

# **Documentation of LIMES-EU - A long-term electricity system model for Europe**

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This document presents a detailed documentation of LIMES-EU - the Long-term Investment Model for the Electricity Sector of Europe. LIMES-EU is a linear optimization model that simultaneously optimizes investment and dispatch decisions for generation, storage and transmission technologies. Its integrated approach together with an intertemporal optimization from 2010 to 2070 allows for analyzing comprehensive scenarios on the cost-effective future development of the European power system and the European Union's Emission Trading System (EU ETS). Despite the model's long-term focus, LIMES-EU effectively accounts for the short-term variability of electricity demand and the renewable energy sources wind and solar. In order to provide transparency, this documentation gives a detailed overview of the model's underlying assumptions, its input data and a full list of the model equations.

This model documentation is still largely based on the 2014 documentation (Nahmmacher et al., 2014).

## Version log

Date	Version	Changes	Link
10/14	--		<a href="https://www.pik-potsdam.de/research/transformation-pathways/models/limes/DocumentationLIMESE_U_2014.pdf/view">https://www.pik-potsdam.de/research/transformation-pathways/models/limes/DocumentationLIMESE_U_2014.pdf/view</a>
12/18	--	New technologies (hydrogen, waste, oil, other gases, batteries, electrolysis); vintages for gas, lignite and hard coal; updated technology parameters (e.g., fuel costs and RES investment costs); updated 2020-2050 demand forecast; transmission and generation capacities in 2015 fixed; reference transmission capacities for 2020 and 2030; updated potential for vRES and hydropower; implementation of a robustness constraint (de-rating factors specified); comparison between model and historic data updated to 2015; implementation of carbon price floor	<a href="https://www.pik-potsdam.de/research/transformation-pathways/models/limes/limes-documentation-2018">https://www.pik-potsdam.de/research/transformation-pathways/models/limes/limes-documentation-2018</a>
4/20	2.35	New technologies (BECCS); updated parameters (e.g., PV costs and fuel costs); adjustment of vRES availability factors; adjustment of hourly patterns bases on historic peak demand; new references NTC for 2020 and 2040; updated demand forecast; bounds on transmission and generation capacity in 2020; storage costs split into power and reservoir costs; additional calibration details (e.g., adjusting 2020 demand and capacities); additional test for model robustness (e.g., impact of representative days modelled on results); implementation of reserves; implementation of MACC for the energy-intensive industry; implementation of the MSR; elaboration on the EU ETS modelling (e.g., assumptions for aviation and heating).	<a href="https://www.pik-potsdam.de/research/transformation-pathways/models/limes/limes-documentation-april-2020/view">https://www.pik-potsdam.de/research/transformation-pathways/models/limes/limes-documentation-april-2020/view</a>

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# 1. Introduction

The Paris Agreement demands strong actions to decarbonize the electricity systems. In Europe several policies are in place with the aim to reduce emissions, namely national renewable support and the European Union's Emission Trading System (EU ETS). However, there are still numerous open questions of how to achieve a strong transformation of the electricity system - comprising technical, economic and policy aspects. This paper introduces a techno-economic model suitable to analyze such questions called The **Long-term Investment Model for the Electricity Sector of EU**rope (LIMES-EU).

At the EU-level, the long-term target of the European Commission is to reach carbon neutrality by 2050 (European Commission, 2018a). This target has to be translated into specific measures for the two systems covering all the economic activities, i.e., the Effort Sharing Decision (ESD) and the EU ETS. LIMES-EU models the electricity sector in detail and the energy-intensive industry which are covered by the EU ETS. For the period 2020-2030, the EU has recently tightened the EU ETS cap (European Parliament and Council of the European Union, 2018) , but aiming for climate neutrality, with intended reductions of 50-55% by 2030 (European Commission, 2019a), would imply a more stringent cap for the EU ETS. In addition, the EU aims for renewable energy share of at least 32% by 2030 (European Commission, 2018a). Such measures certainly have a strong impact on the power sector which can be analyzed with LIMES-EU.

The core assets of the power sector - electricity generation, storage and transmission technologies - are characterized by long technical lifetimes that span over several decades. Long-term planning by relevant actors such as policy makers, transmission system operators and electricity producers is therefore pivotal. In order to support policy makers in identifying robust policy targets long-term scenarios are needed to explore possible pathways for the European electricity sector that are technically feasible and economically sensible.

LIMES-EU was developed to facilitate a long-term assessment of the European power system on aggregate and national level. Incorporating electricity generation, storage and transmission technologies LIMES-EU simultaneously optimizes investment decisions in 5-year steps from 2010 to 2070 for each country of the EU (except Cyprus and Malta), Norway, Switzerland and the (non-EU) Balkan region taking into account European-wide and country-specific climate and energy targets. In this way LIMES-EU delivers consistent and cost-effective scenarios for the future European power system.

LIMES-EU is especially useful to analyze the integration of variable renewable energy sources (vRES) such as wind and solar into the European power system while considering flexibility operational constraints. Despite its long-term focus it accounts for short-term fluctuations of demand and vRES supply when determining the optimal electricity generation mix. Its comprehensive approach to simultaneously optimize investments in generation and storage technologies as well as cross-border transmission capacities allows for a sound technological and economic analysis of vRES integration options. Although the core of the model is the power sector, LIMES-EU also incorporates a rough representation of the energy-intensive industry such that the EU ETS as a whole can be analyzed.

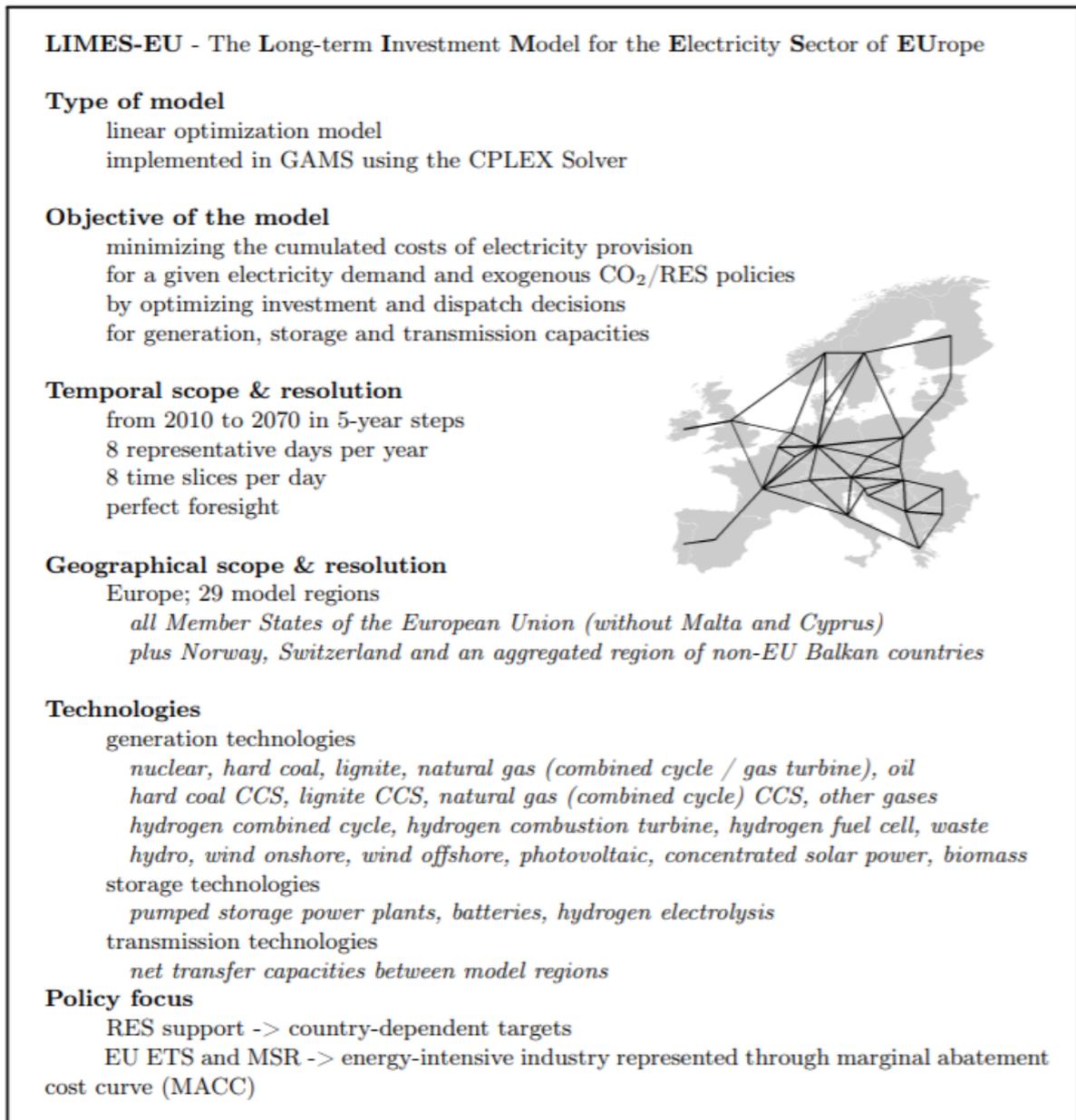


Figure 1. LIMES-EU in a nutshell.

This documentation aims to give a comprehensive and detailed description of LIMES-EU. Many of the parameters used in the model depend on future technological, economic and political developments and are therefore highly uncertain. In order to facilitate a correct interpretation of our model results and to provide a maximum amount of transparency, we aim to disclose all parameter values used for our default scenarios and describe the assumptions on which our parameter choice is based. A large part of the model equations as well as some calibration data did not change from the earlier LIMES-EU versions of the model. Though they

are already discussed in the supplementary material of the papers in which it has been used (e.g., Haller et al. (2012)) they are stated here again for the sake of comprehensiveness.

The following Section gives an overview about the model and its basic functioning. Section 3 briefly presents an approach for efficiently decreasing the intra-annual resolution of the model. It allows for keeping computational demand to a minimum while at the same time correctly reflecting the short-term variability of vRES. A more detailed description of the approach is provided in Nahmmacher et al. (2016). Sections 4 and 5 discuss the standard parameter assumptions used to run the model, with Section 4 focusing on technology-specific parameters that are same for every model region and Section 5 focusing on region-specific input data. All prices and cost stated in this paper are given in 2010 prices. An overview about different climate and energy-related policies that can be implemented in LIMES-EU is presented in Section 7. Sections 8 and 9 provides more detail of the model calibration. A comprehensive list of all model equations can be found in Appendix A. Region names are often abbreviated by a two-letter code in this documentation; an explanation of the codes, which are based on ISO 3166-1, is given in Appendix B.

## **2. Model Overview**

### **2.1. Objective Function**

The model is formulated as an intertemporal social planner problem with perfect foresight. It minimizes the cumulated discounted costs of electricity provision for all model regions over the whole model time span simultaneously (Equation (1)). The total system costs  $C^{tot}$  are the intertemporal sum of the costs for capacity investments  $C_t^I$ , fuel costs  $C_t^F$ , operation and maintenance costs  $C_t^{OM}$  as well as possible CO<sub>2</sub> emission costs  $C_t^{CO_2}$  of each time step  $t$ . The factor  $\Delta t$  accounts for the time span between two model years. A salvage value  $V$  for the

capacity stock that remains at the end of the time horizon is subtracted. All values are discounted to present values using the discount rate  $\rho$  which is set to 5% in the standard case. A comprehensive list of all model equations is given in Appendix A.

$$C^{tot} = \sum_t \left( \Delta t e^{-\rho(t-t_0)} (C_t^I + C_t^F + C_t^{OM} + C_t^{CO_2}) \right) - e^{-\rho(t_{end}-t_0)} V \quad (1)$$

The electricity demand is exogenous to the model. The focus is on the supply side of the electricity system and its interactions with the transmission infrastructure. Using a social planner approach, the model abstracts from the nearly infinite amount of heterogeneous players in the electricity sector. The social planner solution is equivalent to the outcome of a decentralized market under perfect market conditions. Thus the model results show how a cost-optimal European electricity system under the given assumptions would look like, not how the European electricity system that faces considerable market distortions will evolve within the next decades. The model is formulated in GAMS<sup>2</sup> and uses the linear solver CPLEX.

## 2.2. Geographical Resolution

The current version of LIMES-EU optimizes the electricity system and abatement of the energy-intensive industry of the EU countries (excluding Cyprus and Malta) plus the Balkan region, Norway, Switzerland and the United Kingdom. Except for the Balkan region, all countries are modeled as individual entities. They differ with respect to electricity demand, initial generation and storage capacities, natural resource endowments and national energy policies. Their location is also relevant as countries are connected via an electricity transmission grid. Natural resource endowments include the availability of lignite and biomass as well as

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<sup>2</sup> General Algebraic Modelling System, <http://www.gams.com>.

hydro, wind and solar power. Due to the country-specific resolution, energy policy targets can be set on the national level or for a specified group of model regions (e.g. EU Member States).

### **2.3. Temporal Resolution**

In order to accommodate both long-term investment decisions and short-term fluctuations of wind, solar irradiance and demand, LIMES-EU makes use of two different time scales. The long-term scale ranges from 2010 to 2070 and is subdivided in 5-year *time steps*. The short-term scale subdivides the time steps into multiple *time slices*. Eight time slices - with a length of three hours each - add up to one representative day. A weighting factor is given to each representative day; together they add up to one model year. Assigning different weights to representative days allows for representing both days with common and rare load patterns. Section 3 presents the approach of how to select these representative model days.

While investments in generation, storage and transmission capacities are endogenously determined for each of the 5-year *time steps*, the balancing of electricity demand and supply, i.e. the dispatch of generation, storage and transmission capacities, is modeled for each time slice. The short-term perspective is needed to correctly value the available investment options by accounting for the intra-year variability of the electricity demand and intermittent renewable resources.

### **2.4. Technologies**

The following briefly introduces the three kinds of technologies represented in LIMES-EU, namely generation, storage and transmission technologies. Section 3 provides a more detailed description of each technology. Power plants, transmission lines and storage facilities are not

represented on a single unit basis in LIMES-EU, but are aggregated based on their economic and technical characteristics<sup>3</sup>. Modelling technology classes rather than individual units considerably simplifies the model, which otherwise could not be solved due to computational constraints.

**Generation Technologies** Generation technologies convert primary energies to electricity.

Lignite, hard coal and gas combined cycle are split in four vintages each one according to the time they were commissioned (before 1980, between 1980 and 1995, between 1995 and 2010, and after 2010) in order to account for the technological development. Each of the 4 vintages is treated as an individual technologies with a different efficiency. There are thus 29 different generation technologies in LIMES-EU that are classified into intermittent and dispatchable generation technologies. Wind onshore, wind offshore, solar photovoltaic (PV) and concentrated solar power (CSP) are intermittent with their availability varying both on a spatial and temporal scale. To account for intra-regional differences in wind and solar resources, the potential and availability of each technology is subdivided into three resource grades per intermittent generation technology. The availability of dispatchable technologies for each model region remains constant throughout the year. Dispatchable technologies in LIMES-EU comprise lignite, hard coal, natural gas combined cycle power plants and gas turbines as well as nuclear, biomass, hydrogen, waste, other gases, oil and hydro power plants. Electricity generation based on lignite, hard coal, natural gas, oil, waste and other gases is associated with CO<sub>2</sub> emissions. Optionally, lignite, hard coal, combined cycle natural gas plants and biomass can be enhanced with carbon capture and storage (CCS) technology that reduces their CO<sub>2</sub> emissions by storing them underground. Biomass CCS (BECCS) indeed provides negative emissions, as it is considered that its emission

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<sup>3</sup> e.g. all hard coal power plants of a similar age in France are aggregated to one class.

factor equals the carbon captured during the life of the plant. Hence, when capture is enabled, the captured emissions are accounted as negative emissions.

**Transmission Technologies** Transmission technologies enable the transfer of electricity between neighboring regions. Transmission is modelled as a transport problem from the center of one region to the center of a neighboring region - with the maximum transmissible amount of electricity being restricted by the installed net transfer capacity (NTC). The transmission of electricity between model regions is associated with losses. Network constraints and transmission losses within a region are not explicitly modelled in LIMES-EU ('copperplate' assumption).

**Storage Technologies** Demand and supply of electricity have to be balanced in every time slice. Storage technologies may serve as an additional consumer in times of oversupply of electricity from generation technologies and as an additional producer of electricity in times of undersupply. The shift of electricity provision from one time slice to another is subject to storage losses. Three different storage technologies are available in LIMES-EU: pumped storage power plants (PSP), batteries, hydrogen electrolysis. The former two are assumed to do only *intraday* arbitrage and hydrogen electrolysis is allowed to do also *interday* arbitrage. While *intraday* storages can only shift electricity provision between time slices of the same day, *interday* storages are able to shift electricity provision between all-time slices of the same year. Furthermore, hydrogen electrolysis is assumed to only transform power into hydrogen and store it. Hydrogen is then used by one of the hydrogen-based generation technologies.

### 3. Time Slice Approach

Long-term models with endogenous investments are computationally demanding, especially when optimizing intertemporally, i.e., optimizing investment decisions for multiple time steps simultaneously. A common way to reduce temporal complexity is to optimize dispatch decisions only for a limited number of representative time slices instead of modelling every hour of the year. However, it is not obvious which time slices should be selected from historic data in order to preserve the characteristic variability of electricity demand and vRES infeed. Consequently, Golling (2012), Nagl *et al.* (2013), de Sisternes Jimenez and Webster (2013), Poncelet *et al.* (2017) and others developed new approaches for selecting characteristic vRES infeed and demand pattern. However, none of those are satisfyingly applicable to the present model as they either focus on only one RES technology or disregard different spatial compositions of load levels, which is pivotal in a multi-regional model.

Nahmmacher *et al.*, 2016) develops a reproducible algorithm that is applied for LIMES-EU. It is used to select representative days with a given number of eight diurnal time slices; however it can also be applied for selecting separate representative time slices or other groups of consecutive time slices. Due to its generic design, our method is applicable to all kinds of power system models with multiple fluctuating time series, i.e. models with multiple vRES technologies and/or multiple regions. The algorithm is meant to optimally fulfill three essential requirements, namely that the derived time slices should sufficiently reflect:

- the annual electricity demand and average vRES capacity factors for each region,
- the load duration curve of each time series, and
- the spatial and temporal correlation of electricity demand and vRES infeed.

The first requirement ensures that the quality of a region with respect to solar and wind power is correctly reflected. By replicating both common and rare situations of load and vRES infeed

as well as their respective frequency of occurrence (second requirement), the time slices neither overestimate nor underestimate single events. This serves to correctly value both base and peak load plants. The third requirement ensures that the characteristics of an interconnected multi-regional electricity system are correctly assessed and features such as large-area pooling and geographic smoothing are taken into account.

Our approach is based on Ward (1963)'s hierarchical clustering algorithm. We apply this algorithm on historic electricity demand and weather data to group days with similar diurnal demand and vRES infeed patterns. As a result, each group of days is reflected by a representative day in the power system model.

### **3.1. Data**

We use ENTSO-E (2011) data for the historic electricity demand levels and historic weather data from the ERA-Interim dataset (Dee et al., 2011) for the vRES infeed. Using weather data rather than historic infeed data allows for taking into consideration a longer time span which prevents the overestimation of unusual years. The ERA-Interim dataset (Dee et al., 2011) comprises 33 years of ground solar irradiance and wind speed levels at 120m height for Europe. For every third hour between 1979 and 2011 the respective information is given for local data points in a spatial resolution of  $0.75^\circ \times 0.75^\circ$ . The conversion from weather data to vRES capacity factors is subject to the technology-specific power curves given in Section 4.

The three-hourly infeed of vRES technologies is averaged over all weather data grid cells belonging to the same region-specific resource grade. A comparison with real historic onshore wind feed-in levels however shows that realized capacity factors in mountainous countries<sup>4</sup> are much higher than the ones derived from the weather data. The spatial resolution of  $0.75^\circ \times$

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<sup>4</sup> Spain in particular but also Austria and Italy.

0.75° is obviously not high enough to reflect the variations in wind speeds between mountain valleys and ridges. As wind turbines are predominantly installed on ridges rather than in valleys we adjust the wind data in the following way:

$$\{v_{adj}\} = \{v_{era}\} + 0.01(\{h_{q3}\} - \{h_{mean}\}) \quad (2)$$

$$\text{with } [v] = m/s, [h] = m$$

It is assumed that the representative elevation  $h_{q3}$  of wind sites equals the third quartile of the elevation distribution within a weather data grid cell<sup>5</sup>. It is further assumed that the increase in local wind speed ( $v_{adj} - v_{era}$ ) at a point within a grid cell is in direct proportion to the difference in elevation of this point to the average elevation  $h_{mean}$  of the grid cell. The increase of  $0.01 \frac{m/s}{m}$  is chosen in order to best reflect the infeed levels of wind power observed in 2010 and 2011 (derived from EUROSTAT (2013a) and EUROSTAT (2013b)).

Country-specific demand data is retrieved from ENTSO-E (2011) in an hourly resolution. Compared to the vRES infeed, the intra-year demand fluctuations are less stochastic and follow distinct diurnal, intra-week and seasonal patterns. Though the absolute demand levels change between different years due to demographic and economic reasons, the relative intra-year fluctuations remain the same. The hourly demand data of 2010 and 2011 that is available for all model regions is therefore assumed to be representative for the *intra*-year demand side fluctuations between 1979 and 2011. Future *inter*-year growth of annual demand is subject to scenario assumptions (see Sections 5.1 and 7).

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<sup>5</sup> the distribution of elevation within a grid cell is based on NGDC (2013).

## 3.2. Clustering Approach

We apply an approach based on the hierarchical clustering algorithm described by Ward (1963) to select a limited number of characteristic days from the total of 12053 days between 1979 and 2011 for which the weather data is available (Dee et al., 2011). The approach ultimately yields a set of representative days that minimizes the sum of squared errors between all observed days and their representatives. By employing a multidimensional clustering algorithm, the approximation of any load duration curve of a region's electricity demand or vRES infeed is optimized while at the same time accounting for the simultaneous load and vRES levels of the other model regions.

The distance between two days (observations) is defined as the Euclidean distance respecting a total of 3016 dimensions<sup>6</sup> per observation. Before starting the clustering algorithm all-time series are normalized to their maximum value. Subsequently, the algorithm iteratively groups similar days together until only one cluster containing all days remains. In each step, the clustering is done in a way that minimizes the variance within each cluster. Figure 2 visualizes the clustering procedure of our data.

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<sup>6</sup> Each observation contains data about 29 regions, 4 technologies, 3 resource grades per technology and region as well as region-specific demand data; each for every third hour of the day.

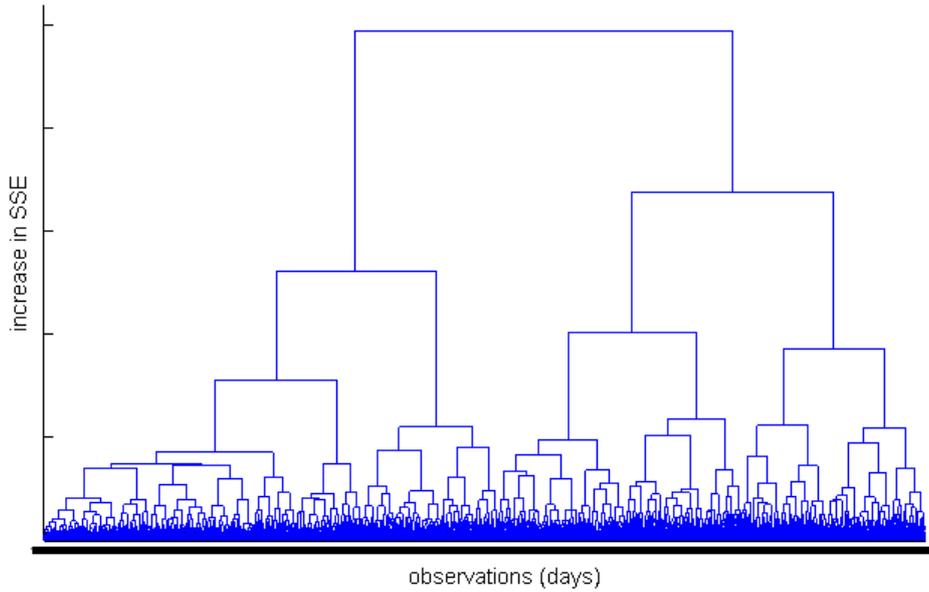


Figure 2. Dendrogram of clustering procedure. Showing the consecutive grouping of two clusters to a joint cluster and the resulting increase in the overall sum of squared errors (SSE, y-axis). All days (x-axis) are consecutively grouped together until only one cluster is left. Source: Own computation with model-specific data.

### 3.3. Resulting Time Slices

Once the clustering algorithm is finished, the model operator is free to choose the amount of clusters to use for the model and thereby trade off temporal resolution against computation time. For each cluster, there is one representative day in the model. We choose that day as the representative day that is closest to the cluster's mean vector. In the model, a weighting factor is assigned to every representative day according to the number of days within its cluster. To ensure correct average demand levels and capacity factors per technology and region the time series are scaled if necessary.

Nahmmacher *et al.* (2016) analyze the differences in model results depending on the number of time slices. They show that already 48 time slices, i.e., 6 representative days, are sufficient to reflect the characteristic fluctuations of electricity demand and vRES infeed in LIMES-EU. Further model tests show that emissions are very similar for runs with 6 or more days. However,

more days are needed for vRES and storage deployment to converge (see Section 9). We therefore use a number of representative days according to the aim of the study/research, e.g., 6 days (i.e., 48 time slices) would be appropriate for studies focused on the EU ETS as these are enough to capture long-term emission patterns, and 8-10 days for studies focused on long-term investments in the power sector.

## 4. Technology Characteristics

### 4.1. Generation Technologies

#### 4.1.1. Intermittent Generation Technologies

Intermittent technologies comprise the generation technologies that are based on wind and solar power. For wind power LIMES-EU discerns between onshore and offshore power plants. Solar power technologies are divided into PV cells and CSP plants. Table 1 and Table 2 give the techno-economic characteristics of these power plants. As the future development of their investment costs is highly uncertain, it is usually subject to a sensitivity analysis. Table 2 presents the investment cost assumptions for our default scenario, which are based on REMIND<sup>7</sup>.

*Table 1. Characteristics of wind and solar power plants.*

	Fixed O&M (%/a)	Lifetime (a)
Wind Onshore	3	25
Wind Offshore	5	25
PV	1	25
CSP	3	30

Source: Haller *et al.* (2012) and own assumptions.

<sup>7</sup> For REMIND detailed harmonized model documentation is available at the Common IAM documentation, [https://www.iamcdocumentation.eu/Model\\_Documentation\\_-\\_REMIND](https://www.iamcdocumentation.eu/Model_Documentation_-_REMIND)

The output of intermittent generation technologies is constrained by the region- and time-slice-specific availability and subject to technology-specific power curves. Power curves describe the relation between resource availability (wind speed or solar irradiance) and possible electricity production of a respective power plant.

Table 2. Default assumptions for vRES investment costs (€/kW). Investments costs after 2050 are assumed to remain constant at the 2050 value.

	Wind Onshore	Wind Offshore	PV	CSP
2010	1750	4750	2500	6250
2015	1600	4400	1100	5100
2020	1550	4050	700	4750
2025	1500	3800	600	4750
2030	1450	3500	550	4750
2035	1400	3350	500	4600
2040	1400	3150	475	4450
2045	1375	3000	450	4000
2050-2070	1350	2850	425	3560

Source: REMIND data and own assumptions.

Turbine-specific wind power curves are published by the respective turbine producers. However, using power curves of commonly installed wind turbines to derive capacity factors from the weather data yields much higher values compared to historically realized full load hours (see Boccard (2009) for possible reasons). We therefore use the following regression to derive an aggregated wind power curve for the model (Equation (3)). It is based on 2011-data of hourly German wind power production  $P_{Wind}$  (ÜNB, 2013a) and installed capacities<sup>8</sup>  $cap_i$  (ÜNB, 2013b) as well as the ERA-Interim wind speed data  $v_i$  (Dee et al., 2011) per weather data grid cell  $i$ . It is assumed that the power output is proportional to the fifth power of the wind speed<sup>9</sup>. The resulting wind power curve which is defined by the five coefficients  $\beta_{1-5}$  is depicted in Figure 3.

<sup>8</sup> The plant-specific installed capacities are aggregated according to the weather data grid.

<sup>9</sup> The power  $P$  of a free flowing wind stream is given by  $P = \frac{1}{2} v^2 \dot{m} = \frac{1}{2} v^2 (vA\rho)$ , with  $\dot{m}$  denoting the mass flow rate,  $v$  the wind speed,  $\rho$  the air density and  $A$  the flow cross-section. Hence the power *input* of a wind turbine is

$$P_{Wind} = \sum_i cap_i (\beta_1 v_i + \beta_2 v_i^2 + \beta_3 v_i^3 + \beta_4 v_i^4 + \beta_5 v_i^5) \quad (3)$$

The output of PV cells is assumed to be in a linear relation to the solar irradiance. In contrast to PV cells that use both direct and diffuse irradiance, CSP plants can only produce electricity from direct solar irradiance. Following Haller *et al.* (2012), the direct solar irradiance is derived from a simplified approximation which assumes that the direct normal irradiance  $DNI_i$  is a function of the global solar irradiance  $I_i$  and the latitude  $lat_i$  of the weather data grid cell  $i$  (Equation (4)). This way the DNI share of global irradiance is 75% at a latitude of  $30^\circ$  and decreases for larger latitudes.

$$DNI_i = I_i \left( 1 - 0.25 \left( \frac{lat_i}{30} \right)^{1.6} \right) \quad (4)$$

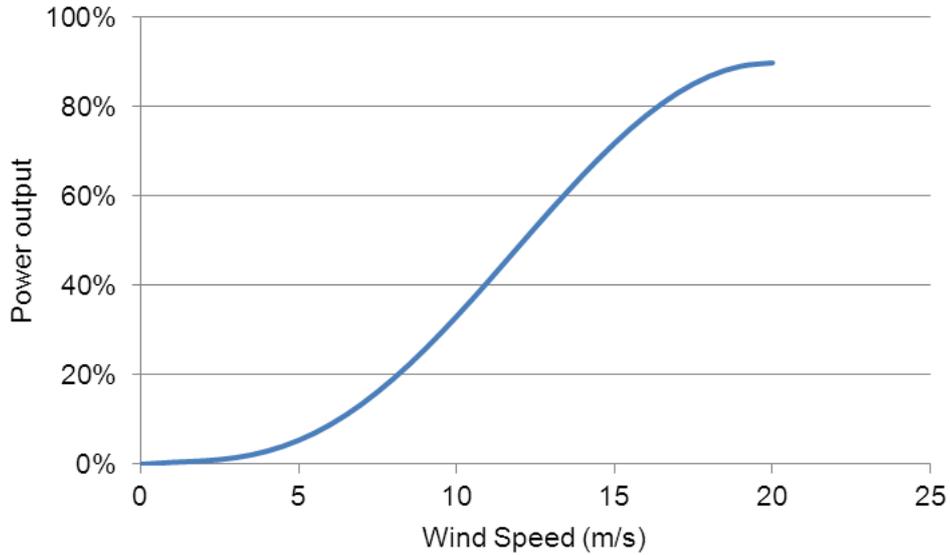


Figure 3. Aggregated wind power curve. Source: Own calculations based on Dee *et al.* (2011), ÜNB (2013a) and ÜNB (2013b).

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proportional to the third power of the wind speed. The power *output* is nonetheless subject to a wind speed dependent power coefficient which is accounted for by also including the 4th and 5th power of  $v$ .

As in Haller *et al.* (2012), CSP plants are modelled with an collector area that is four times the size required to reach nominal output at reference conditions (SM4<sup>10</sup> configuration). Each CSP plant is equipped with an internal thermal storage with a capacity large enough to level out the diurnal fluctuations in solar energy input. Thus, even though solar irradiance varies between time slices, CSP plants are dispatchable within the limits of their daily availability factors that differ across days.

#### 4.1.2. Dispatchable Generation Technologies

Power plants using fossil fuels, uranium, biomass or hydro power as a primary energy source are dispatchable within the limits of their annual availability. Except for hydro<sup>11</sup>, the annual availability of these technologies is equal for all model regions (80%). Hourly availability for all technologies is defined as 100% minus the auto consumption rate (from Agora (2014)). Table 3 gives an overview about the techno-economic characteristics of fuel- and hydro-based power plants in LIMES-EU.

*Table 3. Techno-economic characteristics of thermal and hydro power plants.*

	Investment Costs (€/kW)	Efficiency (%)	Autocons. (%)	Fixed O&M (%/yr)	Variable O&M (e/MWh)	Min Load (%)	Max Ramp (%)	Lifetime (yr)
Nuclear	7000	33	5	3	5	40	-	60
Hard Coal	1800	38-50	8	2	6	30	35	45
Hard Coal CCS	see Table 4	43	8	2	29	30	35	45
Lignite	2100	36-47	8	2	9	50	25	55
Lignite CCS	see Table 4	42	8	2	34	50	25	55
Gas CC	900	54-60	3	3	4	40	50	45
Gas CC CCS	see Table 4	52	3	3	18	40	50	45
Gas GT	400	41	3	3	3	0	100	45
Oil	400	42	9	4	3	0	100	40
Hydrogen CC	1170	58	3	3	4	0	100	40

<sup>10</sup> SM: solar multiple.

<sup>11</sup> See Section 5.3.2.

	Investment Costs (€/kW)	Efficiency (%)	Autocons. (%)	Fixed O&M (%/yr)	Variable O&M (€/MWh)	Min Load (%)	Max Ramp (%)	Lifetime (yr)
Hydrogen CT	520	33	3	4	3	0	100	40
Hydrogen FC	see Table 4	45	3	2	3	0	100	40
Waste	2000	22	2	4	3	0	35	40
Other gases	900	76	8	3	3	40	50	40
Biomass	2000	42	5	4	6	0	35	40
BECCS	see Table 4	42	30	2	6	0	35	40
Hydro	2500	100	2	2	0	0	100	80

Source: Haller *et al.* (2012), Markewitz *et al.* (2018), Bundesnetzagentur (2018), UBA (2018), IEA (2016), BMWi (2018), Agora (2014); own assumptions.

Table 4. Default assumptions for dispatchable technologies with time-dependent investment costs (€/kW). Investments costs after 2050 are assumed to remain constant at the 2050 value.

	Hard Coal CCS	Lignite CCS	Gas CC CCS	Hydrogen FC	BECCS
2010	3748	3748	2113	2000	3800
2015	3748	3748	2113	1800	3800
2020	3475	3475	1942	1600	3800
2025	3200	3200	1800	1400	3625
2030	3000	3000	1700	1200	3450
2035	2900	2900	1600	1000	3270
2040	2800	2800	1550	900	3090
2045	2700	2700	1500	800	3045
2050-2070	2600	2600	1450	700	3000

Source: REMIND, IEA (2016), Capros *et al.* (2018) and own assumptions.

Power plants with steam turbines are subject to minimum load restrictions and ramping constraints. In order to represent these characteristics, the dispatch is limited via two equations: first, the model chooses the maximum capacity that is operating during a representative day. Then, it can reduce the generation in each time slice of that day down to the minimum load times the operating capacity, as long as the variation between two time steps is within the ramping limit. The minimum load and maximum ramping restrictions are given in Table 3 as the share of the operating capacity constraining the variation in generation within a day. Efficiency losses due to part load operation are disregarded. We furthermore limit the flexibility

of nuclear such that the operating capacity has to be the same for each representative day within one year.

The prices for primary energy sources used in thermal power plants are exogenous to LIMES-EU and thus independent from demand<sup>12</sup> (see Table 5); as part of the calibration process we add cost markups for lignite, gas and hard coal for certain model regions. However, the availability of certain fuels, namely lignite and biomass, differs between model regions (see Section 5.3.2).

Power generation from hard coal, lignite, natural gas, oil, waste and other gases emits greenhouse gases; the CO<sub>2</sub> intensity of these primary energy sources is given in Table 5 as well. The stated emission factors are estimated from the BMWi (2018) and are considered equal for every model region for simplicity and due to the lack of sufficient data. In reality, the emission intensity of lignite significantly depends on the site of extraction and differs not only between but also within regions. The emission factors for all the fuels in the model fall nonetheless within the ranges provided by the IPCC (Gomez et al., 2006).

The only technology considered able to provide negative emissions is biomass coupled with CCS. Owing to carbon emissions associated with the initial land use change and these subsequent emissions, the actual amount of emissions removed depends entirely on the choices made throughout the supply chain (Fajardy and Dowell, 2017). For instance, according to Fajardy and Dowell (2017)'s estimations, carbon intensity would vary as much as ~-1100 to 1000 gCO<sub>2</sub>/kWh for short rotation cropping willow as the offset effect is exacerbated with indirect land use changes. It is clear that the supply chain emissions cannot be entirely accounted because some of these emissions are already covered by the EU ETS or ESD (e.g., transport of biomass, included in the ESD). However, unlike other primary energies, harvesting

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<sup>12</sup> i.e. all model regions are assumed to be price takers on the fuel markets.

biomass directly affects the absorption of CO<sub>2</sub>, and thus the countries' emission inventories. Hence, land use change (LUC) and indirect land use change (ILUC) should be accounted. Based on a carbon content of 100 tCO<sub>2</sub>/TJ for biomass (Gomez et al., 2006), and assuming a capture rate of 90%, efficiency of 29% and an offset factor of 50%<sup>13</sup>, the emission factor for BECCS would be -551 gCO<sub>2</sub>/ kWh<sub>el</sub>. Further research is required to estimate more accurately to what extent negative emissions from BECCS are offset.

Table 5. Prices and CO<sub>2</sub> intensity of fuels. Fuel prices after 2050 are assumed to remain constant at the 2050 value.

	Fuel prices (€/GJ)									CO <sub>2</sub> intensity	
	2010	2015	2020	2025	2030	2035	2040	2045	2050-2070	tCO <sub>2</sub> /TJ	tCO <sub>2</sub> /kWh <sub>th</sub>
Hard Coal	2.9	2.3	3.0	3.0	3.0	3.1	3.2	3.4	3.6	96	347
Lignite	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	107	387
Natural Gas	5.7	5.3	6.2	6.8	7.1	7.8	8.3	8.4	8.9	56	200
Uranium	0.5	0.6	0.7	0.8	1.0	1.2	1.4	1.7	2.0	0	0
Biomass	5.9	5.9	5.9	8.1	8.8	9.7	11.0	11.5	11.2	100	360
Oil	10.7	8.0	11.9	13.2	14.3	16.4	16.0	17.6	19.3	81	290
Waste	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	154	554
Hydrogen	12.5	12.5	13.9	13.9	13.9	13.9	13.9	13.9	13.9	0	0
Other gases	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	203	730

Source: fuel prices taken from respective REMIND runs, emission factors estimated from BMWi (2018) and Gomez et al. (2006); own assumptions.

## 4.2. Transmission Technologies

Transmission expansion between countries is modelled endogenously in LIMES-EU. For enabling the joint optimization of generation, storage and transmission expansion within one model run the transmission grid is represented by 'net transfer capacities' (NTC). The NTC-approach abstracts from the complex power flows of the highly intermeshed European

<sup>13</sup> Different estimations about the negative emissions potential are found in literature. For instance, Fajardy and Dowell (2017) estimate this between 46% and 62% of the carbon intensity, depending on whether LUC and ILUC are accounted. Heck et al. (2018) estimate also negative emissions potentials accounting for ~50% of the total captured by BECCS.

transmission network by stating a simple transport-problem for the electricity exchange between two neighboring countries. The installed NTC between two countries defines the maximum tradable power flow within a given time slice and remains constant throughout the year. Higher power flows are possible after investing in transmission expansion and thereby increasing the NTC between two countries. Investment costs depend on the additional capacity to be installed and the distance between the two country-centers. Table 6 summarizes the techno-economic characteristics of NTCs applied in the model.

The specific NTC investment cost vary significantly in the literature: Instead of the 1M€/GWkm in Hirth (2013) and LIMES-EU, Schaber *et al.* (2012) and Fürsch *et al.* (2013) only assume costs of 0.4 M€/GWkm. However, 0.4M€/GWkm rather reflect the costs for thermal transfer capacity than for NTC: NEP (2013) state costs of 1.4 M€/km for a 380kV overhead double-circuit. With a transfer capacity of about 1.8 GW per circuit, this results in 0.4 M€ per GWkm of thermal capacity (cf. DENA (2010), IZES *et al.* (2011)). There are several reasons, why we assume the costs per NTC to be much higher: (1) NTC values are significantly smaller than thermal transfer capacities; (2) the stated costs only cover the lines and do not comprise substations and converters; and (3) costs for underground and sea cables are considerably higher than for overhead lines. We therefore assume that 1M€ per GWkm NTC is an appropriate approximation of the real transmission investment costs.

*Table 6. Characteristics of transmission technologies.*

	Inv. Costs (M€/GWkm)	Availability (%)	Lifetime (yr)	Losses (%/1000km)
Net Transfer Capacity	1.0	80	100	7

Source: Haller *et al.* (2012), Short *et al.* (2011), NEP (2013); own assumptions.

### 4.3. Storage Technologies

The purpose of storage technologies is to ease the match between supply and demand over time. In LIMES-EU we consider three storage technologies: pumped storage power plants (PSP) and batteries for balancing between time slices of the same day (*intraday* storage), and hydrogen electrolysis for balancing between time slices of the same year (*interday* storage). The technical and economic features of the three storage options are given in Table 7 and Table 8. We do not account for possible regional expansion constraints, e.g., suitable sites for pumped-hydro storage systems, regarding these specific storage technologies. Still, PSP investments are usually limited in the model.

The representative days are not modelled in a fixed order, and thus stored energy in hydrogen electrolysis is only regarded on an annual basis, while still being constraint by hydrogen capacity in each time slice. While this approach significantly helps to reduce computation time, it may overestimate the potential for hydrogen electrolysis. Furthermore, unlike PSP and batteries we assume that hydrogen electrolysis facilities do not have a generation unit, i.e., they cannot generate electricity from the hydrogen produced. The stored hydrogen can only be used by any of the three hydrogen-based generation technologies (see Table 3 and Table 4 above) considered. Therefore, hydrogen electrolysis parameters in Table 7 and Table 8 only reflect the power-to-hydrogen unit.

*Table 7. Characteristics of storage technologies.*

	Power Inv. Costs (€/kW)	Reservoir Inv. Costs (€/kWh)	Fixed O&M (%/a)	Variable O&M (€/MWh)	Efficiency (%)	Lifetime (yr)
Pumped storage	1500	80	1	0	80	80
Batteries	see Table 8	see Table 8	1	0	80	20
Hydrogen electrolysis	see Table 8	see Table 8	2	3	70	20

Source: Schmidt et al. (2019) and own assumptions.

Table 8. Storage technologies with time-dependent investment costs. Investments costs after 2050 are assumed to remain constant at the 2050 value.

		2010	2015	2020	2025	2030	2035	2040	2045	2050-2070
Batteries	Power (€/kW)	678	678	373	231	156	122	108	102	95
	Reservoir (€/kWh)	5417	5417	4550	3575	2871	2383	2113	1950	1788
Hydrogen Electrolysis	Power (€/kW)	1595	1595	1282	973	662	629	596	563	530
	Reservoir (€/kWh)	31	31	26	20	16	14	12	11	10

Source: Schmidt et al. (2019), Saba et al. (2018) and own assumptions.

#### 4.4. Depreciation of installed capacities

All technologies in LIMES-EU are characterized by technology-specific lifetimes. However, even before reaching their maximum lifetime, installed capacities are subject to degradation. This is implemented via the depreciation factor  $\omega_{\tilde{t},te}$  which depends on the lifetime  $\psi_{te}$  of a technology  $te$  and the time  $\tilde{t}$  that has passed since its installation (Equation (5)). Only the share  $\omega_{\tilde{t},te}$  of the installed capacity can be used for electricity generation, storage or transmission, respectively. Figure 4 visualizes the depreciation factor  $\omega_{\tilde{t},te}$  for three different technological lifetimes: 20, 40 and 60 years.

$$\omega_{\tilde{t},te} = 1 - \left(\frac{\tilde{t}}{\psi_{te}}\right)^6 \quad \forall te, \tilde{t} \leq \psi_{te} \quad (5)$$

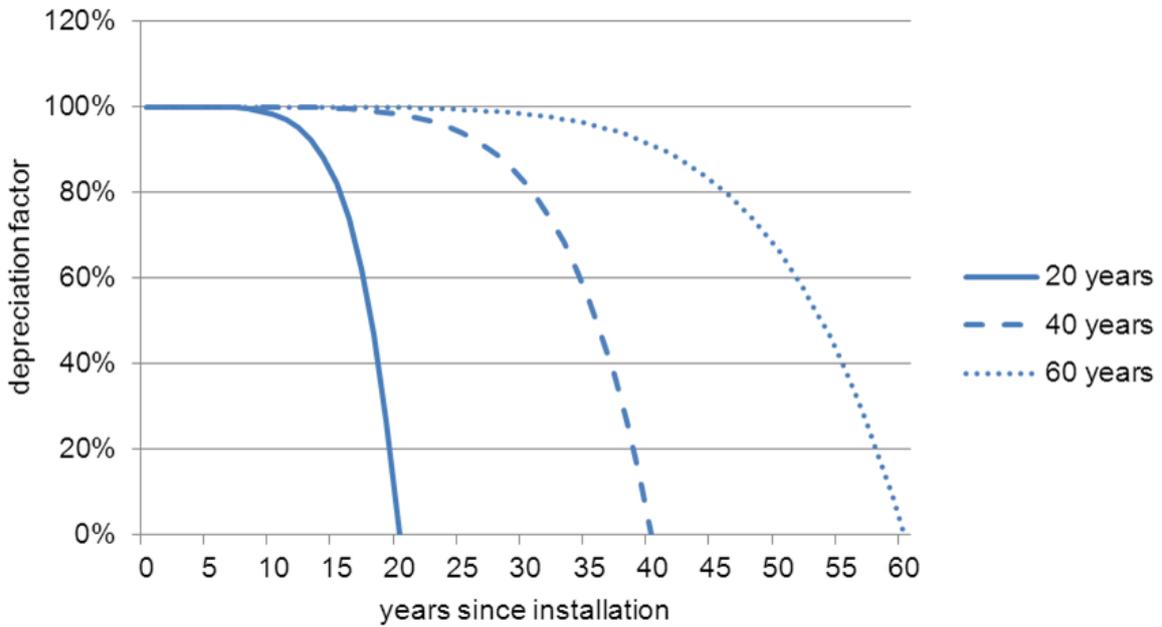


Figure 4. Depreciation factor  $\omega$  for three different technological lifetimes (20, 40, 60 years).

#### 4.5. Security of supply and reserves

Besides the operating constraints considered for dispatchable technologies (minimum load and ramping constraints), we assume that countries implement measures to ensure secure power system operation by having sufficient overcapacity for an emergency. A 15% capacity margin is considered, i.e., firm capacity (after applying derating factors) and reserves have to exceed demand by at least 15% at any time. Although the capacity requirements are considered for all the time slices, these are normally only binding at peak hours. Table 9 shows the assumed derating factors and the variables that they multiply in order to estimate the de-rated capacity. While de-rated capacity of dispatchable technologies is computed on the installed capacity, the de-rated capacity of intermittent technologies (i.e., variable renewables) is computed on their maximum output using a substantially lower derating factor (with respect to dispatchable technologies) to account for their lower reliability. The maximum output already depends on vRES availability factors, and thus accounts for hourly and seasonal patterns. For storage we

de-rate output to avoid overestimating the adequacy contribution of these technologies, and only 70% of net imports are considered. The detailed calculations are presented in Appendix g.

Table 9. Derating factors.

Dispatchable technologies	0.93	Installed capacity
Intermittent technologies	0.25	Max. availability
Storage technologies	0.5	Output
Net imports	0.7	Volume

Source: Own assumptions.

## 5. Region-Specific Input Data

### 5.1. Electricity Demand

#### 5.1.1. Annual demand

As discussed in Section 3, the intra-year variation of the model regions' electricity consumption is based on ENTSO-E (2016). Final annual electricity consumption for 2010 and 2015 is retrieved from EUROSTAT (2018a) for all countries except Switzerland, for which BFE (2017) statistics are used. Demand projections until 2050 are based on European Commission (2016) for EU members and BFE (2013) for Switzerland for default scenarios. Future demand for Norway and Balkan countries is estimated based on the growth rates of their neighboring countries for which data is available. To account for the most recent estimations regarding sector coupling due, mainly, to larger electrification of heating and transportation, we scale 2020-2050 demand using the data (at EU level, data at national-level not available) from the EU's "strategic long-term vision for a prosperous, modern, competitive and climate-neutral economy by 2050" (European Commission, 2018b). For years after 2050 until 2070 we assume that the demand is fixed at 2050 values.

Table 10 reports both the historical data for 2010 and 2015, and the default projections for future electricity demand. Regarding the year 2050, electricity consumption is projected to rise

in every model region. However, the relative increase differs strongly across countries, with Switzerland (+4%) and Luxembourg (+94%) being at the lower and upper end, respectively. An explanation of the region codes used in this document is given in Appendix B. Based on historical data, it is assumed that the required production of electricity has to exceed the reported final electricity consumption by 8% to account for intra-regional transmission and distribution losses.

*Table 10. Default assumptions for final electricity demand (in TWh).*

	2010	2015	2020	2025	2030	2035	2040	2045	2050-2070
BE	83.4	82.5	84.7	88.3	93.9	98.7	105.4	114.7	124.2
BG	27.2	28.3	29.3	31.2	32.8	34.0	35.5	37.9	40.9
CZ	56.2	56.8	61.5	66.3	69.8	74.0	77.8	84.4	90.9
DK	32.1	30.7	33.1	35.7	37.7	40.6	43.1	47.0	51.1
DE	532.4	514.7	534.6	563.9	590.0	603.4	613.4	639.0	666.2
EE	6.9	6.9	7.7	8.1	8.8	9.2	9.6	10.5	11.3
IE	25.3	25.5	26.4	28.2	29.7	31.5	33.2	35.8	39.0
GR	53.1	50.8	53.7	53.8	53.3	56.8	58.8	61.5	64.8
ES	245.4	232.1	248.6	257.8	271.0	282.7	292.9	311.3	334.3
FR	443.7	421.6	455.9	473.7	495.4	525.3	550.9	587.5	629.1
HR	15.9	15.3	16.3	16.8	17.3	18.4	19.4	21.3	23.6
IT	299.3	287.5	306.8	316.8	331.1	360.7	389.2	420.8	453.8
LV	6.2	6.5	7.3	7.9	8.5	9.0	9.8	10.6	11.4
LT	8.3	9.3	10.4	10.8	10.8	11.1	11.4	12.5	13.4
LU	6.6	6.2	7.0	7.8	8.8	10.0	11.3	12.6	13.8
HU	34.2	37	36.2	39.5	41.3	43.6	46.5	50.8	54.2
NL	107.4	103.6	111.4	118.3	122.8	127.4	133.4	142.1	152.6
AT	60.3	60.8	67.7	72.1	76.5	80.2	84.2	90.3	95.1
PL	118.7	127.8	143.2	161.3	177.6	190.2	201.4	216.8	232.5
PT	49.9	45.8	47.5	49.3	50.5	52.0	53.7	56.3	58.6
RO	41.5	43.1	47.6	50.9	53.9	57.2	61.0	66.2	71.6
SI	11.9	12.8	13.6	15.2	15.9	16.5	17.3	18.5	19.8
SK	24.1	24.4	27.3	30.4	32.8	34.6	35.8	37.6	39.3
FI	83.4	78.4	80.4	85.2	88.6	92.7	96.2	103.1	110.4
SE	131.2	124.9	136.6	144.3	152.2	159.1	165.3	177.9	190.5
GB	329	302.9	324.9	341.4	359.4	381.6	414.5	450.3	471.5
NO	113.5	110.8	120.2	123.8	128.0	131.4	135.4	141.6	147.1
CH	59.8	58.2	58.6	58.3	58.1	57.8	58.8	59.8	60.8
Balkan	57.7	57.7	60.0	61.5	62.2	64.6	67.6	70.4	73.4

Source: European Commission (2016), EUROSTAT (2018a), BFE (2013), BFE (2017); own assumptions.

### 5.1.2. Hourly patterns

As explained in Section 3.2, we use a clustering algorithm to derive the hourly demand. These nonetheless follow the patterns from original data (2010-2011). Although demand is scaled using annual demand, the changes in peak demand in certain countries in the last decade are larger than changes in annual demand. For instance, peak demand in GB decreased from 61 GW in 2010 to (expectedly) 48 GW in 2020 (ENTSO-E, 2019a) (see Table 11), i.e., 21%. In the same period, annual demand decreased from 329 to 325 TWh. To account for changes in such patterns over time, we rescale hourly demand as of 2020 using the peak demand for the winter 2019/2020 ( $peakdem_{t,r}$ ). Our rescaling methodology ensures that the variability of the clustered demand remains unchanged.

Table 11. Peak demand in 2010 and 2020.

Region	2010	2020	Region	2010	2020	Region	2010	2020
FI	14.6	13.4	PL	19.5	25.1	SI	1.9	2.4
NO	20.7	21.9	DE	84.7	79.9	FR	88.6	82.2
SE	24.8	26.7	BE	14.0	13.2	HR	2.8	2.9
EE	1.3	1.4	LU	1.0	1.0	BG	4.9	6.3
LV	1.1	1.2	CZ	9.6	10.6	IT	51.9	51.6
LT	1.4	2.1	SK	3.9	4.6	ES	38.9	39.5
DK	6.0	6.0	AT	10.1	11.5	PT	8.8	7.3
GB	60.6	48.1	CH	9.7	10.3	GR	8.8	8.0
IE	4.5	5.3	HU	5.6	6.3	Balkan	10.6	12.2
NL	18.1	18.2	RO	6.8	9.3			

Source: ENTSO-E (2011, 2019a); own assumptions

We assume that ‘capacity factor’ ( $cf_r$ ) of peak demand is constant for every country.

$$cf_r = \left( \sum_{\tau} d_{2020,\tau,r} / peakdem_{2020,r} \right) (1/8760) \quad (6)$$

We calculate the variability of the maximum clustered demand ( $deltadem_r$ ) assuming the recalculated ‘capacity factor’.

$$deltadem_r = \left( \max_{\tau} d_{2020,\tau,r} * cf_r - \sum_{\tau} d_{2020,\tau,r} * (1/8760) \right) / (1 - cf_r) \quad (7)$$

We then aggregate such delta and the (original) clustered hourly demand

$$dem\_nonadj_{\tau,r} = d_{2020,\tau,r} + deltam_r \quad (8)$$

We recalculate the demand scale ( $demscale\_adj_{\tau,r}$ ), i.e., ratio between demand and average demand

$$demscale\_adj_{\tau,r} = dem\_nonadj_{\tau,r} * 8760 / \sum_{\tau} dem\_nonadj_{\tau,r} l_{\tau} \quad (9)$$

And use such demand scale to compute (again) the hourly demand as of 2020 ( $d_{t,\tau,r}$ )

$$d_{t,\tau,r} = demscale\_adj_{\tau,r} * \sum_{\tau} d_{2020,\tau,r} * (1/8760) \quad \forall t \geq 2020 \quad (10)$$

## 5.2. Installed Capacities in 2015 and 2020

### 5.2.1. Generation

As the model is calibrated to 2015 as base year, installed capacities in 2015 are set exogenously. The existing capacities of generation and storage technologies (see Table 12) are derived from Open Power System Data (2018), which aggregates data from different official sources, e.g., ENTSO-E, local TSOs and local ministries. For instance, in the specific case of Germany, data from the BMWi (2018) is used. The age structure of technologies is derived from Platts (2011) and EUROSTAT (2018b). Due to lack of reliable data for the rest of countries, waste and other gases capacities are only considered in Germany.

Table 12. Installed generation and storage power capacities in 2015 (in GW).

	Nuclear	Hard coal	Lignite	Natural gas CC	Natural gas GT	Oil	Waste	Other gases	Hydro	Biomass	Wind onshore	Wind offshore	PV	CSP	PSP	PSP*
FI	2.8	4.6	0.0	1.5	1.0	2.2	0.0	0.0	3.3	2.0	0.7	0.0	0.0	0.0	0.0	0
NO	0.0	0.0	0.0	1.0	0.7	0.0	0.0	0.0	29.9	0.0	0.7	0.0	0.0	0.0	1.4	11000
SE	10.0	0.1	0.0	0.6	0.3	4.3	0.0	0.0	16.2	4.1	4.6	0.2	0.0	0.0	0.1	--
EE	0.0	2.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.0	0.0	0.0	0.0	0
LV	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	1.6	0.1	0.2	0.0	0.0	0.0	0.0	0
LT	0.0	0.0	0.0	2.6	0.0	0.0	0.0	0.0	0.1	0.1	0.4	0.0	0.1	0.0	0.9	0
DK	0.0	2.4	0.0	1.3	0.8	0.1	0.0	0.0	0.0	1.4	3.7	1.3	0.6	0.0	0.0	0
GB	9.4	17.9	0.0	28.9	4.1	1.1	0.0	0.0	1.7	1.8	8.5	4.3	9.1	0.0	2.7	33
IE	0.0	0.9	0.4	3.5	0.8	0.9	0.0	0.0	0.2	0.0	2.7	0.0	0.0	0.0	0.3	2
NL	0.5	7.5	0.0	18.2	2.7	0.0	0.0	0.0	0.0	0.4	2.8	0.4	1.3	0.0	0.0	0
PL	0.0	19.5	8.6	1.0	0.1	0.0	0.0	0.0	0.6	0.7	3.8	0.0	0.0	0.0	1.8	11
DE	10.8	28.8	21.2	22.5	6.7	2.7	0.8	2.9	4.0	7.4	41.0	3.3	39.8	0.0	6.4	39
BE	5.9	0.5	0.0	5.1	1.3	0.2	0.0	0.0	0.1	1.4	2.1	0.9	3.1	0.0	1.3	8
LU	0.0	0.0	0.0	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	1.3	--
CZ	3.7	1.2	8.3	1.3	0.7	0.1	0.0	0.0	1.1	0.4	0.4	0.0	2.2	0.0	1.2	7
SK	2.3	0.5	0.6	1.0	0.2	0.3	0.0	0.0	1.6	0.2	0.0	0.0	0.5	0.0	1.0	4
AT	0.0	1.3	0.0	5.1	0.5	0.2	0.0	0.0	9.6	0.6	2.5	0.0	0.7	0.0	3.4	125
CH	3.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	11.9	0.3	0.1	0.0	1.1	0.0	1.8	369
HU	1.9	0.1	0.8	3.5	0.8	0.4	0.0	0.0	0.1	0.3	0.6	0.0	0.0	0.0	0.0	0

	Nuclear	Hard coal	Lignite	Natural gas CC	Natural gas GT	Oil	Waste	Other gases	Hydro	Biomass	Wind onshore	Wind offshore	PV	CSP	PSP	PSP*
RO	1.3	1.4	4.4	2.6	0.1	0.0	0.0	0.0	5.2	0.1	3.0	0.0	2.0	0.0	1.3	--
SI	0.7	0.3	1.1	0.1	0.1	0.0	0.0	0.0	1.1	0.0	0.1	0.0	0.3	0.0	0.2	--
FR	63.1	3.0	0.0	6.4	4.5	8.7	0.0	0.0	21.0	0.0	10.3	0.0	6.2	0.0	2.5	184
HR	0.0	0.5	0.0	1.0	0.1	0.5	0.0	0.0	1.8	0.0	0.4	0.0	0.0	0.0	0.3	--
BG	2.0	1.4	4.0	1.0	0.1	0.0	0.0	0.0	2.1	0.1	1.1	0.0	1.2	0.0	1.1	2
IT	0.0	9.9	0.0	45.2	4.2	8.1	0.0	0.0	17.0	4.3	9.6	0.0	19.3	0.0	8.2	--
ES	7.6	10.0	1.1	27.5	5.3	3.5	0.0	0.0	13.9	0.9	23.0	0.0	4.7	2.3	6.4	1530
PT	0.0	1.8	0.0	3.4	1.3	0.1	0.0	0.0	4.4	0.6	4.8	0.0	0.4	0.0	1.8	107
GR	0.0	0.0	4.5	4.0	1.6	2.5	0.0	0.0	2.7	0.1	1.8	0.0	2.6	0.0	0.7	21
Balkan	0.0	0.0	7.9	0.0	0.0	0.2	0.0	0.0	5.0	0.0	0.4	0.0	0.0	0.0	3.1	--

Source: Open Power System Data (2018), BMWi (2018), Platts (2011), EUROSTAT (2018b); own assumptions.

\*PSP reservoir capacity (in GWh)

Table 13. Installed generation and storage power capacities in 2020 (in GW).

	Nuclear	Hard coal	Lignite	Natural gas	Oil	Waste	Other gases	Hydro	Wind onshore	Wind offshore	PV	CSP	PSP
FI	2.8	2.3	0.0	1.9	1.4	1.6	0.1	3.1	3.1	0.4	0.1	0.0	0.0
NO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	32.6	2.9	0.0	0.1	0.0	0.0
SE	7.7	0.2	0.0	0.8	3.2	0.2	0.1	16.3	8.8	0.2	0.7	0.0	0.0
EE	0.0	0.0	0.0	0.2	2.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
LV	0.0	0.0	0.0	1.0	0.0	0.1	0.1	1.6	0.1	0.0	0.0	0.0	0.0
LT	0.0	0.0	0.0	1.8	0.0	0.0	0.0	0.1	0.5	0.0	0.1	0.0	0.9
DK	0.0	1.5	0.0	1.7	0.9	0.0	0.0	0.0	5.0	2.3	1.1	0.0	0.0
GB	9.2	10.2	0.0	31.2	1.2	0.0	0.0	1.3	13.6	9.7	17.1	0.0	2.9
IE	0.0	0.9	0.0	3.9	0.9	0.3	0.0	0.2	4.1	0.1	0.1	0.0	0.3
NL	0.5	4.0	0.0	18.5	0.0	0.4	0.4	0.0	5.1	2.4	10.5	0.0	0.0
PL	0.0	20.4	7.4	3.5	0.0	0.0	0.0	0.9	7.1	0.0	0.5	0.0	1.3
DE	8.1	18.2	17.6	23.9	2.1	2.0	2.0	5.3	59.5	7.6	56.2	0.0	8.0
BE	5.9	0.0	0.0	6.8	0.2	0.0	0.0	0.1	2.5	2.3	4.0	0.0	1.3
LU	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.2	0.0	0.1	0.0	1.3
CZ	4.0	1.6	8.8	1.3	0.0	0.0	0.0	1.0	0.6	0.0	2.4	0.0	1.2
SK	1.9	0.2	0.3	1.1	0.3	0.2	0.2	1.6	0.1	0.0	0.6	0.0	0.9
AT	0.0	0.2	0.0	4.9	0.2	0.5	0.5	5.8	3.9	0.0	2.0	0.0	5.9
CH	3.3	0.0	0.0	0.0	0.1	0.3	0.3	12.3	0.1	0.0	2.6	0.0	4.0
HU	1.9	0.0	1.0	4.1	0.4	0.0	0.0	0.1	0.3	0.0	0.8	0.0	0.0

	Nuclear	Hard coal	Lignite	Natural gas	Oil	Waste	Other gases	Hydro	Wind onshore	Wind offshore	PV	CSP	PSP
RO	1.3	1.0	3.1	2.9	0.0	0.0	0.0	6.4	3.2	0.0	1.5	0.0	0.0
SI	0.7	0.0	1.0	0.5	0.1	0.1	0.1	1.1	0.0	0.0	0.3	0.0	0.2
FR	63.1	2.9	0.0	6.7	2.3	2.6	2.6	18.6	18.3	1.1	14.6	0.0	5.0
HR	0.0	0.3	0.0	0.7	1.0	0.0	0.0	1.8	0.8	0.0	0.1	0.0	0.3
BG	2.2	0.4	4.1	1.0	0.0	0.0	0.0	2.3	0.9	0.0	1.3	0.0	0.9
IT	0.0	7.4	0.0	45.8	1.3	0.2	0.2	15.3	11.3	0.0	23.9	0.1	7.6
ES	7.1	9.2	0.0	29.0	0.0	0.3	0.3	14.3	26.7	0.0	13.0	2.3	6.0
PT	0.0	1.8	0.0	4.6	0.0	0.0	0.0	4.3	5.5	0.0	1.8	0.0	2.8
GR	0.0	0.0	3.9	4.9	0.0	0.0	0.0	2.7	3.3	0.0	2.7	0.1	0.7
Balkan	0.0	0.0	8.1	0.5	0.3	0.0	0.0	7.5	1.4	0.0	0.1	0.0	1.1

Source: ENTSO-E (2019a), WindEurope (2018), SolarPower Europe (2019) and own assumptions.

Due to the closeness of 2020, we also fix the capacities for 2020. Dispatchable capacities and PSP are derived from the Winter Outlook 2019/2020 (ENTSO-E, 2019a). Capacities from vRES are interpolated between the current capacities (IRENA, 2018) and the expected capacities from WindEurope (2018) and SolarPower Europe (2019) outlooks. Due to the lack of data, we assume the share of CCG and GT gas plants of 2015 remains in 2020; biomass is assumed to vary  $\pm 10\%$  from capacity in 2015; and CSP corresponds to the one installed by 2018.

### 5.2.2. Transmission

The cross-border transmission capacities (Table 14) correspond to the average value of NTC's in both directions for each of the existing and potential cross-border links (according to the 2018 Ten Year Network Development Plan - TYNDP (ENTSO-E, 2017a). The 2010 values are derived from the summer NTC values reported by ENTSO-E (2010). The 2015 values are derived from the ACER/CEER (2017) report. For those links for which 2015 NTC's are not reported (countries with market coupling, e.g., FR-BE), the values from 2010 are used. We also derive NTCs for 2020 (ENTSO-E, 2018), 2025 (ENTSO-E, 2019b) and 2040 (ENTSO-E, 2017a). Capacities for 2020 are also fixed due to the proximity of the year. The values for 2025 and 2040 are used as reference NTCs for different scenario analyses. As the precise age structure of the transmission network is unknown, we assume that the existing lines in 2010 were either constructed or refurbished after 1985 and that investments into the grid were equally distributed between 1985 and 2010 (relevant for the obsolescence of transmission capacities).

Table 14. Transmission capacities between model regions (GW).

Link	2010	2015	2020	2025	2040	Link	2010	2015	2020	2025	2040
AT-CH	0.8	1.0	1.2	1.2	1.7	AT-SI	0.9	0.9	1.0	1.0	2.2
AT-CZ	0.7	0.6	0.9	0.9	1.1	AT-SK	0.0	0.0	0.0	0.0	0.0
AT-DE	1.6	1.6	5.0	5.4	7.5	BE-DE	0.0	0.0	1.0	1.0	2.0
AT-HU	0.4	0.6	0.8	0.8	1.0	BE-FR	2.1	2.1	2.6	3.6	4.6
AT-IT	0.1	0.2	0.3	0.6	1.5	BE-LU	0.0	0.0	0.4	0.4	0.4

Link	2010	2015	2020	2025	2040	Link	2010	2015	2020	2025	2040
BE-NL	2.3	2.3	1.9	2.4	4.4	HR-HU	0.8	1.1	2.0	1.7	2.0
BG-GR	0.5	0.5	0.5	1.1	2.9	HR-SI	0.8	1.5	1.5	2.0	3.0
BG-Balkan	0.5	0.5	0.6	0.9	2.2	HU-Balkan	0.6	0.6	0.6	0.6	2.1
BG-RO	0.4	0.2	0.3	1.2	1.5	HU-SI	0.0	0.0	1.2	1.2	1.2
CH-DE	3.2	2.7	3.7	3.7	5.3	HU-SK	0.8	0.9	2.0	2.2	2.0
CH-FR	2.1	2.1	2.2	2.5	5.0	LT-PL	0.0	0.0	0.5	0.5	1.0
CH-IT	2.5	2.3	2.7	2.7	4.9	LU-DE	1.0	1.0	2.3	2.3	3.3
CZ-PL	1.4	0.2	0.7	0.3	0.7	LU-FR	0.0	0.0	0.2	0.2	0.2
CZ-SK	1.6	1.4	1.5	1.5	1.6	LV-LT	1.2	0.8	1.4	1.0	1.4
DE-CZ	1.5	1.7	1.8	1.8	2.3	NL-DE	4.0	4.0	4.3	5.0	5.0
DE-DK	1.8	1.1	2.6	4.5	4.0	NL-NO	0.7	0.7	0.7	0.7	1.7
DE-FR	2.9	2.9	2.1	3.0	5.8	NO-SE	3.6	3.0	3.8	3.8	3.8
DE-PL	1.0	0.0	1.8	1.0	3.3	PL-SE	0.3	0.2	0.5	0.6	0.6
DE-SE	0.6	0.6	0.6	0.6	2.3	PT-ES	1.2	2.5	3.9	3.9	4.4
DK-NO	1.0	1.4	1.6	1.6	1.6	RO-HU	0.6	0.6	1.1	1.1	1.9
DK-SE	1.9	1.9	2.2	2.2	3.2	RO-Balkan	0.5	0.5	0.9	0.9	1.8
EE-FI	0.4	0.9	1.0	1.0	1.0	SI-IT	0.2	0.6	0.6	0.6	1.6
EE-LV	0.5	0.7	0.9	1.0	1.8	SK-PL	0.6	0.1	1.0	0.5	1.0
ES-FR	0.9	1.2	2.7	5.0	10.0	DE-NO	0.0	0.0	0.0	1.4	1.4
FI-SE	1.9	2.4	2.4	3.2	4.1	LT-SE	0.0	0.0	0.7	0.7	0.7
FR-GB	2.0	1.8	2.0	4.0	5.9	IT-Balkan	0.0	0.0	0.6	0.6	1.2
FR-IT	1.6	1.7	3.1	3.2	3.4	BE-GB	0.0	0.0	1.0	1.0	2.0
GB-IE	0.2	0.5	0.5	1.7	0.5	FR-IE	0.0	0.0	0.0	0.0	1.2
GB-NL	0.0	0.0	1.0	1.0	1.0	GB-DK	0.0	0.0	0.0	1.4	1.4
GB-NO	0.0	0.0	0.0	2.8	2.9	DK-PL	0.0	0.0	0.0	0.0	1.5
GR-Balkan	0.3	0.3	1.2	1.2	2.3	DK-NL	0.0	0.0	0.7	0.7	0.7
GR-IT	0.5	0.4	0.5	0.5	0.5						
HR-Balkan	0.9	0.9	1.3	1.2	3.9						

Source: ACER/CEER (2017), ENTSO-E (2010), ENTSO-E (2017a), ENTSO-E (2018), ENTSO-E (2019b); own assumptions.

## 5.3. Resource Endowments

### 5.3.1. Wind & Solar

A country's wind and solar power potential is defined by two determinants: (1) the achievable capacity factors at the respective sites and (2) the installable capacity of wind and solar power plants. The achievable capacity factors allow us to scale the hourly availability factors from Section 4.1.1. For capacity installed until 2020 we use the average annual availability factors between 2010 and 2015 for each technology and country (IRENA, 2017a). For capacity built

after 2030, we consider derived capacity factors from NREL (2013) for wind onshore and offshore and Pietzcker *et al.* (2014) for PV. For 2025, we assume an average between historical data and those for 2030-2050. Given the lack of data for CSP generation, we do not scale the hourly availability for this technology. The former sources are used also to estimate the installable capacity for these technologies.

To account for the varying quality of wind and solar sites within a country, we define three resource grades per intermittent renewable technology for every model region. Each resource grade comprises a certain share of the resource potential and its assigned average technology-specific capacity factor of this area. Table 15 shows the technologies' capacity potentials per model region; the corresponding capacity factors per region and resource grade are given in Table 16.

Table 15. Installable capacities of wind and solar power plants per region and resource grade (in GW).

	Wind Onshore			Wind Offshore			PV			CSP		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
FI	0	5	253	0	29	51	69	278	333	0	1	3
NO	63	264	99	1	69	0	169	677	813	0	1	1
SE	0	40	316	0	155	67	92	367	440	1	2	4
EE	0	4	45	0	19	14	9	37	44	0	1	1
LV	0	4	67	0	38	28	19	75	90	0	1	2
LT	0	4	140	0	15	0	36	142	171	1	2	3
DK	0	106	0	74	146	0	31	124	148	1	2	3
GB	17	494	0	87	390	0	233	933	1120	3	10	21
IE	36	183	0	11	22	0	148	592	710	1	3	5
NL	0	35	44	3	159	0	31	125	150	0	1	2
PL	0	11	753	0	54	11	150	599	719	3	9	18
DE	0	73	496	16	74	2	230	921	1105	3	10	20
BE	0	6	65	0	16	0	33	131	157	0	1	2
LU	0	0	6	0	0	0	3	11	13	0	0	0
CZ	0	0	175	0	0	0	34	137	165	1	3	5
SK	0	0	105	0	0	0	24	95	114	0	1	2
AT	0	0	163	0	0	0	31	125	150	1	2	4
CH	0	0	60	0	0	0	23	91	109	0	1	2
HU	0	0	304	0	0	0	40	162	194	1	3	6

	Wind Onshore			Wind Offshore			PV			CSP		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
RO	0	0	653	0	0	48	155	619	743	3	8	17
SI	0	0	32	0	0	0	12	48	58	0	0	1
FR	0	85	1255	0	98	61	480	1921	2305	6	17	35
HR	0	0	135	0	0	36	7	30	36	0	1	2
BG	0	0	281	0	0	20	74	296	355	1	3	6
IT	0	0	700	0	0	77	218	872	1046	3	9	17
ES	0	11	1310	0	10	32	773	3093	3712	6	17	33
PT	0	0	195	0	0	9	171	685	822	1	2	4
GR	0	5	248	0	0	8	204	817	980	2	5	10
Balkan	0	0	535	0	0	1	37	149	179	2	6	12

Source: Dee *et al.* (2011), NREL (2013), FAO (2018), Held (2010); own assumptions.

NREL (2013) provides global onshore and offshore wind supply curves based on the National Center for Atmospheric Research's (NCAR) Climate Four Dimensional Data Assimilation (CFDDA) mesoscale climate database. For onshore it provides the resource potential at different distances (0-50 miles [near], 50-100 miles [transitional] and 100-5000 miles [far]). Each of these areas is broken into nine resource grades according to an average capacity factor (0.16-0.48). Using only the resource potential for "near" areas, we aggregate these into only three resource grades and for each of them estimate the weighted average capacity factor and the total resource potential.

Likewise, for wind offshore, NREL (2013) provides the resource potential at different distances (5-20 miles [near], 20-50 miles [transitional] and 50-100 miles [far]). In this case, we use the data for areas "near" and "transitional" and estimate the capacity factors and resource potentials for three resource grades as for wind onshore.

For PV Pietzcker *et al.* (2014) provides the capacity factors of 9 resource grades (best 1%, 1% to 5%, etc) and the usable land for two type of areas (1-50 km from settlement and 50-100 km from settlement). We use the "1-50 km from settlement" data to estimate the capacity factors

and installable potential of 3 resource grades aggregating the data from 0-5%, 5-25% and 25-100%.

For CSP, the installable capacity is determined by a set of three factors. First, by the area that is suitable for installing a specific technology. We derive the size of this area from land cover data (FAO, 2018). However, due to public acceptance and competing usage possibilities only a certain share of this area is actually available for power production; this share is the second determining factor. CSP plants may only be installed on former agricultural area, of which we assume that only the 2% is available for CSP installations (Held, 2010). And third, the amount of capacity that can be installed on the available area is subject to technology-specific restrictions. As we assume a SM4 configuration<sup>14</sup> in LIMES-EU, using data from Trieb *et al.* (2009) and Ong *et al.* (2013), we estimate the maximum installable capacity area to be 10 MW/km<sup>2</sup>. The allocation of the resource potential into the three grades is made in a way that the first resource grade comprises the best resource sites of a region that together add up to 10% of the region's area. The second resource grade comprises the next best sites that add up to 30% of the region's area. Consequently, the third resource grade contains 60% of a region's area subsuming the sites with the lowest capacity factors.

Table 16. Maximum capacity factors of wind and solar power plants per region and resource grade (%).

	Wind Onshore			Wind Offshore			PV			CSP		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
FI	0	32	25	0	32	28	13	13	12	10	8	5
NO	40	34	26	40	35	0	11	10	9	12	10	4
SE	0	32	25	0	34	27	12	12	11	15	12	6
EE	0	32	28	0	32	28	13	13	13	13	13	12
LV	0	32	27	0	32	27	13	13	12	15	15	14
LT	0	32	28	0	32	0	13	13	12	17	16	15
DK	0	34	0	40	34	28	12	12	12	18	17	15
GB	40	34	0	40	36	0	12	10	9	23	20	15
IE	40	36	0	40	36	0	11	9	9	21	19	17

<sup>14</sup> See Section 4.1.1.

	Wind Onshore			Wind Offshore			PV			CSP		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
NL	0	34	28	40	36	0	11	11	10	22	21	20
PL	0	32	26	0	33	28	11	11	11	23	22	19
DE	0	33	25	40	35	28	12	11	10	26	24	20
BE	0	32	28	0	35	0	12	11	10	24	23	22
LU	0	0	25	0	0	0	11	10	10	24	24	23
CZ	0	0	24	0	0	0	11	11	10	25	24	23
SK	0	0	19	0	0	0	12	12	11	28	27	25
AT	0	0	22	0	0	0	13	12	12	29	28	26
CH	0	0	23	0	0	0	12	12	12	32	31	28
HU	0	0	18	0	0	0	13	12	12	32	31	28
RO	0	0	18	0	0	24	13	13	12	36	34	29
SI	0	0	17	0	0	16	14	13	13	32	31	30
FR	0	32	24	0	33	26	14	12	12	40	35	27
HR	0	0	18	0	0	18	14	13	12	38	35	32
BG	0	0	19	0	0	23	14	13	13	41	39	37
IT	0	0	19	0	0	17	17	15	14	53	44	35
ES	0	34	20	0	32	22	17	16	16	57	52	44
PT	0	0	22	0	0	25	18	16	15	55	52	46
GR	0	32	21	0	32	24	18	17	15	53	49	43
Balkan	0	0	18	0	0	24	14	13	13	43	39	35

Source: Dee *et al.* (2011), NREL (2013); own assumptions.

### 5.3.2. Fuels & Hydro

As stated in Section 4.1.2, fuel prices vary only slightly across regions (use of markups to improve calibration for 2015). However, the availability of certain fuels differ largely across regions. Hard coal, natural gas and uranium are available to every model region in unrestricted quantities. Lignite, biomass, waste and other gases, however, can only be consumed in their country of origin. LIMES-EU does not allow for trade of these fuels as the calorific value of both lignite and many biofuels is too low for a cost-efficient long-distance transport. Not all regions have lignite resources; the consumption of lignite is therefore limited to those countries with existing lignite production in 2010 or 2015. In addition, we assume that new the maximum

annual consumption of waste and other gases is fixed to the maximum between 2010 and 2015 levels.

The bioenergy potential is based on EEA (2006) which states the environmentally sustainable biomass potential for the EU25 Member States. We assume that two thirds of the environmentally sustainable biomass potential can be deployed at competitive prices and that the transport and heat sector demand about 50% of the available biomass stock. Therefore, only one third of the potential stated in EEA (2006) is considered eligible for electricity production in LIMES-EU. Biomass potentials of countries for which no data is available in EEA (2006) are calculated based on the extent of arable land and forests in these countries (FAO, 2018) as well as the land structure and biomass potential of the surrounding countries with available data. In case the potential calculated for a specific country is smaller than its biomass deployment target stated in the Member States' National Renewable Energy Action Plans (NREAPS) (European Commission, 2013), the potential is adjusted to cover this target<sup>15</sup>. Table 17 shows the maximum deployment of biomass per model region.

The limited availability of sites suitable for deploying hydropower is reflected by a maximum installable capacity of hydro power plants. As the potential for further hydro power capacities is low in most European countries, capacity additions are only allowed up to the maximum of the level needed to fulfill the national targets for electricity production from hydro as stated in the NREAPS (European Commission, 2013), the historical capacity in 2010 and 2015, and the capacity in 2020 from ENTSO-E (2019a). In addition to the maximum installable capacity, the capacity factors of hydro power plants also vary among model regions. As the availability of hydro power varies significantly between years, we use an average of the realized capacity

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<sup>15</sup> This is the case for Denmark, the Netherlands, Belgium and Luxembourg.

factors between 2006 and 2015 that are derived from IRENA (2017a). Both installable capacities and annual availability factors are given in Table 17.

*Table 17. Regional biomass and hydropower potential.*

	Biomass			Hydro	
	Annual primary energy potential (in PJ)			Installable capacity (GW)	Annual availability (%/a)
	2010-2015	2020	2030-2050		
AT	96	109	121	10.1	56
BE	97	97	97	0.2	33
BG	19	33	39	2.3	22
CZ	53	63	70	1.3	24
DE	432	472	603	5.3	54
DK	77	77	77	0.0	26
EE	21	31	36	0.0	49
ES	230	307	350	14.3	26
FI	134	137	131	3.3	51
FR	438	519	662	22.6	37
GB	229	265	342	2.1	36
GR	22	47	53	2.7	22
HR	34	36	39	1.8	42
HU	50	63	78	0.1	47
IE	15	17	18	0.2	36
IT	226	261	346	17.0	37
LT	57	106	138	0.1	43
LU	3	3	3	0.0	36
LV	18	27	33	1.7	21
NL	145	145	145	0.1	31
PL	332	461	548	0.9	46
PT	50	54	57	5.7	29
RO	129	165	204	7.7	30
SE	163	181	188	16.9	47
SI	25	24	25	1.3	45
SK	31	33	50	2.0	31
Balkan	64	92	109	7.5	41
CH	34	40	49	12.5	35
NO	103	112	116	32.6	52

Source: Open Power System Data (2018), EEA (2006), FAO (2018), ENTSO-E (2019a), European Commission (2013), IRENA (2017a); own assumptions.

## **6. Emissions from other EU ETS sectors**

In order to represent the entire EU Emission Trading System (EU ETS) emissions from heating (large plants such as cogeneration heat and power (CHP) and district heating), aviation and the energy-intensive industry need to be considered as well. For heating and aviation sectors, we assume exogenous emissions, estimated as shares deducted directly from the emission cap., while for the energy-intensive industry we derive a marginal abatement cost curve (MACC) to roughly model its emissions and abatement costs.

### **6.1. Heating**

The combustion sector emissions added up to 1163 MtCO<sub>2</sub> (66% of stationary sector emissions) in 2017, accounting mainly for power plants. To differentiate electricity- and heat-related emissions, we estimate them using the primary energy consumed from power plants (Eurostat, 2019) and the emission factors from the IPCC's guidelines (Gomez et al., 2006). We allocate the emissions from CHP plants according to the power plants output. We estimate that heating-related emissions added up to 11% of the total stationary sector emissions in 2017. We thus assume exogenous emissions accounting for 11% of the cap for the entire modelling period.

### **6.2. Aviation**

This sector has its own cap (~37 MtCO<sub>2</sub>/yr have been allocated since 2013), but is allowed to buy certificates from the stationary sector. Emissions have increased from 53 MtCO<sub>2</sub> in 2013 to 64 MtCO<sub>2</sub> in 2017, the sector having always a negative balance of EU allowances for aviation (EUAA), i.e., airlines have had to buy allowances from the stationary sector to cover their emissions. The EU forecast aviation emissions (under the current scope of the EU ETS, i.e.,

only covering intra-EEA flights) to be between 65 and 70 MtCO<sub>2</sub> in 2030 (EEA, 2018). In addition, it is not clear whether this scope will remain, as the current derogation from the EU ETS obligations for flights to and from third countries is extended until 31 December 2023, subject to review. There is also significant uncertainty about the future demand and technical improvements as well as on feasibility of implementing alternative fuels on a large scale (ICAO, 2016). We assume that emissions from aviation remain at 60 MtCO<sub>2</sub>/yr and the cap – starting in 37 MtCO<sub>2</sub>/yr in 2020 – decreases at the same pace as the stationary cap. The difference between emissions and the aviation cap are thus subtracted from the stationary cap.

### **6.3. Energy-intensive industry**

To estimate the costs of emission reductions in the energy-intensive industry, we rely on a marginal abatement cost curve (MACC). We base our approach on a study by the Federation of German Industries (BDI) (Gerbert et al., 2018), which provides a MACC for the German industry by 2050. This comprises 33 abatement options, which, without considering those electricity-related, add up to 175 MtCO<sub>2</sub> abatement potential in 2050 (i.e., baseline emissions). Gerbert *et al.* (2018) also provide the energy use of the different sectors in 2050. We upscale this MACC to the entire EU ETS assuming that the share of energy use from each sector and country remains unchanged over time and that other countries' emission factor change in the same proportion as the German one. Through this approach we estimate a total abatement potential of 701 MtCO<sub>2</sub> for the industries covered by the EU ETS, of which ~600 MtCO<sub>2</sub> can be achieved at a price lower than 100 €/tCO<sub>2</sub> (see Figure 5). To estimate the MACC for each time step, we scale the MACC based on the 2015 total emissions from EU ETS industry (771 MtCO<sub>2</sub>) (European Commission, 2019b). We assume constant baseline emissions after 2050.

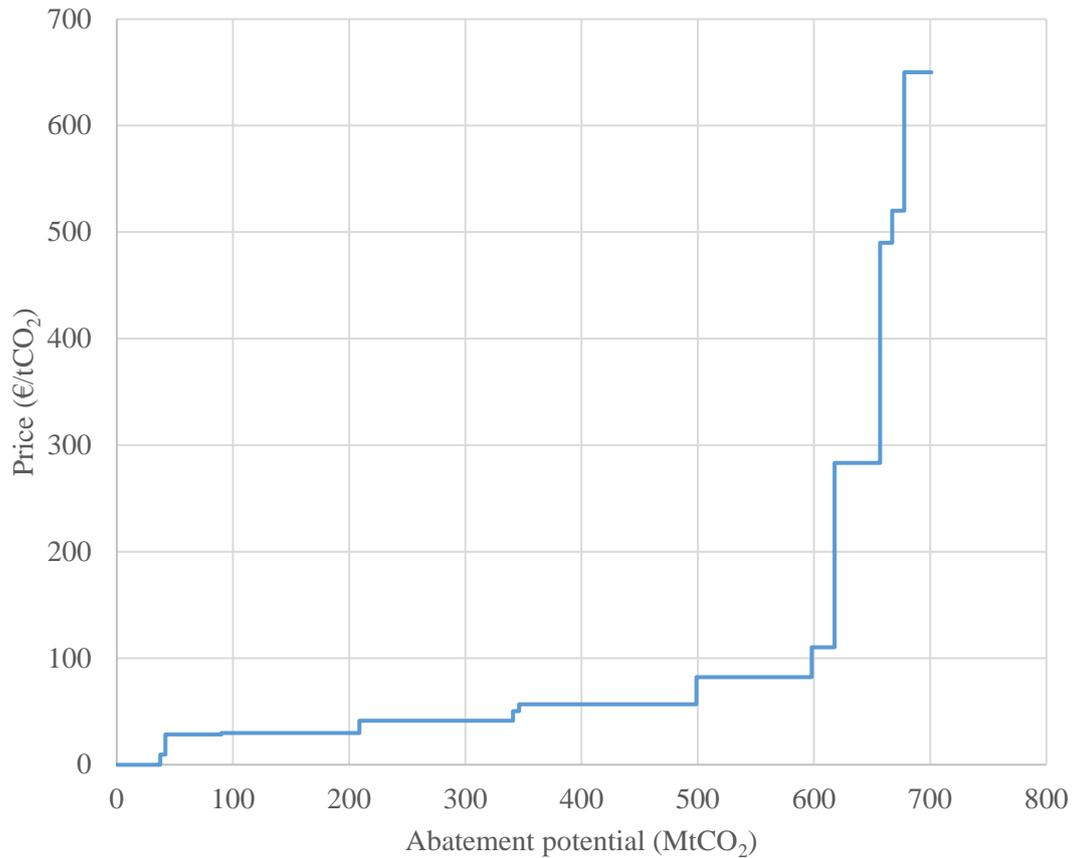


Figure 5. Estimated MACC in 2050 for the energy-intensive industry covered by the EU ETS.

## 7. Implementation of Policies

The model allows for implementing climate and energy policy targets by including constraints on CO<sub>2</sub> emissions or on the deployment of certain technologies. Targets can be set for single countries or for aggregate regions such as the EU Member States. As LIMES-EU is a social planner optimization model with perfect foresight, policy targets will always be fulfilled in a cost-effective way. Hence, results from LIMES-EU provide useful benchmarks on the future development of the European electricity system, but potentially underestimate important obstacles such as public acceptance or institutional capacity (cf. Hughes and Strachan (2010)).

**Climate Policy** Different stylized policies can be implemented in LIMES (emission intensity, CO<sub>2</sub> taxes, emission caps and budgets) for different countries, regions and primary energy sources. Moreover, the EU ETS is modelled where explicit design options as certificate banking, the Market Stability Reserve (MSR) and price floors are considered as described in Appendix A.h. Currently, the annual cap of the EU ETS in 2020 is set to 1816 MtCO<sub>2</sub> and will decrease at the linear reduction factor of 2.2% (of the average cap during phase II i.e. 48.4 MtCO<sub>2</sub> per year) until 2030 (end of the phase IV of the EU ETS). In default scenarios, we assume the cap keeps decreasing afterwards at the same rate.

**Renewable Policy** LIMES-EU allows for implementing technology-specific renewable energy targets for single model regions as well as implementing technology unspecific targets on EU or country level. Furthermore, we assume a RES target for Germany of at least 40% in 2025, 55% in 2035 and 80% 2050, and interpolate these values for the remaining years of our time-horizon. Targets are implemented as lower bounds on electricity production from these technologies.

**Energy Efficiency Policy** Energy efficiency translates to less electricity demand as compared to the reference scenario. As the electricity demand is given exogenously its reduction is not part of the optimization but set exogenously as well.

**Nuclear, Coal & CCS-related Policies** In several countries nuclear power plants, coal-fired plants and CCS technology face problems in public acceptance e.g. due to environmental risks. In order to accommodate this, their future deployment can be constrained by upper limits on investments. These limits can be set for each model region separately.

In the standard scenario we assume a progressive nuclear phase-out to be completed in Belgium by 2025, in Germany by 2022 and in Switzerland by 2044. Investments in

coal-fired plants are only allowed in Poland, Greece and Balkan, as these countries did not support this sector's public announcement of not building coal-fired power plants after 2020 (UNFCCC, 2018).

## 8. Evaluating base-year dispatch

Validating a long-term social planner model is conceptually challenging as the model does not aim to replicate historic developments but is designed to generate a socially optimal benchmark without considering real world market failures. A full-fledged validation is beyond the scope of this document. Nevertheless, complementary to the documentation of the model structure and its parameter values, this Section aims to build further trust in the model and to make its reasoning more accessible.

For the base year 2015, only the dispatch of generation, storage and transmission technologies is optimized by LIMES-EU. The installed capacities are given exogenously. In this Section we compare the dispatch resulting from LIMES-EU with historic electricity production data from ENTSO-E (2017b) (given the lack of fossil-based generation data for the Netherlands, we use data from Mantzos *et al.* (2018)). In addition, we compare the modelled carbon emissions with the historic emissions<sup>16</sup> in 2015.

In order to replicate the historic dispatch, we assume an exogenous CO<sub>2</sub> price of 8 €/tCO<sub>2</sub> which is consistent with the average price for EU ETS allowances in this year. Figure 6 gives the historic and model based electricity generation mix of each region and of the EU28 Member States in total. The main variations occur in France, where only a small share of electricity was

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<sup>16</sup> To estimate the electricity-related emissions, we allocate the emissions from CHP according to the share of their gross electricity output in their total output (heat and electricity) using data for the EU from Mantzos *et al.* (2018). Due to the lack of data, for Norway, Switzerland and Balkan we use emissions from public electricity and heat production from IEA (2017).

provided by hard coal and natural gas-fired power plants in 2015, while in the model these sources are replaced by larger nuclear generation. This is because there is only a simplified representation of CHP for Germany in the model, while in the other countries no additional revenues for heat from CHP plants are represented. Accordingly, we underestimate their dispatch.

Other regional electricity mixes deviate from historic data, e. g. hard coal is overrated in Italy and underrated in Poland. This is due to the fact that differences in prices for primary energy sources are only accounted very roughly due to lack of data. It optimizes the overall European electricity system, without taking into account market failures that might distort the cost-effective outcome in reality. This is certainly a drawback when aiming at reproducing historic market outcomes, but it is reasonable in order to derive benchmarks for the cost-effective future development of the European electricity system.

However, the aggregated electricity mix of the EU28 is well reproduced by the model. Only lignite is somewhat overrated while biomass and vRES generation is lower than in reality. The lower vRES generation is due to the higher availability factors in 2015 than those used in the model. This is explained by an improvement in technologies efficiency. Recall that we assume for capacity installed before 2015 has annual capacity factors equivalent to the average capacity factors between 2010 and 2015, e.g., the weighted average capacity factor for wind offshore in the EU between 2010 and 2015 was 30.7%, while the historical value for 2015 was 37.2% (IRENA, 2017a).

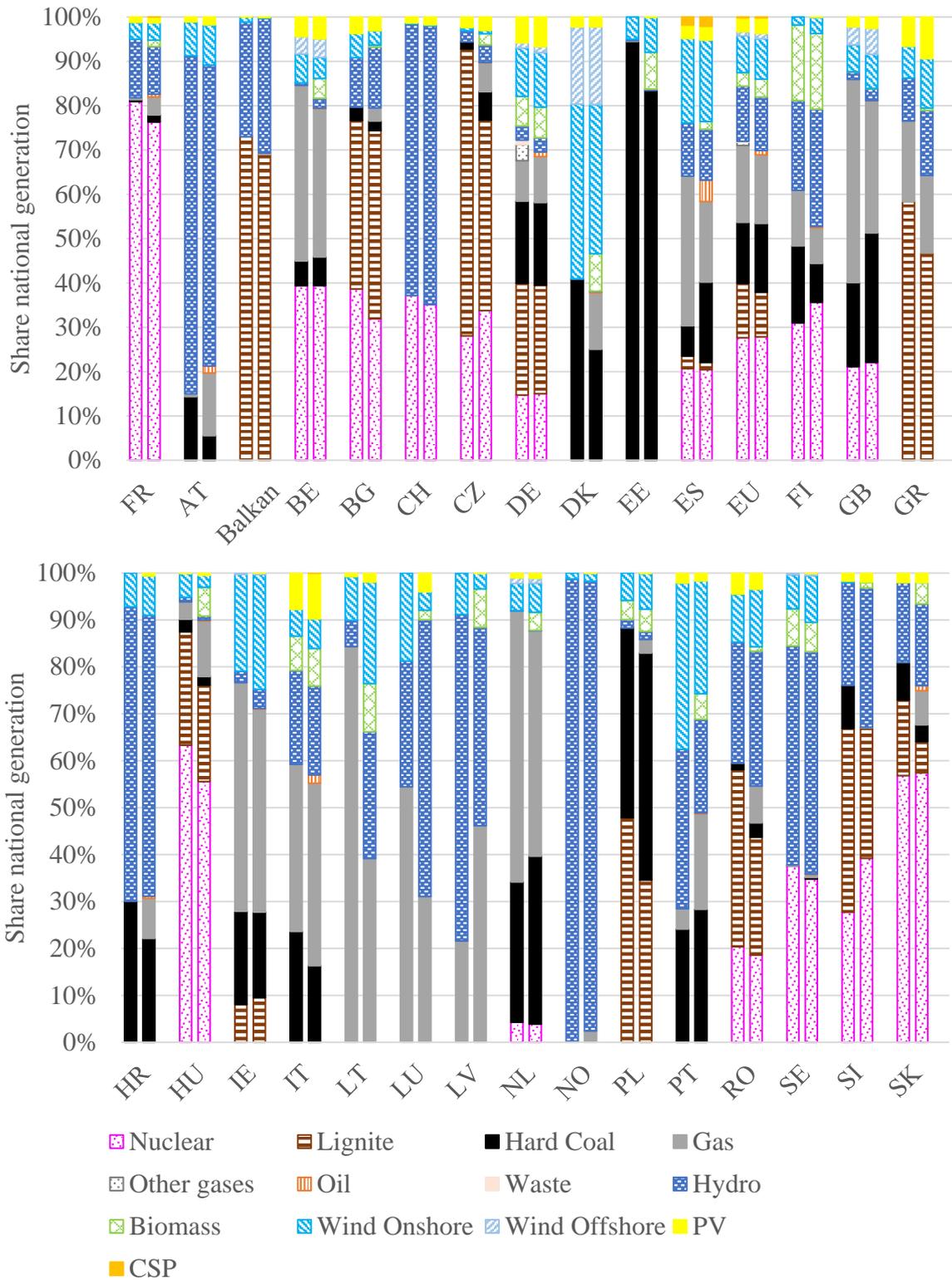


Figure 6. Comparison of the model-derived (left bar) and the historic (right bar) region-specific electricity generation mix in 2015. Source: ENTSO-E (2017b); own model results.

Figure 7 shows both historic emissions and model results for 2015. For Germany, we also present the historical emissions from a national source, the Öko Institute (Harthan and Hermann, 2018), which is in charge of reporting on the national emissions. This value is closer to our modelled results. As most of French generation is emission-free, this underestimation of gas and hard-coal generation leads to a sizable relative error between the modelled and historical results. However, these have little impact on EU aggregate emissions as French emissions represent a very small portion of them. Despite the simplifying model assumptions, the fit between historic emissions and model results is appropriate.

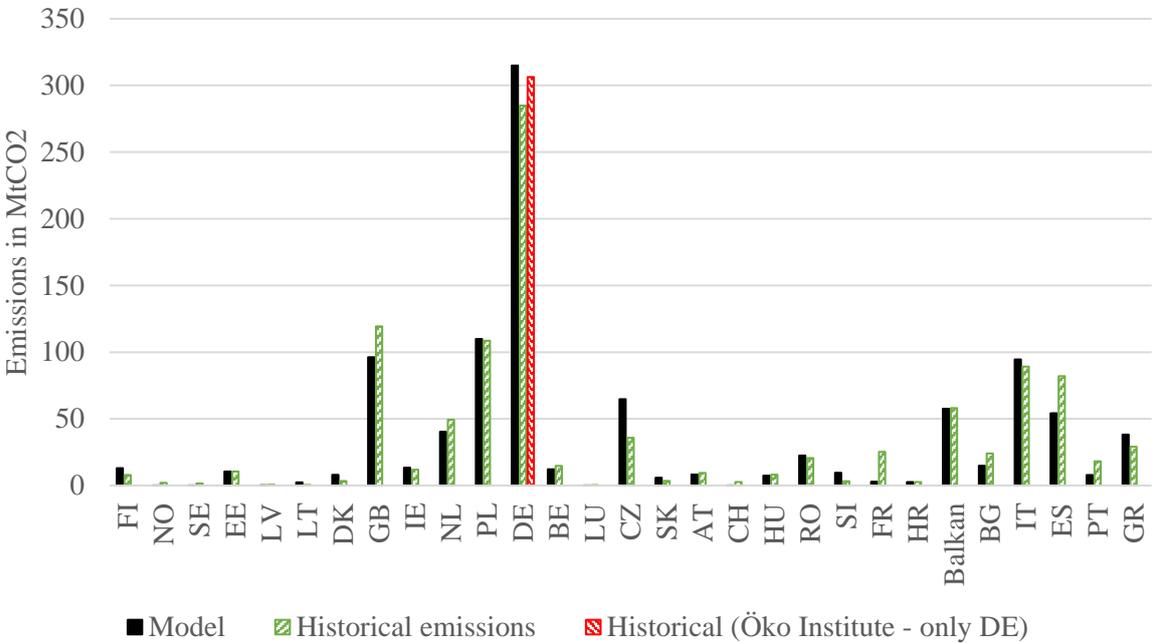


Figure 7. Comparison of historic and modelled region-specific CO<sub>2</sub> emissions in 2015. Source: Mantzos et al. (2018), IEA (2017), Harthan and Hermann (2018); own calculations and model results.

### 9. The impact of the representative days choice

The more representative days are included the higher the model accuracy, yet also the higher the computational effort. However, robustness of results is required to assess long-term impacts in the power sector. For instance, VREs variability has a substantial impact on market

dynamics. Large amounts are desirable to reach emission targets, but might be difficult to accommodate in the grid. Hence, estimating the required investments in vRES, while still ensuring that their operation is technically feasible, is important as the short-term operation has strong implications on investments and technology choice for other technologies, i.e., on the sector long-term planning (IRENA, 2017b). It is thus of paramount importance to find a compromise between the computational efficiency<sup>17</sup> and the robustness of results.

We evaluate the impact of the number of representative days on a default scenario, which features the standard scenario characteristics where the EU ETS cap decreases according to current policies (i.e. a linear reduction factor of 2.2% after 2020 is assumed, see Section 7) such that the annual cap reaches zero by 2057. We run the model with up to 30 representative days (i.e., 240 time slices per year). We show the variables related to the EU ETS (emissions and prices). We only show prices in 2030 as they rise at the interest rate (when the allowances borrowing constraint is not binding). We also show the variables that could be affected by the short-term impact of more/less renewables due to the higher model granularity, namely generation and capacity-mix at the EU ETS level.

As left panel of Figure 8 shows, emissions tend to converge for runs with more than 5 days for all the years evaluated. For instance, emissions in 2050 do not vary more than 7% (3%) in runs with more than 6 days, compared to value of 6 representative days. Likewise, carbon prices in 2030 tend to converge for runs with more than 5 days. They remain between 31 and 33 €/tCO<sub>2</sub> (see right panel of Figure 8).

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<sup>17</sup> Obtaining results for runs with less than 10 representative days take less than 24 hours, while those with 30 representative days could take up to 7 days.

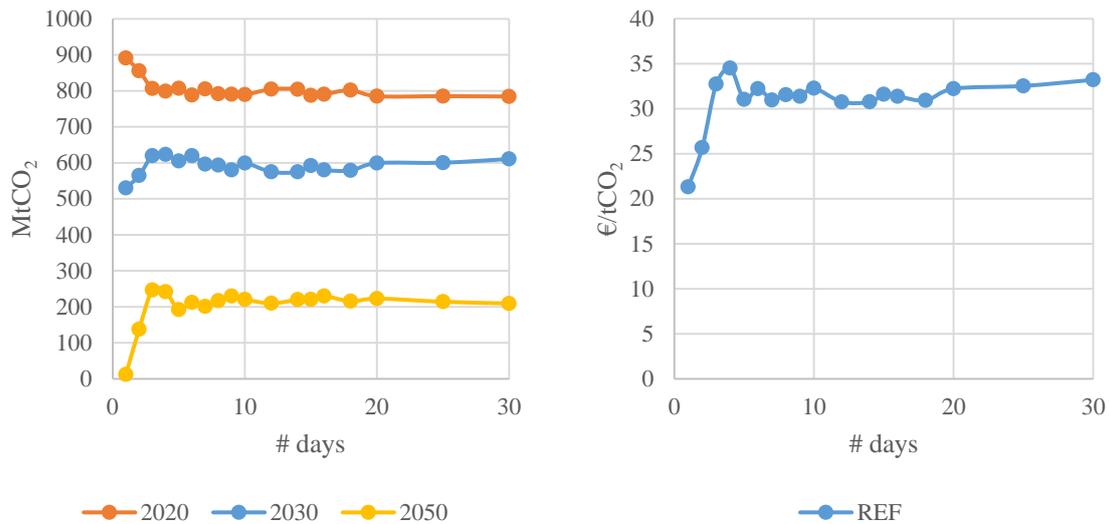


Figure 8. Emissions in 2020, 2030 and 2050 at the EU ETS level (left panel) and carbon prices in 2030 (right panel).

Larger differences appear in the generation-mix, although there seems to be no interaction between the number of days and the stringency of the cap. The lower granularity smooths the vRES profiles, so it is easier to accommodate their output, i.e., electricity systems are easier to decarbonise when few representative days are considered. This is highlighted by high share of RES and low share of gas generation in both 2030 and 2050 when less than 4 days are considered. In 2030, in the runs with 5-10 days, the main variations occur between gas, hydropower and wind energy. They are respectively within the range of  $730 \pm 50$ ,  $620 \pm 80$  and  $1090 \pm 90$  TWh, i.e., a variation up to 13% of the medium value. In 2050, in the runs with 5-10 days, there appears to be an interaction between wind power and PV, whose volumes are in the range of  $2330 \pm 240$  and  $3300 \pm 170$ , i.e., variation remains below 10%. Generation from technologies that are not deployed at large scale, but are expected to play a key role in the long-term, e.g., batteries and hydrogen-based generation, also tend to converge when more than 6 days are considered. **Error! Reference source not found.** also shows that variation in the generation-mix tend to decrease when 8 or more days are considered, and that figures shown by >20-days runs are similar to those obtained with 10 days.

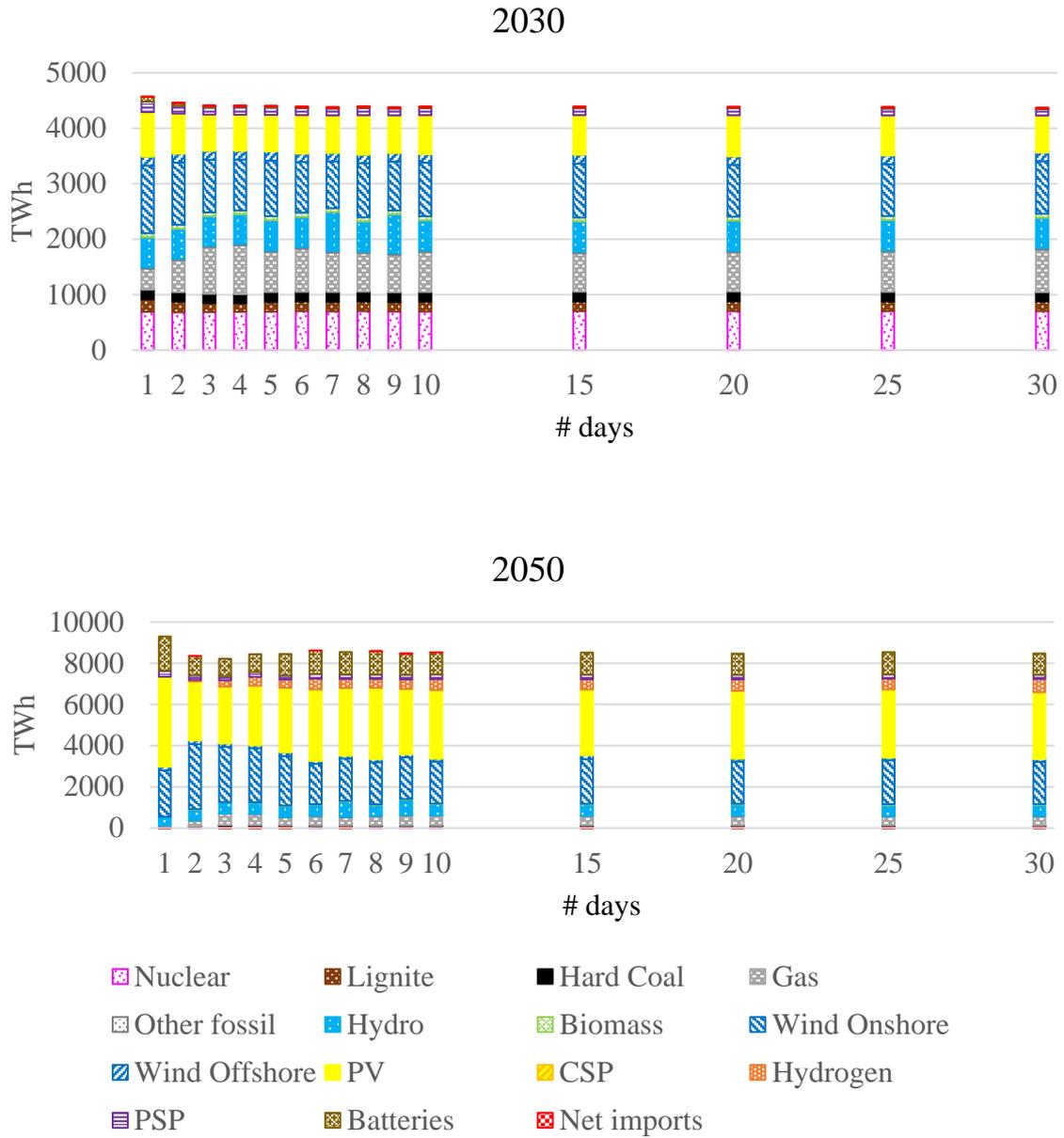


Figure 9. Impact of modelled representative days on the generation-mix at the EU ETS level in 2030 and 2050.

Finally, we also show the variations in the capacity-mix in 2050. Although generation is the key indicator of the level of deployment of certain technologies, estimating the magnitude of investments is of paramount importance for long-term planning. For balancing purposes, investments in some technologies might still be substantial, despite their dispatch being expected to remain low. This is particularly the case of batteries and gas-fired plants. Figure 10

shows that variation of installed capacity is similar to that of generation, and that runs with 8-10 days provide robust results of long-term investments.

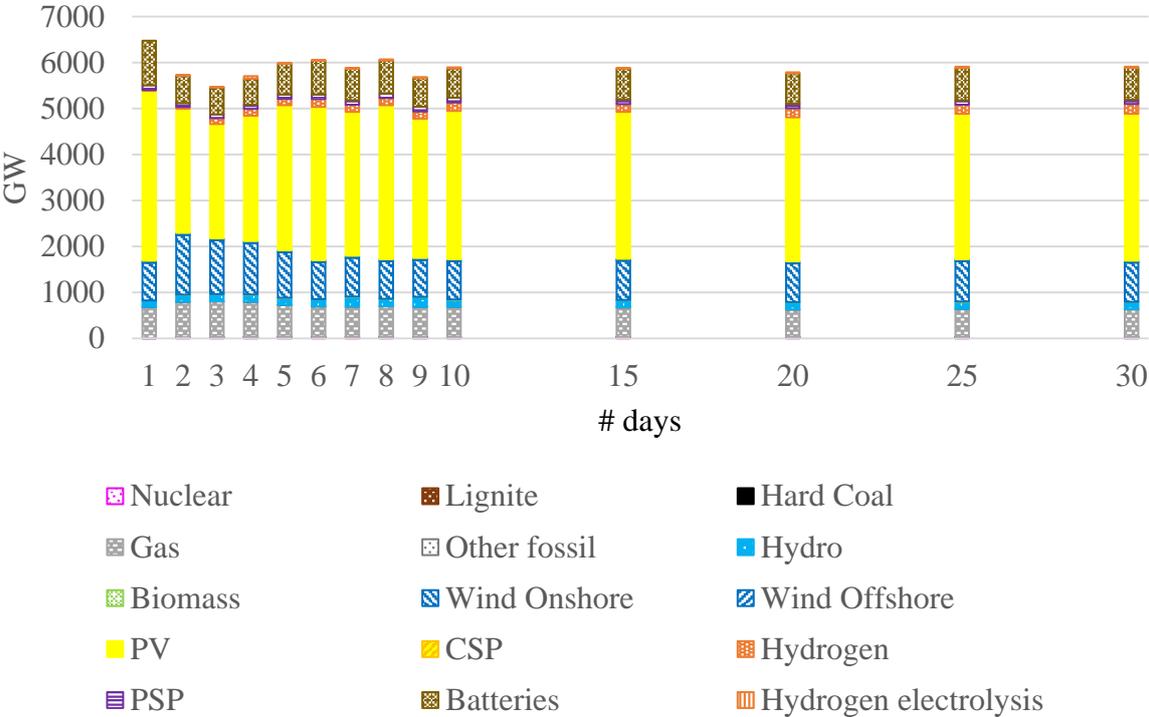


Figure 10. Impact of modelled representative days on the capacity-mix at the EU ETS level in 2050.

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## A. Mathematical Model

### a. Sets, Indices, Parameters and Variables

Table A1 to Table A4 give an overview about the symbols for indices, sets, parameters and variables used in the equations. All variables are constrained to be non-negative.

*Table A1. Indices.*

Symbol	Description
$t, tt$	years
$day$	days
$\tau$	time slices
$r$	regions
$rg$	vRES resource grades
$te$	electricity generation technologies
$st$	storage technologies

Symbol	Description
$cn$	transmission connections
$pe$	primary energy types
$s$	sector (e.g., electricity)
$m$	abatement measure in the industry

Table A2. Sets.

Symbol	Description
$R$	all regions
$R^{pol}$	regions with a common policy
$T_{ETS}$	year until the EU ETS operates
$T$	all time slices
$T_{day}$	time slices of a specific $day$
$TE$	all electricity generation technologies
$TE_{pe}$	electricity generation technologies working with a specific $pe$
$TE_{pe}^{CCS}$	CCS equipped electricity generation technologies working with $pe$
$TE^{disp}$	dispatchable electricity generation technologies
$TE^{ramp}$	thermal electricity generation technologies with ramping constraints
$TE^{RES}$	RES technologies
$TE^{vRES}$	vRES technologies
$ST$	all storage technologies
$ST^{interday}$	interday storage technologies
$ST^{intraday}$	intraday storage technologies
$CN$	all transmission connections
$CN_r^{out}$	transmission connections defined as starting in region $r$
$CN_r^{in}$	transmission connections defined as ending in region $r$

Table A3. Parameters.

Symbol	Description
$\rho$	discount rate
$\Delta t$	time span (in years) between model years
$l_\tau$	length of time slice $\tau$
$\lambda_{pe}$	emission factor of primary energy $pe$
$\psi_{te}, \psi_{st}, \psi_{cn}$	lifetime of technology $te$ / storage $st$ / connection $cn$
$\mu_{te}$	minimum load of technology $te$
$\varphi_r$	minimum share of domestic electricity supply for region $r$

Symbol	Description
$c_{t,te}^I, c_{t,st}^I, c_{t,cn}^I$	power capacity investment cost
$c_{t,st}^{IR}$	reservoir capacity investment cost
$c_{t,pe}^F$	fuel cost
$c_{te}^{OMF}, c_{st}^{OMF}$	fixed operation and maintenance cost
$c_{te}^{OMV}, c_{st}^{OMV}$	variable operation and maintenance cost
$c_{t,r,s}^{CO_2}$	CO <sub>2</sub> emission cost
$macc_{t,r,m}^{CO_2}$	marginal abatement costs in the industry
$abat_{t,r,m}^{CO_2}$	abatement potential in industry (i.e., baseline emissions)
$v_{\tilde{t},te}, v_{\tilde{t},st}, v_{\tilde{t},cn}$	salvage value factor
$\omega_{\tilde{t},te}, \omega_{\tilde{t},cn}$	depreciation factor
$d_{t,\tau,r}$	electricity demand
$\alpha_{\tau,r,te,rg}^{vRES}, \alpha_{r,te}, \alpha_{\tau,r,te}, \alpha_{cn}$	availability factor
$\eta_{te}, \eta_{st}$	conversion efficiency
$\gamma_{cn}$	transmission losses
$p_{t,r,pe}^{max}$	maximum primary energy consumption
$cap_r^{CCScum}$	maximum CCS storage capacity
$res_{t,r}$	target for minimum electricity production from RES
$cap_t^{CO_2}, cap_{t,r}^{CO_2}$	CO <sub>2</sub> emissions cap
$bud^{CO_2}, bud^{CO_2}$	CO <sub>2</sub> emissions budget
$cap_{avi_t}^{CO_2}$	CO <sub>2</sub> emissions cap for the aviation sector
$euaa_t^{CO_2}$	EU allowances used by the aviation sector
$e_{t,avi}^{CO_2}$	CO <sub>2</sub> emissions from the aviation sector
$a_{te}$	auto-consumption rate
$r_{te}$	ramping factor
$f_{te}, f_{st}$	firm capacity factor for <i>te</i> , <i>st</i> and imports
$rm$	reserve margin
$\vartheta^{RK}$	maximum share of reserves in demand
$\mu_t$	share of heating-related emissions in the EU ETS cap

Table A4. Variables.

Symbol	Description
$C^{tot}$	total system cost
$C_t^I$	investment cost
$C_t^F$	fuel cost
$C_t^{OM}$	operation and maintenance cost
$C_t^{CO_2}$	CO <sub>2</sub> emission cost
$A_{t,r,m}^{CO_2}$	abatement in industry by implementing measure <i>m</i>

Symbol	Description
$V$	salvage value
$P_{t,\tau,r,pe}$	primary energy consumption
$K_{t,r,te}, K_{t,r,st}, K_{t,cn}$	installed capacity
$\Delta K_{t,r,te}, \Delta K_{t,r,st}, \Delta K_{t,cn}$	new capacity
$SK_{t,r,st}$	reservoir capacity
$\Delta SK_{t,r,st}$	new reservoir capacity
$K_{(t-\tilde{t}),r,te,rg}^{RG}$	installed capacity (resource grade specific)
$\Delta K_{(t-\tilde{t}),r,te,rg}^{RG}$	new capacity (resource grade specific)
$G_{t,\tau,r,te}$	electricity generation
$E_{t,r,s}^{CO_2}, E_{t,s}^{CO_2}$	CO <sub>2</sub> emissions
$E_{t,r}^{CCS}$	captured CO <sub>2</sub> (via CCS)
$S_{t,\tau,r,st}^{IN}, S_{t,\tau,r,st}^{OUT}$	storage input/output
$L_{t,\tau,r,st}$	storage level
$H_{t,\tau,r,te}$	hydrogen produced by electrolysis used by hydrogen-based generation technologies
$F_{t,\tau,cn}^+, F_{t,\tau,cn}^-$	transmission flow in positive / negative direction
$OP_{t,\tau,r,te}, OP_{t,day,r,te}$	operating (running) capacity
$RK_{t,r,te}$	reserve capacity
$Ramp_{t,\tau,r,te}$	maximum generation variation between two time slices
$DK_{tt,t,r,te}, DK_{tt,t,cn}$	disinvestment (decommissioning) in $t$ of capacity built in $tt$
$DK_{tt,t,r,te,rg}^{RG}$	disinvestment in $t$ of capacity built in $tt$ (resource grade specific)
$TNAC_t^{CO_2}$	total number of allowance in circulation in EU ETS
$SupEUA_t^{CO_2}$	supply of EUA
$FreeEUA_t^{CO_2}$	free-allocated EUA
$AucEUA_t^{CO_2}$	auctioned EUA
$Emi_t^{CO_2}$	EUA rendered to the EU ETS

### a. Objective function

Equation (A.1): Objective function

$$C^{tot} = \sum_t \left( \Delta t e^{-\rho(t-t_0)} (C_t^I + C_t^F + C_t^{OM} + C_t^{CO_2}) \right) - e^{-\rho(t_{end}-t_0)} V \quad (A.1)$$

Equation (A.2): Fuel costs (some of the hydrogen might be produced by electrolysis [internal to the model])

$$C_t^F = \sum_{r,pe} c_{t,pe}^F \sum_{\tau} l_{\tau} \left( P_{t,\tau,r,pe} - \sum_{te|te=\{HCC,HCT,HFC\}} H_{t,\tau,r,te} \Big|_{pe|pe=\{\text{hydrogen}\}} \right) \quad \forall t \quad (\text{A.2})$$

Equation (A.3): Investment costs

$$C_t^I = \sum_{r,te} (c_{t,te}^I \Delta K_{t,r,te}) + \sum_{r,st} (c_{t,st}^I \Delta K_{t,r,st}) + \sum_{r,st} (c_{t,st}^{IR} \Delta SK_{t,r,st}) + \sum_{cn} (c_{t,cn}^I \Delta K_{t,cn}) \quad \forall t \quad (\text{A.3})$$

Equation (A.4): Operation and maintenance costs

$$C_t^{OM} = \sum_{r,te} \left( c_{te}^{OMF} c_{t,te}^I (K_{t,r,te} + RK_{t,r,te}) + c_{te}^{OMV} \sum_{\tau} l_{\tau} G_{t,\tau,r,te} \right) + \sum_{r,st} \left( c_{st}^{OMF} c_{t,st}^I K_{t,r,st} + c_{st}^{OMV} \sum_{\tau} l_{\tau} S_{t,\tau,r,st}^{OUT} \right) \quad \forall t \quad (\text{A.4})$$

Equation (A.5): Emission costs

$$C_t^{CO_2} = \sum_r \left( \sum_s c_{t,r,s}^{CO_2} E_{t,r,s}^{CO_2} + \sum_m \text{macc}_{t,r,m}^{CO_2} A_{t,r,m}^{CO_2} \right) \quad \forall t \quad (\text{A.5})$$

Equation (A.6): Salvage value

$$\begin{aligned}
V = \Delta t & \left( \sum_{te,r} \sum_{\tilde{t}=0}^{\psi_{te}} v_{\tilde{t},te} c_{(t_{end}-\tilde{t}),te}^I \Delta K_{(t_{end}-\tilde{t}),r,te} \right. \\
& + \sum_{st,r} \sum_{\tilde{t}=0}^{\psi_{st}} v_{\tilde{t},st} c_{(t_{end}-\tilde{t}),st}^I \Delta K_{(t_{end}-\tilde{t}),r,st} \\
& \left. + \sum_{cn} \sum_{\tilde{t}=0}^{\psi_{cn}} v_{\tilde{t},cn} c_{(t_{end}-\tilde{t}),cn}^I \Delta K_{(t_{end}-\tilde{t}),cn} \right) \quad \forall t
\end{aligned} \tag{A.6}$$

### b. Electricity balance

Equation (A.7): Electricity balance

$$\begin{aligned}
d_{t,\tau,r} = \sum_{te} G_{t,\tau,r,te} + \sum_{st \in ST^{intraday}} S_{t,\tau,r,st}^{OUT} - \sum_{st} S_{t,\tau,r,st}^{IN} \\
+ \sum_{cn \in CN_r^{in}} \left( (1 - \gamma_{cn}) F_{t,\tau,cn}^+ - F_{t,\tau,cn}^- \right) \\
+ \sum_{cn \in CN_r^{out}} \left( (1 - \gamma_{cn}) F_{t,\tau,cn}^- - F_{t,\tau,cn}^+ \right) \quad \forall t, \tau, r
\end{aligned} \tag{A.7}$$

### c. Equations for generation technologies

Equation (A.8): Expansion, decommissioning and depreciation of generation technologies

$$\begin{aligned}
K_{t,r,te} = \Delta t & \left( \sum_{\tilde{t}=0}^{\psi_{te}} \omega_{\tilde{t},te} \Delta K_{(t-\tilde{t}),r,te} \right. \\
& \left. - \sum_{(tt,\tilde{t}):(\tilde{t} \in (0,\psi_{te}) \cap tt > t-\tilde{t})} \omega_{\tilde{t},te} DK_{tt,(t-\tilde{t}),r,te} \right) \quad \forall t, r, te
\end{aligned} \tag{A.8}$$

Equation (A.9): Expansion, decommissioning and depreciation of generation technologies per resource grade

$$\begin{aligned}
& K_{t,r,te,rg}^{RG} \tag{A.9} \\
&= \Delta t \sum_{\tilde{t}=0}^{\psi_{te}} \omega_{\tilde{t},te} \Delta K_{(t-\tilde{t}),r,te,rg}^{RG} \\
&- \Delta t \sum_{(tt,\tilde{t}):(\tilde{t} \in (0,\psi_{te}) \cap tt > t-\tilde{t})} \omega_{\tilde{t},te} DK_{tt,t-\tilde{t},r,te,rg}^{RG} \quad \forall t,r,rg,te \in TE^{vres}
\end{aligned}$$

Equation (A.10): Expansion of vRES technologies in regions and resource grades

$$\Delta K_{t,r,te} = \sum_{rg} \Delta K_{t,r,te,rg}^{RG} \quad \forall t,r,te \in TE^{vRES} \tag{A.10}$$

Equation (A.11): Decommissioning of vRES technologies in regions and resource grades

$$DK_{tt,t,r,te} = \sum_{rg} DK_{tt,t,r,te,rg}^{RG} \quad \forall tt,t,r,te \in TE^{vRES} \tag{A.11}$$

Equation (A.12): Constraint on disinvestments

$$\sum_{tt} DK_{tt,t,r,te} \leq \Delta K_{t,r,te} \quad \forall t,r,te \tag{A.12}$$

Equation (A.13): Constraint on disinvestments in resource grades

$$\sum_{tt} DK_{tt,t,r,te,rg}^{RG} \leq \Delta K_{t,r,te,rg}^{RG} \quad \forall t,r,te \in TE^{vRES},rg \tag{A.13}$$

Equation (A.14): Capacity constraint for dispatchable generation technologies

$$G_{t,\tau,r,te} \leq K_{t,r,te} \alpha_{\tau,r,te} (1 - a_{te}) \quad \forall t, \tau, r, te \in TE^{disp} \quad (A.14)$$

Equation (A.15): Availability of Wind Onshore, Wind Offshore and PV

$$G_{t,\tau,r,te} \leq \sum_{rg} \alpha_{\tau,r,te,rg}^{vRES} K_{t,r,te,rg}^{RG} \quad (A.15)$$

$$\forall t, \tau, r, te \in \{Wind\ Onshore, Wind\ Offshore, PV\}$$

Equation (A.16): Availability of CSP

$$\sum_{\tau \in T_{day}} l_{\tau} G_{t,\tau,r,te} \leq \sum_{\tau \in T_{day}} l_{\tau} \sum_{rg} \alpha_{\tau,r,te,rg}^{vRES} K_{t,r,te,rg}^{RG} \quad \forall t, day, r, te \in \{CSP\} \quad (A.16)$$

Equation (A.17): Availability of Hydro

$$G_{t,\tau,r,te} \leq 1.25 \alpha_{r,te} K_{t,r,te} \quad \forall t, r, te \in \{Hydro\} \quad (A.17)$$

Equation (A.18): Annual availability of dispatchable generation technologies

$$\sum_{\tau \in T_{day}} l_{\tau} G_{t,\tau,r,te} \leq \sum_{\tau \in T_{day}} l_{\tau} \alpha_{r,te} K_{t,r,te} \quad \forall t, r, te \in TE^{disp} \quad (A.18)$$

Equation (A.19): Operation constraint for dispatchable generation technologies

$$OP_{t,\tau,r,te} \leq K_{t,r,te} \quad \forall t, \tau, r, te \in TE^{disp} \quad (A.19)$$

Equation (A.20): Generation constraint for dispatchable generation technologies

$$G_{t,\tau,r,te} \leq OP_{t,\tau,r,te} \alpha_{\tau,r,te} (1 - a_{te}) \quad \forall t, \tau, r, te \in TE^{disp} \quad (A.20)$$

Equation (A.21): Minimum load constraint for dispatchable generation technologies

$$G_{t,\tau,r,te} \geq \mu_{te} OP_{t,\tau,r,te} \quad \forall t, \tau, r, te \in TE^{disp} \quad (A.21)$$

Equation (A.22): Operating capacity constraint for thermal generation technologies (except nuclear)

$$OP_{t,\tau \in T_{day},r,te} = OP_{t,day,r,te} \quad \forall t, \tau, r, te \in TE^{ramp} \wedge te \neq Nuclear \quad (A.22)$$

Equation (A.23): Operating capacity constraint for nuclear power plants

$$OP_{t,\tau,r,te} = OP_{t,\tau+1,r,te} \quad \forall t, \tau, r, te \in TE^{ramp} \wedge te = Nuclear \quad (A.23)$$

Equation (A.24): Ramping constraint for thermal generation technologies

$$G_{t,\tau \in T_{day},r,te} = G_{t,(\tau+1) \in T_{day},r,te} + Ramp_{t,\tau,r,te} \quad \forall t, \tau, r, te \in TE^{ramp} \quad (A.24)$$

Equation (A.25): Ramping-up and -down constraint for thermal generation technologies

$$-OP_{t,\tau,r,te} r_{te} \leq Ramp_{t,\tau,r,te} \leq OP_{t,\tau,r,te} r_{te} \quad \forall t, \tau, r, te \in TE^{ramp} \quad (A.25)$$

#### d. Equations for transmission technologies

Equation (A.26): Expansion and depreciation of transmission capacity

$$K_{t,cn} = \Delta t \left( \sum_{\bar{t}=0}^{\psi_{cn}} \omega_{\bar{t},cn} \Delta K_{(t-\bar{t}),cn} \right. \quad (A.26)$$

$$\left. - \sum_{(tt,\bar{t}):(\bar{t} \in (0,\psi_{cn}) \cap tt > t-\bar{t})} \omega_{\bar{t},cn} DK_{tt,(t-\bar{t}),cn} \right) \quad \forall t, cn$$

Equation (A.27): Constraint on disinvestments of transmission capacity

$$\sum_{tt} DK_{tt,t,cn} \leq \Delta K_{t,cn} \quad \forall t, cn \quad (A.27)$$

Equation (A.28): Transmission constraint

$$F_{t,\tau,cn}^+ \leq \alpha_{cn} K_{t,cn} \quad \forall t, \tau, cn \quad (A.28)$$

$$F_{t,\tau,cn}^- \leq \alpha_{cn} K_{t,cn} \quad \forall t, \tau, cn$$

#### e. Equations for storage technologies

Equation (A.29): Expansion and depreciation of power capacity

$$K_{t,r,st} = \Delta t \left( \sum_{\bar{t}=0}^{\psi_{st}} \omega_{\bar{t},st} \Delta K_{(t-\bar{t}),r,st} \right. \quad (A.29)$$

$$\left. - \sum_{(tt,\bar{t}):(\bar{t} \in (0,\psi_{cn}) \cap tt > t-\bar{t})} \omega_{\bar{t},st} DK_{tt,(t-\bar{t}),r,st} \right) \quad \forall t, r, st$$

Equation (A.30): Expansion of reservoir capacity

$$SK_{t,r,st} = \Delta t \left( \sum_{\tilde{t}=0}^{\psi_{st}} \omega_{\tilde{t},st} \Delta SK_{(t-\tilde{t}),r,st} \right) \quad \forall t, r, st \quad (\text{A.30})$$

Equation (A.31): Constraint on disinvestments of power capacity

$$\sum_{tt} DK_{tt,t,r,st} \leq \Delta K_{t,r,st} \quad \forall t, cn \quad (\text{A.31})$$

Equation (A.32): Power constraint

$$S_{t,\tau,r,st}^{IN} \leq K_{t,r,st} \quad \forall t, \tau, r, st \quad (\text{A.32})$$

$$S_{t,\tau,r,st}^{OUT} \leq K_{t,r,st} \quad \forall t, \tau, r, st$$

Equation (A.33): Reservoir level

$$L_{t,\tau-1,r,st} + \eta_{st} l_{\tau} S_{t,\tau,r,st}^{IN} - l_{\tau} S_{t,\tau,r,st}^{OUT} = L_{t,\tau,r,st} \quad \forall t, \tau, r, st \in ST^{intraday} \quad (\text{A.33})$$

Equation (A.34): Constraint on reservoir level

$$L_{t,\tau,r,st} \leq SK_{t,r,st} \quad \forall t, \tau, r, st \in ST^{intraday} \quad (\text{A.34})$$

Equation (A.35): Interday storage balance

$$\eta_{st} \sum_{\tau} l_{\tau} S_{t,\tau,r,st}^{IN} = \sum_{\tau} l_{\tau} S_{t,\tau,r,st}^{OUT} \quad \forall t, r, st \in ST^{interday} \quad (\text{A.35})$$

Equation (A.36): Intraday storage balance

$$\eta_{st} \sum_{\tau \in T_{day}} l_{\tau} S_{t,\tau,r,st}^{IN} = \sum_{\tau \in T_{day}} l_{\tau} S_{t,\tau,r,st}^{OUT} \quad \forall t, day, r, st \in ST^{intraday} \quad (A.36)$$

#### f. Primary energy demand and CO<sub>2</sub> emissions

Equation (A.37): Primary energy demand

$$P_{t,\tau,r,pe} = \sum_{te \in TE_{pe}} G_{t,\tau,r,te} / (\eta_{te}(1 - a_{te})) \quad \forall t, \tau, r, pe \quad (A.37)$$

Equation (A.38) : Primary energy constraint

$$\sum_{\tau} l_{\tau} P_{t,\tau,r,pe} \leq p_{t,r,pe}^{max} \quad \forall t, r, pe \quad (A.38)$$

Equation (A.39): Hydrogen produced by electrolysis ('helec') is used by hydrogen-based technologies, namely hydrogen CC (HCC), hydrogen CT (HCT) and hydrogen FC (HFC)

$$S_{t,\tau,r,st}^{OUT|st=\{helec\}} = \sum_{te|\{HCC,HCT,HFC\}} H_{t,\tau,r,te} \quad \forall t, \tau, r \quad (A.39)$$

Equation (A.40): CO<sub>2</sub> emissions from electricity generation

$$E_{t,r,elec}^{CO_2} = \sum_{pe} \lambda_{pe} \sum_{\tau} l_{\tau} P_{t,\tau,r,pe} - E_{t,r}^{CCS} \quad \forall t, r \quad (A.40)$$

Equation (A.41): Avoided CO<sub>2</sub> emissions via CCS

$$E_{t,r}^{CCS} = 0.9 \sum_{pe} \lambda_{pe} \sum_{\tau} l_{\tau} \sum_{te \in TE_{pe}^{CCS}} G_{t,\tau,r,te} / \eta_{te} \quad \forall t, r \quad (\text{A.41})$$

Equation (A.42): CCS storage constraint

$$\Delta t \sum_t E_{t,r}^{CCS} = cap_r^{CCScum} \quad \forall r \quad (\text{A.42})$$

### g. Security of supply

Equation (A.43): Robustness condition

$$\begin{aligned} (1 + rm)d_{t,\tau,r} \leq & \sum_{te \in TE^{disp}} (f_{te}K_{t,r,te} + RK_{t,r,te}) + \sum_{st} f_{st}S_{t,\tau,r,st}^{OUT} \\ & + \sum_{te \in TE^{vRES}} f_{te} \sum_{rg} \alpha_{\tau,r,te,rg}^{vRES} K_{t,r,te,rg}^{RG} \\ & + f_{imp} \left( \sum_{cn \in CN_r^{in}} ((1 - \gamma_{cn})F_{t,\tau,cn}^+ - F_{t,\tau,cn}^-) \right. \\ & \left. + \sum_{cn \in CN_r^{out}} ((1 - \gamma_{cn})F_{t,\tau,cn}^- - F_{t,\tau,cn}^+) \right) \quad \forall t, \tau, r \end{aligned} \quad (\text{A.43})$$

Equation (A.44): Reserves constraint

$$RK_{t,r,te} \leq \Delta t \sum_{tt} (DK_{t,tt,r,te} + 0.8DK_{t-1,tt,r,te}) \quad \forall t, r, te \quad (\text{A.44})$$

$$RK_{t,r,te} \leq RK_{t-1,r,te} + \Delta t \sum_{tt} DK_{t,tt,r,te} \quad \forall t, r, te$$

Equation (A.45): Maximum reserves

$$\sum_{te} RK_{t,r,te} \leq \vartheta^{RK} d_{t,\tau,r} \quad \forall t, \tau, r \quad (\text{A.45})$$

#### h. The EU ETS

Equation (A.46): Emissions from energy-intensive industry

$$E_{t,r,ind}^{CO_2} = \sum_m abat_{t,r,m}^{CO_2} - A_{t,r,m}^{CO_2} \quad \forall t, r \quad (\text{A.46})$$

Equation (A.47): Emissions from heating (assumed exogenous)

$$E_{t,r,heat}^{CO_2} = \mu_t cap_t^{CO_2} \quad \forall t, r \quad (\text{A.47})$$

Equation (A.48): EUA needed by the aviation sector

$$euaa_t^{CO_2} = \max(0, e_{t,avi}^{CO_2} - cap_{avi}^{CO_2}) \quad \forall t \quad (\text{A.48})$$

Equation (A.49): Total demand of (stationary) EU allowances (EUA)

$$Emi_t^{CO_2} = \sum_{r \in R^{pol}} \sum_s E_{t,r,s}^{CO_2} + euaa_t^{CO_2} \quad \forall t \quad (\text{A.49})$$

Equation (A.50): Supply of certificates EUA

$$SupEUA_t^{CO_2} = cap_t^{CO_2} \quad \forall t \quad (\text{A.50})$$

Equation (A.51): Banking of EUA

$$TNAC_t^{CO_2} = TNAC_{t-1}^{CO_2} + \Delta t(SupEUA_t^{CO_2} - Emi_t^{CO_2}) \quad \forall t \leq T_{ETS} \quad (A.51)$$

Note that the borrowing constraint is implicitly included since the TNAC variable cannot be negative.

Equation (A.52): EUA trading ends in year

$$TNAC_t^{CO_2} = 0 \quad \forall t > T_{ETS} \quad (A.52)$$

The Market Stability Reserve (MSR) and the price floor are additional measures within the EU ETS which are described in the following. These are modules that can be switched on depending on the research aim.

#### *h.1. The Market Stability Reserve (MSR)*

Following the EU ETS reform in 2015, the MSR was created with an amendment of the Directive 2003/87/EC (European Commission, 2015). It was later also amended so as to allow EUA cancellation (European Parliament and Council of the European Union, 2018), among other changes, and started operating in 2019. Its main purpose is to deal with the growing surplus of EUA, while still ensuring the stability of the system. It is supposed to work as a safe valve, withdrawing allowances when there is surplus and releasing them when there is scarcity. The MSR has three main rules: (i)  $X$  certificates are transferred to the MSR instead of being auctioned when the bank size of the previous year is higher than 833 MtCO<sub>2</sub>,  $p\_intake$  equalling 24% (until 2023 and 12% afterwards) of the bank size; (ii)  $X$  certificates are transferred back from the MSR to the market when the bank size of the previous year is lower than 400 MtCO<sub>2</sub>,  $p\_outtake$  equalling 100 MtCO<sub>2</sub> (available through auctions); and (iii) when

the size of the MSR stock is higher than the number of certificates to be auctioned in the previous year, the difference between both is cancelled from the MSR.

Given the non-linearity of the MSR conditions, it is not possible to embed such equations directly in LIMES-EU. Indeed, it would also be inconsistent to include the MSR in an optimization model as it violates the perfect competition assumption which we assume throughout all other parts of the model. We thus couple LIMES-EU with a simulation of the MSR, following an iterative approach, which is illustrated in Figure A1. The underlining logic is to find an emission path consistent with the bank, and thus with the total certificates available. The additional sets, parameter and variables (on an annual basis) are shown in Table A5.

*Table A5. Indices, parameters and variables required to simulate the MSR.*

<b>Symbol</b>	<b>Description</b>
Indices	
$t_2$	years (annual)
Parameters	
$p\_cap_{t_2}$	EU ETS cap
$p\_emi_{t_2}$	EU ETS aggregated emissions
$p\_freeEUA_{t_2}$	Free allocated allowances
$p\_prelaucEUA_{t_2}$	Preliminary auction
$p\_lower\_threshold_{t_2}$	Lower threshold
$p\_upper\_threshold_{t_2}$	Upper threshold
$p\_rateintakeMSR_{t_2}$	Intake rate to the MSR
$p\_rateoutakeMSR_{t_2}$	Outtake rate from the MSR
$p\_extraintake_{t_2}$	Additional intake to the MSR
$p\_sharefreeEUA_{t_2}$	Share of allowances to be freely allocated
Variables	
$p\_TNAC_{t_2}$	total number of allowance in circulation in EU ETS
$p\_intake_{t_2}$	Intake of allowances into the MSR
$p\_outtake_{t_2}$	Outtake of allowances from the MSR
$p\_MSR_{t_2}$	MSR level
$p\_aucEUA_{t_2}$	Allowances finally auctioned
$p\_cancellation_{t_2}$	Allowances cancelled from the MSR

The cap on an annual basis ( $p\_cap_{t2}$ ), based on the assumed linear reduction factor (LRF), is equivalent to the cap used in LIMES-EU (cap into a 5-year value,  $cap_t^{CO_2}$ ). More precisely,  $cap_t^{CO_2}$  averages the corresponding 5 year values to each year in LIMES-EU<sup>18</sup>. For instance, the cap in LIMES-EU in 2020 equals the average of the annual cap between 2018 and 2022. In a first iteration, the certificates supply ( $SupEUA_t^{CO_2}$ ) equals the cap ( $cap_t^{CO_2}$ ), as specified in Eq. (A.50).

From the LIMES-EU results, we use the total EUA rendered ( $Emi_t^{CO_2}$ ) and the bank at the end of 2015 ( $TNAC_{2015}^{CO_2}$ ) as input for the MSR. These 5-year-based inputs nonetheless have to be ‘translated’ into annual values for the MSR simulation. This is necessary because of the MSR operation criteria, e.g., use TNAC from year  $t2-1$  to estimate the intake into the MSR in  $t2$ , works on an annual basis. Recall that each year in LIMES-EU corresponds to the 5 years around it. To smoothen the input, we interpolate the emission volumes between LIMES-EU years and then normalize them to ensure that the 5-years average equals the LIMES-EU value. Unlike emissions, which are a flow, the TNAC in 2015 from LIMES-EU ( $TNAC_{2015}^{CO_2}$ ) is a stock. This corresponds to the initial TNAC used in the MSR simulation,  $p\_TNAC_{2017}$  (TNAC at the end of 2017). From the annual cap, we estimate the preliminary auctions ( $p\_prelaucEUA_{t2}$ , see Eq. (A.53)) and certificates to be freely allocated ( $p\_freeEUA_{t2}$ , see Eq. (A.54)).

We thus simulate the MSR operation estimating the intake (Eq. (A.55)), outtake (Eq. (A.56)), cancellation (Eq. (A.57)), MSR level (Eq. (A.58)), certificates to be auctioned (Eq. (A.59)) and TNAC (Eq. (A.60)) on an annual basis as of 2019.

$$p\_prelaucEUA_{t2} = p\_cap_{t2} \times (1 - p\_sharefreeEUA_{t2}) \quad (A.53)$$

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<sup>18</sup> To distinguish the variables and parameters computed in LIMES-EU from those computed in the MSR simulation, we name the latter as  $p\_*$ . In addition, the index  $t$  is only used for input from or variables used in LIMES-EU (5-year step basis, i.e.,  $t = 2015, 2020 \dots 2055$ ), while  $t2$  is only used for those related to the MSR simulation (annual basis, i.e.,  $t2 = 2017, 2018 \dots 2057$ ).

$$p_{freeEUA_{t2}} = p_{cap_{t2}} \times p_{sharefreeEUA_{t2}} \quad (A.54)$$

$$\text{If } p_{TNAC_{t2-1}} > p_{upper\_threshold_{t2}}, \quad (A.55)$$

$$p_{intake_{t2}} = \min\left(\frac{2}{3} p_{TNAC_{t2-2}} \times p_{rateintakeMSR_{t2-2}} + \frac{1}{3} p_{TNAC_{t2-1}} \times p_{rateintakeMSR_{t2-1}}, p_{prelaucEUA_{t2}}\right),$$

$$\text{in other case } p_{intake_{t2}} = 0$$

$$\text{If } p_{TNAC_{t2-1}} < p_{lower\_threshold_{t2}}, \quad (A.56)$$

$$p_{outtake_{t2}} = \min(p_{MSR_{t2-1}}, p_{rateouttakeMSR_{t2}}),$$

$$\text{in other case } p_{outtake_{t2}} = 0$$

$$p_{cancellation_{t2}} = 0 \quad \forall t2 \leq 2023 \quad (A.57)$$

$$p_{cancellation_{t2}} = \max(p_{MSR_{t2-1}} - p_{prelaucEUA_{t2-1}}, 0) \quad \forall t2 > 2024$$

$$p_{MSR_{t2}} = p_{MSR_{t2-1}} + p_{extraintake_{t2}} + p_{intake_{t2}} - p_{outtake_{t2}} \quad (A.58)$$

$$- p_{cancellation_{t2}}$$

$$p_{aucEUA_{t2}} = p_{prelaucEUA_{t2}} - p_{intake_{t2}} + p_{outtake_{t2}} \quad (A.59)$$

$$p_{TNAC_{t2}} = p_{TNAC_{t2-1}} + p_{aucEUA_{t2}} + p_{freeEUA_{t2}} - p_{emi_{t2}} \quad (A.60)$$

The intake to the MSR (Eq. (A.55)) is modelled in detail, i.e., the exact time in which allowances are removed from the auctions is considered. The European Commission informs each May about the TNAC by the end of the previous year and about the volume of certificates to be transferred to the MSR. A volume calculated on the basis of the TNAC of a year  $t-1$  is removed from the auctions between September in year  $t$  and August of year  $t+1$ . Since the MSR only starts absorbing certificates in January 2019, 16% of the TNAC in 2017, informed in May 2018 (1.65 GtCO<sub>2</sub>), i.e., 264 MtCO<sub>2</sub>, will be transfer to the MSR between January and August 2019<sup>19</sup>. Likewise, the TNAC at the end of 2018, informed in May 2019 (1.65 GtCO<sub>2</sub>), determined the amount of certificates being removed from auctions between September 2019 and August 2020<sup>20</sup> and transferred to the MSR. Accordingly, it can be assumed that the intake for each year  $t$  amounts to two thirds of the volume calculated on the basis of the TNAC by the end of  $t-2$  and one third of the volume calculated on the basis of the TNAC by the end of the year  $t-1$ , such volume depending on the intake rate.

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<sup>19</sup> Communication from the Commission C(2018) 2801 final, available at [https://ec.europa.eu/clima/sites/clima/files/ets/reform/docs/c\\_2018\\_2801\\_en.pdf](https://ec.europa.eu/clima/sites/clima/files/ets/reform/docs/c_2018_2801_en.pdf)

<sup>20</sup> Communication from the Commission C(2019) 3288 final, available at [https://ec.europa.eu/clima/sites/clima/files/ets/reform/docs/c\\_2019\\_3288\\_en.pdf](https://ec.europa.eu/clima/sites/clima/files/ets/reform/docs/c_2019_3288_en.pdf)

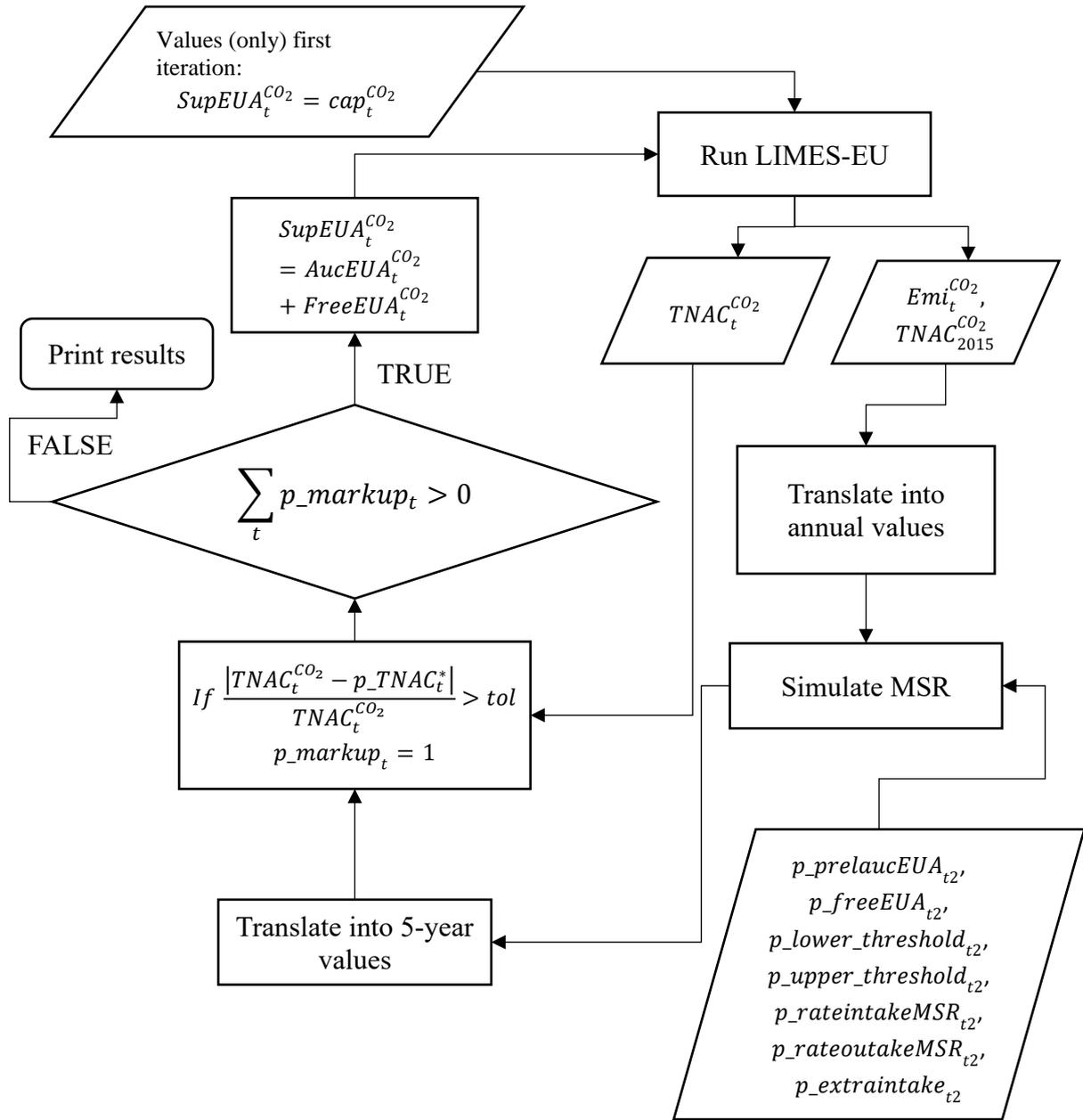


Figure A1. Iterative process to couple LIMES-EU with the MSR simulation.

This output is ‘translated’ into 5-year data. For flow-type variables we compute the average for the 5-corresponding years. For instance, the average EUA auctioned ( $p\_aucEUA_{t2}$ ) between 2018 and 2022 is used for the 2020 volume in LIMES-EU ( $AucEUA_{2020}^{CO2}$ ). For stock-type variables,  $p\_TNAC_{t2}$  and  $p\_MSR_{t2}$ , we use the value from the last corresponding year. For instance, their level in 2022 would correspond to 2020 in LIMES-EU years. We compute the

error between the ‘translated’ TNAC from the MSR simulation ( $p\_TNAC_t^*$ ) and that from LIMES ( $TNAC_t^{CO_2}$ ). If the error is higher than the tolerance margin ( $tol = 0.05$ ) for any  $t$ , LIMES-EU is run again with an updated supply of certificates ( $SupEUA_t^{CO_2}$ ), recalculating Eq. (A.50). This equals the sum between the ‘translated’ free allocated EUA ( $FreeEUA_t^{CO_2}$ , based on  $p\_freeEUA_{t2}$ ), which does not change across iterations, and the ‘translated’ final auctioned EUA ( $AucEUA_t^{CO_2}$ , based on  $p\_aucEUA_{t2}$ ), estimated through the MSR simulation. This process is followed until the TNAC from both LIMES-EU and the MSR simulation converge.

## *h.2. Carbon price floor (CPF)*

A carbon price floor is a policy gaining momentum as an alternative to decarbonize the electricity sector, in particular given the success of its implementation in UK. The interaction between this and the EU ETS remains nonetheless complex and requires a proper analysis. Its implementation in LIMES-EU is not straightforward as a carbon price floor implies non-linear conditions. We consider two different types of price floors. First, EU ETS countries may issue less allowances in order to raise the ETS price. Second, EU ETS countries may put a top-up on the ETS price without issuing fewer allowances which corresponds to the UK price floor.

The first case is straightforward to implement in the model. In doing so, we follow Fell et al. (2012). Fell *et al.* (2012) formulate a model that allows estimating the amount of certificates required to be withdrawn from a cap-and-trade system (e.g. the EU ETS) in order to reach a CPF. We accordingly modify the objective function (Eq. (A.1)) to include the costs of withdrawing EUA (see Eq. (A.61)), where the parameter  $cpf_t$  is the previously defined carbon price floor for the entire EU ETS, and the variable  $Efloor_t$  is the volume of EUA withdrawn. The latter ( $Efloor_t$ ) also affects the TNAC, and thus Eq. (A.62) replaces Eq. (A.51).

$$C^{tot} = \sum_t \left( \Delta t e^{-\rho(t-t_0)} (C_t^I + C_t^F + C_t^{OM} + C_t^{CO_2} - \mathbf{cpf}_t \times \mathbf{Efloor}_t) \right) \quad (\text{A.61})$$

$$- e^{-\rho(t_{end}-t_0)} V$$

$$TNAC_t^{CO_2} = TNAC_{t-1}^{CO_2} + \Delta t (Seua_t^{CO_2} - Emi_t^{CO_2} - \mathbf{Efloor}_t) \quad \forall t \leq T_{ETS} \quad (\text{A.62})$$

The second case, where some EU members implement unilaterally their own CPF, is more complicated because the CO<sub>2</sub> price in LIMES-EU results from the shadow price of the emissions constraint (banking, cap or budget). The formulation from Fell *et al.* (2012) does not work when only one country or a group of countries within a cap-and-trade system implement a top-up tax in order to reach a CPF, because the total emission constraint results in only one CO<sub>2</sub> price for all the countries belonging to the cap-and-trade system. We thus develop an iterative process that allows us implement any top-up CO<sub>2</sub> tax in any country within a larger ETS (see Figure A2).

In a first iteration ( $i=1$ ) the model is run with only the emissions constraint and no exogenous top-up CO<sub>2</sub> tax ( $x_{t,r,i} = 0$ ). The carbon price in the model ( $P_{t,i}$ ) results from the EUA banking constraint (Eq. (A.51)). If  $P_{t,i}$  is lower than the desired CPF ( $P_{t,r}^*$ ) (considering a tolerance parameter  $tol = 0.01$ ), the model is run again. In a second iteration we run the model assuming an exogenous CO<sub>2</sub> price, i.e., the needed top-up CO<sub>2</sub> tax, which equals the difference between  $P_{t,r}^*$  and  $P_{t,i}$  (see Figure A3). We thus iterate until the resulting CO<sub>2</sub> price from two consecutive iterations converge.

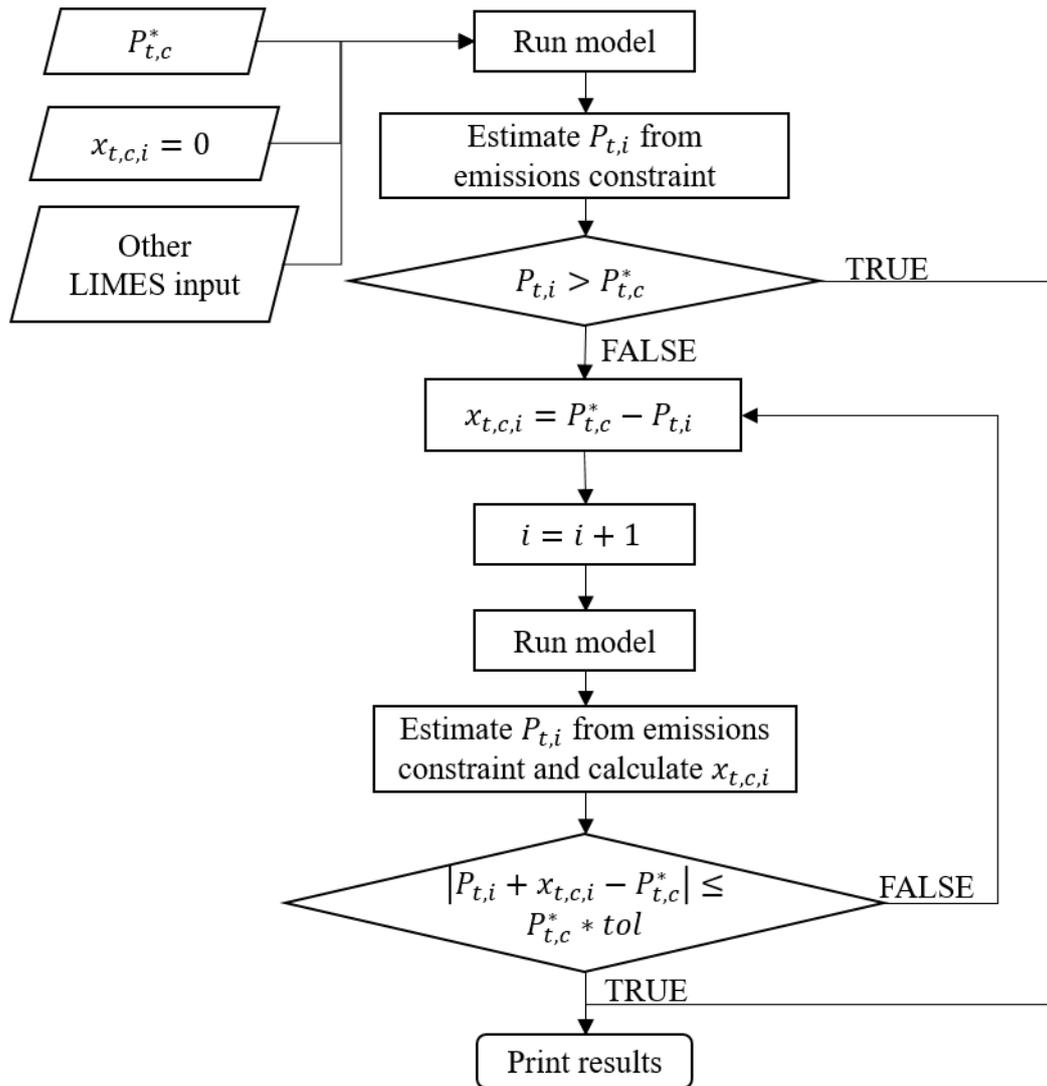


Figure A2. Flow diagram explaining the iterative process formulated to run the model when a minimum CO<sub>2</sub> price is implemented.

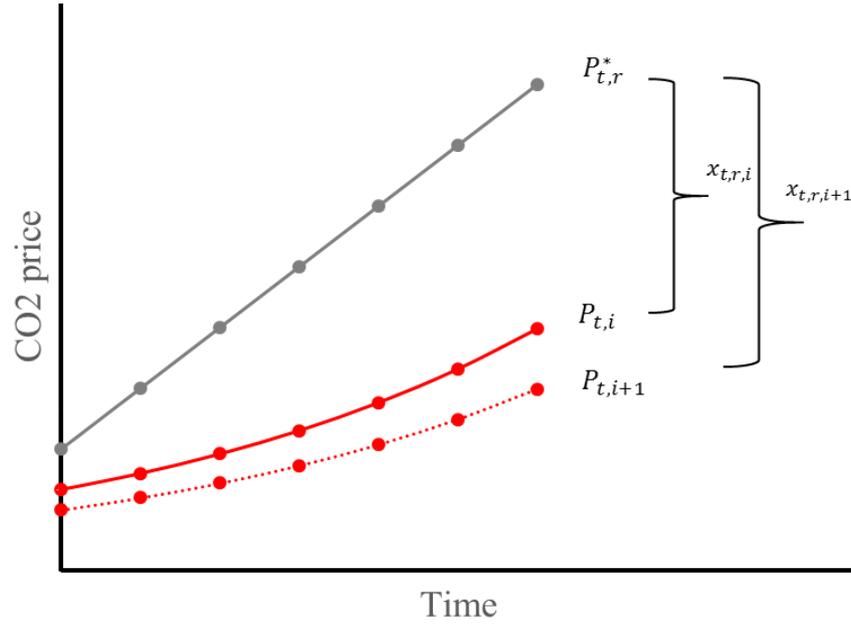


Figure A3. Top-up CO<sub>2</sub> price adjustment between two iterations for countries implementing a minimum CO<sub>2</sub> price.

### i. Other electricity sector policies

Equation (A.63): CO<sub>2</sub> emission target for a group of regions

$$\sum_{r \in R^{pol}} E_{t,r,elec}^{CO_2} \leq cap_t^{CO_2} \quad \forall t \quad (A.63)$$

Equation (A.64): CO<sub>2</sub> emission target for a single region

$$E_{t,r,elec}^{CO_2} \leq cap_{t,r}^{CO_2} \quad \forall t, r \quad (A.64)$$

Equation (A.65): CO<sub>2</sub> budget for a group of regions

$$\Delta t \sum_t \sum_{r \in R^{pol}} E_{t,r,elec}^{CO_2} \leq bud^{CO_2} \quad (A.65)$$

Equation (A.66): CO<sub>2</sub> budget for a single region

$$\Delta t \sum_t E_{t,r,elec}^{CO_2} \leq bud_r^{CO_2} \quad \forall r \quad (\text{A.66})$$

Equation (A.67): National RES target

$$\sum_{\tau} l_{\tau} \sum_{te \in T^{RES}} G_{t,\tau,r,te} \leq res_{t,r} \quad \forall t, r \quad (\text{A.67})$$

Equation (A.68): Target on minimum amount of electricity provided domestically

$$\sum_{\tau} l_{\tau} \sum_{te \in T^{RES}} G_{t,\tau,r,te} \leq \phi_r \sum_{\tau} l_{\tau} d_{t,\tau,r} \quad \forall t, r \quad (\text{A.68})$$

## B. Region Codes

The region codes in this documentation are based on standard ISO 3166-1.

*Table A6. Region codes.*

Region code	Region name
AT	Austria
BE	Belgium
BG	Bulgaria
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
GB	United Kingdom
GR	Greece
HR	Croatia

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Region code	Region name
HU	Hungary
IE	Ireland
IT	Italy
LT	Lithuania
LU	Luxemburg
LV	Latvia
NL	The Netherlands
PL	Poland
PT	Portugal
RO	Romania
SE	Sweden
SI	Slovenia
SK	Slovakia
Balkan	Albania, Bosnia and Herzegovina, Kosovo, Montenegro, The former Yugoslav Republic of Macedonia, Serbia
CH	Switzerland
NO	Norway

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