1. SUPPLEMENTARY MATERIAL: MODEL DESCRIPTION

1.1 Additional constraints

To ensure that dispatch-related variables comply with the installed capacities, the constraints defined by eqs. (1) to (4) are introduced. Eqs. (1) and (2) enforce this for thermal and renewable energy technologies, respectively. Eq. (3) controls the inout and output capacity of storage, while eq. (4) ensures the storage level does not exceed the storage capacity. To compute storage size from capacity, the parameter ε_s corresponding to the energy-to-power ratio is used:

$$
\begin{aligned}
Sup_{j,t} &\leq Capa_j \; ava_{j,t} && \forall j \in J, t \in T && (1)\\
Sup_{k,t} &\leq capa_k \; ava_{k,t} && \forall k \in K, t \in T && (2)\\
StIn_{s,t} + Sup_{s,t} &\leq capa_s && \forall s \in S, t \in T && (3)\\
StLvl_{s,t} &\leq capa_s \; \varepsilon_s && \forall s \in S, t \in T && (4)
\end{aligned}
$$

Analogously to the supply and storage variables, demand and utilization variables are subject to an upper limit that reflects maximum consumption for the respective group. The limits are denoted as $\hat{dem}_{c,t}$ and $\hat{utl}_{c,t}$, respectively, and enforced by eqs. (5) and (6):

$$
\begin{aligned}
Dem_{c,t} &\leq \hat{dem}_{c,t} && \forall c \in C, t \in T && (5)\\
Utl_{c,t} &\leq \hat{utl}_{c,t} && \forall c \in C, t \in T && (6)
\end{aligned}
$$

Lastly, constraints are introduced ensuring that sufficient reserve capacities are available to maintain grid stability. The required reserves are divided into positive reserves rr_t^{pos} and negative reserves rr_t^{neg}. Only the effect of providing reserve capacities is modeled, whereas effects on the market caused by the utilization of reserves, if demand and supply unexpectedly deviate from expected values, are not incorporated. In the short-term simulation, these requirements are represented by the two following constraints (based on Brouwer et. al, 2016):

$$
\begin{aligned}
rr_t^{pos} &\leq \sum_{j \in J}(Capa_j - Sup_{j,t}) + \sum_{s \in S}(Capa_{s,t} - Sup_{s,t}) + \sum_{s \in S} StIn_{st,t} && \forall t \in T && (7)\\
rr_t^{neg} &\leq \sum_{j \in J \cup S} Sup_{j,t} + \sum_{s \in S}(Capa_{s,t} - StIn_{s,t}) && \forall t \in T && (8)
\end{aligned}
$$

Eq. (7) ensures grid stability if demand, unexpectedly, exceeds supply. It guarantees that, in sum, thermal power plant and storage unit operators can increase supply, or storage operators can decrease demand in order to meet rr_t^{pos} in each time period t. Eq. (8) serves the same purpose in the case where supply unexpectedly exceeds demand, and a negative net change of generation is required.

1.2 Import and export

In the model, import and export to neighboring markets are represented by additions to the supply and demand curve. To derive these additions, first a very generalized simulation of each neighboring market is performed, which is described by eqs. (9) to (11). For exogenously set capacities $capa_i$ and demand dem_t, a cost-minimizing dispatch is computed in order to obtain $Sup_{i,t}$.

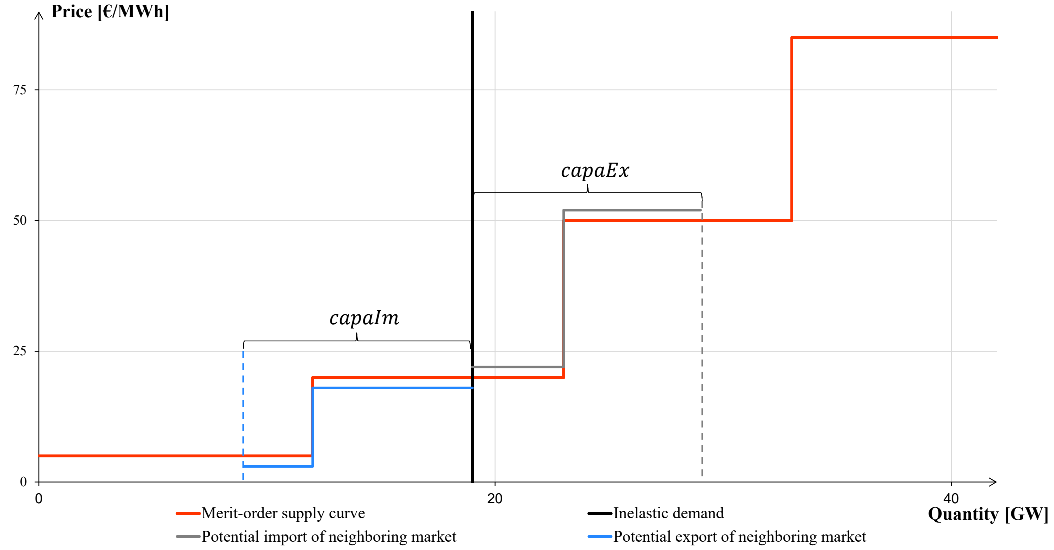
$$min \sum_{i\in I}\sum_{t\in T} Sup_{i,t}\, mc_i \tag{9}$$

$$dem_t = \sum_{i\in I} Sup_{i,t},\ \forall t \in T \tag{10}$$

$$Sup_{i,t} \leq ava_{i,t}\, capa_i,\ \forall t \in T, i \in I \tag{11}$$

In the following step, results of the simulation are used to determine the quantities and price of potential imports and export from the neighboring market in each time period. The mechanism applied for this purpose is illustrated in Figure 1. The plot shows the market outcome for a given time period *t* for one of the simulated external markets. The inelastic demand curve is a vertical line whose interception with the merit-order supply curve gives the market equilibrium and the market price. Import of electricity takes place if the price of importing undercuts the marginal costs of the utilized generation capacities. The maximum quantity that can be imported depends on the installed cross-border capacity available for importing *capaIm*. Export of electricity takes place if the revenue of exports exceeds the marginal costs of generation. Again, the quantity exported is limited by the cross-border capacity available for exporting *capaEx*. The potential import of the neighboring market is then added to the demand curve of the main model, whereas the potential export of the neighboring country is added to the supply curve.

Figure 1: Potential import and export of neighboring countries



2. SUPPLEMENTARY MATERIAL: MODEL PARAMETRIZATION

2.1 Demand

The only technology modeled as cross-price-elastic demand in the case study corresponds to batteries of electric cars. Any other technology cannot be modeled due to a lack of data. The most relevant data, total quantity demanded and power capacity of electric cars, are again based on Gerhardt et al. (2015). The total quantity demanded is distributed across hours of the year according to average driving profiles taken from a nationwide survey used to obtain the upper limit of utilized quantities (infas, 2008). The temporal profile for the upper limit of demand is taken from corresponding research and scaled according to the power capacity to reflect the electric capacity of car batteries connected to the electric grid in each hour (Jacqué, 2013). The discharge duration of a car battery is derived from the literature and projected, based on the electric capacity, to obtain the maximum shiftable quantity, i.e. the capacity of all car batteries (Styczynski and Sauer, 2015).

Due to the lack of adequate data the discharging rate $\gamma^X_{c,t}$ is assumed to be unity, but charging the battery a long time in advance is avoided by limiting $TS_{c,t}$ to 24 hours. Since the total quantity demanded already reflects conversion losses, $\eta^X_{c,t}$ is set to unity as well. $TR_{c,t}$ is set to zero, because the frequency of utilization is unrestricted in this case. The utility of using electric cars is set to the value of lost load, thus assuming that the demand for mobility is covered in any case.

Total demand electricty demand relating to power-to-gas processes dem^{P2G} and the upper limit of Dem^{P2G}_t equaling the installed input capacity of PtG processes, are again set according to Gerhardt et al. (2015).

2.2 Supply

Gerhardt et al. (2015) consider five renewable energy technologies: rooftop photovoltaic, open-space photovoltaic, onshore wind, offshore wind and run-of-river, as well as two storage technologies (lead-acid batteries and pumped-hydro storage), whose generating capacities are set accordingly in the model. Any other parameters describing the generation and storage technologies are adopted from the same series of publications, including the storage capacity of lead-acid batteries and pumped-hydro storage (Rech and Elsner, 2015; Reuter and Elsner, 2015; Styczynski and Sauer, 2015; Welker and Elsner, 2016; Elsner and Sauer, 2015; Görner and Sauer, 2015). The values used are average projections for 2050. The thermal power plant technologies for Germany considered in the model are gas turbine (GT), combined-cycle gas turbine (CCGT), hard coal, and lignite. Capacity costs are derived from these sources using an internal interest rate of 7.5% to annualize investment costs. Marginal costs are based on these sources as well, but they also depend on the commodity prices assumed (Öko and ISI, 2015, 98). Full-load hours of variable renewables (VRE) are derived from data given in Gerhardt et al. (2015) and used to scale the generation profiles for Germany in 2016 taken from ENTSO-E (2017), whereas availability curves of thermal power plants in 2016 are taken from online publications (EEX, 2017). Quantities supplied by combined heat and power plants can also be found in Gerhardt et al. (2015). Tables 1-5 provide an overview of the parameter values used.

Table 1: Parameter values assumed for thermal power plants

Technology	**Efficiency** [%]	**Variable costs** [$\frac{EURO}{MWh}$]	**Fuel price** [$\frac{EURO}{MWh_{th}}$]	**Emission factor** [$\frac{tCO_2}{MWh_{th}}$]
Hard-coal power plant	50	0	6.14	0.411
Lignite power plant	50	0	16.25	0.34
Biomass plant¹	100	10	0	0
Gas turbine	46	0	50.18	0.202
Combined-cycle-gas turbine	64	0	50.18	0.202
Nuclear plant	33	0	2.232	0

Source: Görner and Sauer (2015); Welker and Elsner (2016); UBA (2013); Öko and ISI (2015)

Table 2: Investment cost assumptions for thermal power plants

Technology	**Investment costs** [$\frac{EURO}{MW}$]	**Lifetime** [a]	**O&M costs** [$\frac{\%\, Invest}{a}$]
Hard-coal power plant	1,400,000	50	2.6
Lignite power plant	1,800,000	50	3.3
Biomass plant	5,250,000	10	2.71
Gas turbine	400,000	20	2.5
Combined-cycle-gas turbine	900,000	32.5	2.58

Source: Görner and Sauer (2015); Welker and Elsner (2016)

Table 3: Parameters of VRE

Technology	Investment costs $[\frac{EURO}{MW}]$	Lifetime $[a]$	O&M costs $[\frac{\%\,Invest}{a}]$	Full-load hours $[h]$	Installed capacity $[MW]$
Run-of-river	2,300	50	2	4,577	5,000
Onshore wind	1,032,000	22.5	3.6	2,250	140,000
Offshore wind	3,235,000	22.5	2.6	4,200	38,000
Photovoltaic, roof	577,000	25	1.7	1,000	100,000
Photovoltaic, open space	460,000	25	2.2	1,000	100,000

Source: Reuter and Elsner (2015); Rech and Elsner (2015); Gerhardt et al. (2015)

Table 4: Parameter value assumed for storage technologies

Technology	Efficiency, in [%]	Efficiency, out [%]	Self-discharging rate [%]	Installed power capacity $[MW]$	Installed storage capacity $[MWh]$
Lead-acid batteries	94.3	94.3	0.99562	18,000	18,000
Pumped-hydro storage	88	91.5	0.999652	8,000	48,000

Source: Elsner and Sauer (2015); Gerhardt et al. (2015)

Table 5: Investment costs assumed for storage technologies

Technology	Invest. costs in $[\frac{EURO}{MW}]$	Invest. costs out $[\frac{EURO}{MW}]$	Invest. costs capacity $[\frac{EURO}{MWh}]$	Lifetime $[a]$	O&M costs $[\frac{\%\,Invest}{a}]$
Lead-acid batteries	0	45,000	146,341	30	0.75
Pumped-hydro storage	350,000	330,000	25,000	40	1.2

Source: Elsner and Sauer (2015)

2.3 Further inputs

According to Brouwer et al. (2016), the requirements for positive and negative reserves are both set equal to the sum of 1% of inelastic demand $Q_t(p_t = \hat{p})$ plus 2% of maximum total generation of VRE in a given hour t. The share of state-induced price components, which remains constant and is not determined within the long-term model, is set to 68.31 €/MWh, which corresponds to the average level of state-induced price components excluding the EEG levy in Germany in 2016 (Ecke and Göke, 2017). The neighboring countries of Germany considered are: France, Slovenia, Poland, the Netherlands, Denmark, Belgium, Austria, and the Czech Republic. Cross-border capacities are based on future projections (ENTSO-E, 2016). Installed generation capacities and total demand quantities in these countries are based on the trend scenario of the European Commission in 2050 (EC, 2016). Total quantities were distributed across the hours of the year according to load profiles from ENTSO-E in 2016 (ENTSO-E, 2017).

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