

Burandt, Thorsten; Löffler, Konstantin; Hainsch, Karlo

Research Report

GENeSYS-MOD v2.0 - Enhancing the Global Energy System Model: Model improvements, framework changes, and European data set

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Data Documentation

GENeSYS-MOD v2.0 – Enhancing the Global Energy System Model Model Improvements, Framework Changes, and European Data Set

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DIW Berlin

Deutsches Institut für Wirtschaftsforschung

Mohrenstr. 58

10117 Berlin

Tel. +49 (30) 897 89-0

Fax +49 (30) 897 89-200

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GENeSYS-MOD v2.0 – Enhancing the Global Energy System Model

Model Improvements, Framework Changes, and European Data Set

Thorsten Burandt^{1,2}, Konstantin Löffler^{1,2}, Karlo Hainsch²

July 2018

Abstract

This Data Documentation presents the second version of the Global Energy System Model (GENeSYS-MOD), an open-source energy system modeling framework. The model endogenously determines cost-optimal investment paths into conventional and renewable energy generation, different storage technologies, and some infrastructure investments in five-year steps until 2050. GENeSYS-MOD hereby focuses on the coupling of the three traditionally segregated sectors electricity, heat, and transportation - including all three sectors and their interconnections in the model. By allowing for different emission targets (such as emission budgets, yearly emission targets, or emission reduction goals), possible cost-minimizing pathways towards a largely (or even fully) decarbonized energy system can be analyzed. The second version of the model features more time slices, a more detailed representation of power trade and its infrastructure, performance improvements, and a fully revised technology data set. Additionally, to model improvements and changes, a high-quality data set for the European region to use with GENeSYS-MOD v2.0 is provided and described. An application of the European version of GENeSYS-MOD v2.0 can be found as an accompanying DIW Discussion Paper No. 1745 (Hainsch et al. 2018).

¹DIW Berlin, Mohrenstraße 58, 10117 Berlin, Germany

²Technische Universität Berlin, Strasse des 17. Juni 135, 10623 Berlin, Germany

Contents

List of Figures	iv
List of Tables	v
List of Acronyms	vi
1 Introduction.....	1
2 The Global Energy System Model, Version 2.0.....	3
2.1 General model structure	3
2.2 Model version and improvements between versions.....	5
2.3 Mathematical formulation.....	5
2.3.1 Power trade.....	6
2.3.2 Phase-in, phase-out and renewable integration	7
2.3.3 Emissions	8
2.3.4 Inter-temporal efficiency	9
2.3.5 Reserve margin.....	10
2.3.6 Performance optimization	11
3 Data.....	14
3.1 Model setup and data	14
3.1.1 Spatial resolution and grid data.....	14
3.1.2 Temporal resolution.....	15
3.2 Technology description and implementation	15
3.2.1 Technology representation in the model	15
3.2.1.1 Technologies that have been fundamentally changed in GENeSYS-MOD v2.0	16
3.2.1.2 New technologies in GENeSYS-MOD v2.0	16
3.2.2 Technology data	17
3.2.3 Potentials of renewable energy sources	17
3.2.4 Capacity factors.....	18
3.2.5 Cost data	19
3.2.5.1 Capital costs	19
3.2.5.2 O&M costs	20
3.2.6 Conventional power plant efficiencies	21
3.2.7 Power plant lifetimes	22
3.3 Demands	22
3.3.1 Electricity.....	22
3.3.2 Low-temperature heat.....	23
3.3.3 High-temperature heat.....	25
3.3.4 Transport	27
3.4 Fossil fuel prices and availability	29
3.5 Biomass potential	30
3.6 Residual capacities.....	30
3.7 Including political boundaries	35
3.8 Trade.....	36
3.8.1 Power trade & grid data	36
3.8.2 Reserve margin.....	37
3.8.3 Trade of energy carriers	38
3.9 Emissions	39

3.9.1	Carbon content and activity ratio	39
3.9.2	Emissions budget	40
3.9.3	CO ₂ storage potential	41
3.9.4	Carbon pricing	42
References	43
Appendix	48

List of Figures

Figure 1	GENeSYS-MOD Logo.	3
Figure 2	Model structure of GENeSYS-MOD v2.0.	4
Figure 3	Block structure of GENeSYS-MOD v2.0.	6
Figure 4	Benchmark results with multiple solvers and workstations.....	12
Figure 5	Benchmark results with reduced amount of regions.	13
Figure 6	Grid structure and node set-up for Europe.....	14
Figure 7	Distribution of process heat demand across all industry branches, distinguished by temperature level.	24
Figure 8	Daily heat demand profile.....	26
Figure 9	Daily passenger transportation demand profile.....	28
Figure 10	Illustrated calculation method of the European Carbon dioxide (CO ₂) budget for the 2° pathway.....	40

List of Tables

Table 1	Hourly assignment of daily time brackets.	15
Table 2	<i>YearSplit</i> of GENeSYS-MOD v2.0.	15
Table 3	Regional potentials for utility-scale solar PV, onshore wind, and offshore wind in GW.	18
Table 4	Capacity factors for selected renewable technologies in Germany.	19
Table 5	Capital cost of power generation and transformation technologies in €/kW.	20
Table 6	Variable costs for transformation and storage technologies, in M€/PJ.	21
Table 7	Input fuel efficiency for common conventional power plants.	21
Table 8	Technical lifetime of power generation and transformation technologies.	22
Table 9	Yearly electricity demand per region in TWh.	23
Table 10	Yearly low-temperature heat demand per region in PJ.	25
Table 11	Share of total heat demand per season and region.	25
Table 12	Yearly high-temperature heat demand per region in PJ.	26
Table 13	Yearly transport demand per region.	27
Table 14	Demand profile for passenger transport in Europe in each time slice.	28
Table 15	Global prices of fossil energy carriers in M€/PJ.	29
Table 16	Local prices of lignite in M€/PJ.	29
Table 17	Fossil fuel reserves per region in PJ.	30
Table 18	Yearly available biomass in PJ.	30
Table 19	Residual power generation capacities in GW.	31
Table 20	Considered political boundaries.	36
Table 21	Power trade capacity between regions in GW.	37
Table 22	Share of required energy production by <i>ReserveMargin</i> technologies [in %].	37
Table 23	Trade costs for energy carriers between regions in M€/PJ.	38
Table 24	Carbon content (in megatons CO ₂) of fuels per PJ primary energy.	39
Table 25	Regional storage potential of CO ₂	41
Table 26	Carbon prices in € per ton of CO ₂ for different emission pathways.	42

List of Acronyms

BECCTS	bio-energy with carbon capture, transport, and storage
CAES	compressed air energy storage
CCTS	carbon capture, transport, and storage
CHP	combined heat and power
CO ₂	carbon dioxide
dynELMOD	dynamic Electricity Model
EU	European Union
GB	gigabyte
GENeSYS-MOD	Global Energy System Model
GHG	greenhouse gas
GHz	gigahertz
gpkm	giga passenger-kilometers
gtkm	giga tonne-kilometers
GW	gigawatt
GWh	gigawatt hours
IEA	International Energy Agency
kW	kilowatt
LP	linear programm
MB	megabyte
MHz	megahertz
O&M	operation and maintainance
OECD	Organisation for Economic Co-operation and Development
OSeMOSYS	Open Source Energy Modelling System
PJ	petajoule
PV	photovoltaic
RAM	random-access memory
redox	reduction–oxidation
RES	renewable energy sources
sec	seconds
TWh	terawatt hours

1 Introduction

One of the biggest contributors of greenhouse gas (GHG) emissions is the energy sector, accounting for more than two thirds of the global emissions (IEA 2016b). The most important greenhouse gas is CO₂, which is responsible for more than 80% of the emissions in the energy sector (Foster and Bedrosyan 2014). Therefore, various challenges arise for different countries when it comes to decarbonize their energy systems. The European Union (EU) has set several climate goal targets, which should lead to an energy system with almost no GHG emissions. Yet, no exact configuration of the energy system is defined, and countries have to promote their own policies to reach the goals.

In recent years, the focus was heavily set on decarbonizing the electricity sector. However, in a fully decarbonized energy system, the heating and transportation sector deserve just as much, if not more attention, due to the challenges of phasing out fossil fuels in these areas. A high degree of electrification in these sectors is predicted in future scenarios, which implicitly affects the power sector.

Energy system models experienced increasing popularity over the last decades. Yet, the concept is much older. The system approach was originally proposed by the biologist von Bertalanffy in 1956. While traditional analyses mostly relied on separating the object of what is being studied, the system approach focuses on the interactions between the matter being investigated and all other parts of the system (Nakata, Silva, and Rodionov 2011).

This system school of thinking is, as the name already tells, of essential importance to energy system analyses. Currently, the different sectors of electricity, heat, and transportation are already interlinked via several technologies (e.g., electric heaters, heat pumps, and electric trains), and more can be expected in the future. In fact, sector coupling is projected to play a major role in the upcoming energy systems (Morris and Pehnt 2016). This leads to the necessity of an overall consideration of energy systems when projecting future developments, especially in the context of a low-carbon transformation (Burandt et al. 2017). Still, and despite these considerations, most studies and papers which analyze low-carbon energy system pathways for Europe or Germany focus on either of the sectors.

The power sector is by far the most wide-spread sector of choice when it comes to analyzing energy system transformations towards less GHG emissions. Some studies focus solely on the electricity sector on a European scale and analyze impacts of high renewable penetration (Gerbaulet et al. 2017; Scholz 2012; PwC 2011; Czisch 2007; Plessmann and Blechinger 2016). Gerbaulet et al. (2017) analyze different scenarios for the European electricity sector with high amounts of renewables, showcasing that neither high shares of carbon capture, transport, and storage (CCTS) nor nuclear power are necessary for such a system to be feasible. Scholz (2012) shows that most European countries will be able to cover their domestic power demand on their own, with countries like Belgium or Luxembourg relying on grid interconnections with other countries. Czisch (2007) comes to similar results, concluding that given enough grid capabilities between European and North African countries, renewable electricity could be produced and distributed at costs similar to today's.

In addition to production and distribution, electricity storages and their incorporation into the power sector are the focus of many other studies. While all of the above-described authors mention storages as

an element of future energy systems, others take a closer look. In general, a positive correlation between high shares of renewables and storage capacities can be found across the literature. In addition, Schill and Zerrahn (2017) highlight that the relevance of power storages is even higher, if other flexibility options are less developed. Bussar et al. (2015) suggest storage capacities of 804,300 Gigawatt hours (GWh) in 2050, most of which consist of gas storages. Also, a negative correlation between storage and trade capacities can be observed, showcasing the power grid as another form of storage. In contrast, Rasmussen, Andresen, and Greiner (2012) find that, without additional balancing, storage capacities of 320 Terawatt hours (TWh) are required. However, they acknowledge that hydrogen storages would increase this number substantially.

Several studies which analyze German pathways towards 100% renewables, focus on electricity production but the other sectors gain attention as well. Samadi et al. (2014) come to the conclusion that a German electricity sector relying mainly on renewable generation is technically and economically feasible by 2050. Again, the import of electricity plays a major role, allowing for fewer storage technologies but increasing technical, financial and political complexity (Samadi et al. 2014). Breyer et al. (2014) find that a power system consisting of solely renewable generation would not result in a significant increase in system costs. Another conclusion highlights that the level of centralization of the generation capacities has negligible effects on the mentioned costs. In addition to the power sector, Palzer and Henning (2014) also incorporate the heating sector into their model calculations. They conclude that, given major reductions in residential heating demand, both sectors could be decarbonized. Similar to previously mentioned work, the costs of such a system are not higher than for the current configuration. In a different work, Henning and Palzer (2013) analyze the German energy system as a whole, including the power, heating, and transportation sector. While the assumptions are very conservative (i.e., only 81% reduced CO₂ emissions, 40% fossil fueled vehicles), wind (on- and offshore), as well as Photovoltaic (PV), are the backbone of the energy system, with sector coupling playing a role in the heating sector. A shortcoming is the negligence of energy trading with adjacent countries, but it shows an economically and technically feasible configuration of a low-carbon energy system.

On a global scale, Jacobson et al. (2017a) published one of the most comprehensive studies lately, showcasing 100% renewable energy roadmaps for 139 countries of the world. Electricity is produced by wind, water, and solar technologies and a significantly more aggressive pathway than what the Paris agreement calls for is projected. However, his methodology and results of a different paper were origin to a controversy between researchers (Clack et al. 2017; Jacobson et al. 2017b). This not only showcases the prevalence of the topic, but it also highlights the various paradigms within the field.

The following sections will introduce the updated version of GENeSYS-MOD, as well as the data set for Europe. An application of the European version of GENeSYS-MOD v2.0, analyzing various pathways towards a low-carbon energy system for Europe, can be found as an accompanying DIW Discussion Paper No. 1745 (Hainsch et al. 2018).

2 The Global Energy System Model, Version 2.0

This chapter describes GENeSYS-MOD, its core functionalities, model structure, and the changes between the two versions of the model.



Figure 1: GENeSYS-MOD Logo.

Source: Own illustration.

GENeSYS-MOD is a linear program, minimizing total system costs. Energy demands are exogenously predefined and the model needs to provide the necessary capacities to meet them. To achieve a cost-optimal energy mix, the model considers a plethora of different technology options, including generation, sector coupling, and storages.

2.1 General model structure

Energy system models are mathematical optimization models which aim to represent parts of or entire energy systems in a given region. The spectrum of existing models varies substantially, with each formulation focusing on different aspects of energy systems. The reason for that lies in the complexity of the issue, which leads to heavy constraints when it comes to computational resources. A comprehensive classification of the different kind of models can be found in Herbst et al. (2012).

Out of the different energy system models or frameworks, the formulation which was chosen for this work can be classified as a techno-economic model (Löffler et al. 2017b). This group of models offers a great amount of technological detail due to its bottom-up approach, which allows for profound analysis of the impact of technologies, their costs and efficiency development over time, and the effect of policies on to the energy system (Herbst et al. 2012). In contrast, they usually lack the ability of depicting very long term time horizons with short re-investment cycles, as well as some important macro-economic factors (Herbst et al. 2012).

In essence, the present model can be illustrated as a flow-based optimization model. The different nodes are represented as *Technologies*, which are connected by *Fuels*. Examples for *Technologies* are production entities like wind or solar power, conversion technologies like heat pumps, storages, or vehicles. *Fuels* serve as connections between these technologies and can be interpreted as the arcs of the network. In general, *Fuels* represent energy carriers like electricity or fossil fuels, but also more abstract units like demands of a specific energy carrier or areas of land are classified as *Fuels*. Also, *Technologies* might require multiple different *Fuels* or can have more than one output fuel. As an example, a combined heat and power plant could use coal as an input fuel and produce electricity and heating energy as an output fuel. Efficiencies of the technologies are being accounted for in this exact process, which would allow to

model energy losses due to conversion. Figure 2 gives a general overview of the different technologies and the connections between them.

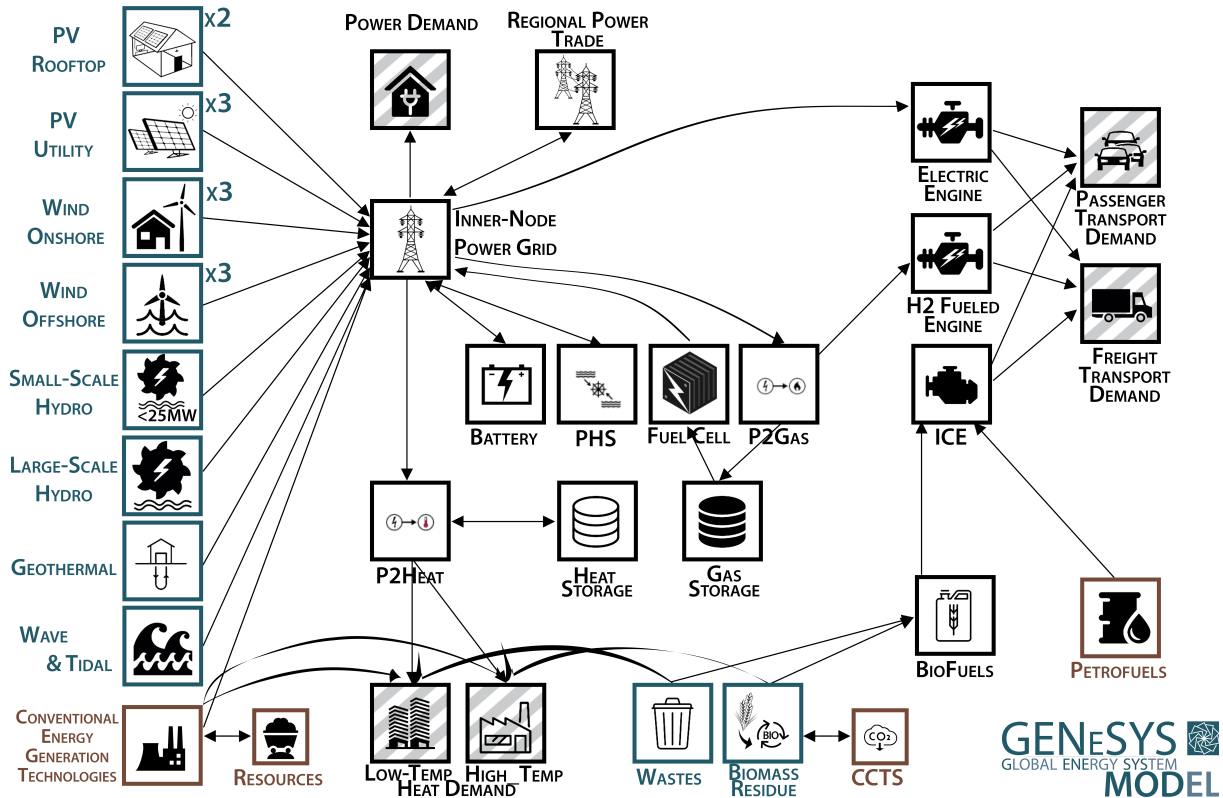


Figure 2: Model structure of GENeSYS-MOD v2.0.

Source: Own illustration.

In the previous paragraph, energy demand was mentioned, without giving a comprehensive explanation about what kinds of energy demand exist and their role within the model. First, energy demands are classified into three main categories: electricity, heating, and transportation. They are exogenously defined for every region and each year. The model then seeks to meet these demands through a combination of *Technologies* and trade between the different regions. While it builds the different *Technologies*, certain things have to be kept in mind:

- The general nature of the model is that it seeks to minimize total costs. In this case, total costs are defined as the discounted sum of all costs in all regions and all time periods. Costs are either investment costs into and operating costs of *Technologies*, costs for trading a *Fuel* between regions, costs for expanding trade capacities, and emission penalty costs on a production base for greenhouse gases.
- The minimization of the total costs is subject to certain constraints which aim to represent natural bounds. For example, these constraints can be of the form of maximum capacities for certain *Technologies* (due to physical or political reasons) or serve to avoid unrealistic developments like erratic increases in capacities within short time spans. Also, an emission budget is implemented as a constraint, limiting the total amount of *Emissions* for a single or multiple regions over the model period.

- Since the aim of the model is to analyze pathways towards future energy systems, a sequence of multiple years is being analyzed. While the model returns results for any specific year, e.g., 2020, it takes later developments into account when doing so (e.g. the model is optimizing under perfect foresight). The result is that the final configuration of the year 2020 might not be the (cost) optimal one, given this year in a vacuum, but certainly is, when considering later developments. However, this integrated approach comes at the price of computational complexity, allowing for less accuracy in other areas.

2.2 Model version and improvements between versions

The model setup is based on the formulation of the Global Energy System Model (GENeSYS-MOD), as described by Löffler et al. (2017b). In order to overcome some of the key shortcomings of the aforementioned model, especially when it comes to renewables, the model has been revised and improved to a new version. The model version described by Löffler et al. will be referenced as Global Energy System Model (GENeSYS-MOD) v1.0 from here on, whereas the new version being presented here is named GENeSYS-MOD v2.0.

GENeSYS-MOD v2.0 offers a fully revised data set for all global parameters, such as fuel prices, general cost assumptions, and emissions data. Also, the temporal resolution has been updated from utilizing a total of six time slices (summer, intermediate, and winter - each with a day and night cycle) to a reworked 16 time slice model. Furthermore, the list of available technologies has been revised and extended, now including more options in the transportation sector, as well as a representation of CCTS plants. Additionally, the model has been upgraded with new equations and revised formulations that offer more and new functionalities which will be described in the following section:

- The trade system (especially with respect to power trade) has further been improved.
- New constraints limit the phase-in and phase-out of new technologies, as well as renewable electricity growth.
- Emission targets can be set globally as well as for individual regions.
- The efficiency of technologies depends now on the year of construction, rather than on the current date, avoiding an overestimation of potentials.
- The *ReserveMargin* has been redefined to better fit the flexibility requirements of a largely decarbonized system.
- Implemented performance optimization reduce the necessary memory resources and calculation time.

Figure 3 illustrates the changes and improvements to the various blocks of functionality of GENeSYS-MOD v2.0.

2.3 Mathematical formulation

This section describes the model improvements mentioned in section 2.2, introducing the new equations, as well as the changes to existing ones.

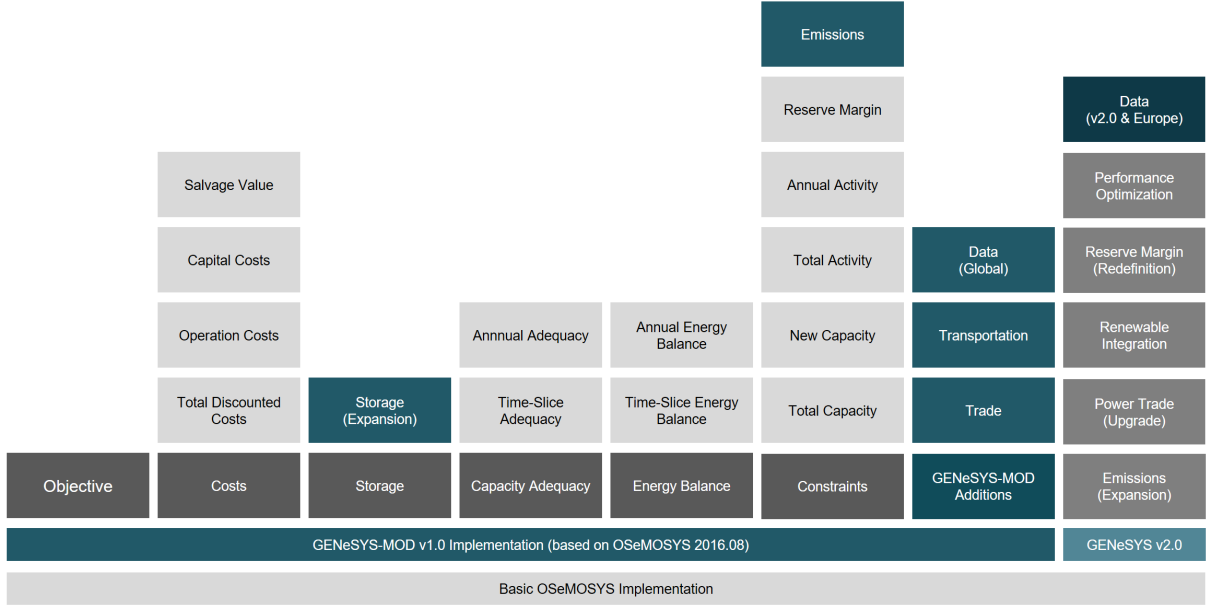


Figure 3: Block structure of GENeSYS-MOD v2.0.

Source: Own illustration, based on Howells et al. (2011).

2.3.1 Power trade

GENeSYS-MOD v1.0 already featured a reworked trade system compared to the original Open Source Energy Modelling System (OSeMOSYS) source code. This remodeling of the trade block is now upgraded once more, focusing on the power sector. It introduces transmission capacities and the option for the model to endogenously expand them. The approach for the endogenous grid expansion is the same as described by Hosenfeld et al. (2017) and has been produced in cooperation.

First, the variable $TotalTradeCapacity$ is defined in equation 1 as the upper limit of the power trade for each time slice.

$$\begin{aligned} & (Import_{y,l,Power,r,rr} + Export_{y,l,Power,r,rr}) / (31.56 * YearSplit_{l,y}) \\ & \leq TotalTradeCapacity_{y,Power,r,rr} \quad \forall y, l, r, rr; TradeRoute_{y,Power,r,rr} > 0 \end{aligned} \quad (1)$$

Equation 2 shows that the $TotalTradeCapacity$ for the base year 2015 is defined as the available grid capacity. The $TotalTradeCapacity$ for all following years is given by the available grid structure from the year before, as well as new grid additions in the current year as seen in equation 3. The variable $NewTradeCapacity$ is endogenously calculated by the model and serves for modeling investments into grid expansions.

$$TotalTradeCapacity_{y,Power,r,rr} = TradeCapacity_{y,Power,r,rr} \quad \forall r, rr; y = 2015 \quad (2)$$

$$\begin{aligned} TotalTradeCapacity_{y,Power,r,rr} = & TradeCapacity_{y-1,Power,r,rr} \\ & + NewTradeCapacity_{y,Power,r,rr} \quad \forall r, rr; y > 2015 \end{aligned} \quad (3)$$

To allow these investments, the maximal possible expansion is limited by the parameter *GrowthRateTradeCapacity*, which is defining how much the existing network can be expanded between the calculated years. The maximal possible network addition is defined as a fraction of the total trade capacity of the previous year. Thus the parameter *GrowthRateTradeCapacity* has to be defined with a value greater than zero to allow investments into grid infrastructure. This parameter can, for example, symbolize the existing grid expansion plans of governments. Equation 4 shows the limitation by the mentioned parameter.

$$\begin{aligned} & GrowthRateTradeCapacity_{y,Power,r,rr} * TotalTradeCapacity_{y-1,Power,r,rr} \\ & \geq NewTradeCapacity_{y,Power,r,rr} \quad \forall y, r, rr; TradeRoute_{y,Power,r,rr} > 0 \end{aligned} \quad (4)$$

Finally, these capacity additions are subject to grid expansion costs. These costs are defined for each new unit of capacity between two regions (compare equation 5). They are then discounted to the base period in order to keep costs comparable over the modeling period (see equation 6). The discounted costs are added to the objective function.

$$\begin{aligned} & NewTradeCapacity_{y,Power,r,rr} * TradeCapacityGrowthCosts_{Power,r,rr} \\ & = NewTradeCapacityCosts_{y,Power,r,rr} \quad \forall y, r, rr \end{aligned} \quad (5)$$

$$\begin{aligned} & \frac{NewTradeCapacityCosts_{y,Power,r,rr}}{(1 + DiscountRate_r)^{YearVal_y - \min(y)+0.5}} \\ & = DiscountedNewTradeCapacityCosts_{y,Power,r,rr} \quad \forall y, r, rr \end{aligned} \quad (6)$$

2.3.2 Phase-in, phase-out and renewable integration

Since the model is formulated as a linear programm (LP), the special aspects of this model class need to be taken into account. One of them is the tendency to adhere to corner solutions (e.g., build either 100% or 0% of a technology). To avoid these extreme solutions and gain more realistic results, constraints have to be added. The new phase-in and phase-out equations make sure that new future technologies (such as renewable energy sources) are not being used in one year and then completely disregarded in the next, as well as old technologies being constructed and then ending as a stranded asset.

The Parameters *PhaseIn* and *PhaseOut* represent a relative change to the current production values. A value of 1 represents the same amount as the year before, while a *PhaseOut*-value of 1.2 would allow the model to increase the production up to 20% compared to the previous year. Hence, *PhaseOut* serves as an upper bound, which limits how much of a technology can be installed in the next period. The subsets *PhaseInSet* and *PhaseOutSet* are both subsets of the *Technology* set, including renewable and fossil-fuel based generation technologies, respectively. Equations 7 and 8 illustrate the implementation of

the mentioned bounds. The overall result is a smoother and more realistic transition of the energy system and its technologies.

$$\begin{aligned}
 & \text{ProductionByTechnologyAnnual}_{y, \text{PhaseInSet}, f, r} \\
 & \geq \text{ProductionByTechnologyAnnual}_{y-1, \text{PhaseInSet}, f, r} * \text{PhaseIn}_y \\
 & \qquad \qquad \qquad \forall r, \text{PhaseInSet}, f; y > 2015 \quad (7)
 \end{aligned}$$

$$\begin{aligned}
 & \text{ProductionByTechnologyAnnual}_{y, \text{PhaseOutSet}, f, r} \\
 & \leq \text{ProductionByTechnologyAnnual}_{y-1, \text{PhaseOutSet}, f, r} * \text{PhaseOut}_y \\
 & \qquad \qquad \qquad \forall r, \text{PhaseOutSet}, f; y > 2015 \quad (8)
 \end{aligned}$$

Also, the new equation 9 makes sure that the electricity system is not put on too much of a burden due to the fluctuating nature of renewable energy. To achieve this, an approach similar to Ram et al. (2017) has been implemented, limiting the additional amount of renewable electricity generation per time period to 20% of the total generation of the previous 5-year-period.

$$\begin{aligned}
 & \sum_{t, \text{RETagTechnology}_{r,t,y}=1} \text{ProductionByTechnologyAnnual}_{y,t, \text{Power}, r} \\
 & \leq 1.2 * \sum_t \text{ProductionByTechnologyAnnual}_{y-1,t, \text{Power}, r} \quad \forall r; y > 2015 \quad (9)
 \end{aligned}$$

2.3.3 Emissions

The emission system of OSeMOSYS differentiates between regions when it comes to emission limits. This has been changed in GENeSYS-MOD (read Löffler et al. (2017b)) in order to facilitate the use one global CO₂ budget instead. This enabled the optimization of world-wide emissions from a strict planner view, looking for the least-cost solution on the path towards 100% renewable energy utilization, since the model was thus able to freely determine the optimal regional CO₂ outputs. For some scenarios though, a regional differentiation between carbon budgets is desired, or even needed. Thus, a new equation, as well as a new parameter,³ have been put in place to enable this feature. Now, the user can choose between regional or model-wide carbon budgets, instead of being limited to only one of these options.

$$\text{ModelPeriodEmissions}_{e,r} \leq \text{RegionalModelPeriodEmissionLimit}_{e,r} \quad \forall e, r \quad (10)$$

Additionally, the way emissions are treated in general, has been changed. Before, emissions occurred for the resource - meaning that the *extraction* of fossil fuels was utilized to account for the actual CO₂ emissions (Löffler et al. 2017b). This proves problematic when considering regional distributions of CO₂ budgets, since all emissions occur at the source, instead of the actual usage of the fuel. While this poses

³The equation is named *E10_RegionalModelPeriodEmissionsLimit* and is situated in the *Emissions* block. The new parameter is called *RegionalModelPeriodEmissionLimit* and has to be given for each *Emission* and *Region* (equation 10). The default value is 999999, which GENeSYS-MOD takes as infinite.

an interesting approach for analyses, the general possibility to account for emissions at the place they are actually produced, was added to the model. The user can still choose to place CO₂ emissions at the extraction point, but the default setting in GENeSYS-MOD v2.0 is set to the production-side.

To achieve this, *Fuels* now have an *EmissionContent*, signifying how much carbon dioxide is released when burning the fuel. The parameter *EmissionActivityRatio* now defines which technologies emit CO₂ when burning their respective fuels - and how many of these emissions might be captured (which is important for the implementation of CCTS technologies). Equation 11 shows the changes made to equation *E1_AnnualEmissionProductionByMode*_{y,t,e,m,r}. The additions are highlighted in red.

$$\begin{aligned}
 & \textit{EmissionActivityRatio}_{r,t,e,m,y} * \sum_f (\textit{TotalAnnualTechnologyActivityByMode}_{y,t,m,r} \\
 & \quad * \textit{EmissionContentPerFuel}_{f,e} * \textit{InputActivityRatio}_{r,t,f,m,y}) \\
 & = \textit{AnnualTechnologyEmissionByMode}_{y,t,e,m,r} \quad \forall y, t, e, m, r \quad (11)
 \end{aligned}$$

In some cases, technologies can have non-zero emissions, but they do not have to pay a separate carbon tax for them (IEA 2016b).⁴ In this case, the *Technology* would have a positive *EmissionActivityRatio*, but the *EmissionsPenalty* would need to be zero. Since the parameter *EmissionsPenalty* is only defined per *Region*, *Fuel*, and *Year*, a new parameter *EmissionsPenaltyTagTechnology* has been added. This enables the user to define certain *Technologies* that are excluded from paying a carbon tax.

The associated equation has been adapted to include the new parameter. This change is shown in equation 12.

$$\begin{aligned}
 & \textit{AnnualTechnologyEmission}_{y,t,e,r} * \textit{EmissionsPenalty}_{r,e,y} \\
 & \quad * \textit{EmissionsPenaltyTagTechnology}_{r,t,e,y} \\
 & = \textit{AnnualTechnologyEmissionPenaltyByEmission}_{y,t,e,r} \\
 & \quad \forall y, t, e, r, \quad \textit{EmissionsPenalty} <> 0 \quad (12)
 \end{aligned}$$

Also, the variables concerning the *EmissionsPenalty* have been changed from positive variables to free variables, in order to enable negative emissions payments in the case of CCTS. The user is free to choose between negative payments or no payments via the aforementioned parameters.

2.3.4 Inter-temporal efficiency

An issue of the basic implementation of OSeMOSYS, that was carried over to the first version of GENeSYS-MOD, is the handling of changing efficiencies over the years. Since the *RateOfActivity* was only calculated based on the *TotalCapacityAnnual*, the model did not take into account the efficiency parameters of the construction point in time, but the one of the currently calculated period instead (and thus assuming already installed RES capacities to become more and more efficient). This leads to an overestimation of possible

⁴For example, the carbon pricing in Europe only accounts for the sectors power, industry, and aviation.

outputs, especially for some renewable technologies, where higher *CapacityFactors*, *AvailabilityFactors*, or higher efficiency ratios over the years are assumed.

$$\begin{aligned} \text{RateOfTotalActivity}_{y,l,t,r} &\leq \text{TotalCapacityAnnual}_{y,t,r} * \text{CapacityFactor}_{r,t,l,y} \\ &\text{CapacityToActivityUnit}_{r,t} \quad \forall r, l, t, y \end{aligned} \quad (13)$$

Instead, the reformulated equation 13 sums up the parameters only for the construction year of the desired capacity. As before, only valid (or actually functioning) technology capacities are taken into account, those with expired *OperationalLives* are not included in the calculation. The main change is to how the sum is being calculated, with parameters such as *CapacityFactors* now being calculated individually for each year. Equations 14 and 15 show the new functionality.

$$\text{RateOfTotalActivity}_{y,l,t,r} \leq \text{TotalActivityPerYear}_{r,l,t,y} \quad \forall r, l, t, y \quad (14)$$

$$\begin{aligned} &\sum_{\substack{yy, \\ y-yy < \text{OperationalLife}_{r,t}, \\ y-yy \geq 0}} (\text{NewCapacity}_{yy,t,r} * \text{CapacityFactor}_{r,t,l,yy} * \text{CapacityToActivityUnit}_{r,t}) \\ &+ (\text{ResidualCapacity}_{r,t,y} * \text{CapacityFactor}_{r,t,l,2015} * \text{CapacityToActivityUnit}_{r,t}) \\ &= \text{TotalActivityPerYear}_{r,l,t,y} \quad \forall r, l, t, y \end{aligned} \quad (15)$$

The same approach is also being used in calculations for operation and maintainance (O&M) costs of technologies. This ensures that built capacities retain their operational costs over the course of their lifetimes.

While it would theoretically be possible to formulate the improvement of efficiencies or costs as multiple technologies to prevent the described problem, this quickly becomes impractical when dealing with large models and datasets, as each technology greatly increases the matrix size which has to be solved by the solver. The implemented approach enables to implement learning curves and technological progress within one technology, while still retaining the correct valuation for each separate construction.

2.3.5 Reserve margin

The implementation of the reserve margin has been redesigned from the original OSeMOSYS implementation, which was used in GENeSYS-MOD v1.0. The original formulation required the model to build over-capacities of selected technologies for selected fuels, determined by the maximum load occurring in a year. A reserve margin of, for example, 20% for the *Fuel* 'Power' meant that the model needed an excess capacity of electricity-generating services of 20% of the peak demand value. While this approach is useful for adding a 'safety buffer' when calculating peak demand loads and reducing possible shortages in the energy system due to unforeseen events, simply adding this additional capacity does not necessarily lead to network stability, especially when including high shares of renewables.

Instead, the new formulation requires the model to produce a certain share of its production of a selected *Fuel* (e.g., power) with selected *Technologies* that offer the necessary flexibility when it comes to load balancing. As an example, this might include technologies with fast ramp-up times, such as electric storages or gas-fired plants. To achieve this, the parameter *TotalCapacityInReserveMargin* has been replaced with *TotalActivityInReserveMargin*. The resulting equations 16 and 17 with highlighted changes are shown below.

$$\sum_{t,f} (\text{ProductionByTechnology}_{y,l,t,f,r} * \text{ReserveMarginTagFuel}_{r,f,y} * \text{ReserveMarginTagTechnology}_{r,t,y}) = \text{TotalActivityInReserveMargin}_{r,y,l} \quad \forall y, l, r \quad (16)$$

Equation 16 shows the changes from a capacity-based to an activity-based approach. This change leads to the necessity to include the parameter *YearSplit* in equation 17, since the *RateOfProduction* (given in terms of power) needs to be multiplied with the respective time to achieve the demand in units of energy.

$$\sum_f (\text{RateOfProduction}_{y,l,f,r} * \text{YearSplit}_{l,y} * \text{ReserveMarginTagFuel}_{r,f,y}) = \text{DemandNeedingReserveMargin}_{y,l,r} \quad \forall y, l, r \quad (17)$$

2.3.6 Performance optimization

Some performance optimization was performed, reducing the matrix size, and thus lowering memory requirements needed for solving the mathematical problem, as well as its solving time. Through the addition of conditions in some of the most crucial equations, these equations are now only considered when they are actually needed (e.g., when the connected technology has an *OutputActivityRatio*). This drastically reduces the amount of "empty" equations that would be generated otherwise. The equations *EBa1_RateOfFuelProduction*_{1,y,t,f,m,r} and *EBa4_RateOfFuelUse*_{1,y,t,f,m,r} are now only considered, if the respective *OutputActivityRatio*, or the *InputActivityRatio*, respectively, are not equal to zero.⁵ This is being achieved by the \$-operator in GAMS, which is put next to the declaration of the equation. An improvement of around 40% less memory usage could be observed in our tests.

Additionally, a model analysis using the GAMS function *gamschk* has been conducted. This model analysis shows unnecessary variables and equations that increase the model size and runtime by listing unused variables, equations that are always zero, and non-binding constraints. After this analysis, the following equations have been altered:

- Equation *CAb1_PlannedMaintenance*_{y,l,r} is now only calculated if the respective *AvailabilityFactor* is lesser than one.
- Equation *OC1_OperatingCostsVariable*_{y,l,r} is now only calculated if the associated *VariableCosts* are not zero.

⁵These are two of the largest equations in the model, as they are computed for each *Year*, *Technology*, *Fuel*, *Mode of operation*, and *Region*, generating multiple million lines for calculation.

- Equations $RM1_ReserveMargin_TechnologiesIncluded_In_Activity_Units_{y,l,r}$, $RM2_ReserveMargin_FuelsIncluded_{y,l,r}$, and $RM3_ReserveMargin_Constraint_{y,l,r}$ will now only be included if the respective *ReserveMargin* is greater than zero.
- Equation $E1_AnnualEmissionProductionByMode_{y,t,e,m,r}$ is now only calculated for associated *EmissionActivityRatios* that are not equal to zero.
- Equation $E3_EmissionsPenaltyByTechAndEmission_{y,t,e,r}$ is now only calculated for non-zero values of the respective *EmissionsPenalty*.
- All equations of the transportation block⁶ have been changed to use the subset *TransportFuels* instead of all *Fuels* included in the model. The new subset *TransportFuels* consists of the two demand fuels *Mobility_Passenger* and *Mobility_Freight*.

Figure 4 shows the changes in both calculation time and memory usage of the model optimization stages for two different workstations.⁷ Surprisingly, CPLEX did worse across all trial runs utilizing only the first set of optimizations, up to the point of not being able to solve at all (user cancellation after 10,000 seconds). GUROBI, on the other hand, was not able to compute the model results for the unoptimized case, exiting with an "out-of-memory" error for each run. This shows the general larger need for computational resources of GUROBI (especially when it comes to RAM).

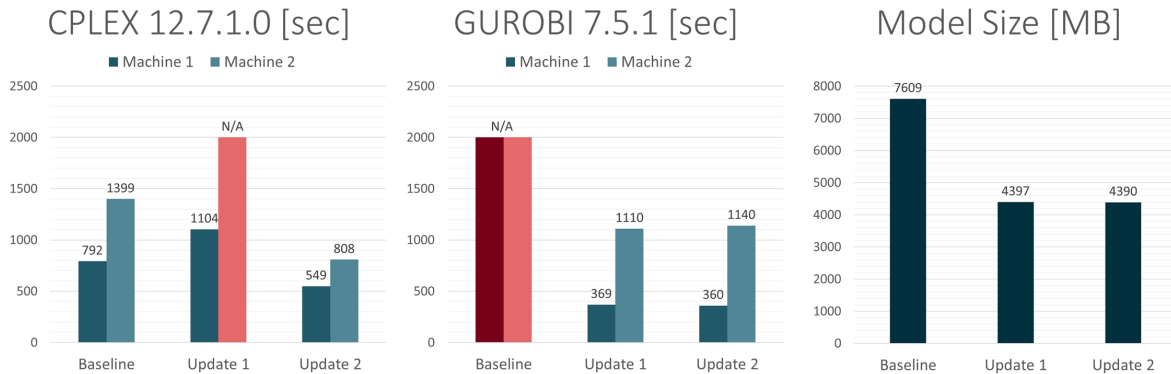


Figure 4: Benchmark results with multiple solvers and workstations.

Source: Own illustration.

Also, the two test machines behaved quite differently when it came to model runtimes. While the more powerful test machine 1 showed better results for GUROBI (compared to CPLEX) across all tests (up to a stunning performance difference of 66%), the weaker machine worked better with CPLEX, outclassing GUROBI by almost 30% in the fully optimized scenario.

For a better comparison of the results, the *Region* set was reduced to a total of eleven regions instead of 15—just enough to be able to run GUROBI in the unoptimized case. The results (shown in figure 5) are

⁶Namely $T1a_SpecifiedAnnualDemandByModalSplit_{mt,r,f,y}$, $T1b_AccumulatedAnnualDemandByModalSplit_{mt,r,f,y}$, $T2_ProductionOfTechnologyByModalSplit_{mt,r,f,y}$, and $T3_ModalSplitBalance_{mt,r,f,y}$.

⁷For the result calculations, two different machines have been used. The specifications, memory load, and environment stayed the same over the benchmarks. As solvers, GUROBI version 7.5.2 and CPLEX version 12.7.1.0 have been used. Machine 1: 4-core-CPU, 4.4 GHz, 16 GB Memory, DDR3 - 2133 MHz. Machine 2: 4-core-CPU, 2.66 GHz, 14 GB Memory, DDR3 1600 MHz.

quite surprising, especially considering the results from the previous full calculation (as seen in figure 4). With the reduced set, CPLEX performed better than GUROBI for almost all cases. The first set of optimizations seemed to pose problems for machine 1, actually leading to a significant *increase* in runtime. This result was constant across multiple tests. The tests for GUROBI showed a steady decline in runtime across the optimizations.

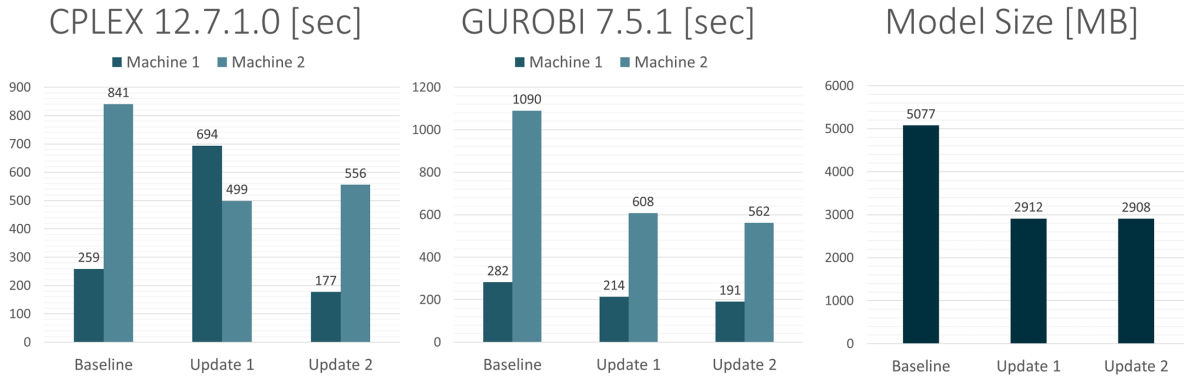


Figure 5: Benchmark results with reduced amount of regions.

Source: Own illustration.

In general, both optimization stages together resulted in a roughly 42% decrease in model size and an average of 35% runtime improvement. These optimizations are especially valuable considering future model additions, such as updated calculations on a global scale. GUROBI proved to be more consistent, providing faster results, especially when paired with high clock speeds on the workstation, but needs a lot more resources as a downside.

This means that no clear recommendation for a solver can be made at this point. Instead, frequent benchmarks are advised to optimize model runtime for each use case.

3 Data

The general data foundation as described in Löffler et al. (2017b) has been revised and updated with a new spatial and temporal resolution. Also, new regional data for Europe has been researched and was added to the model. The list of available technologies has been updated with their respective cost assumptions, potentials, and efficiency parameters. Emission data and fuel costs for fossil energy carriers have been updated. If not stated otherwise, data is adopted from GENeSYS-MOD v1.0 (see Löffler et al. (2017b) and Burandt et al. (2016)).

3.1 Model setup and data

3.1.1 Spatial resolution and grid data

Since the focus of this work is the European region, a corresponding geographical resolution had to be found. Similar to the case study for India conducted with the first version of GENeSYS-MOD (see Löffler et al. (2017a)), the broad world region "Europe" was split up into multiple smaller regions to fit the scope of the study.

The European energy system is represented by 15 nodes. A focus has been placed on Germany and its central role, both geographically and politically. Hence, Germany and all its neighboring countries are modeled as single regions (with Luxembourg being the exception), whereas the resolution gets broader moving to the edges of the European region. There, multiple countries are aggregated into one region, based on matching regional potentials and conditions. The chosen regional disaggregation of Europe with 15 nodes in total leads to a stylized version of the European electricity grid. The resulting grid structure with its possible connections between nodes can be found in figure 6. Grid capacities for Europe have been taken from Gerbaulet and Lorenz (2017). Grid expansion costs have been adapted from Hosenfeld et al. (2017), citing a value of 222.9 million € per gigawatt (GW) additional grid capacity.

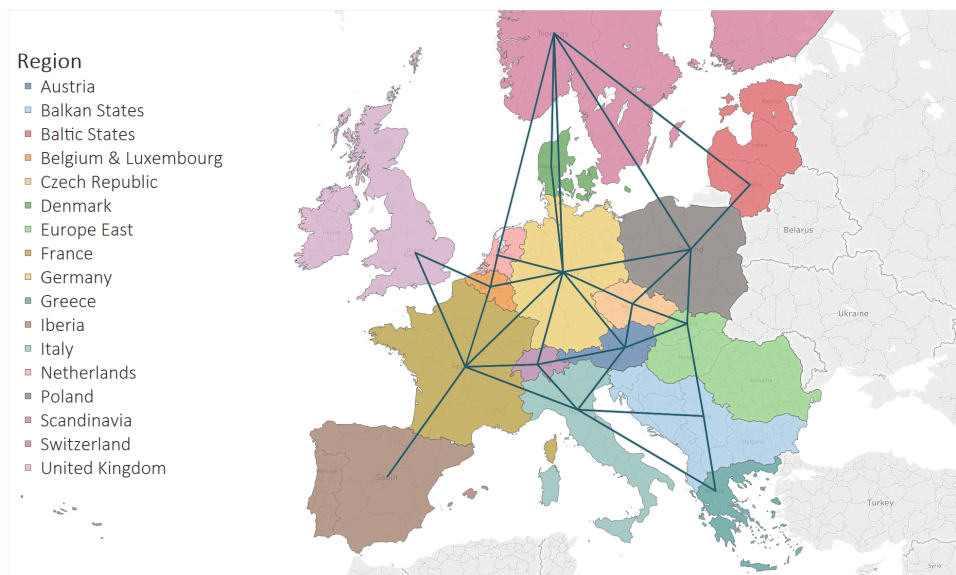


Figure 6: Grid structure and node set-up for Europe.

Source: Own illustration.

3.1.2 Temporal resolution

GENeSYS-MOD v1.0 featured a total of six time slices, allocated as day and night over a total of three seasons. While this approach is useful for fast calculations and rough estimates, its limitations arise quickly when taking a closer look at energy sources with high temporal variability (such as solar or wind power). This also directly affects storages, especially those meant for short-term storage (such as batteries).

This temporal disaggregation has been revised and updated, now featuring four quarters of a year, and four daily time brackets, to a total of 16 time slices per year. A similar approach can be found in Welsch et al. (2012), where they show that an energy system model using an enhanced version of OSeMOSYS, utilizing 16 time slices, can achieve almost the same results as a full hourly dispatch model.

For each quarter, the daily time brackets which determine the time slices are slightly different. This approach was chosen to facilitate a better match of solar load profiles, since sun availability vastly differs between seasons. Each day is split up into a) morning, b) peak, c) afternoon, and d) night. The daily sun-hours for Germany (taken as representative for Europe, since its central geographical location gives a good mean value for the region) have been used as outlines for the daily time brackets. Table 1 shows the chosen hours per day for each time slice.

Table 1: Hourly assignment of daily time brackets.

[hours:minutes]	Q1	Q2	Q3	Q4
Morning	07:30 - 09:00	05:00 - 08:00	06:00 - 08:00	07:30 - 11:00
Peak	09:00 - 13:00	08:00 - 16:00	08:00 - 15:00	11:00 - 13:30
Afternoon	13:00 - 17:00	16:00 - 21:00	15:00 - 20:30	13:30 - 16:00
Night	17:00 - 07:30	21:00 - 05:00	20:30 - 06:00	16:00 - 07:30

Source: Based on average sun hours in Germany for the year 2015.

The resulting temporal resolution in percentages of a year can be found in table 2.

Table 2: YearSplit of GENeSYS-MOD v2.0.

Fraction of year [in %]	Q1	Q2	Q3	Q4	Total
Morning	1.56	3.13	2.08	3.65	10.42
Peak	4.17	8.33	7.29	2.60	22.39
Afternoon	4.17	5.21	5.73	2.60	17.71
Night	15.10	8.33	9.90	16.15	49.48
Total	25.00	25.00	25.00	25.00	100.00

Source: Own assumptions.

3.2 Technology description and implementation

3.2.1 Technology representation in the model

The list of technologies has been taken from the prior model version and has then been revised. Some technologies did receive updates in their implementation, others were added, and some have been removed. Heating technologies no longer have centralized and decentralized counterparts. This simplification is due to our rough regional disaggregation, which does not profit from such a distinct analysis of

heating technologies. Instead, centralized and decentralized heating technologies for each type (e.g., low-temperature gas heating) have been combined into one unified technology. A total of 15 centralized heating technologies (including the area technologies) have been omitted from the model.

The refinery for biofuels has been removed from the list of technologies. Instead, the transformation losses and costs have been added to the *InputActivityRatio* and costs. This change is in line with the non-existence of refineries for petrofuel in the model and serves as a simplification, reducing the total number of technologies. The list of all technologies that have been omitted can be found in Appendix A2.

3.2.1.1 Technologies that have been fundamentally changed in GENeSYS-MOD v2.0

All technologies that are able to utilize more than one sort of input fuel now have multiple modes of operation instead of being classified as technologies of their own.⁸ This has the advantage of avoiding having to spend capital costs multiple times when the model wants to switch from, e.g., a natural gas-powered plant to a biogas-powered one.⁹ Additionally, this further reduces the total amount of technologies for the model to handle, improving model runtime (since every technology occurs in several equations and thus has to be considered by the solving algorithm). Usages and production values for each *Fuel* can be obtained via the corresponding *ModeOfOperation* for each *Technology*.

3.2.1.2 New technologies in GENeSYS-MOD v2.0

New technologies for the import of fossil fuels outside of the modeled region have been implemented. This is important when conducting case studies, where the rest of the world is not being calculated endogenously. Since resources might be scarce in the modeled region (such as crude oil reserves in Europe, for example), the model now has the option to import fossil fuels at world market prices. The model now distinguishes between hard coal and lignite—a change that was necessary considering the strong usage of lignite, as well as large amounts of existing capacities, in some parts of the European region. For this purpose, new technologies for the use and production of lignite have been implemented (but no import technology, since lignite is inefficient to transport and instead is used in close proximity to the mining site).

The list of transportation technologies has been revised and expanded by new technologies not previously considered in GENeSYS-MOD v1.0. Electric options for road-based freight transport were added to the model.¹⁰ Passenger road-based transport was expanded by plug-in hybrid electric vehicles and air-based transport has a new technology using biokerosene. These new technologies have been added to offer a broader variety of options for the model to choose from, including more possible future solutions for the transportation sector.

Furthermore, two new storage technologies for electricity storage were added to the model: reduction–oxidation (redox)-flow-batteries and compressed air energy storage (CAES). Also, a new methanation

⁸For example, a gas-based heater can now use either methane from natural gas, biomethane, or synthetic methane—whereas before, three different technologies for each input fuel were implemented.

⁹Before, the model would have had to construct two separate power plants, since each technology was only able to handle one input fuel. This meant spending double the capital cost and stranded assets.

¹⁰New technologies for electricity-based road freight transport: overhead-powered trucks, battery-electric trucks, plug-in hybrid electric trucks.

technology has been put in place. It is able to transform biomass and synthetic hydrogen to methane, thus enabling more options for sector coupling inside the model. The produced methane is treated the same way as methane out of natural gas.

Carbon capture, transport, and storage (CCTS) for biomass-based power plants is now added as a technology into GENeSYS-MOD v2.0. Using it in conjunction with biomass may enable negative net emissions. In order to be able to better compare our results with such models, the option for bio-energy with carbon capture, transport, and storage (BECCTS) has been added.

Residual capacities for 2015 for the power production of all European countries have been taken from Farfan and Breyer (2017). The future capacities were then projected based on the construction years and the respective *OperationalLife*. For the heating sector, capacities described by Fraunhofer ISI et al. (2016) were considered.

3.2.2 Technology data

Most technology parameters have been updated with more current sources, raising the overall data quality. The new parameter values for key technologies will be presented in the following section. For a complete list of all technology parameters, please refer to the supplementary material.

3.2.3 Potentials of renewable energy sources

The total potential for renewable technologies is often disputed, even among experts, with heavily varying values. The choice of maximum land usage, as well as the underlying weather data (e.g., choice of the base year), strongly impact these numbers and quickly lead to an over- or underestimation of actually available potentials. The renewable potential data for the European region presented in this study stem from the model dynamic Electricity Model (dynELMOD) (Gerbault and Lorenz 2017), which, in turn, is based on an expert assessment by the Potsdam Institute for Climate Impact Research. The potential capacity per region is given in appendix 3.

Table 3: Regional potentials for utility-scale solar PV, onshore wind, and offshore wind in GW.

	Solar PV	Wind Onshore	Wind Offshore	Total
Austria	29.2	45.8	0	75
Balkan States	145.9	237.5	64.5	447.9
Baltic States	41.6	81.8	108.2	231.6
Belgium & Luxembourg	22.8	19.4	9.1	51.3
Czech Republic	38.3	56.1	0	94.4
Denmark	22.5	32.6	149	204.1
Europe East	173.8	278.4	24.3	476.5
France	251.8	381.7	133.7	767.2
Germany	200.4	222.6	83.6	506.6
Great Britain	212.2	268.8	364.6	845.6
Greece	62.8	105.6	27.6	196
Italy	159.9	190.2	77.7	427.8
Netherlands	31.8	23.6	57.1	112.5
Poland	134.4	193.9	40.7	369
Portugal & Spain	256.7	417.9	71.7	746.3
Scandinavia	62.3	197.4	420.4	680.1
Switzerland	18.7	20.8	0	39.5
Total	1865.1	2774.1	1632.2	6271.4

Source: Gerbaulet and Lorenz (2017).

3.2.4 Capacity factors

Capacity factors for renewable generation have been taken from Pfenninger and Staffell (2016), given as an hourly time series for the year 2014. For each region, multiple samples have been taken, placed into a category, and then taken as average for each region, category and time slice. Solar PV and onshore wind are divided up into the three categories a) optimal, b) average, and c) inferior, while offshore wind has been categorized as a) shallow, b) transitional, and c) deep.¹¹ The categories of PV and onshore wind only differ in the capacity factors whereas the particular types of offshore wind parks additionally have different capital and O&M costs. Therefore, we decided to use another kind of categorization for offshore wind.

The hourly data for each quarter of the year has been aggregated with the corresponding time slice definition, as described in section 3.1.2. This leads to the final capacity factors for each *Timeslice*. Because of the high dependency of the capacity factors on the selected year from Pfenninger and Staffell (2016) for aggregating the modeled *Timeslices*, further sensitivity analyses have to be underdone. Especially extreme weather conditions in individual years are flattened out or not included in this aggregation. Hence, we have the plan to add additional *Daytypes* to reflect different possible weather conditions for the power generation of renewable energy sources (RES). Table 4 shows the capacity factors for selected technologies in the German node of the model.

¹¹The regional potential has been assumed to be evenly distributed across the categories, as per Gerbaulet and Lorenz (2017)

Table 4: Capacity factors for selected renewable technologies in Germany.

	Q1	Q2	Q3	Q4
Solar PV (average location)				
Morning	0.18	0.21	0.24	0.19
Peak	0.30	0.44	0.45	0.23
Afternoon	0.11	0.04	0.07	0.07
Night	0.00	0.00	0.00	0.00
Onshore wind (average location)				
Morning	0.28	0.16	0.16	0.24
Peak	0.30	0.21	0.20	0.26
Afternoon	0.30	0.21	0.20	0.27
Night	0.29	0.21	0.20	0.26
Offshore wind (near-shore)				
Morning	0.42	0.23	0.24	0.42
Peak	0.42	0.24	0.25	0.42
Afternoon	0.42	0.26	0.26	0.42
Night	0.42	0.25	0.25	0.42

Source: Pfenninger and Staffell (2016), aggregated for each time slice.

3.2.5 Cost data

3.2.5.1 Capital costs

For utility-scale PV and onshore wind, expenses have been assumed to be the same across all three categories. For offshore wind, the placement of turbines influences the resulting construction costs a lot more (e.g., near-shore vs. deep-water placement) with cost estimate ranges of up to more than double the price. Hence, offshore wind has its capital costs given separately for each category. The capital costs for fossil-based plants are assumed to be constant over the years, while renewables experience decreasing costs over the modeled time frame. Fixed costs are assumed as a percentage of capital costs, as in GENeSYS-MOD v1.0. Variable costs for renewable technologies are still considered to be zero. The capital costs for for renewable energy generation, as well as storages, and key transformation technologies can be found in table 5.

Table 5: Capital cost of power generation and transformation technologies in €/kW.

	2015	2020	2025	2030	2035	2040	2045	2050
Renewables								
PV Utility	1000	580	466	390	337	300	270	246
PV Rooftop [commercial]	1360	907	737	623	542	484	437	397
PV Rooftop [residential]	1360	1169	966	826	725	650	589	537
CSP	3514	3188	2964	2740	2506	2374	2145	2028
Onshore Wind	1250	1150	1060	1000	965	940	915	900
Offshore Wind [shallow]	3080	2580	2580	2580	2330	2080	1935	1790
Offshore Wind [transitional]	3470	2880	2730	2580	2480	2380	2330	2280
Offshore Wind [deep]	4760	4720	4345	3970	3720	3470	3370	3270
Hydro [large]	2200	2200	2200	2200	2200	2200	2200	2200
Hydro [small]	4400	4480	4490	4500	4500	4500	4500	4500
Biomass Power Plant	2890	2620	2495	2370	2260	2150	2050	1950
Biomass CHP	3670	3300	3145	2990	2870	2750	2645	2540
Biomass Power Plant + CCTS	4335	3930	3742	3555	3390	3225	3075	2925
Biomass CHP + CCTS	5505	4950	4717	4485	4305	4125	3967	3810
Geothermal	5250	4970	4720	4470	4245	4020	3815	3610
Ocean	9890	5095	4443	3790	3083	2375	2238	2100
Conventional Power Generation								
Gas Power Plant (CCGT)	650	636	621	607	593	579	564	550
Gas Power Plant (CCGT) + CCTS ¹²	1750	1750	1750	1750	1750	1750	1750	1750
Gas CHP (CCGT)	977	977	977	977	977	977	977	977
Oil Power Plant (CCGT)	650	627	604	581	558	535	512	490
Hard Coal Power Plant	1600	1600	1600	1600	1600	1600	1600	1600
Hard Coal Power Plant + CCTS ¹²	3350	3020	2935	2850	2850	2850	2850	2850
Hard coal CHP	2030	2030	2030	2030	2030	2030	2030	2030
Lignite Power Plant	1900	1900	1900	1900	1900	1900	1900	1900
Lignite Power Plant + CCTS ¹²	4200	4200	4200	4200	4200	4200	4200	4200
Lignite CHP	2030	2030	2030	2030	2030	2030	2030	2030
Nuclear Power Plant	6000	6000	6000	6000	6000	6000	6000	6000
Transformation & Storage								
Electrolyzer	800	685	500	380	340	310	280	260
Methanizer	492	421	310	234	208	190	172	160
Fuel Cell	3570	2680	2380	2080	1975	1870	1805	1740
Li-Ion Battery	490	170	155	140	140	140	140	140
Redox-Flow Battery	1240	810	770	730	520	310	310	310
Compressed-Air Energy Storage	600	600	565	530	520	510	480	450

Source: European Commission et al. (2014), Gerbaulet and Lorenz (2017), and Ram et al. (2017).

3.2.5.2 O&M costs

Fixed costs are assumed as a percentage of capital costs, as in GENeSYS-MOD v1.0. Variable costs for renewable technologies are still considered to be zero. The new and changed variable costs for transformation and storage technologies can be found in table 6.

¹²Currently, the option for fossil fuel based power generation with CCTS is disabled.

Table 6: Variable costs for transformation and storage technologies, in M€/PJ.

	2015	2020	2025	2030	2035	2040	2045	2050
Electrolyzer	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Methanizer [synthetic gas]	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Methanizer [biogas]	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
Fuel Cell	11.11	6.94	6.67	6.39	5.42	4.44	4.44	4.44
Li-Ion Battery	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
Redox-Flow Battery	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Compressed-Air Energy Storage	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33

Source: European Commission et al. (2014).

3.2.6 Conventional power plant efficiencies

Table 7: Input fuel efficiency for common conventional power plants.

	2015	2020	2025	2030	2035	2040	2045	2050
CCGT (Natural Gas)	58%	60%	61%	62%	62%	62%	63%	63%
CCGT (Oil)	38%	38%	39%	39%	40%	40%	41%	41%
Hard Coal	45%	46%	47%	48%	48%	48%	48%	48%
Lignite	42%	45%	46%	47%	47%	47%	47%	47%
Nuclear	37%	37%	38%	38%	40%	42%	42%	42%

Source: European Commission et al. (2014).

3.2.7 Power plant lifetimes

Table 8: Technical lifetime of power generation and transformation technologies.

	Years
Renewables	
PV Utility	20
PV Rooftop	20
CSP	30
Onshore Wind	20
Offshore Wind	20
Hydro Power Plant	80
Biomass Power Plant	30
Geothermal	40
Ocean	20
Conventional Power Generation	
Gas Power Plant (CCGT)	30
Oil Power Plant (CCGT)	30
Hard Coal Power Plant	30
Lignite Power Plant	30
Nuclear Power Plant	40
Transformation & Storage	
Electrolyzer	10
Methanizer	10
Fuel Cell	10
Li-Ion Battery	10
Redox-Flow Battery	20
Compressed-Air Energy Storage	30

Source: Gerbaulet and Lorenz (2017), European Commission et al. (2014) and Burandt et al. (2016).

3.3 Demands

3.3.1 Electricity

Electricity demands have been taken from Gerbaulet and Lorenz (2017), as described in the European reference scenario for dynELMOD. Yearly demands have been taken and aggregated for our chosen regional set-up. The demand split for each time slice has been aggregated from an hourly resolution in the original data, in order to fit the chosen time slices.

Table 9: Yearly electricity demand per region in TWh.

	2015	2020	2025	2030	2035	2040	2045	2050
Austria	70.31	76.94	83.93	75.27	77.59	79.47	78.19	76.09
Balkan States	155.38	171.46	180.13	150.87	151.99	154.01	155	156.17
Baltic States	28.62	32.41	36.69	29.17	29.56	30.31	29.83	29.64
Belgium & Luxembourg	98.45	107.98	114.23	114.43	116.71	115.79	111.81	108.78
Czech Republic	63.45	65.14	67.23	82.00	82.13	84.42	85.52	85.16
Denmark	35.68	37.11	39.17	40.00	40.46	40.76	40.83	38.49
Europe East	132.67	146.78	160.22	143.86	147.24	149.98	151.92	154.35
France	502.80	522.30	536.70	562.86	580.82	590.57	581.83	565.23
Germany	543.60	562.20	562.20	611.01	596.06	590.48	582.20	574.40
Great Britain	355.92	353.67	365.28	451.56	458.85	470.56	476.79	468.18
Greece	53.30	56.40	70.80	74.93	75.96	76.28	76.07	74.70
Italy	361.92	375.12	389.65	390.90	404.27	409.69	421.08	432.36
Netherlands	122.85	132.34	142.57	127.40	128.32	131.07	130.94	129.95
Poland	162.14	178.49	205.88	171.42	176.94	181.82	184.54	176.36
Portugal & Spain	335.52	376.09	415.59	418.01	430.33	435.28	450.28	429.14
Scandinavia	377.40	389.30	402.30	346.70	340.11	335.55	333.33	328.25
Switzerland	64.40	69.38	74.74	76.22	78.58	80.47	79.18	77.05
Total	3464.41	3653.11	3847.31	3866.61	3915.92	3956.51	3969.34	3904.3

Source: Gerbaulet and Lorenz (2017).

Table 9 shows the yearly electricity demand per region in TWh. The electricity demand profile for each time slice and region can be found in the supplementary material.

3.3.2 Low-temperature heat

The low-temperature heat demand values are fundamentally being reworked compared to GENeSYS-MOD v1.0. While in earlier iterations the data was extrapolated for the different time slices, weather data was used in order to calculate them for the present work.

It is assumed that houses will be heated if the indoor temperature drops below 21°C during the day and below 18°C during the night. In addition, it is assumed that indoor temperature is three degree Celsius higher than the outside temperature. As a result, given hourly weather data, we can calculate the total heat demand for a region. Subsequently, we can divide the total demand into the different time slices, allowing for a much more accurate way of assessing low-temperature heat demand.

Most of the weather data for the different regions comes from Weather Underground (The Weather Company 2018) which state that the data is obtained from weather stations across the world. The only exception is Germany, where the *Deutscher Wetterdienst* (DWD 2017) provides hourly data. Since the other data only reports daily maximum, minimum and average temperatures, a weather profile was applied for each region. This profile serves as a temperature distribution which allows an extrapolation of temperatures for each hour of each day. The profiles for Spain, Czech Republic and Sweden were taken from Weatherspark (Cedar Lake Ventures, Inc 2017), for all other countries one of these three profiles was taken, depending on geographical similarity. Finally, these hourly values are aggregated into the different time slices.

Low-temperature heat demand only changes slightly over the course of the model period, with a decreasing trend: The most notable reason for this being efficiency improvements in the building sector. In addition to the domestic spatial heating demand which was calculated as described above, industrial low-temperature heat has to be considered as well. Low-temperature heat of below 100° Celsius is needed across many industrial sectors, most prominently in the sectors food, machinery, and wood (see figure 7). Low-temperature process heat demands have been adapted from Naegler et al. (2015).

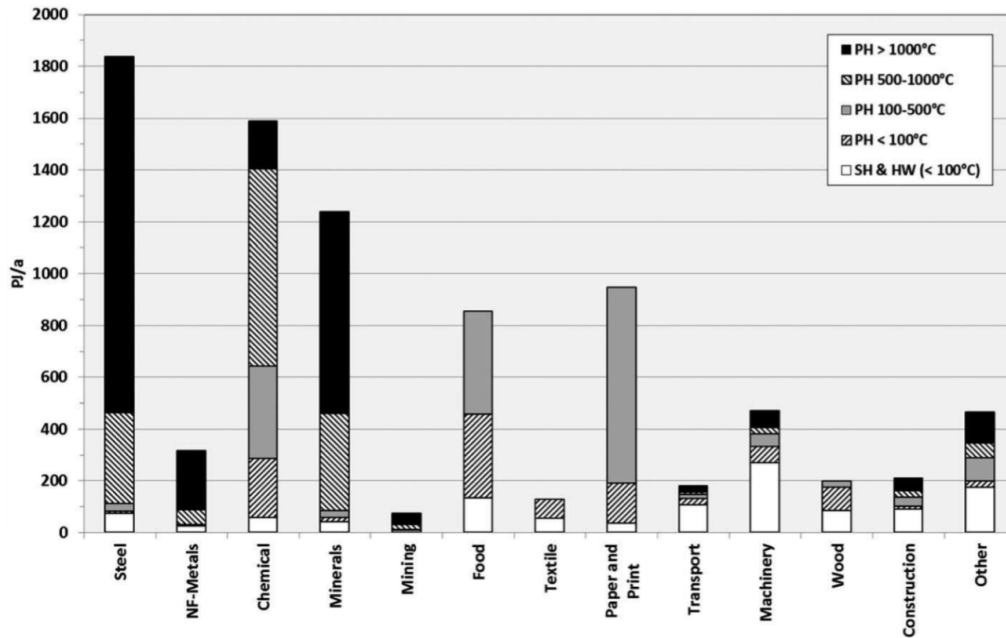


Figure 7: Distribution of process heat demand across all industry branches, distinguished by temperature level.

Source: Naegler et al. (2015).

Table 10 shows the total combined heating demand per region, based on hourly temperature and industrial demands, while Table 11 illustrates the different profiles for the three base regions.

Table 10: Yearly low-temperature heat demand per region in PJ.

	2015	2020	2025	2030	2035	2040	2045	2050
Austria	346.00	326.45	309.67	292.92	280.26	266.42	259.50	254.31
Balkan States	287.00	289.87	291.79	294.35	296.76	299.92	301.06	301.35
Baltic States	185.00	174.55	165.58	156.62	149.85	142.45	138.75	135.98
Belgium & Luxembourg	503.00	474.58	450.19	425.84	407.43	387.31	377.25	369.71
Czech Republic	342.80	323.43	306.81	290.21	277.67	263.96	257.10	251.96
Denmark	231.50	218.42	207.19	195.99	187.52	178.26	173.63	170.15
Europe East	714.00	721.14	725.92	732.28	738.28	746.13	748.99	749.70
France	2106.40	1987.39	1885.23	1783.28	1706.18	1621.93	1579.80	1548.20
Germany	3250.80	3067.13	2909.47	2752.13	2633.15	2503.12	2438.10	2389.34
Great Britain	2084.70	1966.91	1865.81	1764.91	1688.61	1605.22	1563.53	1532.25
Greece	165.00	166.65	167.76	169.22	170.61	172.43	173.09	173.25
Italy	1552.40	1464.69	1389.40	1314.26	1257.44	1195.35	1164.30	1141.01
Netherlands	729.10	687.91	652.54	617.26	590.57	561.41	546.83	535.89
Poland	924.50	872.27	827.43	782.68	748.85	711.87	693.38	679.51
Portugal & Spain	939.30	886.23	840.67	795.21	760.83	723.26	704.48	690.39
Scandinavia	1093.30	1031.53	978.50	925.59	885.57	841.84	819.98	803.58
Switzerland	278.60	262.86	249.35	235.86	225.67	214.52	208.95	204.77
Total	15733.40	14922.01	14223.31	13528.61	13005.25	12435.40	12148.72	11931.35

Source: Naegler et al. (2015), SFOE (2015), and Persson and Werner (2015).

Table 11: Share of total heat demand per season and region.

Share of demand [in %]	Q1	Q2	Q3	Q4
Czech Republic	45.4	13.3	3.1	38.2
Spain	48.6	16.5	1.2	33.7
Sweden	45.2	16.7	4.7	33.4

Source: Own calculations, based on Cedar Lake Ventures, Inc (2017), DWD (2017), and The Weather Company (2018).

3.3.3 High-temperature heat

The data for high-temperature heat demands comes mostly from Naegler et al. (2015), except for the countries Norway and Switzerland. Values for these countries have been taken from the Organisation for Economic Co-operation and Development (OECD) World Energy Balances (IEA 2016a) and the report "Energy Consumption in Switzerland 2014" (SFOE 2015). The resulting values can be found in table 12.

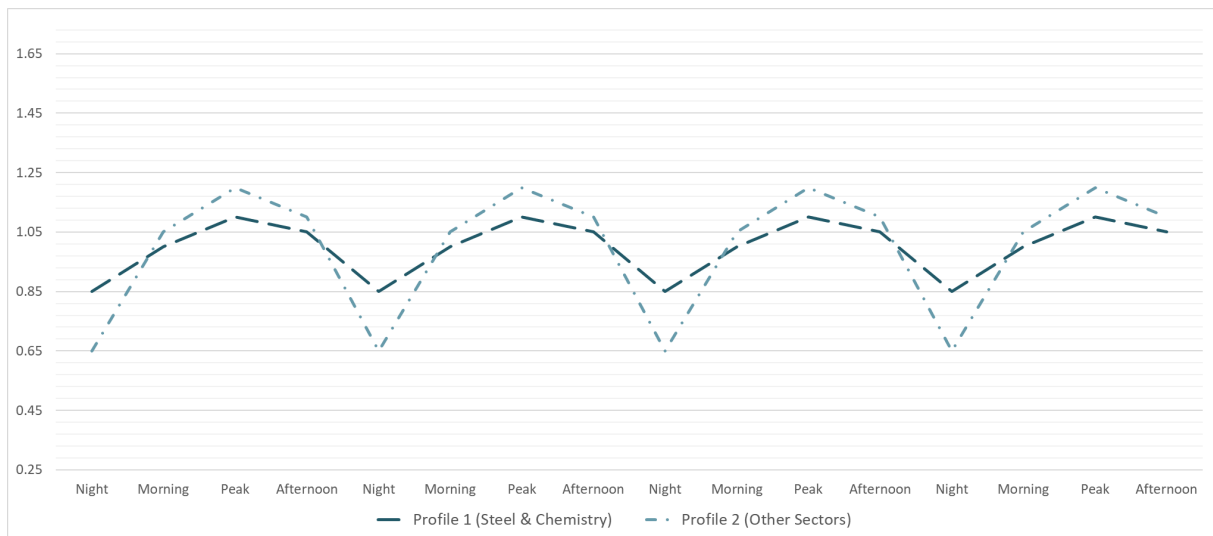
Table 12: Yearly high-temperature heat demand per region in PJ.

	2015	2020	2025	2030	2035	2040	2045	2050
Austria	173.20	167.48	157.79	148.09	139.20	130.25	121.60	113.00
Balkan States	75.00	75.75	76.25	76.92	77.55	78.38	78.68	78.75
Baltic States	49.70	48.06	45.28	42.49	39.94	37.37	34.89	32.42
Belgium & Luxembourg	298.40	288.55	271.84	255.13	239.82	224.40	209.51	194.68
Czech Republic	172.20	166.52	156.87	147.23	138.40	129.49	120.90	112.34
Denmark	44.00	42.55	40.08	37.62	35.36	33.09	30.89	28.71
Europe East	295.00	297.95	299.93	302.55	305.03	308.28	309.46	309.75
France	638.60	617.53	581.76	546.00	513.24	480.23	448.36	416.62
Germany	1316.70	1273.25	1199.51	1125.78	1058.23	990.16	924.46	859.02
Great Britain	555.10	536.78	505.70	474.61	446.13	417.44	389.74	362.15
Greece	142.00	143.42	144.37	145.64	146.83	148.39	148.96	149.10
Italy	673.80	651.56	613.83	576.10	541.53	506.70	473.07	439.59
Netherlands	282.50	273.18	257.36	241.54	227.05	212.44	198.34	184.30
Poland	332.90	321.91	303.27	284.63	267.55	250.34	233.73	217.18
Portugal & Spain	584.60	565.31	532.57	499.83	469.84	439.62	410.45	381.39
Scandinavia	538.60	520.83	490.66	460.50	432.87	405.03	378.15	351.38
Switzerland	92.60	89.54	84.36	79.17	74.42	69.64	65.01	60.41
Total	6264.90	6080.17	5761.43	5443.83	5152.99	4861.25	4576.20	4290.79

Source: Naegler et al. (2015), IEA (2016b), and SFOE (2015).

Finding a reliable source for regional industrial heat demand profiles proved to be a difficult task. Since actual hourly (or even daily) demand profiles were not available, an assessment for each country had to be made.

Two theoretical load profiles were generated: one for the steel & chemistry sectors, which usually observe a rather constant demand curve, and one for the other industrial sectors, which are more time-dependent. Then, country-specific shares of steel and chemistry industries (based on Naegler et al. (2015)) have been taken to obtain a weighted average of these two profiles, specifically tailored to each country.

**Figure 8: Daily heat demand profile.**

Source: Own illustration.

The two base profiles, as well as the country-specific loads, can be seen in Figure 8. The actual values for each time slice and each country can be found in the supplementary material.

3.3.4 Transport

The yearly transport demands for both passenger and freight transportation services have been taken from Eurostat (2017a, 2017b). Also, the modal split for the different transportation options (e.g., rail, road, and waterways for freight transport) has been adapted from the same data, taking the shares of the year 2015 for each method of transportation. The resulting yearly demands for transportation services can be found in table 13.

Table 13: Yearly transport demand per region.

	2015	2020	2025	2030	2035	2040	2045	2050
Passenger Transport [in gpkm]								
Austria	107.90	114.14	119.63	124.44	129.35	134.43	139.01	142.89
Balkan States	195.10	205.59	218.10	229.03	238.55	248.51	255.90	262.40
Baltic States	52.60	55.46	57.62	60.09	62.74	65.30	67.33	68.93
Belgium & Luxembourg	142.60	149.47	155.50	161.37	166.43	172.79	177.81	182.96
Czech Republic	103.90	114.41	123.78	133.79	142.85	151.45	160.35	168.70
Denmark	70.20	75.76	79.75	83.78	86.58	89.36	92.32	95.23
Europe East	301.20	334.37	362.72	388.63	416.08	443.00	466.46	490.89
France	899.80	962.55	1001.00	1043.07	1082.11	1126.17	1153.84	1184.10
Germany	1101.60	1120.07	1151.13	1181.44	1201.85	1227.23	1249.35	1268.76
Great Britain	778.00	827.54	862.92	906.38	936.46	972.69	1006.22	1035.29
Greece	122.40	128.60	132.53	137.84	144.30	149.71	154.53	158.91
Italy	841.40	886.90	915.25	948.93	977.09	985.73	1029.88	1045.93
Netherlands	162.60	170.44	177.31	184.01	189.77	197.02	202.75	208.62
Poland	259.60	295.97	324.25	352.82	376.61	397.89	414.66	427.67
Portugal & Spain	492.90	534.01	580.39	625.35	672.69	712.61	740.14	779.91
Scandinavia	288.60	311.46	327.84	344.42	355.95	367.37	379.54	391.48
Switzerland	118.50	125.35	131.38	136.66	142.05	147.64	152.67	156.93
Total	6038.90	6412.09	6721.10	7042.05	7321.46	7588.90	7842.76	8069.60
Freight Transport [in gtkm]								
Austria	46.50	49.62	53.01	56.43	60.06	63.14	65.34	67.30
Balkan States	91.50	104.26	114.62	122.09	130.33	138.81	145.73	151.55
Baltic States	83.50	96.55	107.06	117.35	126.32	135.06	142.91	149.81
Belgium & Luxembourg	58.70	63.94	67.77	70.67	72.76	75.52	77.28	78.87
Czech Republic	72.50	79.18	85.52	92.18	98.36	104.40	110.14	115.52
Denmark	17.80	20.41	22.01	23.25	24.64	26.00	27.17	28.37
Europe East	158.80	172.99	190.19	206.93	221.34	233.69	244.02	256.09
France	196.30	223.58	247.21	274.39	288.90	304.23	314.46	324.10
Germany	486.80	535.88	569.15	602.32	620.66	640.38	654.36	662.02
Great Britain	181.10	188.88	197.26	206.08	215.11	223.69	231.68	238.69
Greece	20.10	21.16	21.92	22.70	23.62	24.50	25.19	25.84
Italy	137.70	147.24	155.59	164.21	171.28	176.19	183.69	188.23
Netherlands	124.00	135.07	143.15	149.29	153.70	159.53	163.26	166.62
Poland	311.40	352.69	400.26	443.58	477.73	508.51	529.88	542.99
Portugal & Spain	255.00	275.80	295.76	314.63	332.62	349.39	359.94	373.49
Scandinavia	121.80	139.68	150.62	159.10	168.58	177.94	185.93	194.11
Switzerland	24.90	26.57	28.38	30.22	32.16	33.81	34.99	36.04
Total	2388.40	2633.50	2849.48	3055.42	3218.17	3374.79	3495.97	3599.64

Source: Eurostat (2017a, 2017b).

Freight transport demand is assumed to be evenly distributed across all time slices and thus is given as an *AccumulatedAnnualDemand*. This means that the model can choose freely when to satisfy said demand

and can optimize capacities accordingly. Passenger transport, on the other hand, is strongly dependent on the time of day, usually with peaks in the morning and afternoon hours.

A study by Gruschwitz and Follmer (2013) has been consulted for the intra-daily demand shares for passenger transport. Figure 9 shows the relative demand in each hour of the day.

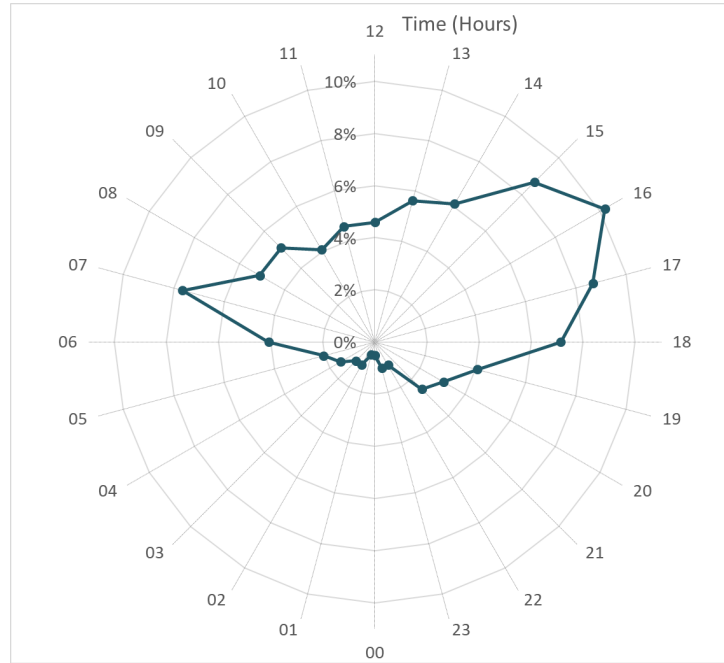


Figure 9: Daily passenger transportation demand profile.

Source: Own illustration, based on Gruschwitz and Follmer (2013).

This leads to the demand shares for each time slice (*SpecifiedDemandProfile*), shown in table 14.

Table 14: Demand profile for passenger transport in Europe in each time slice.

Share of Demand [in %]	Q1	Q2	Q3	Q4	Total
Morning	3.97	5.56	3.70	6.35	19.58
Peak	4.76	9.13	8.47	3.84	26.19
Afternoon	7.54	8.20	10.19	2.91	28.84
Night	8.73	2.12	2.65	11.90	25.40
Total	25.00	25.00	25.00	25.00	100.00

Source: Own assumptions, based on Gruschwitz and Follmer (2013).

3.4 Fossil fuel prices and availability

The prices for fossil fuels in the second version of GENeSYS-MOD have been split up into local and global prices. These global prices are tied to the global market price of each fuel and have been updated from the 2015 version of the World Energy Outlook of the International Energy Agency (IEA) to the 2016 version (IEA 2016b). This means a drastic reduction in the price forecast, especially for oil (where the difference results in an almost halved future oil price compared to the forecast from 2015 (IEA 2015)). The resulting global prices for fossil energy carriers can be found in table 15.

Table 15: Global prices of fossil energy carriers in M€/PJ.

	2015	2020	2025	2030	2035	2040	2045	2050
Crude Oil	7.12	10.18	11.02	11.86	11.37	10.88	10.39	9.91
Hard Coal	1.52	1.54	1.53	1.52	1.44	1.36	1.28	1.20
Natural Gas	6.63	6.54	7.72	8.91	9.15	9.38	9.62	9.86

Source: IEA (2016b, p. 45)¹³.

Because of the regionally dependent availability and usage of lignite, local prices have been applied, where available.¹⁴ For hard coal, natural gas, and crude oil, it has been assumed that local production is 5% cheaper than the global market price.¹⁵ The regional values for lignite can be found in table 16.

Table 16: Local prices of lignite in M€/PJ.

	2015	2020	2025	2030	2035	2040	2045	2050
Balkan States	1.68	1.71	1.72	1.72	1.63	1.46	1.23	0.97
Czech Republic	0.73	0.74	0.75	0.75	0.71	0.63	0.53	0.43
Europe East	1.68	1.71	1.72	1.72	1.63	1.46	1.23	0.97
Germany	1.09	1.11	1.12	1.12	1.06	0.95	0.8	0.63
Greece	1.68	1.71	1.72	1.72	1.63	1.46	1.23	0.97
Poland	1.19	1.21	1.22	1.22	1.16	1.04	0.87	0.69
Portugal & Spain	1.17	1.19	1.20	1.20	1.14	1.02	0.86	0.68

Source: Booz & Company (2014).

The availability of fossil fuel reserves has been adapted from BP (2017) and is shown for each region in table 17.

¹³The prices for 2045 and 2050 were calculated by using a linear trend from the previous years.

¹⁴The value for Portugal & Spain is the average of the other values, since no reliable source for a specific value was found.

¹⁵Only countries that currently mine hard coal are assumed to have this price advantage. Countries that have reserves, but do not currently mine hard coal, have their price increased by 5% compared to the market price to avoid the unrealistic domestic production in such cases.

Table 17: Fossil fuel reserves per region in PJ.

	Crude Oil	Hard Coal	Lignite	Natural Gas
Balkan States	0	25	219240	0
Czech Republic	0	31987	38595	0
Europe East	3441	8323	43695	3768
Denmark	2294	0	0	0
Germany	0	348	543000	0
Great Britain	0	2030	0	7536
Greece	0	0	4350	0
Italy	2867	0	0	0
Netherlands	0	0	0	26376
Poland	0	542300	81915	3768
Portugal & Spain	0	25172	4785	0
Scandinavia	43593	0	0	67826

Source: BP (2017).

3.5 Biomass potential

Table 18: Yearly available biomass in PJ.

	2015	2020	2025	2030	2035	2040	2045	2050
Austria	152.80	169.40	161.17	152.94	147.18	141.43	137.39	133.36
Balkan States	225.61	243.04	249.70	256.36	261.02	265.68	268.94	272.20
Baltic States	123.34	140.47	144.24	148.00	150.64	153.28	155.13	156.97
Belgium & Luxembourg	95.31	99.02	98.60	98.18	97.89	97.59	97.39	97.18
Czech Republic	144.38	151.56	154.91	158.26	160.61	162.95	164.59	166.23
Denmark	71.85	87.92	85.52	83.11	81.42	79.74	78.56	77.38
Europe East	439.57	543.24	548.83	554.42	558.33	562.24	564.98	567.72
France	663.44	828.48	801.77	775.06	756.36	737.66	724.58	711.49
Germany	716.88	810.98	769.60	728.21	699.24	670.27	649.99	629.71
Great Britain	456.11	482.28	477.32	472.35	468.88	465.41	462.98	460.55
Greece	96.15	93.91	103.90	113.88	120.87	127.86	132.75	137.65
Italy	359.44	388.62	369.42	350.23	336.79	323.35	313.94	304.54
Netherlands	63.03	68.04	64.18	60.33	57.64	54.94	53.05	51.16
Poland	376.06	461.76	428.79	395.82	372.74	349.66	333.50	317.35
Portugal & Spain	595.26	644.56	623.48	602.40	587.64	572.88	562.55	552.23
Scandinavia	755.71	923.04	815.62	708.21	633.01	557.82	505.19	452.55
Switzerland	152.80	169.40	161.17	152.94	147.18	141.43	137.39	133.36
Total	5487.74	6305.71	6058.21	5810.70	5637.45	5464.19	5342.91	5221.63

Source: Elbersen et al. (2012).

3.6 Residual capacities

Residual capacities for 2015 for the power production of all European countries have been taken from Farfan and Breyer (2017). The future capacities were then projected based on the construction years and the respective *OperationalLife*. For the heating sector, capacities described by Fraunhofer ISI et al. (2016) were considered. The residual capacities for all modeled regions for the power sector can be found in table

Table 19: Residual power generation capacities in GW.

	2015	2020	2025	2030	2035	2040	2045	2050
Austria								
Biomass	0.52	0.48	0.48	0.45	0.21			
Hard Coal	0.41							
Large-Scale Hydro	4.60	4.60	4.57	4.33	4.09	3.79	3.36	3.07
Natural Gas	4.57	4.57	4.57	4.00	2.06	0.85		
Oil	0.04	0.04	0.02					
Onshore Wind	1.90	1.83	1.10	0.84				
Pumped Hydro Storage	3.80	3.80	3.60	3.60	3.48	3.18	3.18	3.18
PV (Utility-Scale)	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
Small-Scale Hydro	5.41	5.41	5.19	5.02	4.91	4.55	3.93	3.45
Balkan States								
Biomass	0.12	0.12	0.12	0.11	0.11	0.07		
Large-Scale Hydro	6.80	6.80	6.80	4.00	6.34	5.40	4.49	3.00
Lignite	15.94	9.56	5.74	2.87	1.43	0.57	0.23	
Natural Gas	0.29	0.29	0.29	0.29				
Nuclear	2.00	2.00	2.00	2.00	1.00	1.00		
Oil	0.37	0.37	0.32	0.10	0.10			
Onshore Wind	1.10	1.10	1.09	0.43				
Pumped Hydro Storage	2.91	2.91	2.91	2.31	2.91	2.90	2.90	2.30
PV (Utility-Scale)	1.36	1.36	1.36	1.32	1.06	1.06	1.06	1.06
Small-Scale Hydro	3.21	3.21	3.18	2.38	3.07	2.82	2.50	1.77
Baltic States								
Biomass	0.05	0.04	0.03	0.02	0.02	0.02	0.01	
Large-Scale Hydro	0.07	0.07	0.07	0.07	0.07			
Natural Gas	2.15	1.72	1.38	1.10	0.88	0.71	0.56	
Oil	3.49	2.79	2.23	1.79	1.43	1.14	0.91	
Onshore Wind	0.26	0.21	0.17	0.13	0.11	0.08	0.07	
Pumped Hydro Storage	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
PV (Utility-Scale)	0.08	0.08	0.08	0.08	0.01	0.01	0.01	0.01
Small-Scale Hydro	1.12	1.12	1.12	1.12	1.12	1.09	0.19	0.19
Belgium & Luxembourg								
Biomass	1.27	1.27	1.27	1.24	1.10	0.43		
Large-Scale Hydro	0.07	0.07	0.07	0.07	0.05	0.05	0.05	0.04
Natural Gas	6.03	6.03	5.05	3.41	2.25	0.98		
Nuclear	5.93	5.93	4.53	4.53	0.43	0.43	0.43	0.22
Offshore Wind	0.54	0.54	0.54	0.43	0.35	0.28	0.22	0.18
Oil	0.11	0.08	0.06	0.02				
Onshore Wind	2.05	2.03	1.84	1.01				
Pumped Hydro Storage	2.60	2.60	2.60	2.60	2.60	2.60	1.70	1.23
PV (Utility-Scale)	3.35	3.35	3.35	3.32	3.12	3.12	3.12	3.12
Small-Scale Hydro	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02

Table 18: Residual power generation capacities in GW (cont.).

	2015	2020	2025	2030	2035	2040	2045	2050
Czech Republic								
Biomass	0.45	0.45	0.45	0.41	0.31	0.09		
Hard Coal	0.24	0.24	0.23	0.04	0.04	0.03		
Large-Scale Hydro	0.82	0.82	0.82	0.79	0.64	0.51	0.13	0.13
Lignite	2.12	2.12	2.08	0.37	0.34	0.29		
Natural Gas	1.30	1.30	1.30	1.00	1.00	0.91		
Nuclear	3.88	3.88	3.88	3.88	3.42	2.01	2.01	2.01
Onshore Wind	0.28	0.28	0.26	0.07				
Pumped Hydro Storage	1.18	1.18	1.13	1.13	1.13	1.13	1.13	1.13
PV (Utility-Scale)	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17
Small-Scale Hydro	0.17	0.17	0.14	0.13	0.12	0.11	0.07	0.07
Denmark								
Biomass	1.39	1.37	1.24	1.09	0.83	0.18		
Hard Coal	1.29	1.04	0.65	0.24	0.24			
Natural Gas	2.46	2.46	2.28	1.45	0.33			
Offshore Wind	1.27	1.67	2.27	2.27	1.82	1.45	1.16	0.93
Oil	0.05	0.04	0.04	0.04	0.02			
Onshore Wind	4.78	3.00	2.09	1.30				
PV (Utility-Scale)	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Europe East								
Biomass	1.07	1.07	1.07	1.01	0.92	0.58		
Hard Coal	0.47	0.22	0.19	0.17	0.16			
Large-Scale Hydro	6.82	6.82	6.82	6.80	6.68	6.25	6.02	5.67
Lignite	2.00	0.92	0.81	0.72	0.69			
Natural Gas	5.15	5.00	4.78	4.22	3.10	2.05		
Nuclear	3.15	3.15	3.15	3.15	2.21	2.21	2.21	0.68
Oil	0.41	0.41	0.41					
Onshore Wind	4.12	4.12	4.09	3.38				
Pumped Hydro Storage	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
PV (Utility-Scale)	1.83	1.83	1.83	1.68				
Small-Scale Hydro	2.14	2.14	2.14	2.13	2.09	2.04	1.94	1.89
France								
Biomass	1.06	1.03	0.91	0.76	0.61	0.43		
Geothermal	0.02	0.02	0.02	0.01	0.01	0.01		
Hard Coal	0.13	0.13	0.13	0.13				
Large-Scale Hydro	10.29	10.29	9.85	9.14	7.45	6.16	4.42	3.42
Natural Gas	10.17	10.14	10.13	9.71	7.94	2.55		
Nuclear	63.13	63.13	63.13	53.25	31.51	12.54	5.99	2.99
Oil	0.91	0.88	0.80	0.51	0.51	0.10		
Onshore Wind	9.16	9.10	8.39	3.14				
Pumped Hydro Storage	6.94	6.94	6.94	6.94	6.16	5.45	5.41	5.35
PV (Utility-Scale)	5.62	5.62	5.62	4.57				
Small-Scale Hydro	5.17	5.17	5.00	4.57	3.66	3.13	2.55	1.58
Tidal & Wave	0.24	0.24	0.24	0.24	0.24	0.24	0.24	

Table 18: Residual power generation capacities in GW (cont.).

	2015	2020	2025	2030	2035	2040	2045	2050
Germany								
Biomass	7.17	6.09	5.02	3.94	2.15	1.08		
Geothermal	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.04
Hard Coal	28.65	24.35	20.06	15.76	8.60	4.30		
Large-Scale Hydro	1.68	1.68	1.67	1.67	1.61	1.58	1.55	1.53
Lignite	21.42	18.21	14.99	11.78	6.43	3.21		
Natural Gas	28.36	24.11	20.49	16.87	13.26	7.23	3.62	
Nuclear	10.80	10.80	10.80	10.80	5.46			
Offshore Wind	2.91	5.36	5.36	5.36	4.29	3.43	2.74	2.19
Oil	4.40	3.74	3.08	2.42	1.32	0.66		
Onshore Wind	41.30	41.30	41.30	33.04	26.43	21.15	16.92	
Pumped Hydro Storage	4.46	4.46	4.17	4.02	3.92	3.59	2.96	2.52
PV (Utility-Scale)	39.22	39.22	39.22	31.38	25.10	20.08	16.06	
Small-Scale Hydro	2.50	2.50	2.31	2.29	2.05	1.84	1.55	1.34
Great Britain								
Biomass	3.66	3.58	3.44	3.13	2.94	2.59		
Hard Coal	2.88	0.29	0.29	0.12	0.02	0.01		
Large-Scale Hydro	1.37	1.37	1.37	1.11	0.92	0.73	0.21	0.21
Natural Gas	40.71	40.56	33.50	19.91	13.55	5.39		
Nuclear	9.23	9.23	8.74	6.98	6.46	1.19		
Offshore Wind	3.04	5.35	5.35	5.35	4.28	3.42	2.74	2.19
Oil	0.80	0.78	0.66	0.48	0.27			
Onshore Wind	15.25	14.92	13.54	8.56				
Pumped Hydro Storage	2.73	2.73	2.73	2.73	2.69	2.68	2.32	2.32
PV (Utility-Scale)	5.26	5.26	5.26	5.21				
Small-Scale Hydro	0.53	0.53	0.53	0.45	0.36	0.29	0.05	0.05
Tidal & Wave	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Greece								
Biomass	0.05	0.05	0.05	0.04	0.01			
Large-Scale Hydro	2.24	2.24	2.24	2.24	2.15	2.06	2.06	1.52
Lignite	2.21	1.30	0.70	0.33				
Natural Gas	5.38	5.38	5.38	4.81	3.76	1.73		
Oil	0.88	0.83	0.72	0.40	0.21	0.03		
Onshore Wind	1.77	1.60	1.28	0.56				
Pumped Hydro Storage	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
PV (Utility-Scale)	2.59	2.59	2.59	2.38				
Small-Scale Hydro	1.04	1.04	1.04	1.04	0.99	0.95	0.95	0.70
Italy								
Biomass	2.68	2.66	2.62	2.46	1.88	0.89		
Concentrated Solar Power	0.01	0.01	0.01	0.01	0.01			
Geothermal	0.81	0.81	0.81	0.75	0.54	0.37	0.12	0.08
Hard Coal	7.89	7.58	1.64	1.64	1.29			
Large-Scale Hydro	7.16	7.16	6.88	5.73	4.82	3.20	2.63	2.40
Lignite	0.16	0.15	0.03	0.03	0.03			
Natural Gas	46.03	45.55	42.86	36.98	19.33	2.55		
Oil	4.57	3.83	2.90	0.95				
Onshore Wind	8.83	8.46	7.16	2.96				
Pumped Hydro Storage	7.54	7.54	7.54	7.54	7.54	7.54	6.91	6.87
PV (Utility-Scale)	18.33	18.33	18.33	14.84				
Small-Scale Hydro	3.81	3.81	3.57	2.98	2.50	1.69	1.36	1.24

Table 18: Residual power generation capacities in GW (cont.).

	2015	2020	2025	2030	2035	2040	2045	2050
Netherlands								
Biomass	1.06	1.04	0.91	0.73	0.72	0.15		
Hard Coal	4.60	2.71	1.48	1.48	1.48	1.48		
Large-Scale Hydro	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02
Natural Gas	16.78	15.18	12.97	9.39	8.36	4.73		
Nuclear	0.48	0.48						
Offshore Wind	0.37	0.97	1.29	1.29	1.04	0.83	0.66	0.53
Oil	0.12	0.12	0.12					
Onshore Wind	2.75	2.57	1.77	0.73				
PV (Utility-Scale)	1.05	1.05	1.04	0.96				
Small-Scale Hydro	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Poland								
Biomass	1.08	1.08	1.08	1.08	1.01	0.74		
Hard Coal	20.70	16.56	13.25	10.60	8.48	6.78		
Large-Scale Hydro	0.37	0.37	0.31	0.31	0.31	0.25	0.22	0.09
Lignite	8.80	7.04	5.63	4.51	3.60	2.88		
Natural Gas	0.76	0.60	0.48	0.39	0.31	0.25		
Oil	0.53	0.42	0.34	0.27	0.22	0.17		
Onshore Wind	3.79	3.78	3.72	2.43				
Pumped Hydro Storage	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.50
PV (Utility-Scale)	0.03	0.03	0.03	0.03				
Small-Scale Hydro	0.17	0.17	0.17	0.17	0.16	0.13	0.10	0.04
Portugal & Spain								
Biomass	1.66	1.54	1.48	1.17	0.55	0.21		
Concentrated Solar Power	2.35	2.35	2.35	2.35	2.35	1.72		
Geothermal	0.03	0.03	0.03	0.03	0.02	0.02	0.02	
Hard Coal	2.66	1.76	1.09					
Large-Scale Hydro	17.04	17.04	16.95	16.62	15.27	14.14	11.65	7.60
Lignite	0.14	0.09	0.06					
Natural Gas	37.49	37.19	36.24	32.82	20.87	3.44		
Nuclear	7.12	7.12	7.12	7.12	3.05			
Oil	3.22	3.06	2.78	1.84	0.63	0.26		
Onshore Wind	27.62	25.27	16.06	3.31				
Pumped Hydro Storage	6.01	6.01	6.01	6.01	6.01	5.64	5.22	5.14
PV (Utility-Scale)	5.61	5.61	5.59	1.70				
Small-Scale Hydro	4.77	4.77	4.74	4.65	4.03	3.63	2.89	2.61
Scandinavia								
Biomass	4.88	4.48	3.99	3.33	2.22	0.76		
Hard Coal	3.77	3.02	2.41	1.93	1.54	1.24	0.99	
Large-Scale Hydro	32.15	32.15	32.15	32.15	32.15	32.15	32.15	32.15
Natural Gas	5.33	4.26	3.41	2.73	2.18	1.75	1.40	
Nuclear	10.85	8.05	6.01	3.72	2.32	1.17		
Offshore Wind	0.21	0.21	0.21	0.17	0.14	0.11	0.09	0.07
Oil	4.33	1.35	1.35	1.34	1.34	1.10	0.42	0.32
Onshore Wind	7.06	6.83	6.28	4.43				
Pumped Hydro Storage	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
PV (Utility-Scale)	0.50	0.10	0.10	0.08				
Small-Scale Hydro	14.74	14.74	14.74	14.74	14.74	14.74	14.74	14.74

Table 18: Residual power generation capacities in GW (cont.).

	2015	2020	2025	2030	2035	2040	2045	2050
Switzerland								
Biomass	0.45	0.44	0.39	0.33	0.22	0.08		
Large-Scale Hydro	7.50	7.50	7.33	6.90	6.15	5.17	3.53	2.96
Natural Gas	0.28	0.18	0.18	0.15	0.12	0.06		
Nuclear	3.33	2.97	2.23	1.22				
Oil	0.01	0.01	0.01	0.01	0.01	0.01		
Onshore Wind	0.07	0.07	0.06	0.04				
Pumped Hydro Storage	3.22	3.22	3.21	3.21	2.70	2.55	2.04	1.34
PV (Utility-Scale)	1.05	1.05	1.05	0.96				
Small-Scale Hydro	3.31	3.31	3.20	2.99	2.58	2.32	1.67	1.27

Source: Ram et al. (2017) and Gerbaulet and Lorenz (2017).

3.7 Including political boundaries

As mentioned in the previous section, future planned developments of the European energy system need to be taken into account when analyzing pathways over such a long period. Currently, multiple countries are already tackling the transformation towards a low-carbon energy system. Mostly, these countries introduced regulatory and political frameworks that prohibit them from building new conventional power plants (or at least certain types of them). Furthermore, several power plants already have fixed phase-out plans, especially nuclear ones. Even the use of coal, which is currently the world-wide dominating fuel for power generation, will be abolished in some countries (IEA 2017).

In order to prevent the model to add capacities despite a country already having declared its fossil fuel phase-out, bounds representing these political decisions have been implemented. The bounds listed in table 20 have been included in the model and thus represent fixed phase-out constraints. Only actually passed laws and policy instruments are included in these bounds.

Table 20: Considered political boundaries.

Region	Coal	Nuclear
Austria	No power production by coal from the year 2030 on.	No power production by nuclear energy.
Baltic States	No power production by coal.	–
Belgium & Luxembourg	No power production by coal from the year 2020 on.	No power production by nuclear energy from the year 2030 on.
Czech Republic	–	–
Denmark	–	–
France	No power production by coal from the year 2025 on.	–
Germany	No domestic production of hard coal from the year 2020 on; imports are still allowed.	No power production by nuclear energy from the year 2020 on.
Great Britain	No power production by coal from the year 2030 on.	–
Italy	No power production by coal from the year 2030 on.	–
Netherlands	No power production by coal from the year 2035 on.	–
Poland	–	–
Portugal & Spain	No domestic production of lignite from the year 2020 on.	–
Scandinavia	No power production by coal from the year 2035 on.	–
South-East Europe	–	–
Switzerland	No power production by coal.	No new capacities of nuclear power plants.

Source: Bundeskanzleramt (1999), Radiation Truth (2017), Appunn (2018), HM Government (2017), EUROCOAL (2017), and <https://beyond-coal.eu/>.

3.8 Trade

As mentioned in section 2, the trade system of GENeSYS-MOD has been expanded significantly, especially when it comes to power trade. This section therefore describes the accompanying data requirements and chosen inputs for the European energy system.

3.8.1 Power trade & grid data

The available capacities for the trade of electricity, as well as grid data for 2015 are adopted from Gerbaulet and Lorenz (2017) and are illustrated in table 21. For the following model periods, the model can add up to 20% additional capacities per 5-year-period.

Table 21: Power trade capacity between regions in GW.

	AT	Balk	Balt	BeLu	CH	CZ	DE	DK	East	FR	GB	GR	Iber	IT	NL	PL	Scan
AT	–	0.95			0.47	0.6	4.9		0.75					1.82			
Balk	0.95	–							1.6			1.05		0.66			
Balt			–													0.5	0.7
BeLu				–			1			2.3	1				3.65		
CH	0.47				–		3.5			1.1				4.965			
CZ	0.6					–	2.025		2.2							0.1	
DE	4.9				1	3.5	2.025	–	1.95	3.2					4.25	0.85	2
DK							1.95	–									3.39
East	0.75	1.6				2.2			–							0.6	
FR				2.3	1.1		3.2			–	4		4.4	2.575			
GB				1						4	–						
GR		1.05										–		0.5			
Iber										4.4			–				
IT	1.82	0.66			4.965					2.575		0.5		–			
NL				3.65			4.25								–		0.7
PL			0.5			0.1	0.85		0.6							–	0.6
Scan			0.7				2	3.39							0.7	0.6	–

Source: Gerbaulet and Lorenz (2017).

3.8.2 Reserve margin

The modifications made to the implementation of the calculation of the reserve margin (described in section 2.3.5) require a change of the underlying parameter values. *Fuels* and *Technologies* are tagged to indicate whether they need a reserve margin, or can contribute to the reserves, respectively.¹⁶ The parameter *ReserveMargin* then sets the required relative amount of energy that has to come out of flexible supply technologies.

For this model set-up, only the *Fuel* 'Power' requires this form of load balancing. Technologies that are able to fulfill these flexibility requirements are gas- and oil-based power plants, batteries, and pumped hydro storages, as well as fuel cells.

The development of the required amount of electricity provided by *ReserveMargin* technologies is shown in table 22. ENTSO-E (2013) suggests a *ReserveMargin* between 5 and 10% on a country level, acknowledging that high shares of variable renewables might require higher percentages of additional capacity. Hence, our assumed values increase at the beginning to reflect that development. Simultaneously, it is mentioned that a high degree of interconnection between different regions lowers the need for such measures. Therefore, we opted to reduce the necessary reserve margin for the later model periods.

Table 22: Share of required energy production by *ReserveMargin* technologies [in %].

	2015	2020	2025	2030	2035	2040	2045	2050
	9	10.5	11	11.5	11	10	8.5	7

Source: ENTSO-E (2013) for 2015, following years based on own assumptions.

¹⁶The functionality of these tags has not been changed from the original OSeMOSYS version and is documented in Howells et al. (2011).

3.8.3 Trade of energy carriers

The costs for the trade of different energy carriers is shown in table 23, given in M€per PJ.

Table 23: Trade costs for energy carriers between regions in M€/PJ.

	AT	Balk	Balt	BeLu	CZ	DK	East	FR	DE	GB	GR	IT	NL	PL	Iber	Scan	CH
Hard Coal																	
AT	–				0.42		0.42		0.44			0.45					0.44
Balk		–					0.43				0.44	0.44					
Balt			–											0.44		0.43	
BeLu				–				0.43	0.43	0.43			0.42				
CZ	0.42				–		0.43		0.43					0.44			
DK						–			0.44								0.44
East	0.42	0.43			0.43		–							0.44			
FR				0.43				–	0.43	0.43		0.46			0.46		0.43
DE	0.44			0.43	0.43	0.44		0.43	–				0.43	0.45		0.45	0.43
GB				0.43				0.43		–							
GR		0.44									–	0.42					
IT	0.45	0.44						0.46			0.42	–					0.44
NL				0.42					0.43				–				0.46
PL			0.44		0.44		0.44		0.45					–			0.45
Iber								0.46							–		
Scan			0.43			0.44			0.45				0.46	0.45		–	
CH	0.44							0.43	0.43			0.44					–
H ₂																	
AT	–				0.06		0.05		0.15			0.19					0.17
Balk		–					0.10				0.13	0.13					
Balt			–											0.14		0.11	
BeLu				–				0.06	0.08	0.08			0.04				
CZ	0.06				–		0.11		0.10					0.13			
DK						–			0.16								0.13
East	0.05	0.10			0.11		–							0.13			
FR				0.06				–	0.12	0.08		0.27			0.26		0.11
DE	0.15			0.08	0.10	0.16		0.12	–				0.09	0.22		0.20	0.09
GB				0.08				0.08		–							
GR		0.13									–	0.04					
IT	0.19	0.13						0.27			0.04	–					0.17
NL				0.04					0.09				–				0.28
PL			0.14		0.13		0.13		0.22					–			0.20
Iber								0.26							–		
Scan			0.11			0.13			0.20				0.28	0.20		–	
CH	0.17							0.11	0.09			0.17					–

Table 22: Trade costs for energy carriers between regions in M€/PJ (cont.).

	AT	Balk	Balt	BeLu	CZ	DK	East	FR	DE	GB	GR	IT	NL	PL	Iber	Scan	CH
Oil																	
AT	–				2.25		2.11		3.20			3.53					3.37
Balk		–					2.74				3.01	3.04					
Balt			–											3.11		2.82	
BeLu				–				2.30	2.47	2.48			1.94				
CZ	2.25				–		2.83		2.74					3.01			
DK						–			3.35								3.02
East	2.11	2.74			2.83		–							3.08			
FR				2.30				–	2.92	2.55		4.09			4.01		2.81
DE	3.20			2.47	2.74	3.35		2.92	–				2.61	3.75		3.61	2.61
GB				2.48				2.55		–							
GR		3.01									–	1.92					
IT	3.53	3.04					4.09				1.92	–					3.38
NL				1.94					2.61				–				4.12
PL			3.11		3.01		3.08		3.75					–			3.61
Iber								4.01							–		
Scan			2.82			3.02			3.61				4.12	3.61			–
CH	3.37							2.81	2.61			3.38					–
Biomass																	
AT	–				0.42		0.42		0.44			0.45					0.44
Balk		–					0.43				0.44	0.44					
Balt			–											0.44		0.43	
BeLu				–				0.43	0.43	0.43			0.42				
CZ	0.42				–		0.43		0.43					0.44			
DK						–			0.44								0.44
East	0.42	0.43			0.43		–							0.44			
FR				0.43				–	0.43	0.43		0.46			0.46		0.43
DE	0.44			0.43	0.43	0.44		0.43	–				0.43	0.45		0.45	0.43
GB				0.43				0.43		–							
GR		0.44									–	0.42					
IT	0.45	0.44					0.46				0.42	–					0.44
NL				0.42					0.43				–				0.46
PL			0.44		0.44		0.44		0.45					–			0.45
Iber								0.46							–		
Scan			0.43			0.44			0.45				0.46	0.45			–
CH	0.44							0.43	0.43			0.44					–

Source: IEA (2007b), IEA (2007a), Hirschhausen (2010) and Burandt et al. (2016).

3.9 Emissions

3.9.1 Carbon content and activity ratio

The overall mathematical definition of emissions in GENeSYS-MOD v2.0 has been changed as described in section 2.3.3. The parameter values for *EmissionContentPerFuel* can be found in table 24. To align with the model dynELMOD, the carbon contents for fuels are based on IPCC (2006).

Table 24: Carbon content (in megatons CO₂) of fuels per PJ primary energy.

	Biomass	Crude Oil	Hard Coal	Lignite	Natural Gas
Carbon Content	0.110	0.073	0.095	0.101	0.056

Source: IPCC (2006).

The *EmissionActivityRatio* has been set to 1 for all fossil fuel-based technologies. For bio-energy with carbon capture, transport, and storage (BECCTS), a value of -0.7 has been chosen in accordance with Gerbaulet and Lorenz (2017). This means that every unit of activity for each fossil fuel-based technology emits 100% of the given carbon content, while BECCTS yields 70% negative net emissions.

3.9.2 Emissions budget

The emissions budget available for the model has been revalidated in GENeSYS-MOD v2.0. Additionally, a regional, European, limit was obtained from the given global emission budgets that are provided in the most recent literature.

In the modeled scenarios, keeping the temperature well below 2° Celsius is the primary goal, and the corresponding available CO₂ budgets provided by the IPCC (2014) are used. For the calculation of the total CO₂ budget for Europe, data provided by the Stockholm Environment Institute was used (Karthia 2013). This discussion briefly assesses the pathways that were released in the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC 2014) and further elaborates different budgets for the various types of greenhouse gases. Accordingly, a global CO₂ budget of 890 GtCO₂ for the years 2012 to 2050 is accessible. Based on the yearly CO₂ emissions of around 36 Gt, as found in the Global Carbon Atlas,¹⁷ the global budget is reduced to 782 GtCO₂ for the modeled base year 2015. Because GENeSYS-MOD does not include exogenous CO₂ emissions from specific industrial branches (e.g., cement manufacturing), we reduce the limit by 2 GtCO₂ for all years from 2015 to 2050 (Boden, Andres, and Marland 2017; UNFCC 2017; BP 2017). This leaves a final global CO₂ budget of 712 GtCO₂ available until 2050. The calculation is illustrated in figure 10.

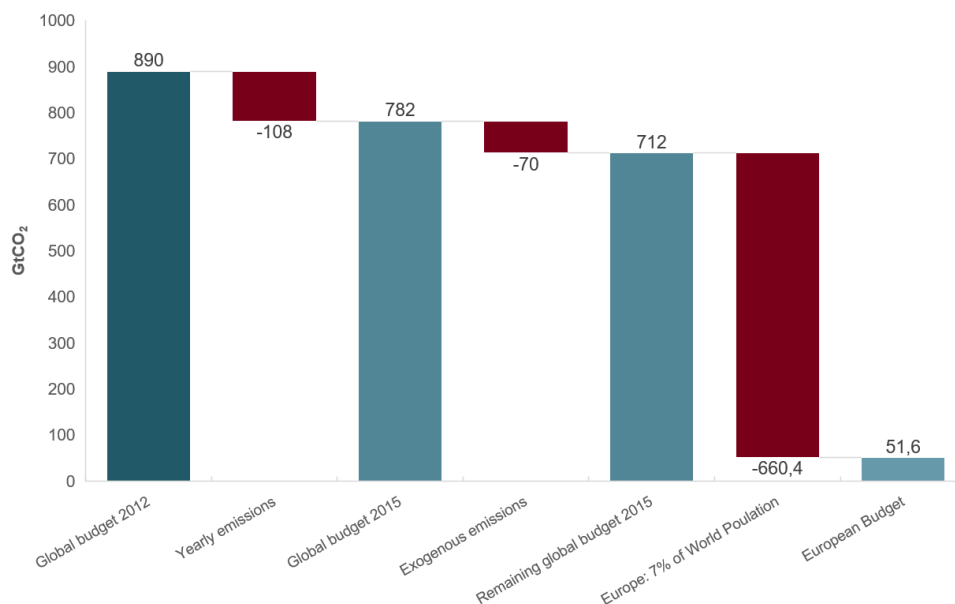


Figure 10: Illustrated calculation method of the European CO₂ budget for the 2° pathway.

Source: Kartha (2013), Boden, Andres, and Marland (2017), UNFCC (2017), and BP (2017).

¹⁷See <http://www.globalcarbonatlas.org/en/CO2-emissions> for further information. Data is based on Boden, Andres, and Marland (2017), UNFCC (2017), and BP (2017).

To derive the regional limit for Europe, the population was used as an indicator to determine the available share for Europe. Based on data from the World Bank,¹⁸ Europe hosts around 7.19% of the Global population. Thus, our modeled region receives an emission limit of 51.597 GtCO₂.

For the calculation of the European budget for the 1.5° Celsius scenario, we used the same method of estimates. With a starting budget of 527 GtCO₂ (Karthä 2013) and yearly emissions of 36 GtCO₂ for the years from 2012 until 2015, a remaining global budget of 419 GtCO₂ can be derived. When further decreasing the limit by subtracting CO₂ emissions from industrial branches that are not included in the model, the global budget is reduced to 349 GtCO₂. Applying the population of Europe as key indicator, our entire modeled region has only 25.291 GtCO₂ left. Considering the current yearly CO₂ emissions of around 5.6 GtCO₂, this budget would be exhausted within the next four to five years.

3.9.3 CO₂ storage potential

The available CO₂ storage potentials for CCTS are given on a regional basis. As the current political framework prohibits the transport of pollutants and waste, CO₂ must be captured within each country. Thus, countries without any CO₂ storage capacities cannot utilize CCTS technologies. Based on the calculations and data available from Oei, Herold, and Mendelevitch (2014), only offshore storage capacities in aquifers, and depleted gas fields are included. The resulting CO₂ storage potentials are shown in table 25.

Table 25: Regional storage potential of CO₂.

Region	Storage potential of CO ₂ in MtCO ₂
Austria	0
Baltic States	1300
Belgium & Luxembourg	0
Czech Republic	0
Denmark	2500
France	0
Germany	1200
Great Britain	23300
Italy	0
Netherlands	500
Poland	3500
Portugal & Spain	3500
Scandinavia	13800
South-East Europe	0
Switzerland	0
Total	49600

Source: Oei, Herold, and Mendelevitch (2014).

Considering the yearly European emissions of 5.6 GtCO₂, the total CO₂ storage potential of 49.6 GtCO₂ is only sufficient to store around eight to nine years worth of emissions. Furthermore, CO₂ storage is mostly available to regions which have a high potential of RES and low shares of conventional power production (e.g., Scandinavia). Showcasing that, Germany and Poland, both countries with a high reliance on electricity from the burning of carbon-intense coal, have only limited storage potentials. Therefore,

¹⁸See <https://data.worldbank.org/> for further information.

CCTS should not be used as the "simple solution" to replace the efforts of decarbonizing the energy system, but as an additional tool, suited to negate past failings and missed opportunities. This is especially important given the fact that CCTS is not yet commercially available and it is unclear if it will be in the near future.

3.9.4 Carbon pricing

While the global implementation of GENeSYS-MOD v1.0 (Löffler et al. 2017b) opted for a strict emissions budget and a 100% renewable energy target, the constraint of a fixed RES target for 2050 has been lifted. Before, no carbon price was set, since the much stricter target for renewable energies and perfect foresight of the model showed that the difference in terms of model results was negligible (Burandt et al. 2016). With the removal of said limitations, the introduction of a carbon price to the model was necessary. The carbon prices for Europe have been taken from the (IEA 2016b). The resulting values in € per ton CO₂ for the different emission pathways are shown in table 26. The 1.5 & 2 degree pathways have no carbon price included, as they have set a strict carbon budget.

Table 26: Carbon prices in € per ton of CO₂ for different emission pathways.

	Sectors	2020	2030	2040	2050
1.5 & 2 degree pathways	Power, industry, aviation	0	0	0	0
Business as usual pathway	Power, industry, aviation	15.06	25.11	33.48	33.48

Source: IEA (2016b, p. 39).

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Appendix A: Additional Data

A1 List of all technologies. Green are new, blue significantly reworked.

Name	Description
Power Generation	
P_Biomass	Biomass power plant.
P_Biomass_CCS	Biomass power plant with CCS technology.
P_Coal_Hardcoal	Hard coal power plant.
P_Coal_Lignite	Lignite power plant.
P_Gas	Natural gas power plant.
P_Nuclear	Nuclear power plant.
P_Oil	Oil power plant.
CHP_Biomass	Combined heat and power plant fueled by biomass.
CHP_Biomass_CCS	Combined heat and power plant fueled by biomass with CCS technology.
CHP_Coal_Hardcoal	Combined heat and power plant fueled by hard coal.
CHP_Coal_Lignite	Combined heat and power plant fueled by lignite.
CHP_Gas	Combined heat and power plant fueled by natural gas.
CHP_Nuclear	Combined heat and power plant fueled by uranium.
RES_Biomass	Domestic biomass production.
RES_CSP	Concentrated solar power collectors.
RES_Geothermal	Geothermal power plant.
RES_Hydro_Large	Large sized hydro power plant.
RES_Hydro_Small	Small sized hydro power plant.
RES_Ocean	Tidal or wave power plant.
RES_PV_Rooftop_Commercial	PV panels on commercial rooftops.
RES_PV_Rooftop_Residential	PV panels on residential rooftops.
RES_PV_Utility_Avg	Utility scale PV on locations with average potential.
RES_PV_Utility_Inf	Utility scale PV on locations with inferior potential.
RES_PV_Utility_Opt	Utility scale PV on locations with optimal potential.
RES_Wind_Offshore_Deep	Offshore wind turbines in deep waters.
RES_Wind_Offshore_Shallow	Offshore wind turbines in shallow waters.
RES_Wind_Offshore_Transitional	Offshore wind turbines in waters between deep and shallow.
RES_Wind_Onshore_Avg	Onshore wind turbines, locations with average potential.
RES_Wind_Onshore_Inf	Onshore wind turbines, locations with inferior potential.
RES_Wind_Onshore_Opt	Onshore wind turbines, locations with optimal potential.
Heating Technologies	
HHT_Biomass	High temperature heat generation via biomass.
HHT_Coal_Hardcoal	High temperature heat generation via hard coal.
HHT_Coal_Lignite	High temperature heat generation via lignite.
HHT_Electric_Furnace	High temperature heat generation via an electric furnace.
HHT_Gas	High temperature heat generation via natural gas.
HHT_Geothermal	High temperature heat generation via geothermal energy.
HHT_H2	High temperature heat generation via hydrogen.
HHT_Oil	High temperature heat generation via oil.
HLT_Biomass	Low temperature heat generation via biomass.
HLT_Coal_Hardcoal	Low temperature heat generation via hard coal.
HLT_Coal_Lignite	Low temperature heat generation via lignite.

Name	Description
Heating Technologies	
HLT_Electric_Furnace	Low temperature heat generation via an electric furnace.
HLT_Gas	Low temperature heat generation via natural gas.
HLT_Geothermal	Low temperature heat generation via geothermal energy.
HLT_Heatpump	Low temperature heat generation via heatpumps.
HLT_Oil	Low temperature heat generation via oil.
HLT_Rooftop_Commercial	Low temperature heat generation via solarthermal collectors on commercial rooftops.
HLT_Rooftop_Residential	Low temperature heat generation via solarthermal collectors on residential rooftops.
Transportation Technologies	
FRT_Rail_Conv	Freight rail transport, petro-fueled.
FRT_Rail_Electric	Freight rail transport, electric.
FRT_Road_BEV	Freight road transport, battery electric vehicle.
FRT_Road_H2	Freight road transport, hydrogen.
FRT_Road_ICE	Freight road transport, internal combustion engine.
FRT_Road_OH	Freight road transport, overhead electric vehicle.
FRT_Road_PHEV	Freight road transport, plug-in hybrid electric vehicle.
FRT_Ship_Bio	Freight ship transport, bio-fueled.
FRT_Ship_Conv	Freight ship transport, petro-fueled.
PSNG_Air_Bio	Passenger air transport, bio-fueled.
PSNG_Air_Conv	Passenger air transport, petro-fueled.
PSNG_Air_H2	Passenger air transport, hydrogen based.
PSNG_Rail_Conv	Passenger rail transport, petro-fueled.
PSNG_Rail_Electric	Passenger rail transport, electric.
PSNG_Road_BEV	Passenger road transport, battery electric vehicle.
PSNG_Road_H2	Passenger road transport, hydrogen based.
PSNG_Road_ICE	Passenger road transport, internal combustion engine.
PSNG_Road_PHEV	Passenger road transport, plug-in hybrid electric vehicle.
Resources	
R_Coal_Hardcoal	Domestic hard coal production.
R_Coal_Lignite	Domestic lignite production.
R_Gas	Domestic natural gas production.
R_Nuclear	Domestic uranium production.
R_Oil	Domestic Oil production.
Z_Import_Gas	Import of natural gas from regions not modeled.
Z_Import_Hardcoal	Import of hard coal from regions not modeled.
Z_Import_Oil	Import of oil from regions not modeled.
Transformation	
X_Electrolysis	Transformation technology, transforming water and electricity into hydrogen.
X_Fuel_Cell	Transformation technology, transforming hydrogen into electricity.
X_Methanation	Transformation technology, transforming biomass into biogas or Fisher-Tropsch synthesis.

Name	Description
Storages	
S_Battery_Li-Ion	Lithium-Ion battery.
S_Battery_Redox	Redox-flow battery.
S_CAES	Compressed air storage.
S_Gas_H2	Hydrogen storage.
S_Heat	Heat storage.
S_PHS	Pumped hydro storage.
Areas	
A_CCS_Capacity	Suitable area for CCS capacities per Region.
A_Rooftop_Commercial	Suitable commercial rooftop area for PV panels per region.
A_Rooftop_Residential	Suitable residential rooftop area for PV panels per region.

A2 Omitted technologies in GENeSYS-MOD v2.0.

Technology name	Reason for not including it
Area_DistrictHeating_avg	Heating technologies rework.
Area_DistrictHeating_inf	Heating technologies rework.
Area_DistrictHeating_opt	Heating technologies rework.
ST_Heat_cen	Heating technologies rework.
T_heat_low_bio_cen	Heating technologies rework.
T_heat_low_bio_chp_cen	Heating technologies rework.
T_heat_low_coal_cen	Heating technologies rework.
T_heat_low_coal_chp_cen	Heating technologies rework.
T_heat_low_elfur_cen	Heating technologies rework.
T_heat_low_gas_cen	Heating technologies rework.
T_heat_low_gas_chp_cen	Heating technologies rework.
T_heat_low_heatpump_cen	Heating technologies rework.
T_heat_low_oil_cen	Heating technologies rework.
T_heat_low_res-gas_cen	Heating technologies rework.
T_heat_low_res-gas_chp_cen	Heating technologies rework.
BIOFLREFINERY	Costs of the transformation and losses are now assigned to the InputActivityRatio.
ST_PSP_Residual	Different calculation of storage costs don't require this technology anymore.