

Simulation of a Multilevel Storage Model for a Renewable German Electricity System

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Abstract—This study analyses energy storage requirements on the basis of a completely renewable energy supply in Germany, taking into account several storage classes. Real hourly data of the provided electrical energy and the existing installed generation capacities for wind power and solar power from 2012 to 2018 serve as a basis. It is shown that low-wind years like 2014 strongly influence the requirements for a storage system. As the wind and solar power plants available in the period under consideration only partially cover the electricity demand, a scaling of the existing capacities is carried out, simulating a sufficiently large supply of electrical energy. The calculation model introduces five different storage classes, which differ in terms of their capacities and efficiency factors and thus represent different energy storage technologies. The calculation results show the required storage capacity for a demand-oriented renewable power generation. Furthermore, it is shown that the storage capacity can be reduced by excess capacities of renewable sources. At this point, the influences from the respective efficiencies of different storage technologies and the effects from the limitation of the charging power, which exceeds the grid capacity due to the high peak power, are shown. Furthermore, investigations are carried out with regard to the complete storage cycles of the different storage classes which are relevant for the economic efficiency of the storage facilities. Further suggestions for reducing the required storage capacities are discussed, which form the basis for further investigations.

Keywords—Storage Model, Germany, 100% Renewable Energy, Optimization, Storage composition

I. INTRODUCTION

Countries around the world are in a long-term process of shifting their power generation from fossil to renewable energy sources [1]. In recent years, a steady expansion of renewable electricity has been recorded. Considering the German sector, in 2000, a total of 9.35 TWh of wind power and 0.06 TWh of solar power were produced. In 2016, 78.60 TWh of wind power and 38.10 TWh of solar power were generated [2]. With the decided "Energiewende" and the phasing out of nuclear energy by 2022, a far reaching restructuring of the electricity supply system in Germany and Europe is imminent. The climate protection targets can be achieved by expanding the use of renewable energy sources in the electricity supply. In Germany the expansion of the energy system within the framework of the "Energiewende" will be dominated by technologies in the areas of wind energy and solar energy. In this context, energy storage systems can provide a balance between electricity production and demand [3].

Which type of storage system would be the best choice for renewable energy on a larger scale is difficult to answer and

depends on many influences. Briefly there are two basic characteristics of storage systems that need to be considered from a technical point of view. The generation of electrical energy from renewable sources is exposed to greater fluctuations depending on the weather. For this reason, storage systems must be able to handle short-term generation peaks, which come with high requirements to the charging performance. In addition, longer periods with a below-average production rate can occur. For such cases, a correspondingly high storage capacity is required to bridge these periods [4].

The need for storage capacities on the basis of renewable energy sources have already been investigated in several studies with different approaches. For example, M. Popp uses data from weather records and determines the corresponding generation capacities for electricity production from the values of solar radiation and wind speeds [5]. S. Weitemeyer relies directly on the recorded data of the generated power [6]. An interesting compilation of studies already carried out can be found in the article of F. Cebulla [7].

Furthermore, a distinction must be made between electricity production from solar power and wind power with regard to the requirements for a storage system. It is stated, that in general a grid with a high share of solar power directly correlates with high storage power and energy capacities compared to wind power. The assumption here is that there are no limitations with regard to the performance of the electricity grid. It is therefore recommended that the energy mix available at the selected location should be taken into account more closely when carrying out further studies [7].

When generating electricity from wind power, a distinction must be made between onshore and offshore plants. Offshore plants provide a higher wind energy yield due to the higher wind speeds at sea, which rise with increasing distance from the coast. Furthermore, larger free areas in the sea are available, which allows the construction of bigger parks. The disadvantage of this method are the higher costs for construction and operation compared to onshore plants [8]. Because the existing studies differ greatly in their approach and also in their results, it is difficult to compare the studies. However, certain basic commonalities regarding storage requirements can be found in the majority of publications. In general, it can be stated that a combination of generation and storage systems from a smaller network tends to place higher demands on energy storage systems than those from a larger

network. The larger volume of facilities can compensate for local fluctuations caused by the weather and thus reduce the overall volatility. Additional compensation mechanisms can be created by taking import and export processes into account [5]. In this way, fluctuations shift more in the direction of long-term weather events that cover a larger geographical area and do not represent local influences [9]. For this reason, estimates of the required storage capacity must always be made within the framework of several years in order to take such influences into account [10].

Previous investigations show that a power supply based almost entirely on renewable energies require a high level of storage capacity as well as a high performance for charging and discharging. An energy storage system must be able to absorb short-term power peaks from production as well as being large enough to compensate for seasonal production losses. These requirements can be reduced by assumptions such as a cross-national supply balances which in turn, requires further demands on a particularly powerful supply network. Even if the power supply system is expected to show strong growth in renewable energy, a complete supply from renewable energy sources seems rather unrealistic in the coming decades. Nevertheless, it can be expected that energy storage technologies will become increasingly important as volatile generation capacities are being expanded. In the context of the investigations carried out in the article of W. Schill it is stated that surpluses obtained from weather-dependent generation methods can be partially reduced by flexible controllable thermal power plants. Power plants using biomass as fuel would be an option in the context of a fully renewable energy supply [11].

Furthermore, thermal power plants have the possibility to make the generated heat available to the customers and thus additionally reduce the total storage requirement. For this reason, it makes sense to consider a combination of energy storage systems that are technically and economically acceptable in the context of a combination of weather-based and fuel-based energy sources.

This study describes the modeling of an energy storage composition consisting of different size-classes. In the context of a hypothetical complete renewable power supply from wind and solar power, the modeling is based on the German power grid. 5 storage classes are introduced, which differ in their storage capacity, triggering times and efficiency. In a first step, the generated electricity quantities in the form of real data from the years 2012-2018 are used and scaled in such a way that they could cover the electricity demand in the same period on the basis of unlimited storage capacity. In the second step, the storage classes are dimensioned and the necessary capacities are determined on the basis of the scaled real data. In the third step, it is shown how an increase in generation capacity affects the storage capacities and it becomes visible, which behaviour the filling level curves assume.

II. EXAMINATION OF THE SOURCE DATA

The modeling is based on data from the period 2012 to 2018, in which large amounts of wind and solar power plants are already in operation. The input data is available in the form of 61368 hourly resolved data sets and thus allow 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. In addition, the influence of the efficiency of various storage technologies on the storage requirements as well as a limitation of the charging power is examined.

The input data shows the values of the generated wind power $P_w(t_i)$, the solar power $P_s(t_i)$ and the current power demand $P_d(t_i)$. $P_d(t_i)$ contains the influences for imports and exports across national borders of electrical energy and is defined as follows.

$$\begin{aligned} \text{total load } P_d(t_i) &= \text{total generation} \\ &- \text{auxiliary/self} \\ &- \text{consumption in power plants} \\ &+ \text{imports} \\ &- \text{exports} \\ &- \text{consumption by storages}^1 \end{aligned}$$

Furthermore, the installed generation capacities from wind power $P_{wc}(t_i)$ and solar power $P_{sc}(t_i)$ from the years 2012 to 2018 are contributed to the German power grid. The raw data is taken from the sources of the BNetzA and the German TSOs, which in turn were provided via the database [13].

From the beginning of 2012 until the end of 2018, the annual average from wind power \bar{P}_w is growing from 5221 MW to 12394 MW. In addition, the solar average \bar{P}_s , is growing from 3177 MW to 4707 MW. The annual averages of the total demand \bar{P}_d are nearly staying the same and rise slightly from 58745 MW to 59085 MW. The increase of $P_w(t_i) + P_s(t_i)$ and the chart of $P_d(t_i)$ are shown in figure 1.

The years in the given observation period have different suitable weather conditions for the application of wind and solar power, which is expressed in the utilisation of the power plants. The increase of the output of renewable energies within the time period is due to the expansion of the production capacities.

¹The energy consumed by PHS is insignificant due the small amount of stored energy i.e. of 8 TWh in Germany 2015 [12].

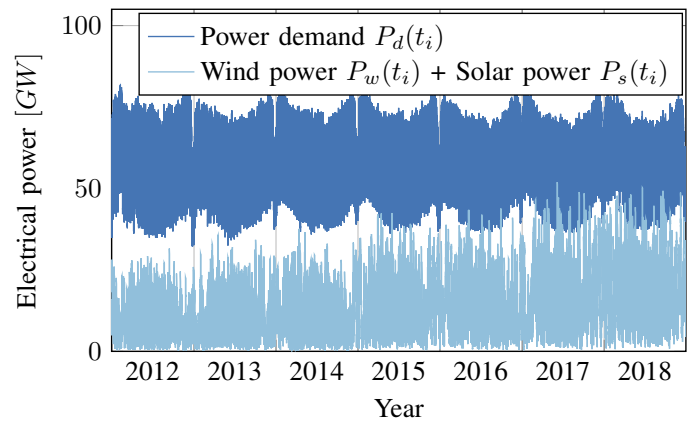


Fig. 1: The chart of the sum of $P_w(t_i)$ and $P_s(t_i)$ is showing that with the progress of time the renewable energy sources are rising and do approach the demand $P_d(t_i)$. In addition the figure shows the seasonal characteristics of power supply and demand.

Comparing the data series of the produced electrical powers $P_w(t_i)$ and $P_s(t_i)$ with the generation capacities $P_{wc}(t_i)$ and $P_{sc}(t_i)$, the effects of weather-related influences on electricity generation become visible. Wind energy always experiences a higher utilization than solar power. Wind power is more weather dependent and its utilisation fluctuates between 17% and 22%. Solar power is operated relatively evenly within a utilization between 10% and 11%.

Figure 2 shows the utilisation of wind power and solar from 2012 to 2018.

Figure 3 and Figure 4 present a closer look to 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 17.0% and in 2017 about 22.5%. Considering the same years the utilisation for solar power is nearly constant with 10.1% for 2014 and with 9.9% for 2017.

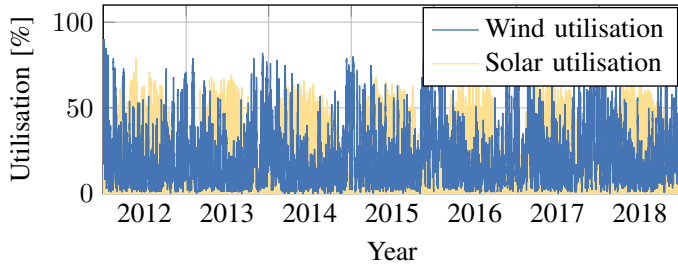


Fig. 2: Utilisation of installed wind power and solar power for the years 2012 to 2018.

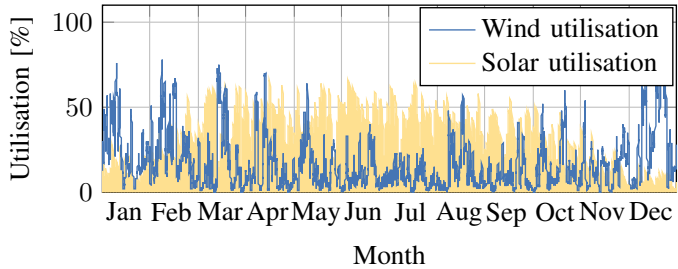


Fig. 3: Utilisation of installed wind power and solar power in 2014.

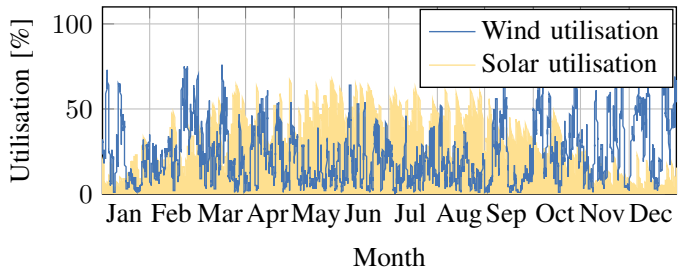


Fig. 4: Utilisation of installed wind power and solar power in 2017.

Table I is showing the annual average power outputs $\overline{P_w}$; $\overline{P_s}$, power capacities $\overline{P_{wc}}$; $\overline{P_{sc}}$ and the calculated utilisation factor of wind and solar for the years 2012 until 2018.

TABLE I
MEAN VALUES FOR CAPACITIES, OUTPUTS AND UTILISATIONS.

Year	$\overline{P_{wc}}$ [MW]	$\overline{P_w}$ [MW]	$\frac{\overline{P_w}}{\overline{P_{wc}}}$ [%]	$\overline{P_{sc}}$ [MW]	$\overline{P_s}$ [MW]	$\frac{\overline{P_s}}{\overline{P_{sc}}}$ [%]
2012	27737	5221	18.9	29324	3175	10.9
2013	30352	5388	17.7	34480	3388	9.8
2014	34333	5839	17.0	36961	3728	10.1
2015	40353	8843	21.9	38411	3985	10.4
2016	45928	8767	19.1	39649	3935	9.9
2017	52010	11720	22.5	41366	4096	9.9
2018	57205	12394	21.7	43481	4707	10.8

In the year 2012 the combination of wind and solar power had a share of 14.3% roughly to the total load and grew until the end of 2018 to roughly 28.9% [13].

III. METHODOLOGY OF MODELING STORAGE SYSTEMS

The generation of electrical power includes the increase in generation capacity during the period considered. For the development of a storage model with subdivisions into different storage classes, it is useful to freeze this growth of the capacities and to assume that the generation park remains unchanged.

For this purpose, the static generation capacities $\overline{P_{wc}}$; $\overline{P_{sc}}$ are calculated, which are defined as the 7 year average of the capacities in the period under consideration between 2012 and 2018 by using the 61368 hourly data values.

$$\overline{P_{wc}} = \frac{\sum_{i=1}^{61368} P_{wc}(t_i)}{61368} = 41128 \text{ MW} \quad (1)$$

$$\overline{P_{sc}} = \frac{\sum_{i=1}^{61368} P_{sc}(t_i)}{61368} = 37665 \text{ MW} \quad (2)$$

The calculated values of $\overline{P_{wc}}$; $\overline{P_{sc}}$ show that the 7-year average of installed generation capacity is approximately equal to the 2015 level (See table I). Thus, the power provided correlates directly with the existing weather situations from which the fluctuations in renewable electricity production originate. Using $\overline{P_{wc}}$ and $\overline{P_{sc}}$ simplifies the modeling so that no expansion of storage facilities in line with the power plant park has to be taken into account. By using the averaged generation capacities, the scaled produced electrical power of wind $P'_w(t_i)$ and solar $P'_s(t_i)$ can now be calculated, which are defined as follows.

$$P'_w(t_i) = \frac{P_w(t_i)}{P_{wc}(t_i)} \cdot \overline{P_{wc}} \quad (3)$$

$$P'_s(t_i) = \frac{P_s(t_i)}{P_{sc}(t_i)} \cdot \overline{P_{sc}} \quad (4)$$

These scaled data series are the basis of the storage modeling. Founded on the given values, the renewable energy sources are not sufficient to fully guarantee the supply of electricity. In order to represent a complete energy supply from renewable energy sources, the factor m is introduced by which the scaled produced electrical power values $P'_w(t_i)$; $P'_s(t_i)$ are multiplied, initially assuming unlimited storage capacity. The factor m is determined with an interactive calculation procedure so that at the end of the period the same amount of stored energy is available as at the beginning. The charging process of the

storage park is thus directly scalable via m and also serves to compensate for the existing losses of the respective storage classes and the influences of the charge limitation. On the basis of the data, $P'_w(t_i)$ and $P'_s(t_i)$ have to be multiplied by $m = 6.15$ to completely cover the existing demand in the considered period. For all further calculations this state is frozen and defined as a normalized initial situation with $\underline{m}_n = 1$, where \underline{P}_{wc} would have a size of 253000 MW and \underline{P}_{sc} would have a size of 232000 MW. In figure 7 the charts of the total amount of stored energy E_{sum} show the influence of m by rising it up from $m = 1$ to $m = 6.15$.

From a technical and economical point of view, it makes little sense to use a single technology to store energy, as the available principles have their individual advantages and disadvantages. A detailed overview of the available technologies can be found for example in [14]. For this reason, five storage classes are introduced, which differ in capacity and efficiency and are ordered in ascending order of size. Exemplary storage technologies were used, which seem suitable from our point of view. In addition, it should be noted that a single storage class is not to be understood as a stand-alone system, but as the sum of the available capacities in Germany.

For the modeling of the storage park the energy capacities $C_1 \dots C_5$ and their sum C_{sum} , as well as the corresponding efficiencies $\eta_1 \dots \eta_5$ are introduced. The capacities of the storage classes $C_1 \dots C_4$ are determined by using geometrical division to each other and uses a quotient of the consecutive elements of $q = 5$.

The maximum discharge volume that can be achieved within an hour based on the given consumption data $P_d(t_i)$ is 78513 MWh. The smallest storage class should be able to serve this hourly value and is therefore set to $C_1 = 90000$ MWh, including a supplement of 11487 MWh.

Class 1 could be represented e.g. by an lithium battery storage device because the very fast reaction time allows energy to be absorbed and released almost immediately. In addition, it would be conceivable to cover functions for the primary reserve with this method as well. Class 2 consists of sodium batteries and pumped-storage power plants in order to be able to offer a sufficiently fast activation in combination with a sufficient storage volume. Class 3 could be represented in the form of heat accumulators, since here already a larger storage volume is necessary and the control speed is lower compared to the preceding classes. Class 4 has the characteristics of power-to-hydrogen technologies and is suitable for medium to long-term storage intervals. The large possible volume is the reason for the choice at this point as well.

For storage class 5, the power-to-methane principle is envisaged in order to be able to map very long storage intervals with maximum volumes. In each model calculation, C_5 is determined in such a way that C_{sum} is sufficiently large to exclude a supply bottleneck. Based on the maximum required storage capacity C_{sum} , the storage classes $C_1 - C_5$ can be dimensioned as follows.

$$C_{sum} = \sum_{i=1}^4 C_1 \cdot q^{i-1} + C_5$$

$$= C_1 + C_1 \cdot q + C_1 \cdot q^2 + C_1 \cdot q^3 + C_5 \quad (5)$$

TABLE II
THE TECHNOLOGIES AND EFFICIENCIES ARE TAKEN FROM [14].

Class	Technology	Efficiency (η)	Capacity (C) [GWh]
1	Lithium battery	0.95	90
2	Sodium battery and PHS	0.80	450
3	Heat accumulators	0.60	2250
4	Power-to-hydrogen*	0.40	11250
5	Power-to-methane*	0.30	variable**

* With $\eta_{el} = 0.6$ and a compression to 80 bar.

** The capacity of storage class 5 is determined for each calculation.

The technologies, capacities and efficiencies are listed in table II. The developed calculation model shows, how the storage park would be controlled by using currently available technologies. In how far it is economically efficient to use the storage systems in the described way is not examined.

Another parameter for the modeling is the initial filling level of the storage E_{start} . This is selected so that in combination with $m_n = 1$ there is no supply bottleneck at the time of the lowest storage level. It is assumed that at the beginning of the calculation all storage devices are filled to 100%. If there is an energy surplus above this maximum filling level, it is not transferred to the storage system and can therefore be considered a loss. These conditions occur exclusively in the year 2012, which is not affected by unfavourable weather conditions.

The modeling is set up in such a way that at the beginning of a charging or discharging process the smallest available storage class with free capacity is first triggered. If the capacity limits are reached, the system switches to the next larger class during charging and discharging. This procedure means that the smallest storage class 1 carries out the most frequently charging and discharging processes, the largest class 5 the least. For this purpose, the following definition can be made for charging and discharging of each class where the efficiencies $\eta_1 \dots \eta_5$ are taken into account in the discharging processes:

if $\Delta E(t) > 0$ then

$$\begin{cases} \text{if } E_n(t) + \Delta E(t) \leq C_n \text{ then } E_n(t) + \Delta E(t) \\ \text{if } E_n(t) + \Delta E(t) > C_n \text{ then } E_{n+1}(t) + \Delta E(t) \end{cases} \quad (6)$$

if $\Delta E(t) < 0$ then

$$\begin{cases} \text{if } E_n(t) + \frac{\Delta E(t)}{\eta_n} \geq 0 \text{ then } E_n(t) + \frac{\Delta E(t)}{\eta_n} \\ \text{if } E_n(t) + \frac{\Delta E(t)}{\eta_n} < 0 \text{ then } E_{n-1}(t) + \frac{\Delta E(t)}{\eta_{n-1}} \end{cases} \quad (7)$$

$$E_1 \geq 0; E_2 \geq 0; E_3 \geq 0; E_4 \geq 0; E_5 \geq 0;$$

$$E_1 \leq C_1; E_2 \leq C_2; E_3 \leq C_3; E_4 \leq C_4; E_5 \leq C_5$$

Multiplying the generation capacities by m_n can result in very high load powers of more than 200 GW for the storage park. It seems rather unrealistic that such high load powers can be handled by the currently available storage technologies. Therefore, a conservative assumption is made and the maximum charging power is equalised to the maximum power demand during the observed period and limited to 80 GW. Any power production in excess of this is not stored and is considered a loss.

IV. RESULTS

A. $m_n = 1$ without losses, without charge limitation

Assuming a lossless storage park without limitation of the charging power of 80000 MW, the storage requirement is $C_{sum} = 31.3 \text{ TWh}$. The filling level curve of E_{sum} is shown in Figure 5.

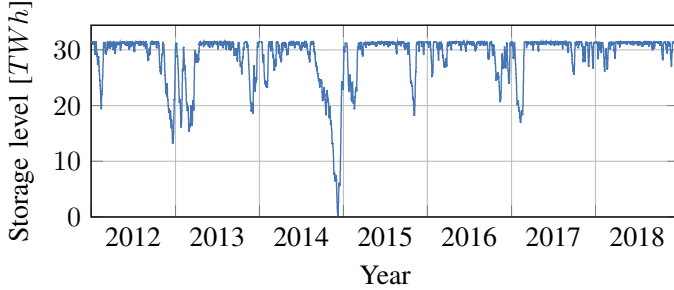


Fig. 5: Level history of all storages E_{sum} with a multiplication factor of $m_n = 1$.

B. $m_n = 1$ with losses, without charge limitation

By taking into account the efficiencies of the storage classes $\eta_1 - \eta_5$ at the discharging process, the storage requirement increases to $C_{sum} = 201.5 \text{ TWh}$. The level curve E_{sum} is shown in Figure 6.

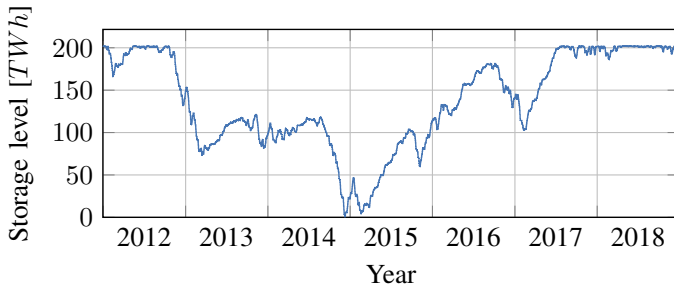


Fig. 6: Level history of all storages E_{sum} with a multiplication factor of $m_n = 1$ including the consideration of different efficiencies $\eta_1 - \eta_5$ when discharging the storages.

C. $m_n = 1$ with losses, with charge limitation

In a scenario with a charge limitation of 80 GW and taking into account the respective efficiencies, a storage requirement of $C_{sum} = 263.6 \text{ TWh}$ would be required by using a multiplication of $m = 6.15$. Figure 7 shows the charts of E_{sum} . The filling level curves for the individual storage classes are shown in the charts in figure 9. The curves show that the smallest storage class 1 is accessed most frequently and the largest storage class 5 is driven least often. The initiation for charging occurs more frequently than for discharging, which is particularly noticeable for storage class 1 and is shown with a ratio of approx. 1.9 : 1. If the total volume charged is divided by the storage capacity, the number of complete utilization cycles is obtained. At this point it is evident that storage class 1 absorbs a large part of the volatility with 136.1 complete cycles in one year. It is notable that storage class 5 only goes through less than 0.3 complete cycles in one year. The individual charging and discharging activities as well as the complete cycles can be seen in figure 8.

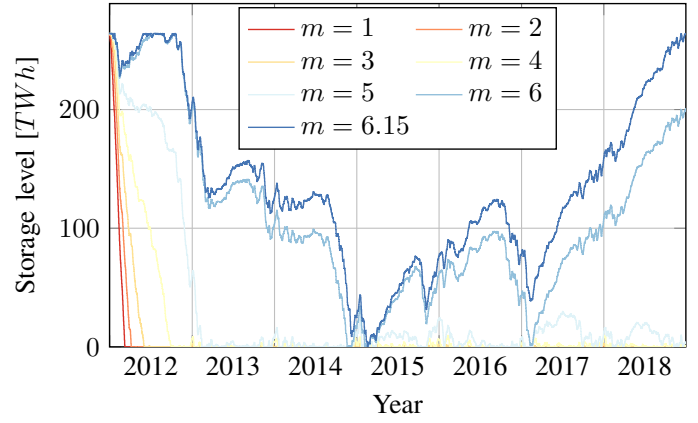


Fig. 7: History of the sum of all storage levels E_{sum} with a stepwise increase from $m = 1$ to $m = 6.15$ including the consideration of efficiencies during the discharge processes of the storage park.

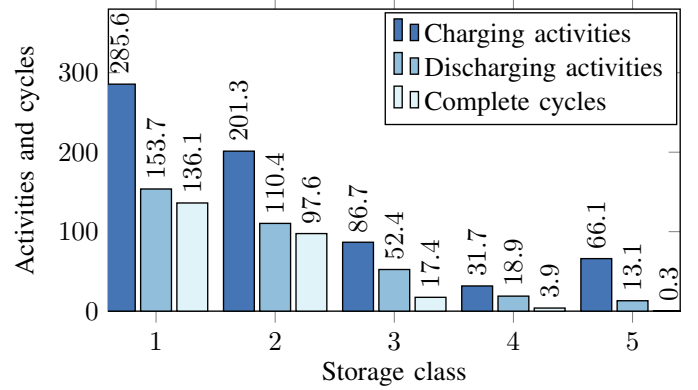


Fig. 8: Overview of the annual loading and unloading activities, as well as the number of complete storage cycles of the storage classes per year.

D. Parameter study for $m_n = 1$ to 2.5

Based on the model calculation in chapter IV-C a parameter study for m_n in a range from 1 to 2.5 was carried out. The increase of the generation capacity results in a reduction of the required storage capacities. For the largest storage class 5 since the capacities of the remaining storage classes are static. Figure 10 shows the development of the required storage capacity C_{sum} and C_5 with a stepwise increase of the generation capacities. The small visible discontinuities of the calculation points result from the different control sequences of the storage classes. In example, an energy portion ΔE which can be covered by a storage class in one configuration would have to be covered by the next larger class due to the increase of m_n . These discontinuities have only a marginal influence on the calculation result and can be neglected. The curves of C_{sum} and C_5 in figure 10 show a multi linear decay which arises from the reduction of the negative peaks of E_{sum} which is explained exemplary in figure 11. Whenever a gradual growth of m_n increases the available generation capacity in such a dimension that the characteristic level chart is changed, a transition from one linearity to the next occurs.

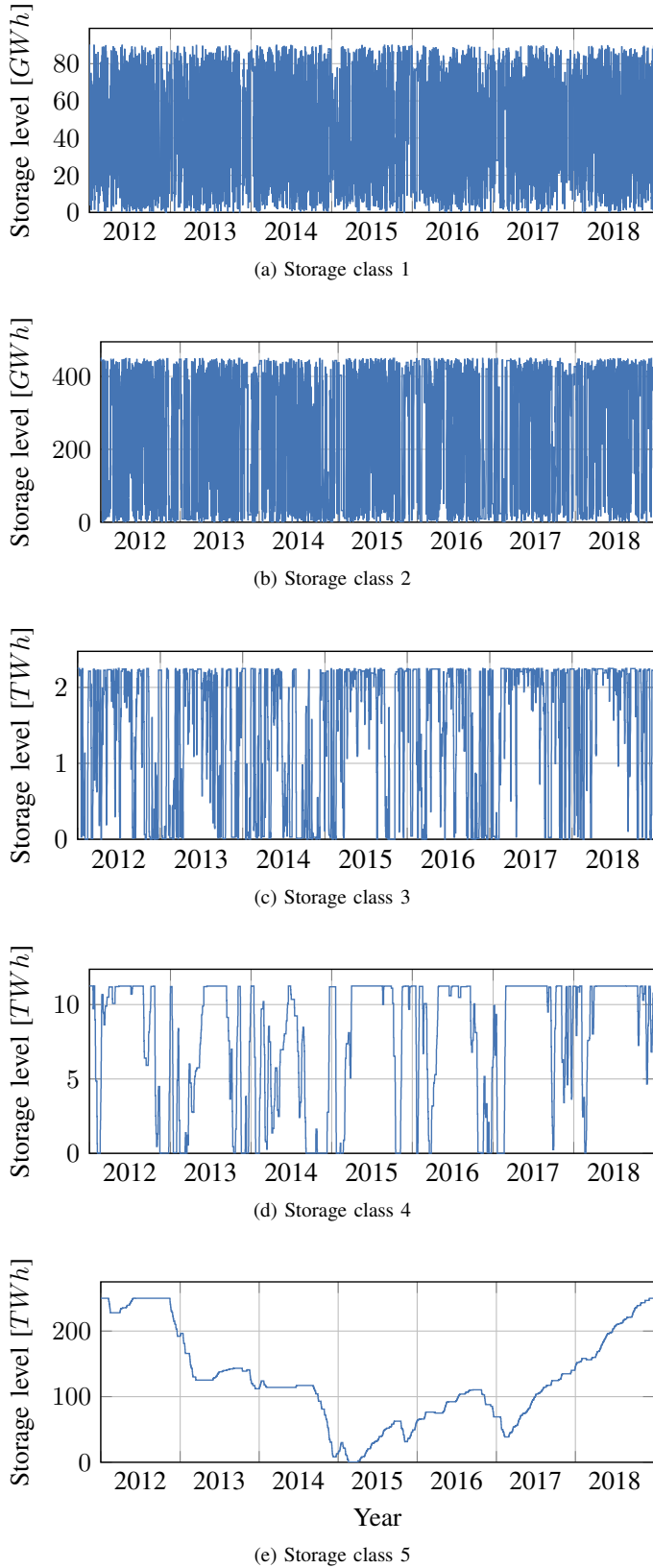


Fig. 9: Filling level curves of the storage classes 1-5.

V. DISCUSSION

A. $m_n = 1$

The results of the model calculations show that without taking efficiencies into account and without charge limitation,

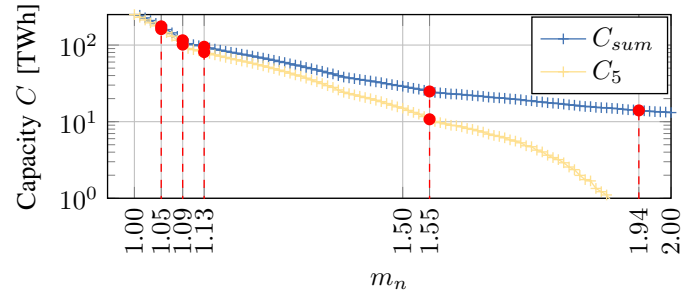


Fig. 10: The Charts of C_{sum} and C_5 show a multi linear character. The red lines are showing the largest switching point between several linear changes. The chart of E_5 is touching the zero line about at $m_n = 1.94$. From this point on class 5 is not needed any further.

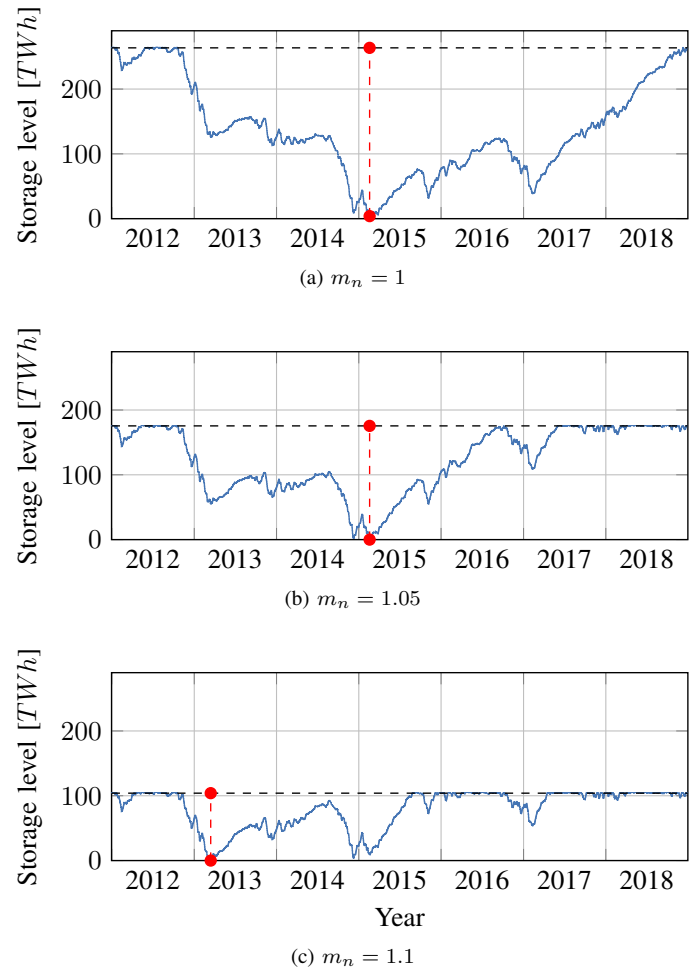


Fig. 11: The figures shows an example of the behaviour of the filling level curve with the multipliers of $m_n = 1$; 1.05; 1.1. The vertical line is representing the size and the time spot of the largest storage capacity demand.

a storage capacity of $C_{sum} = 31.3 \text{ TWh}$ would be sufficient for an electricity supply entirely from wind and solar power, as long as the generation capacities were sufficiently available and without limitations of the transmission grid. By taking into account the efficiencies for the storage facilities, the demand increases to $C_{sum} = 201.5 \text{ TWh}$ and including the charge

limitation of 80000 MW to $C_{sum} = 263.6 TWh$. This enormous storage requirement is generated not only by taking into account the efficiencies and the charge limitation, but also results from the windless years 2013 and 2014, after which the deepest point of the storage level is reached. From the data used, an average daily electrical energy demand of 1.41 TWh is calculated over the years 2012 to 2018. On this basis, table III shows how many daily charges would result from the calculated storage capacities. The curves of C_{sum} in figure

TABLE III
SUMMARY OF THE STORAGE CAPACITY REQUIRED AND THE RESULTING
NUMBER OF DAILY CHARGES.

Class	Calculation case	C_5 [TWh]	C_{sum} [TWh]	Daily charges
1	Without efficiencies, without charge lim.	17.2	31.3	22.2
2	With efficiencies, without charge lim.	187.6	201.5	142.9
3	With efficiencies, charge lim.	249.6	263.6	187

Here the influences of the efficiency and the charge limitation are shown. In particular, it can be seen that storage class 5 always has the largest share of the storage park.

7 show how sensitive the storage requirement is dependent on every weather situation and are of considerable importance, especially for very long-term, seasonal storage models.

B. Parameter study for $m_n = 1$ to 2.5

In principle, an increase in generation capacities and the associated reduction in storage capacities always leads to an earlier time at which the lowest storage level is reached. By discussing the curve of C_{sum} in figure 10 up to $m_n = 1.05$ there is a linear decrease of the required storage capacity and the time point of the negative peak remains unchanged. At $m_n = 1.06$ the first small bend in the curve becomes noticeable and the time of the lowest storage level shifts from the beginning 2015 to the end 2014. With a further increase of the multiplier to $m_n = 1.1$ the curve is changed in a way that the time of the lowest level moves from the end 2014 to the beginning of 2013.

Within this range the curves of C_{sum} and C_5 show the strongest decrease of the required storage capacity. This is mainly caused due to the fact that the supply bottleneck from the years 2013 and 2014 is reduced by the increasing generation capacities. Once, this shows how strongly the influence of different weather conditions affects the required storage capacities. Second, it is shown that a slight overcapacity of electricity generation of about 9% from m to m_n leads to a strong reduction of the storage volume from 263.6 TWh to 115.4 TWh which, especially is a compensation for the years with low power generation.

From $m_n = 1.09$ on the influence from the years with low production is already strongly reduced. By further increasing the generation capacities, the storage requirement can be reduced to about 24.8 TWh at $m_n = 1.55$. Thus, a further increase in generation capacity will lead to a further reduction in storage requirements, but the associated effects are smaller. In the range of $1.94 < m_n$ the electrical overproduction is already so large that the largest storage class C_5 is not

addressed and is practically no longer needed. This is shown by the curve of C_5 in figure 10. The calculations were performed up to a multiplication factor of $m_n = 2.5$, where the storage requirements are about 8.1 TWh.

VI. CONCLUSION

The study examines how much storage capacity is required for a completely renewable power supply from wind and solar energy. As input data the hourly recorded generation and capacity values from the years 2012 to 2018 are used. These are scaled up by the multiplication factors m and m_n , which is leading to a complete coverage of the electricity consumption. For the simulation a calculation model with 5 storage classes was created, which uses a sequential triggering control including the individual efficiencies of the storage technologies. Of particular importance are the characteristics of the comparatively windless years 2013 and 2014 which lead to a longer production deficit and therefore require a long-term storage of energy.

Based on the data used, the generation capacities would have to be scaled up at least by a factor of $m = 6.15$ to have the same amount of energy in the beginning and in the end in the storage park, by which the normed multiplication factor $m_n = 1$ is defined. This is correlating to 231.6 GW installed capacity in the wind power sector, which would be 5.2 times the installed generation capacity at the end of the year 2018. For solar power, this would correlate to an installed capacity of 252.9 GW and would be 4.3 times the installed capacity at the end of the year compared to 2018.

With this capacities the storage park would result in an enormous total storage volume of approx. 263.6 TWh which is equivalent to about 187 daily charges of the German electricity demand. It has been shown that the storage requirement can be reduced by providing additional generation capacities within the calculations. In table IV, the reduction of the necessary storage park size is shown with the increase of the generation capacities for selected factors m_n . An interesting aspect of the

TABLE IV
LIST OF THE MULTIPLICATION FACTORS m_n , m AND THE STORAGE
CAPACITIES C_5 AND C_{sum} .

m_n	m	C_5 [TWh]	C_{sum} [TWh]	Factor to wind 2018*	Factor to solar 2018*
1.00	6.15	249.6	263.6	4.3	5.2
1.05	6.46	161.5	175.5	4.5	5.4
1.09	6.70	101.4	115.4	4.7	5.6
1.13	6.95	81.0	95.0	4.9	5.8
1.55	9.53	10.7	24.8	6.7	8.0
1.94	11.93	0	14.0	8.3	10.0
2.37	14.58	0	8.7	10.2	12.2
2.50	15.38	0	8.1	10.7	12.9

* In relation to the end of 2018.

The shown values are correlating to figure 10. In addition, the ratios in relation to the installed capacities from 2018 are visible.

research shows that the largest storage class 5, which is a long-term seasonal storage, has by far the largest storage capacity, but only fulfills 0.3 load cycles in one year. In view of the high storage costs that are likely to be incurred by the construction of class 5 facilities, alternatives should be considered. For example, the storage class 5 could be replaced by natural gas power plants that are switched on when needed. According

to the calculated operating profile for the class, this option would be applicable to cover seasonal supply shortages. With a CO₂ output of about 0.2 kg/kWh, natural gas power plants have a comparatively low emission value [15].

In the case of regenerative generation capacities without overproduction and therefore $m_n = 1$, the replacement of the storage class 5 by natural gas power plants would thus cause annual CO₂ emissions of about 12.6 million tonnes. Compared to 866 million tons of CO₂ emitted in Germany in 2018, this is a relatively small amount [16]. This could be a cost-effective alternative even if it is a fossil fuel source and greenhouse gas emissions remain at a comparatively low level.

From our point of view, further investigations should determine the ideal balance between a sensible overcapacity of renewable energy sources and the associated storage requirements, taking into account the specific cost factors. These studies should cover periods of several years and also include years of low production, as these have a significant impact on the calculations. In further steps, investigations should be carried out to find out how the high storage requirement can be reduced through the use of appropriate alternative energy sources. The investigations carried out indicate a considerable reduction potential through a demand-based addition of thermal power plants.

VII. ABBREVIATIONS

$P_d(t_i)$	Demand of electrical power (hourly value)	[MW]
$\overline{P_d}$	Annual average of power demand	[MW]
$P_w(t_i)$	Produced electrical wind power (hourly value)	[MW]
$P_s(t_i)$	Produced electrical solar power (hourly value)	[MW]
$\overline{P_w}$	Annual average of wind power	[MW]
$\overline{P_s}$	Annual average of solar power	[MW]
$P_{wc}(t_i)$	Installed wind power capacity (hourly value)	[MW]
$P_{sc}(t_i)$	Installed solar power capacity (hourly value)	[MW]
$\overline{P_{wc}}$	Annual average of installed wind power	[MW]
$\overline{P_{sc}}$	Annual average of installed solar power	[MW]
$\overline{\overline{P_{wc}}}$	7 year average of installed wind power	[MW]
$\overline{\overline{P_{sc}}}$	7 year average of installed solar power	[MW]
t_i	hourly time increment	[h]
$P'_w(t_i)$	Scaled produced wind power (hourly value)	[MW]
$P'_s(t_i)$	Scaled produced solar power (hourly value)	[MW]
m	Factor for multiplying the el. power	[-]
m_n	Normalized factor for multiplying el. power	[-]
E_{start}	Stored energy at the beginning	[MWh]
C_{sum}	Total energy storage capacity	[MWh]
$C_1 - C_5$	Capacities of the storage classes	[MWh]
ΔE	Hourly surplus or demand	[MWh]
E_{sum}	Total energy storage level	[MWh]
$E_1 - E_5$	Filling level of the energy storage	[MWh]
$\eta_1 - \eta_5$	Efficiencies of the storage classes	[-]
q	Quotient of successive segments	[-]
BNetzA	German Federal Network Agency	
TSO	Transmission system operator	
PHS	Pumped hydro storage	

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