Babrowski, S.; Jochem, P.; Fichtner, W. (2016)

Electricity storage systems in the future German energy sector : An optimization of the German electricity generation system until 2040 considering grid restrictions.

*Computers & operations research*, 66, 228-240. doi:10.1016/j.cor.2015.01.014

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# Electricity Storage Systems in the Future German Energy Sector

## An Optimization of the German Electricity Generation System until 2040 Considering Grid Restrictions

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Abstract:

Due to the growing feed-in of electricity based on renewables, electricity storage systems will be essential in the future energy sector. Because of the volatile feed-in, electricity will have to be shifted temporally. Additionally, load centers and regions of potentially high wind-based electricity production are located far away from each other in Germany, resulting in the need to transport electricity from the north to the south. According to the targets defined by the German government, more than 60% of electricity generation in 2040 is to be based on renewables. A strategic allocation of storage systems might help to improve the utilization of grid capacities and integrate renewables at the same time. To analyze this, we implemented the possibility to commission storage systems throughout Germany in the energy system model PERSEUS-NET-ESS. This investment and dispatch model includes a DC approach of the German transmission grid and, thus, calculates not only the installed capacities, but also their optimal allocation. Besides storage systems, gas turbines or load shift potentials can be used for the integration of renewables. In this paper, we use PERSEUS-NET-ESS to evaluate the alternatives taking the grid restrictions into account. Results indicate that it is beneficial to commission about 3.2 GW of battery storage systems until 2040, provided that storage investment will drop to about 150 €/kWh until then. The main part of the capacity is to be deployed in northern Germany close to the sea, where electricity from off-shore wind parks will be fed into the grid. At the same time, the storage systems will be located mainly close to congested grid lines. For the case of battery storage systems being impossible in the model, gas turbines are commissioned instead. Modeling will also consider the load shift potential due to electric mobility. It can substitute almost all of the commissioned storage systems and at the same time reduce the total generation capacity needed.

*Keywords: Electricity Storage Systems, Energy System Modeling, Load Shift Potential*

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## 1. Introduction

According to the targets defined by the German government, more than 50% of the gross electricity consumption in Germany is to be based on renewables in 2030, with this proportion rising to more than 60% in 2040 [1]. Because of the volatile character of wind and solar electricity generation, such a raise in renewables will not be possible without adjustments in the transmission grid. Additionally, either a huge back-up generation system with few full load hours or electricity storage systems (ESS) will be needed to satisfy the demand at all times.

So far, electricity has always been produced close to where it was needed and at the time it was needed. In the future, this is going to change. The wind and solar electricity supply is independent of the demand, leading to the need of shifting electricity in time. To make things worse, good wind conditions in Germany are encountered in the north, while the load centers are located in the south. Accordingly, generation and demand are increasingly separated geographically. This will lead to an increasing amount of electricity that will have to be transported within Germany. According to the Dena Net Study II [2], 3,600 km of transmission lines will be needed until 2020 already to reach the 35% target. In the near future, however, ESS do not seem to be an economical alternative to grid extensions [2-4]. They can only be temporary alternatives to grid extensions when the extension process is delayed due to acceptance or approval issues [3]. Nevertheless, with an increasing share of renewables to 40% and more, ESS will be needed for the integration of volatile renewables [5]. According to the government plans, this will already be the case within the next 10 to 15 years.

As a result of the high investments required, commissioning of ESS is not economically efficient in Germany at the moment nor will it be cost-efficient until 2020 [3,5,6]. However, the energy installation costs for high-temperature batteries, such as the sodium-sulfur (NaS) battery, are predicted to drop until 2030 to about one fourth (80-150 €/kWh) of today's price of 500-700 €/kWh. The costs for the converter will drop from 150-200 €/kW to about 35-65 €/kW at the same time [7]. Another example is the price development for lithium-ion batteries. Prices have already dropped significantly in the past years. Driven by the development on the electric vehicle market, they might drop even further [8] and reach energy installation costs of 150-300 €/kWh by 2030 [7]. Consequently, the question of how many and up to which percentage of renewable feed-in ESS will be needed is addressed in many studies (e.g. [3,5,6,9-11]).

Still, none of these studies optimizes the need for ESS endogenously together with their allocation, taking into account the transmission grid and alternative technologies at the same time. For this reason, we will implement the possibility to build up ESS throughout Germany in the German energy system model PERSEUS-NET-ESS that includes a DC approach of the transmission grid [12,13]. The model has been extended in order to analyze this research problem in the context of the future energy system. The renewables are integrated based on hourly historic feed-in data and as an alternative technology to ESS, the option of load shifting through electric vehicles (EVs) is integrated.

For this purpose, the PERSEUS-NET-ESS model and its input parameters will be described in the following section. First, the basic model equations that are mostly common to all PERSEUS models will be described before the constraints specifically adjusted or newly added for our study will be introduced. These constraints mainly consist of the chosen time structure, the integration of renewables based on historical feed-in data, and the mapping of the ESS. Furthermore, the additional demand for EVs is integrated. Depending on the settings, charging will take place either according to a fixed load curve or it can be shifted throughout the day as part of the optimization. In section three, the approach used to handle the computing time and the three scenarios considered will be presented. The resulting generation systems and electricity mixes will be described and compared in section four, with the focus lying on

ESS. Besides, the curtailment of renewables as well as the dispatch of the ESS will be addressed. Additionally, their allocation will be analyzed for the reference scenario. The paper will be completed by a critical reflection and a conclusion.

## 2. The PERSEUS-NET-ESS Energy System Model

### 2.1 General Description

The PERSEUS-NET-ESS (Program **P**ackage for **E**mission **R**eductions **S**trategies in **E**nergy **U**se and **S**upply-**NET** - **E**lectricity **S**torage **S**ystems) optimizing energy system model is a bottom-up model representing the German electricity system [12,13]. It is part of the PERSEUS model family [14]. The model is written in GAMS and is based on a myopic (mixed integer) linear optimization that is solved with CPLEX.

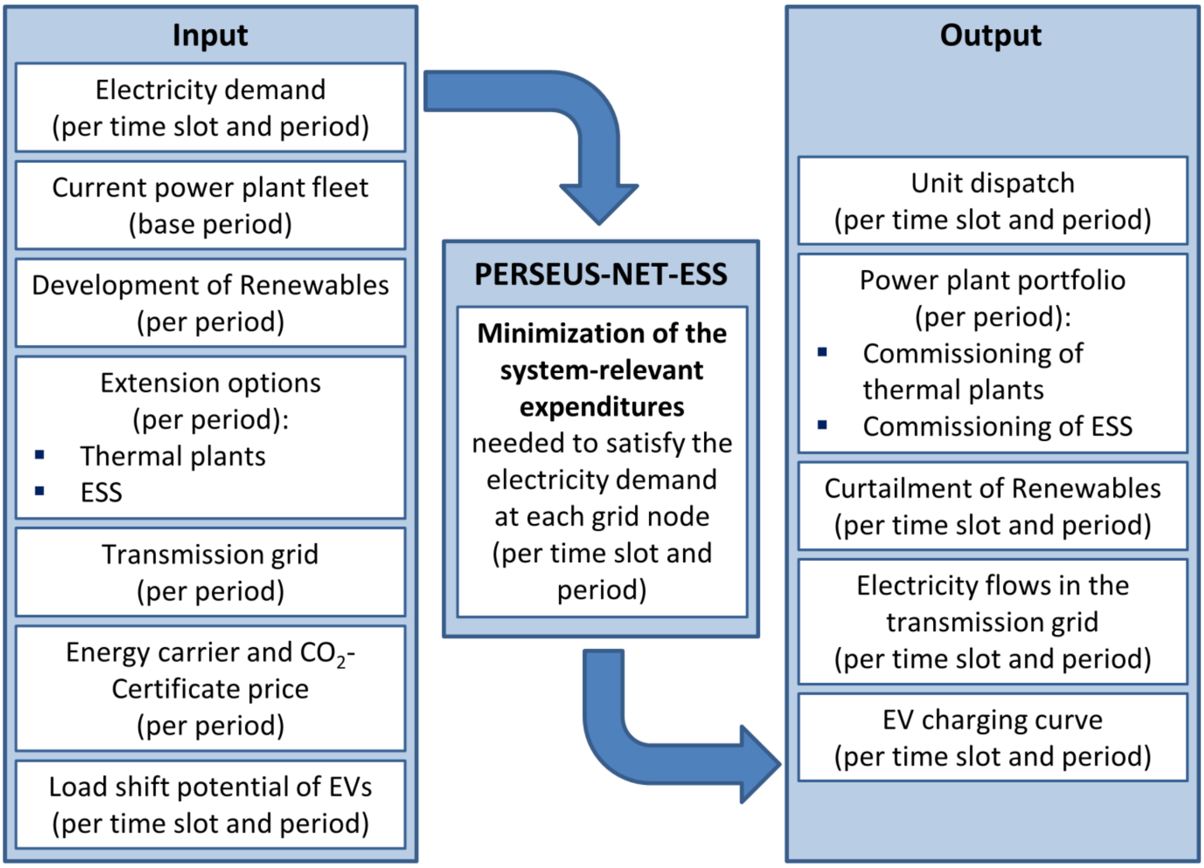

Figure 1: Input and Output of the PERSEUS-NET-ESS model

PERSEUS-NET-ESS includes a nodal pricing approach based on a direct current (DC) approximation of the German transmission network. It calculates the redevelopment plans for coal, lignite, and gas power plants as well as ESS throughout Germany. The driving force is the exogenously given demand at each grid node, which has to be satisfied while minimizing the system-relevant expenditures of each period (see Fig.1). The electricity demand on each grid node[1] can either be satisfied by the transfer of electricity from neighboring grid nodes or by the generation of electricity in power plants allocated at the grid node. If there is not enough generation capacity available, new thermal power plants or ESS can

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[1] Exceptions are grid nodes representing junctions without an electric power substation.

be commissioned. Subsequently it is possible to calculate the economic need for ESS with the PERSEUS-NET-ESS model while technological alternatives such as gas turbines or load shifting are considered as well as grid restrictions.

In PERSEUS-NET-ESS 440 administrative districts (Kreise) are modeled with their specific power plants and demands. The current generation system is based on the list of power plants of the German Federal Network Agency [15]. In the model, existing power plants are decommissioned 40 years after their commissioning or refurbishment. While bigger power plants (> 100 MW) are connected directly to the grid nodes of the transmission grid, decentralized small power plants are accumulated for each district and assigned to the two closest grid nodes. The exogenously given electricity demand is also specified for each grid node. Conventional demand is calculated for each district based on the estimated population growth and the gross domestic product [13]. The conventional demand is assumed to decline slightly from 503 TWh in 2012 to 486 TWh in 2040 (see Table A.1 in the appendix). This demand is complemented by an additional demand for EVs that is described in section 2.3.4. The mapping of the transmission net is based on the printed map of the UCTE network [16] and the extension projects determined by the power grid extension act ("EnLAG" [17]). Changes are made by integrating extension projects that have passed the plan approval procedure according to the 2012 power grid development plan as well as current delays [18]. For estimating the needed ESS capacity, we integrated an expansion option for a gas turbine and a combined cycle plant as well as an option for an ESS at each grid node. Furthermore, options for lignite power plants are given for grid nodes allocated close to the lignite mining industry. Coal expansion options are only allowed for grid nodes, where coal power plants exist today already, since the allocation of new coal plants is a question of sufficient water access and, not less important, of its local acceptance. The techno-economic parameters of the thermal expansion options are based on the German pilot study [19]. The fuel prices for oil, gas, and coal and the $CO_2$ certificate prices are exogenously given and set according to the forecasts of the world energy outlook [20]. For details, see Tables A.2 and A.3 in the appendix.

## 2.2 Mathematical Description of the Basic Model

PERSEUS-NET-ESS is structured as a graph in which so called producers ($pd \in PD$) form the nodes and material and energy flows form the edges in between. Accordingly, different flows may connect the producers. Processes ($pc \in PC$) are assigned to (generation) units ($u \in U$) and each unit is then assigned to a producer. Imports from outside the system boundaries are the sources of the graph ($ip \in IP \subset PD$). Exports in form of demand processes are the sinks of the graph ($ep \in EP \subset PD$).

The objective function (equation 1) covers all system-relevant expenditures of the considered period ($t \in T$)[2] [12,13]. The first summand comprises all fuel expenditures, the costs ($C^{Fuel}_{ip,pd,ec,t}$) to import an energy carrier ($ec \in EC$) into the system to a specific producer multiplied by the corresponding energy carrier flow ($FL_{ip,pd,ec,t}$). The costs for $CO_2$ emissions are already included in the fuel costs. The second summand comprises the variable costs ($C^{Var}_{pc,t}$) of electricity generation ($PL_{pc,t}$) for each conversion process. Additionally, costs ($C^{LC}_{pc,t}$) for load changes ($LC^{up}_{pc,s-1,s,t}, LC^{d}_{pc,s-1,s,t}$) from one time slot ($s \in S$) to the next are considered for the generation of electricity from coal, lignite, uranium, and gas combined cycles. The third summand reflects the fixed costs ($C^{Fix}_{u,t}$) of all installed capacities ($Cap^{Tot}_{u,t}$) and all specific expenditures ($C^{Inv}_{u,t}$) for the installation of new capacities ($Cap^{New}_{u,t}$) for all generation units.

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[2] For the complete nomenclature, please see the appendix A.1

$$\min\left[\begin{array}{l} \left(\sum_{ip\in IP}\sum_{ec\in EC}\sum_{pd\in PD} FL_{ip,pd,ec,t}\cdot C^{Fuel}_{ip,pd,ec,t}\right) \\ +\sum_{pc\in PC}\left(\begin{array}{l} PL_{pc,t}\cdot C^{Var}_{pc,t} \\ +\sum_{s\in S}\left(LC^{up}_{pc,s-1,s,t}+LC^{d}_{pc,s-1,s,t}\right)\cdot C^{LC}_{pc,t}\end{array}\right) \\ +\sum_{u\in U}\left(\begin{array}{l} Cap^{Tot}_{u,t}\cdot C^{Fix}_{u,t} \\ +Cap^{New}_{u,t}\cdot C^{Inv}_{u,t}\end{array}\right)\end{array}\right]$$

$$\forall t \in T \subset \{2012, 2015, 2020, 2025, 2030, 2035, 2040\} \qquad (1)$$

The model balances the material and energy flows for each period via producers. The flows of the non-seasonal energy carriers ($ec \in EC^T \subset EC$), such as gas or oil, are balanced once for each period (equation 2). Import flows from outside of the system boundaries ($FL_{ip,pd,ec,t}$) or from other producers ($FL_{pd',pd,ec,t}$) plus the generation ($PL_{pc,t} \cdot \lambda_{pc,ec}$) through generation processes ($pc \in PC^G_{pd} \subset PC$) corresponding to the producer equal the outflows ($FL_{pd,ep,ec,t}$, $FL_{pd,pd',ec,t}$) and use of the electricity ($PL_{pc,t} * \lambda_{pc,ec}$) by this producer in demand processes ($pc \in PC^D_{pd} \subset PC$). The efficiency of the flows and the use process ($\eta_{pd,ep,ec,t}$, $\eta_{pd,pd',ec,t}$, $\eta_{pc,t}$) is considered.

$$\sum_{ip\in IP} FL_{ip,pd,ec,t} + \sum_{pd'\in PD} FL_{pd',pd,ec,t} + \sum_{pc\in PC^G_{pd}} PL_{pc,t}\cdot\lambda_{pc,ec}$$

$$= \sum_{pd'\in PD} \frac{FL_{pd,pd',ec,t}}{\eta_{pd,pd',ec,t}} + \sum_{ep\in EP}\frac{FL_{pd,ep,ec,t}}{\eta_{pd,ep,ec,t}} + \sum_{pc\in PC^D_{pd}} PL_{pc,t}\cdot\frac{\lambda_{pc,ec}}{\eta_{pc,t}}$$

$$\forall t \in T;\ \forall pd \in PD;\ \forall ec \in EC^T \qquad (2)$$

As the electricity demand has to be satisfied at each time slot electricity is modeled as a seasonal energy carrier ($el \in EC^S \subset EC$). It is therefore balanced for each of the considered time slots instead of only once for the whole year (equation 3). In contrast to the energy carriers that are balanced using the non-seasonal balancing equation, electricity cannot be imported from out of the system boundaries. Another equation (4) states that the use or the generation of seasonal energy carriers in processes ($PS_{pc,t,s}$) over all time slots equals the yearly level of that process ($PL_{pc,t}$). The same is true for the seasonal flows ($FS_{pd,pd',el,t,s}$) and the yearly levels of the electricity flows ($FL_{pd,pd',el,t}$).

$$\sum_{pd'\in PD} FS_{pd',pd,el,t,s} + \sum_{pc\in PC^G_{pd}} PS_{pc,t,s}\cdot\lambda_{pc,el}$$

$$= \sum_{pd'\in PD}\frac{FS_{pd,pd',el,t,s}}{\eta_{pd,pd',el,t}} + \sum_{ep\in EP}\frac{FS_{pd,ep,el,t,s}}{\eta_{pd,ep,el,t}} + \sum_{pc\in PC^D} PS_{pc,t,s}\cdot\frac{\lambda_{pc,el}}{\eta_{pc,t}}$$

$$\forall t \in T;\ \forall s \in S;\ \forall pd \in PD;\ \forall el \in EC^S \qquad (3)$$

$$\sum_{s\in S} PS_{pc,t,s} = PL_{pc,t}$$

$\forall t \in T;\ \forall pc \in (PC \setminus PC_{EC^{v}})$[3] (4)

The demand for electricity is modeled as an export flow to outside of the system boundaries (i.e. the term $FS_{pd,ep,ec,t,s}$ in equation 3). The balanced producer has to export enough electricity out of the system to satisfy the given electricity demand ($D_{pd,el,t,s}$) in every time slot (equation 5).

$$FS_{pd,ep,el,t,s} = D_{pd,el,t,s}$$

$\forall t \in T;\ \forall s \in S;\ \forall pd \in PD;\ \forall\ ep \in EP$ (5)

The restrictions imposed on the generation units are important for the calculation of the future need for ESS. In the PERSEUS-NET-ESS database maximum full load hours ($Vlh_{u,t}^{Max}$ ) are set for all generating units and their processes. Combined with the installed capacity, the full load hours determine the upper limit of the yearly power generation of each unit (equation 6).

$$Vlh_{u,t}^{Max} \cdot Cap_{u,t}^{Tot} \geq \sum_{\mathrm{pc} \in PC_u} PL_{pc,t}$$

$\forall t \in T;\ \forall u \in U$ (6)

Another equation restricts the energy generation of the processes of a unit ($\mathrm{p}c \in PC_u \subset PC$) within a time slot to the installed capacity multiplied by an availability factor ($A_{u,t}$) and the hours ($Z_s$) of the considered time slot (equation 7).

$$Cap_{u,t}^{Tot} \cdot A_{u,t} \cdot Z_s \geq \sum_{\mathrm{pc} \in PC_u} PS_{pc,s,t}$$

$\forall t \in T;\ \forall s \in S;\ \forall u \in U$ (7)

Coal, lignite, nuclear, and combined cycle power plants may vary their load over time, but they have specific costs for load changes, which limit their flexibility. Renewables, gas turbines, and ESS have no such costs. Power increases and decreases of the processes ($LC_{pc,s-1,s,t}^{up}$, $LC_{pc,s-1,s,t}^{d}$)) are calculated by subtracting the process level of one time slot from the process level of the previous time slot and weighting it with the number of times this change occurs per year ($No_{s-1,s}$) (equation 8).

$$\begin{aligned} LC_{pc,s-1,s,t}^{up} - LC_{pc,s-1,s,t}^{d} \\ = No_{s-1,s} \cdot \left( \frac{PS_{pc,t,s}}{Z_s} - \frac{PS_{pc,t,s-1}}{Z_s} \right) \cdot \frac{1}{\eta_{pc,\mathrm{t}}} \end{aligned}$$

$\forall t \in T;\ \forall s \in S;\ \forall pc \in PC$ (8)

If the available generation capacity is not sufficient to satisfy the electricity demand, new capacities have to be commissioned. Combined with the capacity that already existed at the beginning of the period considered ($Cap_{u,t}^{Res}$), the newly installed capacity forms the total capacity installed of the period considered (equation 9).

$$Cap_{u,t}^{Tot} = Cap_{u,t}^{Res} + Cap_{u,t}^{New}$$

$\forall t \in T;\ \forall u \in U$ (9)

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[3] The exception for the volatile energy carriers is explained in section 2.3

The power flow between grid nodes in PERSEUS-NET-ESS is subject to restrictions based on the DC approximation of the German transmission network and its thermal limits. For more information about the theory of the DC representation please refer to [21,22].

$$\sum_{el\in EC}\frac{FL_{y,y',el,\mathrm{t,s}}}{Z_s}=\gamma_{y,y'}\cdot\left(\theta_{y,t,s}-\theta_{y',t,s}\right)$$

$\forall y,y'\in Y;\ \forall t\in T;\ \forall s\in S$ (10)

According to the DC representation the active power flow ($FL_{y,y',el,\mathrm{t,s}}$) over the transmission line from one grid node ($y\in Y$) to another grid node ($y'\in Y$) has to equal the product of the susceptance of the line ($\gamma_{y,y'}$) and the phase angle difference ($\theta_{y,t,s}-\theta_{y',t,s}$) of the two grid nodes at any time (equation 10). In doing so, grid nodes are modeled as a subset of the producers ($\mathrm{y}\in Y\subset \mathrm{PD}$) and are subsequently balanced over equation 3. For a reference level one grid node has to be defined as slack bus with a phase angle difference of zero (equation 11).

$$\theta_{y,t,s}\cdot SL_y=0$$

$\forall y\in Y;\ \forall t\in T;\ \forall s\in S$

$with\ SL_y=\begin{cases}1, & if\ slack\ bus\\ 0, & oherwise\end{cases}$ (11)

Additionally, the active flow in either direction over a line is restricted by the thermal limits ($TL_{y,y',t}$) of the line (equation 12).

$$(-1)\cdot TL_{y,y',t}\leq\frac{FL_{y,y',el,\mathrm{t,s}}}{Z_s}\leq TL_{y,y',t}$$

$\forall y,y'\in Y;\ \forall t\in T;\ \forall s\in S$ (12)

If there is no sufficient transmission capacity between certain grid nodes, there might be a surplus of generated electricity on one side of the bottleneck and a shortage on the other side, leading to the use of more expansive plants and thus to different nodal prices. A comprehensive overview on the integrated nodal pricing approach is given by [13].

Besides the basic equations and input parameters described above that are mostly common to all of the PERSEUS models (e.g. [14]), we integrated several constraints to specifically address the need for ESS in an energy system with a high share of renewables. These constraints refer to the integration of renewables, the ESS, and the load shift potential (LSP) of EVs. Before those constraints will be addressed, the time structure chosen for this analysis will be described below.

## 2.3 Changes and Extensions focusing on ESS

### 2.3.1 Time Structure and Foresight

As the computing time is a critical factor for PERSEUS-NET-ESS, it is not possible to calculate 20 years or more based on its 8,760 hours [12]. Instead, at least every fifth year is calculated to represent a period of up to five years. Moreover, so-called time slots (or time slices) are used to represent each calculated period. In former model versions, time slots were determined by changes in the demand and summarized several hours. Especially for the hours during the night, not much information and variability was lost by doing that. However, this has changed. Due to the volatile renewable feed-in, there is the need for a more refined time structure. Ludig et al. [23] even come to the conclusion that a high temporal resolution in a power system model increases the share of flexible gas technologies in the optimal technology mix. As the need for daily ESS is highly dependent on the volatility of renewable feed-in and the available amount of flexible power plants, we chose time slots with a duration of one hour in order to account for the variability of the future German energy system. The variability of the demand is accounted for via three days of a type: One weekday representing Monday to Friday, the Saturday, and the Sunday. As renewable feed-in depends on the season, each season is represented separately via three days of a type. Thus, a year is represented through the hourly mapping of three days for each season, resulting in a total of 288 time slots. It has to be noted that only short-term (daily) ESS can be considered as a consequence of this time resolution.

Since such a comparably high number of time slots comes along with a large increase in computing time, the optimization used in this analysis is based on a myopic approach instead of a perfect foresight approach. This means that one period after the other is calculated instead of calculating the whole time horizon at once. As no one has perfect foresight in reality, the myopic approach might be considered more realistic. On the other hand, the results do not show the global optimum anymore. For more details about perfect foresight vs. myopic optimization, see e.g. Babrowski et al. [12] or Krey [24]. Based on the PERSEUS-NET model Babrowski et al. found out that differences in the results generated with the myopic approach and with the perfect foresight approach are marginal for scenarios with a steady development [12]. Subsequently the myopic approach is considered suitable for producing reliable results with PERSEUS-NET-ESS.

### 2.3.2 The Integration of Renewables

The focus of this paper is on assessing the need for ESS induced by a growing share of renewables, while possible alternatives, such as thermal generation or load shifting, are considered at the same time. Consequently, the development of renewable power plants is not part of the optimization. Instead, the development of renewable units at each grid node is given exogenously. In addition, renewable units are neither constructed based on economic reasons alone, nor because of a strategically good position in terms of the demand, but rather because of regulations, politics, and regional potentials. Thus, the installed renewable capacity until 2040 will be based on the development calculated in the German pilot study [19] and its regional distribution is calculated considering regional potentials [13].

In order to represent the renewable feed-in of volatile energy carriers ($ecv \in EC^V \subset EC$), we integrated a new equation. The equation (13) states for each time slot that the maximal output of the renewable energy generator in one period ($PL_{pc,t}$) multiplied by a factor ($X_{ecv,s}$) between 0 and 1 that schedules the diversification of the output to the different time slot has to be greater than or equal to the generation of that process in the considered time slot. The sum of this factor over all time slots equals one. Thus, the maximal generation of a process in the considered period is limited to $PL_{pc,t}$ which itself is limited by the installed capacity and the maximal full load hours, see equation (6).This yields a time-dependent upper bound for the renewable feed-in of a specific generator ($PS_{pc,s,t}$).

$$PL_{pc,t} \cdot X_{ecv,s} \geq PS_{pc,s,t}$$

$$\forall t \in T;\ \forall s \in S; \forall pc \in PC_{ecv};\ \forall ecv \in EC^V \qquad (13)$$

This equation also implies that the renewable feed-in can be curtailed in time slots where this is needed, as for example in time slots with high wind and solar feed-in, little demand, and limited ESS capacity or power. To ensure this, the volatile energy carriers (wind and solar) have to be excluded from equation (4). It has to be noted that through the scaling of the feed-in course to the sum of 1, the possibility of having no wind or solar feed-in throughout the whole period is excluded.

The course of the renewable feed-in for wind and solar units is taken from historic feed-in values [25]. The data of the actual feed-in during the first weeks of February, May, August, and November from 2007 until 2012 are taken to determine a possible course of the electricity production for each season. The maximum feed-in of wind and solar units for each calculated period resembles the feed-in data of one of these years. This distribution is freely chosen and does not consider all relevant aspects of a stochastic approach representing the volatile feed-in. However, as the long-term development of the generation system – including ESS – is the main result of PERSEUS-NET-ESS, we consider this approximation to be sufficient.

### 2.3.3 Integration of ESS

Further alterations of the model concern the ESS themselves. ESS are embedded in the PERSEUS-NET-ESS structure as a subset of units ($ess \in ESS \subset U$) with two processes, one to generate electricity ($out \in PC_{ess} \subset PC$) and one to pump or charge ($in \in PC_{ess} \subset PC$). Modeling of the ESS includes a maximum power of its generating and charging process, the efficiency of both processes, and the maximum state of charging (SOC) (see Fig. 2).

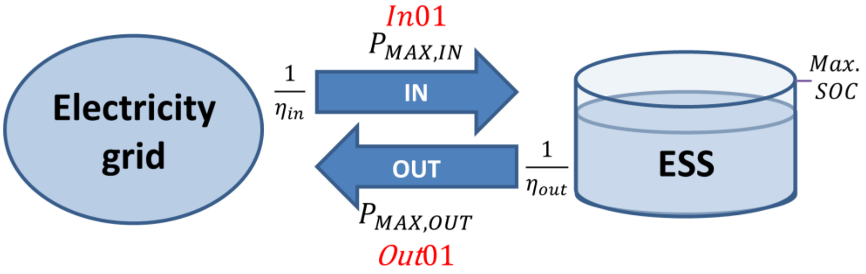

Figure 2: Mapping of ESS in PERSEUS-NET-ESS

The first storage equation (14) considers the SOC ($SOC_{ess,s,t}$ ) in terms of the amount of energy stored inside and ensures that it is kept within its limits. The equation is valid for every time slot, but the first in each season. This restriction is implemented by a help subset of timeslots ($s \in S^{help} \subset S$) which contains each first time slot of a season. The equation states that from the second time slot on, the SOC of the ESS in the considered time slot is the SOC of the time slot before plus the positive flow into the storage system ($PS_{in,t,s}$) minus the level of the positive flow out of the ESS ($PS_{out,t,s}$), elevated by its efficiency ($\eta_{out,t}$)[4].

$$SOC_{ess,s,t} = SOC_{ess,s-1,t}$$

$$+\frac{PS_{in,t,s}}{Z_s} - \frac{PS_{out,t,s}}{Z_s} \cdot \frac{1}{\eta_{out,t}}$$

$$\forall\, t \in T;\ \forall s \in \left(S \backslash S^{help.}\right);\ \forall in, out \in PC_{ess};\ \forall ess \in ESS \qquad (14)$$

While the lower limit is zero, the upper limit of the storage state is set by an exogenously given parameter representing the actual storage volume ($V_{ess,t}$). The 20 largest German hydropower stations (HPS) ($hps \in HPS \subset ESS$) already existing are considered at their specific grid nodes with an overall installed

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[4] The efficiency of the inflow is already considered by equation 3

capacity of about 6.6 GW in total [15]. Besides the existing HPS, new stations are integrated as expansion options on ten grid nodes, where projects currently are in the planning phase (see project pages and for an overview [26]). The investment is set to 1,150 €/kW, knowing that due to local conditions, the investment can vary between 600 and 3,000 €/kW [3]. To prevent those HPS expansion options from being given an advantage in the linear optimization, the storage volume has to be connected to the ratio of the installed capacity and the planned capacity of the respective project ($Cap_{hps,t}^{Max}$) (equation 15). Otherwise, the whole storage volume would be available with the first MW of a project.

$$SOC_{hps,s,t} \leq \frac{Cap_{hps,t}^{Tot}}{Cap_{hps,t}^{Max}} \cdot V_{hps,t}$$

$\forall\, t \in T;\ \forall\, s \in S;\ \forall\, hps \in ESS$ (15)

Since the other expansion options for ESS have to be available independently of the geographic circumstances of their allocation, they are meant to be battery storage systems ($bat \in BAT \subset ESS$). No specific battery technology is described here, since a time horizon until 2040 means that it is not clear which technology is going to be suited most for stationary applications in the transmission grid. Moreover, the exact technology is not important for determining the best allocation of ESS and therefore not discussed here. An overview of current developments of technologies for ESS is given in [5,27] for example. As the focus is on daily ESS, their upper level of the SOC is set by another equation to a [MWh/MW] ratio of five times the installed generating power ($Cap_{bat,t}^{Tot}$) that is going to be commissioned (equation 16). This is done in accordance with the characteristics for short-term ESS used in the study of the VDE [5].

$$SOC_{bat,s,t} \leq 5 \cdot Cap_{bat,t}^{Tot}$$

$\forall\, t \in T;\ \forall\, s \in S;\ \forall\, bat \in ESS$ (16)

As time slots are modeled to depict a season, the first time slot of each season has to be connected to the last time slot of that season. Within the time structure chosen here, the weekday is weighted five times more than the Saturday or Sunday. Therefore, the first time slot of each weekday also has to be connected to the last time slots of the same day (equation 17). Finally, since we want to determine the need for daily ESS, the shifting of electricity between the seasons is not allowed.

$$SOC_{ess,s,t} = \frac{4}{5} \cdot SOC_{ess,s+23,t} + \frac{1}{5} \cdot SOC_{ess,s+71,t}$$
$$+ \frac{PS_{in,t,s}}{Z_s} - \frac{PS_{out,t,s}}{Z_s} \cdot \frac{1}{\eta_{out,t}}$$

$\forall t \in T; \forall s \in S^{help.}; \forall ess \in ESS$ (17)

The power at which an ESS can be charged or electricity can be generated is limited to its capacity by equation (7). However, since the rate of pumping is not necessarily the rate of generation for the HPS, a pumping/generating ratio ($R_{hps,t}$) is included into equation (18) for the pumping process of HPS.

$$Cap_{hps,t}^{Tot} \cdot Z_s \cdot A_{hps,t} \cdot R_{hps,t} \geq PS_{in,s,t}$$

$\forall t \in T;\ \forall s \in S;\ \forall hps \in ESS;\ \forall in \in PC_{hps}$ (18)

So far, the described equations have mapped an ESS with two positive variables describing the in- and outflows and one variable for the SOC. With that simple mapping, however, electricity can be stored and generated in the same time slots. Thus, the ESS can be used as a way to abolish redundant electricity. Because of the load changing costs of thermal units, this can make sense for the optimization. Since this is no efficient use of an ESS, another restriction has to be added. According to Epe [28], this can be achieved through binary variables. Therefore, we integrate for each ESS and each time slots a binary variable describing whether the system is in a charging mode ($In01_{ess,t,s}$) or in a generating mode ($Out01_{ess,t,s}$). Through a term $M$ that is higher than the maximum operating level of the ESS, the binary variables are connected to the mode the system is in (equations (19) and (20)). Another equation (21) prevents both binary variables from equalling 1 in the same time slot.

$$PS_{in,t,s} - In01_{ess,t,s} \cdot M \leq 0 \tag{19}$$

$$PS_{out,t,s} - Out01_{ess,t,s} \cdot M \leq 0 \tag{20}$$

$$In01_{ess,t,s} + Out01_{ess,t,s} \leq 1 \tag{21}$$

$$with\ M > Maximum\ of\ PS_{pc,t,s}$$

$$\forall t \in T; \forall s \in S; \forall in, out, pc \in PC_{ess};\ \forall ess \in ESS$$

The configuration of the ESS is essential to the question of how much storage capacity will be commissioned in the future. In particular, the assumed investment and the life time are crucial. The calculations in this paper are based on forecasts of future technology development made by the VDE [5]. According to the VDE study, the biggest potential for a decrease in costs is identified for the NaS battery with costs of 220 €/kWh in 2020 and 110 €/kWh in 2050. Furthermore, the VDE predicts a technical life time for the NaS batteries of 20 years in 2020 and 25 years in 2050 and an efficiency of 84% in 2020 and 87% in 2050. The characteristics of the ESS expansion options mapped in the PERSEUS-NET-ESS model are based on the linear development of these values until 2040 (see Table A.4 in the appendix).

### 2.3.4 LSP of EVs

Demand response is considered to be an alternative to the commissioning of daily ESS. This term refers to an electricity demand that can be shifted within certain boundaries in order to meet the electricity supply. In households, for example, this could be the cooling phase of a refrigerator. Still, the potential to shift load in households presently is rather low, as was pointed out by Hillemacher et al. [29]. However, the situation might change with an increasing penetration rate of EVs [30]. According to the ambitious German national development plan for electric mobility, one million EVs are targeted until 2020 and six million by 2030 [1]. During night-time and working hours, vehicles are often parked for hours. This results in many possibilities of when and with which power charging could take place and, hence, to a big LSP [31]. There is a broad range of forecasts as to how electric mobility is going to develop [32]. For the context of this paper, we assume that the target of six million vehicles is reached by 2030. Assuming an average mileage of 12,000 km per year and a consumption of 20 kWh/100 km, this penetration results in an extra demand of 14.4 TWh in 2030 (see Table 1). For 2040, we assume a total of 15 million electric vehicles in Germany, resulting in an extra demand of 36 TWh. This demand is distributed to the grid nodes of the transmission grid based on a calculation that considers regional aptitude for electric mobility [33].

In the PERSEUS-NET-ESS model, charging can either take place uncontrolled or controlled. Uncontrolled means that the vehicles are charged immediately when arriving at charging stations, either at home or at the workplace. The charging pattern of immediate charging was extracted from a comprehensive German trip data base [34] considering the starting and ending time, the trip distances, and the trip [31,33]. For modeling uncontrolled charging, no further equations are needed, because the additional electricity demand for EVs ($elEV \subset EC$) in each time slot ($D_{pd,elEV,t,s}$) is balanced using equations (5) and (3).

When charging takes place in a controlled manner, the electricity needed can be shifted throughout the day within an upper and a lower limit (equation 22). The upper limit is derived from the availability of vehicles at a charging station for each hour ($EV_s^{Max}$). This share is multiplied by the electricity needed daily by EVs. The lower limit is based on the assumption that at least 10% of the drivers start charging directly after arrival, because their daily trip length exceeds the distance of 100 km/day that can be covered with one battery charge [31]. Due to acceptance aspects, this lower bound might even be too low. Most likely, it is a technical limitation rather than a realistic one.

$$EV_s^{Max} \cdot D_{pd,elEV,t,s} \geq PS_{pc,t,s} \geq 10\% \cdot D_{pd,elEV,t,s}$$

$$\forall pc \in PC_{pd}^{D};\ \forall pd \in PD;\ \forall elEV \in EC;\ \forall t \in T;\ \forall s \in S \qquad (22)$$

Because of the focus on daily ESS and the chosen time structure, we assume that the electricity needed for driving each day has to be charged on that very day. It is specified by equation (23) that the cumulated amount charged until a specific time slot meets the exogenously given share of the yearly demand for EVs ($DL_{pd,elEV,t}$) that has to be charged until this specific time slot ($EVD_{t,s}$). This equation has been developed on the basis of [33]. The shares are given for the last time slot of each day.

$$\sum_{s=1}^{s'} PS_{pc,t,s} = EVD_{t,s'} \cdot DL_{pdelEV,t}$$

$$\forall pc \in PC_{pd}^{D};\ \forall pd \in PD;\ \forall t \in T;\quad \forall s \in S \qquad (23)$$

## 3 Preselection of Suitable ESS Allocations and Scenarios

### 3.1 Predetermination of ESS Allocations

With the PERSEUS-NET-ESS model, the technology and the allocation of commissioned plants can be determined. Accordingly, the endogenously installed ESS capacity can be analyzed. However, as mentioned above binary variables are needed for each time slot and ESS to prevent them from storing and generating at the same time. Hence, the model has to be solved via a mixed-integer optimization. With 288 hours (12 days) considered for each period, every implemented ESS expansion option leads to a significant increase in computing time. In order to avoid the simultaneous bidirectional use of ESS and keep the computing time acceptable, we chose a two-step approach for this analysis. First, ideal ESS with an efficiency of 100% are implemented. In this case, PERSEUS-NET-ESS can be solved linearly with a comparably short computation time, while about 350 nodes spread across Germany are provided with expansion options for ESS. The calculation of the 7 periods does not take more than a few hours each[5]. About 2.4 million equations, 2.2 million variables, and about 12 million non-zero elements are considered for each of the periods. In a second step, the model is solved again as a mixed-integer optimization with real ESS that have an efficiency of about 85%. For this optimization, however, only the grid nodes at which ideal ESS have been commissioned in the first run are provided with an option to commission real ESS. The calculation time is much longer and may be up to a few days for one of the later periods. For those periods, the model consists of about 2.1 million equations, 1.9 million variables, and about 10 million non-zero elements. Additionally, about 10 to 15 thousand binary variables have to be considered depending on the number of integrated storage options. The results presented below are based on this recalculation of PERSEUS-NET-ESS as a mixed-integer problem.

### 3.2 Scenarios Considered

In the following section, the commissioning of ESS is analyzed by comparing three different scenarios. In the reference scenario (Scenario “REF”), the charging of the EVs is uncontrolled according to a fixed charging curve. Options to commission battery storage systems are available at every grid node. Secondly, the model is calculated with the same settings, but without the integration of battery storage expansion options (Scenario “NoBat”). In the third scenario considered, the commissioning of battery storage systems is allowed, but the charging of EVs is controlled (Scenario “LSP”).

## 4 Results

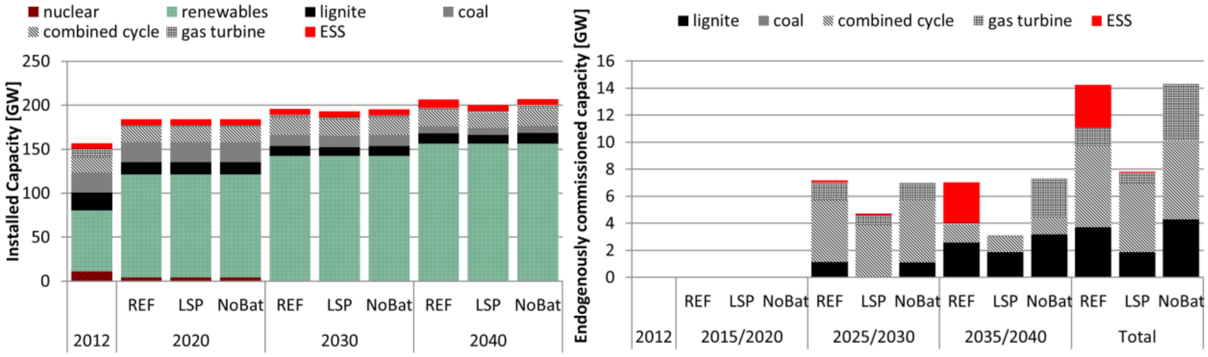

Figure: 3 Installed capacity (left) and endogenously commissioned capacity (right)

One of the main results of PERSEUS-NET-ESS is the capacity that is commissioned until 2040. The overall capacity of the three scenarios considered develops rather similarly (see Fig. 3 on the left) and reaches about 200 GW in 2040. As almost 75% of the installed capacity are renewables by that time and, thus, predetermined, this is not so surprising. However, a look at the endogenously commissioned capacities reveals major differences between the scenarios (Fig. 3 on the right). Only in the REF scenario is a significant amount of ESS installed additionally (approx. 3.2 GW). All of them are battery storage systems. Except for the already existing HPS, no further HPS are commissioned in any scenario. A reason might be that the investment for HPS strongly depends on geographic surroundings and that natural inflows are not taken into account due to a lack of data. Accordingly, there is a total of approx. 10 GW storage capacity installed by 2040 in the REF scenario.

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[5] Computer configuration: Windows 2008 2 Enterprise; Intel(R) CPU E5-1650 @ 3.20 Ghz; 96 GB RAM; 64 Bit; 12 threads.

In contrast to that, almost all (about 96%) of that commissioned battery storage capacity is substituted by using the LSP with EVs in the LSP scenario. Furthermore, only about half of the lignite capacity is commissioned in the LSP scenario. Also, about 20% less gas capacities are commissioned. In total, approx. 45% of the capacities commissioned in the REF scenario were not needed due to the LSP. Differences can already be seen by 2030 when the shifted electricity demand of EVs amounts to less than 3% of the total demand.

The total amount of the commissioned capacity in the NoBat scenario resembles the amount of the REF scenario. However, without the option to commission battery storage systems, more lignite units (approx. 116%) and significantly more gas turbines (approx. 300%) are commissioned instead.

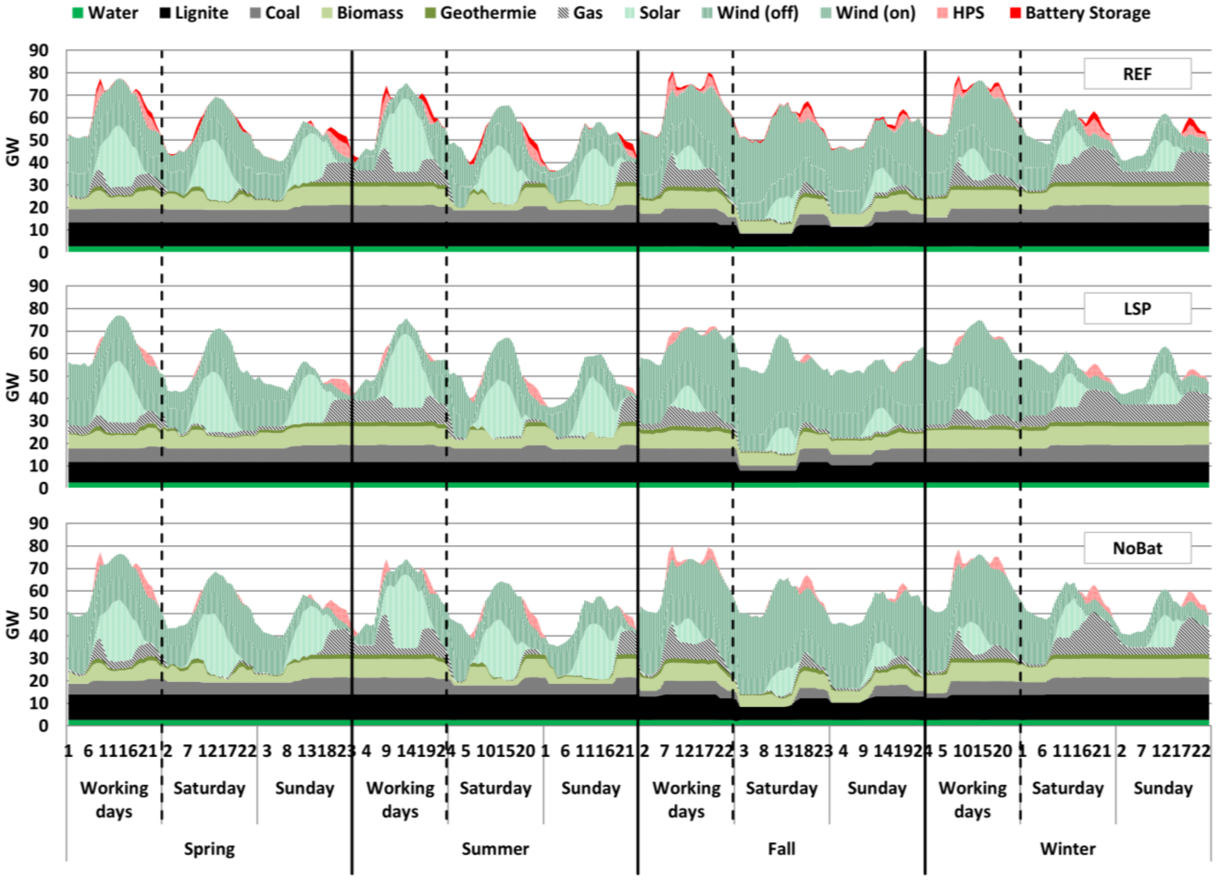

Figure 4: Scenario specific German electricity mix in 2040

As regards the resulting electricity mix (see Fig. 4) of 2040, the main differences between the REF and the LSP scenario lie in the load curve (cf. Fig 5). The uncontrolled EV charging curve has a morning and an evening peak that has to be satisfied in the REF scenario. For this task, ESS or gas turbines are often used (see for example the peaks on the working days in fall (Fig. 4)). In the LSP scenario, those peaks do not occur. Instead, the EV load is used for valley filling or even to increase the load peak during the day in addition to the demand of the existing ESS. This demand shift through either ESS or LSP leads to a better integration of solar electricity in all scenarios. A closer look at the electricity mix (Fig. 4), however, reveals that it also prevents thermal units (lignite or coal) from changing their load. This leads to an increase in their full load hours and, therefore, to a more efficient use of the installed capacities. In the NoBat scenario, only the demand of already existing HPS is used to change the load curve. This and less ESS generation result in a more flexible generation from gas compared to the other scenarios (see for example working day in summer (Fig. 4)). Hence, commissioning of gas turbines is increased in this scenario (cf. Fig. 3).

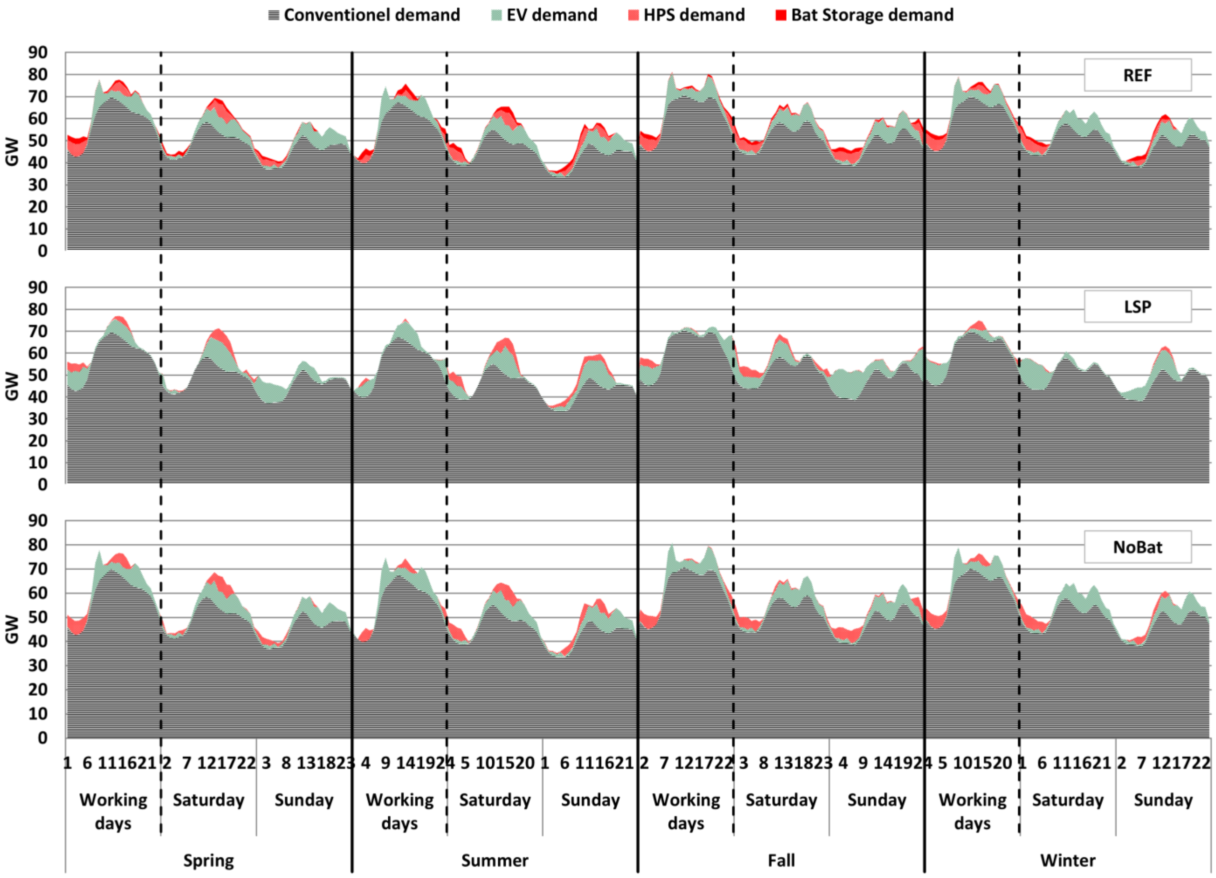

Figure 5: Components of the scenario-specific load curve in 2040

Of the possible electricity generation from volatile renewables (wind and solar), about 15.6% are curtailed in the REF and the LSP scenarios. With about 16%, this proportion is only slightly higher for the NoBat scenario. Concerning the amount of the curtailment, it has to be noted that according to the German pilot study, a huge amount of off-shore wind parks is planned. This amount is integrated in PERSEUS-NET-ESS. Also, the net extension plans are only integrated in accordance with the EnLaG and the current progress. Beyond 2020, no future extensions are considered. Looking at the solar and the onshore wind feed-in, their curtailment only amounts to about 5.6% of their maximal feed-in for all scenarios. There are time slots in which curtailment and, at the same time, generation from ESS take place (see Fig. 6 at the bottom). This indicates that there are bottlenecks in the transmission grid (see Fig. 7). These bottlenecks occur mostly in the northwest of Germany, where most of the wind feed-in takes place. These congestions increase over time and lead to increasingly different nodal prices throughout Germany (see Fig. 8). In the south and west of Germany, nodal prices are higher than in the north and east. Not surprisingly, prices are the lowest in the northwest, on the surplus side of the bottlenecks. This is true for all the scenarios.

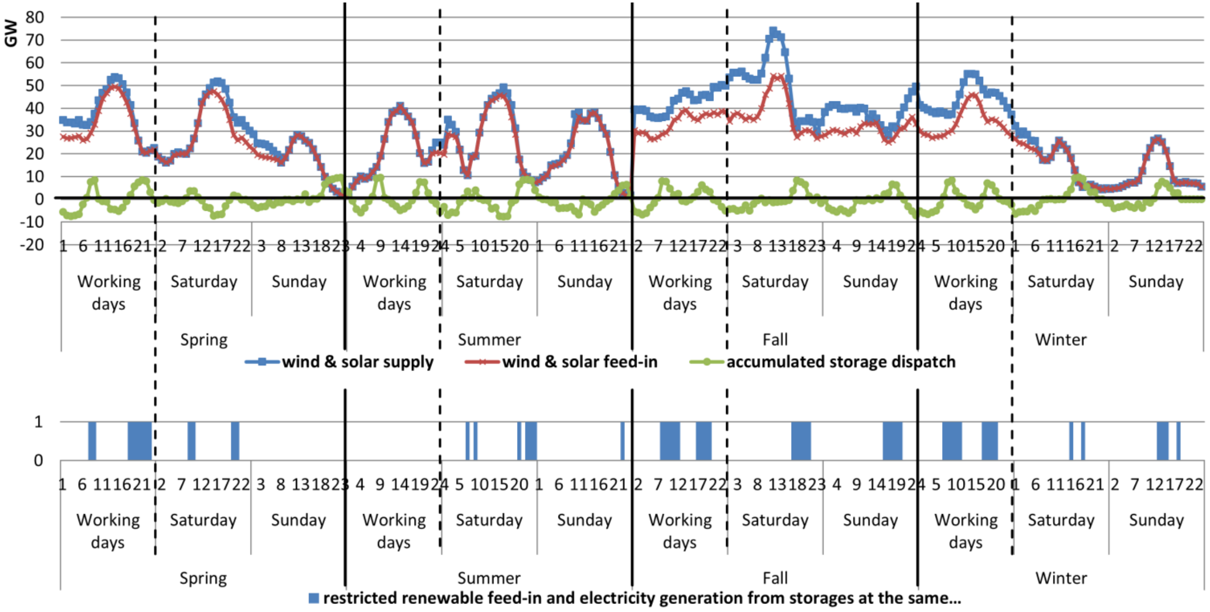

Figure 6: Curtailment of renewables and storage generation (REF scenario)

Traditionally, daily ESS are used to shave peak load during the day (peak shaving) and to shift this day load to the night (valley filling) [7]. In contrast to that, the ESS in the PERSEUS-NET-ESS model mostly run two cycles on every working day (see Fig. 6). They still demand electricity at nighttime, but instead of shaving the load peak during daytime, they elevate it even further in order to integrate the solar peaks (see Fig. 5). Thus, they demand electricity at night, generate in the morning, demand again during the midday hours, and generate throughout the evening again.

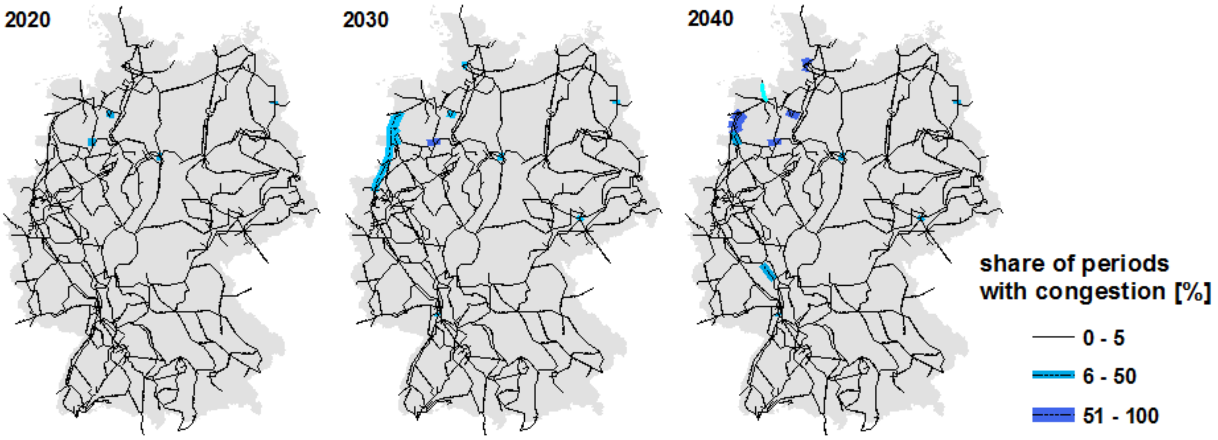

Figure 7: Congestions in the transmission grid (REF scenario)

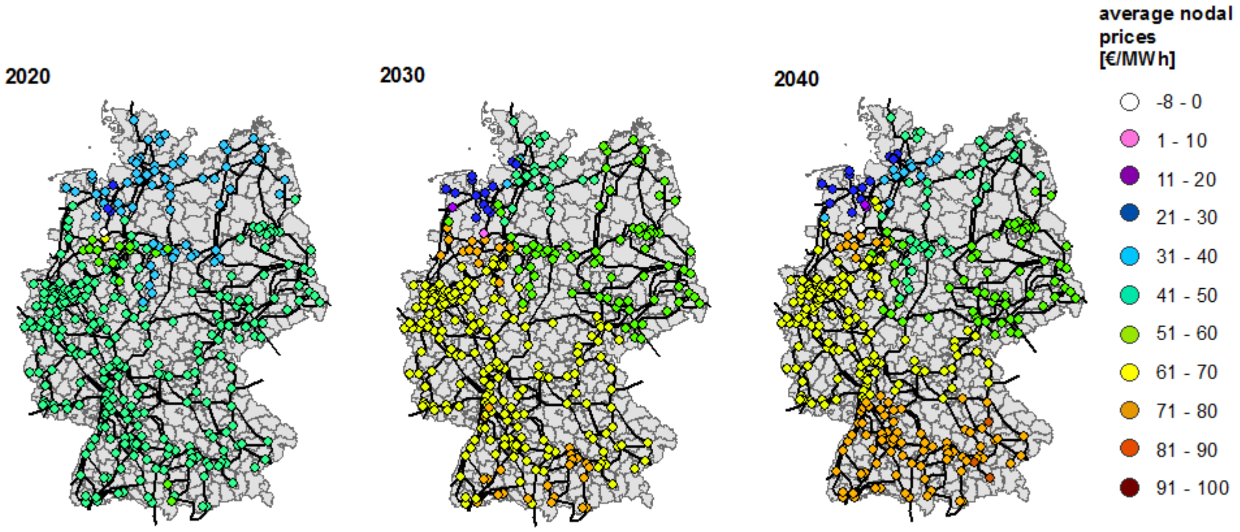

Figure 8: Nodal prices (REF scenario)

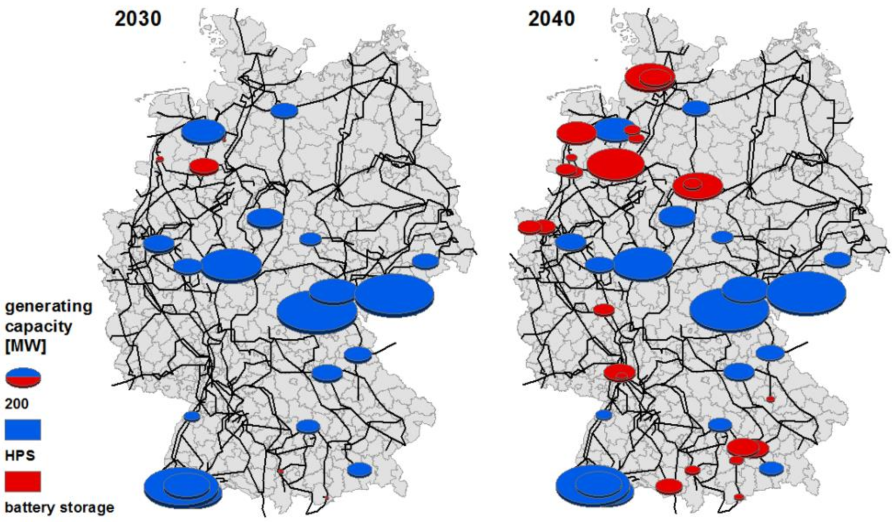

Figure 9: Installed storage capacities (REF scenario)

In the REF scenario, about 150 MW of battery storage capacities will be built until 2030. This capacity will be commissioned in the northwest, at the grid node with the lowest nodal price, i.e. at one side of a bottleneck (see Fig. 9). Of the about 3,200 MW that are built until 2040, a big part is also built in the northwest. Almost all battery storage capacities are built at one side of a power line that is congested in at least one time slot. At about one third of the lines where sometimes congestions occur, ESS are built at the grid nodes on both sides of that line. Allocation of the small storage capacities built in the south is harder to explain. Some capacities are built close to load centers (e.g. Munich), others are built at grid nodes with a high solar or coal (e.g. GKM at Mannheim) feed-in.

## 5 Critical Reflection of the Modeling Approach

The main drawback of the model developed is the limited amount of time slots considered. Due to the limited amount of time slots, no extreme weather conditions are considered, such as periods of no winds over several days. The year is depicted using typical days without extreme events, neither on the surplus nor on the demand side. However, as the model optimizes not only the dispatch of existing generation units and transmission lines, but also the commissioning of new units, the number of variables is high and computation time does not allow for a more refined time structure or any stochastic approach. Consequently, the endogenously commissioned capacity of ESS might be underestimated because of the limited number of time slots and the lack of extreme events. When interpreting the results, this has to be kept in mind.

An integration of stochastic processes would be desirable in this context (e.g. for the wind feed-in). However, we currently do not see the potential to do so without reducing the content and with that the complexity of the model considerably.

Furthermore, the electricity exchange with neighboring countries is not considered, although it may help balance demand and generation. As no extreme events are considered, however, we assume that the German electricity system has to be able to act self-sufficiently.

Advantages of ESS, such as the provision of system-relevant services, for example, positive and negative frequency leveling (auxiliary services), are not taken into account here. Those advantages might also lead to an increase in the installation of ESS. Moreover, it has to be noted that after 2020, no further grid extension projects are considered within the model. Calculations without considering grid restrictions have shown that more renewable feed-in, especially off-shore wind in northern Germany, could be integrated in that case.

## 6 Conclusions

This paper presents the development of the PERSEUS-NET-ESS dispatch and investment model to analyze how many ESS will be needed in the future German electricity sector. Accordingly, a time resolution with 288 time slices representing the year has been chosen. Three days of a type per season are mapped in an hourly manner. As renewable feed-in is one of the main drivers of commissioning ESS, potential electricity generation from volatile renewables is integrated based on historical data. This electricity generation can be curtailed it when needed. Besides the implemented options for ESS, technological alternatives, such as gas turbines or LSP, are implemented and considered endogenously. As the model also integrates a nodal pricing approach based on a DC power flow analysis of the transmission grid, not only the amount of commissioned ESS, but also their allocations can be analyzed.

The commissioning of approx. 3.2 GW additional daily ESS may help integrate cost-efficiently over 60% renewables (about 46% volatile) by 2040 in Germany. The results of the cost-minimizing PERSEUS-NET-ESS model show that the expansion option for ESS are used endogenously used when investment prices drop to about 150 €/kWh by 2040. Before 2030 and 50% renewable electricity generation (about 41% volatile), daily ESS are not beneficial and, thus, not commissioned endogenously. In our model, ESS tend to complete two cycles every day instead of one in order to integrate the growing solar feed-in. The amount of beneficial ESS depends highly on the underlying cost structure and on the alternatives. If the price development is going to be too slow and prices will be too high for stationary ESS, the needed flexibility could also be provided by gas turbines. Another alternative could be the use of the LSP of EVs. According to the model results, almost the whole capacity of commissioned daily ESS could be replaced by controlled charging of 15 million EVs in 2040. Additionally, the total installed generation capacity needed could be reduced by the use of LSP. Interestingly, controlled charging has no positive effect on the integration of renewables according to the PERSEUS-NET-ESS model. In 2040, about 6% of the solar and onshore wind feed-in are curtailed, no matter whether charging is controlled or whether there are additional ESS. In the case of ESS being commissioned, they are mainly placed at grid nodes with a surplus of electricity in the northwest of Germany. The surplus leads to low nodal prices on the surplus side of bottlenecks in the transmission grid. Often, however, storage capacities are also built on the other side of the bottleneck, ensuring the best use of the congested transmission line.

The PERSEUS-NET-ESS results indicate the importance of flexibility in the future German energy system. This flexibility can either be achieved by ESS, gas turbines or by LSP. If LSP is available and does not lead to additional costs, it should be used. Otherwise, the commissioning of ESS seems to be favorable. Most likely, the amount of approx. 3.2 GW beneficial daily ESS is underestimated, as the limited amount of time slots considered levels the variability of renewable feed-in. As regards the allocation of ESS, it can be said that a strategic allocation seems to support grid management.

Future work with PERSEUS-NET-ESS will concentrate on different framework conditions. Further model runs with different wind and solar courses will have to be performed to determine the influence of different weather conditions on the model results. As they might help to integrate renewables, grid extension projects after 2020, such as the projects currently discussed in the net extension plan of 2013 [35], will be integrated and tested. Moreover, alternative ESS with different capacity to power ratios and/or prices should be analyzed in further scenarios.

# **Appendix**

## Appendix A.1 Nomenclature

### Indices and Sets

| | |
|---|---|
| $ec \in EC$ | Energy carriers and materials |
| $ec \in EC^T \subset EC$ | Non-seasonal energy carriers |
| $ec \in EC^S \subset EC$ | Seasonal energy carriers |
| $ecv \in EC^V \subset EC$ | Energy carrier with a volatile feed-in (solar and wind) |
| $el \in EC^S \subset EC$ | Electricity as energy carrier |
| $elEV \in EC^D \subset EC$ | Electricity used by electric vehicles as energy carrier |
| $ep \in EP \subset PD$ | Sinks of the graph structure |
| $ess \in ESS \subset U$ | Electricity storage systems |
| $hps \in ESS \subset U$ | Hydro pumped storage |
| $ip \in IP \subset PD$ | Sources of the graph structure |
| $in \in PC$ | Charging process of a storage system |
| $out \in PC$ | Generation process of a storage system |
| $pc \in PC$ | Processes |
| $pc \in PC^D \subset PC$ | Demand processes |
| $pc \in PC^G \subset PC$ | Generation processes |
| $pd \in PD$ | Producers |
| $s \in S$ | Time slots |
| $s \in S^{help} \subset S$ | First time slot in each season |
| $t \in T$ | Year, period |
| $u \in U$ | Units |
| $y \in Y \subset PD$ | Grid nodes of the transmission grid |

### Parameters

| | |
|---|---|
| $\lambda_{pc,ec}$ | Share of energy carrier *ec* related to total input/output of the process *pc* |
| $\eta_{pd,pd',ec,t}$ | Flow efficiency of energy carrier *ec* between producers *pd* and *pd'* |
| $\eta_{pc,\mathrm{t}}$ | Efficiency of process *pc* in period *t* |
| $\gamma_{y,y'}$ | Susceptance of the line connecting grid node *y* and grid node *y'* |
| $A_{u,t}$ | Availability factor for the generation unit *u* in period *t* |
| $Cap^{Res}_{u,t}$ | Installed capacity of unit *u* at the beginning of period *t* |
| $Cap^{Max}_{hps,t}$ | Planned capacity of the hydro pump storage *hps* in the planning phase |
| $C^{fix}_{u,t}$ | Fixed annual operation costs of the generation unit *u* in period *t* |
| $C^{fuel}_{ip.pd.ec.t}$ | Fuel costs for the delivery of the energy carrier *ec* to producer *pd* in period *t* |
| $C^{inv}_{u,t}$ | Specific investment for commissioning the unit *u* in period *t* |
| $C^{LC}_{pc,t}$ | Load change costs for the generation process *pc* in period *t* |
| $C^{var}_{pc,t}$ | Variable operating costs of the process *pc* in period *t* |
| $D_{pd,el,t,s}$ | Demand of producer *pd* for electricity *el* in time slot *s* in period *t* |
| $EV^{Max}_s$ | Upper limit of the load shifting potential in time slot *s* |
| $No_{s-1,s}$ | Quantity of transitions from time slot *s-1* to *s* per year |
| $R_{ess,t}$ | Ratio of pumping and generation power for storage *ess* |
| $SL_y$ | Indicator if grid node *y* is the slack bus |
| $TL_{y,y',t}$ | Thermal limit of the line connecting grid node *y* and grid node *y'* |
| $Vlh^{Max}_{u,t}$ | Maximal full load hours of unit *u* |
| $V_{hps,t}$ | Planned storage volume of HPS in the planning phase |

| | |
|---|---|
| $X_{ecv,s}$ | Factor for the diversification of the feed-in from volatile energy carriers *ecv* to the time slots *s* with values ∈ [0,1] |
| $Z_s$ | Number of occurrences of the time slot *s* per year |

Variables

| | |
|---|---|
| $\theta_{y,t,s}$ | Phase angle difference at grid node *y* in time slot *s* |
| $Cap_{u,t}^{Tot}$ | Installed capacity of the generation unit *u* at the end of period *t* |
| $Cap_{u,t}^{New}$ | Newly installed capacity of generation unit *u* in a period *t* |
| $FL_{ip,pd,ec,t}$ | Level of *ec*-flow from the source *ip* of the graph structure to producer *pd* in period *t* |
| $FL_{pd,pd',ec,t}$ | Level of *ec*-flow from producer *pd* to producer *pd'* in period *t* |
| $FL_{pd,ep,ec,t}$ | Level of *ec*-flow from producer *pd* to the sink *ep* of the graph structure in period *t* |
| $FS_{pd,pd',el,t,s}$ | Level of electricity *el* flow from producer *pd* to producer *pd'* per time slot *s* in period *t* |
| $FS_{pd,ep,el,t,s}$ | Level of electricity *el* flow from producer *pd* to the sink of the graph structure *ep* per time slot *s* in period *t* |
| $In01_{ess,t,s}$ | Binary variable describing whether a storage system *ess* is in the charging mode in the time slot *s* in period *t* |
| $LC_{pc,s-1,s,t}^{up}$, $LC_{pc,s-1,s,t}^{d}$ | Positive and negative load change of generation unit *u* between the time slots *s-1* and *s* in period *t* |
| $Out01_{ess,t,s}$ | Binary variable describing whether a storage system *ess* is in the generating mode in the time slot *s* in period *t* |
| $PL_{pc,t}$ | Activity level of process *pc* per year in period *t* |
| $PS_{pc,t,s}$ | Activity level of process *pc* in time slot *s* in period *t* |
| $SOC_{ess,s,t}$ | Charging level of the storage system *ess* at the end of time slot *s* in period *t* |

## Appendix A.2 Model Data

**Table A.1: Assumption for the demand development (based on [13])**

| [TWh] | 2012 | 2020 | 2030 | 2040 |
|---|---|---|---|---|
| Conventional | 503 | 506 | 493 | 486 |
| Electric mobility | 0 | 1 | 14 | 36 |
| Total | 503 | 512 | 510 | 522 |

**Table A.2: Configuration of thermal expansion options (based on [19])**

| | | Gas turbine | Combined cycle gas turbine | Coal unit | Lignite unit |
|---|---|---|---|---|---|
| Investition | [€/kW] | 400 | 700 | 1300 | 1500 |
| Fixed costs | [€/(kW*a)] | 14 | 14 | 95 | 102 |
| Variable costs | [ct/kWh] | 0.3 | 0.3 | 0.15 | 0.2 |
| Efficiency | [%] | 46 | 61.1 | 50.9 | 49.1 |
| Economic lifetime | [a] | 25 | 25 | 25 | 25 |

**Tabelle A.3: Price development of energy carriers and $CO_2$ certificates (based on [20])**

| | 2012 | 2020 | 2030 | 2040 | Source |
|---|---|---|---|---|---|
| [ct/kWh] | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Coal | 1.1 | 1.0 | 1.0 | 1.0 | [20] |
| Lignite | 0.4 | 0.4 | 0.4 | 0.4 | [13] |
| Gas | 2.4 | 2.8 | 3.0 | 3.1 | [20] |
| Oil | 4.9 | 5.4 | 5.6 | 5.7 | [20] |
| [€/ton] | | | | | |
| $CO_2$ certificates | 9 | 21.5 | 28.8 | 35.9 | [20] |

**Table A.4: Configuration of ESS expansion options (based on [5])**

| | | Battery 2020 | Battery 2025 | Battery 2030 | Battery 2040 | HPS 2012-2030 |
|---|---|---|---|---|---|---|
| Investment | [€/kW] | 1100 | 1008 | 917 | 734 | 1500 |
| or | [€/kWh] | 220 | 202 | 183 | 147 | n.a. |
| Fixed costs | [€/(kW*a)] | 110 | 101 | 92 | 73 | 150 |
| Variable costs | [ct/kWh] | - | - | - | - | 0,2 |
| Efficiency | [%] | 85 | 85 | 85 | 86 | 49,1 |
| Economic lifetime | [a] | 20 | 21 | 22 | 23 | 25 |
| Cycle stability | [#] | 10.000 | 10.000 | 10.000 | 10.000 | n.a. |

Preprint of article "Electricity storage systems in the future German energy sector: An optimization of the German electricity generation system until 2040 considering grid restrictions" *in Computers & operations research, 66, 228-240.* *doi:10.1016/j.cor.2015.01.014*

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