DIETER Version 1.2.0

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1 Version history

1.1 Changes in version 1.2.0 compared to version 1.1.0

Compared to version 1.1.0, we have made the following changes in version 1.2.0.

Major changes:

- Prosumage has been introduced. A specified segment of load is attributed to prosumage, which must fulfill a minimum self-generation requirement, either by contemporaneous self-generation or delayed self-generation using its own storage. The minimum self-generation level is varied in scenarios. See equations (12a–12l).

Minor changes:

- Model acceleration: the GUSS tool has been implemented to loop over scenarios. The GUSS tool compiles the model once and subsequently only alters those parameters by which scenarios differ.
- Due to the change to GUSS, the file 'clear.gms' is not necessary any more and, thus, removed
- The file 'report_to_excel.gms' has been removed

1.2 Changes in version 1.1.0 compared to version 1.0.1

Compared to version 1.0.1, we have made the following changes in version 1.1.0.

Major changes:

- Electric vehicles have been introduced. Equations (11a–11k) describe demand, battery level dynamics, and charging restrictions. Likewise, the objective function (1), the energy balance (5), and the constraint on minimum renewables requirements (8d) have been augmented.

Minor changes:

- Equations (6e-g) are condensed to one new equation (6e). The reaction time for reserves activation in minutes, which used to be hard-coded, is now given by parameter t_r^{reac}
- A new switch has been introduced to restrict the cross-over method after the LP has been solved with the barrier method. Barrier primal-dual tolerance, by which fraction the solution diverges from its theoretical optimum, is by default set to 10^{-8}. Extensive testing has shown that results are qualitatively unaffected, and quantitatively negligibly changed.
- The reporting has further improved and transferred to a separate .gms file.
- The representation of efficiency losses of DSM load shifting has improved. Losses are now also accounted for in the minimum renewables requirement equation (8d).
- Equation (10a) has been corrected to also include reserves provision in the maximum DSM load curtailment duration.
- Units for parameters have been added in Table 3.
- Several typos and minor mistakes in equations, such as missing indices, have been corrected.
- Correction for reserves activation of storage and electric vehicles has been condensed into *Balancing Correction Factors.*

1.3 Changes in version 1.0.1 compared to version 1.0.0

Compared to version 1.0.0, we have made the following changes in version 1.0.1.

Minor changes:

- Primary reserve provision is now separated into pr^+ and pr^-. Moreover, primary reserves are not only provided, but also activated (analogous to other reserve qualities).
- Reserve activation by storage technologies has been corrected with respect to costs in the objective function and the level of stored energy $STO^l_{sto,h}$.
- Likewise, energy constraints for reserve provision have been corrected.
- Nomenclature in the code is now improved:
  - Variables are generally set in upper case letters, exogenous parameters in lower case letters.
  - Cost parameters are consistently labeled.
  - All shares are consistently labeled ϕ.
- Introduction of a switch that easily allows to set run-of-river capacity to zero, treat it as an exogenous parameter (without reserve provision) or handle it as an endogenous variable (including reserve provision).
- The reporting section has improved.

2 Model description

DIETER minimizes total system costs over 8760 hours of a full year. System costs comprise annualized investment costs and fixed costs as well as variable costs of conventional generators, renewables, power storage, electric vehicles, and DSM. For storage, separate investment decisions on power and energy capacities are made. The model ensures that power generation equals price-inelastic demand at all times, while also accounting for the provision and activation of balancing reserves. The full analytical formulation is provided in the following. Capital letters denote variables, and lowercase letters denote parameters. Tables 1, 2, and 3 provide an overview of the sets, variables, and parameters used.

Table 1: Sets

Set	Element	Description
Basic model		
$\mathfrak{C}$	$\ni con$	Conventional generation technologies
$\mathfrak{H}$	$\ni h, hh$	Hours
$\mathfrak{RE}$	$\ni res$	Renewable generation technologies
$\mathfrak{S}$	$\ni sto$	Storage technologies
Demand-side management		
$\mathfrak{LC}$	$\ni lc$	DSM load curtailment technologies
$\mathfrak{LS}$	$\ni ls$	DSM load shifting technologies
Electric vehicles		
$\mathfrak{EV}$	$\ni ev$	Electric vehicle types
Reserves		
$\mathfrak{R}$	$\ni r$	Reserve energy qualities (pr^+, pr^-, sr^+, sr^-, mr^+, mr^-)
$\mathfrak{R} \supseteq \mathfrak{R}^+$	$\ni r^+$	Positive reserve energy qualities (pr^+, sr^+, mr^+)
$\mathfrak{R} \supseteq \mathfrak{R}^-$	$\ni r^-$	Negative reserve energy qualities (pr^-, sr^-, mr^-)

Table 2: Variables

Variables	Unit	Description
Basic model		
$CU_{res,h}$	[MW]	Curtailment renewable technology *res* in hour *h*
$G^l_{con,h}$	[MW]	Generation level conventional technology *con* in hour *h*
$G^+_{con,h}$	[MW]	Generation increase conventional technology *con* in hour *h*

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Variables	Unit	Description
$G^{-}_{con,h}$	[MW]	Generation decrease conventional technology *con* in hour *h*
$G_{res,h}$	[MW]	Generation renewable technology *res* in hour *h*
N_{con}	[MW]	Installed capacity conventionals
N_{res}	[MW]	Installed capacity renewables
N^{E}_{sto}	[MWh]	Installed capacity storage energy
N^{P}_{sto}	[MW]	Installed capacity storage power
$STO^{in}_{sto,h}$	[MW]	Storage inflow technology *sto* in hour *h*
$STO^{out}_{sto,h}$	[MW]	Storage outflow technology *sto* in hour *h*
$STO^{l}_{sto,h}$	[MWh]	Storage level technology *sto* in hour *h*
Demand-side management		
$DSM^{cu}_{lc,h}$	[MW]	Load curtailment curtailment technology *lc* in hour *h*
$DSM^{+}_{ls,h}$	[MW]	Net load increase shifting technology *ls* in hour *h*
$DSM^{-}_{ls,h,hh}$	[MW]	Net load decrease shifting technology *ls* in hour *hh* accounting for increases in hour *h*
$DSM^{d+}_{ls,h}$	[MW]	Load increase taking effect in the wholesale segment shifting technology *ls* in hour *h*
$DSM^{d-}_{ls,h}$	[MW]	Load decrease taking effect in the wholesale segment shifting technology *ls* in hour *h*
N_{lc}	[MW]	Installed capacity DSM load curtailment
N_{ls}	[MW]	Installed capacity DSM load shifting
Electric vehicles		
$EV^{+}_{ev,h}$	[MW]	Battery grid charging of electric vehicle type *ev* in hour *h*
$EV^{-}_{ev,h}$	[MW]	Battery grid discharging of electric vehicle type *ev* in hour *h*
$EV^{l}_{ev,h}$	[MW]	Battery charge level of electric vehicle type *ev* in hour *h*
$EV^{ged}_{ev,h}$	[MW]	Battery grid electricity demand of electric vehicle type *ev* in hour *h*
$EV^{fuel}_{ev,h}$	[MW]	Conventional fuel demand of plug-in hybrid electric vehicle type *ev* in hour *h*
Prosumage		
$CU^{pro}_{res,h}$	[MW]	Curtailed energy renewable technology *res* in hour *h* in the prosumage segment
G^{m2pro}_{h}	[MW]	Energy in hour *h* transferred from the market to the prosumage segment
$G^{pro2m}_{res,h}$	[MW]	Energy from technology *res* in hour *h* sent from the prosumage segment to the market
$G^{pro2pro}_{res,h}$	[MW]	Direct self-consumption of technology *res* in hour *h* in the prosumage segment
N^{pro}_{res}	[MW]	Installed capacity renewable technology *res* in the prosumage segment
$N^{E,pro}_{sto}$	[MWh]	Installed energy capacity storage technology *sto* in the prosumage segment
$N^{P,pro}_{sto}$	[MW]	Installed power capacity storage technology *sto* in the prosumage segment
$STO^{in,m2m}_{sto,h}$	[MW]	Storage inflow technology *sto* in hour *h* in prosumage segment, earmarked as coming the from market for subsequent discharge to market

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Variables	Unit	Description
$STO^{in,m2pro}_{sto,h}$	[MW]	Storage inflow technology *sto* in hour h in the prosumage segment, earmarked as coming from the market for subsequent self-consumption
$STO^{in,pro2m}_{sto,res,h}$	[MW]	Storage inflow technology *sto* in hour h in the prosumage segment, earmarked as coming from self-generation with technology *res* for subsequent discharge to market
$STO^{in,pro2pro}_{sto,res,h}$	[MW]	Storage inflow technology *sto* in hour h in the prosumage segment, earmarked as coming from self-generation with technology *res* for subsequent self-consumption
$STO^{l,m2m}_{sto,h}$	[MW]	Storage level technology *sto* in hour h in the prosumage segment, earmarked as coming from the market for subsequent discharge to market
$STO^{l,m2pro}_{sto,h}$	[MW]	Storage level technology *sto* in hour h in the prosumage segment, earmarked as coming from the market for self-consumption
$STO^{l,pro2m}_{sto,h}$	[MW]	Storage level technology *sto* in hour h in the prosumage segment, earmarked as coming from self-generation for subsequent discharge to market
$STO^{l,pro2pro}_{sto,h}$	[MW]	Storage level technology *sto* in hour h in the prosumage segment, earmarked as coming from self-generation for subsequent self-consumption
$STO^{out,m2m}_{sto,h}$	[MW]	Storage outflow technology *sto* in hour h in the prosumage segment, earmarked as coming from the market for subsequent discharge to market
$STO^{out,m2pro}_{sto,h}$	[MW]	Storage outflow technology *sto* in hour h in the prosumage segment, earmarked as coming from the market for subsequent self-consumption
$STO^{out,pro2m}_{sto,h}$	[MW]	Storage outflow technology *sto* in hour h in the prosumage segment, earmarked as coming from self-generation for subsequent discharge to market
$STO^{out,pro2pro}_{sto,h}$	[MW]	Storage outflow technology *sto* in hour h in the prosumage segment, earmarked as coming from self-generation for subsequent self-consumption
Reserves		
BCF_h	[MW]	*Balancing Correction Factor* in hour h
D_r	[MW]	Reserves demand of quality r
$RP_{r,con,h}$	[MW]	Reserves provision quality r in hour h by conventional technology *con*; analogous for renewable and DSM technologies
$RP^{G2V}_{r,ev,h}$	[MW]	Reserves provision quality r in hour h by electric vehicle type *ev* while battery charging
$RP^{V2G}_{r,ev,h}$	[MW]	Reserves provision quality r in hour h by electric vehicle type *ev* while battery discharging
$RP^{in}_{r,sto,h}$	[MW]	Reserves provision quality r in hour h by storage technology *sto* while storing in
$RP^{out}_{r,sto,h}$	[MW]	Reserves provision quality r in hour h by storage technology *sto* while storing out

The basic unit for variables is megawatts (MW). As the model has an hourly temporal resolution, variables representing energy quantities can in this vein be interpreted as megawatt hours per hour.

Table 3: Parameters

Parameters	Unit	Description
Basic model		
c^{cu}	[€/MW]	Curtailment costs
c^{fix}	[€/MW]	Annual fixed costs
c^{i}	[€/MW]	Annualized specific investment costs
c^{iE}_{sto}	[€/MWh]	Annualized specific investments into storage energy
c^{iP}_{sto}	[€/MW]	Annualized specific investments into storage power
c^{m}	[€/MW]	Marginal costs
c^{+}	[€/MW]	Load change costs for increases
c^{-}	[€/MW]	Load change costs for decreases
d_h	[MW]	Hourly wholesale demand
η_{sto}	[0,1]	Storage roundtrip efficiency
m	[MW]	Maximum installable capacity conventional/renewable/DSM technologies
m^{E}_{bio}	[MWh]	Yearly energy cap for biomass
m^{E}_{sto}	[MWh]	Maximum installable storage capacity energy
m^{P}_{sto}	[MW]	Maximum installable storage capacity power
$\phi^{avl}_{res,h}$	[0,1]	Hourly available energy from renewables as fraction of installed capacity
$\phi^{avl}_{ror,h}$	[0,1]	Hourly available energy from run-of-river plants as fraction of installed capacity
ϕ^{ini}_{sto}	[0,1]	Initial storage level as fraction of storage energy installed
$\underline{\phi^{res}}$	[0,1]	Minimum fraction of annual total net load served by renewables
Demand-side management		
η_{ls}	[0,1]	DSM load shifting efficiency factor
t^{dur}	[h]	Duration DSM
t^{off}	[h]	Recovery time DSM
Electric vehicles		
b^{ph}_{ev}	$\{0,1\}$	Binary indicator whether electric vehicle of type *ev* is a plug-in hybrid
c^{fuel}_{ev}	[€/MW]	Conventional fuel costs for electric vehicles
$d_{ev,h}$	[MW]	Hourly electric vehicle electricity demand
n^{E}_{ev}	[MWh]	Battery energy capacity of electric vehicle type *ev*
$n^{P}_{ev,h}$	[MW]	Power rating of charging connection of electric vehicle type *ev* in hour *h*
ϕ^{ev}_{ev}	[0,1]	Share of electric vehicles of type *ev*
ϕ^{ini}_{ev}	[0,1]	Initial battery charging of electric vehicle type *ev* level as fraction of storage energy installed
q_{ev}	[#]	Total number of electric vehicles
Prosumage		
$m^{E,pro}_{sto}$	[MWh]	Maximum installable capacity storage energy in prosumage segment
$m^{P,pro}_{sto}$	[MW]	Maximum installable capacity storage power in prosumage segment
m^{pro}_{res}	[MW]	Maximum installable capacity renewables in prosumage segment
$\phi^{ini,pro}$	[0,1]	Initial storage level overall prosumage storage
$\phi^{pro,load}$	[0,1]	Share of prosumage segment among total load
$\phi^{pro,self}$	[0,1]	Minimum share of self-generation in the prosumage segment

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Parameters	Unit	Description
Reserves		
int^r		Intercept of reserve demand regression line
$\phi^{\pm}$	[%/min]	Maximum load change per minute
$\phi^{call}_{r,h}$	[0,1]	Hourly called fraction of provided reserves
$\overline{\phi^{call}}_r$	[0,1]	Mean activation of reserve type r
ϕ^{pr}	[0,1]	Demand for primary reserves as fraction of demand for other reserves types
ϕ^{shr}_r	[0,1]	Fraction of secondary (minute) reserves among positive and negative reserves
slp^r		Slope of reserve demand regression line
t^{reac}_r	[min]	Reaction lead time for activation of reserves of type r

Parameters referring to energy quantities, usually given in megawatt hours, can be interpreted as taking effect for megawatt hours per hour.

DIETER minimizes the total cost of investment and hourly dispatch in the wholesale and reserve markets, comprising conventional and renewable generators, storage, DSM, and electric vehicles. The objective function is given as

$$
\begin{aligned}
C = \sum_h \Bigg[& \sum_{con} \left(c^m_{con} G^l_{con,h} + c^+_{con} G^+_{con,h} + c^-_{con} G^-_{con,h} \right) + \sum_{res} c^{cu}_{res} CU_{res,h} \\
& + \sum_{sto} c^m_{sto} \left(STO^{out}_{sto,h} + STO^{in}_{sto,h} \right) + \sum_{ls} c^m_{ls} \left(DSM^{d+}_{ls,h} + DSM^{d-}_{ls,h} \right) + \sum_{lc} c^m_{lc} DSM^{cu}_{lc,h} \\
& + \sum_{sto} c^m_{sto} \left(STO^{out,pro2pro}_{sto,h} + STO^{out,pro2m}_{sto,h} + STO^{out,m2pro}_{sto,h} + STO^{out,m2m}_{sto,h} \right) \\
& + \sum_{sto} c^m_{sto} \left(\sum_{res} \left(STO^{in,pro2pro}_{sto,res,h} + STO^{in,pro2m}_{sto,res,h} \right) + STO^{in,m2pro}_{sto,h} + STO^{in,m2m}_{sto,h} \right) \\
& + \sum_{ev} \left(c^m_{ev} EV^-_{ev,h} + c^{fuel}_{ev} EV^{fuel}_{ev,ph} \right) \Bigg] \\
& + \sum_{con} \left[\left(c^i_{con} + c^{fix}_{con} \right) N_{con} \right] + \sum_{res} \left[\left(c^i_{res} + c^{fix}_{res} \right) N_{res} \right] + \sum_{res} \left[\left(c^i_{res} + c^{fix}_{res} \right) N^{pro}_{res} \right] \\
& + \sum_{sto} \left[\left(c^{iP}_{sto} + \frac{1}{2} c^{fix}_{sto} \right) N^P_{sto} + \left(c^{iE}_{sto} + \frac{1}{2} c^{fix}_{sto} \right) N^E_{sto} \right] \\
& + \sum_{sto} \left[\left(c^{iP}_{sto} + \frac{1}{2} c^{fix}_{sto} \right) N^{P,pro}_{sto} + \left(c^{iE}_{sto} + \frac{1}{2} c^{fix}_{sto} \right) N^{E,pro}_{sto} \right] \\
& + \sum_{lc} \left[\left(c^i_{lc} + c^{fix}_{lc} \right) N_{lc} \right] + \sum_{ls} \left[\left(c^i_{ls} + c^{fix}_{ls} \right) N_{ls} \right] \\
& + \sum_h \Bigg[\sum_{sto} \left(\sum_{r^+} \phi^{call}_{r^+,h} c^m_{sto} \left(RP^{out}_{r,sto,h} - RP^{in}_{r,sto,h} \right) + \sum_{r^-} \phi^{call}_{r^+,h} c^m_{sto} \left(RP^{in}_{r,sto,h} - RP^{out}_{r,sto,h} \right) \right)
\end{aligned}
$$

$$+\sum_{lc} c^m_{lc}\left(\sum_{r^+\in\mathfrak{R}^+\setminus pr^+}\phi^{call}_{r^+,h}RP_{r^+,lc,h}\right)+\sum_{ls} c^m_{ls}\left(\sum_{r\in\mathfrak{R}\setminus\{pr^+,pr^-\}}\phi^{call}_{r,h}RP_{r,ls,h}\right)$$
$$+\sum_{ev} c^m_{ev}\left(\sum_{r^+}\phi^{call}_{r^+,h}RP^{V2G}_{r^+,ev,h}-\sum_{r^-}\phi^{call}_{r^-,h}RP^{V2G}_{r^-,ev,h}\right)\Bigg] \tag{1}$$

Specifically, capacity investments N occur per technology without addressing discrete units. A fixed exogenous capacity limit for conventionals, renewables, storage and DSM can be given by m.

$$N_{con} \leq m_{con} \qquad \forall con \tag{2a}$$
$$N_{res} \leq m_{res} \qquad \forall res \tag{2b}$$
$$N^P_{sto} \leq m^P_{sto} \qquad \forall sto \tag{2c}$$
$$N^E_{sto} \leq m^E_{sto} \qquad \forall sto \tag{2d}$$
$$N_{lc} \leq m_{lc} \qquad \forall lc \tag{2e}$$
$$N_{ls} \leq m_{ls} \qquad \forall ls \tag{2f}$$
$$N^{pro}_{res} \leq m^{pro}_{res} \qquad \forall res \tag{2g}$$
$$N^{P,pro}_{sto} \leq m^{P,pro}_{sto} \qquad \forall sto \tag{2h}$$
$$N^{E,pro}_{sto} \leq m^{E,pro}_{sto} \qquad \forall sto \tag{2i}$$

Yet to account for different flexibility capabilities of conventional installations in following residual demand, we model the generation level of technology *con* in hour h, $G^l_{con,h}$, which can be altered by costly increases $G^+_{con,h}$ and $G^-_{con,h}$. The attached load change costs c^+_{con}, c^-_{con} vary by technology and reflect different levels of flexibility. The constraint for these generation dynamics is given by

$$G^l_{con,h} = G^l_{con,h-1} + G^+_{con,h} - G^-_{con,h} \qquad \forall con, h > 1 \tag{3a}$$
$$G^l_{con,1} = G^+_{con,1} \qquad \forall con \tag{3b}$$

together with an initial condition for the first model period (3b). Generation level $G^l_{con,h}$ and load changes $G^+_{con,h}$, $G^-_{con,h}$ are net in the sense that they comprise both energy actually delivered to the wholesale market and activated reserves. For the hourly energy balance (5), equalizing wholesale supply and demand, the generation level has to be corrected for the reserves share. To this end, we introduce the *Balancing Correction Factor* $BCF_{con,h}$.

$$BCF_{con,h} \equiv \sum_{r^-} \phi^{call}_{r^-,h} RP_{r^-,h} - \sum_{r^+} \phi^{call}_{r^+,h} RP_{r^+,h} \qquad \forall con, h \tag{4}$$

where for reserves of type r, $RP_{r,con,h}$ is the capacity provided by technology con in hour h. In this respect, index r^- comprises negative reserves, index r^+ positive reserves. If a certain amount of reserve capacities is provided, fraction $\phi^{call}_{r,h} \in [0,1]$ will be called, following actual data from the base year. Balancing correction factors are defined analogously for the other generation technologies.

Wholesale gross supply by conventional generators is thus expressed as $G^L_{con,h} + BCF_{con,h}$. The wholesale energy balance reads

$$\begin{aligned}
&\left(1-\phi^{pro,load}\right) d_h + \sum_{sto} STO^{in}_{sto,h} + \sum_{ls} DSM^{d+}_{ls,h} + \sum_{ev} EV^{+}_{ev,h} \\
&+ G^{m2pro}_h + \sum_{sto} \left(STO^{in,m2pro}_{sto,h} + STO^{in,m2m}_{sto,h}\right) \\
&= \sum_{con} \left(G^l_{con,h} + BCF_{con,h}\right) + \sum_{res} G_{res,h} + \sum_{sto} STO^{out}_{sto,h} + \sum_{lc} DSM^{cu}_{lc,h} + \sum_{ls} DSM^{d-}_{ls,h} \\
&\quad + \sum_{ev} EV^{-}_{ev,h} + G^{pro2m}_h + \sum_{sto} \left(STO^{out,pro2m}_{sto,h} + STO^{out,m2m}_{sto,h}\right) \qquad \forall h
\end{aligned} \tag{5}$$

Equally for secondary and minute reserves r, provision by conventional generators, storage, renewables, DSM load curtailment, and DSM load shifting, must equal demand D_r in each hour.

$$\begin{aligned}
&\sum_{con} RP_{r,con,h} + \sum_{sto} \left(RP^{in}_{r,sto,h} + RP^{out}_{r,sto,h}\right) + \sum_{res} RP_{r,res,h} + \\
&\qquad \sum_{lc} RP_{r,lc,h} + \sum_{ls} RP_{r,ls,h} = D_r \quad \forall h, r \in \mathfrak{R} \setminus \{pr^+, pr^-\}
\end{aligned} \tag{6a}$$

where load curtailment cannot provide negative balancing power. DSM is assumed not to be suited to satisfy primary reserves, which can only be supplied by conventional, renewable and storage technologies.

$$\sum_{con} RP_{r,con,h} + \sum_{res} RP_{r,res,h} + \sum_{sto} \left(RP^{in}_{r,sto,h} + RP^{out}_{r,sto,h}\right) = D_r \quad \forall h, r \in \{pr^+, pr^-\} \tag{6b}$$

Reserves demand is constant over all periods. For secondary and minute qualities, it is determined endogenously in the model as a function of installed wind and solar PV capacities according to the following equation

$$D_r \equiv 1000 * \phi_r^{shr} * \left(int_r^r + \sum_{res} slp_{r,res}^r \left(N_{res} + N_{res}^{pro}\right)/1000 \right) \qquad \forall r \in \mathfrak{R} \setminus \{pr^+, pr^-\} \tag{6c}$$

Parameter ϕ_r^{shr} is the split between secondary and minute reserves, for positive and negative reserves separately.[1] Intercept and slope of the reserves regression line are int_r^r, and $slp_{r,res}^r$ respectively. For the parameters we draw on Ziegenhagen 2013, where a statistical convolution analysis was carried out, determining reserves demand as a function of installed capacities of variable renewables. Demand for primary reserves is symmetric and rendered as fraction ϕ^{pr} of overall demand for the other types of reserves.[2]

$$D_{pr^+} = D_{pr^-} = \phi^{pr} \sum_{r \in \mathfrak{R} \setminus \{pr^+, pr^-\}} D_r \tag{6d}$$

Moreover, we impose flexibility requirements on conventional generators for providing reserves, depending on the current load level of the technology.

$$RP_{r,con,h} \leq t_r^{reac} \phi_{con}^{\pm} \left(G_{con,h}^l + BCF_{con,h} \right) \qquad \forall con, h, r \tag{6e}$$

Equation (6e) restricts reserves provision to the flexibility within t_r^{reac} minutes where $\phi_{con}^{\pm}$ is the maximum technically possible load change per minute.

The maximum production constraint on conventional generators requires gross wholesale generation plus positive reserves provision to be no larger than installed capacity.

$$G_{con,h}^l + BCF_{con,h} + \sum_{r^+} RP_{r^+,con,h} \leq N_{con} \qquad \forall con, h \tag{7a}$$

where for run-of-river plants, $ror \in \mathfrak{C}$, the gross generation limit is augmented by an exogenous hourly availability factor $\phi_{ror,h}^{avl}$. Similarly, conventional generators may produce no less on the wholesale market than provided as negative reserves.

$$\sum_{r^-} RP_{r,con,h} \leq G_{con,h}^l + BCF_{con,h} \qquad \forall con, h \tag{7b}$$

Constraints on renewables comprise the distribution of fed-in energy, (8a), between load

1. Data follow the historical pattern of the years 2010-2012. Variations between years are negligible. We therefore refrain from adapting to the respective base year of the analysis. The dimensioning of the input data demands multiplication and division by the factor 1000.

2. We parametrize ϕ^{pr} resembling the actual ratio for Germany.

serving $G_{res,h}$, curtailment $CU_{res,h}$, and positive reserve provision.[3] For each type of installed capacity N_{res}, $\phi^{avl}_{res,h}$ describes the hourly availability factor as a fraction of installed capacity based on exogenous actual time series from the respective base year. At the same time, renewables may provide no more negative reserves than their scheduled spot market dispatch (8b). Equation (8c) caps the overall energy delivered by biomass at m^{E}_{bio}.

$$G_{res,h} + CU_{res,h} + \sum_{r^+} RP_{r^+,res,h} = \phi^{avl}_{res,h} N_{res} \qquad \forall res, h \tag{8a}$$

$$\sum_{r^-} RP_{r^-,res,h} \leq G_{res,h} \qquad \forall res, h \tag{8b}$$

$$\sum_{h} G^{l}_{bio,h} \leq m^{E}_{bio} \tag{8c}$$

Equation (8d) requires the share of non-renewable generation in the total yearly energy delivered to be no larger than $\left(1 - \underline{\phi^{res}}\right)$. Put differently, $\underline{\phi^{res}}$ prescribes the minimum renewable share in the electricity system.[4] Total yearly consumed energy, in this respect, comprises load minus load curtailment by DSM measures in the wholesale and reserves segments, as well as storage and DSM load shifting losses in both segments, and grid electricity demand and losses by electric vehicles, corrected by actually activated reserves. For convenience, $\overline{\phi^{call}}_r$ denotes the mean hourly activation of reserve type r.

$$\begin{aligned}
&\sum_{con \in \mathfrak{C} \setminus \{bio, ror\}} \sum_{h} G^{l}_{con,h} \leq \\
&\left(1 - \underline{\phi^{res}}\right) \sum_{h} \Bigg[d_h + \sum_{sto} \left(STO^{in}_{sto,h} - STO^{out}_{sto,h} \right) - \sum_{lc} DSM^{cu}_{lc,h} \\
&\quad + \sum_{ls} \left(DSM^{+}_{ls,h} - \sum_{hh, h - t^{dur}_{ls} \leq hh \leq h + t^{dur}_{ls}} DSM^{-}_{ls,h,hh} \right) \\
&\quad + \sum_{ev} \left(EV^{+}_{ev,h} - EV^{-}_{ev,h} \right) \\
&\quad + \sum_{sto} \left(\sum_{res} \left(STO^{in,pro2pro}_{sto,res,h} + STO^{in,pro2m}_{sto,res,h} \right) + STO^{in,m2pro}_{sto,h} + STO^{in,m2m}_{sto,h} \right. \\
&\quad \left. - STO^{out,pro2pro}_{sto,h} - STO^{out,pro2m}_{sto,h} - STO^{out,m2pro}_{sto,h} - STO^{out,m2m}_{sto,h} \right) \\
&\quad + \sum_{r^+} \overline{\phi^{call}}_{r^+} D_{r^+} - \sum_{r^-} \overline{\phi^{call}}_{r^-} D_{r^-}
\end{aligned}$$

3. We set c^{cu}_{res} to zero in the numerical application.

4. The renewable sources biomass and run-of-river are from the model's point of view categorized as a conventional technology, as we assume them dispatchable; both nonetheless adds to the renewable share of the system.

$$+ \sum_{sto} \left(BCF^{in}_{sto,h} + BCF^{out}_{sto,h} \right) + \sum_{ev} \left(BCF^{V2G}_{ev,h} + BCF^{G2V}_{ev,h} \right)$$
$$- \sum_{lc} \sum_{r^+ \in \Re^+ \setminus pr^+} RP_{r^+,lc,h} \phi^{call}_{r^+,h} \Bigg] \tag{8d}$$

By default, electric vehicle grid electricity consumption and losses must account for the same renewables share as the residual electricity system, implemented in (8d) by the term

$$\sum_{h} \sum_{ev} \left(EV^{+}_{ev,h} - EV^{-}_{ev,h} \right) = \sum_{h} \sum_{ev} \left(EV^{ged}_{h,ev} + losses_{ev,h} \right) \tag{8e}$$

Note that the BCF terms for electric vehicles are already accounted for in constraint (8d) and do not appear in the above equation. To impose fully renewable EV grid electricity demand, term (8e) must be replaced by

$$\sum_{h} \sum_{ev} \left(EV^{+}_{ev,h} - EV^{-}_{ev,h} - EV^{ged}_{h,ev} \right) = \sum_{h} \sum_{ev} losses_{ev,h} \tag{8f}$$

such that only charging losses may be served by conventionals. To deactivate any renewables requirements for EV grid electricity demand, (8e) must be changed to

$$\sum_{h} \sum_{ev} \left(EV^{+}_{ev,h} - EV^{-}_{ev,h} + \frac{\phi^{res}}{1-\underline{\phi^{res}}} EV^{ged}_{h,ev} \right) = \sum_{h} \sum_{ev} losses_{ev,h} + \frac{1}{1-\underline{\phi^{res}}} \sum_{h} \sum_{ev} EV^{ged}_{ev,h} \tag{8g}$$

In that case, the entire grid electricity demand by EV moves out of the outer brackets in constraint (8d) and is not subject to any maximum conventionals share.

The next set of constraints is related to storage technologies where efficiency losses in the storage dynamics equation (9b) are attributed equally to loading and generation. Note that storage can provide both negative and positive reserves by both storing in, $RP^{in}_{r^-}$, $RP^{in}_{r^+}$, and storing out, $RP^{out}_{r^-}$, $RP^{out}_{r^+}$; that is through increasing or withholding scheduled inflows or outflows. To counteract model artifacts of excessive loading in the first periods, each technology starts with a fraction ϕ^{ini}_{sto} of installed energy as initial level of energy stored (9a). Likewise, energy stored after the last period of the model horizon must equal that initial level according to (9c).

$$STO^{l}_{sto,1} = \phi^{ini}_{sto} * N^{E}_{sto} + \frac{(1+\eta_{sto})}{2} STO^{in}_{sto,1} - \frac{2}{(1+\eta_{sto})} STO^{out}_{sto,1} \qquad \forall sto \tag{9a}$$
$$STO^{l}_{sto,h} = STO^{l}_{sto,h-1} + \frac{(1+\eta_{sto})}{2} STO^{in}_{sto,h} - \frac{2}{(1+\eta_{sto})} STO^{out}_{sto,h}$$

$$- \sum_{r^+} \phi^{call}_{r^+,h} \left(\tfrac{(1+\eta_{sto})}{2} RP^{in}_{r^+,sto,h} + \tfrac{2}{(1+\eta_{sto})} RP^{out}_{r^+,sto,h} \right)$$

$$+ \sum_{r^-} \phi^{call}_{r^-,h} \left(\tfrac{(1+\eta_{sto})}{2} RP^{in}_{r^-,sto,h} + \tfrac{2}{(1+\eta_{sto})} RP^{out}_{r^-,sto,h} \right) \qquad \forall sto, h > 1 \qquad (9b)$$

$$STO^{l}_{sto,h} = \phi^{ini}_{sto} * N^{E}_{sto} \qquad \forall sto, h = |\mathfrak{H}| \qquad (9c)$$

Investments into energy and power are generally mutually independent—that is we do not impose a predetermined E/P ratio—and power investments are assumed to be symmetric between inflows and outflows; (9d–9f). Equations (9g–9h) restrict provision of reserves to installed storage power. Two additional restrictions concerning reserve provision are required: (9i) constrains generation for satisfying wholesale demand plus positive reserve provision to last period's storage level, and (9j) restricts storage inflow plus negative reserve provision to the wedge between energy capacity and last period's level. Otherwise, for instance, an empty storage could provide reserves while anticipating never being called.

$$STO^{l}_{sto,h} \leq N^{E}_{sto} \qquad \forall sto, h \qquad (9d)$$

$$STO^{in}_{sto,h} + \sum_{r^-} RP^{in}_{r^-,sto,h} \leq N^{P}_{sto} \qquad \forall sto, h \qquad (9e)$$

$$STO^{out}_{sto,h} + \sum_{r^+} RP^{out}_{r^+,sto,h} \leq N^{P}_{sto} \qquad \forall sto, h \qquad (9f)$$

$$\sum_{r^+} RP^{in}_{r^+,sto,h} \leq STO^{in}_{sto,h} \qquad \forall sto, h \qquad (9g)$$

$$\sum_{r^-} RP^{out}_{r^-,sto,h} \leq STO^{out}_{sto,h} \qquad \forall sto, h \qquad (9h)$$

$$\frac{2}{(1+\eta_{sto})} \left(STO^{out}_{sto,h} + \sum_{r^+} RP^{out}_{r^+,sto,h} \right) \leq STO^{l}_{sto,h-1} \qquad \forall sto, h \qquad (9i)$$

$$\frac{(1+\eta_{sto})}{2} \left(STO^{in}_{sto,h} + \sum_{r^-} RP^{in}_{r^-,sto,h} \right) \leq N^{E}_{sto} - STO^{l}_{sto,h-1} \qquad \forall sto, h \qquad (9j)$$

DSM measures are separated into load curtailment (lc) and load shifting (ls). For load curtailment, demand is reduced in one period without recovery at a later point in time. Each installed facility N_{lc} may cut load once every t^{off}_{lc} hours, the recovery period, for a duration of maximally t^{dur}_{lc} hours, implemented by equation (10a). Equation (10b) ensures that maximum load curtailment capacities are not exceeded also within each single period. By reducing demand, load curtailment may also provide positive secondary and minute reserve energy.

$$\sum_{hh,h\leq hh<h+t^{off}_{lc}} \left(DSM^{cu}_{lc,hh} + \sum_{r^+\in\mathfrak{R}^+\setminus pr^+} RP_{r^+,lc,hh}\phi^{call}_{r^+,hh} \right) \leq N_{lc}t^{dur}_{lc} \qquad \forall lc,h \tag{10a}$$

$$DSM^{cu}_{lc,h} + \sum_{r^+\in\mathfrak{R}^+\setminus pr^+} RP_{r^+,lc,h} \leq N_{lc} \qquad \forall lc,h \tag{10b}$$

The implementation of DSM load shifting follows a granular interpretation: units which are shifted up in hour h, denoted by $DSM^+_{ls,h}$, must be shifted down in the surrounding t^{dur}_{ls} hours, corrected by the efficiency factor η_{ls}. In this respect, $DSM^-_{ls,h,hh}$ carries two time indices, representing downshifts in hour hh to account for upshifts in hour h. Equation (10c) employs this double-indexation to ensure that each unit of load on hold is recovered within the specified duration period t^{dur}_{ls} of the DSM technology. Both DSM upshifts and downshifts may either take effect for the wholesale or the reserves segment. Therefore, equation (10d) distributes the respective net upshift $DSM^+_{ls,h}$ into a portion $DSM^{d+}_{ls,h}$ entering the energy balance of supply and demand on the wholesale market (5), and a portion serving negative reserves activation. The analogous distribution equation for negative shifts is given by (10e), where the left-hand side simply represents all downshifts within period h, regardless for which hour's upshifts they account for. Interpreting each installed DSM load shifting unit N_{ls} as one granular unit which in each period can either shift up demand, shift down demand, provide reserves of one quality, or be inactive, equation (10f) ensures that no undue overuse takes place. Equation (10g) specifies a recovery period t^{off}_{ls} for each DSM load shifting installation. For a more in-depth treatment of the implemented DSM representation, see Zerrahn and Schill 2015.

$$\frac{1+\eta_{ls}}{2} DSM^+_{ls,h} = \frac{2}{1+\eta_{ls}} \sum_{hh,h-t^{dur}_{ls}\leq hh\leq h+t^{dur}_{ls}} DSM^-_{ls,h,hh} \qquad \forall h \tag{10c}$$

$$DSM^+_{ls,h} = DSM^{d+}_{ls,h} + \sum_{r^-\setminus pr^-} RP_{r^-,ls,h}\phi^{call}_{r^-,h} \qquad \forall ls,h \tag{10d}$$

$$\sum_{hh,h-t^{dur}_{ls}\leq hh\leq h+t^{dur}_{ls}} DSM^-_{ls,hh,h} = DSM^{d-}_{ls,h} + \sum_{r^+\setminus pr^+} RP_{r^+,ls,h}\phi^{call}_{r^+,h} \qquad \forall ls,h \tag{10e}$$

$$DSM^{d+}_{ls,h} + DSM^{d-}_{ls,h} + \sum_{r\in\mathfrak{R}\setminus\{pr^+,pr^-\}} RP_{r,ls,h} \leq N_{ls} \qquad \forall ls,h \tag{10f}$$

$$\sum_{hh,h\leq hh<h+t^{off}_{ls}} DSM^+_{ls,h} \leq N_{ls}t^{dur}_{ls} \qquad \forall ls,h \tag{10g}$$

Constraints (11a–11k) implement electric vehicles (EV). Energy demand $d_{ev,h}$ of electric vehicles can be satisfied either by electricity from the grid or, if the vehicle is a plug-in hybrid type, by conventional fuel (11a), which is penalized in the objective function. The share of type ev among all electric vehicles q^{ev} is denoted by ϕ^{ev}_{ev}.

$$d_{ev,h}\phi^{ev}_{ev}q^{ev} = EV^{ged}_{ev,h} + b^{ph}_{ev}EV^{fuel}_{ev,h} \qquad \forall ev, h \qquad (11a)$$

Battery charge level dynamics are rendered by (11c), together with an initial and ending condition (11b, 11d), where the battery charging level may not exceed its exogenous capacity (11e). As for storage, electric vehicles can provide both positive and negative reserves when charging (G2V) or discharging (V2G) the battery.

$$EV^{l}_{ev,1} = \phi^{ini}_{ev}n^{E}_{ev}\phi^{ev}_{ev}q^{ev} + \eta^{+}_{ev}EV^{+}_{ev,1} - \tfrac{1}{\eta^{-}_{ev}}EV^{-}_{ev,1} - EV^{ged}_{ev,1} \qquad \forall ev \qquad (11b)$$

$$\begin{aligned} EV^{l}_{ev,h} = {} & EV^{l}_{ev,h-1} + \eta^{+}_{ev}EV^{+}_{ev,h} - \tfrac{1}{\eta^{-}_{ev}}EV^{-}_{ev,h} - EV^{ged}_{ev,1} \\ & + \sum_{r^+}\phi^{call}_{r^+,h}\left(\eta^{+}_{ev}RP^{G2V}_{r^+,ev,h} + \tfrac{1}{\eta^{-}_{ev}}RP^{V2G}_{r^+,ev,h}\right) \\ & - \sum_{r^-}\phi^{call}_{r^-,h}\left(\eta^{+}_{ev}RP^{G2V}_{r^-,ev,h} + \tfrac{1}{\eta^{-}_{ev}}RP^{V2G}_{r^-,ev,h}\right) \qquad \forall ev, h > 1 \qquad (11c) \end{aligned}$$

$$EV^{l}_{ev,h} = \phi^{ini}_{ev}n^{E}_{ev}\phi^{ev}_{ev}q^{ev} \qquad \forall ev, h = |\mathfrak{H}| \qquad (11d)$$

$$EV^{l}_{ev,h} \leq n^{E}_{ev}\phi^{ev}_{ev}q^{ev} \qquad \forall ev, h \qquad (11e)$$

Charging and discharging are further constrained by maximum hourly power rating capacities (11f–11g), and the current battery charging level (11h–11i). Likewise, scheduled charging must exceed hourly reserves provision (11j–11k)

$$EV^{+}_{ev,h} + \sum_{r^-}RP^{G2V}_{r^-,ev,h} \leq n^{P}_{ev,h}\phi^{ev}_{ev}q^{ev} \qquad \forall ev, h \qquad (11f)$$

$$EV^{-}_{ev,h} + \sum_{r^+}RP^{V2G}_{r^+,ev,h} \leq n^{P}_{ev,h}\phi^{ev}_{ev}q^{ev} \qquad \forall ev, h \qquad (11g)$$

$$EV^{+}_{ev,h} + \eta^{+}_{ev}\sum_{r^-}RP^{G2V}_{r^-,ev,h} \leq n^{E}_{ev}\phi^{ev}_{ev}q^{ev} - EV^{l}_{ev,h-1} \qquad \forall ev, h \qquad (11h)$$

$$EV^{-}_{ev,h} + \tfrac{1}{\eta^{-}_{ev}}\sum_{r^+}RP^{V2G}_{r^+,ev,h} \leq EV^{l}_{ev,h-1} \qquad \forall ev, h \qquad (11i)$$

$$\sum_{r^+}RP^{G2V}_{r^+,ev,h} - EV^{+}_{ev,h} \leq 0 \qquad \forall ev, h \qquad (11j)$$

$$\sum_{r^-}RP^{V2G}_{r^-,ev,h} - EV^{-}_{ev,h} \leq 0 \qquad \forall ev, h \qquad (11k)$$

Constraints (12a–12l implement prosumage. A share $\phi^{pro,load}$ of total load is attributed to the prosumage segment. Prosumagers are attributed renewable capacities N^{pro}_{res}, by default only PV, and a storage, $N^{E,pro}_{sto}$, $N^{P,pro}_{sto}$, by default lithium-ion batteries, and must fulfill a minimum self-generation requirement over the year. The prosumage storage is divided into four virtual segments for self-consumption and interactions of prosumagers with the market. Figure 1 provides an illustration.

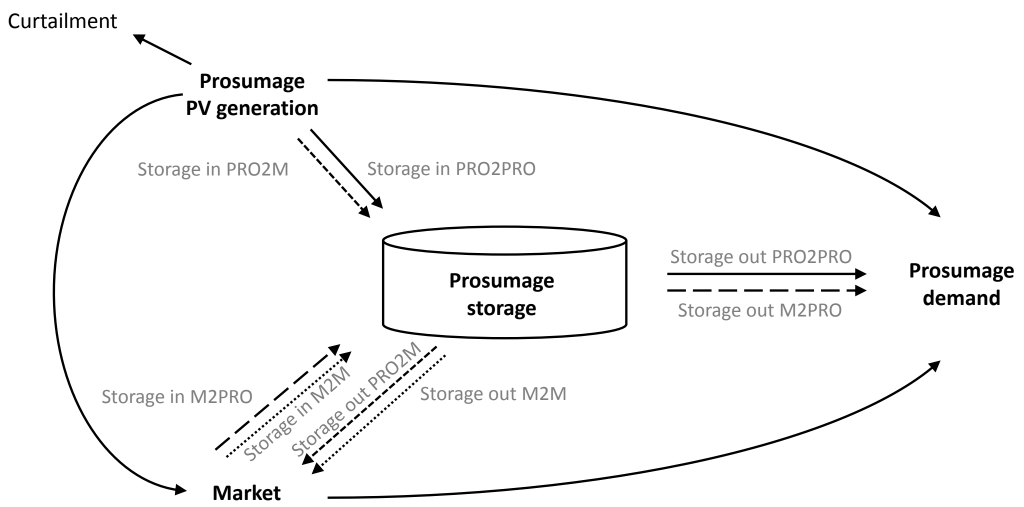

Figure 1: Sketch of the prosumage segment

Equation (12a) distributes hourly generation: it is either consumed directly, $G^{pro2pro}_{res,h}$, sent to the wholesale market, $G^{pro2m}_{res,h}$, curtailed, or stored, either earmarked for being later discharged to self-consumption, $STO^{in,pro2pro}_{sto,res,h}$, or later discharged to the market, $STO^{in,pro2m}_{sto,res,h}$.

$$\phi^{res}_h N^{pro}_{res} = CU^{pro}_{res,h} + G^{pro2pro}_{res,h} + G^{pro2m}_{res,h} + \sum_{sto} \left(STO^{in,pro2pro}_{sto,res,h} + STO^{in,pro2m}_{sto,res,h} \right) \quad \forall res, h \tag{12a}$$

The prosumage energy balance (12a) prescribes that hourly prosumager demand is satisfied from direct self-generation, consumption from the market G^{m2pro}_h, or storage outflow, either earmarked as originating from self-generation, $STO^{out,pro2pro}_{sto,h}$, or the market, $STO^{out,m2pro}_{sto,h}$.

$$\phi^{pro,load} d_h = \sum_{res} G^{pro2pro}_{res,h} + G^{m2pro}_h + \sum_{sto} \left(STO^{out,pro2pro}_{sto,h} + STO^{out,m2pro}_{sto,h} \right) \quad \forall h \tag{12b}$$

Equation (12c) imposes a minimum self-generation share $\phi^{pro,self}$, fulfilled through direct self-consumption or from stored and previously self-generated electricity. The share must hold in total over the year, but not for each hour.

$$\phi^{pro,self} \sum_{h} \phi^{pro,load} d_h \leq \sum_{res,h} G^{pro2pro}_{res,h} + \sum_{sto,h} STO^{out,pro2pro}_{sto,h} \tag{12c}$$

Each virtual storage segment is subject to a law of motion: for prosumage-to-prosumage, the storage level in an hour, $STO^{l,pro2pro}_{sto,h}$, is given by equation (12e), together with an initial and ending condition. Analogous sets of equations apply to the other three virtual storage segments.

$$STO^{l,pro2pro}_{sto,1} = \tfrac{1}{4}\phi^{ini,pro}_{sto} N^{E,pro}_{sto} + \tfrac{1+\eta_{sto}}{2} \sum_{res} STO^{in,pro2pro}_{sto,res,1} - \tfrac{2}{1+\eta_{sto}} STO^{out,pro2pro}_{sto,1} \qquad \forall sto \tag{12d}$$

$$STO^{l,pro2pro}_{sto,h} = STO^{l,pro}_{sto,h-1} + \tfrac{1+\eta_{sto}}{2} \sum_{res} STO^{in,pro2pro}_{sto,res,h} - \tfrac{2}{1+\eta_{sto}} STO^{out,pro2pro}_{sto,h} \qquad \forall sto, h \tag{12e}$$

$$STO^{l,pro2pro}_{sto,h} = \tfrac{1}{4}\phi^{ini,pro}_{sto} N^{E,pro}_{sto} \qquad \forall sto, h = |\mathfrak{H}| \tag{12f}$$

All virtual storage segments together constitute the overall storage level (12g), which is restricted by storage energy capacity (12h).

$$STO^{l,pro}_{sto,h} = STO^{l,pro2pro}_{sto,h} + STO^{l,pro2m}_{sto,h} + STO^{l,m2pro}_{sto,h} + STO^{l,m2m}_{sto,h} \qquad \forall sto, h \tag{12g}$$

$$STO^{l,pro}_{sto,h} \leq N^{E,pro}_{sto} \qquad \forall sto, h \tag{12h}$$

Likewise, power storage capacities take effect for the entirety of all storage inflows (12i) and outflows (12j).

$$\sum_{res} \left(STO^{in,pro2pro}_{sto,res,h} + STO^{in,pro2m}_{sto,res,h} \right) + STO^{in,m2pro}_{sto,h} + STO^{in,m2m}_{sto,h} \leq N^{P,pro}_{sto} \qquad \forall sto, h \tag{12i}$$

$$STO^{out,pro2pro}_{sto,h} + STO^{out,pro2m}_{sto,h} + STO^{out,m2pro}_{sto,h} + STO^{out,m2m}_{sto,h} \leq N^{P,pro}_{sto} \qquad \forall sto, h \tag{12j}$$

To prevent the storage from undue intra-hourly cycling, only that energy can be released that has been in the storage one time step before (12k). Analogously, only so much energy can be stored in as has been the difference between the storage level and the energy capacity one hour before (12l).

$$\left(STO^{out,pro2pro}_{sto,h} + STO^{out,pro2m}_{sto,h} + STO^{out,m2pro}_{sto,h} + STO^{out,m2m}_{sto,h}\right) \tfrac{2}{1+\eta_{sto}} \leq N^{l,pro}_{sto,h-1} \qquad \forall sto, h \tag{12k}$$

$$\left(\sum_{res}\left(STO^{in,pro2pro}_{sto,res,h} + STO^{in,pro2m}_{sto,res,h}\right) + STO^{in,m2pro}_{sto,h} + STO^{in,m2m}_{sto,h}\right) \tfrac{1+\eta_{sto}}{2} \leq N^{E,pro} - N^{l,pro}_{sto,h-1} \qquad \forall sto, h \tag{12l}$$

3 Input Data

The model is loosely calibrated to the German power system with regard to demand, hourly availabilities of fluctuating renewables, and constraints for offshore, wind power, biomass, pumped hydro storage, and DSM[5]. Hourly load values are taken from (ENTSO-E 2016) for the year 2013. For the fraction of reserves called, we divide the mean hourly actually activated reserves, provided by the German TSOs (regelleistung.net 2014a), by the contracted capacities at that point (regelleistung.net 2014b).

Aside from time-related input data, which is based on 2013 under baseline assumptions, all technology-specific input parameters reflect a 2050 perspective. Tables 4 to 8 contain a detailed representation of all technology-specific assumptions of the baseline, including respective units and data sources. Annualized fixed costs are generally calculated by drawing overnight investment costs, fixed costs not related to power generation (where applicable), specific technical lifetimes, and an assumed interest rate of 4%. Monetary values are generally stated in real prices of 2010.

Regarding thermal generation technologies, we include hard coal, combined cycle natural gas (CCGT) and two types of open cycle natural gas turbines (OCGT)—an "efficient" one with lower marginal but higher investment costs, and an "inefficient" type for which the opposite is true. By assumption, investments into nuclear, lignite, and run-of-river hydro power are not possible. In case of nuclear, this reflects the legal situation in Germany. Lignite plants, which have high specific CO_2 emissions, are assumed not to be compatible with a long-term, low-emission, renewable-based system.[6] Run-of-river is excluded because, on the one hand, potentials in Germany are small; on the other, it is a non-dispatchable low-cost technology, such that unlimited investment opportunities would render model results trivial.

The major source for cost parameters for conventional generators and biomass plants is the DIW Data Documentation (Schröder et al. 2013), of which medium projections for 2050 are used. Supplementary information stems from VGB PowerTech (2012), and VDE (2012) for load change flexibility. Marginal production costs of conventional plants are calculated based on the carbon content of the fuel (UBA 2013), an assumed CO_2 price of 100 Euro per tonne, and specific efficiency and fuel costs. Fuel prices follow the "medium" price path within DLR et al. (2012), except for lignite (dena 2012).

Regarding fluctuating renewable technologies, we include onshore and offshore wind power

5. Not only the source code, but also all input data is freely available under `www.diw.de/dieter`.

6. This assumption appears not to be critical. Additional model runs that include a lignite option parametrized according to Table 4 show that no such investments take place under the assumed baseline CO_2 price of 100 Euro per tonne, as lignite plants incur both high investments and variable costs.

as well as solar photovoltaics. In addition, investments in dispatchable biomass generators—which are treated like conventional thermal plants in the model formulation—are possible. Cost data for renewables as well comes from the DIW Data Documentation (Schröder et al. 2013). Under baseline assumptions, a cap on offshore wind power installations of 32 GW is assumed (DLR et al. 2012). We further assume a yearly biomass budget of 60 TWh in the baseline (BMU 2012). We calculate hourly renewable availability factors by dividing the 2013 hourly in-feed of onshore wind (50Hertz 2016b; Amprion 2016b; TenneT TSO 2016b; Transnet BW 2016b), offshore wind (TenneT TSO 2016b), or solar PV (50Hertz 2016a; Amprion 2016a; TenneT TSO 2016a; Transnet BW 2016a), provided by the German TSOs, by the installed capacity in the same year (BMWi 2014).[7].

Building on the "Roadmap Storage" (Pape et al. 2014), we consider seven distinct storage technologies which vary with respect to specific investments into power and energy as well as roundtrip efficiency. In most scenarios, investment choices are restricted to three of these technologies: lithium-ion batteries (Li-ion, as an example for a short-term storage technology), pumped hydro storage (PHS, mid-term), and power-to-gas (P2G, long-term).[8] The remaining four technologies are included only in a sensitivity. These are considered to be either risky with respect to environmental or security concerns, such as lead acid batteries and sodium-sulfur (NaS) batteries, or not to be cost-competitive with the other storage options like redox flow batteries and advanced adiabatic compressed air energy storage (AA-CAES). For DSM potentials and costs, we largely draw upon Frontier (2014) who assemble evidence from numerous academic and applied studies, as well as on Klobasa (2007), Gils (2014), and Agora (2013).

7. For convenience, we impose a linear expansion path on the installed capacities between the beginning and the end of 2013.

8. Here, "power-to-gas" involves the use of electricity to generate hydrogen and later reconversion to electricity. A more precise, but rather lengthy term would be "power-to-hydrogen-to-power".

Table 4: Technical assumptions on conventional power plants

	Parameter	Value	Unit	Source
Lignite				
Efficiency		0.466	-	Schröder et al. (2013)
Carbon content		0.364	$tons/MWh_{th}$	UBA (2013)
Fuel price		4.90	$Euro/MWh_{th}$	dena (2012)
Marginal generation costs	c^m_{con}	88.54	$Euro/MWh$	
Overnight investment costs		1,500	$Euro/kW$	Schröder et al. (2013)
Technical lifetime		35	$years$	Schröder et al. (2013)
Annualized investment costs	c^i_{con}	80	$Euro/kW$	
Annual fixed costs	c^{fix}_{con}	30	$Euro/kW$	Schröder et al. (2013)
Load change costs up and down	c^+/c^-	30	$Euro/MW$	Own assumption
Maximum load change for reserves	$\phi^{\pm}$	4	$\%\ of\ capacity\ per\ minute$	VDE (2012)
Hard Coal				
Efficiency		0.467	-	Schröder et al. (2013)
Carbon content		0.354	$tons/MWh_{th}$	UBA (2013)
Fuel price		23.04	$Euro/MWh_{th}$	DLR et al. (2012)[a]
Marginal generation costs	c^m_{con}	125.12	$Euro/MWh$	
Overnight investment costs		1,300	$Euro/kW$	Schröder et al. (2013)
Technical lifetime		35	$years$	Schröder et al. (2013)
Annualized investment costs	c^i_{con}	70	$Euro/kW$	
Annual fixed costs	$c^{fix_{con}}$	30	$Euro/kW$	Schröder et al. (2013)
Load change costs up and down	c^+/c^-	30	$Euro/MW$	Own assumption
Maximum load change for reserves	$\phi^{\pm}$	6	$\%\ of\ capacity\ per\ minute$	VDE (2012)
CCGT				
Efficiency		0.619	-	Schröder et al. (2013)
Carbon content		0.202	$tons/MWh_{th}$	UBA (2013)
Fuel price		38.16	$Euro/MWh_{th}$	DLR et al. (2012)[a]
Marginal generation costs	c^m_{con}	94.28	$Euro/MWh$	
Overnight investment costs		800	$Euro/kW$	Schröder et al. (2013)
Technical lifetime		25	$years$	Schröder et al. (2013)
Annualized investment costs	c^i_{con}	51	$Euro/kW$	
Annual fixed costs	c^{fix}_{con}	20	$Euro/kW$	Schröder et al. (2013)
Load change costs up and down	c^+/c^-	20	$Euro/MW$	Own assumption
Maximum load change for reserves	$\phi^{\pm}$	8	$\%\ of\ capacity\ per\ minute$	VDE (2012)
OCGT inefficient				
Efficiency		0.396	-	VGB PowerTech (2012)
Carbon content		0.202	$tons/MWh_{th}$	UBA (2013)
Fuel price		38.16	$Euro/MWh_{th}$	DLR et al. (2012)[a]
Marginal generation costs	c^m_{con}	147.37	$Euro/MWh$	
Overnight investment costs		400	$Euro/kW$	Schröder et al. (2013)
Technical lifetime		25	$years$	Schröder et al. (2013)
Annualized investment costs	c^i_{con}	26	$Euro/kW$	
Annual fixed costs	c^{fix}_{con}	15	$Euro/kW$	Schröder et al. (2013)
Load change costs up and down	c^+/c^-	15	$Euro/MW$	Own assumption
Maximum load change for reserves	$\phi^{\pm}$	15	$\%\ of\ capacity\ per\ minute$	VDE (2012)

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	Parameter	Value	Unit	Source
OCGT efficient				
Efficiency		0.457	-	Schröder et al. (2013)
Carbon content		0.202	$tons/MWh_{th}$	UBA (2013)
Fuel price		38.16	$Euro/MWh_{th}$	DLR et al. (2012)[a]
Marginal generation costs	c^{m}_{con}	127.72	$Euro/MWh$	
Overnight investment costs		650	$Euro/kW$	Schröder et al. (2013)
Technical lifetime		25	$years$	Schröder et al. (2013)
Annualized investment costs	c^{i}_{con}	42	$Euro/kW$	
Annual fixed costs	c^{fix}_{con}	15	$Euro/kW$	Schröder et al. (2013)
Load change costs up and down	c^{+}/c^{-}	15	$Euro/MW$	Own assumption
Maximum load change for reserves	$\phi^{\pm}$	15	$\%\ of\ capacity$ $per\ minute$	VDE (2012)

[a] Medium price path.

Table 5: Technical assumptions on renewable power plants (baseline)

	Parameter	Value	Unit	Source
Wind onshore				
Overnight investment costs		1,075	EUR/kW	Schröder et al. 2013
Technical lifetime		25	$years$	Schröder et al. 2013
Annualized investment costs	c^{i}_{res}	69	EUR/kW	Schröder et al. 2013
Annual fixed costs	c^{fix}_{res}	35	EUR/kW	Schröder et al. 2013
Maximum capacity or energy		-	-	
Wind offshore				
Overnight investment costs		3,522[a]	EUR/kW	Schröder et al. 2013
Technical lifetime		25	$years$	Schröder et al. 2013
Annualized investment costs	c^{i}_{res}	225	EUR/kW	Schröder et al. 2013
Annual fixed costs	c^{fix}_{res}	80	EUR/kW	Schröder et al. 2013
Maximum capacity or energy		32	GW	DLR et al. 2012
Photovoltaics				
Overnight investment costs		425	EUR/kW	Schröder et al. 2013
Technical lifetime		25	$years$	Schröder et al. 2013
Annualized investment costs	c^{i}_{res}	27	EUR/kW	Schröder et al. 2013
Annual fixed costs	c^{fix}_{res}	25	EUR/kW	Schröder et al. 2013
Maximum capacity or energy		-	-	
Biomass				
Efficiency		0.487	-	Schröder et al. 2013
Carbon content		0.00	$tons/MWh_{th}$	UBA 2013
Fuel price		23.04	EUR/MWh_{th}	Own assumption
Marginal generation costs	c^{m}_{con}	47.31	EUR/MWh	
Overnight investment costs		1,951	EUR/kW	Schröder et al. 2013
Technical lifetime		30	$years$	Schröder et al. 2013
Annualized investment costs	c^{i}_{con}	113	EUR/kW	
Annual fixed costs	c^{fix}_{con}	100	EUR/kW	Schröder et al. 2013
Load change costs up and down	c^{+}/c^{-}	25	EUR/MW	Own assumption
Maximum load change for reserves	π	15	$\%\ of\ capacity$ $per\ minute$	VDE 2012
Maximum capacity or energy	m^{E}_{bio}	60	TWh/a	DLR et al. 2012

Note: [a]The number includes additional investments for offshore grids. These are 1,429 EUR/kW according to calculations based on 50Hertz et al. 2014.

Table 6: Technical assumptions on power storage (baseline)

	Parameter	Value	Unit	Source
Lithium-ion batteries				
Efficiency	η_{sto}	0.92	-	Pape et al. (2014)
Marginal costs of storage operation		1	$Euro/MWh$	Own assumption
Overnight investment costs power		35	$Euro/kW$	Pape et al. (2014)
Overnight investment costs in energy		187	$Euro/kWh$	Pape et al. (2014)
Technical lifetime		20	$years$	Agora (2014)
Annualized investment costs capacity	c^{iP}_{sto}	3	$Euro/kW$	
Annualized investment costs energy	c^{iE}_{sto}	14	$Euro/kWh$	
Annual fixed costs	c^{fix}_{sto}	10	$Euro/kW(h)$	Own assumption
Maximum power or energy capacity		-	-	
Lead acid batteries				
Efficiency	η_{sto}	0.84	-	Pape et al. (2014)
Marginal costs of storage operation		1	$Euro/MWh$	Own assumption
Overnight investment costs power		35	$Euro/kW$	Pape et al. (2014)
Overnight investment costs in energy		67	$Euro/kWh$	Pape et al. (2014)
Technical lifetime		15	$years$	Pape et al. (2014)
Annualized investment costs power	c^{iP}_{sto}	3	$Euro/kW$	
Annualized investment costs energy	c^{iE}_{sto}	6	$Euro/kWh$	
Annual fixed costs	c^{fix}_{sto}	10	$Euro/kW(h)$	Own assumption
Maximum power or energy capacity		0	MW	
Sodium-sulfur batteries				
Efficiency	η_{sto}	0.88	-	Pape et al. (2014)
Marginal costs of storage operation		1	$Euro/MWh$	Own assumption
Overnight investment costs power		35	$Euro/kW$	Pape et al. (2014)
Overnight investment costs in energy		89	$Euro/kWh$	Pape et al. (2014)
Technical lifetime		15	$years$	Pape et al. (2014)
Annualized investment costs power	c^{iP}_{sto}	3	$Euro/kW$	
Annualized investment costs energy	c^{iE}_{sto}	8	$Euro/kWh$	
Annual fixed costs	c^{fix}_{sto}	10	$Euro/kW(h)$	Own assumption
Maximum power or energy capacity		0	MW	
Redox flow batteries				
Efficiency	η_{sto}	0.8	-	Pape et al. (2014)
Marginal costs of storage operation		1	$Euro/MWh$	Own assumption
Overnight investment costs power		600	$Euro/kW$	Pape et al. (2014)
Overnight investment costs in energy		70	$Euro/kWh$	Pape et al. (2014)
Technical lifetime		25	$years$	Pape et al. (2014)
Annualized investment costs power	c^{iP}_{sto}	38	$Euro/kW$	
Annualized investment costs energy	c^{iE}_{sto}	4	$Euro/kWh$	
Annual fixed costs	c^{fix}_{sto}	10	$Euro/MW(h)$	Own assumption
Maximum power or energy capacity		0	MW	
Pumped hydro storage				
Efficiency	η_{sto}	0.8	-	Pape et al. (2014)
Marginal costs of storage operation		1	$Euro/MWh$	Own assumption
Overnight investment costs power		1,100	$Euro/kW$	Pape et al. (2014)
Overnight investment costs in energy		10	$Euro/kWh$	Pape et al. (2014)
Technical lifetime		80	$years$	Pape et al. (2014)
Annualized investment costs power	c^{iP}_{sto}	46	$Euro/kW$	

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	Parameter	Value	Unit	Source
Annualized investment costs energy	c_{sto}^{iE}	< 1	$Euro/kWh$	
Annual fixed costs	c_{sto}^{fix}	10	$Euro/kW(h)$	Own assumption
Maximum power or energy capacity		300	GWh	Various sources[a]
Adiabatic compressed air energy storage				
Efficiency	η_{sto}	0.73	-	Pape et al. (2014)
Marginal costs of storage operation		1	$Euro/MWh$	Own assumption
Overnight investment costs power		750	$Euro/kW$	Pape et al. (2014)
Overnight investment costs in energy		40	$Euro/kWh$	Pape et al. (2014)
Technical lifetime		30	$years$	Pape et al. (2014)
Annualized investment costs power	c_{sto}^{iP}	43	$Euro/kW$	
Annualized investment costs energy	c_{sto}^{iE}	2	$Euro/kWh$	
Annual fixed costs	c_{sto}^{fix}	10	$Euro/kW(h)$	Own assumption
Maximum power or energy capacity		0	MW	
Power-to-gas				
Efficiency	η_{sto}	0.46	-	Pape et al. (2014)
Marginal costs of storage operation		1	$Euro/MWh$	Own assumption
Overnight investment costs power		1,000	$Euro/kW$	Agora (2014)
Overnight investment costs in energy		0.2	$Euro/kWh$	Pape et al. (2014)
Technical lifetime		22.5[b]	$years$	Pape et al. (2014)
Annualized investment costs power	c_{sto}^{iP}	68	$Euro/kW$	
Annualized investment costs energy	c_{sto}^{iE}	< 1	$Euro/kWh$	
Annual fixed costs	c_{sto}^{fix}	10	$Euro/kW(h)$	Own assumption
Maximum power or energy capacity		-	-	

[a] Based on EnBW (2012), LfU (2014) TMWAT (2011), Fichtner (2014).
[b] Average for electrolysis and reconversion.

Table 7: Technical assumptions on load curtailment (baseline)

	Parameter	Value	Unit	Source
DSM curt cheap (industry)				
Load curtailment costs	c_{lc}^{m}	500	$Euro/MWh$	Frontier (2014)
Overnight investment costs		10	$Euro/kW$	Frontier (2014)
Technical lifetime		10	$years$	Own assumption
Annualized investment costs	c_{lc}^{i}	1	$Euro/kW$	
Annual fixed costs	c_{lc}^{fix}	1	$Euro/kW$	Frontier (2014)
Maximum duration DSM	t^{dur}	4	h	Klobasa (2007)
Recovery time DSM	t^{off}	24	h	
Maximum installable capacity	m_{lc}	3,300	MW	Frontier (2014)
DSM curt medium (industry)				
Load curtailment costs	c_{lc}^{m}	1,500	$Euro/MWh$	Frontier (2014)
Overnight investment costs		10	$Euro/kW$	Frontier (2014)
Technical lifetime		10	$years$	Own assumption
Annualized investment costs	c_{lc}^{i}	1	$Euro/kW$	Frontier (2014)
Annual fixed costs	c_{lc}^{fix}	1	$Euro/kW$	Frontier (2014)
Maximum duration DSM	t^{dur}	4	h	Klobasa (2007)
Recovery time DSM	t^{off}	24	h	Own assumption
Maximum installable capacity	m_{lc}	1,600	MW	Frontier (2014)
DSM curt expensive (industry)				
Load curtailment costs	c_{lc}^{m}	8,000	$Euro/MWh$	Frontier (2014)
Overnight investment costs		10	$Euro/kW$	Frontier (2014)
Technical lifetime		10	$years$	Own assumption
Annualized investment costs	c_{lc}^{i}	1	$Euro/kW$	Frontier (2014)
Annual fixed costs	c_{lc}^{fix}	1	$Euro/kW$	Frontier (2014)
Maximum duration DSM	t^{dur}	4	h	Klobasa (2007)
Recovery time DSM	t^{off}	24	h	Own assumption
Maximum installable capacity	m_{lc}	5,400	MW	Frontier (2014)

Table 8: Technical assumptions on load shifting (baseline)

	Parameter	Value	Unit	Source
DSM shift 1h (climatization, process heat/cold)				
Load shifting costs	c_{ls}^{m}	1	$Euro/MWh$	Frontier (2014)
Overnight investment costs		745	$Euro/kW$	Frontier (2014)
Technical lifetime		10	$years$	Own assumption
Annualized investment costs	c_{ls}^{i}	92	$Euro/kW$	Frontier (2014)
Annual fixed costs	c_{ls}^{fix}	-	$Euro/kW$	
Maximum duration DSM	t^{dur}	1	h	Agora (2013)
Recovery time DSM	t^{off}	1[a]	h	Own assumption
Maximum installable capacity	m_{ls}	793	MW	Frontier (2014)
DSM shift 2h (circulation pumps, heat pumps, ventilation)				
Load shifting costs	c_{ls}^{m}	1	$Euro/MWh$	Frontier (2014)
Overnight investment costs		1,517	$Euro/kW$	Frontier (2014)
Technical lifetime		10	$years$	Own assumption
Annualized investment costs	c_{ls}^{i}	187	$Euro/kW$	Frontier (2014)
Annual fixed costs	c_{ls}^{fix}	-	$Euro/kW$	
Maximum duration DSM	t^{dur}	2	h	Stadler and Bukvic-Schäfer (2003), Agora (2013)
Recovery time DSM	t^{off}	1[a]	h	Own assumption
Maximum installable capacity	m_{ls}	2,535	MW	Frontier (2014)
DSM shift 3h (industry)				
Load shifting costs	c_{ls}^{m}	100	$Euro/MWh$	Own assumption
Overnight investment costs		10	$Euro/kW$	Frontier (2014)
Technical lifetime		10	$years$	Own assumption
Annualized investment costs	c_{ls}^{i}	1	$Euro/kW$	Own assumption
Annual fixed costs	c_{ls}^{fix}	-	$Euro/kW$	
Maximum duration DSM	t^{dur}	3	h	Gils (2014)
Recovery time DSM	t^{off}	1[a]	h	Own assumption
Maximum installable capacity	m_{ls}	1,385	MW	Gils (2014)
DSM shift 4h (white goods, ventilation)				
Load shifting costs	c_{ls}^{m}	1	$Euro/MWh$	Frontier (2014)
Overnight investment costs		835	$Euro/kW$	Frontier (2014)
Technical lifetime		10	$years$	Own assumption
Annualized investment costs	c_{ls}^{i}	103	$Euro/kW$	Frontier (2014)
Annual fixed costs	c_{ls}^{fix}	-	$Euro/kW$	
Maximum duration DSM	t^{dur}	4	h	Own assumption
Recovery time DSM	t^{off}	1[a]	h	Own assumption
Maximum installable capacity	m_{ls}	1,451	MW	Frontier (2014)
DSM shift 12h (storage heaters)				
Load shifting costs	c_{ls}^{m}	1	$Euro/MWh$	Frontier (2014)
Overnight investment costs		30	$Euro/kW$	Frontier (2014)
Technical lifetime		10	$years$	Own assumption
Annualized investment costs	c_{ls}^{i}	4	$Euro/kW$	Frontier (2014)
Annual fixed costs	c_{ls}^{fix}	-	$Euro/kW$	
Maximum duration DSM	t^{dur}	12	h	Agora (2013)
Recovery time DSM	t^{off}	1[a]	h	Own assumption
Maximum installable capacity	m_{ls}	1,050	MW	Frontier (2014)

[a] This means that recovery time is not restricted for shifting processes.

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