Determination of long-term storage capacities for an energy system completely based on renewable Energies in Germany

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***Abstract*— The simulation of long-term storage in a renewable energy system using consumption profiles is a promising approach to meet the challenges of fluctuating energy generation. In this study, different energy system scenarios are modelled using developed producer and private consumer profiles and investigated the required storage capacities. In a scenario with generation profiles of 2045, the longest dark doldrum in the analyzed period of 7 years has been calculated to be 123 days. The storage capacity of a long-term storage system required for this, amounts to about 10 % of the total annual consumption of private households. The provision of this capacity requires a corresponding expansion of renewable energies. The results show that long-term storage can help to compensate for dark doldrums in the energy system and ensure a more stable energy supply. In the next step, an implementation in a Python script would be conceivable. Furthermore, additional load profiles in the sectors agriculture, trade and commerce as well as industry could be generated and used to complete the data basis.**

1 INTRODUCTION

To fight climate change, it is necessary to reduce greenhouse gas emissions to zero. Renewable energies are a key technology for this undertaking and must substitute fossil energy sources. In contrast to fossil energy sources, the energy supply from renewable energies can be difficult to control since those are heavily reliant on the amount of available wind and sunlight. In cases where sunlight and wind are not as readily available, a different source of energy must be considered. Extreme cases where a low amount of energy from sunlight or wind is available are named dark doldrums.

The term "dark doldrum" is not clearly defined. Therefore, in this paper, the term or phenomenon is described as follows.

A dark doldrum occurs when the energy consumption of an energy system exceeds the energy production for a certain period due to a lack of primary energy utilisation from the sun and/or wind.

The volatile nature of renewable energies makes energy storage capacities necessary. Especially in times of dark doldrums. Energy that cannot be provided through PV-modules or wind turbines, must be delivered by means of energy storages. In this Paper needed storage capacities in times of dark doldrums within Germany are determined. It focuses on the energy demand for private heating purposes and private electric vehicles (EV). An adjusted definition of dark doldrums will also be further investigated. Since no energy supply from sunlight and wind is very rare, the terminology of dark doldrum must be adapted, because even 25% of nominal energy supply for example, can be problematic and maybe considered a dark doldrum.

2 APPROACH AND METHODOLOGY

The approach used is the balancing of energy supply and demand, considering the energy system in Germany is completely based on renewable energy sources and greenhouse gas emission neutral.

The Energy demand is divided into different sectors as follows:

- Industry
- Trade and commerce
- Private electric vehicles
- Private heating
- Private Electricity
- Agriculture
- Others

Information about the energy demand of the private sectors (i.e. e-mobility and private heating) are determined with a combination of data from literature, the LoadProfileGenerator (LPG) [1] and a charge profile generator for electric mobility (CPGeM) [2], which will further be discussed in later chapters. Generated load profiles are then normalized to scale them for different scenarios and purposes.

The energy supply is divided into different sources as follows:

- PV
- Wind onshore
- Wind offshore
- Bioenergy
- Waterenergy

Corresponding data is derived from the Bundesnetzagentur in Germany [3] and the Fraunhofer Institut [4]. Data of the years 2015 – 2021 is used. With the generated supply and demand of energy within Germany, the residual load can be calculated, and storage capacities determined. To clearly dark doldrums, energy supply data and the generated load profiles are compared.

2.1 Loadprofilegenerator

The LPG is a modeling tool, that can be used to generate different kinds of load profiles i.e., heat and electricity, for households in Germany. With Information about the weather, stored behavioral studies and other options that can be defined, like the type of household or the relevant time period, synthetic household load profiles are generated in json or csv files [1].

2.2 Charge Profile Generator for electric Mobility

The CPGeM consists of two python scripts which generate synthetic load profiles, of the charging process of EV. Household load profiles from the LPG are used for this tool. Two files are necessary: The electric household load profile and thoughts of household members, which are csv files. The thoughts determine which action is performed to a certain time of the day. Different thoughts own different values and forms of energy. Input parameters i.e., wallbox power or the location can be set in an Excel file, which is considered by the Python scripts. The first script of the CPGeM simulates the mobility behavior, the second creates the loading profiles, with the mobility simulation and data form the LPG. Output of this tool are different plots, one of these plots is a loading profile of EV [2].

In addition to data used from the LPG, other information is embedded in the Python script. EV from different manufacturers, as well as wallboxes and their load behavior are embedded. Necessary data for the simulation of mobility behavior are taken from a social study, which investigated the influence of different parameters like age or residence on the mobility respectively the distance that has to be travelled in Germany [5].

2.3 Demographic

To determine which load profiles should be generated, the demographic within Germany was analyzed. A study by an authority from Germany (Statistisches Bundesamt) is used [6]. This study shows, which percentile of the German population in which household configuration lives i.e., one person, two persons etc. and if employment is present. Data for the community size of the Population is also available. The location data was divided into four categories (metropolis, large town, small town, village), to make it compatible with the CPGeM. The proportions of household configuration, community size as well as employment are then multiplied, to determine the share of people with specific household configurations in specific areas. The individual shares are shown in Figure 1-3.

The share of unemployed persons includes pensioners, which makes this share look somewhat larger than it is.

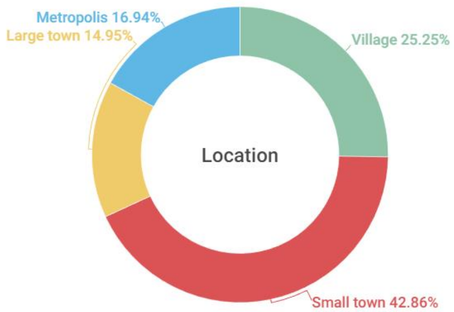

Figure 1: Shares of Residence

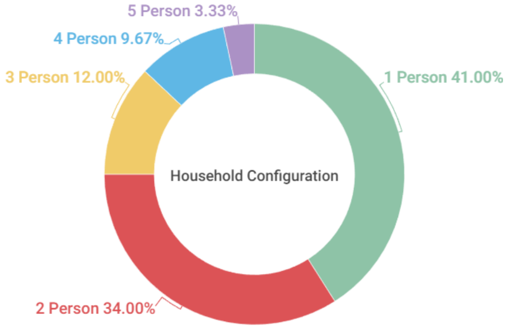

Figure 2: Shares of household configuration

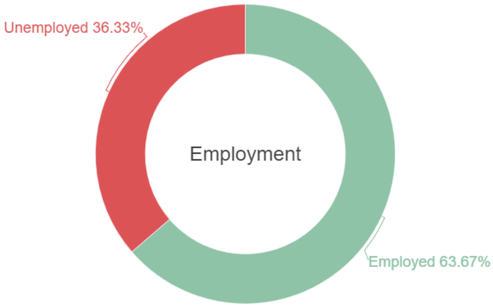

Figure 3: Employment rate

The data about household configuration is used to determine which load profiles must be generated with the LPG. The location specific household configuration data is used to weigh the finished load profiles that have been generated by the CPGeM, according to their share of the total population.

2.4 E-Mobility load profiles

Household load profiles are first created with the LPG. The year that is simulated is 2021, the location that is defined is Berlin. The thoughts file of the LPG consists of values for minutes, which is why the CPGeM also works with / calculates minute values. The performance of the CPGeM-tool allows to only simulate one month at a time, which is why, for the defined households, every month must be simulated separately in the LPG. These are then used to generate load profiles for EV.

To work with the CPGeM tool, the code is adjusted slightly. Outputs of this Python script are pandas-bokeh plots and different csv files, but files with load profiles, are not generated. The code has been adjusted in a way that it creates these missing load profiles as csv files.

The input parameters of the CPGeM are set to default with all simulations. The only exception for this is the parameter for the resident location. This parameter has been changed to metropolis, large town, small town, village for the corresponding load profiles.

The generated monthly load profiles with minute values are then linked to yearly load profiles and the values are transformed into hourly values. The load profiles are then multiplied with the corresponding factors, according to the demographic, that is covered. These profiles are then added to generate a total load profile for e-mobility in Germany.

2.5 Household load profiles

The load profiles for the remaining household consumption are generated using the LPG. Data for demographic distribution was used to generate the correct load profiles. These were scaled using the data on the proportion of the total population, similar to the load profiles for e-mobility.

2.6 Heating load profiles

The load profiles for the electricity to cover the heat demand of the individual households refer to a 100% use of heat pumps. The generation of the heat load profiles is based on the "Guideline - Processing of Standard Gas Load Profiles" by BDEW from 2016 [7].

The generation of the load profiles is based on weather data from the Fraunhofer-Institut for solar energysystems [8]. An hourly resolution of the temperature is used. A moving average is formed over the temperature, which is used to consider the heat capacities stored in the building.

The heat demand can be calculated with Formula 1.

Formula 1 - Heat Demand [7]

$$Q_{ZS} = KW * h(T_{Allo}) * F_{WT}$$

Formula 1 contains the customer value (KW) as well as the SigLinDe function $h(T_{Allo})$ and a weekday factor (F_{WT}). For the SigLinDe function, the allocation temperature is used here [7]. The customer value (KW) depends on the individual consumption of the customer. This is assigned via BDEW profiles. The allocation temperature describes the moving average temperature and is used as the basis for the SigLinDe function. The SigLinDe function is used to calculate the profile value $h(T_{Allo})$ and is described by a combination of sigmoid and linear function. [7]

Since the heat demand is to be covered by an air source heat pump, the outdoor temperature-dependent COP must be considered. For the simulation of the heat pumps, a flow temperature of 40°C and a return temperature of 60°C are assumed. [9]

The electricity demand of the households to cover the heat demand is calculated by dividing the hourly heat demand by the COP [7]. The COP according to Carnot is determined via the temperature difference between source and sink temperature. The Carnot efficiency is then multiplied by an average quality factor of 0.5 to obtain the temperature-dependent COP for the heat pump [9].

The generation of the heat load profiles is realised by adapting the LoadShape generator [10]. Since this Python tool does not store the same household data as the LoadProfile generator, the stored profile data was used. Here, 50 different person-related profiles were combined with the BDEW profiles for "multi-family houses" and "single-family houses". The demographic analysis results in a distribution of 17% single-family houses and 83% multi-family houses [11]. According to this distribution, 100 individual load profiles are combined and standardised into a standard load profile.

2.7 Energy supply data

For the energy supply, an hourly utilisation profile of the energy plants is calculated, which is given as a capacity factor. Data for the generated electricity in Germany is put into relation to installed nominal power of the plants to get a capacity factor. The data for the energy supply within Germany was derived from a study conducted by German authorities (Bundesnetzagentur) [3]. Data about installed nominal power of the plants are derived from the Fraunhofer Institute [4]. In both cases data from the years 2015 – 2021 were used. The data is stated as net power.

Only the power from renewable sources is considered. The current electricity mix is used, but the fossil shares are not taken into account. The output of renewable energies is scaled up accordingly. The methodology was conducted equal to a master’s thesis that was held at the university of applied sciences in cologne [12].

Energy that is being imported into Germany is not considered.

2.8 Standardization

In general, load profiles can be normalized in different ways. Normalization enables comparability and adaptation to the scenario under investigation. In this case, a percentage normalization is used. The percentage approach describes individual hourly consumption data in relation to the total profile consumption over a certain period. This results in a percentage value that can be multiplied by a new total consumption value and a new scale. In this way, consumption data can be scaled as desired.

In contrast to consumption data, the value of energy generation by photovoltaics or similar is represented by a capacity factor. This describes the percentage generation in relation to the installed nominal power in hourly values, an hourly generation profile is created.

2.9 Assembling – Residual load

The superposition of energy generation with the consumption profile leads to a residual load. For this purpose, the generation from renewable energies available at a certain point in time is subtracted from the corresponding demand. This results in either an overproduction or a deficit that must be covered by other energy sources.

3 EXCEL-TOOL STORAGE SIMULATION

The Excel-Tool developed is used to simulate dark doldrums and their effects on grid capacity in Germany. It enables the comparison of different generation and consumption scenarios and thus the simulation of a required long-term storage.

The Excel-Tool is based on renewable energy generation data from 2015 to 2021 in the form of a capacity factor. This enables a variably adjustable generation simulation.

On the consumption side, the generated load profiles for the electricity demand of heat pumps, electromobility and the remaining demand of private households are entered. It should be noted that the electricity demand of the heat pumps is based on the stored weather data and thus an individual demand profile is available for each year. In the area of electric mobility, the simulation is only possible for one year, so the demand profile is applied for each year.

The simulation of the demand of the remaining private households is only possible for the year 2021 in the load profile generator, here it is assumed that the demand changes only slightly over the years.

Annual profiles can be created from the generated generation and consumption profiles in combination with the installed nominal capacity or the electricity demand of the individual sectors. By overlaying these profiles, the hourly surplus or deficit of generated energy can be calculated, which is decisive for the storage simulation.

3.1 Storage facilities

In addition to the long-term storage, the Excel simulation also examines the effect of buffer storages. These are used to shift the loads generated by the consumers. A lithium-ion battery is used as an electrochemical buffer storage.

The lithium-ion battery is assumed to have a charging efficiency of 80% and a discharging efficiency of 86%. In addition, storage losses of 0.025% per year are considered. [13] Since the size of the buffer storage has a major influence on the long-term storage analysis, the buffer storage capacity can be variably adjusted.

In the analysis, the buffer storage is designed in such a way that a negative residual load first covers consumption and is then fed into the buffer storage until it has reached its maximum storage capacity. In the event of a positive residual load, the buffer storage is connected upstream of the long-term storage, and accordingly the buffer storage is discharged first.

3.2 Calculation Method

The main three calculations, that are performed in the created Excel-Tool are the dimensioning of the required long-term storage capacity, the illustration of the hourly state of charge (charging and discharging behavior) of the long-term storage as well as the determination of the dark doldrums that result out of a positive residual load and a lack of buffer storage capacity. The calculation of these three parameters is explained in the following chapter.

3.2.1 Long term storage capacity and state of charge

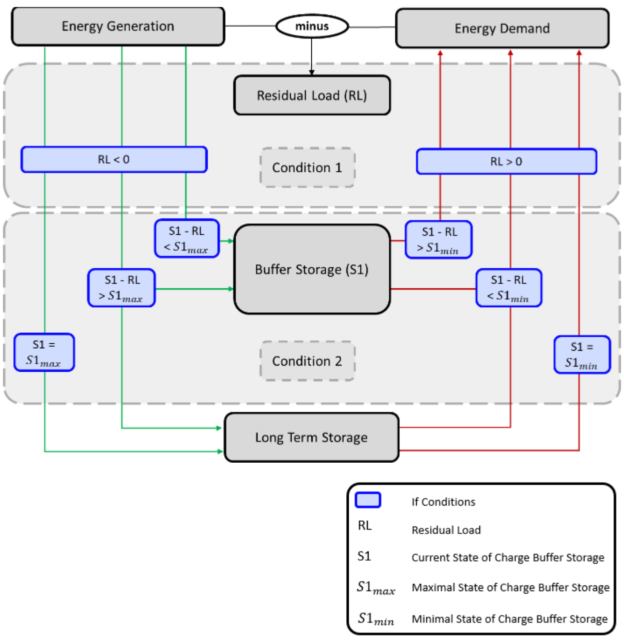

Figure 4 – Structure diagram of calculation

In the figure above the charging and discharging strategy of the grid storages, divided into buffer storages and long-term storages, is shown. As already briefly explained in the abstract above the charging strategy is now described in more detail. In the first place the energy generation is subtracted from the energy demand, which results in the residual load. The following process can be divided into two steps that check two conditions. The first condition is whether the residual load is negative or positive. The second condition checks the state of charge of the predefined buffer storage. The following table shows, the consequences for the charging and discharging behavior of the long-term storage in dependence of condition 1 and 2. In other words, it describes what figure 4 illustrates.

Table 1 – Calculation Scenarios Storage

Cond. 1	**Cond. 2**		**Buffer storage (S1)**	**Long Term Storage**
	Formula	**Description**		
RL < 0	S1 - RL < $S1_{max}$	The max. storage capacity of S1 is not reached	Charge	No charge/ discharge
	S1 - RL > $S1_{max}$	Max. storage capacity of S1 is reached and there is energy surplus left	Charge	Charge
	S1 = $S1_{max}$	The max. storage capacity of S1 is already reached	No charge/ discharge	Charge
RL > 0	S1 - RL > $S1_{min}$	Min. storage capacity of S1 is not reached	Discharge	No charge/ discharge
	S1 - RL < $S1_{min}$	Min. storage capacity of S1 is reached and there is energy demand left	Discharge	Discharge
	S1 = $S1_{min}$	Min. storage capacity of S1 is already reached	No charge/ discharge	Discharge

With this method it is possible to use the tool to determine how big the long-term storage capacity must be, to store the energy, that is required to cover the demand, that cannot be covered by current energy generation. Therefore, the hourly required long-term storage capacity is summed up under the conditions for the charging/ discharging behavior of the long-term storage shown in table 1.

After the minimum storage capacity is calculated, the state of charge of the long-term storage is calculated automatically. Therefore, the hourly residual load is subtracted or added to the current state of charge of the long-term storage, also considering the conditions for the charging/ discharging behavior of the long-term storage as well as the state of charge of the buffer storage shown in table 1.

3.2.2 Dark doldrums

The information about the residual load and the state of charge of the buffer storage, as well as the long-term storage can now be used to analyze the event of "dark doldrums". The term "dark doldrum" is not clearly defined. Therefore, the description of the term or phenomenon used in the introduction will be used first.

The tool can be used to determine the length of a dark doldrum based on the previous definition. Therefore, the hourly values of the following conditions are checked:

1. RL > 0
2. SOC of S1 = $S1_{min}$

If both conditions are true, the hour is counted as a dark doldrum.

It must be noted that the storage capacity and state of charge analysis, as well as the dark doldrums analysis is based on electricity generation profiles that depend on weather data of the years 2015 to 2021. So, the calculations consider a period of seven years.

4 RESULTS

In the results chapter, the Excel-Tool created is used based on 4 scenarios and its results are evaluated. Scenarios for the years 2021 and 2045 are used. Different applications of storage are examined and what influence this has on the maximum capacity of the required long-term storage.

In an energy supply system based 100% on renewable energies, too little supply of photovoltaic and wind energy in the onshore and offshore areas would lead to a positive residual load and thus to the shutdown of various consumers or similar. The frequency and duration of dark doldrums is analyzed with the created Excel-Tool.

4.1 Parameters of Simulation

A simulation with different scenarios is necessary for the calculation of the required storage energies. Based on the "Szenariorahmen zum Netzentwicklungsplan Strom 2037 mit Ausblick 2045, Version 2023" of the German transmission system operators, four comparison scenarios are created [14]. The analysis is based on the installed capacities and the corresponding annual consumption figures shown in the study. The reference consumption data of the study " Szenariorahmen zum Netzentwicklungsplan Strom 2037 mit Ausblick 2045, Version 2023" are only available for the year 2018, but since this only describes the corresponding installed capacity of renewable energies for the year 2021, a scenario is formed from the consumption data of the year 2018 and the generation data of the year 2021. Since the consumption of private households and e-mobility does not correspond to the total demand, the nominal power is adjusted to the consumption. This results in two scenarios for the year 2021 and two scenarios for the year 2045. As an input parameter for all scenarios the buffer storage capacity was set at 57 GWh, which is based on Fraunhofer ISE, which state that until 2045 180 GWh of storage capacity will be needed. [15] The given number was multiplied by the relation of installed electricity generation to the annual electricity demand.

Table 2 shows the installed nominal capacities assumed for the year 2021. The electricity demand for heat consumption of private households in 2021 is 117.390 GWh, the other demand of private households is 11.610 GWh. Private electromobility is 1.000 GWh in the base year of the study. In total, this results in a consumption value of 130.000 GWh per year.

Columns 3 and 4 of table 2 show the installed nominal power adjusted for consumption.

Table 2 - Installed Capacity 2021 [14]

	Total Installed nominal power in 2021	SC 1-1 Installed nominal power in 2021 (consumption-adjusted)	SC 1-2 Installed nominal power in 2021 +30% (consumption-adjusted)
Consumption [GWh]	572.000	130.000	130.000
Wind Onshore [GW]	54,4	12,36	16,07
Wind offshore [GW]	7,8	1,77	2,30
Photovoltaics [GW]	53,7	12,20	15,87
Biomass [GW]	8,8	2,00	2,60
Hydropower [GW]	5,3	1,20	1,57

The electricity demand of private households (heat supply and other) and e-mobility have a share of 22,73% of the total energy demand. Accordingly, the total installed nominal power for the scenario of 1:1 coverage is reduced from 130 GW to 29,55 GW. For the 30% overproduction scenario, the installed nominal power is set at 38,41 GW.

Table 3 shows the installed capacity assumed for the year 2045 and the capacity adjusted to consumption. Due to the electrification of the transport sector, the study assumes a value of 111.100 GWh for private e-mobility. The private heating demand for the year 2045 is 148.603 GWh. The other demand of private households amounts to 14.697 GWh. The annual demand by these sectors is thus 274.400 GWh.

Table 3 - Installed Capacity 2045 [14]

	Total Installed nominal power in 2045	SC 2-1 Installed nominal power in 2045 (consumption-adjusted)	SC 2-2 Installed nominal power in 2045 +30% (consumption-adjusted)
Consumption [GWh]	1.128.200	274.400	274.400
Wind Onshore [GW]	150	36,48	47,43
Wind offshore [GW]	70,8	17,22	22,39
Photovoltaics [GW]	395	96,07	124,89
Biomass [GW]	2	0.49	0,63
Hydropower [GW]	5,3	1,29	1,68

The comparison of the demand for e-mobility and private households considered in the simulation with the total energy demand shows a ratio of 24,32%. Accordingly, the installed nominal powers are adjusted to the consumption as in table 2. This leads to a reduction in installed nominal power from 623.1 GW to 151.55 GW in the case of 1:1 coverage. The scenario with 30% overproduction requires an installed nominal power of 197.01 GW.

In the following chapters, the results are shown in detail by the example of SC 2-2, which is explained in the abstracts above.

4.2 Generation Profile

According to the installed nominal power per scenario, a generation profile results that is adjusted to the consumption in percentage terms. The generation profile of renewable energies according to scenario 2-2 is shown below.

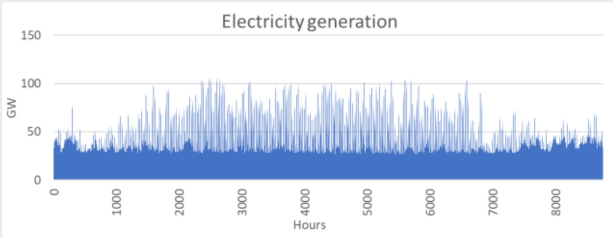

Figure 5 – Generating Profile RE 2045 SC 2-2

4.3 Consumption Profile

The standard load profile for Scenario 2-2 assumes an electricity demand for heat supply of 148.603 GWh and electricity consumption by e-mobility of 111.100 GWh. The other electricity demand of private households amounts to 14.697 GWh. The resulting consumption profile is shown in Figure 6. It can be seen, that the electrical energy consumption increases slightly in the winter because it is assumed, that the heat demand is covered by heat pumps, which run with electricity.

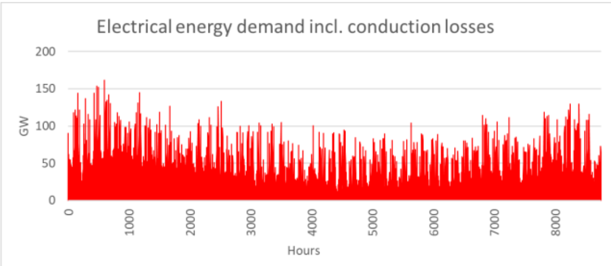

Figure 6 - Consumption Profile 2045

4.4 Residual load

The residual load results from the subtraction of the power generation from the power demand. For SC 2-2 the residual load is shown in figure 7. If the values for the residual load are above zero, it shows, that the current electricity demand is higher than the current electricity supply. Whereas a negative residual load shows a surplus in the electricity generation due to higher solar and / or wind power yields.

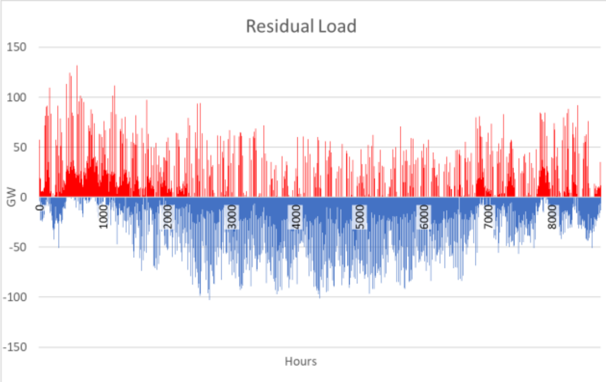

Figure 7 – Residual Load SZ 2-2

4.5 Storage Capacity

The minimum required long-term storage capacity has been calculated for three different technologies: lithium-ion accumulators, redox flow batteries and power to gas (hydrogen). The main difference between these technologies, that has been considered is the charging and discharging efficiency, which are summarized in table 4.

Table 4 – Storage Technologies [13]

Storage technology	Redox-Flow Battery	Lithium-Ion Accumulator	Power to Gas
Charging efficiency	89%	80%	78%
Discharging efficiency	95%	86%	65%

For the scenario 2-2 a required storage capacity for the Redox-Flow Technology of 34.725 GWh has been calculated. This amounts to around 10% of the annual electricity consumption in scenario 2-2 (274.400 GWh).

All results for the four different scenarios in the considered period of seven years are summarized in table 5.

Table 5 – Comparison Technology - Scenario

Storage techno-logy / Scenario	Redox-Flow Battery	Lithium-Ion Accumulator	Power to Gas
Scenario 1-1	366.739 GWh	427.681 GWh	600.228 GWh
Scenario 1-2	191.133 GWh	250.656 GWh	390.160 GWh
Scenario 2-1	83.436 GWh	147.898 GWh	369.441 GWh
Scenario 2-2	34.725 GWh	40.033 GWh	55.636 GWh

The charging/ discharging curve for seven years for the Redox-Flow technology in scenario 2-2 is shown in figure 8, whereas the light blue area shows the previously calculated long-term storage capacity, and the dark blue areas show the state of charge of the long-term storage.

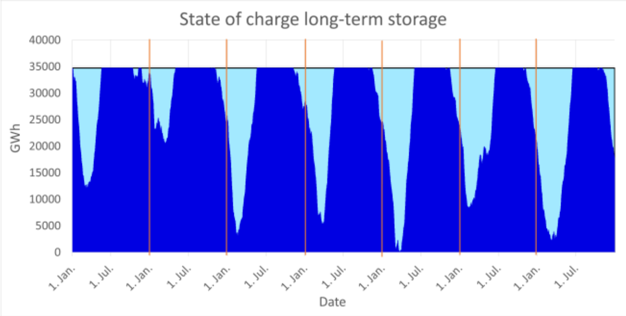

Figure 8 – State of Charge long-term storage SZ 2-2

Figure 9 shows the same charging/ discharging curve for only one year, in this case the last year of the figure above.

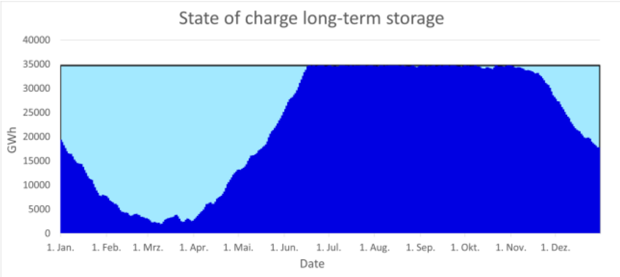

Figure 9 – Charging/Discharging long-term storage

It can be seen, that in some years the storage capacity is fully used during the winter months. Depending on the depth of discharge, it can take around two to three months to refill the long-term storage. The charging/ discharging behavior of the long-term storage is depended on the considered values for the installed power generation, the considered annual electricity demand as well as the size of the buffer storage.

4.6 Dark doldrums

The definition of a dark doldrum is given in chapter 3.2.2. For scenario 2-2 and Redox-Flow Technology the longest occurring dark doldrum during the analyzed seven years period is 139 hours (around 6 days). When using the created Excel-Tool, the duration of the dark doldrum does not change with the different storage technologies. This is because with the given definition in chapter 3.2.2 the residual load, which is the main parameter for the dark doldrum analysis, is not depended on the long-term storage technology. Table 6 shows the duration of longest dark doldrum for all calculated scenarios.

Table 6 – Duration Dark Doldrum

Scenario	Duration of dark doldrum
Scenario 1-1	1.438 h
Scenario 1-2	1.221 h
Scenario 2-1	320 h
Scenario 2-2	139 h

5 DISCUSSION

The simulation of long-term storage for future scenarios requires several assumptions, so that sources of error cannot be avoided. These are listed and discussed below.

5.1 CPGeM

According to the creator of this tool, it could provide even more accurate results. For the out-of-home activities, which are used for the simulation of the load profile, an average behaviour pattern is assumed, which is demographically unspecific.

Currently, the individual load profiles are weighted and then scaled up. Alternatively, it would be possible to generate more load profiles from the same households and add them together to get a more accurate result. This is because the CPGeM generates variables pseudo-randomly. With more load profiles, this effect would be more balanced [2].

5.2 Demographic

When generating the location-specific household load profiles, the current (2018) demographic distribution is used. Data that is determined with this demographic distribution are subsequently normalized. Scaling to, for example, the year 2045, therefore automatically has errors, as future demographic distributions will differ from the data from 2018.

The study by the Federal Statistical Office (Bundesnetzagentur) provides an estimate for the year 2040. This estimate states that there will be more households with two persons and single persons in the future [6]. However, this data is based on assumptions, and it is questionable to what extent the accuracy would increase by including this data.

It is also assumed that the household distribution and employment in cities is the same as in more rural areas, which is not the case. The factors already mentioned affect the accuracy of the load profiles for e-mobility and households.

5.3 E-mobility laod profiles

To generate load profiles some assumptions were made. Load profiles for EV are only conducted for private E-Mobility. Company cars are not considered by these calculations.

In addition it was assumed that every household has one car and one wallbox to charge. This fact may not lead to huge inaccuracies, since a household in Germany has on average 1,14 cars. But the distribution is heavily reliant on income, size and location of households (1,46 cars in more rural areas) [16].

Another assumption made is that all vehicles are fully electrified. Vehicles powered by hydrogen or e-fuels are not considered. The composition is not yet foreseeable and is presumably dependent on the expansion of the technologies at individual times. In which capacity transportation by means of public transportation will substitute EV is also to be determined.

Furthermore, it is assumed that there is a possibility to charge every vehicle. An expansion of the charging infrastructure is to be expected, in which way this will be implemented in apartment buildings is questionable, additional capacities may have to be provided by the expansion of public charging infrastructure.

5.4 Heating load profiles

The consumption profiles for heat demand are temperature dependent. Since the exact development of the temperature profiles cannot be predicted until 2045, the consumption profiles are generated from the weather data of the years 2015 to 2021. With rising ambient temperatures, the heat demand would decrease and thus also the amount of energy required.

In the area of heat supply, this simulation assumes that 100% of heat pumps will be used in Germany. It can be assumed that in the future it is highly likely that part of the heat will be provided via green hydrogen. In this case, the heat demand would remain the same, but the energy demand for heating with green hydrogen would have to be integrated into the consumption profile for heat. Assuming that the outdoor temperatures are not too low and the localities are well isolated, the energy demand for heat generation would increase, since the production of green hydrogen is associated with a higher energy input [17].

In general, the development of the technology cannot be predicted exactly, so that a precise forecast of the heat supply in 2045 is not possible.

5.5 Residual load

The residual load was calculated based on normed generation profiles of the years 2015 to 2021, whereas the normed demand profile for E-Mobility and other private consumption was simulated and created with data only based on the year 2021. Because of the huge data sizes, which emerged during the process of creating the normed demand profile based on simulated household profiles, it was decided to transfer the demand profiles onto the years 2015 to 2020. The resulting error is estimated to be small, as the total annual mileage of passenger cars will only increase by 0.08% from 2016 to 2020 [18].

Therefore, it is important to emphasise, that the Excel-Tool cannot be used to recreate the actual residual load from the years 2015 to 2021.

5.6 Long-term storage capacity and state of charge

As shown in chapter 4.6 the Excel-Tool offers the opportunity to calculate the long-term storage capacity that is needed, to cover the positive residual load, when the buffer storage capacities are not sufficient. It is important to remind, that all results, that are shown rely on certain input parameters, like the installed electricity generation power, the assumed annual electricity demand and the size of the buffer storage. Changing each of those parameters has a significant impact on the required long-term storage capacity as well as the charging/ discharging curve of the long-term storage.

When looking at the results of scenario 1-1 in table 5, it can be seen, that the calculated long-term storage capacity must be extremely high (366.739 GWh with Redox-Flow Batteries) to be able to cover positive residual loads, when the buffer storage capacities are not sufficient. Also, the state of charge curve shows a different behavior compared to scenario 2-2, which can be seen in figure 8.

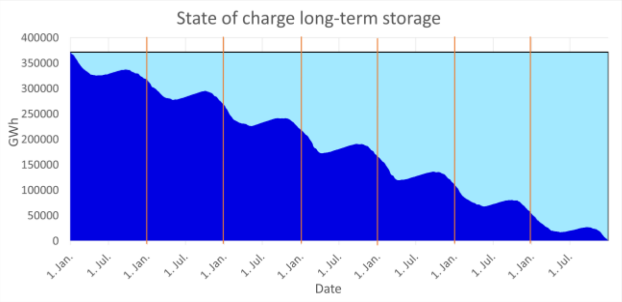

Figure 10 – State of Charge long-term storage SC 1-1

Figure 10 shows, that even though the state of charge rises in the summer months, the full capacity cannot be reached. So the state of charge is decreasing continuously over the considered time period of seven years. This shows that the values for the installed electricity generation are not high enough to cover the electricity demand and at the same time charge the long-term storage for the next winter period. So in reality this scenario (1-1) cannot work out because with every extension of the considered time period, the long-term storage capacity would rise into the infinite. Therefore, to see if the input scenario is realistically feasible, the charging/ discharging curve always has to be checked. If it doesn't reach the full storage capacity again after the beginning of the considered period, it is not realistically feasible. Another indicator that the scenario cannot be taken into reality is the fact, that the required storage capacity exceeds the annual electricity demand.

The example of scenario 1-1 not only shows that the Excel-Tool shows the limits of feasibility. It also offers the opportunity to find out, how big the installed electricity generation must be, to be able to charge the long-term storage after each winter period. Also, different interactions between the installed electricity generation and the long-term storage capacity can be tested and used for an economic analysis for example. It was noticed, that the variation of the installed wind power has a significantly bigger impact on the required long-term storage than the variation of installed solar power.

To analyse the influence of the installed electricity generation on the required long-term capacity the calculated installed capacity of scenario 2-1 has been doubled. As a consequence, the required long-term capacity (with Redox-Flow technology) results in 5.701 GWh, which is only 7% of the calculated long-term storage capacity of scenario 2-1 (83.436 GWh with Redox-Flow technology). This is an indication, that an increase of the installed electricity generation has a massive impact on the need of long-term storage capacities. The state of Charge for this scenario is shown in figure 11.

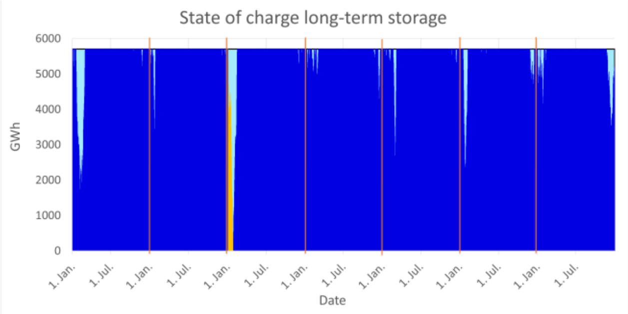

Figure 11: State of charge long-term storage SC 2-1 with doubled installed generation

5.7 Dark doldrums

As already described in chapter 3.2.2, the definition of dark doldrums was set as the period, where the residual load is positive, and the buffer storage capacities are empty. Table 6 shows an overview over the length of the longest dark doldrum that occurs with the different scenarios.

When looking at the duration of the dark doldrum of scenario 2-2, it can be seen, that the longest calculated dark doldrum that occurs is 139 h. Over the considered period of 7 years this dark doldrum occurred 26 times in scenario 2-2. All dark doldrum events with a length >= 90% of the longest dark doldrum have been considered. But when looking at figure 8 (scenario 2-2) the long-term storage is continuously discharged not only for 6 days, but over 2-3 months. This is the reason why the definition is extended as follows.

A dark doldrum occurs when the energy consumption of an energy system exceeds the energy production for a certain period due to a lack of primary energy utilisation from the sun and/or wind. The dark doldrum is the time between the start of a continuous discharge and the time when the state of charge of the long-term storage increases again.

In figure 12 it has been marked with yellow colour, what the longest dark doldrum regarding to the extended definition looks like. The duration of the marked period is 123 days for the Redox-Flow technology in scenario 2-2.

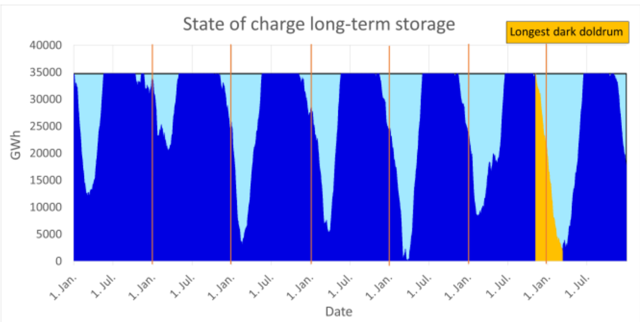

Figure 12 – Duration Dark Doldrum SC 2-2

6 OUTLOOK

Long-term storage simulation for future scenarios offers many possibilities for consideration. Various approaches to expansion are presented below.

The simulation of long-term storage has so far only been based on profiles for private demand. Expanding the data to include profiles for the "trade, commerce and services", "industry" and "agriculture" sectors will enable a more detailed analysis.

The calculated long-term storage capacity represents the minimum needed, to make sure the missing energy in the considered period can be provided by the long-term storage. Whereas the charging and discharging losses of the different storage technologies are included in the calculation, the maximal Depth of Discharge is not considered so far. To get more realistic values for the actually required installed storage capacity, the minimum SOC of the storage technologies could be implemented.

Furthermore, right now the Excel-Tool only enables the user to choose one long-term storage technology at the same time. To widen the variety of scenarios the Excel-Tool can calculate, it is helpful to implement different long-term storage technologies at the same time. Varying weightings of the technologies can also be taken into account here.

A further step towards a more detailed analysis of the dark periods lies in e-mobility. The extension of the private vehicle stock to the entire transport sector, e.g. by including electric commercial vehicles or also rail transport.

If the CPGeM tool is to be used for further e-mobility load profiles, a change in the code could save a lot of work if it could directly use the LPG annual profiles and output load profiles in hours using a CSV file.

In the future, partial coverage of the heat demand by district heating from electrolysers is also conceivable. This could also be considered in the Excel or Python tool.

The energy demand for electrolysis will continue to increase and will probably account for a significant share of the energy demand in Germany. For this reason, electrolysis should also be considered in a future script as an energy consumption that will increase over the years.

Although the different scenarios orientate on actual studies, there are many factors like electricity and hydrogen imports, heat storage and changes in the infrastructure, which are not yet considered in this Excel-Tool [19]. All those factors have a huge impact on the required long-term storage capacities. Therefore, the calculated values are only indicators of how the long-term capacity behaves in different generation-demand relations. In fact, the Excel-Tool enables the user to see how different input parameters have different effects on the required long-term storage capacities, the charging and discharging behaviour of long-term storages and the event of dark doldrums.

The evaluation of the data entered into the Microsoft Excel-Tool so far works, but with more extensive analyses and thus increasing data volumes, the computing power of Excel will no longer be sufficient. Converting the Excel tool to a Python variant is therefore a sensible next step.

In addition, when writing a Python script, the estimates of the Federal Statistical Office (Bundesnetzagentur) can be used to represent the demographics more accurately. Thus, it can be assumed that in different scaling scenarios, either the demographic assumptions for the year 2040 are used or interpolated values between the years 2018 and 2040 [6].

The most important step regarding the integration of long-term storage in an energy system is economic efficiency. The development of an economic concept for the financing and economic operation of storages can accelerate the development and integration.

7 CONCLUSION

The simulation of long-term storage via generation and consumption profiles enables an estimation of the required storage capacities for different scenarios. For this purpose, generation profiles were combined with private household profiles to map a generation deficit over a certain period of time, a so-called dark doldrum.

The definition of dark doldrum must be adapted for the investigation of long-term storage, as short periods of negative residual load are not sufficient to rebuild any required capacities. Accordingly, the definition of dark doldrum remains, but must be expanded to include the capacity of long-term storage.

A dark doldrum occurs when the energy consumption of an energy system exceeds the energy production for a certain period of time due to a lack of primary energy utilisation from the sun and/or wind. The dark doldrum is the time between the start of a continuous discharge and the time when the state of charge of the long-term storage increases again.

The Excel-Tool shows that the longest dark doldrum as defined is 123 days in the considered period of seven years for Redox-Flow technology in scenario 2-2. An overproduction of 30% in the renewable energy sector, can enable a reduction of the required storage capacities by about 58% (SC2-1/SC 2-2). The problem with long-term storage is not the capacity, but the available amount of stored energy. If there is too little generation from renewables, the storage cannot be fully charged and thus a dark doldrum period cannot be fully covered. Therefore, an expansion of renewable energies beyond the consumption figures is necessary.

In summary, the integration of long-term storage in an energy system will be indispensable in the future. However, the corresponding capacity of long-term storage depends on the overproduction of renewable energies.

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