviews. The strength and direction of interdependencies are often quantified using a seven-point scale ranging from – 3 (strongly restricting) to + 3 (strongly promoting). The resulting quantified interdependencies are summarized in the so-called cross-impact matrix. The algorithm ultimately iterates through this matrix and selects sets of trend combinations which fulfill the self-consistency criterium. These combinations pose the resulting set of consistent scenarios. The latter are subsequently clustered and verbalized to provide the storylines also referred to as qualitative scenarios.

The CIB matrix developed in the project eXtremOS serves as input for the combined scenario process. Using CIB for the combined scenario process allowed the quantitative modeling team to trace the basic assumptions behind the developed storylines. Furthermore, it provided the starting point of the FWV procedure, which builds on the structured scenario approach using descriptors and trends. KIT ITAS developed scenarios for each region in eXtremOS: Germany, Nordic countries, Southwestern Europe and Central-Eastern Europe [17], [13]. Descriptors and trends were identified based on literature research and internal brainstorming at KIT ITAS. Subsequently, the list was validated through an online questionnaire as well as expert interviews. For each region, a participatory approach consisting of international expert interviews, workshops and online surveys was followed to derive the respective CIB matrices. A set of 23 consistent scenarios were identified, which were further divided into three scenario clusters. For each scenario cluster one storyline was developed [17], [13]:

[3] Low integration exists if context scenarios are solely an "add-on" to quantitative modeling. High integration is reached when the CIB delivers results which are explicitly tailored to the demands of the quantitative model landscape.

- S1 – A tough government with climate ambitions in a fragmented Europe (based on ten scenarios)
- S2 – No climate target in a fragmented Europe (based on seven scenarios)
- S3 – Together towards a better world (based on six scenarios)

The storylines S2 and S3 were selected to derive integrated scenarios in eXtremOS. The regional differences in S2 and S3 were consolidated to provide European storylines which serve as input for the FWV procedure. The resulting scenarios have been re-named to avoid confusion with the original storylines.[4]

S2 is renamed to *quEU*. The name quEU is short for *quit EU*, thereby referencing one of the main triggers of the described scenario developments – the dissolving of the EU. QuEU is a scenario in which no climate targets exist. Figure 3-2 shows the descriptors and trends for the quEU scenario, including a qualitative interpretation of the descriptor state compared to the status quo (i.e., year 2020).

The quEU scenario is a holistic European energy system scenario in which climate targets are not reached.

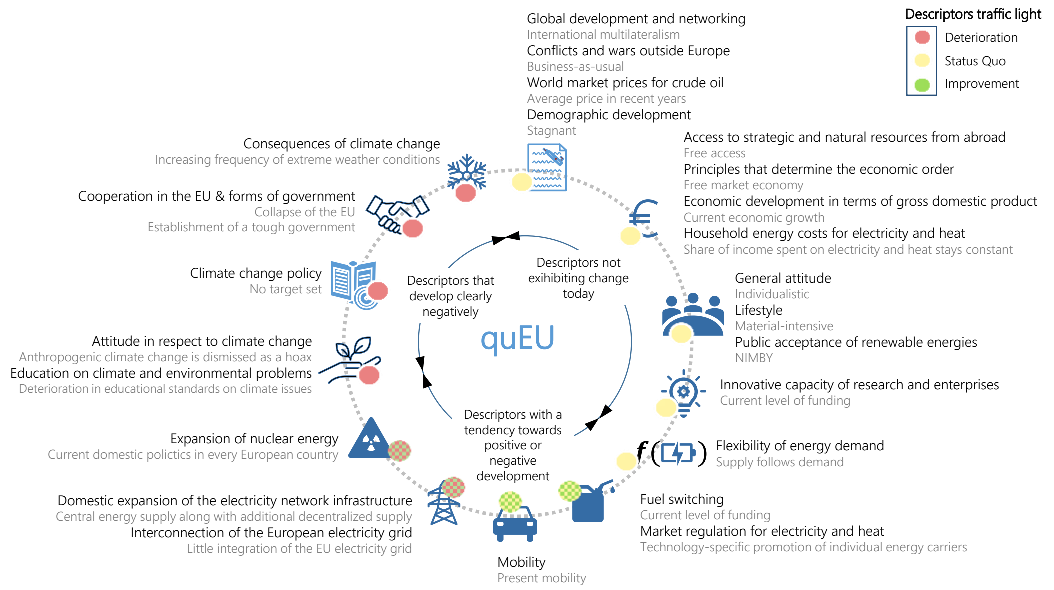


Figure 3-2: quEU scenario descriptors and trends

The scenario describes a sociopolitical setting, in which further countries, besides the United Kingdom, exit the European Union. In addition, nationalist politicians gain influence in several European countries and society perceives that the costs of containing climate change outweigh the benefits. These developments result in the neglect of climate targets. Furthermore, availability of public and private funding for renewable technologies is not expanded compared to today's level. In particular, research and development funding for fuel substitution technologies, beyond the current trend, is not supported. The scenario characterizes a geopolitical setting in which currently visible efforts to improve social equality and welfare fall victim to pure economic competition, in the sense of *homo economicus*. This means climate friendly technologies could be adopted if they were cost competitive. Efforts to accelerate their development however do not go beyond the current state.

S3 is renamed to *solidEU*. The name solidEU is short for *solidarity in the EU*, thereby referencing one of the main triggers of the described scenario developments. SolidEU is a climate protection scenario in which 95 % GHG emission reduction with respect to 1990 levels is

The solidEU scenario is a holistic European energy system scenario in which 95 % GHG mitigation with respect to 1990 is achieved.

[4] Scenario summaries are provided below. For elaborate storyline descriptions confer [17], [13].

reached by 2050 in the EU27+3. National, sectoral and 2030 goals are not considered in solidEU. Figure 3-3 shows the descriptors and trends for the solidEU scenario, including a qualitative interpretation of the descriptor state compared to the status quo.

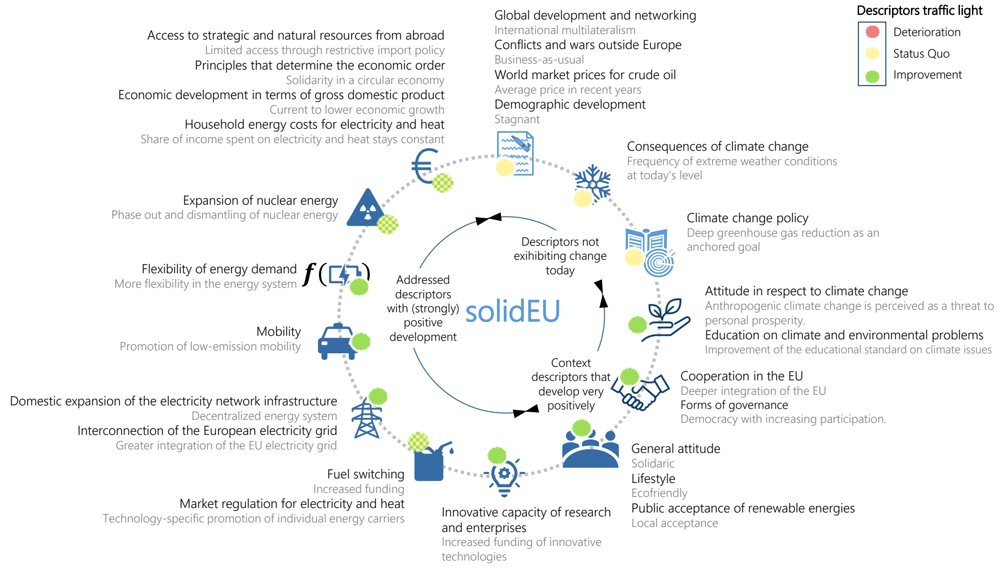


Figure 3-3: solidEU scenario descriptors and trends

The scenario describes a sociopolitical setting characterized by cooperation and a stronger integration of the European Union, with a strengthened participatory democracy. Solidarity and the resulting participative governance are driven by the common understanding that climate change is anthropogenic and poses a serious threat to personal prosperity. This pioneers an ambitious climate policy, supported by the collective goal of deep greenhouse gas reduction at both governmental and societal levels. Consequently, the EU will create a solid national policy framework. The countries which currently have more organized national policies/goals will adapt these to the EU framework. There will be regulations on trade of various resources to implement environmental standards, promote the use of locally available resources, protect sensitive ecosystems, and avoid social conflicts. Intensification of renewables will be promoted by funding research and development as well as technology infrastructure. Moreover, society will work in solidarity for climate protection, triggering lifestyle changes via increased climate awareness. Therefore, people become conscious about their consumption, switching to products with a low carbon footprint. Hence, there will be a new economic order supporting circular economies and reducing consumption of primary resources. Economic growth continues or slows depending on the country. Furthermore, integration of variable renewable energy sources between EU member states is supported with demand-side management.

The quEU and solidEU cross-impact matrices and scenario storylines are matched with the parameters which are exogenous to the eXtremOS model landscape using the FWV procedure.

3.1.3 From Word to Value - Matching Storylines and Numerical Models

The following sections explain how storylines can be matched to numerical models using the FWV procedure depicted in Figure 3-1. An extensive application example for the industry sector can be found in [12].

Visualization of Model-Landscape

A prerequisite for quantifying context scenarios is the identification of model landscape exogenous parameters (mexP). The mexP identification procedure begins with creating an overview of the model landscape including model interdependencies and a full parameter list. Thus, the model landscape is visualized in a flowchart, showing how all model input and output parameters are connected. A positive side-effect is that the visualization of the model landscape sharpens the understanding of the model context and functionalities. This is especially useful when models are developed by different teams. An overview of the eXtremOS model landscape is provided in section 4.

Identification of Model-Landscape Exogenous Parameters

Based on the visualized model landscape and full parameter list, the latter are classified, aiming at identifying mexP, which can subsequently be connected to context descriptors. For this purpose, three types of model parameters are differentiated:

- **Scenario independent mexP** are parameters which can be considered as certain or historical input data (e.g., technology lifetimes or energy savings potentials of individual technologies)
- **Scenario dependent mexP** encompasses all parameters for which assumptions about their future development are required (e.g., production tonnage development)
- **Scenario dependent model endogenous parameters (menPs)** are parameters which result from model calculations within the defined model landscape (e.g., final energy consumption in 2050)

Relevant for the further FWV procedure are mexPs, which are considered exogenous from the perspective of the entire model landscape. For example: electricity consumption in the energy end-use sectors in 2050 is an exogenous parameter from the perspective of the energy system model ISAaR. However, from the perspective of the model landscape, electricity consumption is an endogenous parameter as it is a result of the calculations performed using the energy end-use models. To ensure the consistent quantification of context scenarios across all models, it is necessary to ensure that mexPs which are input to several models (e.g., GVA development) are assigned only one set of values.

Development of Descriptor-Parameter Matrix

In this step of the FWV procedure, previously identified scenario dependent mexPs are matched with the descriptors defined in the qualitative scenario construction phase. Exemplary descriptor parameter matrices for the energy end-use models in eXtremOS and the quEU scenario are shown in [18]. An extensive application example for the industry sector can be found in [12].

The degree of integration between qualitative and quantitative scenario development impacts to what extent links between model parameters and descriptors can be drawn. Three stages of links are defined:

- **A direct link** exists if the descriptor is also a model parameter or translates to a direct influence on one or more parameters.
- **Weak links** occur in situations where the descriptor impacts one or more model parameters but is not equatable to them.
- **No direct or weak link** between descriptor and parameter is drawn if the connection either does not exist or can only be drawn if several intermediate explanatory steps

are required. In such cases the descriptors provide context to the scenario, but do not impact the quantitative scenario directly.

Parameter and descriptor interdependencies are recorded in the descriptor-parameter-matrix (DPM). By evaluating the rows and columns of the DPM, frequently addressed parameters and descriptors can be identified. If a parameter is addressed by multiple descriptors, the value assigned to the parameter during the quantification procedure needs to be consistent across all descriptors and their assumed trends in each scenario. For descriptors addressed by several parameters, comprehensive descriptions in the formulated storylines are required to support consistent parameter quantification.

In addition, the DPM can also be used to identify unaddressed descriptors and parameters. If descriptors or parameters critical to the analysis at hand are not linked, further iterations are required (cf. red connections in Figure 3-1). This can lead to the addition or redefinition of a storyline descriptor or quantitative exogenous model parameter, ultimately allowing for additional links in the DPM. If an important descriptor does not connect to any of the mexPs, an additional parameter can be added to one of the models in the scope of the analysis. If a mexP is not addressed by any descriptor, the parameter is not within the context scenario horizon. If this does not suit the framing and design of the analysis, descriptors can be redefined or added.

Considering that model landscapes used for technoeconomic energy system analysis can encompass several hundred parameters, linking all mexPs to descriptors can be impracticable. If this is the case further literature research might be required to expand the storyline to include details about parameters which cannot be linked to descriptors.

Quantification of Parameters

In the quantification stage of the FWV process mexP as well as other input data are quantified in preparation for model simulations. An extensive application example showing the process of parameter quantification for the industry sector can be found in [12].

Assigned values can differ depending on the trends the descriptors assume. Furthermore, methods used to quantify parameters depend on whether the descriptor trends are qualitative or quantitative.

- **Descriptors** with quantitative trends: the parameter is addressed by a descriptor with concrete values as trends.
- Descriptors with qualitative trends: to translate qualitative trends to quantitative values ideally distinct value intervals for each trend are determined from literature research, expert estimates and/or meta-analyses. The values which are ultimately assigned to parameters should allow for a clear distinction between descriptor trends.

Independent of whether the descriptor trends are qualitative or quantitative, the quantification step cannot be systemized completely. Despite thorough research and experience of the researcher(s) performing the quantification, a certain degree of subjectivity resulting from both the definition and interpretation of descriptor trends is inevitable. This however is not necessarily a disadvantage since further interpretation of the researcher might be required in case the qualitative scenario does not provide sufficient context for traceable quantifications. In such cases the researchers' expertise becomes instrumental to scenario quantification.

In addition to the quantification of the matched scenario dependent mexPs, scenario independent as well as unmatched mexPs are quantified. For parameters with clear technoeconomic boundaries (e.g., efficiencies for incumbent heating technologies) the room for interpretation during quantification is low. Other parameters (e.g., cost data of innovative technologies) can leave more room for interpretation, especially if no direct or weak links to descriptors can be quantified.

3.1.1 Simulation and Usage

In eXtremOS the simulation results for the quEU and solidEU scenarios as well as the solidEU scenario seeds serve two main purposes:

- Gain an in-depth understanding of the complex model interconnections by analyzing the effects that parameter variations have on the simulation results
- Evaluate and understand scenario results to acquire knowledge about the European energy transition in a climate protection scenario

To do so, first, scenario results from the energy end-use models are used as input data for the energy system model ISAaR. The energy end-use model simulation runs yield hourly industrial final consumption data for all NUTS-3 regions in the EU27+3. Through linear optimization, the energy system model ISAaR then determines the cost-optimal European unit dispatch and expansion for each scenario. A GHG emission reduction constraint is deployed in solidEU and its variations, but not in quEU. Scenario results are discussed in sections 5, 6 and 7. In addition to the quEU and solidEU scenario simulations, additional simulation runs are performed which are based on parameter variations within the context of the climate protection scenario solidEU. The identification and selection of these so-called extreme scenario seeds is discussed in the following section.

quEU and solidEU are European socio-technical energy system scenarios. Extreme scenarios are the results of parameter variations within the solidEU scenario world. These variations are called *extreme scenario seeds*.

3.2 Extreme scenario seeds

Extreme scenario seeds are an important element in eXtremOS. While quEU and solidEU present integrated and holistic energy system scenarios, they only partially satisfy the conditions for extreme scenarios as defined in the context of eXtremOS. Hence, a variety of extreme parameter variations are performed in the solidEU context. In eXtremOS consequently several processes were implemented to identify parameter variations which can be considered extreme and have a noticeable and interesting impact on the European energy system. These processes/sources for extreme scenario seeds were:

- Four European stakeholder workshops with more than 70 international energy system experts, organized and led by AGORA Energiewende and FfE.
- Numerous what-if workshops with the eXtremOS project team including the academic and industry partners.
- Two meta studies of energy system scenarios with a European and German geographical scope, conducted by TUM and FfE, respectively [19], [20].

International stakeholder workshops were conducted jointly by AGORA Energiewende, FfE and KIT ITAS. They served as inspiration for identifying extreme developments. More information can be accessed HERE.

The process yielded a long-list of over 100 scenario seeds from which the most frequently mentioned and intensively discussed were selected for implementation into the solidEU scenario framework:

- NTC2020 – reduction of net transfer capacities (NTCs) to historical values
- PVBat – rapid technology cost reduction for solar panels and battery storage systems
- Lyze – rapid technology cost reduction for electrolyzers
- Rino – offshore ring of electricity trading capacities between Nordic countries

Figure 3-4 provides an overview of the scenarios and scenario seeds calculated in eXtremOS.

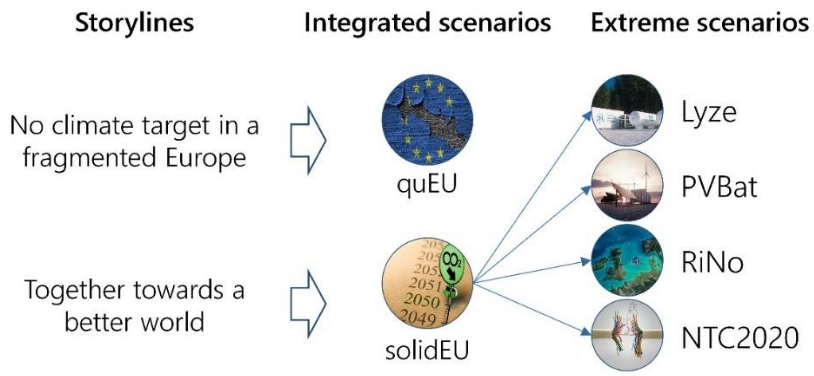


Figure 3-4: Storylines, integrated scenarios and extreme scenarios

In the following section the model landscape used to simulate the integrated and extreme scenarios is introduced.

4 Model Landscape

The quantified scenarios defined in section 3 are direct input for the models in the eXtremOS model landscape, which is depicted in Figure 4-1. In this section, first model interactions and the general functionality of the model landscape are introduced. Subsequently, the core functionalities and eXtremOS specific model expansions are discussed.[5]

Models which are part of the eXtremOS model landscape are also discussed HERE.

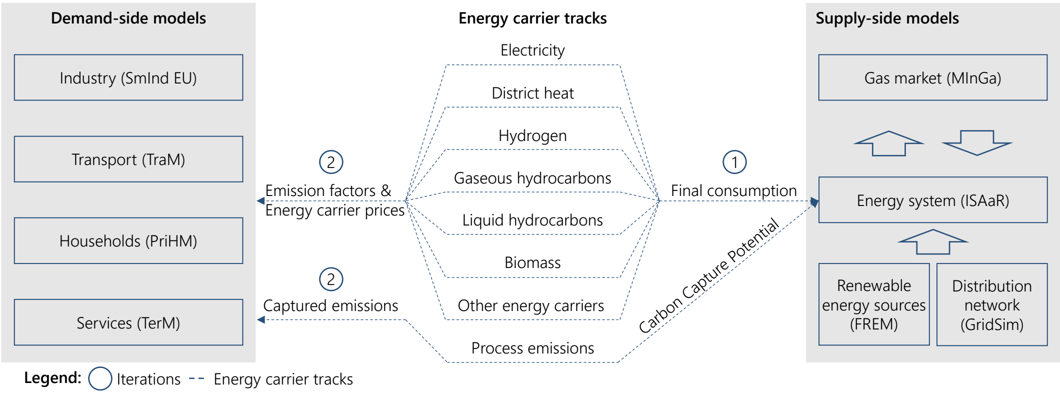


Figure 4-1: eXtremOS model landscape

The eXtremOS model landscape encompassed two sets of models:

- Models used to simulate the final energy consumption sectors: industry (SmInd EU), transport (TraM), households (PriHM) and tertiary (TerM)
- Models used to simulate the energy supply-side and transport: energy system (ISAaR), gas market (MInGa), renwable energy sources (FREM) and distribution network (GridSim)

The demand-side models are used to derive demand side transformation pathways in form of final consumption (FC) values and process emissions [12]. Thereby the term FC entails both final feedstock and final energy consumption. In the first iteration, these pathways are communicated to the Integrated Simulation Model for Unit Dispatch and Expansion with Regionalization (ISAaR) in hourly resolution at NUTS 3 level for the EU27+3. This is done via so called energy carrier tracks [21], [18], [22].

In the ISAaR simulation run, the cost optimal pathway to satisfy the load conditions for electricity, district heat, hydrogen as well as gaseous and liquid hydrocarbons under a given GHG emission cap is determined. ISAaR is a linear optimization model aimed at minimizing total system cost [21], [18], [22]. To satisfy the load condition, the model determines the cost optimal European generation unit dispatch and expansion. The FfE regionalized energy system model thereby provides ISAaR with detailed information about the potential capacity and costs of wind and solar power expansion. Hence, the optimization algorithm determines when and where to expand the capacity of variable renewable energy sources in the given scenario. Furthermore, ISAaR can decide to substitute fossil gaseous and liquid hydrocarbons through emission free synthetic substitutes (SynFuels), in case this is required to clear the GHG emission reduction constraint and/or leads to a reduction of total system cost. ISAaR can also deploy carbon capture (CC) and storage (CCS) or utilization (CCU) measures. Hereby, a CC

[5] The general model description as well as the section on SmInd EU (section 4.1.1) are taken from [12].

potential is communicated from the industry model to ISAaR. It reflects the potentially abatable industrial process emissions through CC measures. ISAaR is also connected to MInGa, which calculates the cost optimal procurement of natural gas. MInGa is a linear optimization model which minimizes the total costs of gas procurement in Europe. It analyses European gas flows as well as the changes in gas prices in each scenario [12]. Ultimately, ISAaR is connected to GridSim via a bidirectional "soft link", which is to allow a generic exchange of time series and parameters via the FREM database. In the scope of eXtremOS this newly defined model interconnection poses a methodological advancement. It is however not applied to scenario calculations performed in the scope of the project.

To guarantee the interplay between the different models in eXtremOS, the interfaces to exchange data between models play a key role. The requirements placed on the interfaces are reduction of error susceptibility, flexibility, and speed. Therefore, a suitable database structure is implemented in FREM, which is used as the central data exchange platform.[6] To use FREM as an intermediary interface has the advantage that writing and reading routines can be standardized and the different models do not have to communicate directly with each other, thus reducing the possibilities for errors and increasing speed. Flexibility is added to the system, as many parameters can now be parametrized when reading data into the ISAaR model. Therefore, the existing interactive GUI was adapted, so that easy data manipulations can be done to the input data without the need to newly compile all data from the models. The modular data retrieval allows the exchange of, for example, cost parameters, load profiles or transformation pathways, by simply changing an ID in the interactive GUI. The flexibility gained with this concept cuts down on the expenses of new calculations.

In the following sections the functionality of the different models used to simulate the scenarios defined in section 3 are discussed.

4.1 Demand-Side

In eXtremOS four demand-side models determine the scenario-based development of European FEC from 2017 until 2050 on NUTS-3 level with a temporal resolution of one hour. Each model is used to simulate the transformation pathway of the respective energy end-use sector: industry, transport, household and tertiary. The resulting demand-side transformation pathways are subsequently communicated to the energy system model ISAaR as shown in Figure 4-1.

Each FEC model is structured into 3 modules, according to Figure 4-2:

- Module 1: annual and country specific final (energy) consumption development from 2017 until 2050
- Module 2: regionalization of FC to NUTS-3 level
- Module 3: increased temporal resolution of regionalized FC via load profiles

In Module 1 the transformation of the annual and country specific final (energy) consumption from 2017 to 2050 is calculated depending on the scenario. Transformation strategies are not differentiated by country; nevertheless, country specific transformation pathways result from scenario simulations since country details on industry branch and process level are considered [12]. In module 2, country-specific results are disaggregated to NUTS-3 level via sector-specific regionalization methodologies. Ultimately, the temporal resolution of annual FC values at NUTS-3 level is increased to hourly values by applying application and technology specific

[6] It is important to note that FREM serves as a general database and as the vRES model.

load profiles. Each module is fitted with fixed input data and adaptable exogenous parameters, so that different scenarios can be calculated by adjusting the parameters. This flexible structure allows the rapid modification in diverse scenarios and a quick adaptation of the models in case of further requirements.

Technical advantages of the modular structure include the flexible adaptation and easy maintenance of each module. Figure 4-2 also shows the differentiation between scenario dependent and scenario independent exogenous model parameters required to allow the structured quantification of the scenarios described in section 3. The scenario storylines are quantified by linking scenario descriptors and model parameters. To do so, scenario dependent exogenous model parameters are separated from scenario independent input data and endogenous parameters. The latter are (intermediate) model results and depend on scenario specific model configuration. The results of each module are stored and processed to load curves at NUTS-3 level in the FfE PostgreSQL database FREM. The database also poses the link to the supply-side models.

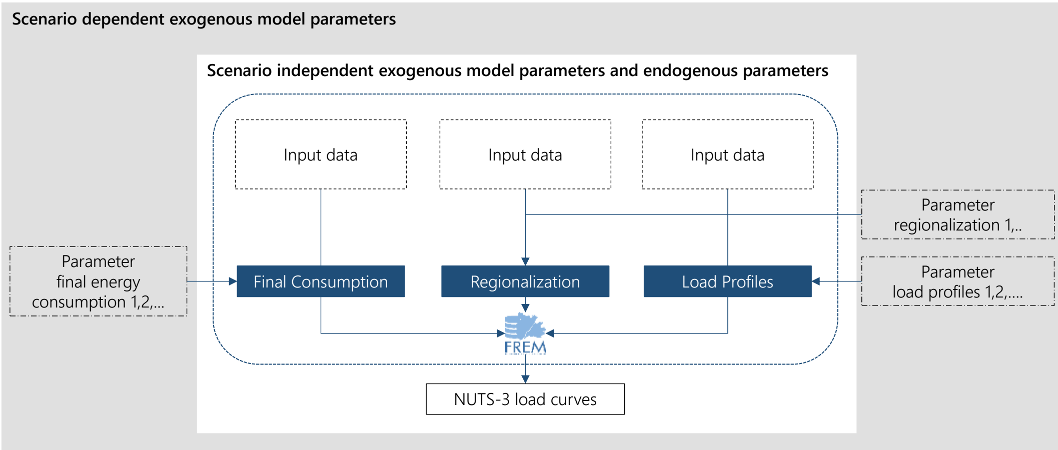


Figure 4-2: Modular structure of eXtremOS sector models

In the following subsections, each sector model is described with a focus on the final consumption development. Since the latter is predominantly influenced by scenario dependent exogeneous assumptions, the FC development for each sector is provided in the respective sections. Scenario results including the demand and supply-side for quEU, solidEU and the extreme scenarios are provided in sections 5, 6 and 7.

4.1.1 Industry Sector

In this section core components of the industry sector model SmInd EU are summarized [12]. An extensive description of the SmInd EU method, input data and results for the quEU and solidEU scenario is provided in [12]. quEU scenario results have previously been published in [18].

In eXtremOS a dissertation about European industrial transformation pathways was created [12].

The aim of SmInd EU is the scenario-based calculation of the spatially and temporally resolved industrial final energy, feedstock consumption and process emissions. The main modules of SmInd EU are structured according to Figure 4-2. First, annual and country specific industrial final consumption and process emissions are calculated until 2050. For this step, industry branch, process, and abatement measure input data are used. Subsequently, the FC and process emissions are regionalized and then scaled with normalized load profiles, to provide

FC time-series in hourly resolution at NUTS 3 level. Data and results of each module are saved in FREM.

The SmInd EU final consumption module is a hybrid bottom-up and top-down MATLAB model. This structure is a result of the necessary trade-off between depicting "… the heterogeneity and complexity of industrial processes whilst achieving full coverage of the …" [17, p. 3], industrial energy, feedstock consumption and process emissions. Changes in FC and process emissions result from the scenario-based implementation of CO_2 abatement measures as well as the development of the macroeconomic metrics gross value added, energy intensity and production tonnages [12].

In the baseline calculation, the final energy and feedstock consumption as well as process emissions are calculated for each region and time interval. The model time horizon is 2017 to 2050, with annual time intervals. FC is calculated for 13 industry branches, 27 industrial process, 12 applications, 14 energy and 4 feedstock carriers. The baseline calculation is followed by the implementation of greenhouse gas abatement measures, which are structured into the four implementation clusters; efficiency measures, innovative processes, low-temperature electrification and other fuel switch measures. Preceding the upload of the model results into the FREM database, the carbon capture potential and district heat split is calculated [12]. This is necessary since the energy system model ISAaR is used to derive the cost-optimal dispatch of carbon capture measures in the energy system. Furthermore, industrial district heat is split into primary energy carriers since ISAaR solely optimizes public district heat procurement when performing calculations on a European level. This is a result of computational constraints. The district heat split is based on the country-specific primary energy consumption for district heat procurement in 2017.

Figure 4-3 shows core assumptions for the development of FC in industry sector for quEU and solidEU. The main drivers for the development of industrial FC in the quEU scenario are economic growth and efficiency improvements. Thereby efficiency measures are sub-divided into process, cross-sectional, and proxy measures. The latter address the parts of the industry sector which are not modeled bottom-up. Efficiency measures are implemented in all industry branches. The starting year of measure implementation is based on the technology readiness level. Cross-sectional-technology (CST) measures, which are characterized by low technical complexity, are implemented as of 2021. More complex process efficiency measures are implemented in 2030 or later. In both cases the technology exchange rate is tied to the technical lifetime of the respective technologies. Fuel switch measures are not relevant in quEU, since it is assumed that insufficient funding for technology development and implementation exists in this scenario.

	CO_2 Abatement Measure	Reference Process / app.	Earliest Measure Start quEU	Earliest Measure Start solidEU	Exchange rate In %/a	Applicatio factor In %
Efficiency	Process efficiency	Process applications	2030	2021	3 – 20	10 – 99
	CST efficiency	CST applications	2021	2021	4 – 100	16 – 99
Fuel substitution (processes)	Electric arc furnace	Primary steel	-	2025	5	Country spec.
	H2-DRI & EAF	Primary steel	-	2025	5	Country spec.
	Methanol-to-Olefins	HVC	-	2025	4	60
	Methanol-to-Aromatics	HVC	-	2025	4	60
	Electrocracker	HVC	-	2040	10	40
	Power-to-Ammonia	Ammonia	-	2025	4	100
	Power-to-Methanol	Methanol	-	2025	4	100
	Multi-fuel & H_2 burners	Cement & lime	-	2030 & 2040	5 & 10	100
	Electrical container glass	Container glass	-	2025	4	100
	Electrical flat glass	Flat glass	-	2025	7	100
	Innovative electrodes**	Primary aluminum	-	2035	10	100
Fuel sub. CSM	Ind. heat pump	HW & PH <100 °C	-	2025	5	100
	Ind. heat pump & electrode boiler	PH 100 °C – 500 °C	-	2025	5	100
	Multi-fuel & H_2 burners	HW & PH	-	2030 & 2040	5 & 10	100
CC	CCS cement / lime	Cement & lime	-	2025	10	100

CSM: Cross-section measure | CC(S): Carbon capture and Storage | CST: Cross-sectional technology | DRI: Directly reduced iron
EAF: Electric arc furnace | HVC: High value chemicals | HW: Heating and hot water | PH: Process heat

Figure 4-3: CO_2-abatement measure implementation overview for quEU and solidEU

As in the quEU scenario, solidEU builds on the implementation of efficiency measures. In solidEU process efficiency measure implementation commences in 2025, due to the availability of additional funding and high sociopolitical transformation pressure. Nevertheless, the number of implemented technical efficiency measures sinks compared to quEU, since interdependencies with fuel switch measures are considered. These game-changer measures become a viable option since sufficient funding for R&D as well as implementation support is available. The industry branch specific transformation pathways resulting from the sociopolitical setting in solidEU are described in [12].

As described in section 3, the socio-political context in quEU is that anti-climate protection and financial incentives are insufficient to facilitate the technology readiness and implementation of deep emission reduction measures. The effect of economic growth and energy efficiency measures on FEC and feedstock consumption are depicted in Figure 4-4.

The left-hand side of Figure 4-4 shows that industrial FEC increases from 3,571 TWh to 3,787 TWh between 2020 and 2050. Efficiency measures cannot contain the FEC increases due to economic growth. Nevertheless, they contribute to containing the FEC increase. Excluding efficiency measures 2050 FEC would amount to ~4590 TWh. Hence, these measures reduce FEC by ~0.6 % p.a. between 2020 and 2050, and thereby, electrical efficiency measures lead to an average gross reduction in electrical FEC of ~1 % p.a. In addition, fuel efficiency measures cause an average gross efficiency increase of ~0.5 % p.a. The difference between the electrical and fuel efficiency measures originates from CST efficiency measures, which predominantly address electrical FEC. In general, efficiency measures can contain FEC growth until 2040. However, the entire technical CST efficiency potential and a large share of the process measure potential are implemented by 2040. Absolute FEC growth therefore occurs mostly between 2040 and 2050. Despite the assumption that there are no significant structural changes to the industry sector in quEU, the share of electrical FEC decreases slightly until 2050, while biomass and methane shares increase. This results from strong electrical efficiency increases and growth in energy-intensive industry branches (e.g., lime, chemicals, paper), respectively. Energy carrier shares of primary steel energy carriers such as COG, BFG and coke decrease until 2050 since growth in primary steel production is low compared to the industry average.

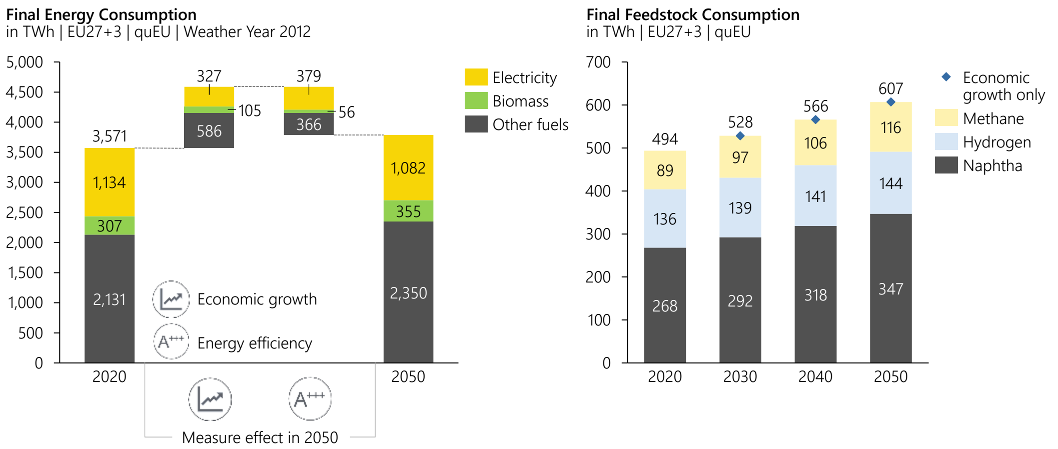


Figure 4-4: Effect of industrial abatement measures for quEU[7]

The right-hand side of Figure 4-4 shows that in addition to the increase in FEC, economic growth in the chemical industry results in an increase of the modeled fossil feedstock for HVC, ammonia, and methanol production by 23 % between 2020 and 2050. This equates to an annual growth of ~0.7 % p.a. Process emissions also increase from 222 Mt_{CO2} in 2020 to 259 Mt_{CO2} in 2050 since measure implementation does not affect them in quEU.

Figure 4-5 shows the effect of measure implementation in the deep emission reduction scenario solidEU. As described in section 3 the socio-political environment is pro climate protection and deep emission reduction targets are set. FEC in solidEU decreases from 3,570 TWh in 2020 to 2,906 TWh in 2050. The reduction in FEC is caused by the implementation of efficiency and electrification measures. Industrial FEC in 2050 is dominated by electricity, biomass, and hydrogen. Between 2020 and 2050 electrical FEC increases by 39 % to 1,576 TWh. Main drivers for the increase in electrical FEC are the electrification of low temperature heat and process route changes in steel, HVC as well as glass production. The use of biomass and RES fuels usage grows from 307 TWh to 761 TWh in the same time period. Main drivers for growth in biomass usage are the cement and lime industry as well as the substitution of fossil solid fuels through biomass, which commences in 2030. The direct use of hydrogen for heat procurement leads to a FEC of 502 TWh_{H2} by 2050. Hereof 160 TWh are used in DRI & EAF steel production route. ~340 TWh are fed into hydrogen burners and CHP plants, thereby substituting natural gas for the provision of process heat. 80 % of this additional H_2 is balanced in the iron and steel, chemical and petrochemical, non-ferrous metal and non-metallic minerals industry branch. In addition to electricity, biomass, and hydrogen 52 TWh of synthetic fuel oil remain in 2050. The latter as well as 8 TWh of peat remaining in 2050 are the only sources of direct energy related emissions in 2050. In addition, process

[7] Results differ slightly from [12] due to different balancing areas between models and since values shown here are weather dependent.

emissions occur. The emission abatement of process emissions is subject to the degree of CCS/U implementation, which is calculated by ISAaR. Hence, it is described in section 6.

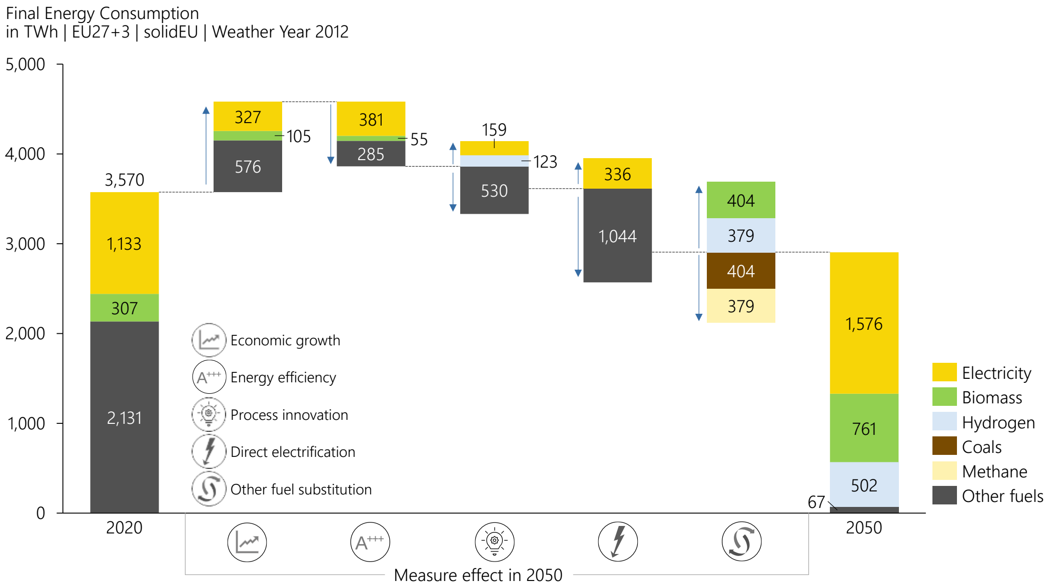


Figure 4-5: Effect of industrial abatement measures for solidEU

Figure 4-5 also shows that economic growth would lead to an increase in FEC of 1008 TWh. This is lower compared to quEU since it is expected that the demand and therefore production of lime in the EU27+3 decreases slightly as a result of the phase out of primary steel. Efficiency measure implementation leads to a reduction of FEC by 721 TWh, which corresponds to an annual efficiency increase of 0.58 % p.a. between 2020 and 2050. The efficiency gain is lower compared to quEU since several measures are excluded due to interdependencies with process substitution measures. The latter result in an increase of the electricity (159 TWh) and hydrogen (123 TWh) FEC and a decrease in fossil fuel consumption (530 TWh). This change in FEC results from the process substitutions in steel, glass, HVC, MeOH and ammonia production. It should be noted that there is an energy efficiency gain resulting from these substitution measures which is however counteracted by the increase in feedstock demand as a result of HVC substitution (cf. Figure 4-6). Direct electrification in the low and medium temperature range results in an increase of the electrical FEC of 336 TWh and a reduction in fossil FEC of 1,044 TWh. This efficiency gain results from the deployment of industrial ground source heat pumps and electrode boilers. The substitution of coal and methane through biomass and hydrogen in measure cluster four results in an increase of 404 TWh and 379 TWh, respectively. Thereby it should be noted that these cross-sectional measures are designed to capture remaining fossil fuel consumption in industrial applications for which the technology structure could not be elicited in eXtremOS. It is assumed that multi fuel burners and hydrogen burners and turbines will enable the direct combustion of these fuels in a variety of industrial processes in future. However, further research into disclosing the existing technology structure at a European level is required to fully prove the accuracy of this assumption.

In addition to FEC change, measure implementation and economic growth in solidEU result in changes to the feedstock consumption. Figure 4-6 depicts the increase in final feedstock consumption from 494 TWh in 2020 to 885 TWh in 2050. The increase in production tonnages alone results in a 23 % increase in feedstock consumption until 2050. Process substitutions influencing the modeled feedstock consumption are the replacement of steamcrackers through the MTO and MTA process routes as well as hydrogen-based steel, ammonia, and methanol production. MTO and MTA process routes lead to a surge in MeOH consumption since the production of one ton of olefines requires ~2.8 t_{MeOH} and the production of one ton of aromatics leads to an additional ~4.3 t_{MeOH}. Since electrical steamcrackers are phased in as of 2040, 185 TWh of naphtha demand remain in 2050. As described in section 5.2.3, the synthetic naphtha and MeOH demand resulting from process substitution measures is covered by imports in solidEU. If produced domestically this could lead to an additional electrical FEC of 1,600 TWh_{el}. In addition to naphtha and MeOH the hydrogen-based production of ammonia, MeOH and steel results in 283 TWh of hydrogen feedstock consumption in the EU27+3. Total industrial solidEU hydrogen FC in 2050 is therefore 785 TWh, which presents a sixfold increase compared to today.[8]

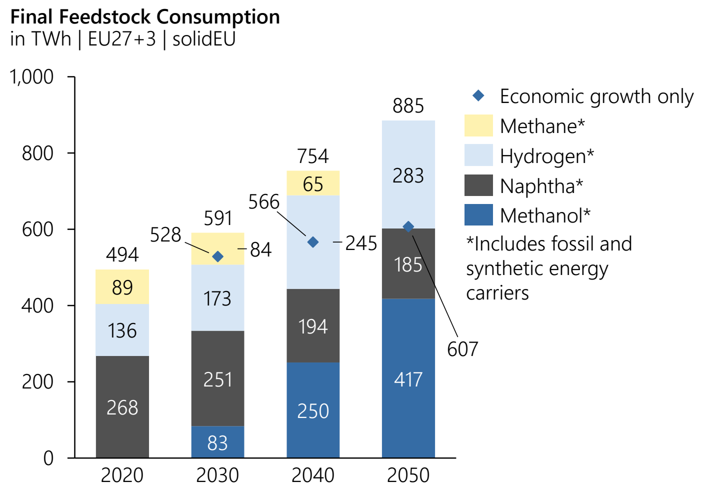


Figure 4-6: Industrial final feedstock consumption by energy carrier for solidEU

The spatial resolution of the annual final energy and feedstock consumption is increased from NUTS-0 to NUTS-3 level using the methodology described in [13], [23], [18]. The basis for the regionalization are point coordinates for emission and energy-intensive industry branches as well as employee and population data. The load profile module of SmInd EU is subsequently used to increase the temporal resolution from annual to hourly or daily FC values. This is done by scaling the load with country, industry branch and energy-carrier specific synthetic load profiles. For heating and hot water it is assumed that the industry sector behaves similarly to the tertiary sector. Hence, the same profile is used as in the tertiary sector. The methodology for deriving synthetic load profiles for all other industrial applications has been developed over a series of dissertations and publications and is summarized in [13], [24], [18]. The methodology derives synthetic load profiles based on real load data collected in energy audits performed by FfE in Austria and Germany. The result of the load profile synthesis is country specific process heat and electricity profiles for all industry branches. Due to a lack of real load data, a constant profile was used for the iron & steel and the paper, pulp and print industry. Since these branches are characterized by high full-load hours, a constant load profile is justifiable.

[8] The decrease in process emissions as a result of measure implementation in the industry sector depends on the amount of process emissions abated due to CCS/CCU implementation in ISAaR. In eXtremOS, the industry sector communicates a CCS/CCU potential to ISAaR, which then derives the cost-optimal implementation depth. Hence, emissions are discussed in the findings (cf. section 6).

The combination of results from each module enables the analysis of final consumption and consequently emissions for all 1348 NUTS-3 regions in Europe, in hourly resolution. Figure 4-7 exemplifies the level of detail in which SmInd EU results can be presented.

Industry sector results are available as open data at FfE Open Data.

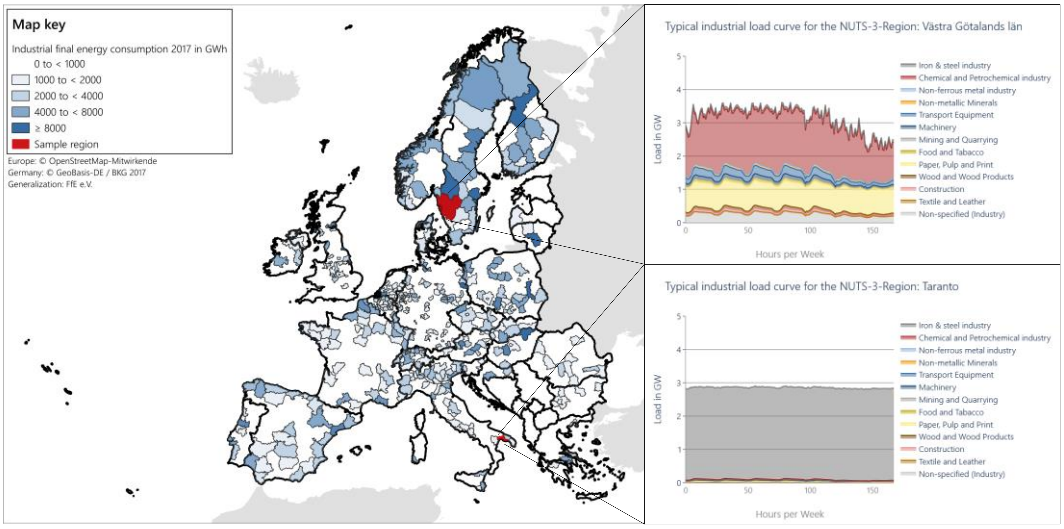


Figure 4-7: Industrial FEC and load curves for typical weeks in exemplary regions

The presented granularity of industrial data can provide a starting point for the identification of regions in Europe which are especially interesting from an industry and energy system perspective. The latter is briefly exemplified by Västra Götaland and Taranto county, which are highlighted in Figure 4-7. Both regions are industrial load centers in their respective countries. When analyzing the respective load curves significant structural differences can be identified. The weekly load curve for Västra Götaland is characterized by basic chemicals and petrochemicals as well as the paper, pulp and print industry. Additional literature research shows that the region is home to the largest Swedish chemical cluster, in which both organic and inorganic basic chemicals as well as products of special chemical industry are produced [117]. Another major consumer in the region is the energy-intensive pulp production. Both the paper and chemical industries are characterized by relatively constant consumption patterns over the course of the presented typical week. This results from high full load hours which in turn indicate that a large part of the processes in these industry branches operates continuously. Lower loads during the weekend mainly result from the machinery and transport industry branches, which reduce their production during the weekend. Compared to Västra Götaland, the Italian Taranto is less heterogeneous and mainly characterized by metal production. Taranto is the only Italian primary steel plant and produces ~20 % of Italian steel.

The significant difference in regional industrial consumption patterns shows that a European or national analysis is insufficient to capture the diversity of regional challenges associated with the energy transition. SmInd EU and the other sector models facilitate the spatially and temporally resolved analysis of the industrial FC and emissions in Europe, thereby enabling the identification of regional differences and the associated challenges.

4.1.2 Transport Sector

The European Transport Model TraM is a bottom-up model used to determine the scenario-based development of European final energy consumption in the transport sector from 2017 until 2050. In addition to the population development, energy efficiency improvements as well as direct and indirect electrification measures drive the scenario-based transformation pathway.

In the bottom-up model the current stock by transport categories, types, vehicles, and classes are differentiated according to energy carriers, which is essential for determining country-specific transformation pathways. In addition, characteristics such as age, lifespan, specific consumption, and annual mileage per vehicle are also considered. A detailed analysis of the current vehicle stock is explained in [18]. Using TraM, the future FEC depending on the development assumed in each transport category area is modeled.

The final energy consumption development until 2050 is calculated in three steps:

1. Change in vehicle stock as a result of population development
2. Change in specific vehicle FEC due to efficiency improvements
3. Change in FEC due to direct and indirect electrification measures

Both quEU and solidEU build on the same assumptions concerning the input data and characteristics of the parameters that influence the first two steps. Differences only occur in the third step, in which direct and indirect electrification measures are implemented. The results of measure implementation are explained in the following. Thereby, Figure 4-8 and Figure 4-9 show the FEC development for quEU and solidEU, respectively.

In the first step, the stock of vehicles in the road transport category changes according to country-specific population trends. On average, a 3 % increase in Europe from 2017 until 2050 is assumed, while the specific number of vehicles per person is held constant. In the second step, an increase in the energy efficiency for different vehicle categories is considered. The specific values are published in [18]. This results in a Europe-wide decrease in final energy consumption of ~800 TWh by 2050.

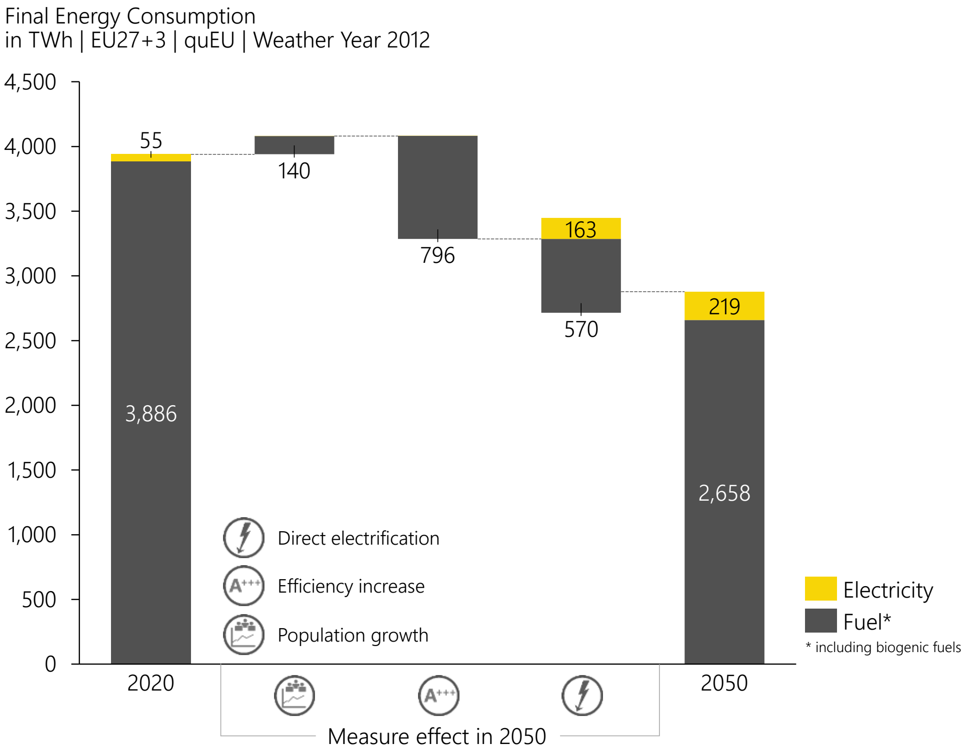


Figure 4-8: Effect of abatement measures in the transport sector for quEU

In the third step, electrification measures are implemented. This step is characterized by direct electrification with battery electric vehicles in both scenarios as well as indirect electrification with fuel cell vehicles in the solidEU-scenario. In quEU only passenger cars and light commercial vehicles are electrified. Lead-free and diesel vehicles are substituted through battery electric vehicles according to country-specific values taken from the Sustainable Transition Scenario of Ten-Year-Network Development Plan [25]. This leads to a reduction in fuel FEC of 570 TWh and an increase in electrical FEC of 163 TWh by 2050, compared to 2020. In quEU, the implementation of all three measure types consequently leads to a total decrease in fuel FEC by 32 % and an increase in electrical FEC of 400 % between 2020 and 2050.

In the solidEU scenario, 90 % of the passenger car fleet is electrified from 2020 to 2050. Approximately one-third of the current fleet is electrified in the first life cycle (end-of-life replacement), one-third in the second life cycle, and the last third in a third life cycle. 10 % of the current passenger car fleet is replaced with fuel cell vehicles starting in 2030. Light commercial vehicles, buses and motorcycles are replaced by battery electric vehicles at their end-of-life as of 2020, medium trucks (>3.5 t <12 t) as of 2023. 60 % of the current stock of trucks >12 t and tractor trailers are electrified by overhead lines after their lifespan as of 2027 and the remaining 40 % are displaced by fuel cell vehicles at their end-of-life as of 2030. The currently non-electrified share of rail traffic will be indirectly electrified with hydrogen as of 2030. The cumulative results of each step are shown in Figure 4-9.

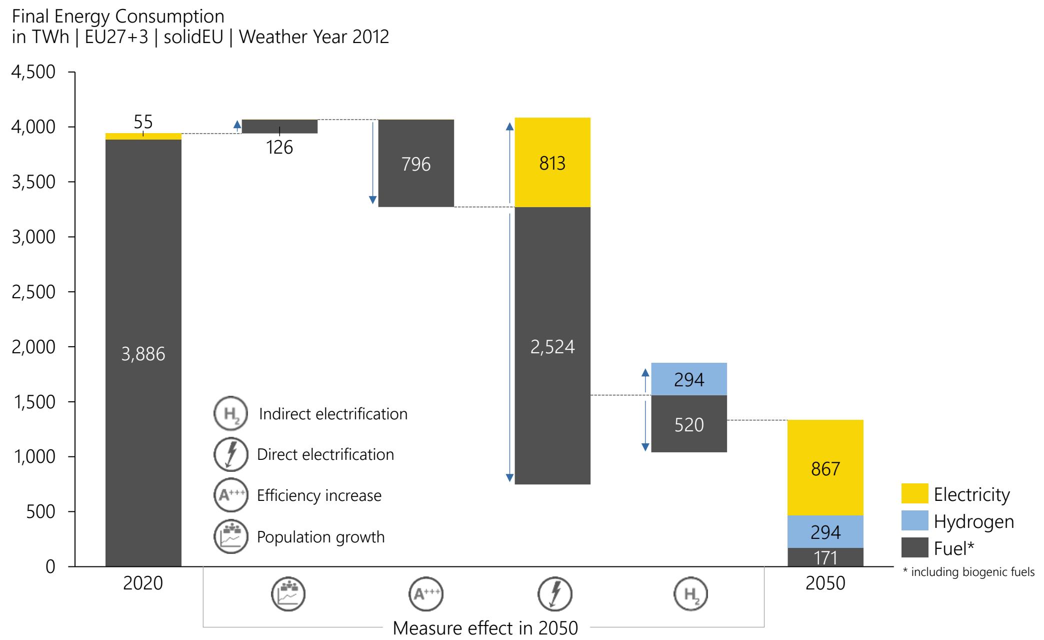


Figure 4-9: Effect of abatement measures in the transport sector for solidEU

In solidEU, the total FEC is reduced by approximately ~2,700 TWh mainly as a result of direct and indirect electrification measures. Thereby, hydrogen and electricity become the main energy carriers by 2050. 65 % of FEC is consumed by electric vehicles and 22 % by fuel cell vehicles.

The country-specific FEC is disaggregated to NUTS-3 level and a temporal resolution of one hour in the regionalization and load profile modules, respectively. First, FEC is distributed to NUTS-2 level via the number of vehicles per category and then to NUTS-3 level via population

Publications and the results as open data are available at RESULTS and OPENDATA statistics. Subsequently, the annual FEC at NUTS-3 level is converted to hourly values through scaling with normalized load profiles. Electrical load profiles are category dependent. For instance, cars, battery electric trucks, or overhead line trucks are characterized by different load profiles. Hence, aggregated load profiles differ regionally, depending on the amount of traffic by transport category. More information about the regionalization and load profile modules can be found in [18], [26] and [21]. Results of the solidEU scenario can be downloaded as open data at [27]. Figure 4-10 exemplifies the electricity consumption at NUTS-3 level in 2050 for the solidEU scenario.

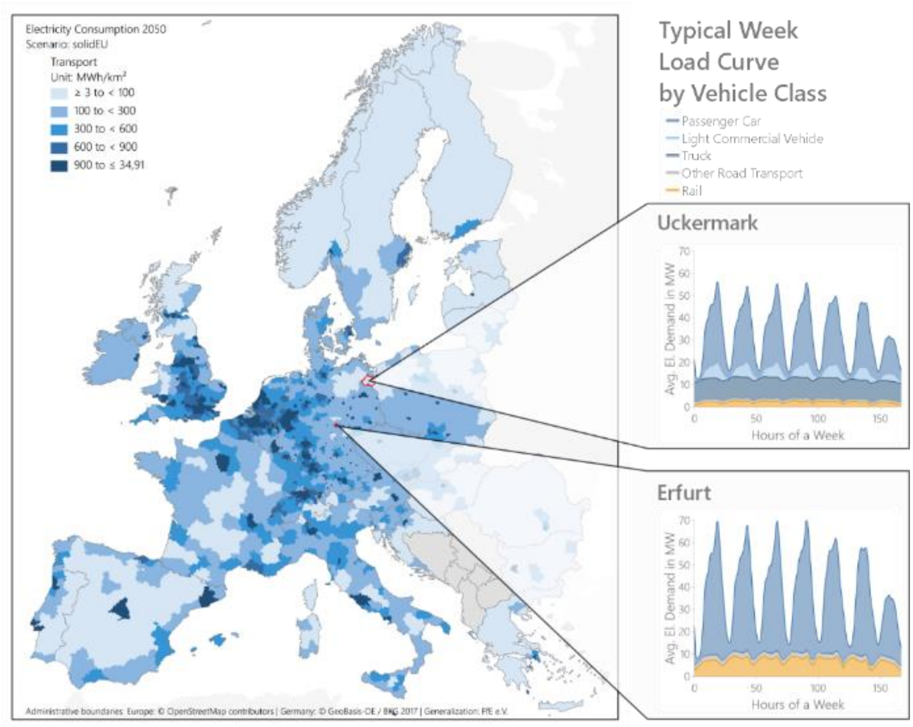


Figure 4-10: Transport FEC and load curves for typical weeks in exemplary regions

4.1.3 Household and Tertiary Sector

Households and the tertiary sector are modeled separately but explained jointly due to structural similarities.

The European Private Household Model *PriHM* and the Tertiary Model *TerM* are top-down models which can be used to determine the scenario-based development of European final energy consumption in the private household sector and the tertiary sector from 2017 until 2050. Energy efficiency and direct electrification are the key drivers in the scenario-based transformation pathways. The structure of both models is similar; hence they are described jointly in the following subsection.

The focus of the implemented abatement measures in the household and tertiary sectors lies on mitigating emissions in heating applications, since 64 % of European household final energy consumption in 2017 was used for space heating and 15 % for warm water (cf. section 2). Accordingly, 55 % of the direct CO_2 emissions in households were generated in space heating and warm water by fossil fuels such as gas, oil, and coal in 2017. Although the heating structures of individual European countries differ from each other, the same development strategy is applied in all European countries. The initial basis of the model is the 2017 application-oriented energy balance (cf. section 2). The final energy consumption of the private household sector is split into energy carriers and applications and that of the tertiary sector is additionally split into branches. Data for heating and cooling applications exhibit an annual temperature dependency. To model the future excluding this weather-year-specific annual characteristic, the space heating and cooling data was adjusted using the long-term average of degree-day numbers over the past 30 years. Thus, the data are independent of weather influences for modeling the country-specific final energy consumption in FEC module. In the load profile module, the weather dependency is re-attached by joining the weather-dependent load profiles. In addition to the temperature dependency the country-specific age structure of heating systems is taken into account when modeling transformation pathways.

The final energy consumption is modeled until 2050 in three steps. Firstly, the effect of population growth on FEC is calculated under the assumption that the FEC per capita remains constant. Secondly, the effect of improved insulation of the building envelope is modeled. A comparison with the bottom-up sector model with focus on Germany [21], which is based on a detailed building structure, has shown that the calculated insulation rate of 1.1 % per year can be transferred to the top-down model in eXtremOS with an annual reduction of the final energy consumption of 1.1 %. In the third step, an energy-related modernization via the installation of heat pumps is modeled. In the quEU scenario the substitution is based on a current market analysis [18]. In solidEU, the heating systems are substituted with heat pumps according to the lifespan of the incumbent heating system and the age structure. Therefore, more heat pumps are used in this scenario, so that in 2050 there are no more fossil heating applications in the system. Thus, in solidEU in private households, the electricity share reaches 65 % in 2050 and 79 % in the tertiary sector. In the quEU scenario only a share of 49 % in private households and 58 % in the tertiary sector can be reached. The results of all three modeling steps for quEU and solidEU are shown in Figure 4-11 and Figure 4-12, respectively.

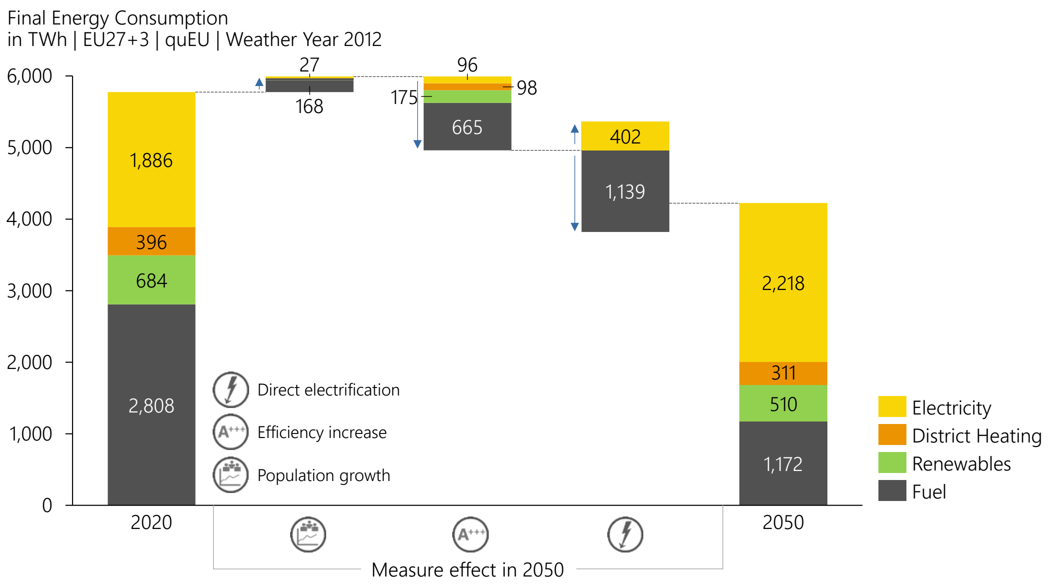


Figure 4-11: Effect of abatement measures in households and tertiary sector, quEU

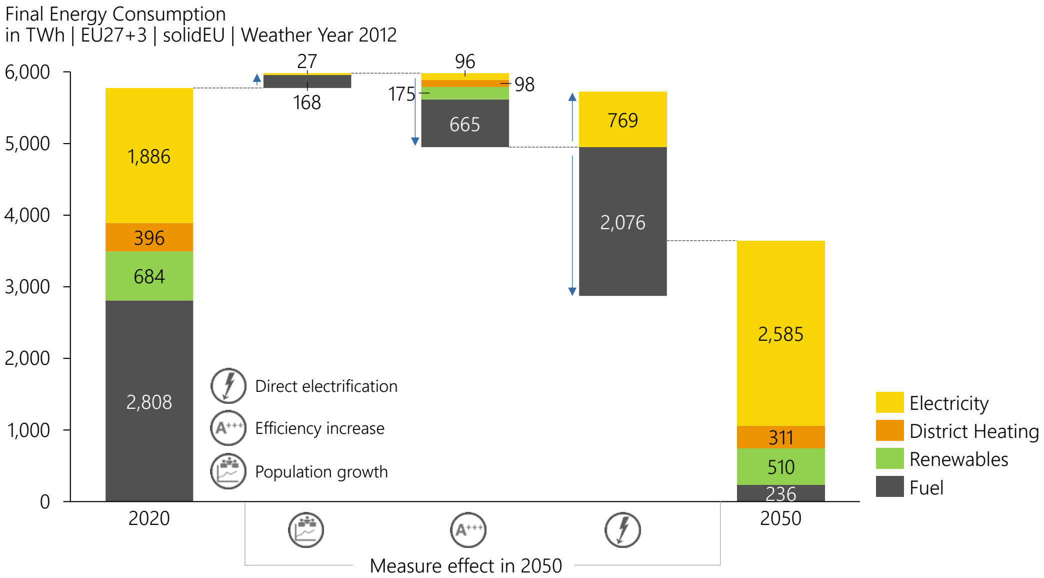


Figure 4-12: Effect of abatement measures in households and tertiary sector, solidEU

The final energy consumption is disaggregated to the NUTS-3 level and to a temporal resolution of one hour. For heating applications, the regionalization to NUTS-3 level is based performed using the heating structure (i.e., share of each energy carrier used for heating within a NUTS-3 region) and population statistics. Furthermore, a weighting by degree-day numbers has been considered for space heating. The population statistics are also the distribution criteria for the final energy consumption of the other applications in the household and tertiary sector.

PriHM and TerM publications and results are available HERE. Load curves are available as open data for both PriHM and TerM.

For the temporal distribution of the data, we assume technology- and application-specific load profiles. These load profiles consider the temperature dependency. For instance: heat pump profiles reflect the temperature dependency of the coefficient of performance. Therefore, climatic conditions within Europe and between different years can be reflected. For example, the heating period is longer in the north than in the south, and peak loads are more significant in the Nordic countries (Figure 4-13). For example, higher temperatures in southern countries in the summer result in a higher load in the cooling application than in more northern regions (Figure 4-14). More information about the regionalization and the load profiles can be found in [18], [28], [29]. Results of the solidEU-scenario can be downloaded as opendata at [30] and [31].

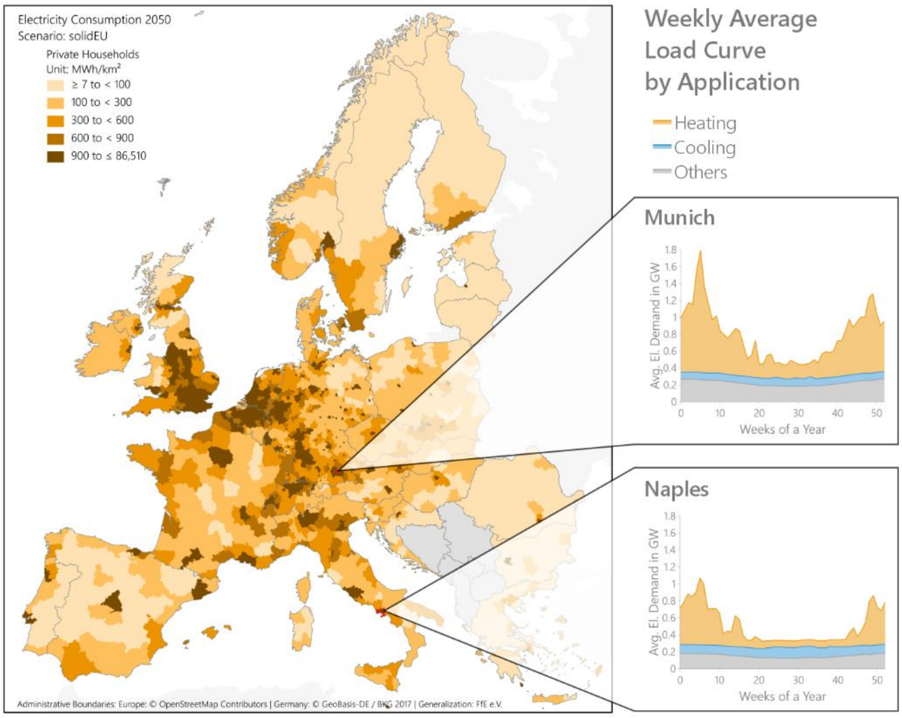


Figure 4-13: Household FEC and load curves for typical weeks in exemplary regions

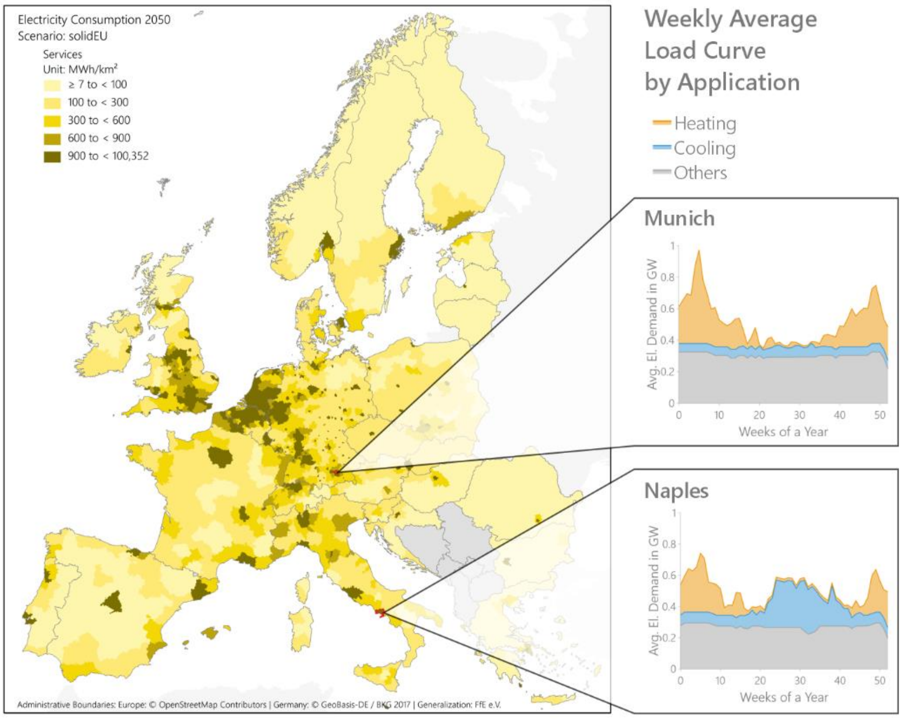


Figure 4-14: Tertiary sector FEC and load curves for typical weeks in exemplary regions

4.2 Regionalized Variable Renewable Energy Sources

As shown in the model landscape overview in Figure 4-1, other models which generate input for ISAaR are the renewable energy source models for PV and wind. In these models, the potential for different RES sources is calculated and communicated to ISAaR. The unit dispatch and expansion model ISAaR finally decides when, where and to what extent these potentials are realized, by performing a cost optimization. In eXtremOS, the vRES wind and solar power are considered. Both are further differentiated by technologies. Wind energy is split into onshore and offshore wind turbines. Photovoltaic modules are installed on rooftops and offsite.

The method is similar for all technologies: The potential and the existing plants are determined via a detailed analysis from geodata and statistical data. Some criteria, such as the maximum sea depth of offshore wind turbines, are expected to evolve over time until 2050. Other criteria are variable and will be determined later in the model chain, for example the minimum yield of onshore wind turbines. The increase in installed capacity is not exclusively based on economic criteria, but also fulfils soft criteria such as a plausible regional distribution.

The models for calculating the time series of electricity generation use weather data and represent the physical processes of electricity generation. In addition, a regression analysis of the time series of these physical models with historical time series is performed. In this way, effects that are not explicitly modeled, such as losses and technical non-availabilities, are also depicted.

The costs of the various technologies are determined in detail for each component and updated. In addition, a plausibility check is carried out with the time series to avoid inconsistencies. For example, the levelized cost of electricity (LCOE) at a low wind site must be higher than at a high wind site, despite the adapted turbine type.

The models are part of the model landscape in eXtremOS. Results are only calculated within a complete scenario. Exemplary results for the scenario solidEU give an impression of the possible results.

4.2.1 Photovoltaic Model

The Photovoltaic model differentiates between rooftop and offsite solar; the NUTS-3 regions define the spatial resolution. The input data comprises the stock, the potential and the time series of production. An external scenario defines the framework for the photovoltaic modeling process.

The installed capacity at national level is derived from Eurostat [32]. The following sources are used for a higher spatial resolution: France [33], Netherlands [34], Denmark [35], Poland [36], Italy [37], Switzerland [38], Austria [39], Slovenia [40], Czech Republic [41], Belgium [42], [43], [44] and United Kingdom [45], [46].

The generation time series is calculated with CAMS radiation data [47]. Its spatial coverage corresponds to the area of Europe with a spatial resolution of 0.2° (cf. Figure 4-15). Local Data from COSMO-EU provides additional parameters (temperature, radiation) and regions (northern Europe) [48]. The calculation of the generation time series considers the different systems - rooftop and offsite solar – and is based on a physical approach: The module temperature is calculated from incoming radiation, outside temperature and wind velocity. As the module temperature rises, the efficiency of power generation decreases.

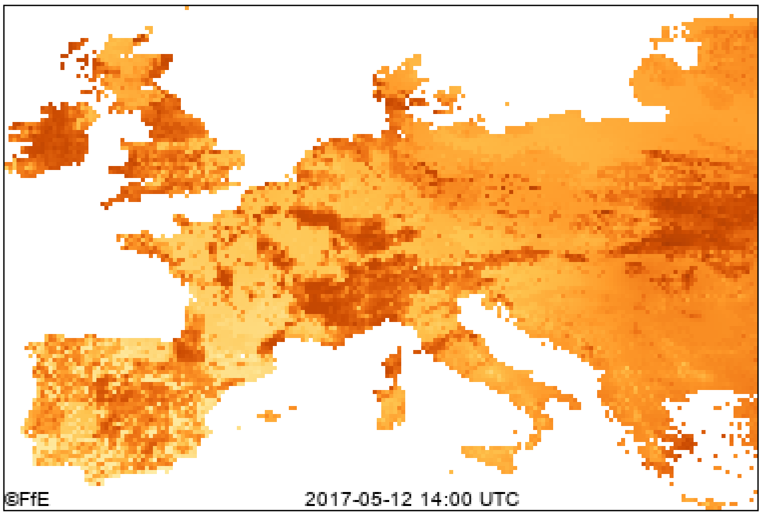


Figure 4-15: CAMS, global irradiation - May 12, 2017

The potential of roof top solar systems in Germany is determined using the FfE building model [49], statistical data [50], OpenStreetMap [51] and the evaluation of solar roof cadaster [52]. In other European countries a different approach is followed: a regression analysis with the German data determines the relationship between the potential and different regional variables. These variables are: the built-up area, the population and the population density.

The potential areas for offsite solar are determined via a GIS analysis (cf. Figure 4-16), and based on the land coverage [53], protected areas and less favored areas [54].

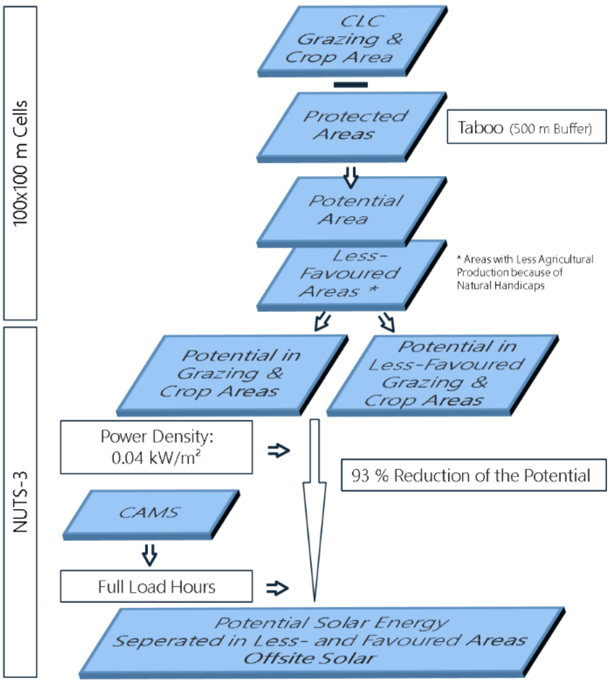


Figure 4-16: Methodology of area identification of offsite solar

The potential areas for off-site solar should not compete with food production. In Germany, energy crops are cultivated on approx. 14 % of arable land [55]. We assume that 7 % of the remaining area could be used for offsite solar.

The calculation of LCOE's for photovoltaic energy requires detailed information about technical parameters (total size of power plant, mounting, inverter) and information about the plant locations (full-load hours). Our analysis evaluates these studies and publications of PV system costs: [56], [57], [58], [59], [60]. CAPEX costs for all components were calculated for different plant sizes. Some costs are related to the area, e.g., mounting systems. This information was used for inter- and extrapolation of the costs for different years.

Figure 4-17 shows the resulting cost for PV systems of different size for the year 2020. As the size of the system increases, the costs of modules and inverters sink. Therefore, large ground-mounted systems in Germany can generate electricity at significantly lower costs than roof-top systems.

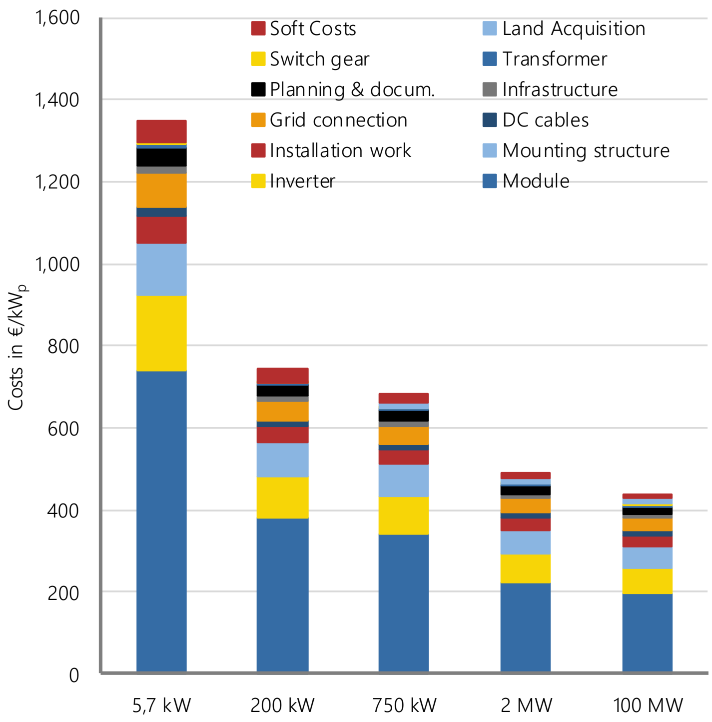


Figure 4-17: Detailed costs for PV systems with different capacities, year 2020

The PV Model provides the potential for photovoltaic development in ISAaR in terms of installed capacity, generation time series and costs. This involves the separate modeling of the deconstruction and replacement of existing plants in the respective NUTS-3 region as well as the modeling of remaining potential for additional expansion. The remaining potential in the NUTS-3 regions of a country is developed in equal proportions according to the expansion planning in ISAaR. The components and input variables of the photovoltaic model are shown in Figure 4-18.

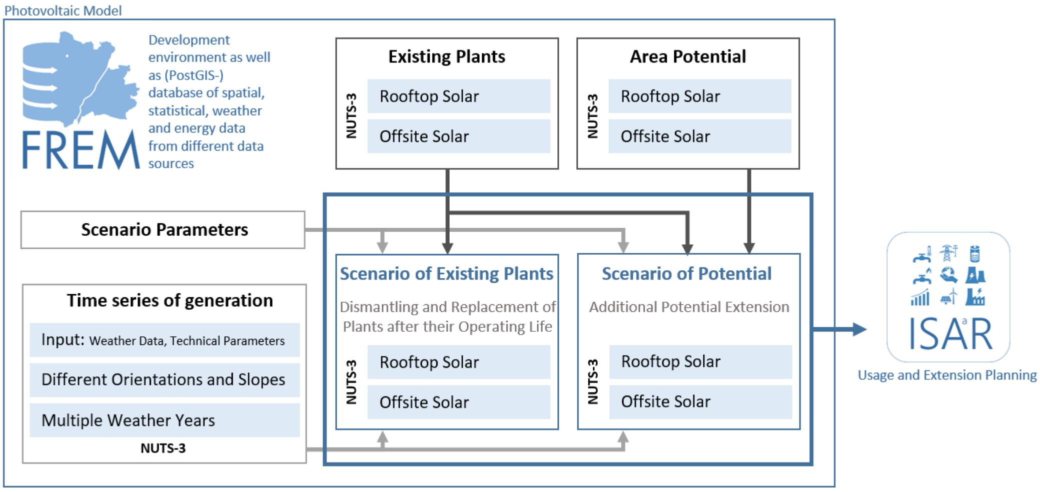
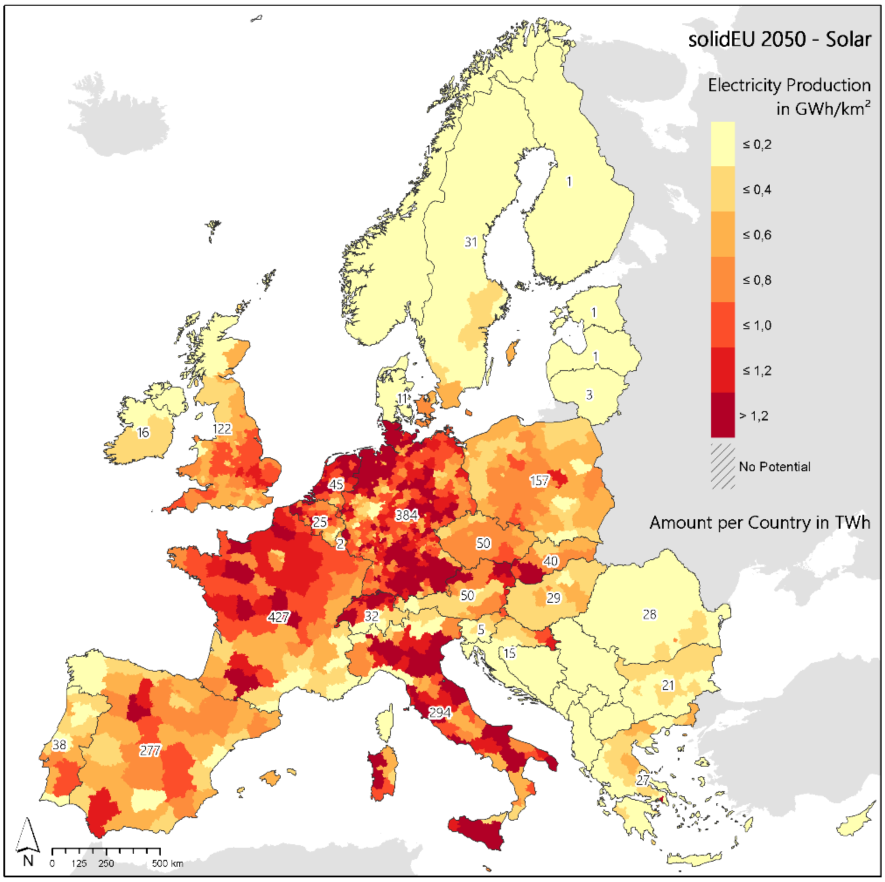


Figure 4-18: Photovoltaic model overview

The results of the Photovoltaic model depend on the boundary conditions in the ISAaR model. For one scenario the resulting dataset is presented in Figure 4-19. The solidEU scenario is a climate protection scenario in which the European countries work together to jointly reduce their greenhouse gas emissions by 95 % in 2050 compared to 1990. This scenario is explained in detail in section 3.



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

Figure 4-19: Distribution of the realized potential of solar in solidEU

4.2.2 Wind Model

The Wind model differentiates between onshore and offshore turbines; the NUTS-3 regions and an offshore grid defines the spatial resolution. The input data comprises the stock, the potential, and the time series of production. An external scenario defines the framework for the wind modeling process.

The installed capacity of wind turbines is based on data of The Wind Power (WP) [61] of October 2018. The total installed capacity in Europe amounts to 163 GW of which 147 GW is accounted for wind onshore and 16 GW for wind offshore. This data is combined with turbine locations and attributes extracted from the OpenStreetMap (OSM) dataset [62].

Wind speeds at different heights are extracted from the DWD's COSMO-EU/ICON-EU weather model [48]. Time series of generation are calculated with the wind speed in hub height and turbine-specific power curves. The wind data is extracted at a so-called measuring point for each NUTS-3 region. For offshore turbines, the data is extracted on a 50 km x 50 km grid. Technical developments such as decreasing power density and increasing tower heights are taken into account in this model and lead to increasing full load hours.

Based on the time series of generation a site-specific power density characterized by four typical wind turbines is determined. By combining the area potential, the power density, and the site-typical time series of the wind turbine, the capacity and the energy potential are calculated. For deriving the technical potential, regulatory and technical conditions are addressed through the parameters of the model. The social acceptance and the economic aspects are integrated in the model to receive the rated potential. The process of the analysis is plotted in Figure 4-20.

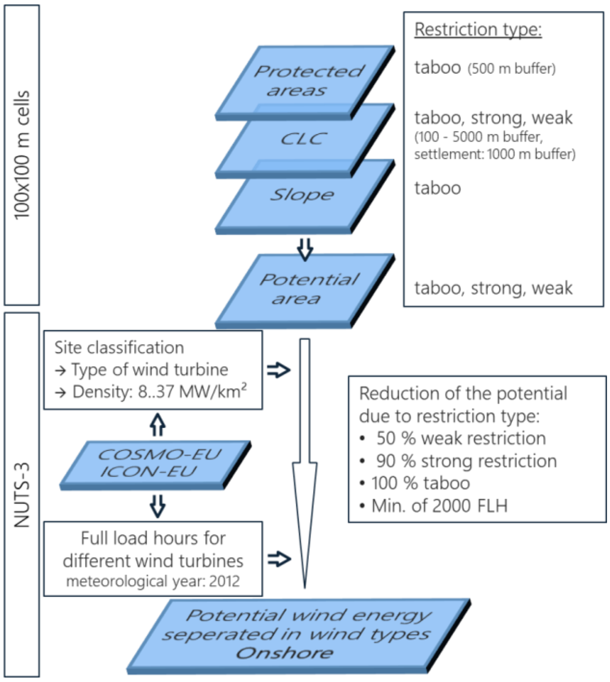


Figure 4-20: Modeling process wind onshore

The wind offshore potential in Europe is the result of an extensive geo-analysis for the identification of areas and their subsequent rating. The former takes into account all relevant sea areas, sub-divided into "exclusive economic zones" (EEZ) for the allocation of states, and subtracts from them all areas that are not eligible for wind turbines (e.g., protected areas, shipping routes). The extracted potential areas are further subdivided into deeper than 80 meters or less than 80 meters, to distinguish between floating or bottom-fixed turbines. To be able to determine the energetic potential, a value for the assumed power density is derived. Finally, the calculated technical potential is rated or reduced by factors such as the distance to the nearest port, sea depth or a full-load hour limit.

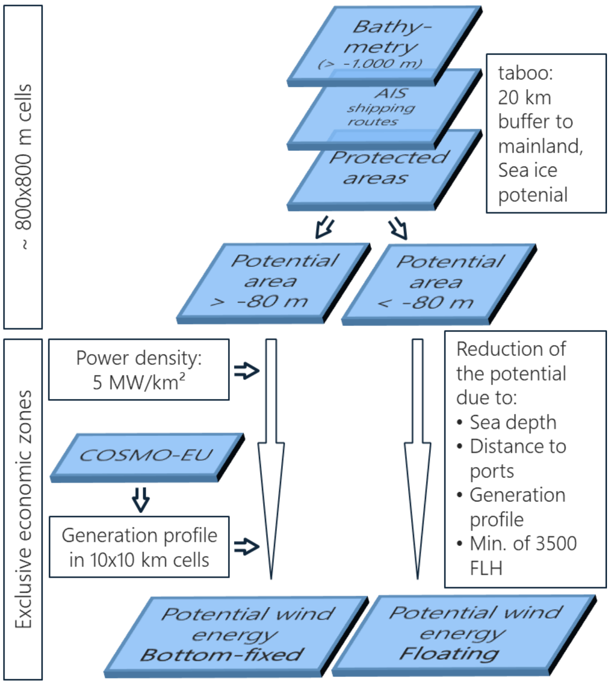


Figure 4-21: Modeling process wind offshore

The calculation of LCOE's for offshore wind energy requires detailed information about technical parameters of the turbine (rotor diameter, hub height, generation capacity) and information about the plant locations (full-load hours). Commonly future wind energy price reports contain incomplete information regarding the underlying assumptions (i.e. technical parameters such as hub height, diameter of the rotors and full-load hours). Missing full-load hours are estimated with AEP curves from [63]. Depending on the power density and the average windspeed typical full-load hours are estimated. Missing technical specifications – especially the power density – are estimated based on the provided full load hours in [64].

Cost of investment is calculated for the different turbine components.

Investment costs and fixed operating costs for wind turbines for different turbine types are calculated. In Dynamis [21], an approach for calculating the investment costs of various wind turbines was developed. It is based on a representation of the individual technical components according to [65]. The relative change of the different components, such as the rotor or tower height, was mapped to a cost factor. The approach is based on [66].

In the next step, the LCOE were calculated for the different plant types and locations. A consistent presentation of the investment costs for the different annual yield values was achieved. An example of the inconsistent presentation of the costs should illustrate the importance of a consistent presentation: If the increase of costs for low wind turbines is lower than the increase in annual yields, sites with worse wind conditions would obtain lower LCOE.

This set of investment costs was developed in [21]. In this research project, the previously mentioned data was validated and updated. For this purpose, the resulting LCOE for a single site was compared with other publications.

In Figure 4-22 the LCOEs derived using the described methodology is compared to different wind turbines mentioned in reports from the Danish Energy Agency [67], TYNDP [68], NREL [69]. The diagram shows that LCOEs calculated in [21] are significantly higher compared to the other reports. The goal of this analysis is to adjust those prices to account for current market development and price reductions. The prices of existing power plants are consequently updated ("FfE Updated") to be in a consistent price range with current reports (e.g., [67] and [69]). The low resulting LCOE for TYNDP [68] with higher specific power is not taken as a benchmark due to missing technical information.

The resulting LCOEs seem unreasonably low which results from the previously described estimation of power density. The LCOEs for wind turbines with specific power levels below 200 W/m² from [69] are cost projections for years 2040 and 2030. They are based on new tower designs and are therefore not used as a benchmark. The updated LCOEs "FfE Future" range from 31.6 €/MWh to 39.9 €/MWh at reference windspeed of 7 m/s in 100 m height. They are located in between lowest and highest currently projected values from reports from [67] and [69], which are assumed as reference for current onshore wind generation costs.

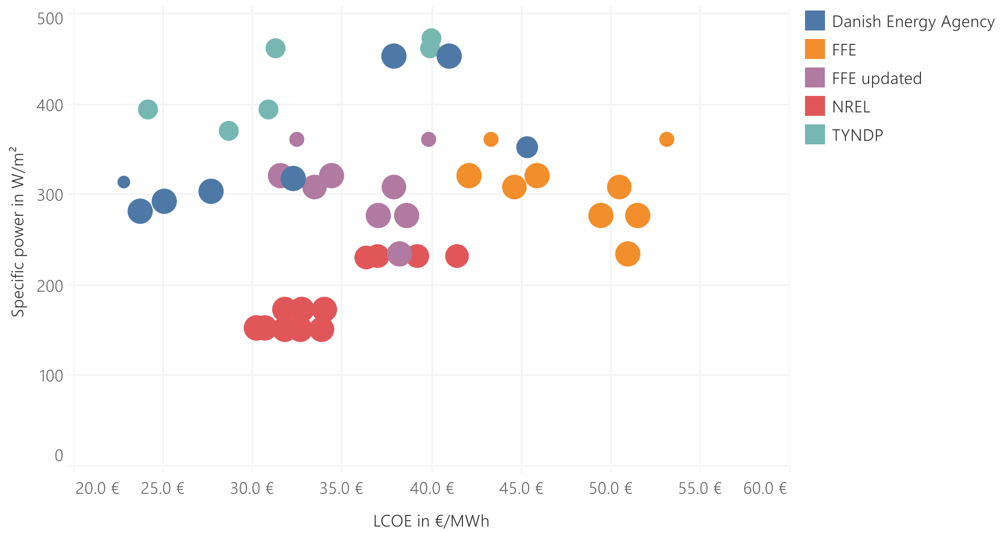


Figure 4-22: Deduced LCOE of all analyzed power plants and all years

The resulting costs for five different types of turbines and site classifications are shown in Table 4-1. The operational costs were assumed to be independent of the plant type.

Table 4-1: Costs of wind turbines

Site classifi-cation	Hub height in m	Diameter in m	Power in MW	Power density in W/m²	Invest. 2020 in €/kW	Invest. 2035 in €/kW	Invest. 2050 in €/kW	Operating costs in €/(kW a)
Weak	140	138	3.5	234	1,950	1,750	1,650	25
	140	126	3.45	277	1,750	1,550	1,500	25
Average	100	117	3.3	307	1,500	1,350	1,300	25
	100	126	4	321	1,200	1,050	1,000	25
Strong	98	91	2.35	361	1,200	1,100	1,050	25

The wind model provides the potential for wind turbine development in ISAaR in terms of installed capacity, generation time series and costs. This involves the separate modeling of the deconstruction and replacement of existing turbines in the respective NUTS-3 region as well as the modeling of the remaining potential for additional expansion. The remaining potential in the NUTS-3 regions of a country is developed in equal proportions according to the expansion planning in ISAaR. The components and input variables of the wind model are shown in Figure 4-23.

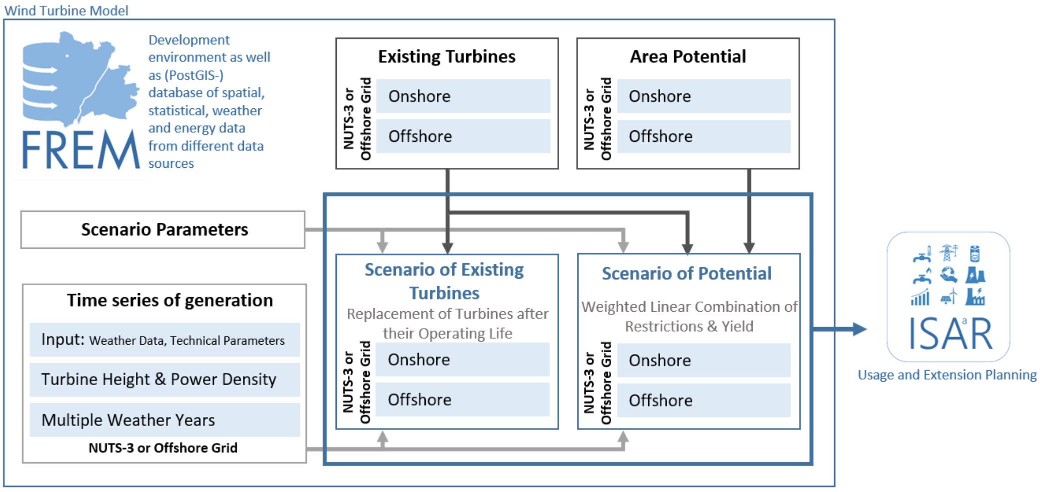
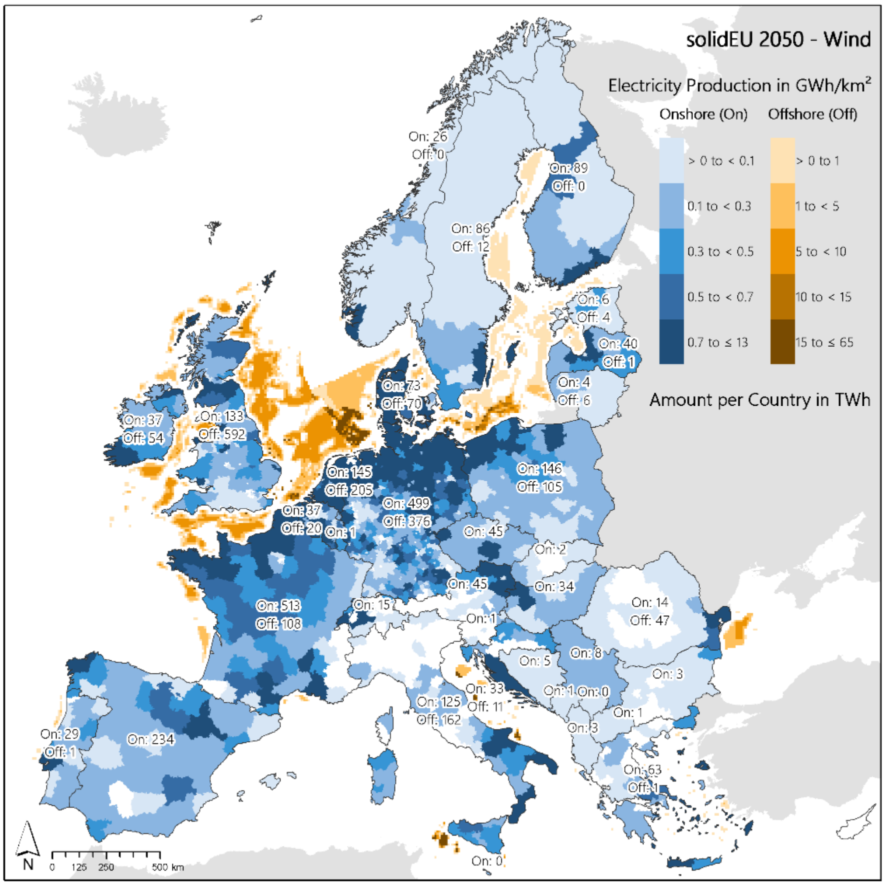


Figure 4-23: Wind model overview

The results of the wind model depend on the boundary conditions in the ISAaR model. For one scenario the resulting dataset is presented in Figure 4-19.



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

Figure 4-24: Distribution of the realized potential of wind in the scenario solidEU

Excursus: Weather Years

XOS scenario results are calculated for the weather year 2012. This excursus shows that the weather year 2012 is a typical average weather year and is therefore suitable for such scenario evaluations.

Based on meteorological data from 1980 onwards, the weather years of the last 10 years are examined in detail. For various criteria, both the annual values for NUTS-0 regions and groups of NUTS-0 regions as well as the small-scale distribution of these annual values are evaluated.

The following four parameters were chosen for the evaluation:

- Annual yield of photovoltaic systems: to distinguish between years with high and low solar yields
- Annual yield of wind turbines: to distinguish between years with high and low yields from wind turbines
- Degree day numbers: indicator for electricity consumption
- Degree day numbers of the coldest week: indicator for the height of the load peak

To reduce the number of evaluations and visualizations and to be able to better illustrate correlations, the results are aggregated for nine different regions as shown in Figure 4-25.

Figure 4-25: Definition of regions for weather year excursus

Weather data from MERRA-2 for the period from 1980 onwards is evaluated. For all NUTS-3 regions the four parameters are calculated. The aggregation to greater regions is based on the eXtremOS regionalization of renewable capacity and load.

The distribution of the different parameters is shown as boxplots in Figure 4-26. The last ten years are marked in different colors. In addition, the year 2012 is marked with red arrows.

The weather year 2012 was typical in terms of heating degree days, not only in Germany but throughout Europe. Thus, the energy consumption - and thus the most important variable - is represented in a typical way.

Electricity generation from wind and solar varies greatly and is not uniform across Europe. In Germany, the weather year 2012 typically represents the electricity generation. Except for southern Europe, the wind power generation is typical across Europe. Except for eastern and southern Europe, PV electricity generation is typically represented.

Even though the weather year 2012 is very typical in many parameters and in most regions, one special detail must be pointed out. There was a particularly cold week throughout Europe in 2012. This should be taken into consideration when evaluating model results, since the peak load witnessed in this year was comparably high. This could mean that electricity grids, power plants and storage capacities are on the one hand sufficiently stable to withstand a particularly cold winter, but on the other hand their capacity might be overestimated.

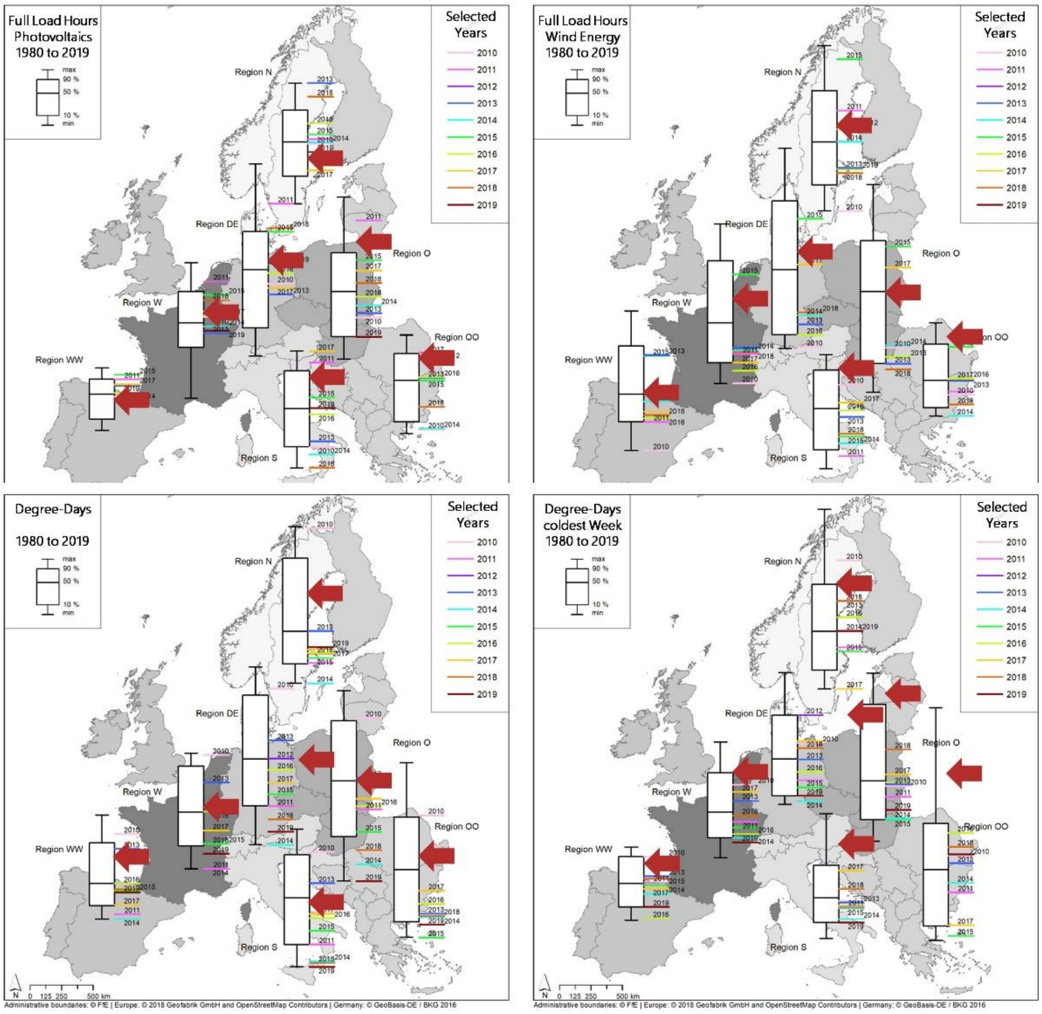


Figure 4-26: Long term analysis of different parameters

4.3 Integrated Simulation Model ISAaR

ISAaR (Integrated simulation model for unit dispatch and expansion with regionalization) is the European energy system model of the *FfE*. The basic outline of ISAaR was developed throughout a series of projects prior to eXtremOS [99], [70], [98], [21]. Building upon the model framework developed in the preceding project Dynamis, which is described in detail in [21] and [22], ISAaR further evolved in eXtremOS. Major advancements implemented are:

- Expansion of the model scope to Europe for all energy carriers
- GHG-emissions CAP with variable regional resolution
- Hydrogen trading options between European countries
- Additional energy carrier balance for CO_2 as feedstock
- Revaluation factor for renewable energy sources

ISAaR is a linear optimization model using perfect foresight, which minimizes the energy system's total costs. It is a nodes-edges model in hourly resolution with flexible spatial resolution. Within the project eXtremOS ISAaR is used to model the energy sector and therefore the provision of energy carriers demanded by the FEC sectors in the modeled European countries. These energy carriers are electricity, (district) heating, hydrogen, gas, liquid hydrocarbons, and biomass. In addition, the provision of CO_2 from industrial emissions as feedstock for methanization was included in ISAaR in the eXtremOS project. ISAaR can therefore be defined as a multi energy carrier system model. Each energy carrier is modeled as a balance between consumption and generation, the so called "energy carrier balances". The interplay between the energy carrier consumption by the FEC sectors, the energy carrier provision by imports, domestic sources and renewables, as well as technologies that connect the energy carrier balances, is shown in Figure 4-27. The mathematical formulation of the optimization problem regarding energy carriers already modeled in Dynamis can be found in [21]. The energy carrier balance for CO_2 will be described in more detail in the section 4.3.4.

The European electricity market coupling is also part of ISAaR. Electricity can be transferred from one country to another. In doing so, the so-called net transfer capacities NTCs, to exchange electricity between neighboring countries, are limited. This approach ensures that each country represents its own market area, since electricity cannot be exchanged indefinitely. However, an increase of NTCs over the years is implemented in ISAaR depending on the scenario. In quEU on the one hand, NTCs are expanded according to the TYNDP2020 [68]. Modeled, European total NTCs increase from 129 GW in 2020 to 287 GW in 2050 and therefore represent an only moderate deepening of the European electricity market coupling. In solidEU on the other hand, European NTCs increase by 508 GW from 129 GW in 2020 to 637 GW in 2050. This increase follows the European Commission's proposal to expand trading capacities to 75 % of the thermal capacities [71]. As the proposal was only implemented to a lesser extent [72], in solidEU from 2030 onwards, possible electricity exchange rates are set to 70 % of the thermal capacities. Here, the solidary character within Europe inherent to the solidEU scenario (see section 3) emerges once more as the increase of NTCs in solidEU reflects a great deepening of the European electricity market coupling. As a result of the modeling approach to trade electricity between countries via NTCs, regional differences between the modeled countries can be found and the impact of the European electricity market coupling on the overall system can be investigated.

In the following sections 4.3.1 to 4.3.5 model enhancements in comparison to [21] are described.

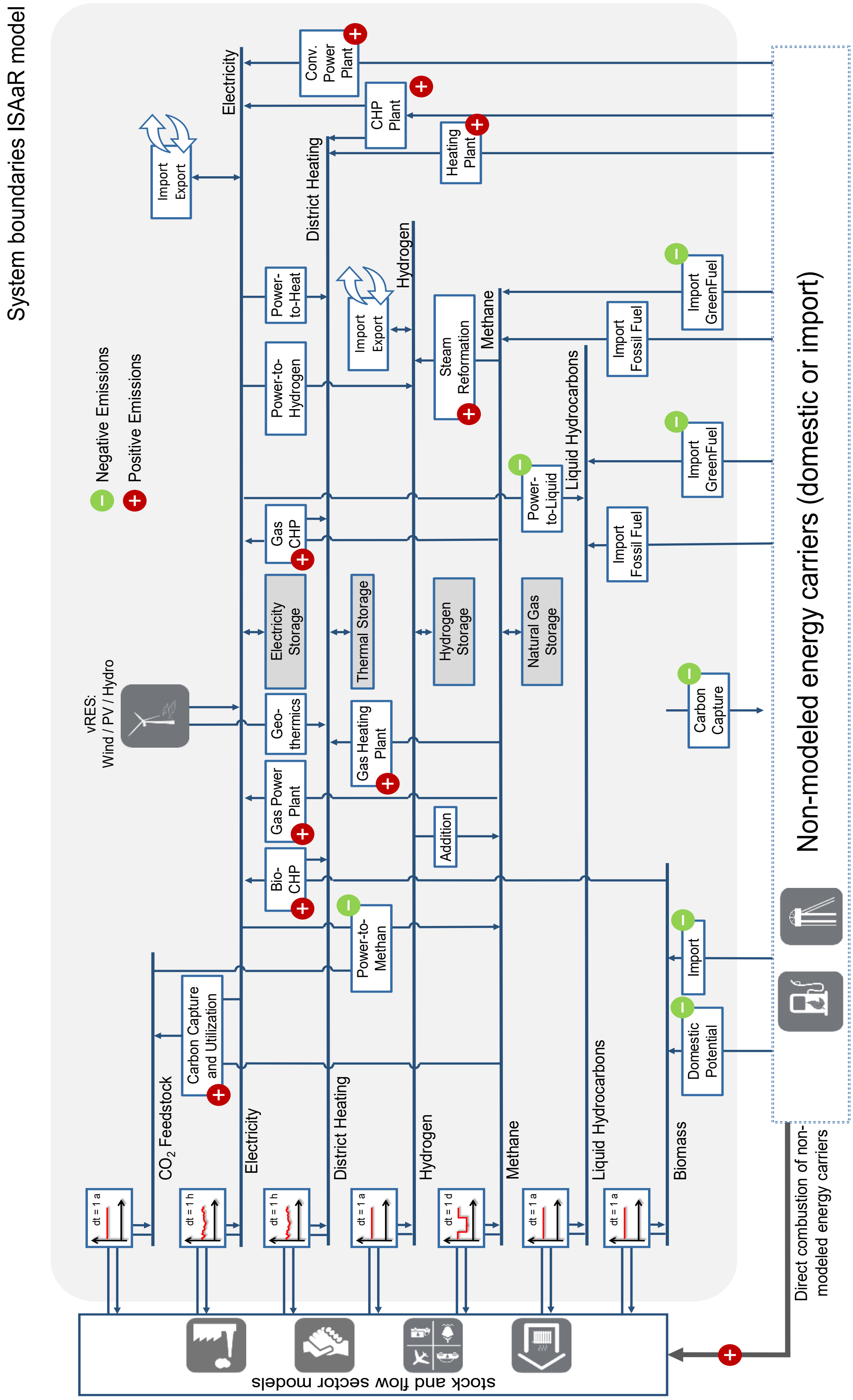


Figure 4-27: Model scope of ISAaR

4.3.1 ISAaR Expansion to Europe

In eXtremOS the model scope of ISAaR was extended to Europe. All energy carrier balances, previously only implemented for Germany, are now implemented for all considered countries: EU27 plus Norway, Switzerland, and the UK. As described in section 4.1 the final energy consumption from the energy end-use sectors is calculated for each country and communicated to ISAaR via the FREM database. This reflects the consumption side of the energy carrier balances for each country. The generation side of the balance is determined by ISAaR, which optimizes the unit dispatch and expansion of generation capacities.

To model the transformation pathways a brown field approach is selected. With this kind of modeling approach parts of the parameters used to describe energy system are quantified exogenously while other parts are included model endogenously in the optimization (also see section 4.3.6). Exogenously given data is the same for solidEU and all solidEU scenario seeds but differs in comparison to the quEU scenario.

A valid basis as a starting point for the optimization is created by assessing the status quo of the European energy system. Existing vRES generation capacities are implemented according to IRENA [8]. Depending on the eXtremOS scenario under investigation their minimum expansion trajectories until 2040 are modeled exogenously (solidEU) according to the TYNDP2020's 'National Trends' scenario [68] or left without a predefined expansion trajectory to ISAaR itself (quEU). Other renewable energy sources, thermal power plant capacities and further generation units as well as their transformation pathways are implemented according to the TYNDP2020's scenario "National Trends" [68] and own assumptions.

In all eXtremOS scenarios national coal exit plans for all European countries are revised and implemented accordingly [73]. Since the TYNDP2020 [68] does not exhibit any data for the timespan from 2040 until 2050, an extrapolation of expansion pathways is not conducted for quEU. For solidEU on the other hand, decommissioning trends are extrapolated while commissioning trends are held at 2040 levels. Additionally, the expansion of nuclear and coal-fired power plants is prohibited by assumption as of 2025 in solidEU. In solidEU the TYNDP2020 [68] is furthermore complemented with data regarding additional hydrogen generation capacities where national hydrogen strategies are available according to [74].

In addition to these model exogenous parameters, ISAaR can calculate the unit expansion for (almost) all elements shown in Figure 4-27 endogenously. While in [21] power plant expansion was only possible in Germany, ISAaR can now expand gas power plant capacities in all European countries to determine a cost optimal supply-side energy carrier balance.

4.3.2 GHG Emissions CAP with Variable Regional Resolution

With the European Climate Law which was proposed by the European Commission in the context of the Green Deal, Europe aims at reducing its GHG emissions drastically by 2050 compared to 1990 [75]. To be able to replicate this effort in ISAaR the modeling of the GHG emissions boundary (CAP) is adapted and designed more flexibly. A differentiation between distinct regional resolutions for the CAP is implemented. The GHG CAP can be either set for each country individually or for all modeled countries at once. Furthermore, it can be decided whether an absolute GHG-emissions budget in tons of CO_2-eq. or a relative reduction target with respect to 1990 is specified. The advantages and disadvantages of different methods that can be realized to model the emissions CAP, as well as national emission reductions targets, are explained in more detail in [76].

In eXtremOS solidEU and its scenario seeds, scenarios are modeled with a relative reduction target of 95 % until 2050 compared to 1990. Data for historic GHG emissions are retrieved from the EU greenhouse gas inventory (report: [77], data: [78]). While the greatest part of the categories of the EU greenhouse gas inventory are explicitly covered by either the FEC sector models or ISAaR, some categories remain unaddressed. To avoid double counting or not considering certain emissions a mapping process between the categories of the GHG inventory and the model landscape in eXtremOS is conducted. Categories, e.g., agriculture, and GHG not addressed explicitly in one of the models, are integrated into the GHG CAP as "other emissions". For the latter a simplified exogenously specified reduction pathway until 2050 is set. "Other emissions" are reduced by 75 % until 2050 compared to the mean between 2014 and 2018.

Emissions covered by one of the models of the eXtremOS model landscape, on the contrary, are included into the optimization as energy and feedstock related CO_2 emissions. Emissions caused by the combustion of energy carriers used for energy-related applications are calculated by multiplying the energy carrier usage with the corresponding emissions factor. The calculation of the emission factors from the Eurostat balance is described in [100].

To calculate an emissions balance in ISAaR, emissions are allocated to the respective emission source. This means that emissions from gas combustion in industrial applications is allocated to the industry sector. When combustion takes place in a gas turbine power plant, emissions are allocated to the supply-side. Following this logic synthetic fuels must be imported into the system with negative emissions, as they cause positive emissions during combustion. In total these fuels are assumed as climate neutral, causing net zero emissions. Emissions can also be retrieved from the system by carbon capture (section 4.3.4) or compensation by emission certificates.

4.3.3 Hydrogen Trading Options

In all climate protection scenarios calculated in eXtremOS hydrogen plays a major role in industrial applications (cf. section 4.1.1). Hydrogen supply and generation however is limited to Europe. This means that hydrogen imports to Europe are excluded by assumption. Consequently, the European hydrogen demand is met through domestic production. However, hydrogen transport between European countries is allowed and modeled using a simplified approach based on the existing natural gas grid [79]. Capacities to trade hydrogen between connected countries are unlimited and not associated with costs. Losses for the transport of hydrogen are considered and depend on the distance over which hydrogen is traded. The losses assumed for the hydrogen trading are 0.5 % per 100 km [80], [81].

In addition to the possibility of trading hydrogen in Europe, hydrogen can also be stored. The storage of hydrogen however is not yet explicitly linked to a hydrogen storage technology or connected to any costs. In ISAaR hydrogen storage is modeled as an annual balance. Hence, hydrogen production must equal hydrogen consumption over the course of a year. The point in time of generation and consumption therefore does not have to coincide.

4.3.4 Energy Carrier Balance for CO_2 as Feedstock

The modeling of CO_2 from industrial processes as feedstock for methanation which was already considered in [21], is being developed further. A new energy carrier balance for CO_2 is implemented in ISAaR. With this modeling approach additional energy expenditures to separate CO_2 from industrial exhaust fumes can be considered. To separate and capture one ton of CO_2 0.5 MWh of thermal energy and 0.11 MWh of electricity is needed [82]. Operating costs amount to 5.5 €/t of CO_2 [82]. An overview of the connection between the energy carrier balance for CO_2 and the other energy carrier balances can be seen in Figure 4-27. The captured CO_2 can then be used to produce synthetic methane in a methanation process. The amount of CO_2 that can be captured and used this way is limited by the amount of CO_2 that can be separated from industrial exhaust gases. The optimization model decides if this route is used to produce synthetic methane, or the CO_2 is released to the atmosphere.

4.3.5 Revaluation Factor for Renewable Energy Sources

The optimization in ISAaR is executed in defined timesteps (see section 4.3.6). Due to this so-called myopic approach, the model has no knowledge of the system's future development in the year of optimization. Decisions to install additional generation capacities are therefore made without knowing the future demand. Consequently, especially due to the combination of the brown field approach and the assumed significant cost degression of vRES, a risk for stranded investments exists. While the addition of generation capacities is profitable in one year, the investment might not be refinanced during its lifetime, as electricity prices might drop in the following optimization year, not yielding the necessary return on investment.

To counteract this kind of uninformed investment inherent to myopic optimization, the assumption is made that each investment of vRES must refinance its investment costs. If investment costs for vRES drop in future, the market reference value of vRES will decrease over time. As a result, future revenues will drop as well. By anticipating sinking revenues in the future, the missing revenues must be added to the marginal levelized cost of energy (LCOE) to recoup the total investment cost during lifetime. To calculate the revaluation factor that needs to be added to the initial investment cost, the net present value (NPV) method is used. In ISAaR the artificially increased investment cost including the revaluation factor (I_0') are calculated using the following expression:

$$0 = I_0' - \sum_{t=1}^{n} c_t \cdot FLH \cdot (1+i)^{-t}$$

I_0' are the adapted investment costs used to calculate the increased LCOEs, which are decisive for the model-endogenous unit additions. FLH are the full load hours, c_t the initial LCOEs of the future timesteps t (meaning the expected revenues of the respective timestep t), and i the interest rate. The interest rate is 3.5 % [83]. The sum over the time steps runs from 1 to the end of the technology's lifetime n. With this method it can be guaranteed that each vRES generation unit built refinances itself during its lifetime and is profitable even though the market values for vRES drop.

4.3.6 Sequencing and Optimization

In energy system modeling, the order in which optimization runs are computed to model system pathways into the future has a major impact on optimization results. When analyzing transformation trajectories, it is important to pass information between runs to ensure a continuous evolution of the system. In the following, the coupling between consecutive optimizations runs, called sequencing, is explained.

In eXtremOS, optimization runs are performed with 5-year steps for the main scenarios solidEU and quEU and 10-year steps for the extreme scenario seeds (for more information on the eXtremOS scenarios see section 3). The starting point for the optimization sequence is the year 2020. As 2020 reflects the status quo of the system, no additions of generation capacities are allowed in this year. In the year 2020 only unit dispatch is subject to the optimization of the energy system. Starting from this basis an iterative process, also called sequence, is started. Each following optimization year accesses information from the previous optimization years, e.g., installed capacities or the year of construction of generation capacities.

Depending on the information concerning the previous year and the exogenously defined expansion trajectories, ISAaR then optimizes the current year under investigation. If generation units were newly built in the previous years and have not reached their end-of-life, these units will be transferred to the current year of optimization. If on the other hand generation units have reached their lifetime expectancies, they are decommissioned but can be rebuilt model-endogenously with the then valid investment costs. An additional exception is assumed for vRES. Capacities already installed in 2020 define the lower boundary of installed capacities and are always repowered when coming to the end of their lifetime. On top of that lower boundary the mechanism for additional expansions and decommissioning is applied as explained above. Figure 4-28 illustrates the process.

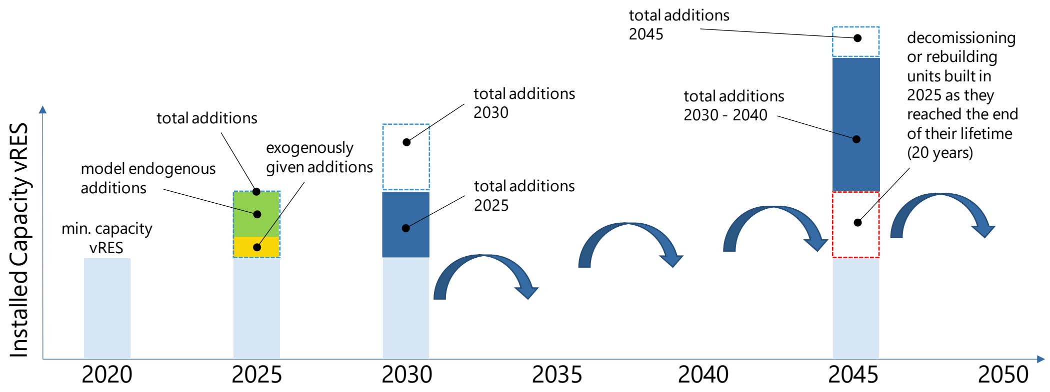


Figure 4-28: eXtremOS sequence for vRES additions for consecutive optimization years

Publications and further information related to GridSim and the calculation of the "flexibility range" are available on our WEBSITE.

Excursus: GridSim –Power Grid and Energy System Model for Distribution Grids

The model framework GridSim is designed as a bottom-up approach, modeling single entities of distribution grid components like households or photovoltaic systems, and focuses on charging strategies of flexible consumers such as heat pumps, battery storages, and electric vehicles. GridSim was developed and used within various projects since 2013. Electrification of the heat and mobility sector and smart charging strategies often played a major role in these projects.

In eXtremOS, GridSim's functionalities have been extended: A bidirectional "soft linking" between the models GridSim and ISAaR was established via a generic exchange of time series and parameters over the FREM database. Additionally, a method to estimate the so-called "Flexibility Range" of typical low voltage distribution grids, which could be provided to higher voltage levels without overloading the distribution grid in respect to its voltage band limitations and its line and transformer utilization, was developed. The term "Flexibility Range" describes the possible change of power based on the current load or operational point in both directions at a point of time.

4.4 Market and Infrastructure Model of the Gas Industry MInGa

The Market and Infrastructure Model of the Gas Industry (MInGa) completes the model landscape shown in Figure 4-1. MInGa is a European gas market model that formulates a mathematical description of the gas market using linear optimization and perfect competition. It includes all relevant producers, LNG terminals, storage facilities and consumers of the European gas market, as well as the transmission network, modeled with their marginal costs, so that a minimization of the total economic costs can be carried. The optimization period is one year with a daily resolution. For further details on MInGa see [84], [85], and [86].

MInGa model expansions in eXtremOS can be divided into two parts: the higher regionalization at NUTS-II-level within XOS Europe[9] and the integration of alternative gases. Regionalization in MInGa before eXtremOS was heterogenous – in Germany there were 128 gas nodes with nodes for each gas storage unit, while in other parts of Europe, each balancing area was modeled with one node. This was harmonized and all components aggregated to NUTS-II-level. The different components in MInGa and their sources are shown in Table 4-2. The technical infrastructure is also displayed graphically in Figure 4-29.

[9] Countries for gas market analysis differ from those relevant for the other models. They include Spain, Portugal, France, Italy, Switzerland, Austria, Great Britain, Denmark, Germany, Czech, Poland, Hungary, Slovakia, the Netherlands, and Belgium. MInGa model runs are performed last, hence this does not cause conflicts.

Table 4-2: Regionalization of Component Modeled in MInGa

Type	Component	Source
Technical Infrastructure	European gas transmission network	[79]
	LNG terminals	LNG Investment Database [87], [88]
	Storage facilities	Storage Database [89]
Gas production	Fixed natural gas production	Regionalization: literature review Annual production: [68]
	Flexible natural gas production	No regionalization performed Annual production limits: [68]
	Biogas	Regionalization: evenly distributed Annual production: [68] & ISAaR results
	Synthetic methane	Regionalization: PtG regionalization Annual production: ISAaR results
	Synthetic hydrogen	Regionalization: PtG regionalization Annual production: ISAaR results
Gas consumption	Different sectors, applications	Results from demand-side models (cf. section 4.1)

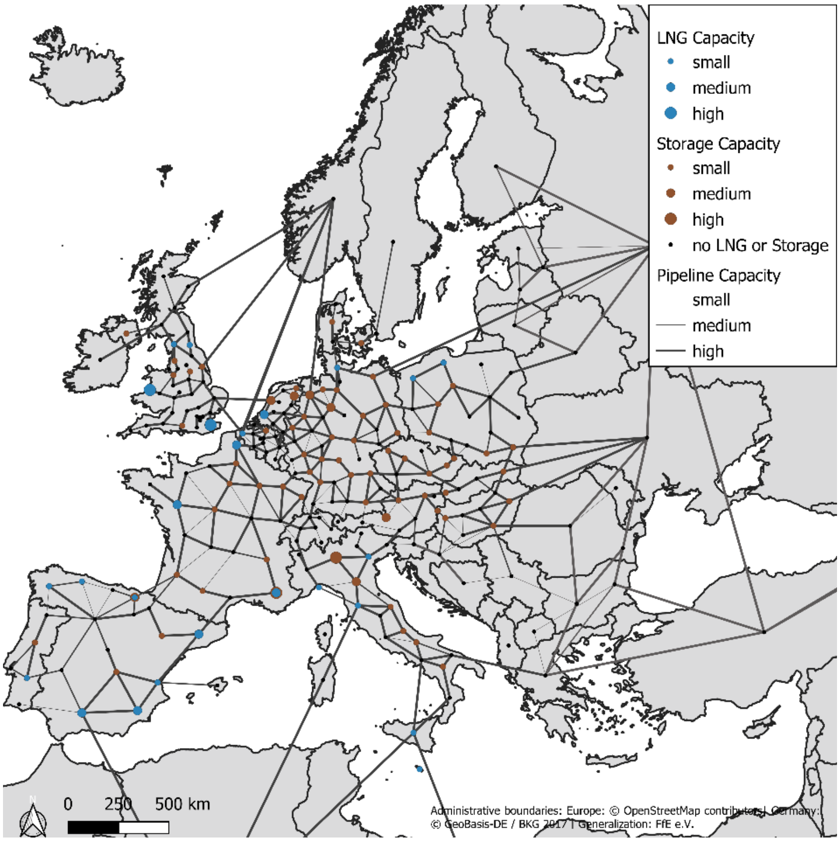


Figure 4-29: Pipelines, storage facilities, and LNG terminals in MInGa

Regionalization factors for power-to-methane and power-to-hydrogen are available as OPEN DATA.

The second expansion in eXtremOS was the integration of alternative gases such as biogas, synthetic hydrogen, and synthetic methane. As mentioned in Table 4-2, biogas is only integrated in a simplified way, with a uniformly distributed regionalization and a fixed production. For synthetic hydrogen and methane, on the other hand, simulation results of ISAaR as well as a new regionalization algorithm are used. To determine the regionalization factors for PtG, the regional distribution of renewable energy sources, the gas network, the gas storage facilities, industrial hydrogen consumers and CO_2 sources are considered. These factors are weighted differently for power-to-methane and power-to-hydrogen processes.

To analyze the impact of the alternative gases on the natural gas infrastructure, they are implemented as new components in MInGa. This facilitates the ex-post calculation of the gas composition at each node. This in turn, is necessary, for example, to determine whether the share of hydrogen in the gas mix is too high. In addition to the ex-post analysis tool, other model adaptations were made to allow for hydrogen injection into the natural gas network, while considering a maximum hydrogen share.

In the following section findings from the quEU (section 5) and solidEU scenario (section 6) as well as extreme scenario seeds (section 7) are discussed.

Further details on these changes and MInGa's methodology in general can be found in the MInGa methodology report available HERE.

5 quEU Scenario Findings

The scenario findings for quEU entails an overview of the final energy consumption development (cf. section 5.1.1), the results of the energy system analysis performed with ISAaR (cf. section 5.1.2) and the effects of demand and supply-side developments on the gas market (cf. section 5.1.3).

5.1.1 Final Energy Consumption

In the *quEU* scenario, final energy consumption in Europe decreases by 18% from ~13,200 TWh in 2020 to ~10,800 TWh in 2050 (cf. Figure 5-1). Key drivers are efficiency measures implemented in all four FEC sectors.

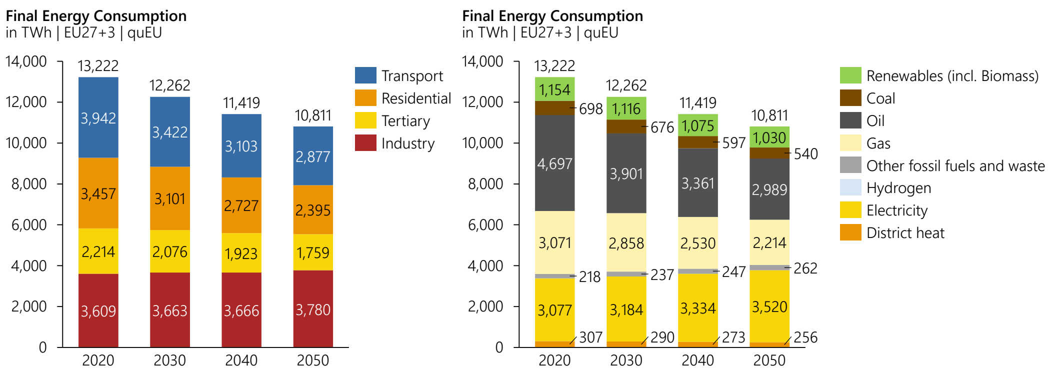


Figure 5-1: Final energy consumption by sector and energy carrier in quEU[10]

Based on the socio-political context in the *quEU* scenario, direct electrification measures are implemented in the residential, tertiary (heat pumps), and transport (battery electric vehicles) sectors. In *quEU* financial incentives for an uptake of fuel switch measures in the industry are insufficient. Resultingly, the share of total FEC of the transport, residential, and tertiary sector decreases until 2050. The industry sector experiences an increase in both absolute and relative FEC as efficiency measure implementation is insufficient for compensating the growth related FEC increase.

The FEC by energy carriers shown on the right-hand side of Figure 5-1 shows that electricity consumption increases from ~3100 TWh to ~3500 TWh. This results from electrification in the transport and buildings sectors, which simultaneously leads to the reduction in oil and gas demand. The energy carrier consumption structure in the European industry sector remains relatively stable in quEU, since solely efficiency measures are implemented.

5.1.2 Energy Supply-Side

In the quEU scenario, the energy sector undergoes a remarkable transformation, as shown in Figure 5-2. Large amounts of vRES are installed until 2050, leading to a share of 83 % of renewable energies of gross electricity consumption.[11] This transformation takes place despite the absence of GHG-emissions targets. This means that no adaption pressure is posed to the

[10] Industrial district heat is allocated to the respective primary energy carriers based on the 2017 district heat split in each country [4].

[11] The gross electricity consumption comprises the net electricity consumption, the internal power consumption of power plants, grid losses as well as storage losses.

energy sector by any GHG-emission targets. Also, the only moderate change of the energy carrier demand structure cannot fully explain the energy system's evolution. One might expect the rising prices for CO_2-certificates, which increases from 30 €/t in 2020 to 85.2 €/t in 2050 [21][12], to be a main driver. However, large amounts of vRES capacities are installed as of 2025, where CO_2 certificates prices are still moderate (5.9 €/t increase compared to 2020). Thus, the transformation of the energy sector cannot be solely explained by the rising prices for CO_2 certificates.

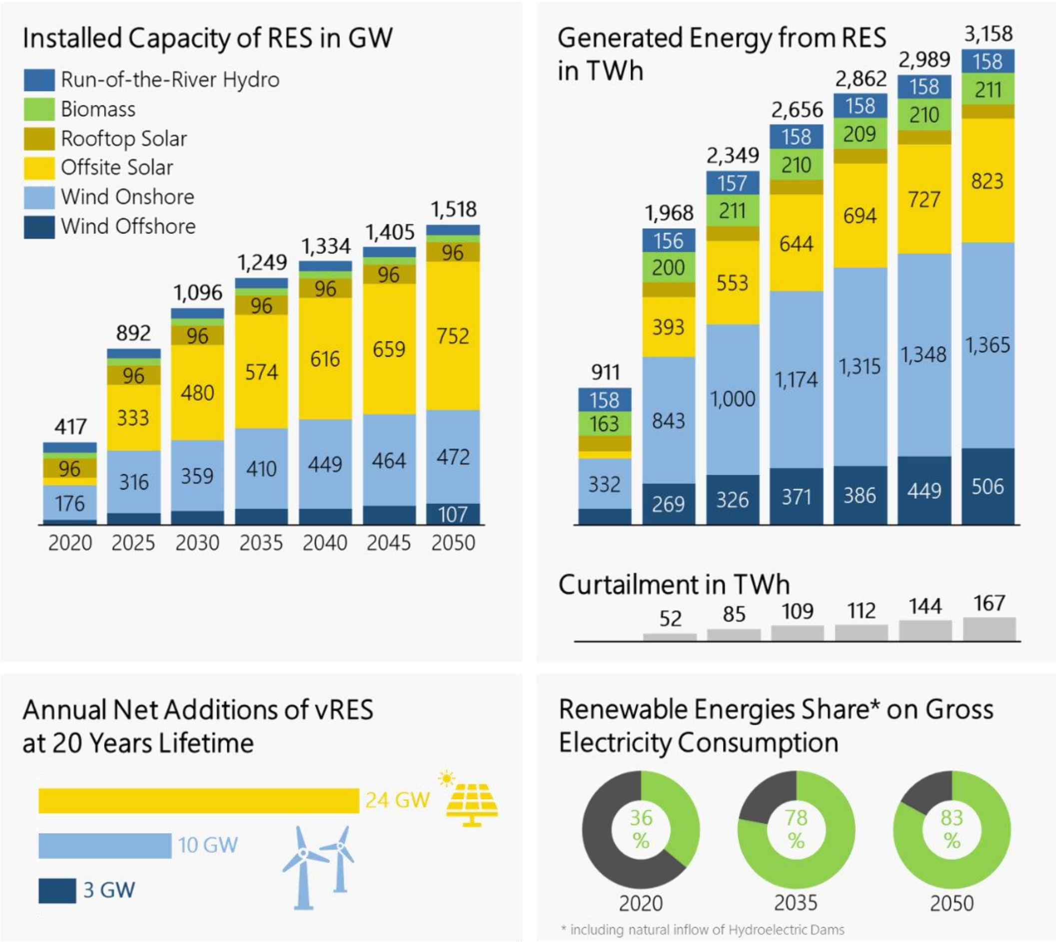


Figure 5-2: RES development overview for quEU

The main driver for the transformation of the energy sector in the quEU scenario is the cost degression of vRES. Installation costs of average site onshore wind turbines drop from 1500 €/kW in 2020 to 1350 €/kW in 2050. Costs for offshore wind turbines drop from 2130 €/kW in 2020 to 1780 €/kW in 2050. Further details for wind turbine costs can be found in [64]. Stronger cost degression can be seen for offsite photovoltaic systems as described in [90]. Here the installation costs for a 100 MW plant drop from 437 €/kWp in 2020 to 223 €/kWp in 2050 (also see section 4.2) The conclusion that these cost degressions are the main drivers for the transformation of the energy sector can be drawn, since in the quEU scenario, exogenous expansion pathways for vRES are not defined. Hence, all additions of vRES are market driven and represent the cheapest option to produce electricity.

[12] Prices for CO_2-certificates were adapted for the years 2020 and 2025 compared to [21] to reflect current price evolutions.

As can be seen in Figure 5-2 the strong cost degression leads to a more than fourfold increase of installed vRES capacities from 2020 to 2050. PV systems account for the largest share of the additional vRES capacities. Here, an increase from 136 GW in 2020 to 848 GW in 2050 can be observed in Europe. In addition, 296 GW of wind onshore capacity enters the system, leading to a total installed wind onshore capacity of 472 GW in 2050. In the same period 85 GW of wind offshore capacity is added to the already existing 22 GW in 2020, leading to a total of 107 GW in 2050. Translated to annual net additions it follows that on average 24 GW of PV, 10 GW of wind onshore and 3 GW of wind offshore is installed between 2020 and 2050. These numbers are in the same order of magnitude as the historic record years for the maximum additions for each of the three technologies [91], [92]. Together with other RES like run-of-the-river hydro, biomass, geothermal and hydroelectric dams, RES cover 83 % of gross electricity consumption in 2050. This corresponds to a production of 3,570 TWh of electricity. In addition to the 3,570 TWh produced, another 167 TWh of renewable energy production cannot be integrated into the market and needs to be curtailed.

Installed capacities in quEU differ compared to the TYNDP2020's "National Trends" scenario. While in the TYNDP2020 347 GW of PV systems and 296 GW of wind onshore systems are installed in the year 2030, quEU has 576 GW and 359 GW respectively. The differences in gas fired power plant capacities are not as significant. In the TYNDP2020 installed capacities amount to 249 GW, while in quEU 264 GW are installed. Only when considering wind offshore capacities, the TYNDP2020 exceeds the installed capacities of quEU. In 2030 TYNDP2020 sees 77 GW installed, while quEU only sees 69 GW. In comparison to the TYNDP2020 quEU clearly sees stronger trends towards additions of PV systems and wind onshore, as they enter the marked representing the cheapest energy source. Here the difference between the market-based approach of quEU and a still policy driven scenario becomes obvious [68].

Interestingly, the largest net additions of vRES generation capacities per year already takes place in 2025, displacing large amounts of electricity production (946 TWh) from thermal power plants (mainly coal and gas). Even though installed capacities of thermal power plants decrease by 75 GW (see Figure 5-3) from 2020 to 2025, the drop in electricity production from thermal power plants cannot solely be explained by the fewer installed capacities. Provided that the designated areas from the eXtremOS analysis for the vRES production potential [93] can be developed without further additional regulatory barriers, it can be concluded that new and unsubsidized vRES capacities can be cost competitive in comparison to existing thermal power plants in large parts of Europe.

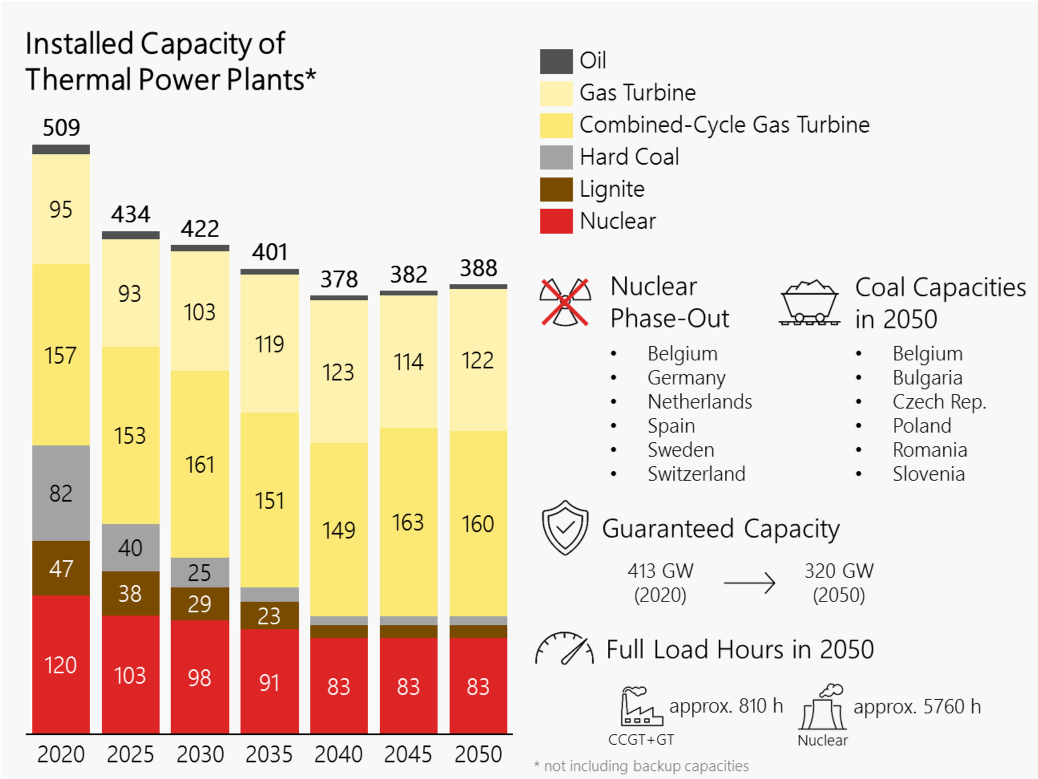


Figure 5-3: Installed Capacities of thermal power plants in quEU

Until 2050 even more thermal power plants are decommissioned. In comparison to 2020 there is 25 % less installed thermal power plant capacity in 2050 (see Figure 5-3). Accordingly, the available capacity[13] drops from 413 GW to 320 GW, while the electrical peak load rises by 24 % from 547 GW in 2020 to 679 GW in 2050. The emerging gap is contained by the increased production capacities of RES in combination with an increase of NTCs as well as flexible consumption and storage technologies like electrolysis and stationary battery storage.

The decline of installed thermal generation capacities, however, is not distributed homogenously across all thermal production technologies. While gas as well as combined-cycle gas turbine plant capacities expand from 222 GW in 2020 to 282 GW in 2050, coal capacities drop sharply from 129 GW to only 19 GW in 2050. Nuclear energy drops from an installed capacity of 120 GW in 2020 to 83 GW in 2050, leading to a mainly gas dominated thermal generation park in 2050. With the change of composition the dispatch of the gas turbine power plants also changes. While nuclear power plants still run on approximately 5750 FLH, in 2050 gas turbine and combined-cycle gas turbine power plants produce electricity only for very few hours of the year (see Table 5-1). It can be concluded that gas turbine power plants are mainly used to cover peak loads.

[13] The guaranteed capacity is calculated by multiplying the installed capacity with the mean availability of each production technology.

Table 5-1: FLH of thermal power plants in the quEU scenario

h/a	2020	2025	2030	2035	2040	2045	2050
Gas	3,518	1,583	893	836	850	844	809
Hard Coal	2,438	671	575	256	124	82	54
Lignite	4,801	3,644	3,036	1,904	741	629	419
Nuclear	6,899	6,187	6,005	5,995	5,776	5,619	5,757

Figure 5-4 shows the energy balance for electricity in Europe. Here again the aforementioned trends are visible. Due to the reduction of thermal generation capacities and the increase of installed vRES capacities, the respective amount of produced energy de-/increases accordingly. In total 3,570 TWh of electricity is produced from RES in 2050. However, the electricity production from RES is insufficient to cover the gross electricity consumption which amounts to 4,318 TWh. Besides the electricity demand from the FEC sectors, electricity is used to produce hydrogen (350 TWh of electricity) and heat for district heating (76 TWh of electricity). In 2050 RES therefore only account for 83 % of gross electricity consumption.

For interactive energy carrier balances for electricity, hydrogen, gas, fluid hydrocarbons, and district heating visit HERE.

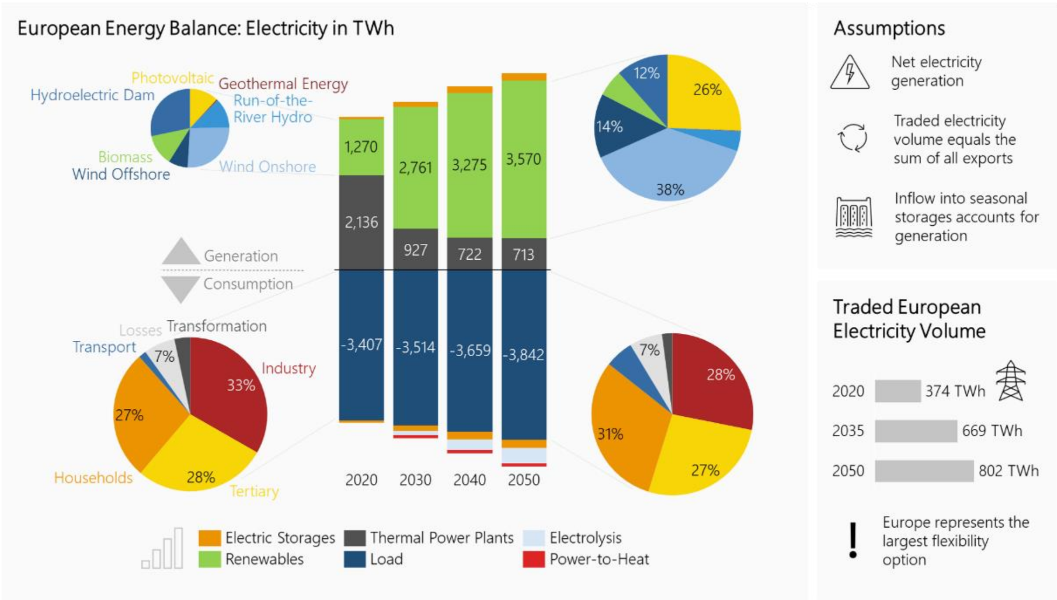


Figure 5-4: Energy carrier balance for electricity in quEU

While the hydrogen demand from the FEC sectors only increases by 5 TWh from 2020 until 2050, the amount of electricity used to produce hydrogen strongly increases from 2030 onwards. This is due to the fact that electrolysis is substituting the production of hydrogen via steam reforming, as the costs for PEM electrolysis are dropping from 1,420,000 €/MW in 2020 to 505,000 €/MW in 2050 [94]. As a result, already in 2030, 91 TWh of electricity is used to produce 59 TWh of hydrogen. From 2035 onwards all hydrogen is produced via electrolysis, which finally leads to 350 TWh of electricity used to produce 247 TWh of hydrogen by 2050. Installed electrolysis capacities amount to 89 GW_{el}. As the FEC sectors only demand 154 TWh of hydrogen in 2050 the surplus of hydrogen production of 89 TWh is blended with gas. The remaining difference (4 TWh) between hydrogen production and consumption can be attributed to losses due to hydrogen transport.

Figure 5-4 also shows the traded amount of electricity throughout Europe, which increases by 114 % in between 2020 and 2050. As mentioned in section 4.3, the NTCs increase from 129 GW in 2020 to 287 GW in 2050. This 122 % increase of NTCs is also reflected in European electricity trades which increase from 374 TWh in 2020 to 802 TWh in 2050, developing the systems flexibility as more electricity can be exchanged within Europe. The European electricity grid can be seen as a flexibility option, as neighboring countries act as functional storages: electricity exports can be interpreted as storage charging, while imports can be equated to discharging. Compared to the energy discharges from battery storages (57 TWh in 2050) and the amount of electricity used in hydrogen production (350 TWh), the European electricity grid represents the largest flexibility option in the European energy system.

The European electricity grid represents the largest flexibility option in the European energy system.

The transformation towards an energy system dominated by RES also impacts the GHG-emissions in the quEU scenario. Even without any GHG-emissions target, emissions drop by 62 % compared to 1990 to 2,616 Mt of CO_2-eq. (see Figure 5-5) until 2050. The main driver of this reduction is the energy sector, which reduces its annual emissions by more than 700 Mt of CO_2-eq. to 94 Mt of CO_2-eq. in 2050. The reduction of emissions emitted by the energy sector can mainly be attributed to the electricity production from RES instead of thermal power plants, avoiding combustion of fossil fuels. The sector "Others", comprising e.g., emissions from agriculture, yields the second largest emission reduction. This reduction is due to the external assumption that these emissions are reduced by 75 % by 2050, compared to the 2014 to 2018 average. It is followed by the transport sector which reduces its emissions by 322 Mt of CO_2-eq. between 2020 and 2030. The decrease mainly stems from the moderate electrification and therefore lower amounts of fuel combustion as explained in section 4.1.2. The emissions decrease in almost all sectors is counteracted by an increase of emissions from the industrial sector. The emissions surplus of 67 Mt of CO_2-eq. between 2020 and 2050 in the industry sector can be explained by the economic growth which cannot be compensated by the efficiency measures. As no fuel switch is assumed in quEU, this leads to higher emissions (also see section 4.1.1).

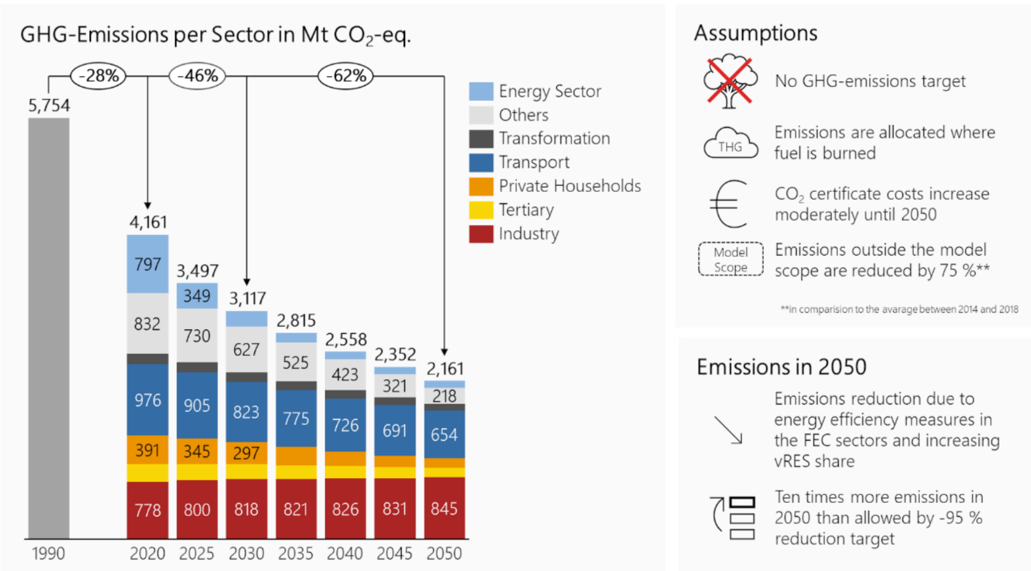


Figure 5-5: GHG-emissions by sector in quEU

In total, however, the market driven expansion of vRES is not sufficient to reach the -95 % emissions reduction target. At the same time, this also means that the 2 °C target of the Paris agreement cannot be reached without an in-depth transformation of the FEC sectors.

5.1.3 Gas Market

In the quEU scenario, the gas sector evolves as a result of a decreasing gas demand (cf. section 5.1.1) and a new gas supplier split. The European gas demand (FEC and primary gas consumption by gas-fired power plants) decreases by approx. 50 % from 5,250 TWh in 2020 to 2,772 TWh in 2050. At the same time European hydrogen demand and production increase, leading to hydrogen injection into the European gas network of 13 TWh in 2040 and 89 TWh in 2050. To meet the demand, gas is imported via pipelines or LNG terminals and distributed within the European gas network. In 2020, as shown on the right-hand side in Figure 5-6, gas is mainly imported from Russia (40 %) and Norway (23 %), with smaller shares (<10 %) from North Africa, the Netherlands, the UK, smaller European production countries, and LNG. With decreasing gas demand and the phase out/decrease in production in most European countries, imports are increasingly covered by Russia leading to a Russian gas share of 65 % in 2050. In the optimization significant flexible gas production exists in Russia, Norway, North Africa, and UK. Furthermore, LNG imports all over the world are flexible as well. The maximum production capacities in Russia and Norway are mostly drawn, while gas from North Africa, as well as LNG imports lie close at the lower bound of the flexible gas production. This effect is visible in the average gas composition in each NUTS-II-region with a strong influence of Russian gas in almost all European countries (see Figure 5-6, left-hand side). However, regional differences can also be observed. In 2030, gas demand in Spain and Portugal is mostly met by LNG and North African gas, while the UK uses regional gas and Norwegian gas. In Germany, the gas demand is met predominantly with Russian gas.

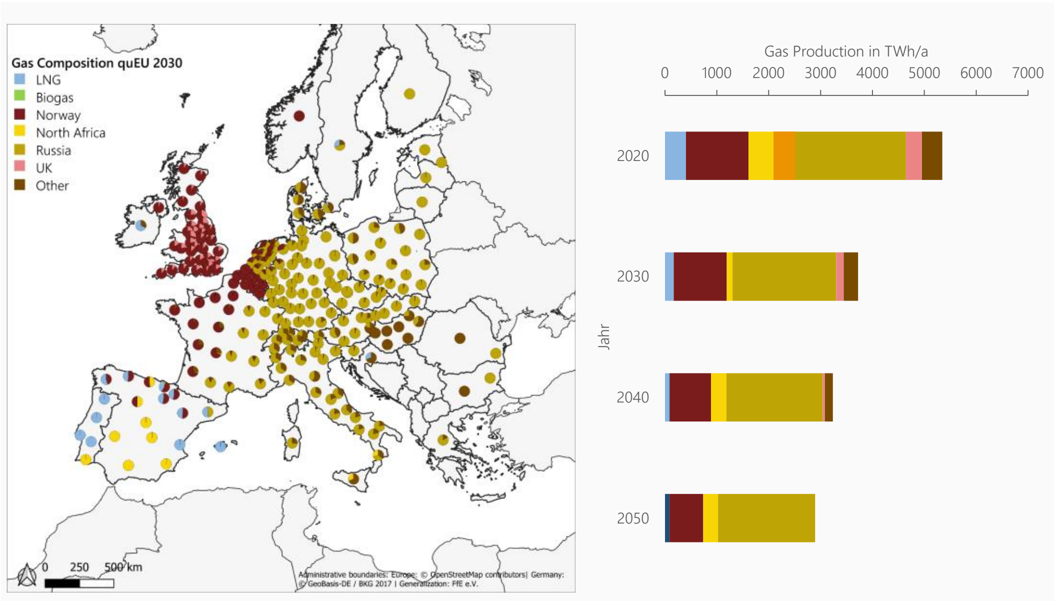


Figure 5-6: Gas composition (Load and Production)

These effects can also be observed when analyzing European average gas flows (cf. Figure 5-7). Several of the main gas transfer routes in 2020 originate from Russia: North Stream gas flows from Russia via Germany to France, other routes are Russia – Belarus – Poland – Slovakia – Austria – Italia and Russia – Turkey – Greece – Italy. Norwegian gas goes mainly to the UK but also to Germany, France, and Belgium. These routes remain the main gas transfer routes until 2040, but gas flows decrease over time (see Figure 5-7, right side). While there can be local increases in average gas flows, as shown for western Germany, this does not affect the general gas transfer in Europe.

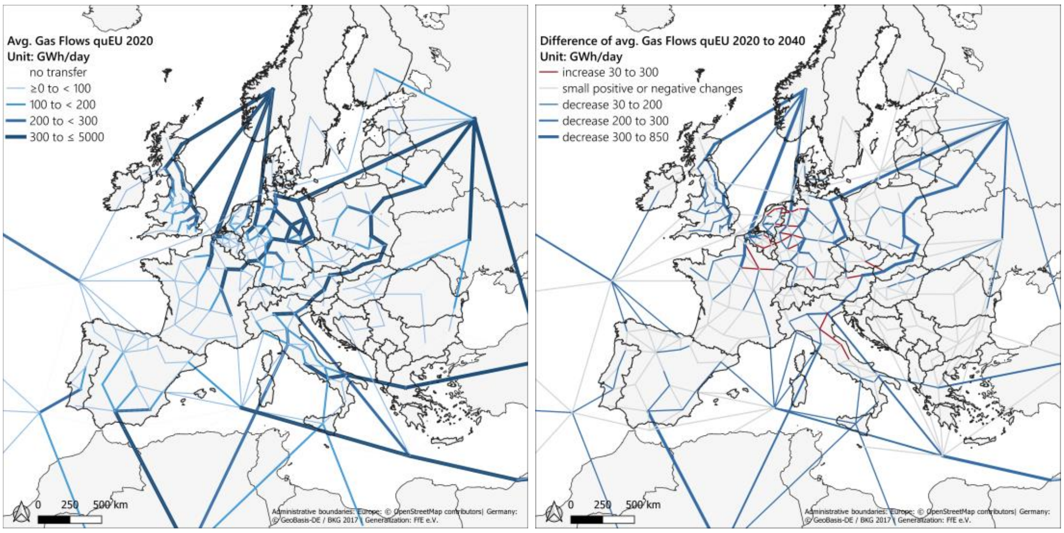


Figure 5-7: Average gas transfer in Europe in 2020 and difference to 2040

All in all, the key finding for quEU is that in this kind of scenario Russia remains Europe's main gas supplier with increasing importance in the future.

Excursus Global Perspective

The aim of this sub-project, carried out by the Technical University of Munich (TUM), was to extend the system boundaries of eXtremOS to encompass the wider global context. In order to understand how extreme developments result in coupling feedback-effects between countries and continents, a model was created that can be used to describe the interactions between the global energy markets and specific national energy systems. In this multi-granular-regionality model, the national models are linked to the global model via the globally available resources and the dynamics of the international energy markets, as well as via the global emissions budget. This allows us to assess the global impact of technological and regulatory energy system developments in Europe, emerging economies, and the world.

XOS scenarios were set into global context by our project partner from the Chair of Energy Economics and Application Technology at the Technical University of Munich (TUM). For more information visit the project website.

6 solidEU Scenario Findings

The scenario findings for solidEU entail an overview of the final energy consumption development (cf. section 6.1.1), the results of the energy system analysis performed with ISAaR (cf. section 6.1.2) and the effects of demand and supply-side developments on the gas market (cf. section 6.1.3).

6.1.1 Final Energy Consumption

In the solidEU scenario, FEC in Europe decreases by ~40 % from ~13,200 TWh in 2020 to ~7,800 TWh in 2050 (cf. Figure 6-1). Key drivers are efficiency, as well as both direct and indirect electrification measures implemented in all four FEC sectors.

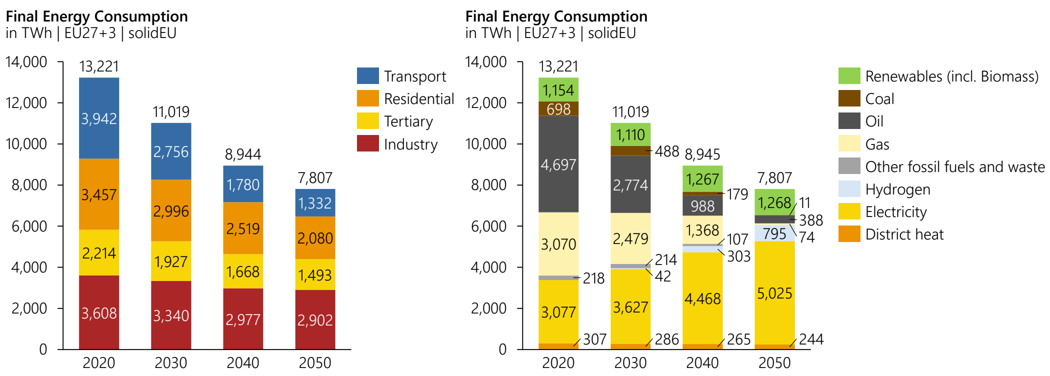
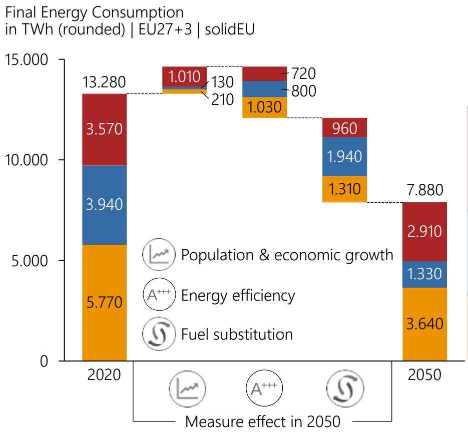


Figure 6-1: Final energy consumption by sector and energy carrier in solidEU

Based upon the socio-political context in the *solidEU* scenario, we assume that financial incentives for research and development as well as the implementation of fuel switch measures are significantly expanded and reach levels sufficient for high degrees of sector coupling in Europe. Electrification leads to a reduction in FEC in all four energy end-use sectors. This can be exemplified by the deep and fast phase-in of battery electric vehicles for passenger road and freight transport, the integration of heat pumps in the tertiary and residential sector, as well as the implementation of innovative process routes such as steel production with directly reduced iron, or electrical steamcrackers.

As a result of measure implementation electricity, biomass and hydrogen become the dominant energy carriers in 2050, with a total share of ~90 % of total final energy consumption. Hereby, electricity consumption shows the largest increase with ~3100 TWh in 2020 to ~5000 TWh in 2050. As shown in section 4.1.1, the demand for electricity could be significantly higher if climate-neutral feedstock (e.g. methanol) would be produced domestically. In addition, the energetic use of hydrogen reaches 795 TWh in 2050. This is a result of the use of hydrogen burners and turbines in a number of industrial processes (e.g. combined heat and power in basic chemicals) as well as the phase-in of fuel cell vehicles in the transport sector. Total biomass usage increases only slightly, thereby respecting the boundaries of the sustainable biomass potential in Europe. However, a shift from buildings and transport towards hard-to-abate industrial applications is assumed. By 2050 two thirds of the annual biomass usage occur in the industry sector. In 2020 only about 25 % of biomass was allocated to the industry.

Figure 6-2 shows the effect of the different FEC drivers (i.e. economic/population growth, energy efficiency and fuels switch measures) by sector as well as a high-level summary of the underlying assumptions.



	Population & economic growth	Energy efficiency	Fuel substitution
Industry	Gross value added + 1 %/a (2020-2050)	Process and cross-sectional tech.	Direct electrification: mainly low-temperature process heat Indirect electrification: energetic and feedstock H_2 usage Biomass: biocoal to replace fossil coal
Transport	Population +3 % (2020-2050)	Efficient internal combustion engines	Direct electrification: cars, light and heavy-duty vehicles Indirect electrification: cars, heavy-duty vehicles and rail
Buildings		Building refurbishm ent	Heat pumps (temperature dependent coefficient of performance)

Figure 6-2: Effects of greenhouse gas abatement measures in 2050 by sector

While population growth of~3 % until 2050 only leads to a slight increase in FEC in the buildings and transport sector, the effect of growth in gross value added (~1 % p.a.) results in an increase of 1010 TWh in the industry sector by 2050, compared to 2020. Across all sectors this demand increase is compensated by the phase-in of more efficient technologies. The largest demand decrease is, however, caused by the implementation of electrification measures, summarized under the category "fuel substitution" in Figure 6-2. Thereby the increasingly predominant use of heat pumps in low-temperature applications in the industry and buildings sector as well as the prevalence of battery electric vehicles leads to efficiency increases.

6.1.2 Energy Supply-Side

In comparison to the quEU scenario, the energy supply-side undergoes an even bigger transformation in solidEU. Figure 6-3 shows the installed RES capacities as well as the produced electricity from RES. From 2020 to 2050 the installed capacity increases from 417 GW to 3,154 GW. Compared to quEU, the installed RES capacity in 2050 is approximately twice as high. Looking at only the installed vRES capacities, the increase is even larger. In 2050 the installed capacities are factor 9 higher compared to 2020. Thereby, offsite solar power systems experience the largest capacity addition. Installed capacity increases from 49 GW in 2020 to 1633 GW in 2050. The second largest capacity additions are found with wind onshore, which increases from 176 GW to 856 GW between 2020 and 2050. Net additions for wind offshore systems amount to 388 GW in the same time span.

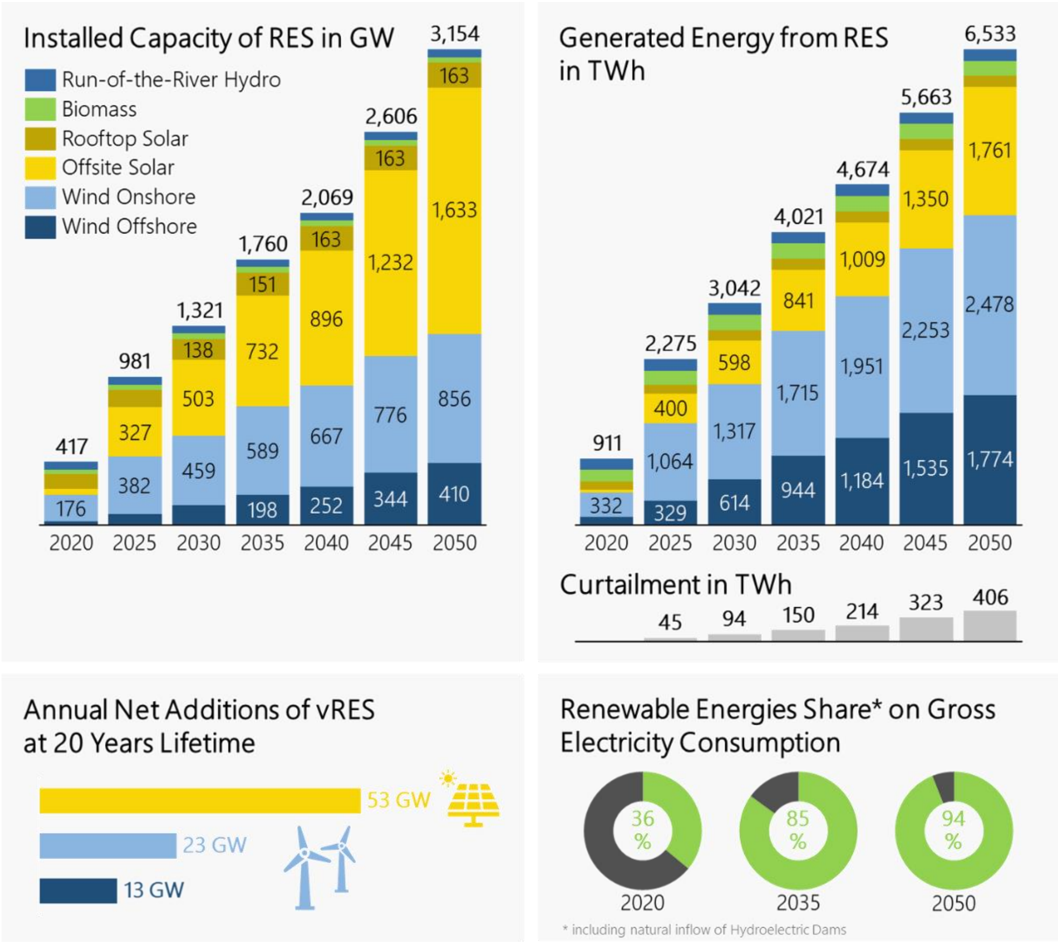


Figure 6-3: RES development overview for solidEU

Translated to annual net additions it follows that on average 53 GW of PV, 23 GW of wind onshore and 13 GW of wind offshore net capacity are installed annually between 2020 and 2050. These numbers exceed the installed capacities of historic record years by far. Years with the highest capacity additions so far are 2011 (for PV) [92], 2017 (wind onshore) and 2019 (wind offshore) [91]. Thus, in 2011, only 21 GW PV systems were added, which is less than half the necessary installation rate in solidEU [92]. For wind onshore 14 GW were added in 2017, which is 9 GW less than needed on average to reach the installed capacities in solidEU in 2050 [91]. Regarding wind offshore, the year with the highest net additions was 2019 with 4 GW additionally installed capacities, which is one third of the mean net additions in solidEU [91]. From these numbers it can be concluded that efforts to increase the installation rates for vRES need to be strengthened to be able to reach a -95 % emissions reduction compared to 1990 until 2050.

Contrary to the quEU scenario, additions of vRES capacities cannot solely be attributed to the cost degression of vRES. Installation costs of average site onshore wind turbines drop from 1500 €/kW in 2020 to 1350 €/kW in 2050. Costs for offshore wind turbines drop from 2130 €/kW in 2020 to 1780 €/kW in 2050. Further cost details for wind turbine costs can be found in [64]. Stronger cost degression can be seen for offsite photovoltaic systems as described in [90]. Here the installation costs for a 100 MW plant drop from 437 €/kWp in 2020 to 223 €/kWp in 2050 (cf. section 4.2) These cost reductions drive capacity additions until 2030. Compared to quEU, capacities added until 2030 are only slightly higher and can be attributed to the increase of 819 TWh in gross electricity consumption and the emissions CAP of -55 % compared to 1990. Only in later years the increase of gross electricity consumption and the emissions CAP of -95 % compared to 1990 in the year 2050 take over as the main drivers for the continuing increase in vRES capacity installations.

Together with other RES like run-of-the-river hydro, biomass, geothermal and hydroelectric dams, vRES cover 94 % of gross electricity consumption in 2050. This corresponds to the production of 6,946 TWh of electricity. Of these 6,946 TWh 36 % are produced from wind onshore systems, 28 % from PV systems and 26 % from wind offshore systems. In addition to the 6,946 TWh produced, another 406 TWh of vRES production cannot be integrated into the market and thus needs to be curtailed.

The cost reduction of vRES, as well as the emissions CAP and the increase in electricity demand, also affect thermal power plants. As can be seen in Figure 6-4 the installed capacities decrease from 2020 to 2025 by 81 GW and then level off at an average of 437 GW in between the years 2030 and 2050. The reduction of thermal capacities from 2020 to 2025 is mainly due to the decommissioning of coal and nuclear power plants. The decommissioning trend for these power plant types continues until 2050. While more than 90 % of coal capacities phase out of the system until 2045, 43 % of nuclear capacities are still in the system in 2050. More than half of the then installed 51 GW can be attributed to France with an installed capacity of 28 GW in 2050. The phase out of coal and nuclear power plants from 2030 onwards is compensated by the increase in installed capacities of gas and combined-cycle gas turbine power plants. Their installed capacity increases by 130 GW from 252 GW in 2020 to 302 GW in 2050.

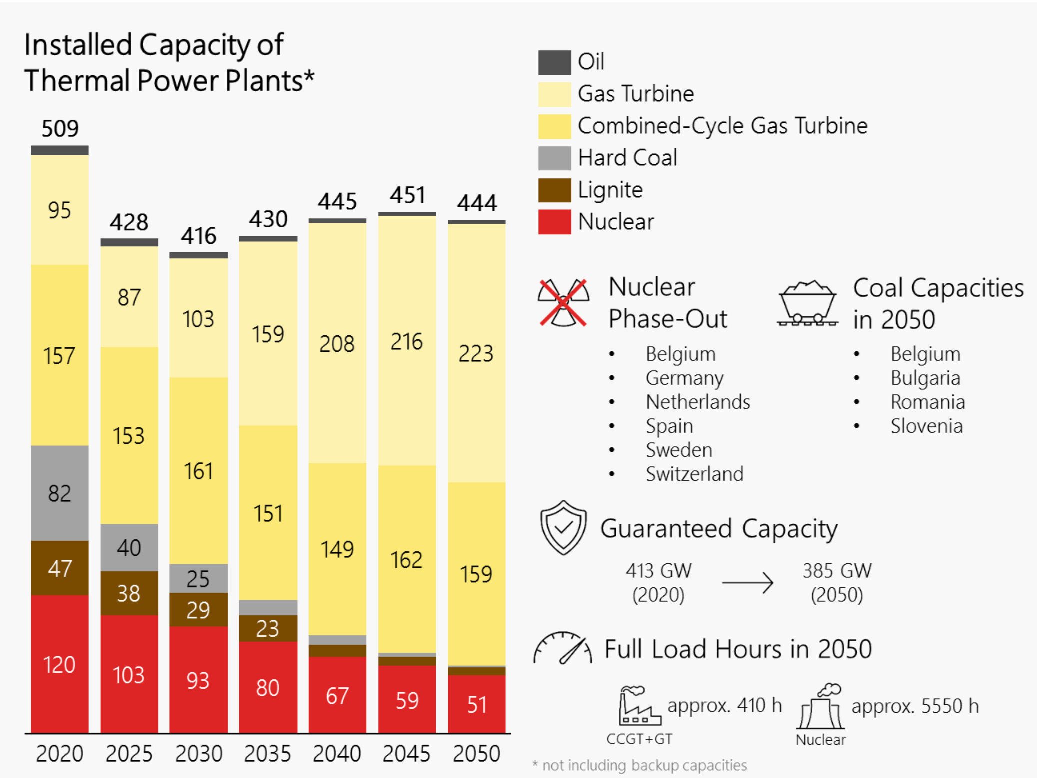


Figure 6-4: Installed Capacities of thermal power plants in solidEU

As in quEU, the characteristic dispatch of the gas and combined-cycle gas turbine power plants and the remaining nuclear power plants strongly differ (cf. Table 6-1). While the FLH of gas fired powerplants decrease from approximately 3500 hours in 2020 to 400 hours in 2050, the FLH of nuclear power plants only decrease by approximately 1350 FLH from 6900 hours to 5550 hours. The dispatch of the two power plant technologies is similar to quEU. As nuclear power plants do not emit GHG-emissions they can still be operated in 2050 to produce electricity. Gas fired power plants on the other hand are only used in few hours of the year. Due to the emissions CAP they need to be operated with climate neutral synthetic methane, which increases the marginal costs to dispatch gas fired power plants. Marginal costs for one MWh of electricity lie in the range of 150 € to 300 €, depending on their efficiencies. Gas fired power plants are therefore only used to cover peak load hours.

Table 6-1: FLH of thermal power plants in the solidEU scenario

	2020	2025	2030	2035	2040	2045	2050
Gas	3,518	1,346	763	731	715	540	407
Hard Coal	2,438	678	585	502	102	43	5
Lignite	4,801	3,591	2,502	2,101	1,328	37	4
Nuclear	6,899	6,171	5,821	5,897	5,644	5,497	5,547

Figure 6-5 shows the European energy balance for electricity. Here the aforementioned trends regarding the installed capacities of RES and thermal power plants can also be seen in the produced amounts of electricity. While electricity production from RES increases by 447 %, electricity production from thermal power plants decreases by 80 %. On the consumption side, the gross electricity consumption increases from 3,507 TWh in 2020 to 7,404 TWh in 2050. The increase of 111 % can mainly be attributed to the increase of the electricity demand from the FEC sectors due to the electrification measures (see section 4.1) in the solidEU scenario. The second main driver for the increase of gross electricity consumption is the hydrogen demand by the FEC sectors with the related electricity consumption, which amounts to 1,539 TWh in 2050.

Interactive energy carrier balances for electricity, hydrogen, gas, fluid hydrocarbons and district heating are accessible HERE

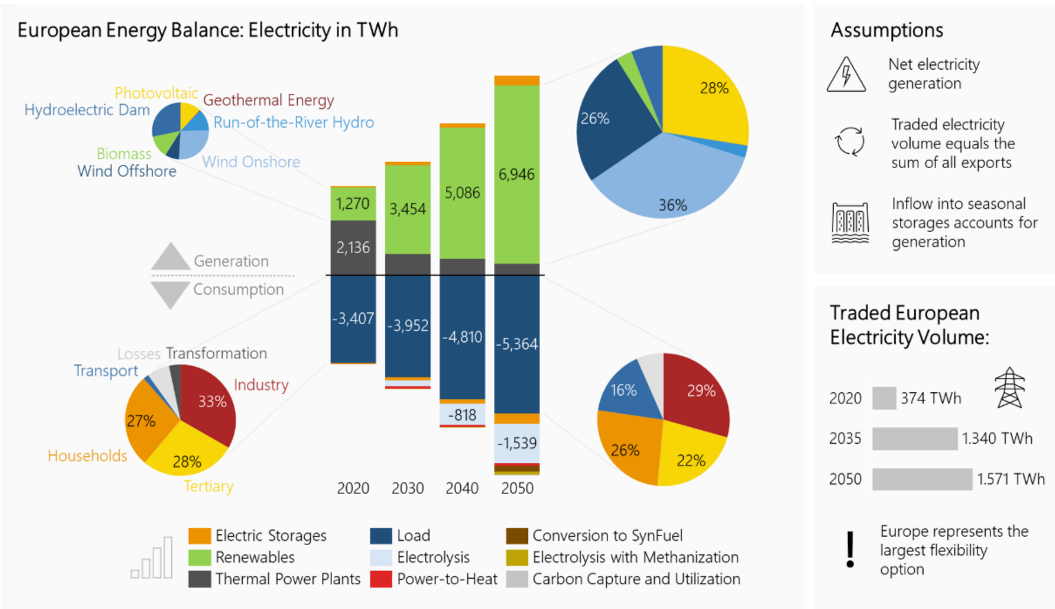


Figure 6-5: Energy carrier balance for electricity in solidEU

As more and more electricity is produced from volatile energy sources, regional electricity production differences are balanced by intensified trading between the European countries. Along with the amplification of NTCs in solidEU (see section 4.3) the traded electricity volume increases from 374 TWh in 2020 to 1,571 TWh in 2050. The European electricity grid can be seen as a flexibility option, as neighboring countries act as functional storages: electricity exports can be interpreted as storage charging, while imports can be equated to discharging. Compared to the energy discharges from battery storages (268 TWh in 2050) and the amount of electricity used in hydrogen production (1,539 TWh), the European electricity grid represents the largest flexibility option in the European energy system.

The European electricity grid can be seen as a flexibility option, as neighboring countries act as functional storages.

As explained in section 3, solidEU represents a climate protection scenario with a -95 % GHG-emissions reduction target in 2050 compared to 1990. Therefore, the emissions CAP is set to 288 Mt of CO_2-eq. in the year 2050. An interim target for the year 2030 was set to -55 % of GHG-emission reductions compared to 1990 in line with the European Climate Law [75]. With emissions of 5,754 Mt of CO2-eq. emitted in Europe in 1990 this means, that in 2030 emission allowances accumulate to only 2,589 Mt of CO_2-eq. For the years in between 2030 and 2050 a linear reduction of the emissions CAP is modeled. An overview of the emissions targets as well as the emitted GHG-emissions by sector can be seen in Figure 6-6.

As can be seen in Figure 6-6 emissions between 2020 and 2030 need to be reduced in the same magnitude as emissions were reduced between 1990 and 2020. In between 2020 and 2030 the energy sector is the sector which reduces its emissions the most. The reduction amounts to 620 Mt of CO_2-eq. and can mainly be attributed to the generation of electricity from RES.

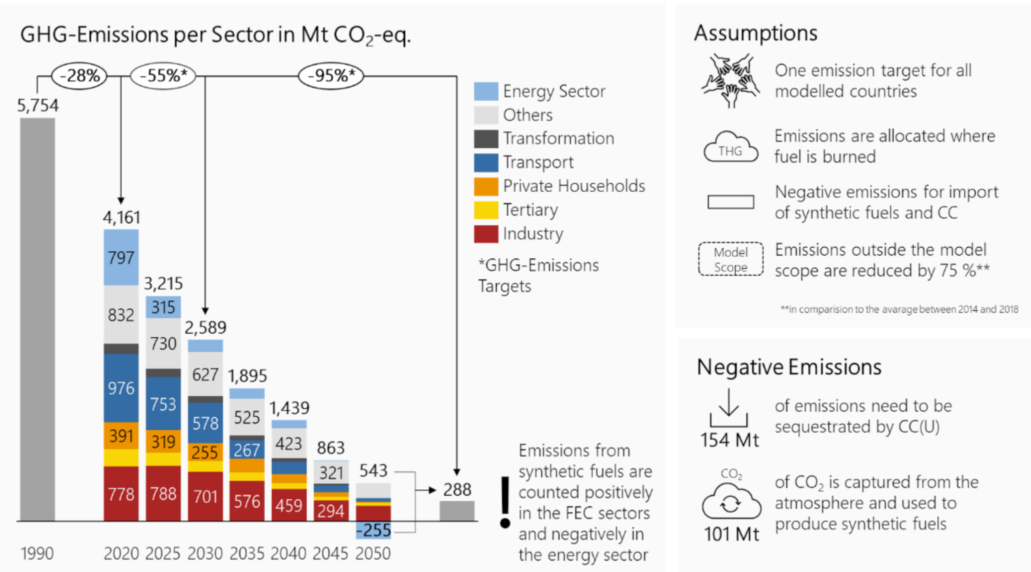


Figure 6-6: GHG-emissions by sector in solidEU

As shown in Figure 6-6, the sector with the second largest emission reductions is the transport sector. In this case, GHG-emissions are reduced by 398 Mt of CO_2-eq. from 2020 until 2030. The main reason for the emissions reductions in the transport sector are the high electrification rates, which lead to emission reduction from fuel combustion. Interestingly the higher electricity demand from the transport sector does not lead to higher emissions in the energy sector, neither in the short nor in the long term, as enough RES are installed to provide the required emission free electricity. The transport and energy sector however are not the only sectors to cut their emissions. GHG-emissions from private households drop by 95 % and emissions from the tertiary sector by 84 % until 2050 compared to 2020. Emissions from the "Others" sector decrease by the assumed 75 % compared to the mean between 2014 and 2018. GHG-emissions from the industrial sector are only strongly reduced from 2030 onwards, as this is when fuel substitution measures replace fossil fuels and their combustion.

In the year 2050 the energy sector must compensate emissions from the FEC sectors to reach the GHG-emissions reduction target. As emissions are allocated where fuels are burned, the energy sector can compensate emissions in two ways: with the import of synthetic fuels (methane or fluid hydrocarbons) or the sequestration of CO_2 from industrial emissions or the atmosphere. In the first case, the import of synthetic fuels is assumed to have negative emissions, as in the synthetization process CO_2 is captured. The CO_2 is then released to the atmosphere again as the fuel is burned. Emissions are allocated to the sector where the combustion takes place. In the second case CO_2 can be captured within Europe. This can be done by sequestering CO_2 either from industrial processes or the atmosphere. While the captured emissions are partly used to produce synthetic fuels, some emissions need to be compensated for via CO_2 certificates. Emissions that cannot be omitted with electrification or fuel switch measures can occur in the industry sector as feedstock emissions, or in the emission category "Others".

In total, 63 Gt CO_2-eq. are emitted in solidEU by 2050. If the remaining 5 % of emissions (288 Mt CO_2-eq.) remain constant and are aggregated until 2100, greenhouse gas emissions amount to about 80 Gt CO_2-eq in 2100. This amount of emissions is just below the remaining budget - under least-cost considerations - of 90 Gt CO_2-eq. for the EU to meet the Paris 2 °C climate target [95]. However, the effort is not sufficient to meet the 1.5 °C climate target that should be aimed for under the Paris Agreement [96].

Figure 6-7 shows the European energy carrier balance for hydrogen. The demand for hydrogen increases by 624 % from 2020 to 2050. The additional hydrogen is mainly used in the industrial sector, but also the transport sector increases its hydrogen demand (for details see section 4.1).

Interactive energy carrier balances for electricity, hydrogen, gas, fluid hydrocarbons and district heating are accessible HERE

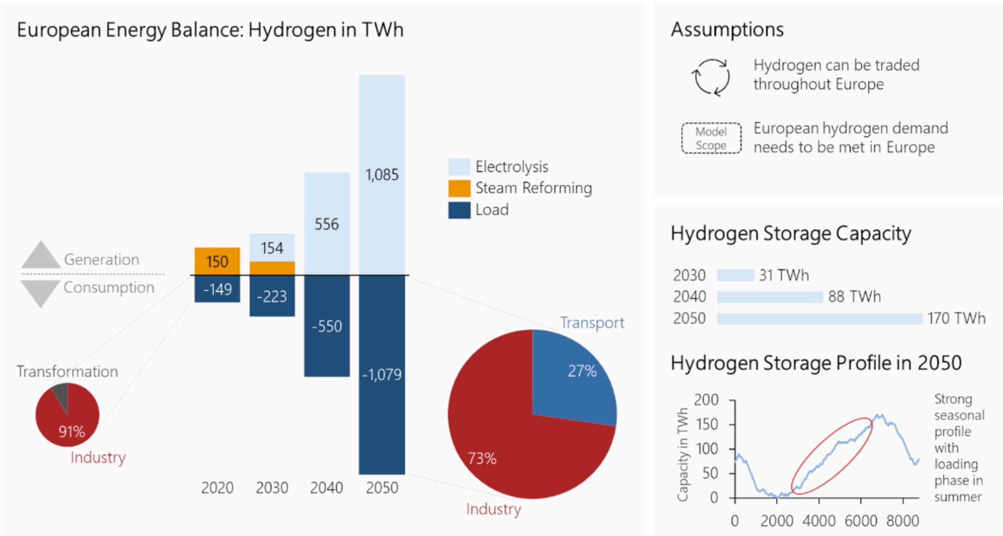


Figure 6-7: Energy carrier balance for hydrogen in solidEU

While in 2020 hydrogen is produced exclusively from steam reforming, noticeable amounts of hydrogen are produced by electrolysis from 2030 onwards. Already in 2040, all hydrogen is produced from electrolysis. In 2050 340 GW_{el} of electrolyzers are installed in Europe, which consume 1,539 TWh of electricity to produce the demanded 1,079 TWh of hydrogen. Transportation losses amount to 6 TWh.

As hydrogen demand and production increase and are partly offset in time, more hydrogen is stored throughout the year. European hydrogen storage facilities reach a combined storage capacity of 170 TWh in 2050. Interestingly, the European hydrogen storage is filled in the months between March and October. During this period, electricity demand from the FEC sectors decreases because, for example, heating demand declines. On the other hand, electricity production from photovoltaics increases due to higher solar radiation, steadying the production of electricity from vRES over the year. This leads to a strong seasonal storage profile of hydrogen storages (see Figure 6-7).

6.1.3 Gas Market

In solidEU, the gas market undergoes a stronger transformation than in quEU. European total gas demand drops sharply from 5,250 TWh to below 400 TWh driven by low FLH of gas power plants and a fuel switch on the demand side. Gas demand is covered by natural gas imports until 2040, before eventually being replaced by synfuel imports and intra-European power-to-methane production of 82 TWh in 2050. There is no hydrogen injection in solidEU even though hydrogen demand increases from 150 TWh in 2020 to 1,085 TWh in 2050. To meet the actual gas demand in 2020, gas imports are mainly covered by flexible Russian (40 %) and Norwegian (23 %) gas production (via pipelines). The share of Russian gas production increases up to 67 % in the following years until 2040 due to both decreasing gas demand and decreasing European gas production (see Figure 6-8, right side). Due to the higher costs, gas imports from North Africa as well as LNG imports lie close to the lower boundary of the flexible gas production in most years. In 2030, Russian gas can be found in every country except UK, Ireland, Norway, Bulgaria, Hungary, and Portugal (see Figure 6-8, left side). In these countries, either Norwegian gas, North African gas, regional gas, or LNG is the main imported gas.

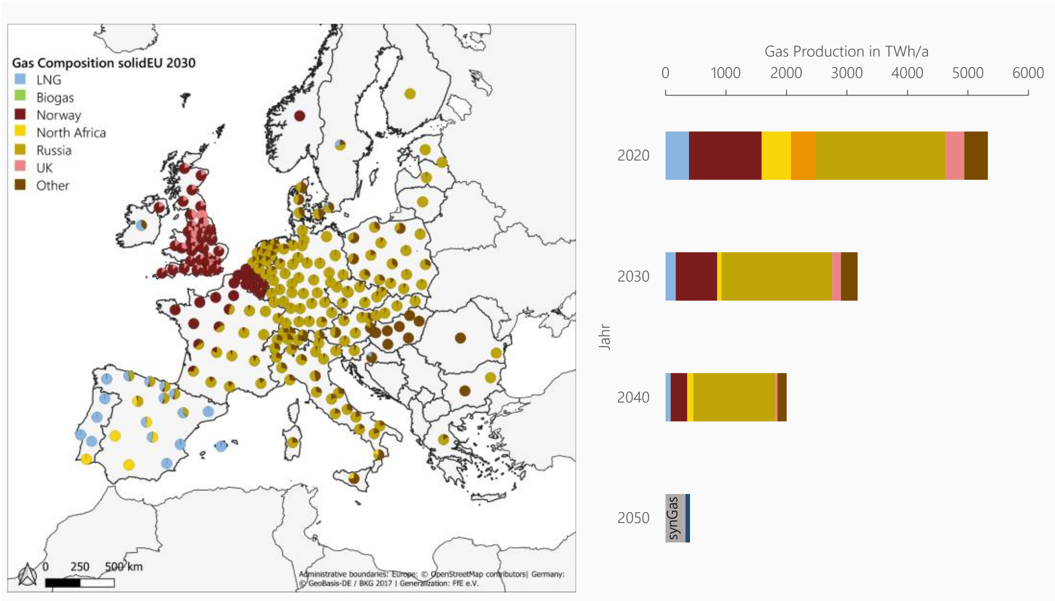


Figure 6-8: Gas composition (Load and Production)

The strongly decreasing gas demand has a significant impact on the gas infrastructure (see Figure 6-9, right side). As explained in section 5.1.3, the gas flows decrease between 2020 and 2040 in most cases, with a high decrease on the main gas routes (see Figure 6-9, left side). Locally, however, there can be higher gas flows (see borders of Germany, the Netherlands, and Belgium).

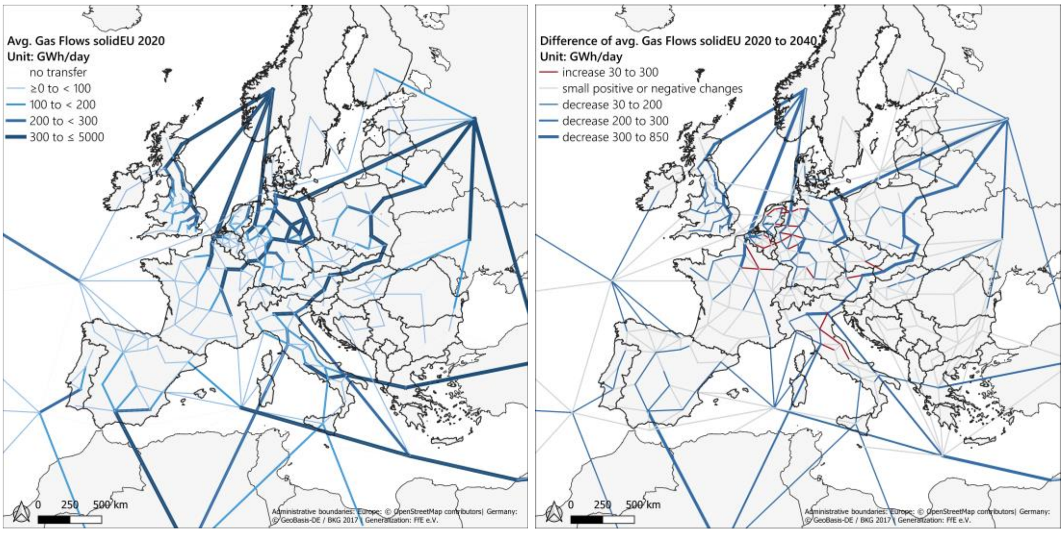


Figure 6-9: Average gas transfer in Europe in 2020 and difference to 2040

Even if parts of the current natural gas pipelines are converted to hydrogen pipelines to transfer the increasing hydrogen demand, the use of the European gas infrastructure decreases in solidEU. Furthermore, a uniform decline in gas demand is expected, so only redundant pipelines can be used when natural gas pipelines are rededicated to hydrogen pipelines, otherwise regions will no longer be connected.

The following key findings have been identified for solidEU:

- Gas imports from Russia are utilized as much as possible, as it is the least expensive import option for many regions in Europe. In the future, the share of Russian gas in Europe will increase while demand will decrease.
- The increase in hydrogen demand does not compensate for the decrease in natural gas demand, so that the transport infrastructure will consequently be utilized less in the future.
- In solidEU the gas demand declines evenly across Europe, so that when natural gas pipelines are converted to hydrogen pipelines, only redundant pipelines can be used, as otherwise regions will no longer be connected.

7 Extreme Scenario Seeds Findings

In eXtremOS variations of solidEU, the so-called scenario seeds are calculated to investigate the influence of extreme events on the results of solidEU (cf. section 3.2 for details). In total four different scenario seeds with different assumptions are calculated:

- NTC2020 – a scenario without any further strengthening of the European electricity market coupling (cf. section 7.1)
- PVBat – a scenario with a stronger price decay of PV systems and battery storages than in solidEU (cf. section 7.2)
- Lyze – a scenario with a stronger price decay of elecrolyzers than in solidEU (cf. section 7.3)
- RiNo – a scenario with increased NTCs between the countries Denmark, Germany, the Netherlands, Great Britain, and Norway (cf. section 0)

7.1 NTC2020

In the NTC2020 scenario, the assumption is made that NTCs remain on the level of 2020. The assumption can be interpreted as that the European electricity market coupling is not strengthened any further. The total NTCs remain at 129 GW for future years. In comparison to solidEU this means a reduction of 80 % of NTCs in the year 2050. With the reduction of NTCs, the possibility to exchange electricity between the countries is also reduced. This is reflected in the amount of electricity traded. While in solidEU in 2050 1,571 TWh of electricity is traded throughout Europe, this value is reduced by 71 % to 456 TWh in NTC2020. The traded 456 TWh of electricity in 2050, however, still reflect an increase of traded electricity of 82 TWh compared to 2020.

Figure 7-1 shows the changes of the mean electricity prices in 2050 in the two scenarios solidEU and NTC2020 as well as the differences in electricity generation. Due to the lack of trading possibilities, volatile renewables are installed on a country-by-country basis rather than optimally across Europe, as fluctuations in generation cannot be balanced as efficiently by other countries as in solidEU. This leads to a shift from wind energy to solar energy, as the electricity production from wind cannot be distributed across Europe as efficiently as in solidEU. In total, a decrease of 42 GW wind offshore and 20 GW wind onshore capacities can be detected in NTC2020 compared to solidEU in the year 2050, while installed PV capacities rise by 291 GW. It follows that electricity production from PV increases by 13 %. But at the same time, the curtailed energy form vRES increases by 32 % from 406 TWh to 535 TWh. It can be concluded that vRES cannot be integrated as well into the energy system in NTC2020 as in solidEU.

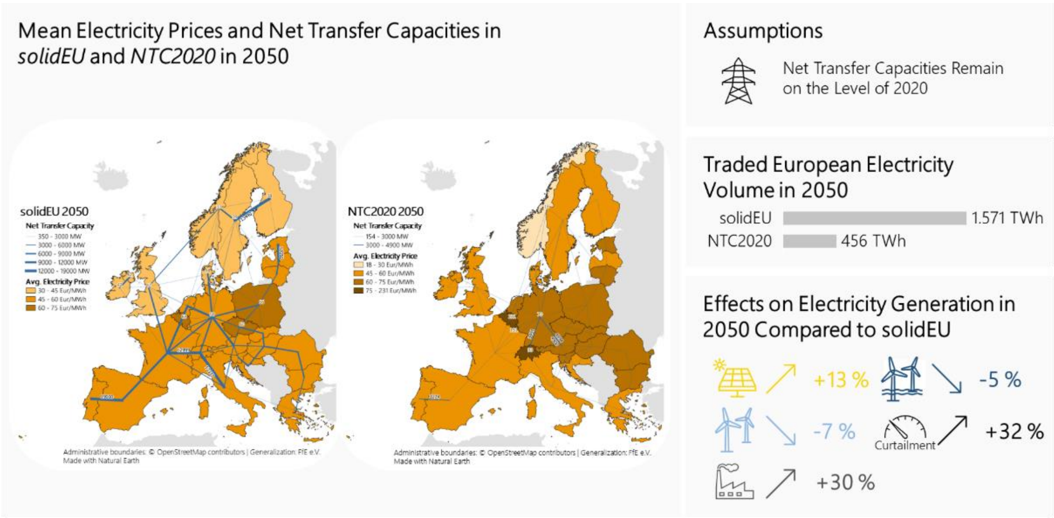


Figure 7-1: Comparison between NTC2020 and solidEU

As the distribution of electricity production from vRES throughout Europe is limited in NTC2020, electricity production from thermal power plants increases by 30 %. Mostly gas fired power plant dispatch increases due to their peak generation characteristics. While in solidEU only 155 TWh are produced from combined-cycle gas and gas power plants, the electricity production from these types of power plants rises to 303 TWh in NTC2020. Installed gas turbine power plant capacities are 96 GW higher in NTC2020 than in solidEU. The FLH of gas fired power plants remain low. In addition to the increase of installed thermal power plant capacities to cover peak load hours, more stationary battery storages are needed to balance the volatile electricity production from vRES. In total, installed battery storage capacity increases by 132 GW_{el} in NTC2020 compared to solidEU in 2050.

The lack of sufficient NTCs and the therefore more nationally focused expansion strategies finally lead to higher electricity prices in almost all countries. This results in a higher average European electricity price[14] of around 65 €/MWh, which poses a 25 % increase compared to solidEU.

7.2 PVBat

In the PVBat scenario, it is assumed that the costs for offsite solar and battery storages decrease by 14 % and 21 % respectively (see Table 7-1) compared to solidEU.

Table 7-1: Offsite solar and battery storage cost in PVBat and cost degression compared to solidEU in percent

	2030	2040	2050
Offsite Solar [€/kW]	266	224 (-11 %)	193 (-14 %)
Battery Storages [€/kWh]	160 (-7 %)	122 (-14 %)	97 (-21 %)

The cost degression of these two technologies leads to an increase in installed offsite solar capacity and battery storages. In 2050, 537 GW more offsite solar capacity installed compared to solidEU. Together with an additional 125 GW of battery storages, 67 GW (5 %) of onshore

[14] The average European electricity price is calculated as the load weighted average of the base price of each country.

and offshore wind capacity and 12 GW (10 %) of gas turbine additions are replaced. The differences per country can be seen in Figure 7-2.

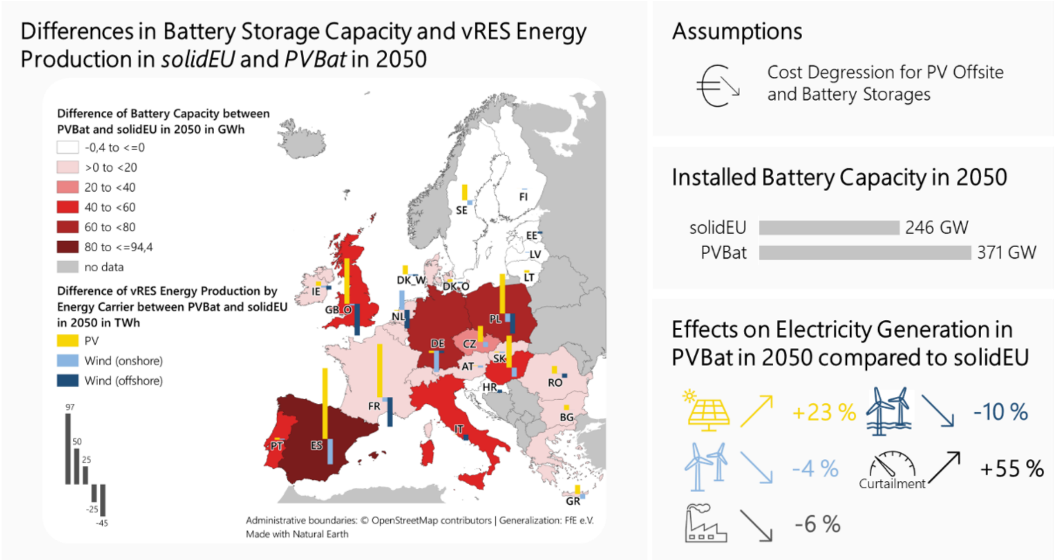


Figure 7-2: Comparison between PVBat and solidEU

However, the substitution of electricity production from wind onshore, wind offshore and thermal power plants by PV systems also leads to higher amounts of curtailed electricity. While in solidEU only 406 TWh of electricity is curtailed as it could not be integrated into the market, the quantity rises to 628 TWh in PVBat. vRES curtailment in 2050 therefore increases from 6 % in solidEU to 9 % in PVBat. This increase in curtailed energy can be explained by the fact, that due to the decrease of LCOEs of PV, more hours of curtailment can be accepted. Therefore, the optimization integrates significantly more PV into the energy system and curtails the electricity production when excess production takes place.

7.3 Lyze

Lyze assumes a stronger cost degression of electrolyzers between the years 2020 and 2050 than in solidEU. In 2050, the installation costs for electrolyzers in Lyze amount to a 42.5 % cost decrease compared to solidEU. The cost degression can mainly be attributed to an assumed increase of electrolysis production capacities. While one MW of electrolyzer capacity in solidEU in 2050 costs 505,000 €, the costs are only 215,000 €/MW in Lyze [97]. The main effect resulting from this cost degression is that additional electrolysis capacity is built in Southern Europe. Spain, France, and Italy together increase their electrolysis capacity by 65 GW_{el}. In addition, 45 GW of offsite photovoltaics are installed. Overall, 10 % more electricity is generated from offsite photovoltaics compared to solidEU and is mainly used for hydrogen production. Curtailment of vRES decreases to 4 % as more flexible consumption technologies in the form of electrolyzers can use the excess electricity to produce hydrogen.

As prices for electrolyzers drop, they can be operated at lower FLH. The average FLH of the electrolyzers decrease by 1000 h, from around 4500 h to 3500 h. The additionally installed electrolyzers (107 GW_{el}), therefore compensate for the decrease in FLH. This also coincides with the fewer FLH of photovoltaic plants, which are additionally installed to produce the electricity for electrolysis. With the combination of cheaper electrolyzers and an increased electricity production from PV to produce hydrogen, other technologies, such as power-to-synfuels, can operate at higher FLH and thus become more profitable. In total, 36 GW_{el} of power-to-synfuel production units are added to the energy system in Lyze compared to solidEU.

As additional hydrogen production capacities move to Southern Europe and are dispatched in combination with PV systems a stronger seasonal hydrogen storage profile emerges, leading to higher storage capacities. As even more hydrogen is produced during the summer months in Lyze compared to solidEU, the storage capacities for hydrogen increase by 32 TWh to 202 TWh.

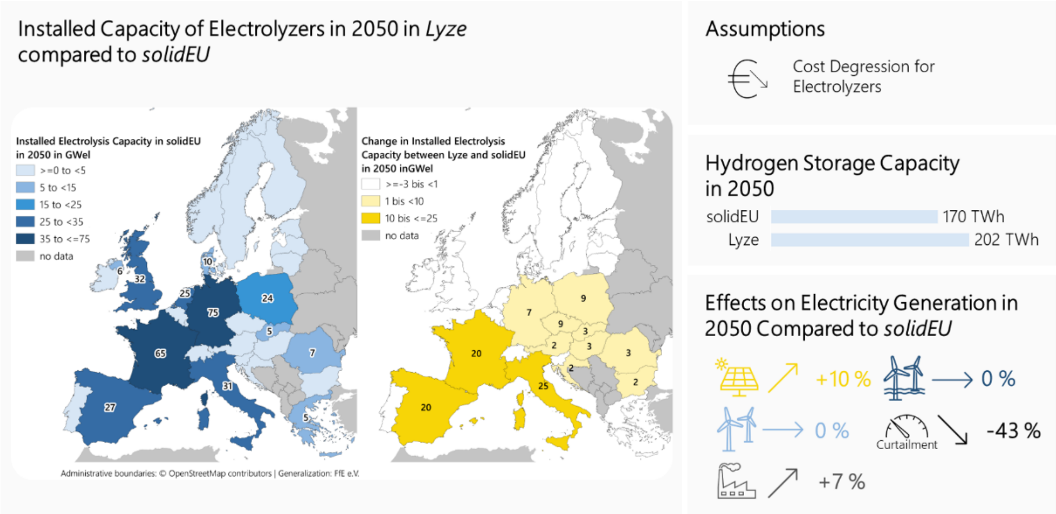


Figure 7-3: Comparison between Lyze and solidEU

7.4 RiNo

In the RiNo scenario, offshore electricity trading capacities between the countries Denmark, Germany, the Netherlands, Great Britain, and Norway increase by an additional 15 GW compared to solidEU. These countries are referred to as the RiNo countries. The increase in electricity trading capacities leads to a migration of wind energy production from Germany to the other RiNo countries.

While Germany installs 26 % less wind onshore capacity, Norway, Great Britain, and Denmark increase their installed offshore wind capacity by 11 GW, 18 GW and 11 GW, respectively (cf. Figure 7-4). Norway also adds 8 GW of onshore wind capacity. The higher amount of vRES production in the northern RiNo countries is then transferred to Central Europe and used mainly in Germany. However, the resulting changes in total electricity production in Europe remain small and become less significant with distance to the RiNo countries.

Nevertheless, the increase in electricity trading capacity between the RiNo countries leads to a reduction in price spreads within Europe. While Norway's average electricity price, the lowest within Europe, in 2050 increases by 10 % from 33 €/MWh in solidEU to 36 €/MWh in RiNo, Belgium's electricity price, the highest in Europe, decreases by 13 % from 68 €/MWh to 60 €/MWh.

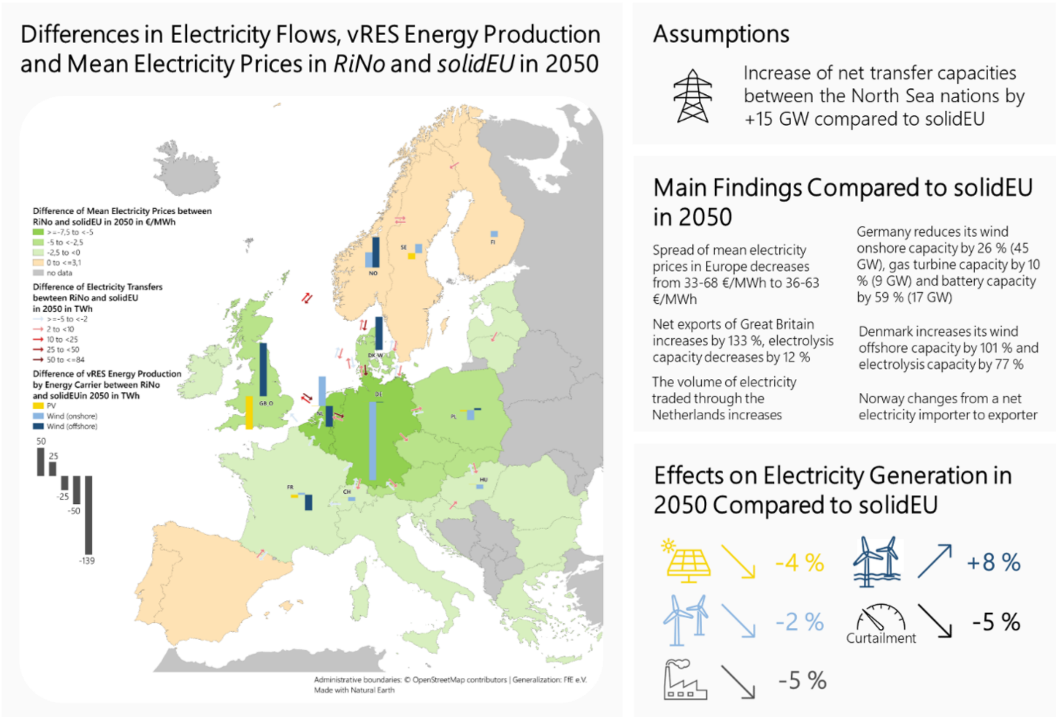


Figure 7-4: Comparison between RiNo and solidEU

8 Conclusion

The eXtremOS results show the importance of a holistic European approach to energy system analysis as well as the added value gained by combining detailed demand and supply-side modeling. Purely national analyses are insufficient to capture the effects that a European energy transition will have on the highly interconnected energy system, since all European countries are committed to the fight against climate change. Future analysis should take this finding into account. While isolated regional analysis might be feasible to answer certain research questions, energy, and climate protection scenarios such as solidEU need to consider the developments of neighboring countries and respect the significant differences between the structure and emission mitigation options of different sectors and countries.

Furthermore, the development and application of the integrated scenario process demonstrate that comparisons between scenario worlds are at the least extremely difficult. Numerous energy political studies at the European and German level however frequently compare climate protection and so-called reference scenarios and go as far as calculating cost differences to derive conclusions about additional costs of climate change. The solidEU and quEU development process, however, shows that the socio-political environment required to trigger quantitative developments leading to climate protection differ significantly from scenarios in which targets are not achieved. This suggests that comparisons between scenarios with completely different underlying drivers and assumptions are not meaningful.

With respect to climate protection in Europe, the eXtremOS results show that vRES will play a crucial role in the transformation of the European energy system. Even without any GHG emission targets in place, the share of RES on the gross electricity consumption could increase to approximately 75 % in 2050. In solidEU the increase of electricity production from vRES is mainly driven by market forces due to the expected price decrease of vRES, given that no additional regulatory barriers are imposed. However, as shown in the quEU scenario, a purely market driven expansion of vRES capacities is insufficient to meet the European climate protection targets.

The 2 °C target of the Paris Agreement is met in solidEU. Cumulative GHG-emissions until 2100 amount to approximately 80 Gt, which is insufficient to reach the 1.5 °C target. The share of RES on the gross electricity production, nevertheless, increases to 94 % in 2050. Remaining thermal power plant capacities are either nuclear power plants or operated on synthetic climate neutral fuels. Besides electrification measures, the production of hydrogen is one main driver for the increase of gross electricity consumption. If the hydrogen demand is met through domestic European production, as modeled in solidEU, 1539 TWh of electricity is consumed by electrolysis. Additionally, a seasonal hydrogen storage is required. The storage will be filled during times of high generation from wind and PV and simultaneously low electrical load (i.e. March to October).

eXtremOS also shows, that the strengthening of the European electricity market coupling is essential to the integration of vRES into the energy system. NTC2020 shows that 75 % less energy is traded between the European countries compared to solidEU when NTC’s stagnate at 2020 levels. This will result in an increase of the average European electricity price by 25 % compared to solidEU.

Further information and results to all the scenarios mentioned above can also be found on the project website and the interactive dashboard.

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