THE COST OF RENEWABLE ELECTRICITY AND ENERGY STORAGE IN GERMANY

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ABSTRACT

Renewable power generation, especially wind power and solar power, is experiencing a strong expansion worldwide and especially in Germany. With high shares of these methods of power generation, energy storage is needed to enable a demand-oriented power supply even with weather-related fluctuations in generation. Against the background of a power supply based entirely on wind and solar power, the question arises as to what total costs arise with the inclusion of storage systems, which is the subject of this article. The calculation model uses hourly resolved real data of German electricity generation from the years 2012 to 2018 to determine the required storage capacities. The electricity generation costs used range between 0.02 and 0.10 EUR/kW/h. The costs for the considered energy storages are calculated based on the Levelised Cost of Storage (LCOS) metric. It is concluded that in an electricity supply system based on wind and solar power, it is not the electricity generation that causes the greatest costs, but the storage. With electricity generation costs of 0.06 EUR/kW/h, the total system costs are in a range of 0.19 to 0.28 EUR/kW/h. This means that, in terms of costs, energy storage is more significant than electricity generation.

KEY WORDS

energy storage, renewable energy sources, Germany, levelised cost of storage

JEL CODES

C32, C53, O13, Q40

1 INTRODUCTION

A high share of weather-depended renewable energy sources requires fundamental changes in today's power supply in order to account for short-term and long-term fluctuations in creating a demand-oriented supply. To compensate for the volatile generation characteristics,

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energy storage systems (ESS) are seen as an essential potential for flexibility and as a contribution to security of supply. Technically suitable energy storage technologies include, for example, pumped hydro storage, various batteries technologies, and power-to-gas (PtG; see IRENA, 2019a, 2019b).

Renewable energy sources (RES), in particular wind power and solar power, will continue to gain significantly in importance and thus represent an essential part of the global energy transformation. According to the International Renewable Energy Agency (IRENA), it is expected that by the year 2050 wind power will account for more than 35% and solar power for about 25% of total electricity generation. The reasons for this trend lie in the targeted reduction of CO_2 emissions, in accordance with the Paris agreement to limit global warming below to 2 °C, compared to pre-industrial levels. Other significant causes are seen in sharply falling costs for these renewable power sources, as well as the resulting improvement in air quality (IRENA, 2019a, 2019b).

With the “Energiewende”, the German Federal Government is pursuing the goal of making its energy supply sustainable. The share of renewable energies in gross electricity consumption was 42% in 2019. The target of at least 35% in 2020 was already exceeded in 2017. By the year 2030, the goal is to increase the share of RES in Germany to 65%. The final goal in 2050 is a completely renewable and climate-neutral energy supply. Electricity generation from onshore wind power grew to a total of 101.2 TWh in Germany in 2019, while offshore plants generated a total of 24.7 TWh. In the solar power sector, a total of 46.4 TWh of electricity was generated in the same year. In total, gross electricity generation from renewable energy sources amounted to 242.5 TWh out of a total electricity generation of 610.2 TWh. The growing share of wind and solar power indicates that renewable energy sources will play a central role in Germany’s future power supply (BMWi, 2021).

Electricity generation from brown coal has decreased in recent years as a result of lower power plant availability. The decrease in nuclear energy since 2006 has been based on the decision to phase out nuclear energy in accordance with the Atomic Energy Act (AtG) of 2002. The share of oil in electricity generation has changed only slightly. The use of natural gas for electricity generation is almost three times as high as in 1990, with more new gas-fired power plants being connected to the grid recently. The share of renewable energies (hydropower, wind energy, biomass, photovoltaics and geothermal energy) has increased more than twelvefold since 1990. This development is particularly due to the introduction of the Renewable Energy Sources Act (EEG). The composition of production from 1990 to 2018 is shown in Fig. 1. The various renewable energy sources contribute differently to the increase in renewable energy in Germany. Hydropower recorded only small increases overall and was responsible for the largest share of renewable electricity production until the year 2000. Thereafter, it was overtaken by solar power, wind power and biomass plants. Today, hydropower generates less than 10% of renewable electricity. In recent years, the importance of wind power has increased most rapidly and today more than half of renewable electricity is generated by onshore and offshore wind turbines. The development of the renewable energy sources in Germany is shown in Fig. 2 (Umwelt Bundesamt, 2020a).

Electricity from renewable energies will be increasingly generated in a decentralised manner in the future. It will therefore be necessary to expand both the generation capacities and the associated transmission grids together and to integrate energy storage systems. In the short term, the expansion of RES will result in additional costs, as investments will have to be made in the construction of new plants. In the long term, however, significant cost advantages are seen compared to conventional electricity generation based on fossil fuels (Umwelt Bundesamt, 2020c).

This raises the question of how much storage capacity is required, which technologies can be used for storing and what costs are associated with it. Several studies have already been carried out to determine the necessary storage capacity for electricity supply with a high share of volatile RES.

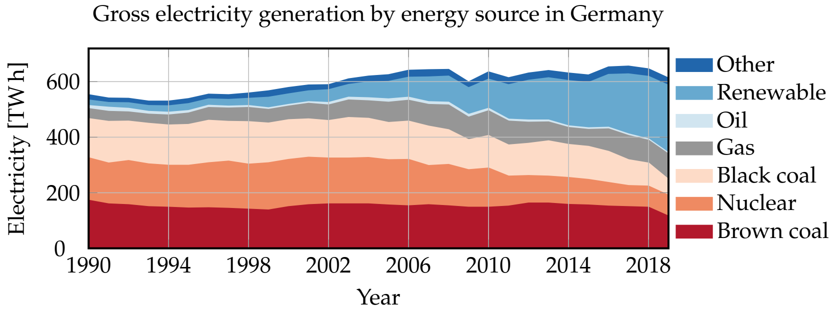

Fig. 1: A significant increase in the amount of renewable electricity generation can be observed (Umwelt Bundesamt, 2020b).

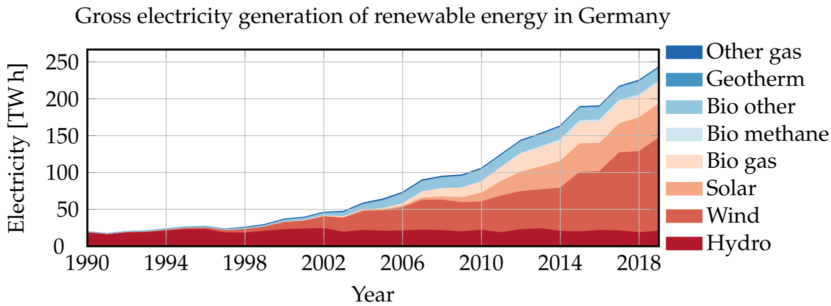

Fig. 2: The majority of RES is generated from wind power and solar power (Umwelt Bundesamt, 2020b).

Popp (2010) determines the required storage capacity for various wind power and solar power generation configurations on the basis of wind speeds and solar radiation data for Germany, resulting in daily loads. A daily load is the energy that is converted in a supply area on a long-term average per day and assumes a value of 1.64 TWh for Germany. The greatest storage demand among the scenarios shown is in the European average of about 104 daily loads (171 TWh for Germany) for supply by solar power alone, without continental interconnection. Heide et al. (2010) are calculate the necessary storage capacity for Europe on the basis of normalised generation data, from the years 2000–2008, based on a power supply from wind and solar power. A total required storage capacity of 400 to 480 TWh is calculated.

Weitemeyer et al. (2015) state that with a lossless storage system in combination with full renewable electricity generation, the required energy capacity would amount to about 80 TWh, which is many times the capacity available today. Estimates of the required storage capacity must always be made in the context of several years in order to cover long-term, seasonal influences.

Schill and Zerrahn (2018) investigate the requirements for electricity storage depending on the share of renewable electricity generation. If the share of RES increases further to 100%, electricity storage requirements almost triple compared to calculations with 80% RES. The growing importance of energy storage systems is highlighted by this.

Cebulla (2017) investigates the demand of energy storage capacity in European scenarios with high shares of volatile RES (more than 80%) and identifies main factors influencing the electricity storage demand. The results lie in a range between 30 and 55 TWh. The calculated capacities underline the need for balanced, diversified storage methods.

In the work of Hameer and van Niekerk (2015), it is concluded that various technologies are suitable for storing energy of several hundred MWh. These include thermal storage, pumped storage, flow batteries, lithium-ion batteries and sodium sulphur batteries.

1.1 Cost of Storage Technologies

Calculating the complete costs of different technologies for energy storage is a more complex issue compared to determining the costs of electricity generation. Storage systems have more technical parameters to take into account, to establish a well-founded calculation method of the costs.

An approach to deriving a calculation method for determining specific storage costs is taken from Mayr and Beushausen (2016) and presented in the following. It starts with the requirement that the sum of all costs must equal the sum of all remunerations.

Time has an impact on the value of capital. Future cash flows have a lower present value than currently generated cash flows. Therefore, a discount factor reflecting the cost of capital, typically the weighted average cost of capital (WACC), must be applied to all outgoing and incoming funds. It is important to "discount" costs as well as remunerations:

$$\sum_{t_l=1}^{\max} \frac{\text{cost}\,(t_l)}{(1+r)^{t_l}} = \sum_{t_l=1}^{\max} \frac{\text{remuneration}\,(t_l)}{(1+r)^{t_l}}. \quad (1)$$

In order to represent all cost drivers, it is useful to map a constant price per unit of energy over the applicable life of the storage facility. The resulting cost metric is called the Levelised Cost of Storage (LCOS). For this reason the remuneration can be expressed by the product of LCOS and electrical energy generated:

$$\sum_{t_l=1}^{\max} \frac{\text{cost}\,(t_l)}{(1+r)^{t_l}} = \sum_{t_l=1}^{\max} \frac{E_{\text{out}}(t_l) \cdot \text{LCOS}}{(1+r)^{t_l}}. \quad (2)$$

Rearranging the formula to LCOS finally produces the general form, in which the sum of all costs is given by the total amount of energy discharged and finally it is possible to express LCOS in accordance with Mayr and Beushausen (2016) as

$$\text{LCOS} = \frac{\displaystyle\sum_{t_l=1}^{\max} \frac{\text{cost}\,(t_l)}{(1+r)^{t_l}}}{\displaystyle\sum_{t_l=1}^{\max} \frac{E_{\text{out}}(t_l)}{(1+r)^{t_l}}}. \quad (3)$$

1.2 Cost Drivers

Considering the capacity, an energy storage system has two core components, the actual energy storage system and the converter required to transfer the energy into the storage medium. In storage systems, both components can be designed independently of each other, whereby the terms energy capacity C_E and power capacity C_P are used (Schmidt, 2018). The capital expenditure or *investment costs* (IC) required is determined from the necessary capacity. The specific costs IC_E for the energy capacity and IC_P for the power capacity are taken from various technical literature. The investment costs usually represent the largest cost driver in energy storage calculations (Schmidt, 2018).

In principle, all infrastructure facilities require regular minor and major maintenance and therefore cause *operating costs* (OC). Depending on the components that need to be replaced and how frequently this needs to be done, this can result in significant additional technology-specific costs. A distinction is made between specific costs in terms of energy OC_E and power OC_P, which ultimately allows the full operating cost OC to be determined. After a storage system has reached the end of its service life, it carries a certain *residual value* based on the achievable sales price for the individual components, including inverters, switchgear and transformers. The shorter the period a storage system has been used, the higher the residual value. To calculate the residual value (RES), the specific values for energy RES_E and RES_P are used.

The *cost of charging* or the cost for the purchase of electricity is defined as k_e. The future financial equivalent is taken into account by mapping the *interest rate* r. A fundamental distinction must be made between one-time payments and annually recurring payments. The time taken to build the plant is also taken into account, since a delay in start-up reduces the value of future revenues (Mayr and Beushausen, 2016). Not all technologies can completely discharge their energy and a certain amount of energy remains in the storage. This specific property is defined as a percentage value, *depth-of-discharge* and represented by the parameter DOD (Schmidt, 2018). Every technology for storing energy has an *efficiency* η. There are different ways to consider whether efficiency is calculated in terms of charging, discharging, or both. Storages with low efficiencies have higher charging costs and require a higher selling price for the discharged energy to be economically viable (Mayr and Beushausen, 2016).

The *lifetime* t_l stands for the expected service life of a storage facility. The number of complete *storage cycles* (SC) indicates the number of equivalent full storage cycles per year. This information relates to the complete energy throughput and thus provides a statement about the degree of utilisation of the system. It is the sum of all cycles that are even partially completed. The degeneration or *degradation* (DEG) refers to the progressive reduction of the nominal storage capacity. In particular, storage systems based on an electro-chemical principle are subject to this effect, while technologies that only require a large volume for storage are not affected (Schmidt, 2018).

With the parameter n the year used for the consideration is defined, or the sequence variable for the sum formulas. By introducing the described variables into equation (3), a formula is created by Mayr and Beushausen (2016) which directly allows the calculation of the levelised costs of storage

$$\mathrm{LCOS} = \frac{\mathrm{IC} + \sum_{n=1}^{t_l} \frac{\mathrm{OC}}{(1+r)^n} - \frac{\mathrm{RES}}{(1+r)^{t_l+1}}}{\mathrm{SC} \cdot \mathrm{DOD} \cdot C_n \cdot \sum_{n=1}^{t_l} \frac{(1-\mathrm{DEG} \cdot n)}{(1+r)^n}} + \frac{k_e}{\eta(\mathrm{DOD})}. \quad (4)$$

Storage costs, based on the LCOS metric for general applications for several storage technologies, can be found in Lazard (2020a, 2020b).

Schmidt (2018) calculates LCOS for the storage technologies of lithium ion batteries, pumped storage plants, Compressed Air Energy Storage systems (CAES), sodium batteries and Gravity Storage Systems. It is assumed that the energy storage units need 8 h to be completely discharged and run through a total of 330 complete storage cycles per year. The interest rate is 8%, the electricity price is 20 USD/MW/h and the ratio between storage capacity and converter power is always 0.125. The costs of the considered storage systems lie in a range between 0.094 and 0.310 EUR/kW/h of discharged electricity.

Jülch (2016) contains a detailed analysis of LCOS for different energy storage technologies. In this, LCOS is calculated for long-term, seasonal storage systems with an energy capacity of 70 GWh and a power capacity of 100 MW with one storage cycle per year. For short-term storage, systems with 400 MWh energy capacity and 100 MW of power capacity and 365 cycles per year are assumed. A distinction is also made between current costs and annual costs in 2030. For short-term storages the costs lie in a range between 0.05 and 0.36 EUR/kW/h. For long-term storages costs between 0.09 and 4 EUR/kW/h are calculated.

Giovinetto and Eller (2019) compare the construction and operating costs of 5 different long-term energy storage technologies using LCOS. In this context, the levelised average costs of molten salt batteries, lithium ion batteries, pumped storage plants, flow batteries, and CAES systems are calculated. The calculation first provides current values using parameters from the year 2019 and projects forecast values into the year 2028. For the year 2028 the calculated storage costs lie in a range between 0.15 and 0.485 EUR/kW/h.

Lai and McCulloch (2017) investigate the costs of stand-alone energy storages and system solutions based on lithium-ion batteries and redox flow batteries. As data input, a 4-year period of the Johannesburg area is investigated in order to consider the utilisation rates. The results show a total system cost of about 0.6 USD/kW/h at an interest rate of 8%.

Lai and Locatelli (2021) investigate the costs of a new type of storage, Generation Integrated Energy Storage system, and compare the main cost drivers with stand-alone storage systems such as lithium-ion storage. One of the conclusions is that stand-alone storage systems are major cost drivers for the overall system. From the author's point of view, this additionally shows the need for system-wide cost considerations.

Rahman et al. (2020) examine the current technological and cost related status of the application of energy storage systems on the basis of a total of 91 publications. Within this work, investment criteria such as the electricity production costs, as well as the required capital costs of storage systems are considered. The conclusion describes the necessity of investigations to determine the electricity supply costs of complete supply systems consisting of electricity generation and storage.

From the investigations of Mostafa et al. (2020), various storage technologies are examined with regard to their costs with given utilisation cycles. This shows that each storage technology has its own techno-economic advantages and disadvantages and that combinations of several technologies are necessary within the framework of system considerations.

1.3 Objective

The works cited above show that there are already studies that either determine the ESS capacity requirements for power supply systems, or calculate the costs of individual, stand-alone systems. Furthermore, there are studies that focus on storage capacities and the associated costs on the basis of synthetic input data sets. Many works conclude that there is a need for further detailed system-wide cost considerations. A calculation approach that maps real fluctuations in the generation of volatile electricity sources and determines the influence on the total costs of the electricity supply system is not covered. This is a key point, because the weather does not follow predetermined and regular cycles, which means that the consideration of real generation and consumption data must be taken into account for a realistic storage and cost calculation. Due to the current transformation process toward renewable electricity in Germany, the main objective of this article is to determine the required total system storage capacities and costs based on real data sets, against the background of a complete electricity supply based on wind power and solar power. Generation and consumption data of the German electricity supply system from the period 2012–2018 serve as data input. Technical and financial data for selected storage technologies are included as further input parameters. The aim is to create a cost range for the resulting total system costs against the background of a renewable electricity supply in combination with energy storage systems.

2 INPUT DATA AND METHODOLOGY

The basis of the model development are data points, resolved on an hourly basis for an arbitrarily spatially delimited area. Basically, it is sufficient to take into account the provided power, the generation capacity and the demand for electrical energy. Within the scope of the study, only the generation methods of wind power and solar power are considered. Therefore the calculation model requires the time series of the following parameter sets:

- wind power (provided energy and installed power capacity);
- solar power (provided energy and installed power capacity);
- demand for electrical energy.

For the development of the model, the German electricity grid is chosen. This area is particularly suitable for consideration of high shares of wind power and solar power due to the ongoing transformation towards renewable energy sources. The input data is taken from BNetzA and the German TSOs, which in turn were provided by the database from Neon (OPSD, 2019).

2.1 Input Data

The modeling is based on data from the period 2012 to 2018, during which large amounts of wind and solar power plants were already in

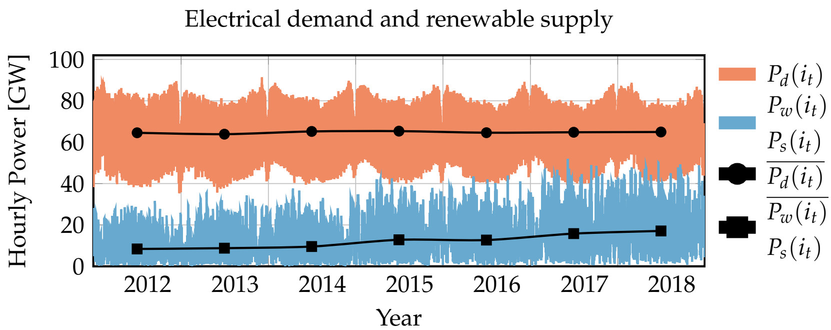

Fig. 3: The chart shows the rise of the sum of wind power and solar power $P_w(i_t) + P_s(i_t)$ (blue) and the approach to the demand $P_d(i_t)$ (orange). In addition the figure shows the annual mean values of supply and demand (black lines).

operation. The input data is available in the form of 61368 hourly resolved data sets and thus allows a representative estimate of the energy storage requirements. An essential aspect is the consideration of the wind-weak years 2013 and 2014, which cause a supply bottleneck within the framework of the data used. The input data consists of the values of the generated wind power $P_w(i_t)$, the solar power $P_s(i_t)$ and the corresponding installed generation capacities for wind power $P_{wc}(i_t)$ and solar power $P_{sc}(i_t)$.

The total electricity production excludes the power plants' own consumption during operation and takes the influences of electricity imports and exports into account. The energy balance from production and consumption is described as total load:

$$
\begin{aligned}
P_d(i_t) &= \text{total generation} \\
&- \text{power plant auxilary} \\
&- \text{power plants' own consumption} \\
&+ \text{imports} \\
&- \text{exports} \\
&- \text{consumption by storages,}
\end{aligned}
$$

whereby the data series of the total demand $P_d(i_t)$ is used further (ENTSOE, 2016b). To calculate the total demand on a realistic basis, an additional correction is required. The reason for this is that the recorded consumption values do not completely reflect the actual demand but are slightly below it. For this reason the data for the electrical demand for the years 2012 and 2013 are divided by the representativeness factor 0.91 and the values for the period 2014 to 2018 are divided by 0.98, considering the coverage ratios (ENTSOE, 2016a). From the beginning of 2012 until the end of 2018, the annual hour-average from wind power $\bar{P}_w$ increases from 5221 MW to 12393 MW. In addition, the solar average $\bar{P}_s$, increases from 3175 MW to 4707 MW. The annual hour-average of the total demand $\bar{P}_d$ remains almost the same, rising slightly from 64555 MW to 64929 MW. The chart of the generation $P_w(i_t)$ + $P_s(i_t)$ and the demand $P_d(i_t)$ are shown in Fig. 3.

Calculating the annual sum values results in produced electrical wind energy of 46 TWh for the year 2012, which increases to 109 TWh over the considered period until the end of 2018. The produced energy from solar power increases in the same period from 28 TWh to 41 TWh. The electrical demand remains relatively stable and has a 7-year average of 568 TWh. The years in the given observation period have different suitable weather conditions influencing the output of wind and solar power, expressed in the utilisation of the power plants. The increase in the output of wind power and solar power within the time period in Fig. 3 is due to the expansion of the production capacities. Comparing the data series of the produced electrical powers $P_w(i_t)$ and $P_s(i_t)$ with the generation capacities $P_{wc}(i_t)$ and $P_{sc}(i_t)$, the effects of weather-related influences on electricity generation become visible. Wind energy always experiences a higher utilisation than solar power. Wind power is more volatile and its utilisation fluctuates between 17% and 22.5%. Solar power is operated relatively evenly

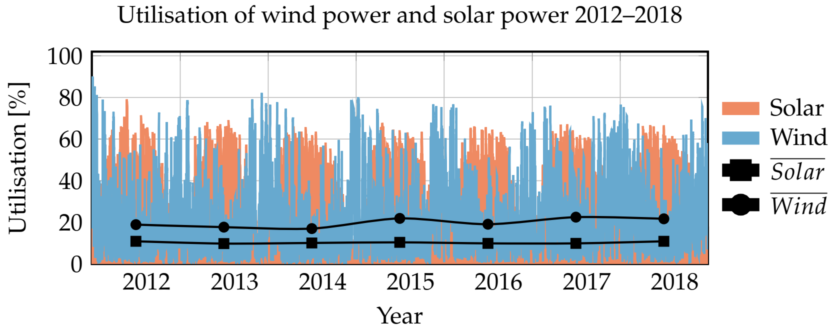

Fig. 4: Wind power shows a higher degree of utilisation especially in the winter months, while solar power is well utilised in the summer time.

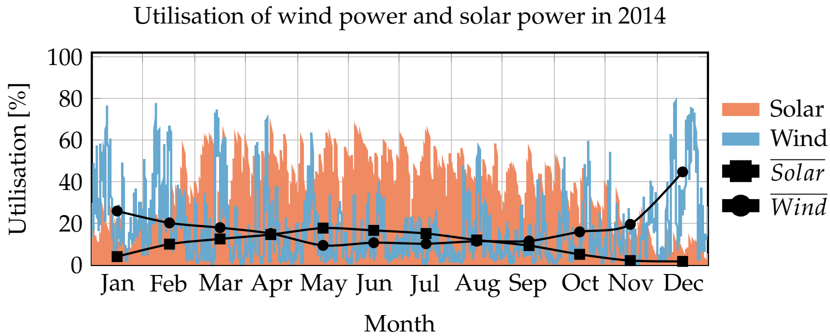

Fig. 5: The charts of the utilisation rates show a comparatively lower utilisation of 17% for wind energy. Solar energy has a utilisation rate of 10.1%.

with a utilisation of between 9.9% and 10.9%. Fig. 4 shows the utilisation of wind power and solar from 2012 to 2018.

Fig. 5 and 6 present a closer look at the utilisation rates of the years 2014 and 2017 and show a low-yielding and a high-yielding period. In 2014, the average utilisation rate in the wind energy sector was about 17% and in 2017 about 22.5%. Considering the same years the utilisation for solar power is nearly constant with 10.1% for 2014 and 9.9% for 2017. The shown weather-dependent differences of the degrees of utilisation in the considered years show that for the simulations of storage systems with a high share of renewable energy sources, always several years have to be considered. This is of crucial importance especially for long-time storage systems.

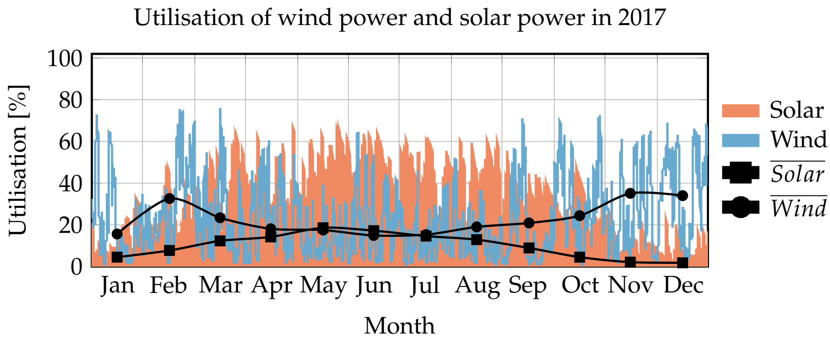

Fig. 6: The charts of the utilisation rates show a comparatively higher utilisation of 22.5% for wind energy. Solar energy has a utilisation rate of 9.9%.

Tab. 1: Annual hour-average values for generation and demand in Germany. In the year 2012 the combination of wind and solar power had a share of 13% of the demand and grew until the end of 2018 to roughly 26%.

Year	Power capacity from wind power $\bar{P}_{wc}$ [MW]	Output from wind power $\bar{P}_w$ [MW]	Power capacity from solar power $\bar{P}_{sc}$ [MW]	Output from solar power $\bar{P}_s$ [MW]	Power demand $\bar{P}_d$ [MW]
2012	27737	5221	29324	3175	64555
2013	30352	5388	34480	3388	63872
2014	34333	5839	36961	3728	65201
2015	40353	8843	38411	3985	65343
2016	45928	8767	39649	3935	64585
2017	52010	11720	41366	4096	64798
2018	57205	12393	43481	4707	64929

Tab. 1 shows the annual hour-average power outputs $\bar{P}_w$ and $\bar{P}_s$, the power capacities $\bar{P}_{wc}$ and $\bar{P}_{sc}$, the power demand $\bar{P}_d$ and the calculated utilisation factors of wind and solar for the years 2012 until 2018. Tab. 2 also shows the annual totals for production and consumption for these categories.

Tab. 2: Annual sum values for generation and demand in Germany.

Year	$\bar{E}_w$ [TWh]	$\bar{E}_w/\bar{E}_{wc}$ [%]	$\bar{E}_s$ [TWh]	$\bar{E}_s/\bar{E}_{sc}$ [%]	$\bar{E}_d$ [TWh]
2012	46	18.9	28	10.9	567
2013	47	17.7	30	9.8	560
2014	51	17.0	33	10.1	571
2015	77	21.9	35	10.4	572
2016	77	19.1	35	9.9	567
2017	103	22.5	36	9.9	568
2018	109	21.7	41	10.8	569

With the data values given, renewable energies are not sufficient to fully guarantee the supply of electricity. Accordingly, a multiplication of the generation capacities has to take place for covering the total demand, initially assuming an unlimited storage capacity. In order to simulate a complete energy supply from renewable sources, the factor m is introduced by which the scaled produced electrical power, given from the data source, is multiplied. The multiplier m is determined with an interactive calculation procedure, with the request that at the beginning and at the end of the time period the energy storage has the same charge level. The charging process of the storage compilation is thus directly scalable via m and also serves to compensate for the existing losses of the respective storage classes. Thus m represents the multiple of the actual generation capacity to completely cover the electricity demand by wind and solar power.

2.2 Storage Classes

From a technical point of view, it makes little sense to use a single technology for storing energy, as available technologies have their individual advantages and disadvantages. A stable electricity grid requires a storage method with fast reaction time and good cycle stability, while long-time storage systems in particular require a very large storage capacity. For this reason, five storage classes are introduced, differing in their technical properties and suitable for the respective application. The storage classes are arranged in descending order of efficiency and in ascending order of capacity. It should be noted that a single storage class is not to be understood as a standalone system, but as the sum of the capacities required in the area under consideration.

The entire composition of the different storage classes establishes therefore a modeling as close to reality as possible within this work. For this reason, it makes little sense, for example, to cover a large capacity requirement with pumped hydro storage plants. The technology itself may appear to be quite suitable for this purpose, but either special geographical conditions are required for the construction, or the construction is only associated with a considerable effort, the implementation of which is unlikely. To cover a wide area of applicability the selected storage technologies should therefore meet the following requirements:

1. A storage system should be independent of geographical conditions and be able to be constructed at almost any location with sufficient subsoil strength.
2. For a storage system the resources necessary for construction and operation should be available in sufficient quantity.
3. Storage systems with a high potential for causing damage to society and environment should not be considered.

Any storage technology can be used, as far as the necessary input parameters are available for the calculation. Due to the above mentioned conditions, the following technologies are chosen within the scope of this study.

For *class 1* a lithium-ion battery (Li-bat) system is selected. Due to its fast response time, this system is able to generate or consume power almost immediately when needed. Furthermore, lithium units have a high stability with regard to the possible number of cycles. Due to the worldwide increase in production capacities in recent years, this technology is available at an acceptable price.

For *class 2* a zinc-air battery system (ZnA-bat) is selected. Since this class already has to cover a multiple of the previous class in storage capacity, a storage where the converter is scalable independently from the storage is suitable. Thus, in this second class, higher amounts of energy can be stored with the same power performance, which has a positive effect on costs. In addition, this type requires high efficiency and high cycle stability as well.

For *class 3* a pumped heat energy storage (PHES) is selected. With this type of storage, the required reaction speed is less important than in the previous classes in favour of a higher storage capacity. The storage volume for thermally charged air can be mapped across different size classes at low cost and the converter can be built completely separate from the storage tank.

For *class 4* a power-to-hydrogen (P-to-H_2) system is selected. For larger energy surpluses hydrogen is directly produced by an electrolysis system. The low efficiency is compensated for at this point by the very high possible storage capacity. Combined cycle gas turbine (CCGT) power plants are used for the discharging process.

For *class 5* a power-to-methane (P-to-CH_4) system is selected. With this method it is possible to map very long, seasonal storage intervals. After the hydrogen electrolysis, a further processing to methane takes place in a separate reactor, which reduces the efficiency even further compared to class 4. If the carbon dioxide required for methanation is extracted from the atmosphere, this is a completely climate-neutral storage system. The greatest advantage and the main reason for methanation is the possibility of storing this gas in the already existing natural gas network. In analogy to class 4, the energy is fed back into the grid by dedicated CCGT power plants.

2.3 Technical Storage Description

With an increase in the generation power by the factor m the necessary performance for the energy converters of the energy storage system would increase as well. Furthermore, the multiplication leads to a higher load on the power grid. In order to exclude unrealistically high charging powers, the parameter P_{lm} is used to limit the charging amount. The energy that exceeds this value during a charging process is evaluated as loss.

The *storage capacities* $C_{E,1}, \ldots, C_{E,5}$ and their sum C_{sum} define the maximum amount of energy a storage device can contain. The capacities of the storage classes $C_{E,1}, \ldots, C_{E,4}$ are determined by means of a geometrical division using a quotient of the consecutive elements of q. Storage capacity $C_{E,5}$ is determined in such a way that the sum of all classes C_{sum} is sufficiently large to exclude a supply bottleneck for the complete simulation. Therefore the total amount of storage capacity C_{sum} can be expressed as

$$\begin{aligned} C_{\text{sum}} &= C_{E,1} + C_{E,1} \cdot q + C_{E,1} \cdot q^2 \\ &\quad + C_{E,1} \cdot q^3 + C_{E,5} \\ &= \sum_{i=1}^{4} C_{E,1} \cdot q^{i-1} + C_{E,5}. \end{aligned} \tag{5}$$

The following explanations refer to a majority of storage classes. For this purpose, the integer index j is introduced for selected parameters, which defines the association with the storage class.

The parameters η_j stand for the *efficiencies* as a ratio of charged to discharged energies and always refer to the electrical quantity. Since an energy storage system is represented as a self-contained subsystem, the efficiencies always represent the losses from the converter and the storage unit. They are always taken into account during the discharging process. The parameter DOD_j describes the maximum *depth-of-discharge* of an energy storage device. In the context of modeling, these parameters are entered as percentage values and thus define the effectively usable capacity. The *self-discharge* of a storage device is given by the parameter SED_j, usually in percent per day. The self-discharge represents a continuously progressing loss, which also falls below the depth-of-discharge but not below zero. The *degradation* DEG_j represents a loss of capacity which progresses over time and gradually limits the maximum load volume. This influence is indicated in an annual value. If this influence were to be included in the calculation unchanged over the entire time considered, the available storage capacity would be considerably reduced, depending on the degree of degradation. In order to represent a behaviour of degradation as close to reality as possible, the parameter *degradation reset* DER_j with the unit 1/year is additionally introduced. This is the number of complete recoveries of the nominal storage capacity per year and thus stands for a consideration of maintenance and revision work in which, for example, defective battery cells are replaced. In power plant technology, major renewal work is often carried out as part of an annual maintenance. In analogy to this, the restoration of the nominal storage capacity also follows with a value of $\mathrm{DER}_j = 1/\mathrm{year}$.

Another required parameter for the modeling is the *initial charging level* of the storage E_{start}. It is assumed that at the beginning of the calculation all storage devices are charged to 100%. If there is an energy surplus above this maximum charging level, it is not transferred to the storage system and can therefore be considered a loss.

2.4 Storage Class Interconnection

The simplest case is the mapping of a serial interconnection, in which the classes are triggered in a strict order depending on their current state of charge. The modeling is structured in such a way that at the beginning of a charge or discharge process always the lowest available storage class with free capacity is driven. If the capacity limits are reached, the system switches to the next higher class during the charging and discharging process. Class 1 performs the most frequent charging and discharging operations, the highest class 5 the least. The class interconnection of a fully serialised storage assembly is shown schematically in Fig. 7.

The technologies of power-to-hydrogen and power-to-methane have very high investment costs in terms of their converter power. From a technical point of view, it is suitable for the hydrogen electrolysis and the methanation processes to be as continuous as possible, which is not the case with a serial interconnection.

For this reason the semi-parallel calculation model applies a parallel charging process for classes 4 and 5, while classes 1–3 remain in serial operation. This leads to the introduction of the parameter *continuous charging* (COC_j), describing a continuous charging power over the simulation time. COC_j thus defines the required converter power for the charging process, which is lower compared to the serial classes and thus also leads to lower investment costs of the plants. Another advantage is that COC_j is taken into account before the limitation of the input power P_{lm} becomes effective. The class interconnection of the semi-parallel storage assembly is shown schematically in Fig. 8.

In the case of discharging, the parallel connected storage classes should be able to continue charging as well. Accordingly the parallel connected storage classes draw on the storage reserves in addition to the electrical demand, which leads to faster discharging. In the case of a near-empty overall system, when discharging

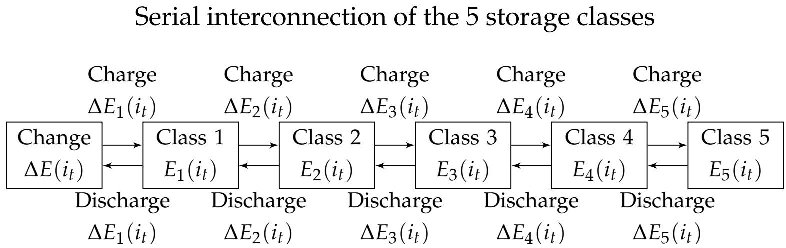

Fig. 7: The change in charge at the input side of one storage class is equal to the change in charge at the output side of the previous storage class.

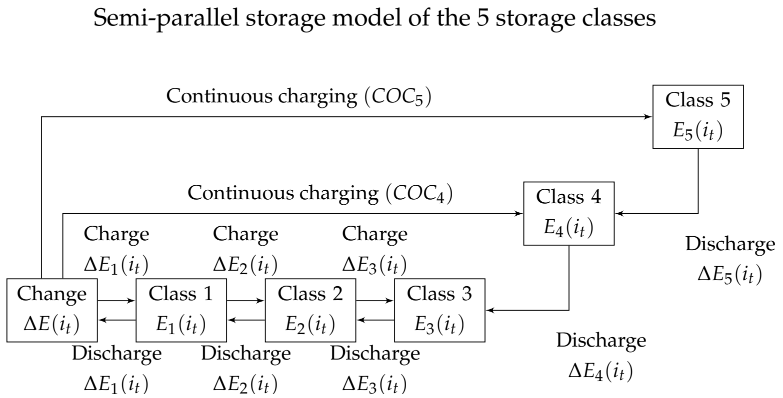

Fig. 8: Up to and including class 3, the entire system operates in serial mode. Class 4 and class 5 experience a continuous energy supply through COC_4 and COC_5.

from hydrogen and methane becomes necessary, a compensation between COC_j and the electrical demand $\Delta E(i_t)$ is thus achieved. In practice, this would be equivalent to simulated charging by electrolysis or methanation and reverse power generation by CCGT plants at the same time.

2.5 Technical Parameter Selection

The total power drawn by all electricity consumers in an electricity grid is subject to fluctuations over time. It is usually higher during the day than at night and higher in winter than in summer. The maximum power that occurs is called the annual peak load. It usually occurs in winter and is also called the winter peak load. Its level is relatively predictable, but also depends on weather conditions. The annual peak load is far smaller than the total output of all installed consumers, since all consumers are never active at the same time (Paschotta, 2012). In the power balance report of the German transmission system operators, a peak load in the range of 78 to 81.6 GW is mentioned (50Hertz et al., 2019). For this reason, the power limitation P_{lm} is set at 80 GW for all of the calculations. The lowest class 1 is dimensioned to cover the largest hourly demand value in the data set, which is 91321 MW and therefore the storage capacity is set at 92000 MWh. The following storage classes are defined with the factor $q = 5$ in ascending order according to equation (5). The last class 5 is always calculated from the remaining necessary storage demand C_{sum}.

Each class requires a set of technical parameters to simulate the respective technology as realistically as possible. The storage technologies used and their associated technical literature parameters are listed in Tab. 3. Assumptions are made for chosen parameters, since either no literature values are available or a deviation is reasonable within the calculations. This applies to the value of the depth-of-discharge for classes 3 to 5, whereby a complete possible discharge is assumed. Class 3, which is represented by a pumped thermal energy storage, has no temperature differences to the environment in the completely discharged state and is therefore considered to be completely discharged. Considering power-to-gas technologies, a similar assumption is made since, e.g. compressors can be used to adjust the pressure when the storage tank is almost empty. In the case of methane storage, there is also the possibility of feeding natural gas into the system for stabilising the working pressure. As the storage capacity of classes 3 to 5 depends on the physical volume, which does not change, a degradation of 0% is applied.

Tab. 3: Technical working parameters for the storage compilation.

Class	Techno-logy	C_E [GWh]	η [%]	DOD [%]	DEG [%/year]	SED [%/day]
1	Li-bat	92	95[a]	90[b]	3[c]	0.01[a]
2	ZnA-bat	460	80[a]	100[d]	1.5[e]	0.01[i]
3	PHES	2300	67[f]	100[i]	0[i]	1[f]
4	P-to-H_2	11500	41[g]	100[i]	0[i]	0.01[h]
5	P-to-CH_4	[j]	32[g]	100[i]	0[i]	0.05[h]

Notes: [a] η: 90–97%, SED: 0.008–0.041% (Sterner and Stadler, 2019); [b] 80–100% (Akhil et al., 2015); [c] PacifiCorp (2016) and Schmidt (2018); [d] η: 80%, DOD: 100% (Akhil et al., 2015); [e] Mongird et al. (2019); [f] η: 52–72%, DEG: 1% (Smallbone et al., 2017); [g] Jülch (2016); [h] 0.03–0.003% (Fuchs et al., 2012); [i] own assumption; [j] depending on calculation result, the parameter for degradation reset der_j is set at 1 $year^{-1}$.

2.6 Financial Parameter Selection

To calculate the total system costs on the basis of the Levelised Cost of Storage metric, further finance-specific parameters are required. The storage-specific cost parameters are summarised in Tab. 4 and 5.

Some storage technologies provide widely varying values in the literature, which is especially the case for battery systems, which are in the process of becoming progressively cheaper. The time parameters, the cost of electricity for storage and the interest rate used are shown in Tab. 6.

It should be noted that the literature sources provide the financial parameters in different metrics, which leads to the situation that some cost items are considered in different parameters. The power generation costs LCOS for wind power and solar power in Germany are in a range between 0.04 and 0.14 EUR/kW/h (Kost et al., 2018). According to IRENA (2019a), the costs for electricity generation are expected to fall in the future. For this reason a cost range for electricity procurement of $k_e = 0.02$ to 0.10 EUR/kW/h is used for the calculations.

Tab. 4: Parameters relating to IC (CapEx) and ICR (CapExR).

Class	Techno-logy	IC_E [EUR/kW/h]	IC_P [EUR/kW]	ICR_E [EUR/kW/h]	ICR_P [EUR/kW]
1	Li-bat	180[a]	200[a]	180[a]	200[a]
2	ZnA-bat	139.4[b]	377[b]	139.4[b]	377[b]
3	PHES	17[c]	573.5[c]	17[c]	573.5[c]
4	P-to-H_2	0.3[d]	880[d]	0[f]	0[f]
4	CCGT	0	727[d]	0	0[f]
5	P-to-CH_4	0[e]	1369[e]	0[f]	0[f]
5	CCGT	0	727[e]	0	0[f]

Notes: [a] IC_E: 140–180 EUR/kW/h, IC_P: 100–200 EUR/kW (Sterner and Stadler, 2019); [b] IC_E: 164 USD/kW/h, IC_P: 443 USD/kW/h (Akhil et al., 2015); [c] scenario 2 target system (Smallbone et al., 2017); [d] IC_E: assumption of an above-ground storage cavern: 0.3–0.6 EUR/kW/h, IC_P: charging with alkaline electrolysis: 410–880 EUR/kW, discharging with CCGT turbine: 727 EUR/kW (Jülch, 2016); [e] IC_E: feeding into the existing natural gas grid: 0 EUR/kW/h, IC_P: charging with alkaline electrolysis and methanation: 790–1360 EUR/kW, one-time investment for H_2 storage and injector system every 100 MW: 2.64 EUR/kW, discharging with CCGT turbine: 727 EUR/kW (Jülch, 2016); [f] covered by IC_E and IC_P; exchange rate: 0.85 EUR/USD.

Tab. 5: Parameters relating to OC (OpEx) and RES (residual).

Class	Techno-logy	OC_E [EUR/kW/h]	OC_P [EUR/kW]	RES_E [EUR/kW/h]	RES_P [EUR/kW]
1	Li-bat	0.5[a]	0	0[f]	0[f]
2	ZnA-bat	0.00043[b]	3.83[b]	0[f]	0[f]
3	PHES	0.0026[c]	11[c]	0[f]	0[f]
4	P-to-H_2	0.003[d]	14.1[d]	0[f]	0[f]
4	CCGT	0	0.44[d]	0	0[f]
5	P-to-CH_4	0.003[e]	30.2[d]	0[f]	0[f]
5	CCGT	0	0.44[d]	0	0[f]

Notes: [a] OC_E: 0.16–0.76 EUR/kW/h, OC_P: covered by OC_E (Sterner and Stadler, 2019); [b] OC_E: 0.0005 USD/kW/h, OC_P: 4.5 USD/kW/h (Akhil et al., 2016); [c] scenario 2 target system (Smallbone et al., 2017); [d] OC_P: charging unit: 1.6% · IC_P, discharging unit: 0.06% · IC_P (Jülch, 2016); [e] OC_P: charging unit: 1.5–2% · IC_P, discharging unit: 0.06% · IC_P, fee for natural gas grid (charging and discharging): 2 · 3.2 EUR/kW (Jülch, 2016); [f] assumed residual value after lifetime, exchange rate: 0.85 EUR/USD.

Tab. 6: Parameters relating to time values and interest rate.

Class	Technology	t_l [year]	t_r [year]	t_c [year]	k_e [EUR/kW/h]	r [%]
1	Li-bat	15[a]	15[a]	1[g]	0.06[g]	8[f]
2	ZnA-bat	15[b]	15[b]	1[g]	0.06[g]	8[f]
3	PHES	20[c]	20[c]	1[g]	0.06[g]	8[f]
4	P-to-H_2	30[d]	25[e]	1[g]	0.06[g]	8[f]
5	P-to-CH_4	30[d]	20[e]	1[g]	0.06[g]	8[f]

Notes: [a] Sterner and Stadler (2019); [b] Akhil et al. (2016); [c] Smallbone et al. (2017).; [d] Sterner and Stadler (2019); [e] 20–30 years for alkaline electrolysis, 20 years for methanation isothermal reactor (de Bucy, 2016); [f] Lazard (2020a, 2020b); [g] own assumption.

3 RESULTS

3.1 Technical Results

In order to fulfil the requirement that the entire storage system is completely filled at the end of period under consideration, a multiplier of at least 6.8 is required calculating the serial model. Compared to the installed wind power at the end of 2018, this corresponds to a multiple of 4.75 and an installed power capacity of 280 GW. Solar power corresponds to a multiple of 5.7 and a total installed power capacity of 256 GW. The point in time when the entire storage system is completely discharged occurs at 2015-02-18 21:00 UTC. This system state thus defines the necessary storage capacity of 268 TWh. In particular, the comparatively low-wind years 2013 and 2014 and the increase in electricity demand in 2014 lead to a depletion of the overall system in these years. This shows that the required storage capacity is strongly dependent on the volatile power supply and the electrical demand profile. For this reason, it is imperative to always map several years with the most diverse weather conditions possible within the scope of storage simulations. Fig. 9 shows the charts of the energy charging levels of the system E_{sum} with an increase in the multiplier of $m = 1$ to $m = 6.8$. Only with $m = 6.8$ the level at the end of 2018 reaches almost the same level as at the beginning.

The class-specific results are evaluated with regard to the charging and discharging processes can be seen in Fig. 10. Graph (a) shows how often a storage class is activated. Class 1 is accessed comparatively often for discharging while the remaining classes are always dominated by the charging process. Graph (b) shows the annual volume changes where Class 5 absorbs the most energy. The differences between charging and discharging arise from the internal losses incurred and are therefore dependent on the efficiency η. Graph (c) shows the operating hours, whereby it can be seen that the utilisation times are of a similar order of magnitude for all classes. Graph (d) shows the maximum converter power. Due to the power limitation P_{lm} of 80 GW, there is a maximum during charging. The power during discharging depends on the time-dependent difference between the electricity supply and the electricity demand, with a maximum of approx. 85 GW.

Considering the semi-parallel interconnection for charging, classes 1 to 3 are arranged in a serial sequence, while classes 4 and 5 are arranged in parallel with a constant power COC of 6 GW. The charging of classes 4 and 5 also takes place when an energy bottleneck occurs and, if necessary, energy from the remaining storage classes must be used for this purpose. The reason for this structure in Power-to-Gas technologies is that different technologies are used for charging and discharging. It is suitable to operate the expensive plants for generating H_2 and CH_4 with smaller power capacities. However, in order to store sufficient energy, the plants must always be able to operate

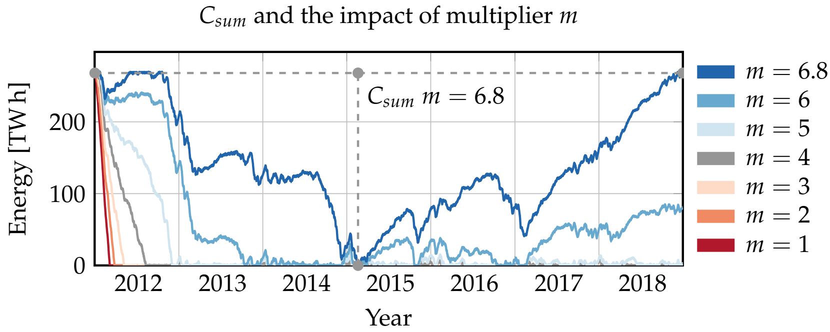

Fig. 9: Serial calculation model. In the case of $m = 1$, it can be seen how quickly the system would empty itself with the historically existing generation capacities. With at least $m = 6.8$ the system is able to reach a fully charged storage interconnection in the end of 2018.

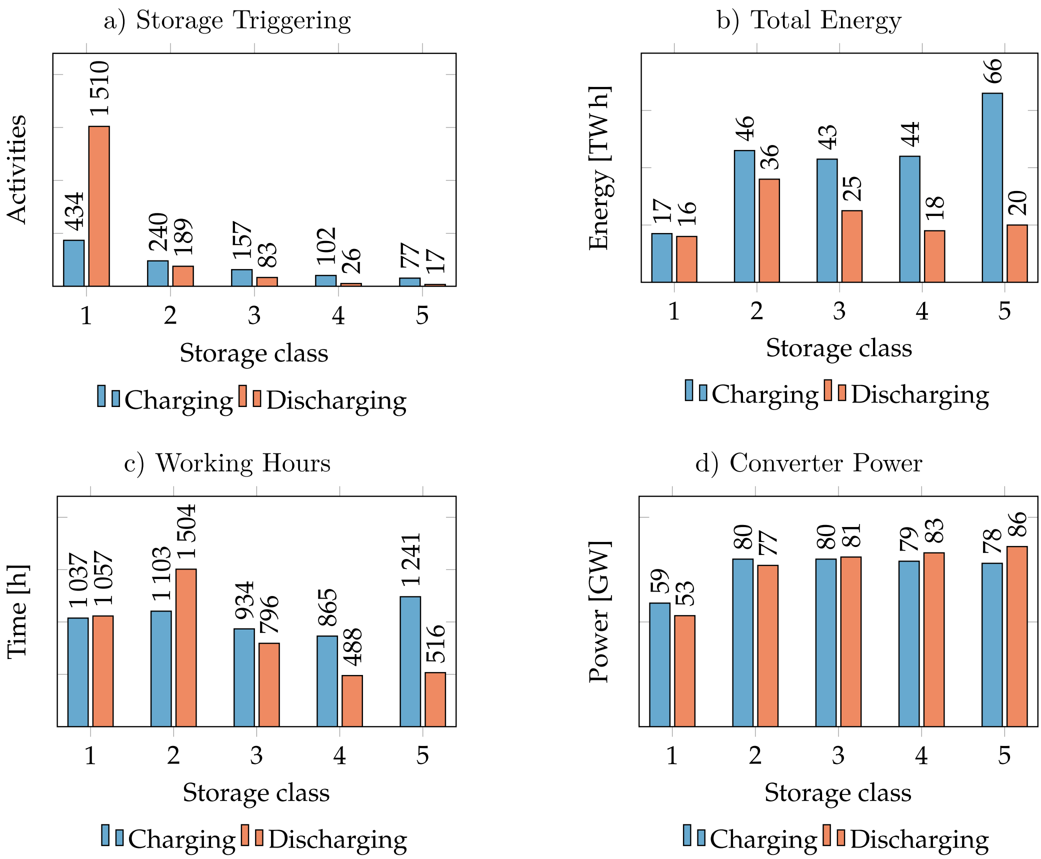

Fig. 10: Compilation of selected result variables for charging and discharging as average annual values.

when the storage capacity is not exhausted. Discharging is done completely in analogy to the serial calculation model in ascending order. The semi-parallel interconnection yields a larger multiplier of $m = 9.12$ compared to the serial consideration. This corresponds in relation to the end of the year 2018 with 375 GW to 6.37 times the installed wind power and with 344 GW to 7.64 times the installed solar power. The lowest value occurs on 2015-02-18 09:00 UTC and is thus almost congruent with the serial calculation. This

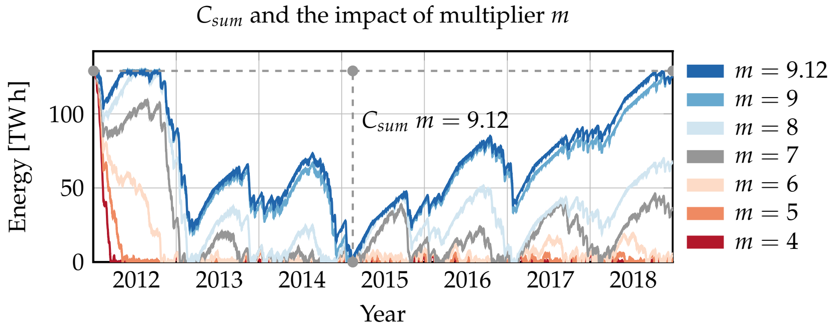

Fig. 11: Semi-parallel calculation model. With at least $m = 9.12$ the system is able to reach a fully charged storage interconnection in the end of 2018.

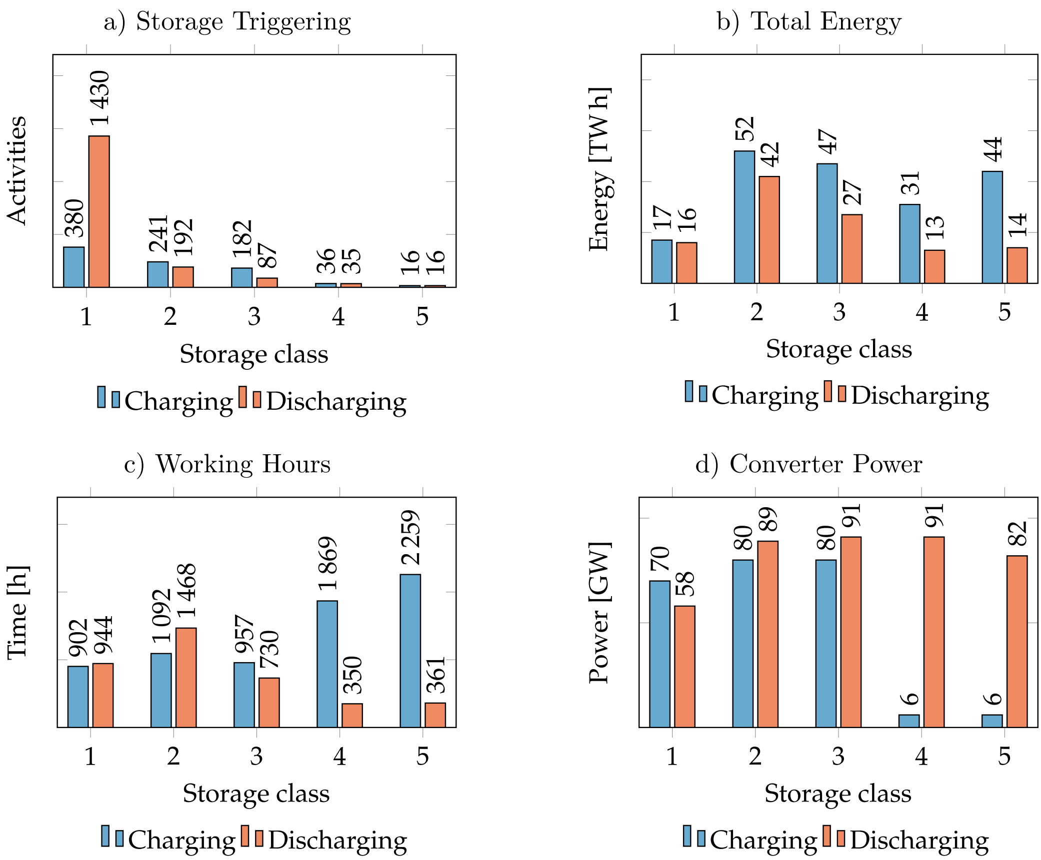

Fig. 12: Compilation of selected result variables for charging and discharging as average annual values.

results in the required total storage capacity of 129 TWh, which is less than half the value from the serial calculation. Therefore, it can be stated that the storage capacity and the generation capacity can compensate for each other. Fig. 11 shows the charts of E_{sum} with an increase in the multiplier of $m = 4$ to $m = 9.12$.

The class-specific results are evaluated with regard to the charging and discharging processes and can be seen in Fig. 12. Graph (a) shows the number of activations, with class 1 showing the most frequent operations in the semi-parallel model, especially when discharging. Graph (b) shows the total charged and

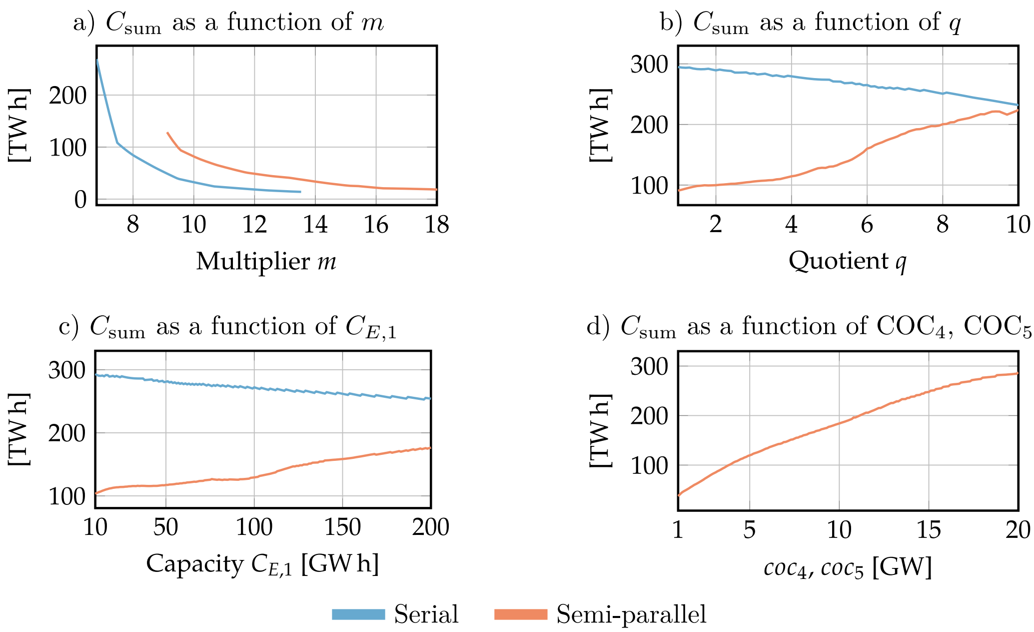

Fig. 13: The graphs show the characteristics of the total storage capacities as a function of the factor-based power production capacity m and the energy capacity ratios of the storage classes to each other, q. Furthermore, as a function of the capacity of class 1 $C_{E,1}$ and of the continuous charging power COC_4 and COC_5. Small discontinuities result from computational uncertainties or changed storage switching processes and can be neglected.

discharged energy, which reveals the influence of the internal losses. Compared to the serial calculation, less energy is stored in class 5 because the class is smaller overall. The working hours are displayed in graph (c). During charging, classes 4 and 5 experience the longest operating times, as they are obviously operated continuously for most of the time. A pause only occurs when the system has no more free capacity. In graph (d), which displays the determined converter power, the influence of the continuous charging of the Power-to-Gas technologies with a value of 6 GW is recognisable. For classes 1 to 3, the charging power is limited by P_{lm} to 80 GW. The converter powers required for charging and discharging for classes 1 to 3 are of a similar order of magnitude in contrast to classes 4 and 5.

Based on the calculated results, parameter studies are carried out to show the influence of the change in several input parameters. Within these studies the following parameters are varied: multiplier m, the quotient for the growth of storage classes q, and the capacity of the first class $C_{E,1}$. The continuous charging powers COC_4 and COC_5 only relate to the semi-parallel calculation model. The development of C_{sum} as a function of m is shown in Fig. 13, graph (a), for the serial and the semi-parallel model. It is shown that in the serial model with $m = 6.80$ and $C_{\text{sum}} = 268$ TWh a sufficient power supply is achieved. With a relatively small overproduction, C_{sum} can be greatly reduced. At $m = 8.09$, the storage capacity is $C_{\text{sum}} = 81$ TWh, which further decays as m increases. The model with semi-parallel interconnection requires smaller storage capacities, but larger power generation. Thus, the power supply is only meeting the demand from $m = 9.12$. An energy storage capacity of $C_{\text{sum}} = 129$ TWh is sufficient. This shows that the serial interconnection requires higher storage capacities, while the semi-parallel interconnection has higher power production requirements.

The variation of the parameters q and $C_{E,1}$ and their influence on the storage capacity is shown in Fig. 13, graphs (b) and (c). An opposite behaviour of the calculation interconnection can be seen, whereby in the serial case, decreasing progressions of C_{sum} and in the semi-parallel case, increasing progressions can be recognised. From this it can be stated that the required storage capacity strongly depends on the interconnection of the individual storage units and their size ratios to each other. Different configurations can cause large variations in C_{sum} of more than 100 TWh. Therefore, the dimensioning of large energy storage systems cannot only be reduced to electricity production and storage capacity, but also requires a detailed consideration of the interconnection dimensioning of storage classes.

The variation of the parameters COC_4 and COC_5 is shown in Fig. 13, graph (d). Here it can be seen that an increase in the continuous charging power is associated with an increase in the storage capacity. The multiplier m is reduced from 14.34 to 8.08 in the range shown. The continuous charging power can be seen as an additional element to control the relationship between storage capacity and generation power. By using parallel storage elements, the required converter power of selected elements can be greatly reduced.

3.2 Cost-Related Results

Based on the results of the technical calculation, detailed statements can be made about the cost aspects of the overall system. The financial calculation results of the serial interconnection show that the levelised cost of storage LCOS increases together with the connection order of the storage classes. This is mainly due to the increasing interest-bearing investment costs and the decreasing number of full storage cycles derived from the working hours. The high costs for the power converters in classes 4 and 5 are particularly striking. In addition, due to the comparatively low number of cycles, they are hardly utilised and are correspondingly expensive. The sum of the costs from the storage system, the external losses and the direct consumption thus gives the total system costs. If these costs are allocated to the total electricity demand, a statement is made about the resulting electricity cost k_{res}, which represents the costs for the complete provision of electricity. The calculation of the resulting electricity cost with the most important intermediate results is shown in Tab. 7.

The total costs of the storage classes are lower in the semi-parallel calculation compared to the serial design. In particular, class 4 and class 5 have significantly lower levelised storage costs, especially due to the lower storage capacity and the investment costs for the energy converters. The total amount of energy delivered by storage and the amount of electricity directly consumed is comparable to the serial interconnection. The costs of external losses, on the other hand, are enormous and a significant cost driver of the total costs, only insignificantly lower than in the serial interconnection. The allocation to the total electrical demand thus produces a similar result for the two calculation cases. On this basis, it can therefore be stated that the savings in the area of the storage capacities are roughly cancelled out by the higher electrical production and the increasing losses. The calculation of the resulting electricity cost for the semi-parallel calculation with the most important intermediate results is shown in Tab. 8.

The parameter studies for the cost-related calculations are carried out to show the influence of the variation of the input parameters m, q, $C_{E,1}$, COC_4 and COC_5 in analogy to the technical consideration. The resulting electricity costs k_{res} depend primarily on the technical dimensioning, on the storage class costs and on the electricity procurement costs k_e. Based on the price ranges for electricity generation in Kost (2018), the parameter studies provide insights into the changes of the resulting electricity costs depending on the input parameters in a range of electricity purchasing costs between 0.02 EUR/kW/h and 0.10 EUR/kW/h.

The parameter studies calculating the energy storage capacity C_{sum} show that an increase in electrical production through the multiplier m leads to a decrease in capacity. What is surprising here is that, with regard to the system costs, there is no reduction in the total costs; in fact, the opposite is the case. Higher production capacity increases the costs for electrical losses that cannot be consumed.

Tab. 7: Annual cost calculation for the total system (serial).

Parameter	**Energy**	**Financial amount**
Class 1 LCOS (92 GWh)		0.30 EUR/kW/h
Class 2 LCOS (460 GWh)		0.44 EUR/kW/h
Class 3 LCOS (2300 GWh)		0.55 EUR/kW/h
Class 4 LCOS (11500 GWh)		0.99 EUR/kW/h
Class 5 LCOS (254960 GWh)		1.22 EUR/kW/h
Class 1 electricity discharged	16364 GWh	4.94 EUR bn
Class 2 electricity discharged	36470 GWh	15.88 EUR bn
Class 3 electricity discharged	25001 GWh	13.63 EUR bn
Class 4 electricity discharged	17931 GWh	17.67 EUR bn
Class 5 electricity discharged	20291 GWh	24.81 EUR bn
Subtotal (k_{sto})	116057 GWh	76.94 EUR bn
Power limitation losses	43415 GWh	2.60 EUR bn
Charge surplus losses	5990 GWh	0.36 EUR bn
Subtotal (k_{los})	49405 GWh	2.96 EUR bn
Direct consumption (k_{dir})	451636 GWh	27.10 EUR bn
System costs (k_{res})	617099 GWh	107.00 EUR bn
Resulting electricity cost (k_{res})	567693 GWh	0.188 EUR/kW/h

Tab. 8: Annual cost calculation for the total system (semi-parallel).

Parameter	**Energy**	**Financial amount**
Class 1 LCOS (92 GWh)		0.32 EUR/kW/h
Class 2 LCOS (460 GWh)		0.40 EUR/kW/h
Class 3 LCOS (2300 GWh)		0.54 EUR/kW/h
Class 4 LCOS (11500 GWh)		0.76 EUR/kW/h
Class 5 LCOS (114221 GWh)		0.75 EUR/kW/h
Class 1 electricity discharged	16352 GWh	5.23 EUR bn
Class 2 electricity discharged	41911 GWh	16.79 EUR bn
Class 3 electricity discharged	27319 GWh	14.67 EUR bn
Class 4 electricity discharged	12906 GWh	9.82 EUR bn
Class 5 electricity discharged	13760 GWh	10.26 EUR bn
Subtotal (k_{sto})	112248 GWh	56.76 EUR bn
Power limitation losses	124155 GWh	7.45 EUR bn
Charge surplus losses	189428 GWh	11.37 EUR bn
Subtotal (k_{los})	313584 GWh	18.82 EUR bn
Direct consumption (k_{dir})	455446 GWh	27.33 EUR bn
System costs (k_{res})	881277 GWh	102.90 EUR bn
Resulting electricity cost (k_{res})	567693 GWh	0.181 EUR/kW/h

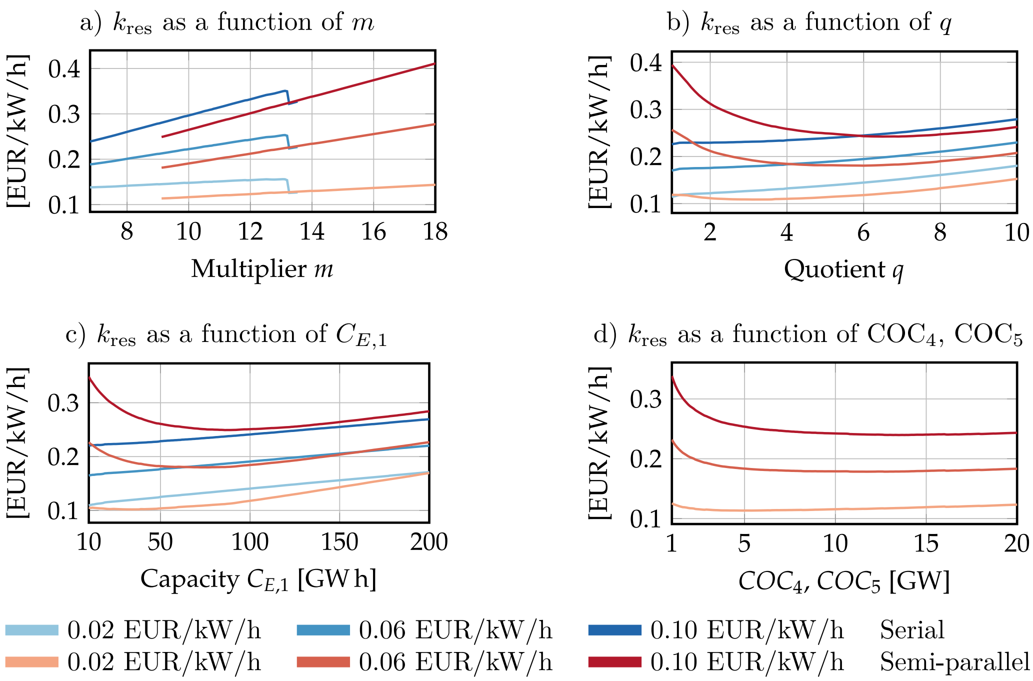

Fig. 14: The figures show the characteristics of the resulting total electricity system costs k_e as a function of the factor-based production capacity m and the capacity ratios of the storage classes to each other q. The curve of k_{res} as a function of m shows a small negative jump at $m = 13.5$. From such a large generation capacity onwards, storage class 5 is not needed, which abruptly eliminates its converter costs. Furthermore k_{res} is presented as a function of the capacity of class 1 and the continuous charging power COC_4 and COC_5.

The costs of losses have a greater impact than the savings in storage capacity. This behaviour is shown in Fig. 14, graph (a), and is similar for the serial and the semi-parallel calculation model.

Considering the serial calculation model, the growth of the parameters q and $C_{E,1}$ defining the energy storage capacity of the storage classes shows a similar behaviour. An increase in q and $C_{E,1}$ leads to rising costs, as more expensive storage classes come into operation with an increase in the parameters. The advantage of having better efficiencies within the total storage capacity is comparatively small in relation the total cost increase. Within the semi-parallel calculation model there is a flat minimum in each case, which represents an optimum from a cost perspective. The position of the optimum depends on the purchase costs for the electrical energy k_e. Basically, it can be concluded that a relatively small dimensioning of the lower storage classes leads to a significant cost increase. The curves for q and $C_{E,1}$ are shown in Fig. 14, graphs (b) and (c). A flat minimum is also seen with the variation of COC_4 and COC_5. This shows that the continuous charging power for the parallel-connected storage classes has a non-negligible influence, depending on the purchase costs for the electricity. From this it follows that the converter power for permanent parallel-connected charging processes should have at least the size of a few GW. This can be seen in Fig. 14, graph (d). Even though using relatively favourable cost data of storage technologies, the results show the significant impact of storage system costs. It should be noted that the calculated costs strongly depend on specific storage costs. Zakeri and Syri (2015) investigate the life cycle costs of several storage technologies by extensive literature research. A literature-related average of 795 EUR/kWh is given, for example, fo the investment costs of lithium battery systems.

4 CONCLUSIONS

Globally, renewable power generation is being expanded, especially wind and solar power. Against the background of the "Energiewende", Germany is striving to promote the expansion of these power generation methods. Due to their dependence on the weather, energy storage facilities are needed to compensate for weather-based shortages when there is a high proportion of volatile generation capacity.

With a complete power supply from wind and solar power, large storage capacities are needed to guarantee the power supply over short and long periods. The two calculated storage combinations lead to a storage demand of 268 TWh (serial) and 129 TWh (semi-parallel) for Germany. Compared to the average annual electricity demand of 567 TWh over the same period, these are shares of 47% and 23% respectively. The required storage capacities can be significantly reduced by changing selected technical parameters, especially by overproducing the electricity. However, this does not lead to reductions in total system costs, as the electricity that cannot be used due to overproduction must be counted as a loss.

The most important conclusion lies in the realisation that in a power supply based on wind power and solar power, it is not the generation of electricity that causes the greatest costs, but the storage. Taking into account the costs of the storage systems and the costs for the losses incurred, the resulting total costs are several times higher than the electricity generation itself, depending on the system configuration. With electricity generation costs of 0.06 EUR/kW/h, the total system costs lie in a range of 0.19 EUR/kW/h to 0.28 EUR/kW/h. This key finding shows that the inclusion of energy storage and the losses incurred from overproduction and inefficiencies must inevitably be seen as key cost drivers in renewable electricity supply systems. An exclusive focus on generation capacity leads to an incomplete and inadequate cost calculation.

Comparison of the storage costs from the work of Schmidt (2018), Jülch (2016) and Giovinetto and Eller (2019) with the total system costs from this work shows a comparable order of magnitude. However it should be noted that the costs of individual storage systems cannot in principle be compared to the costs of the entire system. Depending on which storage technologies are chosen for an overall system and which overcapacities are used, the total system costs change significantly.

Political and economic decision-makers should take these findings into account when planning future power supply systems in order to ensure a sustainable and hopefully cost-effective power supply.

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