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Facilitating energy storage to allow high penetration of intermittent renewable energy

GERMANY

Overview of the electricity supply system and an estimation of future energy storage needs

Supported by INTELLIGENT ENERGY EUROPE

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List of Abbreviations

(P)HES	…	(Pumped) Hydro Energy Storage
AA-CAES	…	(Advanced-) Adiabatic Compressed Air Energy Storage
BAU	…	Business As Usual
CAES	…	Compressed Air Energy Storage
CF	…	Capacity Factor
CHP	…	Combined Heat and Power
DSM	…	Demand Side Management
DSO	…	Distribution System Operator
E	…	Energy
EC	…	European Comission
EEG	…	German Renewable Energy Law (Erneuerbare Energie Gesetz)
		Energy Economics Group
E_{max}	…	Maximum Energy
ENTSO-E	…	European Network of Transmission System Operators for Electricity
ES	…	Energy Storage
ESS	…	Energy Storage System
EU	…	European Union
GW	…	Giga Watt
h	…	Hours
HPP	…	Hydro Power Plant
HSU	…	Helmut-Schmidt-University
HVAC	…	High Voltage Alternating Current
HVDC	…	High Voltage Direct Current
kV	…	Kilo Volt
m24	…	24 hours average value
MW	…	Mega Watt
MWh	…	Mega Watt Hour
NREAP	…	National Renewable Energy Action Plan
P	…	Power
P_{max}	…	Maximum Power
P_{min}	…	Minimum Power
PV	…	Photovoltaics
RE	…	Renewable Energies
RES-E	…	Renewable Energy Sources for Electricity Generation
RL	…	Residual load
TPP	…	Thermal Power Plant
TSO	…	Transmission System Operator
TSO	…	Transmission System Operator
TWh	…	Tera Watt Hour

Executive Summary

Within this Deliverable D5.2 of the stoRE project an estimation about the additional energy storage needs in electricity supply systems with high shares of intermittent/non-controllable electricity production from renewable sources like wind and sun is determined. This report deals with the electricity supply system of Germany and aims to provide a clear overview of the energy storage infrastructure needs in order to achieve high penetration of renewable energy in the electricity system. The existing power generation mix and transmission system, and the planned development and reinforcements are considered, along with the national plans for renewable energy development in the next decades up to 2050. The necessity of new Energy storage facilities and their feasibility from the energy point of view is investigated with the aid of simulations of mainland electricity system operation characteristics, using specially developed software. The produced qualitative and quantitative results highlight the need and benefits of energy storage in future electricity systems.

The electricity production system of Germany

The electricity production system in Germany is manly based on fossil fired power plants like coal, lignite and gas as well as nuclear power plants. After the incident in the nuclear power plant in Fukushima the German government decided to phase out nuclear energy completely until the year 2022. For that reason 8 reactors had to shut down on August 6, 2011 and the rest will follow stepwise until 2022. Nevertheless by the end of 2011, there were still 9 nuclear power plants connected to the grid with a total installed generation power of 12.5 GW. Furthermore there are 20.3 GW of lignite power plants, 25.5 GW of hard coal and 23 GW of gas power plants connected to the German grid.

In 2000 the first renewable energy law came to force with the aim to promote and help the development of technologies to generate electricity from renewable sources and to enable sustainable development of the energy supply system. Figures 1 and 2 show the situation share amongst different primary energy carriers on the installed capacity and the energy production for the years 1999 and 2011 respectively. As can be seen, the installed power of renewable energies was 15.7 GW in 1999. The main contributor was hydropower with 8.9 GW, followed by wind with 4.4 GW. PV had only an installed power of 32 MW. Due to the promotion of RE this changed enormously until the year 2011. Wind had still the highest installed power (28.9 GW) but also PV power increased rapidly to a total installed power of 24.9 GW.

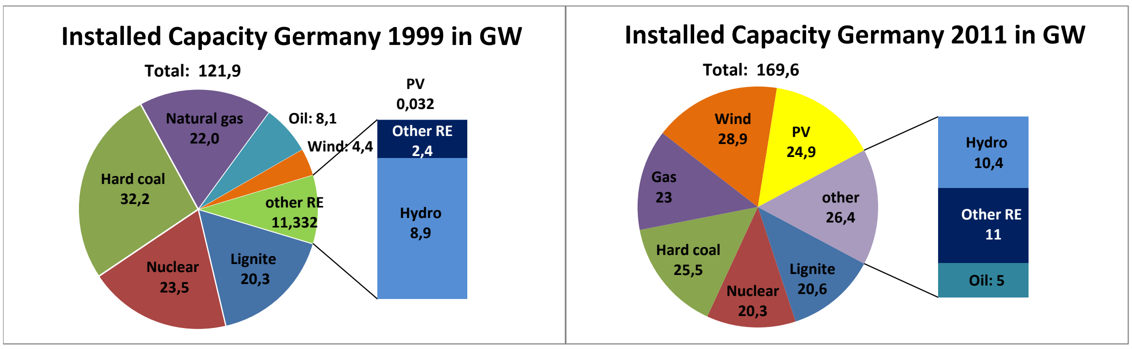

Figure 1: Installed power in Germany according to primary energy carrier in 1999 (left) and 2011 (right)

The same development can also be observed in the energy production. In 1999 the share of RE on the energy production in Germany was at 5 % which was mainly provided by hydropower (around 4 %). Wind just contributed with 1 %. In 2011 however the share of RE was already at 20.5 % . Wind power, hydropower and PV were the main contributors with 8 %, 4 % and 3 % respectively. Other RE includes technologies like biomass, biogas, geothermal energy etc.

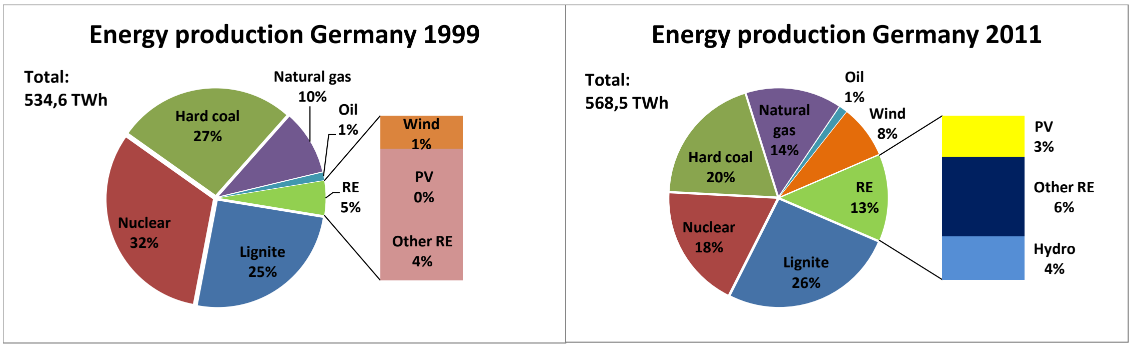

Figure 2: Energy production in Germany in 1999 (left) and 2011 (right)

The promotion and thus the development of renewable energies affected also other sectors besides electricity supply. As can be seen in figure 3, the energy production from renewable energies increased also continuously in the sectors of fuel and heat supply.

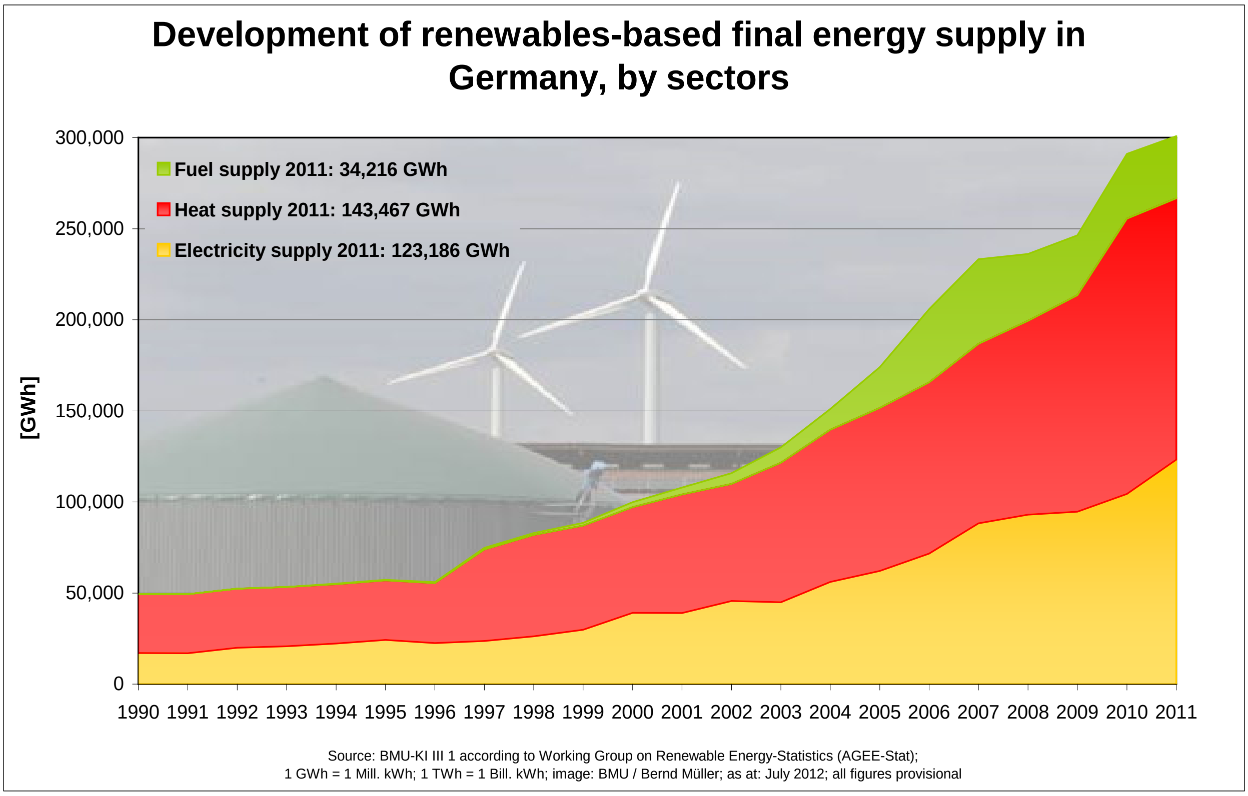

Figure 3 Development of energy supply by renewable energies, by sectors, source BMU

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System development plans (2020 – 2050)

The targets of the German government regarding the development of renewable energies are listed in table 1. Until 2050 the share of renewable energies on the net electricity consumption should increase to 80 %. In the same time the share of RE on the gross energy consumption, including all sectors like transport, heating etc, should increase to 60 %. Mainly wind and solar power will contribute to this high shares.

Table 1 Governmental target for RE shares on the net electricity consumption and gross energy consumption respectively

Until the year	RE share on net electricity consumption [%]	RE share on gross energy consumption [%]
2020	35	18
2030	50	30
2040	65	45
2050	80	60

As can be seen in figure 4, PV and onshore wind will have the highest installed power in 2020. In 2050 Wind and PV will have the highest share amongst the installed power. PV will continue its strong development until 2050 to reach more than 100 GW installed power. The share on the electricity production is relatively low. This is caused by the overall low full load hours of solar collectors in comparison to wind and biomass for example. Wind energy is believed to produce more than half of the total demand in 2050.

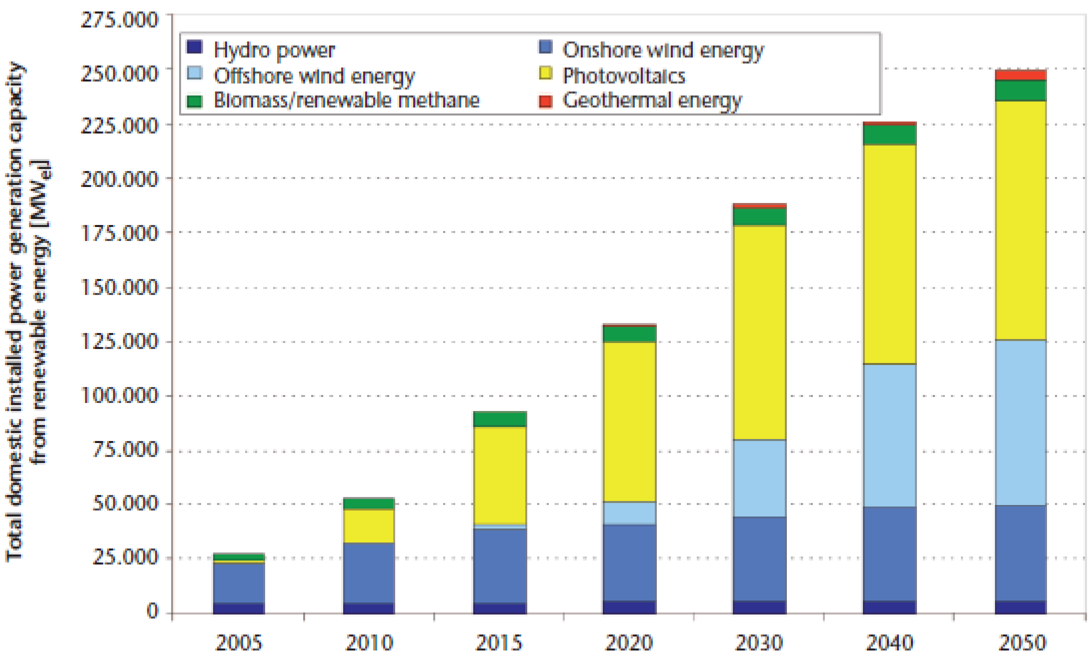

Figure 4 Development in installed power generation capacity in Germany from renewable sources to 2050, source ZWS [1]

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The share of wind energy is rising rapidly after 2015. This is due to the expected development of offshore wind farms, which are expected to contribute 75 GW at the end. This is an extremely high assumption, which is above most of other investigations about the future development of renewable energies in Germany. Nevertheless all studies assume that offshore wind energy will play an important role in the future German power plant mix. The German government has ambitious target for offshore wind farms in the North Sea as well as in the Baltic see.

The renewable energy production units are mostly located away from the main centers of load consumption. Furthermore the development of wind energy will mainly be in the northern and eastern part of Germany and the PV development is mainly concentrated in the southern part. This will pose problems to the transmission grid in Germany, as the wind power has to be transmitted to the south and PV power vice versa. To overcome these problems the German TSOs published their new grid development plan at the end of March 2012. The grid development plans foresees grid extension and reinforcement measures for the next decade to enable the transmission system to fully integrate the rising share of renewable energies. As can be seen in figure 5, the connection of the big offshore wind farms in the North Sea with the accumulation of industry and load centers in the western and southern part of Germany will play an especially important role. For this purpose 4 HVDC corridors should be constructed as an overlay grid to enable the interchange of wind power in the north and solar power in the south of Germany. Furthermore grid reinforcement and optimization is required on existing routes over a length of 4,400 km. New three-phase AC lines will be necessary over a length of 1,700 km. the total investment cost are estimated at 20 billion euros.

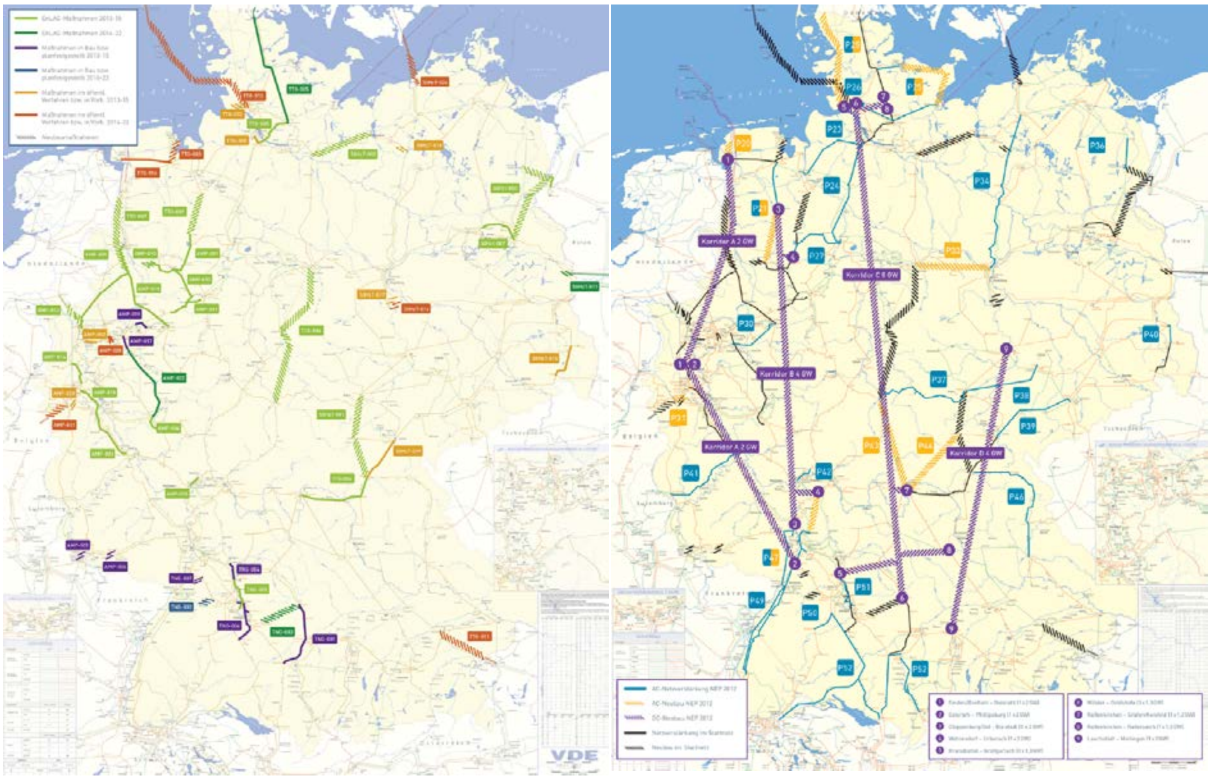

Figure 5: LEFT: transmission lines under construction (purple: completion 2013-15, blue: completion 2016-22), in the approval procedure (orange and red) and measures after the transmission line development law (lime and dark green) RIGHT: grid reinforcement after *NREP (blue), grid extension after NEP2012 (orange: AC-lines, purple: HVDC lines) and planed lines from left side (black) [5]*

The examined future RES development scenarios

In this report 7 different scenarios have been investigated: first a reference scenario with data from 2011, then a scenario for the year 2020 with the shares of RE defined in the national renewable energy action plan (NREAP) and 3 cases of RE development (equal development, favored wind energy development, favoured PV development). These 3 cases have also been investigated for a scenario with an 80% share of renewable energies on the net electricity consumption. This was decided upon the fact that after the year 2020 it is difficult to give a precise outlook on the development of the electricity market. There are too many different uncertainties that could influence the market including politics and other framework conditions. For that reason certain shares of RE are investigated for the years after 2020. The data of the installed capacity for the different scenarios are listed in table 1. Here scenario A stands for an equal development of both technologies, whereas B stands for the favoured development of wind energy and C for the favored development of photovoltaic. The differentiation between the development of wind and PV was made because the development of renewable energies is not totally determined and there are always market drivers that can influence the development of one technology. For Germany the favored development of wind energy is more likely because wind is considered as more constant and economic, especially in the north of Germany.

Table 2: Overview of the installed power plant capacity in Germany for the reference year and the scenarios 2020 and 80% [1]-[3]

	Ref. [GW]	**2020 scenario [GW]**			**80% Scenario [GW]**		
		A	B	C	A	B	C
Thermal power plants							
Nuclear	20.3	12.5			0.0		
Lignite	18.6	15.5			0.0		
Hard coal	25.0	15.7			3.8		
Gas	17.0	Nyk			Nyk		
CHP plants							
Fossil	19,9	24.1			0.0		
Biomass	6,3	7			14.0		
RE power plants							
Wind	28.0	44	52	40.5	86	93	76
Therefrom offshore	0.06	9	11	5.5	26	30	21
PV	25.0	49	30	66	70	45	100
Hydropower	4.1	4.8[1]			5.7[1]		
Geothermal	0.0	0.0			4.2		
Yearly peak load	**79.8**	**80.1**			**79.1**		
Load demand [TWh]	**510.4**	**477.5**			**412.5**		
RE share [%]	**17 %**	**38.6 %**			**80 %**		

[1] For the simulation it is assumed that 60 % of the hydropower plants are not controllable (small run off the river units) and they are producing 40% of the power over the whole year

The maximum excess power and the energy that would be rejected without any energy storage system are summarized in table 3 and 4 for the 2020 and the 80 % scenarios respectively.

As the phase out of nuclear power in Germany will be finalized in 2022, there will still be nuclear power plants connected to the grid in 20202. For that reason a scenario with a penetration limit of 10 GW was introduced to the simulation. This was made because it can be doubted that the German electricity supply system will be flexible enough in 2020 to handy a 100 % load coverage by renewable energies. This means that a certain amount of synchronous generation units have to stay connected to the grid due to grid stability reasons. This amount in combination with base load characteristic of e.g. coal and nuclear power plants led to a calculated penetration limit of 10 GW. The outcomes analyzing the residual load for the year 2020 with and without a penetration limit are shown in table 3.

TABLE 3 OVERVIEW OF THE MAIN OUTCOMES ANALYZING THE RESIDUAL LOAD IN 2020

Scenario	Max. negative power	Rejected Energy w/o storage
A	7.30 GW	52.95 GWh
B	0 GW	0 GWh
C	18.18 GW	573.29 GWh
Scenario with penetration limit of 10 GW		
A	17.30 GW	867.18 GWh
B	8.84 GW	356.91 GWh
C	28.18 GW	1615.54 GWh

TABLE 4 OVERVIEW OF THE MAIN OUTCOMES ANALYZING THE RESIDUAL LOAD, 80 % RE

Scenario	Max. negative Power	Rejected energy w/o storage
A	51.15 GW	21.72 TWh
B	38.85 GW	15.85 TWh
C	69.09 GW	29.04 TWh

It can be observed that the maximum excess power as well as the initially rejected energy is higher in scenario C than in scenarios A and B. This is due to the high installed amount of PV. Due to the lower full load hours of PV in comparison to wind on- and especially offshore, a higher power has to be installed, which consequently can also produce higher surpluses during e.g. sunny days. In the 80 % the rejected energy in scenario C already reaches 29 TWh. This is a share of 7.5 % of the total yearly production from renewable sources. With 69.09 GW the maximum negative power of the residual load in this scenario is even higher than the maximum positive peak.

Computer modeling

The computation methodology follows two steps. First the residual load for the scenario under investigation is calculated. Therefore hourly load and production data of different years per primary energy carrier are used. The second step is the calculation of the overall storage needs. For this purpose an algorithm was developed at the Helmut-Schmidt-University to estimate the energy storage needs just from a system point of view. The aim of the energy storage facilities in this approach is to integrate the maximum renewable energies possible without any focus on the electricity spot market price.

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The residual load is here defined as the load demand minus the non-controllable production from renewable sources. In the case of Germany the controllable production from renewable sources includes wind energy, photovoltaic and Run-of River hydropower plants. As an example the residual load of Germany in scenario 2050 C is shown in figure 3.

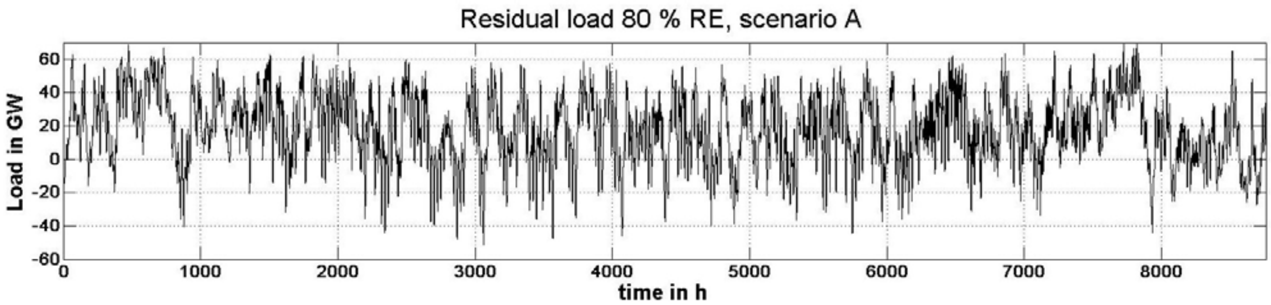

Figure 6: Residual load in Germany, scenario 80% A

As can be seen the residual load is negative especially during summer when there is a high feed in from PV. When the residual load is negative this means that there is a surplus of energy from renewable sources that exceeds the load demand. This surplus can either be rejected by down regulating renewable production units, exported to neighboring countries or stored. Down regulation or energy export is not an option within the computation algorithm. The aim is to use as little power and capacity of the storage system to fully integrate all the surpluses due to renewable energies. In principle the algorithm follows a peak shaving valley filling strategy as shown in figure 5. To minimize the energy storage needs, an intelligent operation strategy was implemented. If it can be expected that there will be a high surplus of renewable energies on the electricity system, the energy storage system (ESS) plans its operation in a way to be able to fully integrate this surplus. If the surplus of renewable energy is expected to exceed the capacity of the ESS, it tries to plan the operation in a way to empty the reservoirs completely before to integrate as much renewable energy as possible.

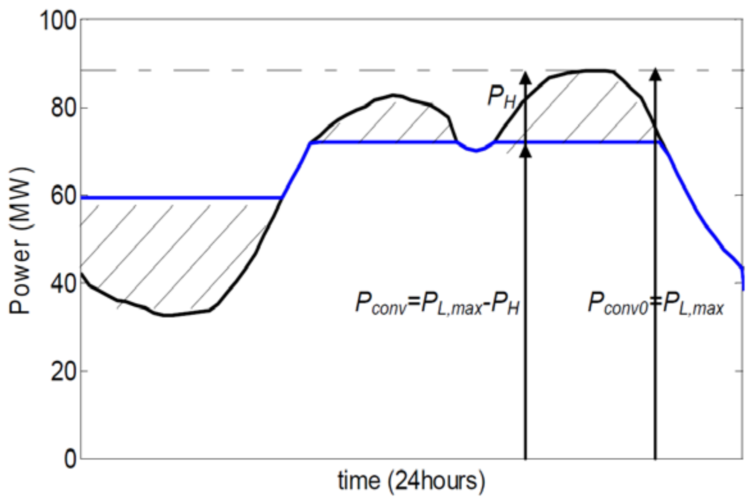

Figure 7: Iindicative effects of PHES operation on the system RL curve

To estimate the additionally needed storage capacity a further technology, in addition to the already existing ESS, is introduced. This technology has an unlimited capacity and power. This technology can take the surplus of renewable energy that cannot be stored by the existing system. Due to the unlimited power and capacity this technology enables the full integration of all renewable energies. The actual used power and capacity of this second technology is an indicator of the additionally needed energy storage system.

Simulation results for Germany

The German PHES system was set to 8 GW in installed turbine and pumping power with a total storage capacity of 60 GWh. This is the system that is expected by 2020. For 2050 no further extensions have been taken into account, as there are no clear plans and the possible additional power and capacity.

In all scenarios, except of 2020 A and B (without penetration limit), the existing and planed PHES system of Germany cannot cover all surpluses produced by renewable energies. The results for the year 2020 are shown in table 4. As can be seen there is still some rejected energy even after the use of the German PHES system. However the rejected energy has been reduced a lot and curtailment of the still remaining energy can be an option.

TABLE 5 OVERVIEW OF THE OUTCOME, SCENARIOS 2020 A TO C

Scenario	Rejected Energy from RE after use of ESS					
	w/o penetration limit			with 10 GW penetration limit		
A	0 GWh			204.20 GWh		
B	0 GWh			44.44 GWh		
C	68.99 GWh			965.76 GWh		
Capacity factor of PHES system						
	w/o penetration limit			with 10 GW penetration limit		
	Charge	Disch.	Total	Charge	Disch.	Total
A	29.51 %	24.01 %	53.52 %	27.23 %	22.71 %	49.94 %
B	27.15 %	22.04 %	49.19 %	22.43 %	20.45 %	42.88 %
C	30.38 %	25.12 %	55,50 %	27.57 %	24.42 %	51.99 %

In all scenarios the capacity factor of the German PHES system is very high. As a rule of thumb an economic operation of a PHES facility can be granted when the capacity factor reaches 25 %. In all investigated scenarios this would easily be possible. Nevertheless it has to be mentioned the operation of the PHES system is planed in a way to minimize the rejected energy from renewable sources. When taking the electricity market into account as well the capacity factor would decrease because there would be many situations where it would not be economical feasible to operate the ESS under the actual market framework conditions. The highest capacity factor is achieved in scenario C. This is caused by the day night characteristic of PV power plants. As there is no sun during the night, the storage reservoirs can be emptied during the night and filled during the day. Wind energy has no such clear characteristic. Wind can blow over longer periods of time and thus

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produce surpluses for multiple days. The same can appear for low wind speeds. In this periods the reservoir is filled in the beginning but cannot take or provide any more energy and has to wait until the situation changes.

In the scenarios with an 80 % share of RE on the net electricity consumption the expected PHES system is has not enough capacity to cover the surpluses of renewable energies. For that purpose a second, unlimited technology is introduced to estimate the additionally needed storage capacity to fully integrate all renewable energies. Figures 8 and 9 are showing the outcome of the simulation for scenario A. After the use of the ESS the residual load is smoothened well and no more negative peaks appear. This means all surpluses from renewable energy sources have been stored and provided during times of shortages.

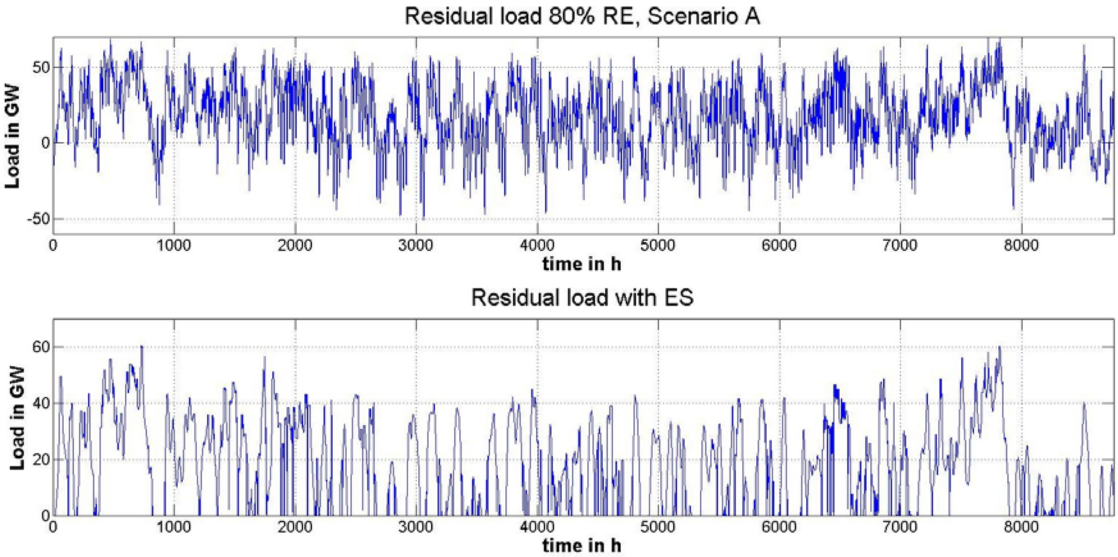

Figure 8: Residual load w/o (above) and with (below) energy storage, Scenario 80% A

In figure 9 the needed power and capacity of the technology 2 are shown. The maximum needed charging power is at 39 GW and the maximum needed discharging power is 25 GW. The charging level of technology two reaches 1,308 GWh. This is more than 30 times the size of the actual PHES system (~40 GWh). This surplus is due to a long period of sunny days and additional constant feed in from wind. This effect can also be observed in the residual load curve of this scenario. Around hour 3000 of the year, the highest negative peaks of the residual load appear and thus produce this high surplus of energy that cannot be discharged right away because there residual load does not turn positive often enough. The same effect can be observed when looking at the used power. Some few hundred hours before hour 3000, the storage system is almost continuously in charging mode. The last peak that appears at the end of the year is mainly due to strong wind energy penetration. This strong wind energy penetration is constant almost from hour 8000 to the end of the year which can also be observed in the low residual load and the needed charging power. Overall the needed storage capacity is more a long term storage. Long term energy storage is seen as an energy storage facility that is filled and emptied only a few times a year like a seasonal energy storage facility in the Alps of Austria. The fluctuations of less than 100 GWh in capacity and with periods of maximum 24 hours could be handled by regular short term storage systems like PHES and CAES. The long term storage needs will be much higher than the short term storage needs, which is shown by the trend of the charging level curve. This is due to periods of “good” and “bad” weather conditions for renewable energies. The separation of long and short term storage can be reached by making a Fourier transformation of the charging level curve. The PHES system is used to a very high degree which is reconfirmed by the high capacity factor of 49.59 %, see table 5. The system is filled and emptied completely very often and can therefore be operated economically feasible.

Technology 2 has an overall low capacity factor in all scenarios. This is due to the aim to fully integrate all renewable energies. With an intelligent curtailment of the maximum peaks, the needed charging power as well as the needed capacity could be decreased and the capacity factor can reach a point where the ESS can operate in an economical way.

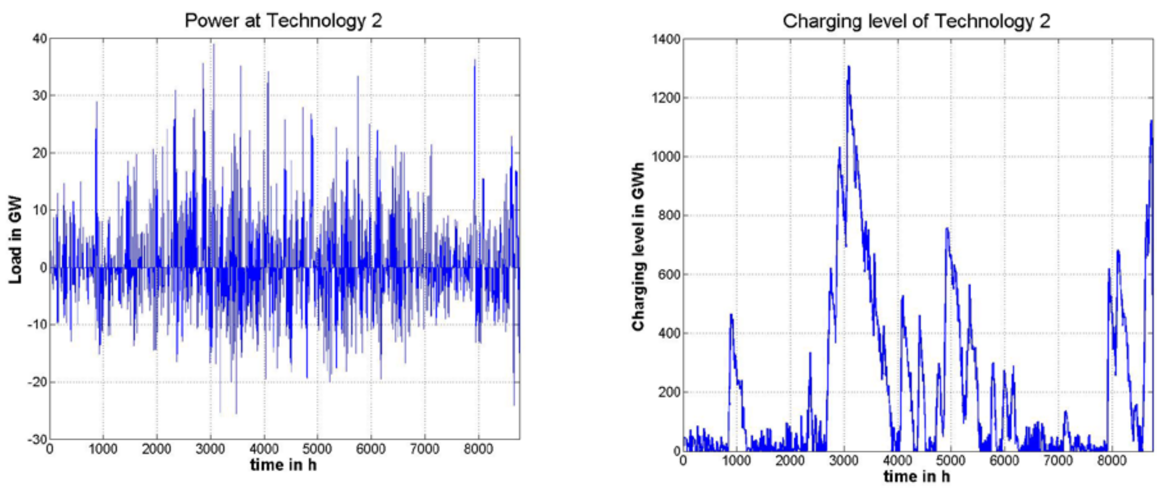

Figure 9: Power at and capacity of Energy storage system 2

When looking at the other two scenarios, the peak of the storage needs is higher in scenario B than in scenario C although the overall altitude of the fluctuations is higher in scenario C. This is due to the very high penetration of wind in December in the investigated year. This can also be seen when looking at the needed power in both scenarios. At the end of the time series the needed charging power is very low at scenario C whereas it is constantly on a high level in scenario B. The highest peak in scenario C appears around hour 3000 like in scenario A. This arises from a combination of constant feed in from wind energy and a very high amount of PV power that is fed in over a long and sunny period of time. The needed power in charging mode is 24 GW higher in scenario C than it is in B (see table 5). This can be derived directly from the overall higher installed RE power (see table 1).

TABLE 6 OVERVIEW OF THE OUTCOME, SCENARIOS 80% A TO C

Scenario	**Needed power (Tech. 2) in GW**		**Needed capacity (Tech. 2) in GWh**
	Charging	Discharging	
A	38.79	25.17	1,308
B	31.85	25.74	1,534
C	55.16	29.04	950

Capacity factor						
	Tech. 1			**Tech. 2**		
	Charge	Disch.	Total	Charge	Disch.	Total
A	27.17%	22.42 %	49.59 %	5.43 %	6.39 %	11.82 %
B	24.99 %	20.32 %	45.31 %	4.97 %	4.48 %	9.45 %
C	30.03 %	24.59 %	54.62 %	5.36 %	8.07 %	13.43

Conclusion

To reach the ambitious target of renewable energies until 2050, set by the German government, energy storage will be needed. In 2020 the storage needs will strongly depend on the flexibility of the electricity supply system and the resulting penetration limit for renewable energies. Without any penetration limit the existing and the planed extension of the German PHES system will be enough to integrated almost all surpluses from renewable energies. With a penetration limit of 10 GW the rejected energy is high enough to enable the economic operation of an additional energy storage facility.

When looking at the results of the simulation of the scenarios with an 80 % share of renewable energies on the net electricity consumption, additional energy storage facilities are needed. The size regarding needed charging and discharging power as well as storage capacity is strongly depended on installed technology of renewable energies. There is a big difference between the scenarios with a favoured development of wind and a favoured development of photovoltaic respectively. The needed power is higher with a stronger development of PV whereas the needed capacity increased with a favoured development of wind power.

Therefore it will be important to define an optimal share amongst renewable energies to minimize the additionally needed energy storage systems. Furthermore the combination of the electricity systems of different countries can bring a lot of benefits. As has been shown in report D5.1 of the stoRE project for Austria, the Austrian PHES system has enough capacity to fully cover the surpluses produced by renewable energies in Germany. However this would result in the need of transmission capacity extension as well as an high extension of the installed pumping and turbine power of the Austrian PHES facilities.

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1 Introduction

The information and discussions presented in this report are part of the European project stoRE (www.store-project.eu). stoRE aims to facilitate the realization of the ambitious objectives for high penetration of variable renewable energies in the European grid by 2020 and beyond, by unblocking the potential for energy storage technology implementation. In the stoRE project the focus of analysis and discussions is set predominantly on bulk energy storage technologies (EST), namely pumped hydro energy storage (PHES) and compressed air energy storage (CAES)[2].

Bulk EST are expected to be one of the key enabling technologies for the integration of large amounts of variable electricity generation from renewable energy sources (RES-E). In particular, the ability to quickly discharge large amounts of stored electricity or to reduce loads during certain points in time throughout a day (i.e. output smoothing)[3] can mitigate many challenges that arise from high shares of variable RES-E generation in the electricity system. Furthermore, bulk EST could also play an important role in optimising the physical and financial functioning of electricity markets and the corresponding commercial energy trading activities[4].

Work-package 5 (WP5) of the stoRE project aims to identify regulatory and market barriers to the development and operation of electricity storage systems (ESS) in the six target countries (Austria, Denmark, Germany, Greece, Ireland and Spain). For achieving that, this document, Deliverable 5.1 (D5.1), provides information about the electricity storage needs in each of the target countries necessary for integrating future RES-E generation in the incumbent electricity system.

This report is dealing with **Germany** (D5.1 - Germany) and is structured into three main parts.

Section 2 gives an overview of the German electricity system – the status-quo in the year 2011 as well as future prospects until 2020 / 2050 of the German electricity generation portfolio and the transmission grid system.

Section 3 of this report provides the development of the German (hourly) residual load until the years 2020 and 2050 – a precondition for the following modelling exercise of the electricity storage needs.

In section 4, the analysis of the future electricity storage needs in Germany is conducted, considering the existing electricity generation mix and transmission grid system (incl. planned development and reinforcements) along with the national plans for renewable energy development up to 2050. The necessity of new ESS and their feasibility from an energy point of view is investigated with the aid of simulations of mainland electricity system operation characteristics, using specially developed software. The produced qualitative and quantitative results highlight the need of energy storage in the future German electricity system and show the benefits it can bring.

Overall conclusions from the analysis carried out in this report are drawn in section 5.

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[2] For a complete picture of energy storage options see Deliverable 2.1 (Zach et al., 2012b) of the stoRE project, which also provides a brief overview of other (non-bulk) EST being outside the scope of stoRE.

[3] Other benefits of bulk EST, i.e. black start capability, area control, frequency response (secondary and tertiary control) etc., are described in Deliverable 2.1 in detail.

[4] See Deliverable 2.2 (Zach et al., 2012c) of the stoRE project for more details about the role of bulk EST in future electricity systems with high shares of RES-E generation.

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2 System data and future scenarios

In this part the actual German power system, the situation of renewable energies as well as the transmission and distribution system will be discussed. Also governmental targets and future development scenarios will be highlighted.

2.1 Status Quo of the Electricity Generation System

The net energy production in Germany in 2011 was 568.5 TWh and thermal power plant mix in 2011 consisted of

- 9 nuclear power plants with a rated power of 12.5 GW
- 15 lignite power plants with a rated power of 20.3 GW
- 43 hard coal power plants with a rated power of 25.5GW
- 28 Gas power plants with a rated power of 23 GW

The data is from December 2011. In August 6, 8 nuclear power plants with a rated installed power of 8,821 MW went offline because of the decision of the German government to phase out nuclear energy until the year 2022. These 8 reactors are not taken into account in the listing above. Furthermore all power plants with a rated power of less than 100 MW were not considered either. In 2000 the first renewable energy law came to force with the aim to promote and help the development of technologies to generate electricity from renewable sources and to enable sustainable development of the energy supply system. Figures 10 and 11 show the share amongst different primary energy carriers on the installed capacity and the energy production for the years 1999 and 2011 respectively. As can be seen, the installed power of renewable energies was 15.7 GW in 1999. The main contributor was hydropower with 8.9 GW, followed by wind with 4.4 GW. PV had only an installed power of 32 MW. Due to the promotion of RE this changed enormously until the year 2011. Wind had still the highest installed power (28.9 GW) but also PV power increased rapidly to a total installed power of 24.9 GW.

As can be further seen in figures 10 and 11, the installed capacity of all thermal production units has been reduced, except of gas. This is due to the fact that the energy systems with high shares of renewables need flexible and fast responding fossil fired power plants to cover the high gradients of the residual load (see also chapter 3 and stoRE deliverable D2.2 and D2.3 [7], [8]). For that reason lignite and nuclear power plants will lose market shares the more renewables push into the grid. Furthermore, after the accident in the nuclear power plant of Fokushima in 2011, the German government decided to totally phase nuclear energy out until 2022.

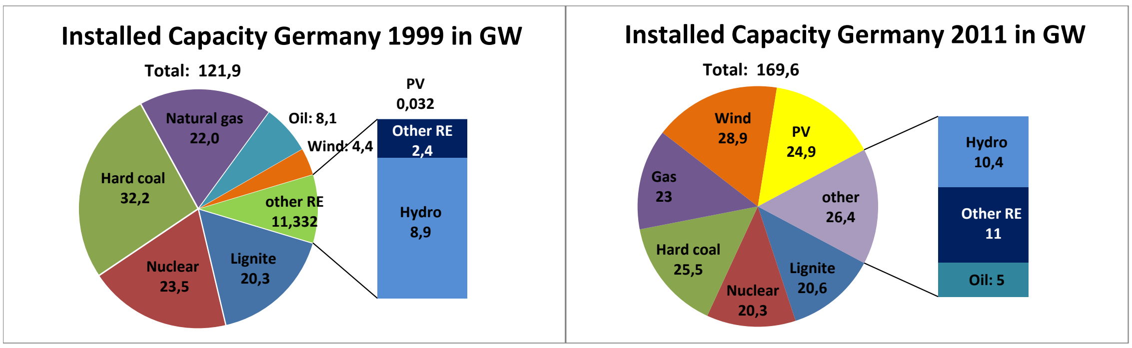

Figure 10: Installed power in Germany according to primary energy carrier in 1999 (left) and 2011 (right)

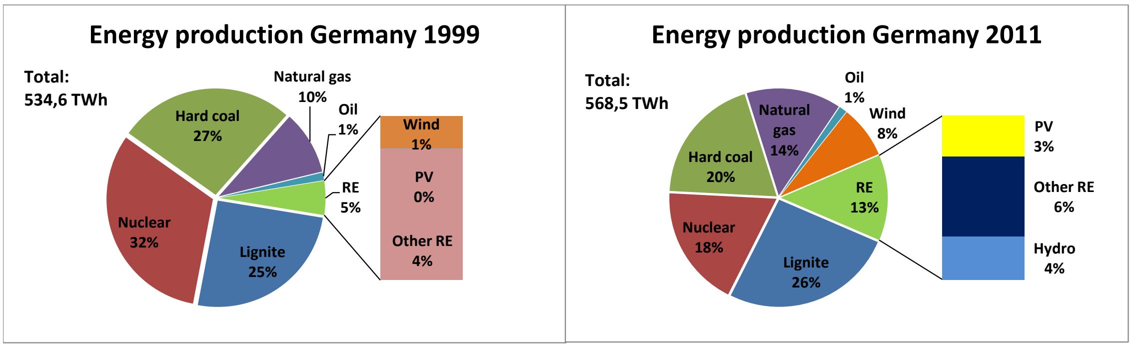

Figure 11: Energy production in Germany in 1999 (left) and 2011 (right)

As can be seen in figures 10 and 11, the installed capacity of all thermal production units has been reduced, except of gas. This is due to the fact that the energy systems with high shares of renewables need flexible and fast responding fossil fired power plants to cover the high gradients of the residual load (see also chapter 3 and stoRE deliverable D2.2 and D2.3 [1], [2]). For that reason lignite and nuclear power plants will lose market shares the more renewables push into the grid. Furthermore, after the accident in the nuclear power plant of Fokushima in 2011, the German government decided to totally phase nuclear energy out until 2022.

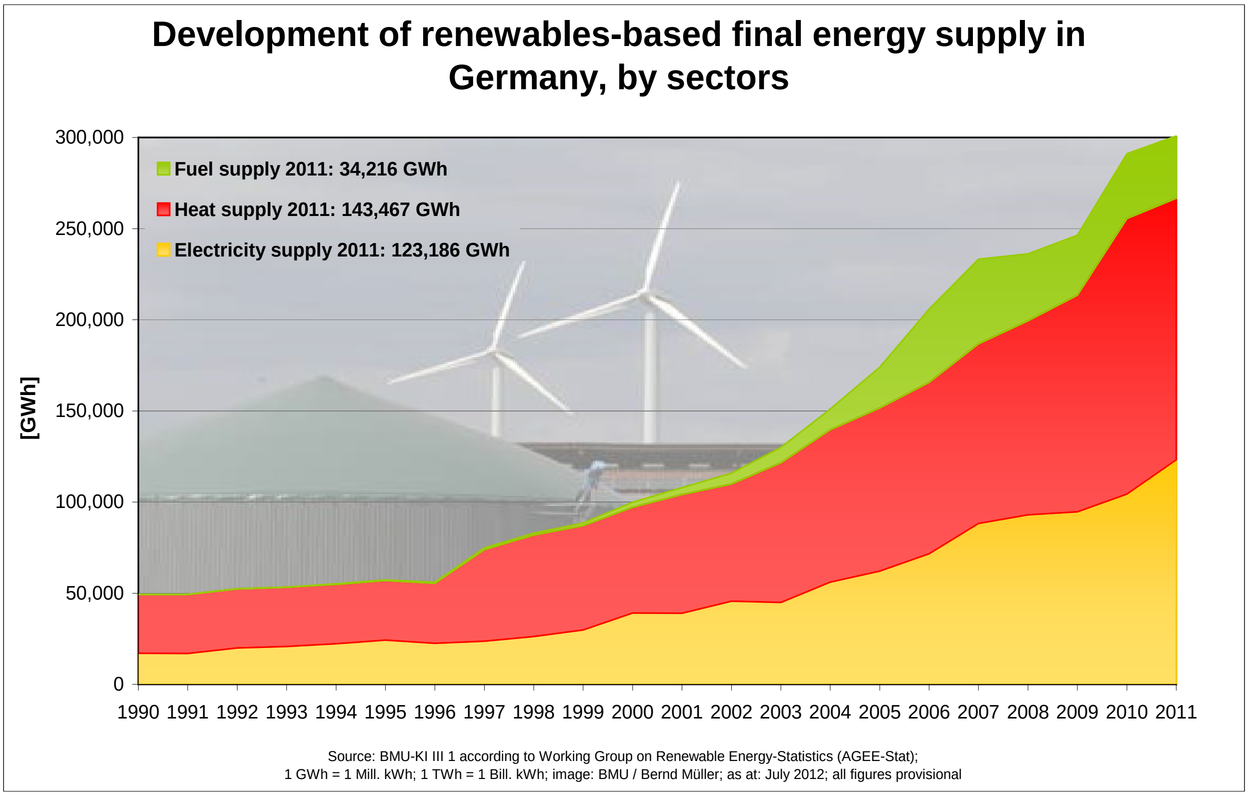

Figure 12 Development of energy supply by renewable energies, by sectors, source BMU [3]

The renewable energy production increased continuously since 1990, see figure 12. From 1990 to 1996 however, the raise was moderately. After a first law promoted renewable energies in the heating sector in 1996 the energy production from RE sources in this sector started to increase

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strongly. The same happened when the first renewable energy law came to force in 2000. From this point on, the energy produced from renewable sources increased strongly until nowadays.

Figure 13 shows the installed wind power in Germany. Most of the wind turbines are concentrated in the north and east of Germany. This leads to high shares of wind energy on the electricity consumption in affected federal states.

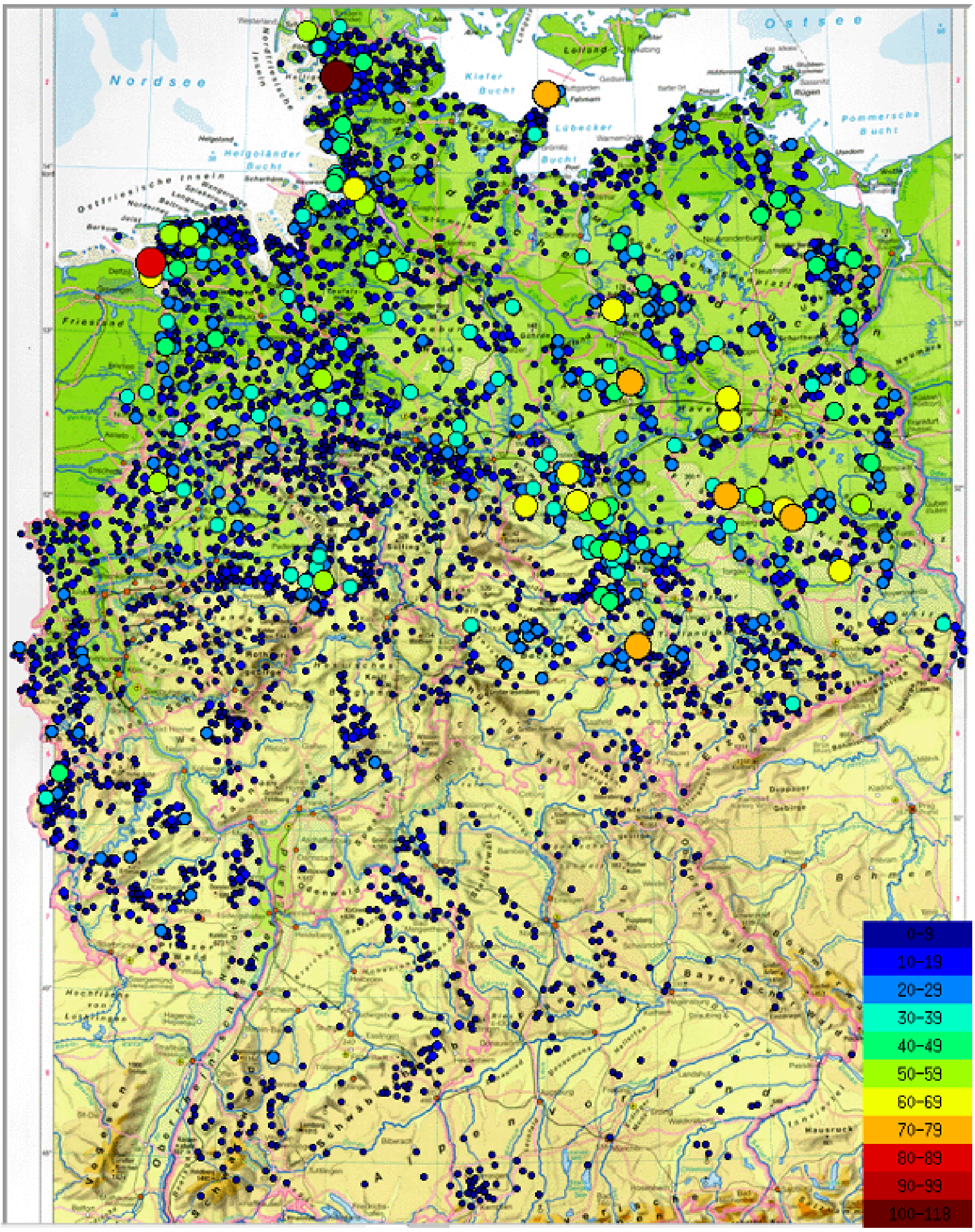

Figure 13: Installed wind power in Germany by December 2011, source Frauenhofer IWES

In 2011 the share of wind energy was already at 53.5 % in Saxony-Anhalt, at 46.5 % in Schleswig Holstein and at 46 % in Mecklenburg-West Pomerania. In these states problems already occur due to this high feed in from wind power. The distribution grids reach their limits in respect to the transmittable power. Also the transmission system will need reinforcement to transmit all the wind energy produced in the north of Germany to the high consumers in the south.

The distribution of installed PV power is concentrated more in the western and southern part of Germany. The global irradiation and solar electricity potential of Germany is shown in figure 14. In bold numbers the installed power of PV collectors per federal state is marked. Especially in Bavaria and Baden-Wuertemberg the high installed power of photovoltaic especially in rural areas is posing some problems to the low voltage grid. However the installed PV power is rising rapidly due to high subsidies of the German government (see next chapter). In September 2012 the installed power of photovoltaic modules first excessed the installed amount of wind power.

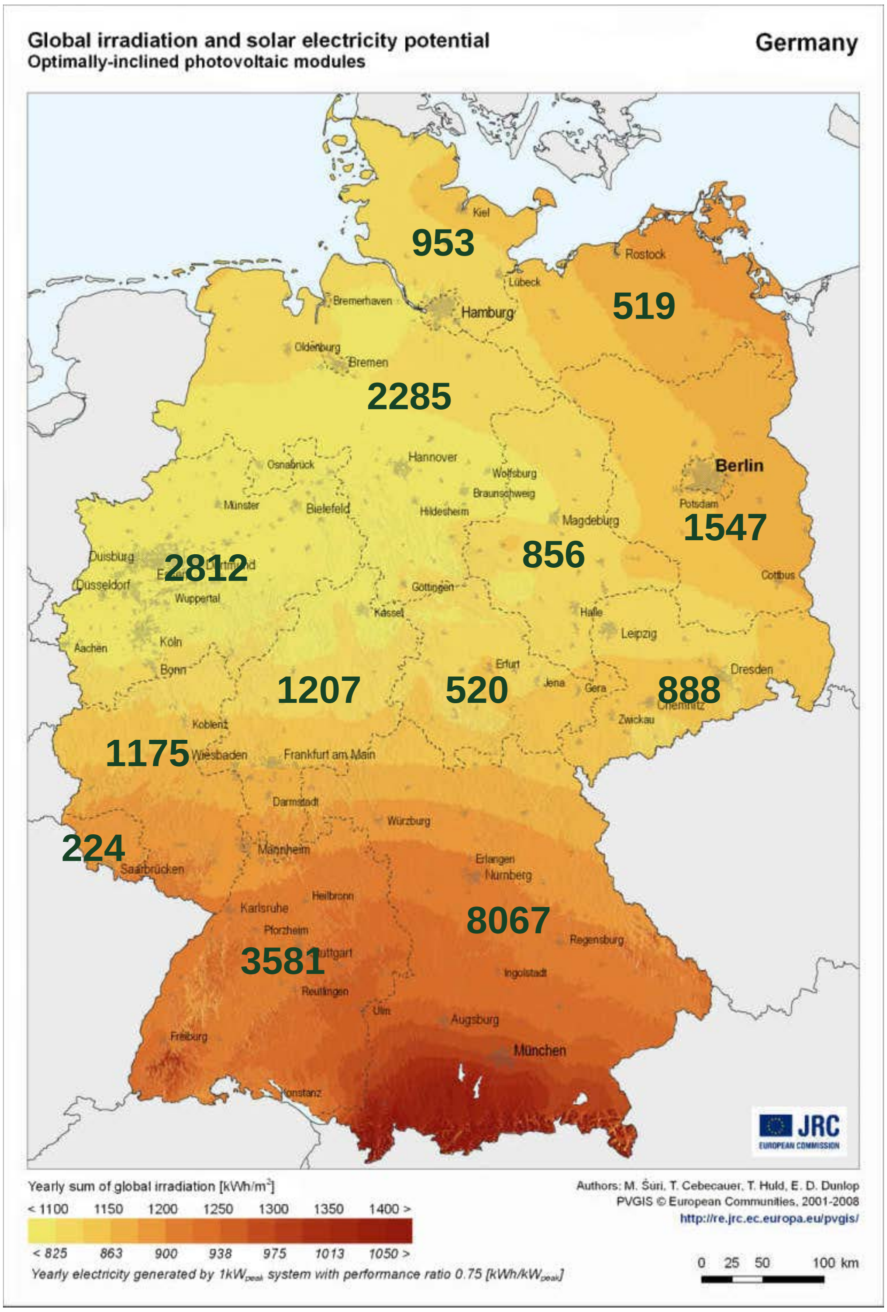

Figure 14: Global iradiation and installed PV power (black numbers), sources JRC, Photon Europe GmbH

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2.2 National Energy Plans for the future

The German government hast ambitious targets for the development of renewable energies. Until the year 2020 the share of renewable energies on the net electricity consumption should be at least 35 %, at least 50 % in the year 2030 and at least 80 % in the 2050, see table 6. The targets for different sectors are highlighted in figure 15.

Table 7 Governmental target for RE shares on the net electricity consumption and gross energy consumption respectively

Until the year	RE share on net electricity consumption [%]	RE share on gross energy consumption [%]
2020	35	18
2030	50	30
2040	65	45
2050	80	60

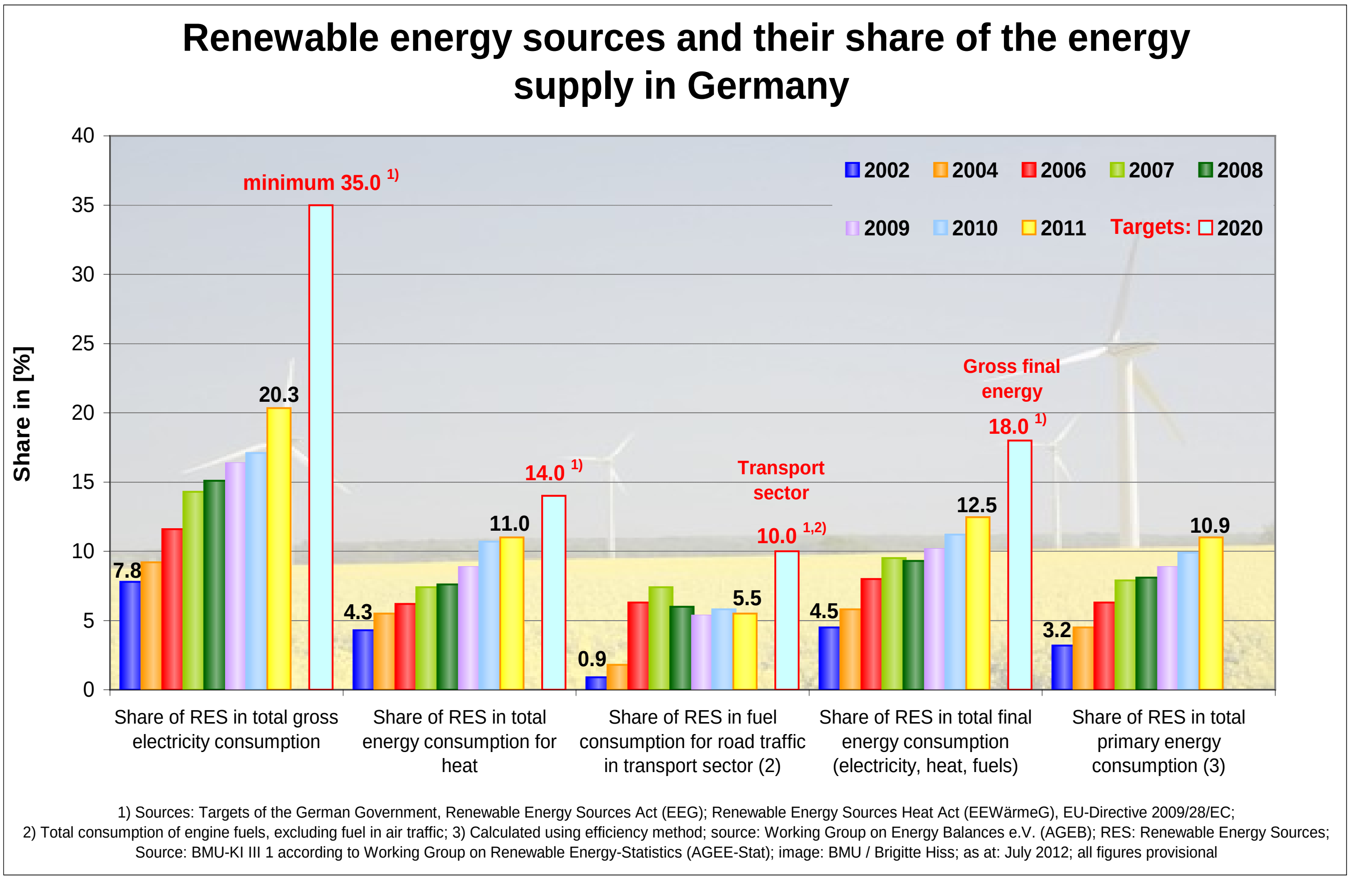

Figure 15 Actual and planned share of RE in different sectors up to 2020 [2]

As has been shown in chapter 1.2 the legislation and has a strong impact on the future development of the different renewable energies. For that reason it is hard to assume a certain development up to the year 2050. There are a lot of studies aiming to create scenarios for the year

2020 and beyond. As an example figure 16 shows the different results for different fossil fired power plants that will shut down until the year 2020. Where EWI Prognos expects a phase out of almost 35 GW, RNA comes to the conclusion that less than 5 GW of fossil fired power plant will shut down.

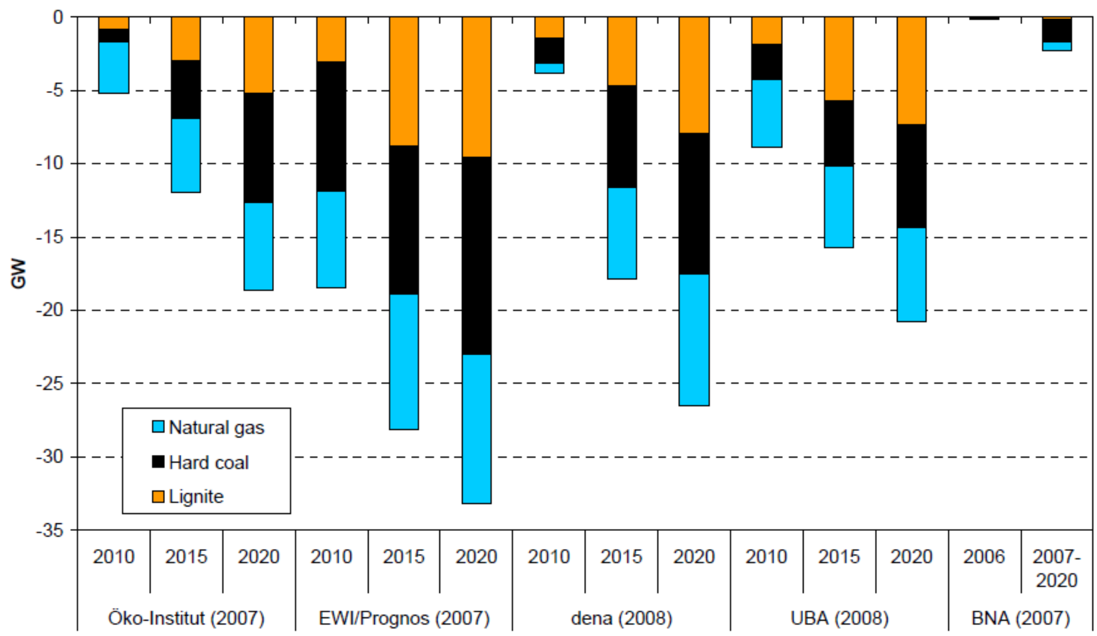

Figure 16 Incubent fossil fired power plants taken out of operation up to 2020 [4], sources: EWI/Prognos, Öko-Institut, BNA, dena, UBA

For the year 2050 the results of different studies differ even wider. The one thing all these studies have in common is a strong and fast development of renewable energies. As an example the results of a study made by ZWS are shown figures 17 and 18. They assume that Germany could have a 100 % renewable electricity sector when also importing renewable energies. These imports will begin playing a role in the year 2030 and then gaining importance until 2050. As can be seen the study expects a decrease in the gross electricity demand until the year 2030 to around 560 TWh. After 2030 a strong increase in the load demand can be observed which reaches more than 750 TWh in 2050. As a reason they highlight the increasing amount of electric devices in each household, e-mobility and the rising share of electricity in the heating sector.

The development of the gross final energy consumption is assumed different in other studies. As an example a study of the German association of electrical engineers (VDE) came to the conclusion that the gross final electricity consumption will decrease from now to a time where the share of renewable energies reaches 80 %, see table 7. According to the goals of the German government this will be in 2050. What they assumed is that the general load demand by the industry and private households will decrease due to a higher efficiency of electronic devices for personal but also industrial use. On the other side e-mobility will play an important role and as well as heat pumps. Also air conditioning will increase constantly. The grid loses will increase from 29.6 TWh in the reference year to 37.5 TWh in the 80 % RE case. This is caused by the areal distribution of renewable energy production units. As centralized power plants are built next to areas of high energy consumption, renewable energies are built where there is a high potential, e.g. offshore wind farms. This however causes a higher need in transmitting the energy to the load centers. This raise in energy transport through the transmission system causes consequently higher grid losses. For the further work the assumptions made by VDE are seen as the more realistic ones and are taken as a base for the later described investigations.

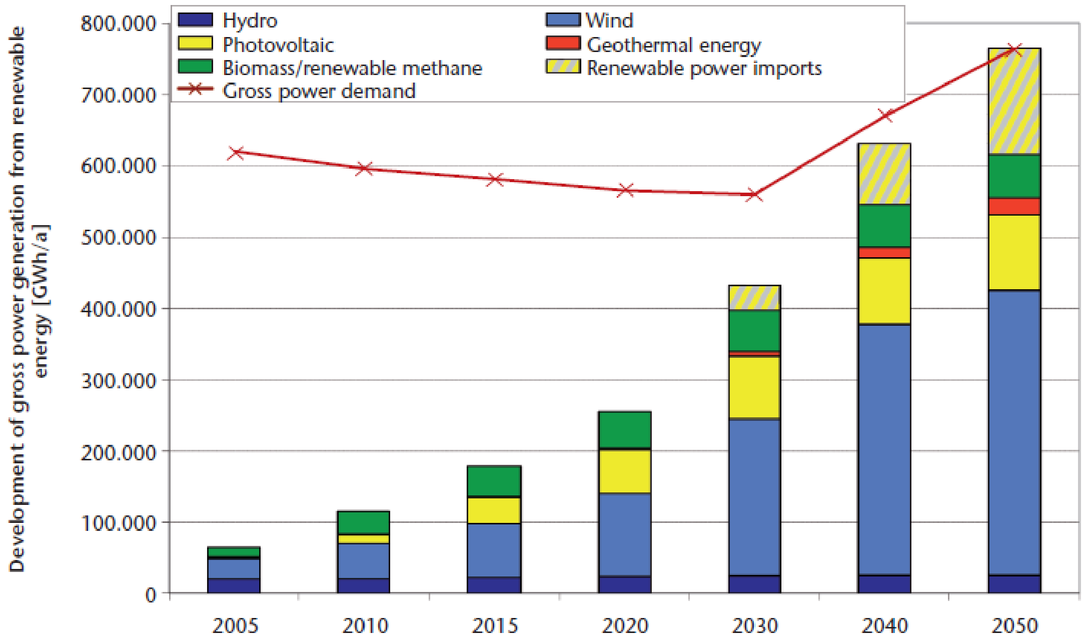

Figure 17 Development of gross final power generation from renewable energy and gross power demand in Germany to 2050, source ZWS [4]

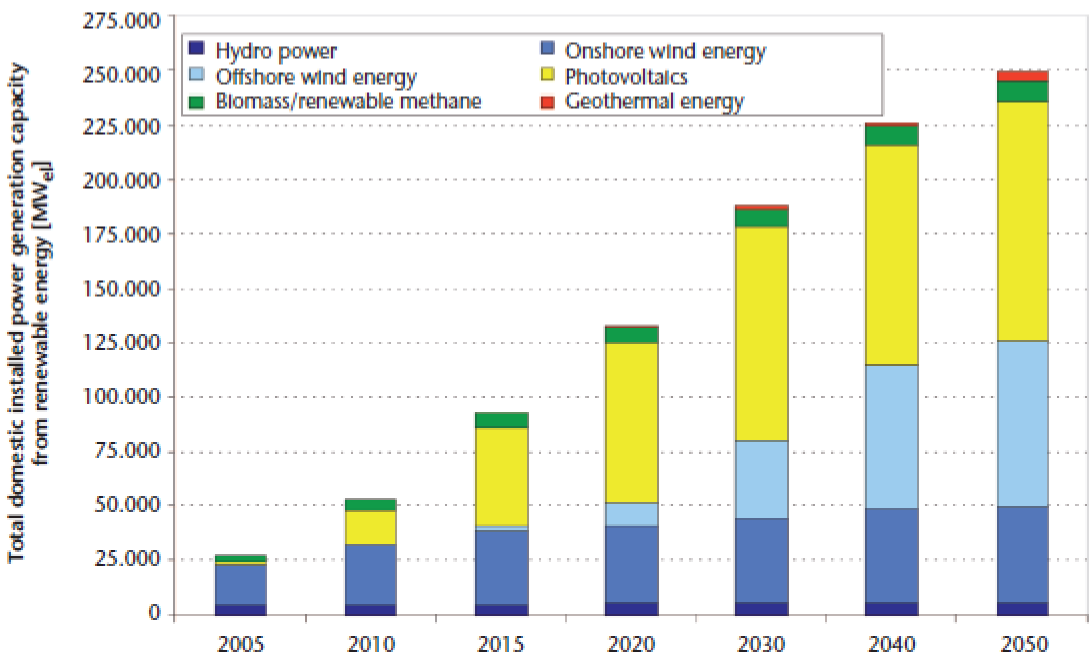

Figure 18 Development in installed power generation capacity in Germany from renewable sources to 2050, source ZWS [4]

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Table 8 Overview of the total yearly energy consumption and RE production for the reference year and the future scenarios [1], [2]

	Reference	2020	80%
RE production	~92	~200	~400
Net electricity consumption [TWh/a]	540	519.8	500
e-mobility [TWh/a]	0.0	3.3	24.7
Heat pumps [TWh/a]	0.0	6.9	15.3
Air conditioning [TWh/a]	0.0	2.5	10
Grid losses [TWh/a]	29.6	29.6	37.5
Normal load [TWh/a]	510.4	477.5	412.5
RE share [%]	17%	38.6%	80%

However, the development of renewable energies is regarded as strong in both above-mentioned studies. As can be seen in figures 17 and 18 the energy produced from renewable sources is rising continuously until 2050. Wind and PV will have the highest share amongst the installed power. PV will continue its strong development until 2050 to reach more than 100 GW installed power. The share on the electricity production is relatively low. This is caused by the overall low full load hours of solar collectors in comparison to wind and biomass for example. Wind energy is believed to produce more than 400 TWh in 2050 whish is more than half of the total demand. The share of wind energy is rising rapidly after 2015. This is due to the expected development of offshore wind farms, which are expected to contribute 75 GW at the end. This is an extremely high assumption, which is above most of other investigations about the future development of renewable energies in Germany.

Nevertheless all studies assume that offshore wind energy will play an important role in the future German power plant mix. The German government has ambitious target for offshore wind farms in the North Sea as well as in the Baltic see. The development plans for both regions are shown in figures 19 and 20.

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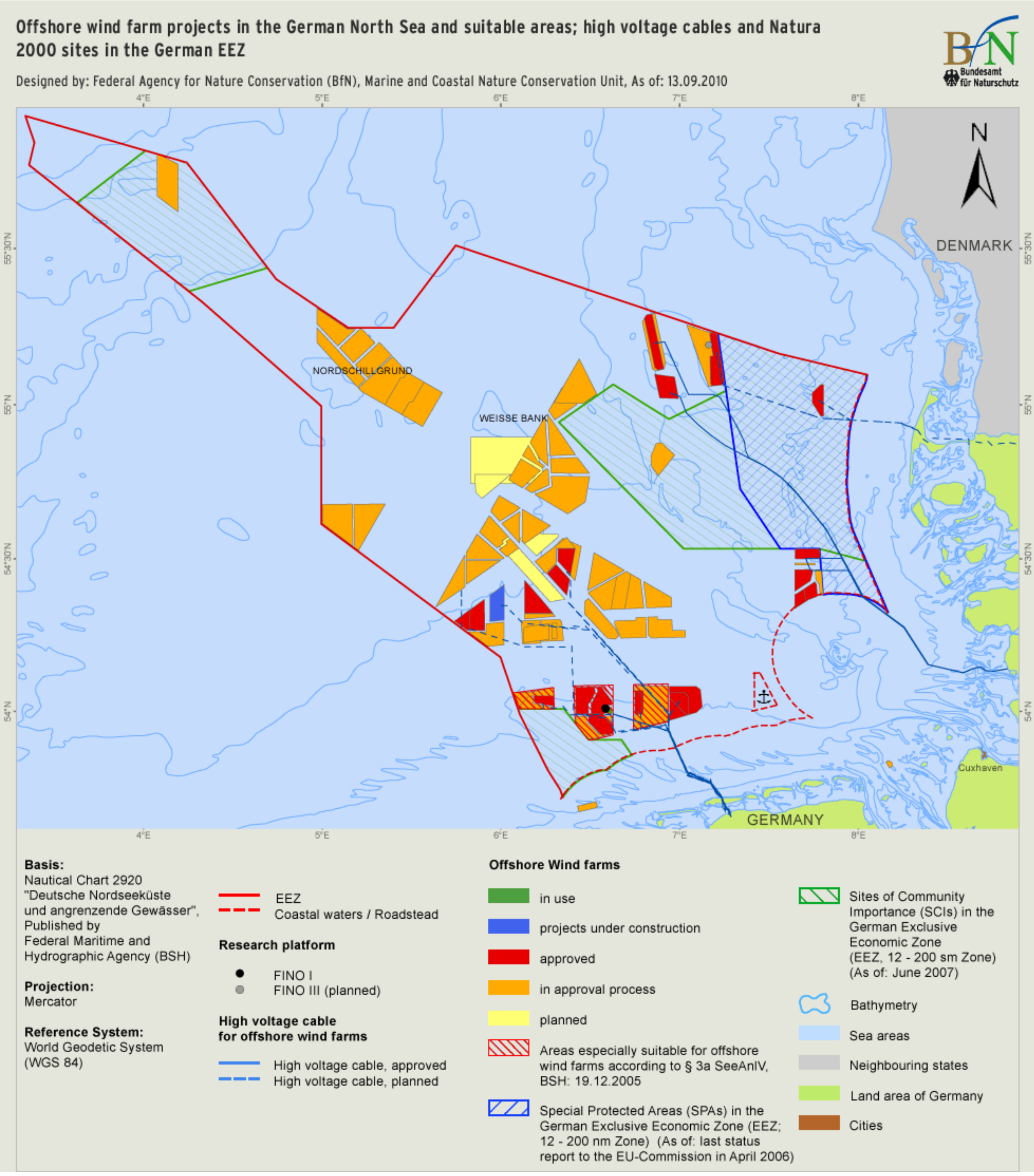

Figure 19: Planed wind farms in the German North Sea, source: German Federal Agency for Nature Conservation

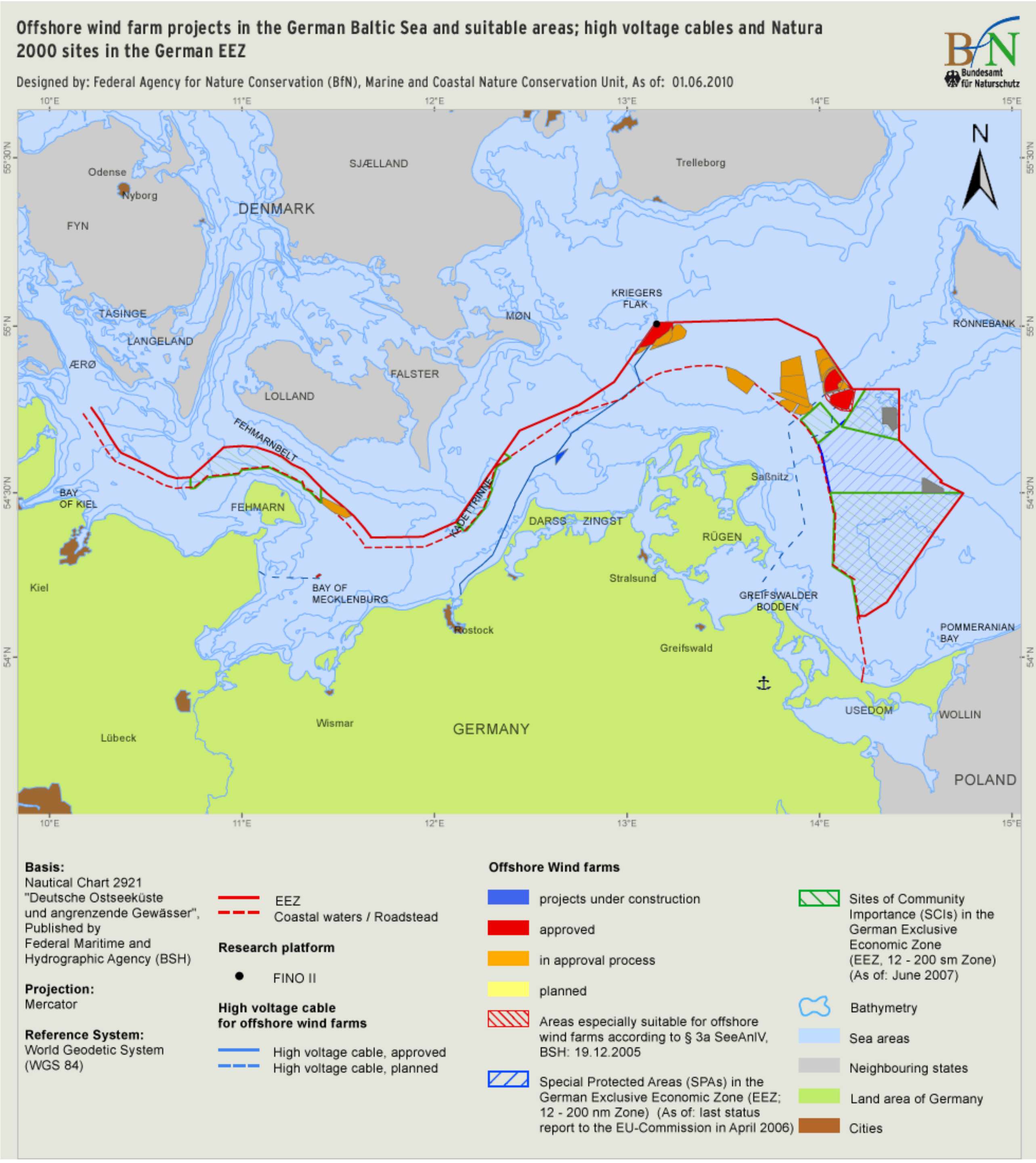

Figure 20: Planed wind farms in the German Baltic Sea, source: German Federal Agency for Nature Conservation

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2.3 German High Voltage Grid and planned reinforcements

The German High Voltage Grid consists of 74,700 km 60 kV to 110 kV transmission lines and 36,000 km of 220 kV and 380 kV transmission lines as well as two High Voltage DC (HVDC) connections to Denmark East and Sweden. The whole German high voltage grid is shown in Fig. 3. There are grid connection points to Austria, Switzerland, France, Belgium, Netherland, Denmark, Sweden, Poland and Check Republic.

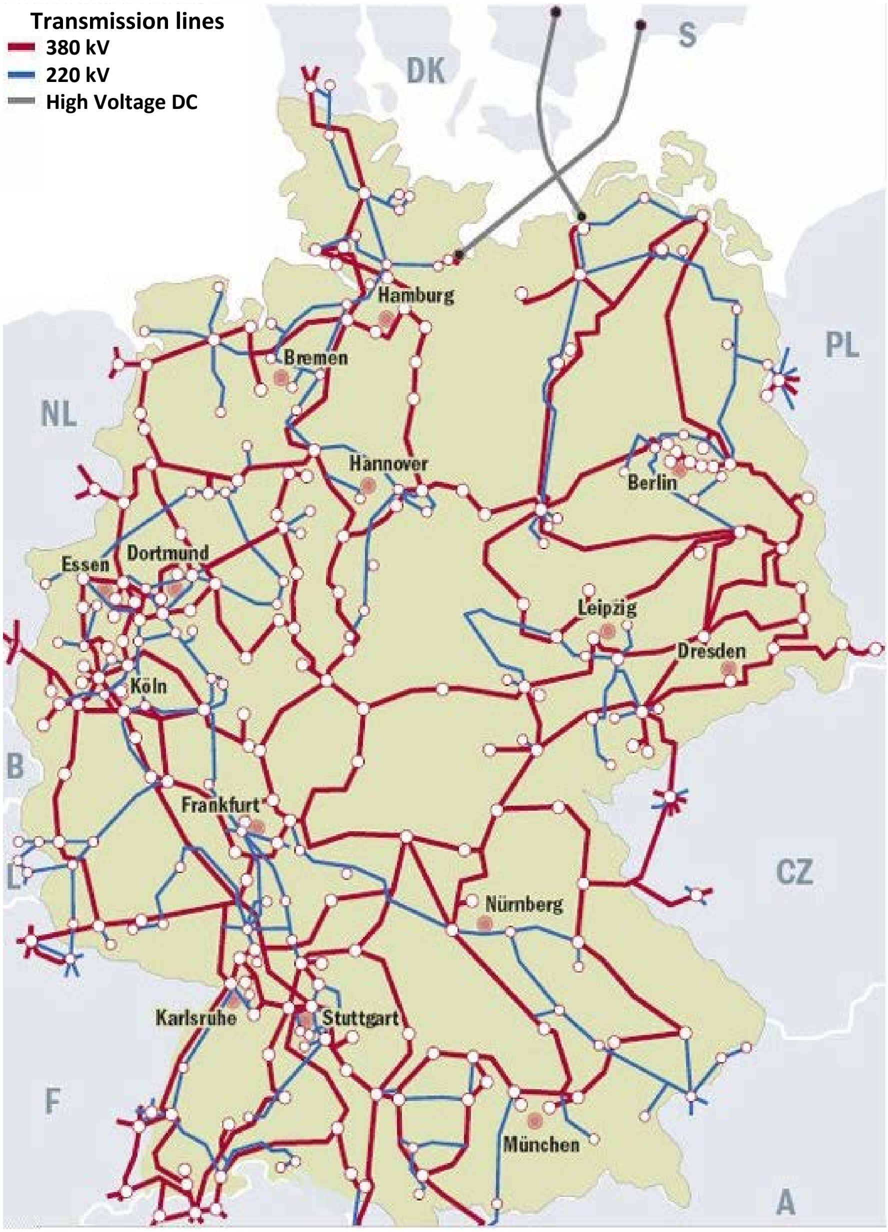

Figure 21: German high voltage grid (220 kV/380 kV) 2008, picture DW

At the end of May 2012 the German TSOs published their new grid development plan 2012 (NEP2012) [3] where they investigated the need of grid reinforcement and expansion to be able to integrate all RE and thus fulfill the ambitious RE targets of the German government. They also took into account the development of a European electricity market under the stipulated energy industry framework conditions. Grid optimization and reinforcement measures where prioritized in comparison with expansion measures. Nevertheless there is a significant need for development throughout Germany. The main focus was on efficient north-south connections. Grid reinforcements and optimizations are required on existing routes over a length of 4,400 km. The new construction requirements include 1,700 km of three-phase line routes and 2,100km of corridors for HVDC lines. They expect total investment costs of about 20 billion Euros. The transmission lines that are already under construction or in the licensing procedure as well as the recommendations from [3] for new transmission lines are shown in figure 4.

As it can be seen, the connection of the big offshore wind farms in the North Sea with the accumulation of industry and load centers in the western and southern part of Germany will play an especially important role. For this purpose 4 HVDC corridors should be constructed as an overlay grid to enable the interchange of wind power in the north and solar power in the south of Germany. Additionally, what is not shown in the figures, are the 7 HVDC lines under construction to connect the offshore wind farms in the north see with the costal grid.

For the further investigation, it is assumed that the grid reinforcement and expansion will be realized fast enough so that there are no restrictions for the integration of energy from renewable sources due to missing grid stability or transmission capacity.

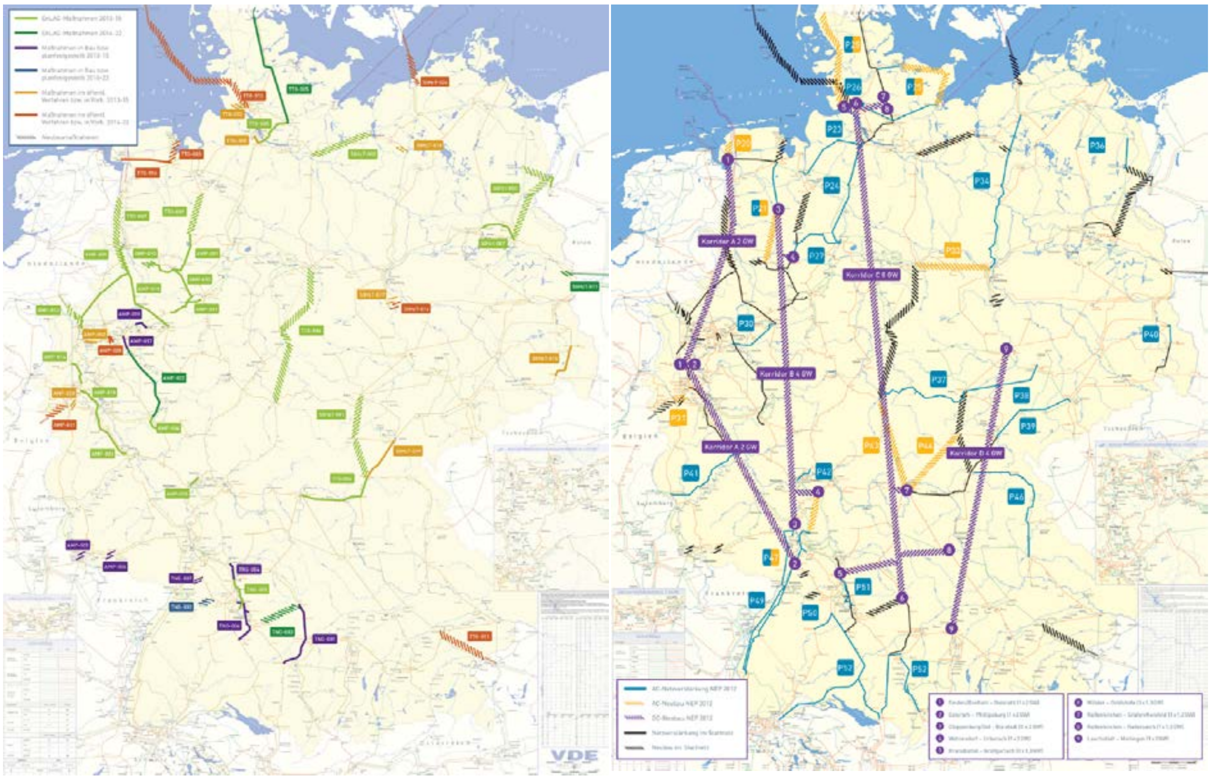

Figure 22: LEFT: transmission lines under construction (purple: completion 2013-15, blue: completion 2016-22), in the approval procedure (orange and red) and measures after the transmission line development law (lime and dark green) RIGHT: grid reinforcement after *NREP (blue), grid extension after NEP2012 (orange: AC-lines, purple: HVDC lines) and planed lines from left side (black) [5]*

2.4 Reference and future scenarios

In the following the energy storage needs of the German electricity system will be analyzed. For that purpose 7 scenarios have been investigated: first a reference scenario with data from 2011, then a scenario for the year 2020 with the shares of RE defined in the national renewable energy action plan (NREAP) and 3 cases of RE development (equal development, favored wind energy development, favored PV development). These 3 cases have also been investigated for a scenario with an 80% share of renewable energies on the net electricity consumption. This was decided upon the fact that after the year 2020 it is difficult to give a precise outlook on the development of the electricity market. There are too many different uncertainties that could influence the market including politics and other framework conditions. For that reason certain shares of RE are investigated for the years after 2020. The data of the installed capacity for the different scenarios are listed in table 7. Here scenario A stands for an equal development of both technologies, whereas B stands for the favored development of wind energy and C for the favored development of photovoltaic. The differentiation between the development of wind and PV was made because the development of renewable energies is not totally determined and there are always market drivers that can influence the development of one technology. For Germany the favored development of wind energy is more likely because wind is considered as more constant and economic, especially in the north of Germany.

Table 9: Overview of the installed power plant capacity in Germany for the reference year and the scenarios 2020 and 80% [1]-[3]

	Ref. [GW]	2020 scenario [GW]			80% Scenario [GW]		
		A	B	C	A	B	C
Thermal power plants							
Nuclear	20.3	12.5			0.0		
Lignite	18.6	15.5			0.0		
Hard coal	25.0	15.7			3.8		
Gas	17.0	Nyk			Nyk		
CHP plants							
Fossil	19,9	24.1			0.0		
Biomass	6,3	7			14.0		
RE power plants							
Wind	28.0	44	52	40.5	86	93	76
Therefrom offshore	0.06	9	11	5.5	26	30	21
PV	25.0	49	30	66	70	45	100
Hydropower	4.1	4.8[5]			5.7[1]		
Geothermal	0.0	0.0			4.2		
Yearly peak load	**79.8**	**80.1**			**79.1**		

[5] For the simulation it is assumed that 60 % of the hydropower plants are not controllable (small run off the river units) and they are producing 40% of the power over the whole year

The next table shows the consumption and RE production for the reference year and the development scenarios 2020 and 80%. For the different development scenarios of wind and solar power the overall consumption stays the same. That is the reason why only one 2020 scenario and one 80% scenario are listed.

Table 10 Overview of the total yearly energy consumption and RE production for the reference year and the future scenarios [1], [2]

	Reference	2020	80%
RE production	~92	~200	~400
Net electricity consumption [TWh/a]	540	519.8	500
e-mobility [TWh/a]	0.0	3.3	24.7
Heat pumps [TWh/a]	0.0	6.9	15.3
Air conditioning [TWh/a]	0.0	2.5	10
Grid losses [TWh/a]	29.6	29.6	37.5
Normal load [TWh/a]	510.4	477.5	412.5
RE share [%]	17%	38.6%	80%

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3 Development of the residual load

The residual load is here defined as the load demand minus the non-controllable production from renewable sources. Following this definition the residual load is the load demand that has to be covered by controllable production units like fossil fired power plants (coal, oil, natural gas) or controllable renewable energies (part of hydropower, biomass, biogas and so on). In the case of Germany, the non-controllable production from renewable sources includes wind energy, photovoltaic and Run-of River hydropower plants. The residual load curves for the different scenarios are shown in figure 23. For the 2020 and the 80% scenario only the equal development is shown.

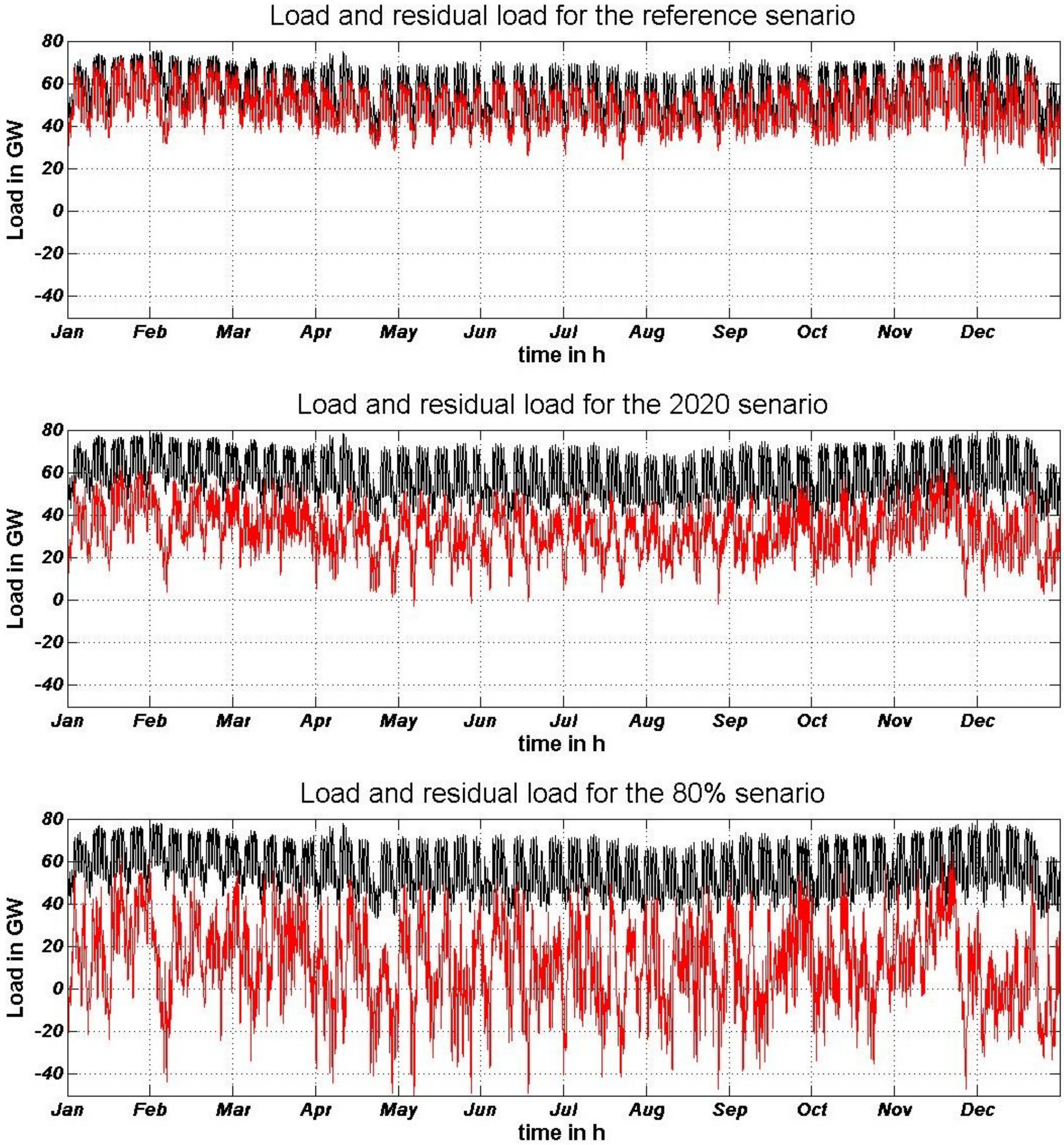

Figure 23: Load (black) and residual load (red) for the reference and future scenarios with equal development of RE sources

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As can be seen the residual load (RL) spreads in altitude the more renewables are installed. For comparison: the spread of the load demand in 2011 was 42 GW whereby the peak load was at 79.8 GW and the minimum load at 36.9 GW. At the 40% scenario the maximum of the RL is at 70.6 GW whereas the minimum is -8 GW. That is a spread of 78.6 GW that has to be covered by thermal power plants, storage technologies or load management measures. When looking at the 80% scenario the spread increases again. The maximum of the RL is still at 63.6 GW whereby the minimum is now at -52 GW. This incorporates a total spread of 115.6 GW. This shows that the gradient of the load fluctuations will increase the more renewables are installed and the higher the share of RE should or will be. This rising load gradient is not only stressing the transmission and distribution grid but also the thermal power plants have to adapt to that new situation. Lignite fired power plants are less flexible than hard coal and especially than gas fired power plants and will therefore become less and less important the more the share of RE is increasing, see also table 1 and [1], [2]. The investigations made in the following part of the report are just made from a system point of view. Economic considerations are taking into account, but on a very basic level. When using a full market model or a just economic approach results could differ.

As long as the RL is positive, flexible thermal units as well as load management measures will play a role and, with enough flexibility in the system, cover the resulting load. When the RL turns negative renewable generation units have to be shut down or the energy has to be sold outside of the control area. Due to a high time correlation of RE production import/export will not always be possible. To be able to use the produced energy from RE sources, it is necessary to store it and provide it then at times of shortages. The rejected energy from renewables, the maximum negative power and load variations per scenario are discussed in more detail in the next chapter.

3.1 2020 Scenarios according to NREAP

As the development of renewable energies is not totally determined there will be 3 subcategories of RE development as specified in table 7. The favored development of wind energy will be the more realistic one for Germany because wind energy is already competitive on an open energy market whereas photovoltaic is still strongly dependent on subsidies. Nevertheless these subsidies have much influence on the development of renewable energies. As the German government decided to reduce the feed in tariff for photovoltaic for 2012 a run on new photovoltaic installations started and led to 5 GW of new installed PV power in the last 3 months of 2011. For that reason a scenario with favored development of photovoltaic is investigated too. The equal development will be investigated first and in much detail, whereby for the other two scenarios only the differences to the fist scenario will be highlighted. In general for all 3 scenarios the share of renewable energies is at ~38.6 %, which is the goal of the German government defined in the NREAP.

At scenario A, without any storage, the total rejected energy from renewable sources would be 52.95 GWh with a maximum negative power of 7.3 GW. At scenario B the residual load never turns negative, so there is no rejection from renewable sources. On the contrary in scenario C the rejected energy from renewables increases strongly to 573.29 GWh with a maximum negative power of 18.2 GW. This strong rise is due to the higher installed power of PV power plants that can consequently also feed-in with a higher rated power at sunny days. The rejected energy is in all scenarios very low (less than 0.003% of total RE production) but the power surplus of scenario C is very high and cannot be stored by the existing energy storage infrastructure of 8 GW installed power and a capacity of 60 GWh.

From a system point of view, it is not yet clear if the German electricity system will be able to handle an interim 100% load coverage by renewable energies. Certainly it will not be economically reasonable to shut down all base load units just for some selected hours during the year. For that purpose a penetration limit of 10 GW was introduced. This includes the overload of distribution systems due to strong penetration of renewables as well as minimum load values for base load production units. With this penetration limit the rejected energy increases strongly. The maximum negative power increases by 10 GW to 17.30 GW in scenario A, 8.84 GW and 28.18 GW in scenario B and C respectively. More important is the rise of the surplus of energy. In scenario A this surplus reaches 867.18 GWh, whereas in scenario B it is less than half of this (356.91 GWh). In scenario C an enormous rise is observed. With a surplus energy from wind and especially sun of almost 3 TWh, this incorporates already a share of 1.5 % of the total renewable energy production. This rise is also illustrated in figures 24 and 25. It can be seen that the frequency of occurrence and the altitude of the rejected energy from renewable sources is much higher at scenario C than it is at scenarios A and B. All outcomes are again summarized in TABLE 11.

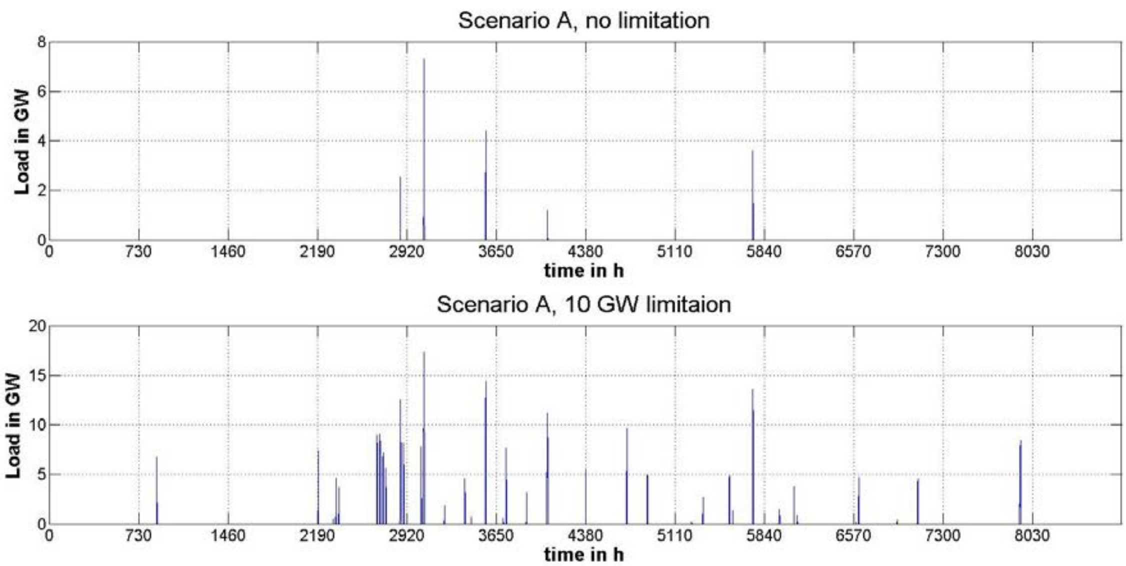

Figure 24: Rejected Energy from intermittent renewable sources without (above) and with 10 GW penetration limit (below)

On the one side, due to its lower full load hours, the installed capacity of solar power has to be higher – in comparison to wind turbines - to produce the same amount of energy. On the other side, when there are good weather conditions for PV installations, these power plants can feed in with a higher amount of power and therefore produce bigger surpluses.

As shown in figure 26 the variation of the load that has to be covered by the left over power plants is rising due to the feed in from renewable energies. This means that future power plants will have to adapt quicker to load changes and will have to shorten their starting times. CHP power plants and single gas turbines will gain particular importance because of their fast start and reaction times, see also stoRE deliverable 2.3. The day-night characteristic of PV installations is the reason why the variations are higher in scenario C than in the other scenarios. Energy storage technologies can here provide more flexibility within the power plant mix because they can cut the peaks and fill the valleys of the residual load and thus smaller the variations, see also chapter 3.

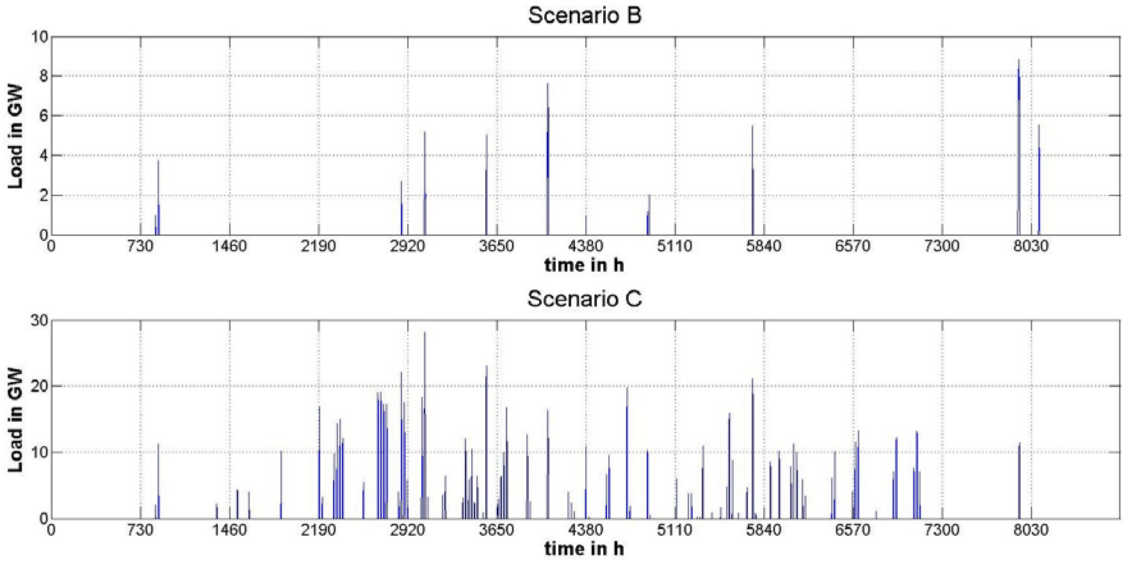

Figure 25: Rejected energy from intermittent renewable sources with penetration limit of 10 GW

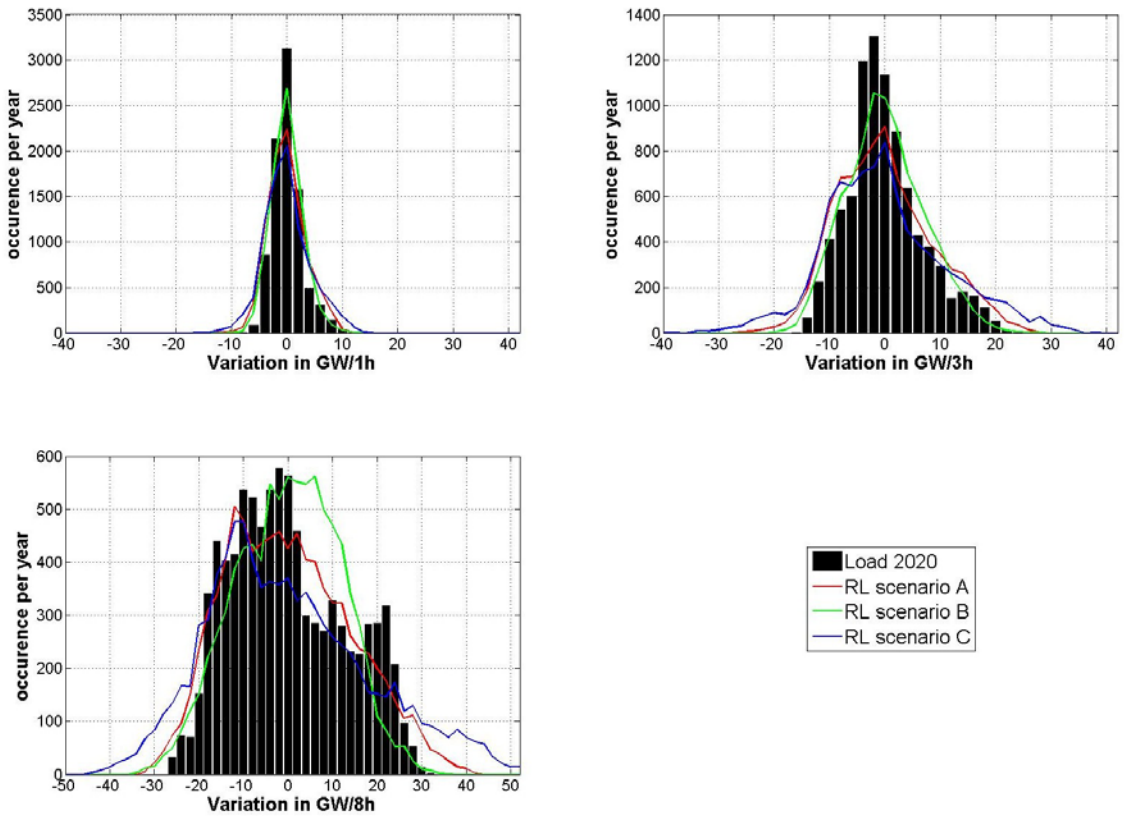

Figure 26: Variation of the load (red line) and the residual load (blue bars) in the scenario 2020 A

TABLE 11 OVERVIEW OF THE MAIN OUTCOMES ANALYZING THE RESIDUAL LOAD

Scenario	Max. negative power	Rejected Energy w/o storage
A	7.30 GW	52.95 GWh
B	0 GW	0 GWh
C	18.18 GW	573.29 GWh
Scenario with penetration limit of 10 GW		
A	17.30 GW	867.18 GWh
B	8.84 GW	356.92 Wh
C	28.18 GW	GWh

3.2 80% Scenario

At scenario A, without any storage, the total rejected energy from renewable sources would be 21.72 TWh with a maximum negative power of 51.15 GW. At scenario B the residual load reaches its minimum at minus 38.85 GW and the total rejected energy from RE decreases in comparison to scenario A to 15.85 TWh. On the contrary in scenario C the rejected energy from renewables increases strongly to 29.04 GWh with a maximum negative power of 69.09 GW. This strong rise is due to the higher installed power of PV that can consequently also feed-in with a higher rated power at sunny days, see also figures 27 and 28.

For these scenarios it is assumed that the leftover thermal plants and the grid can handle an interim100% load coverage by RE. In contrast to the 40% scenario the grid reinforcement and expansion of the German electricity grid will be completed to a level where it is possible to integrate all renewable energies. Therefore no penetration limit is introduced. With a total production of RE of 400 TWh the rejected energy from renewables would be 5.4 % of the total RE production in scenario A, 3.96 % in scenario B and 7.26 % in scenario C respectively.

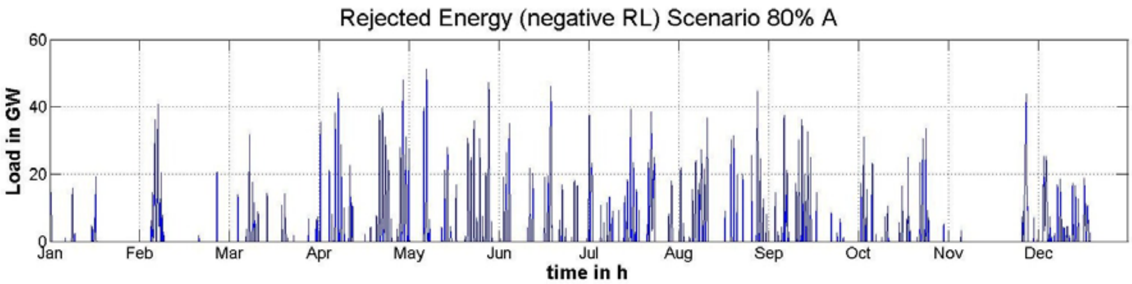

Figure 27: Rejected energy from intermittent renewable sources w/o use of energy storage

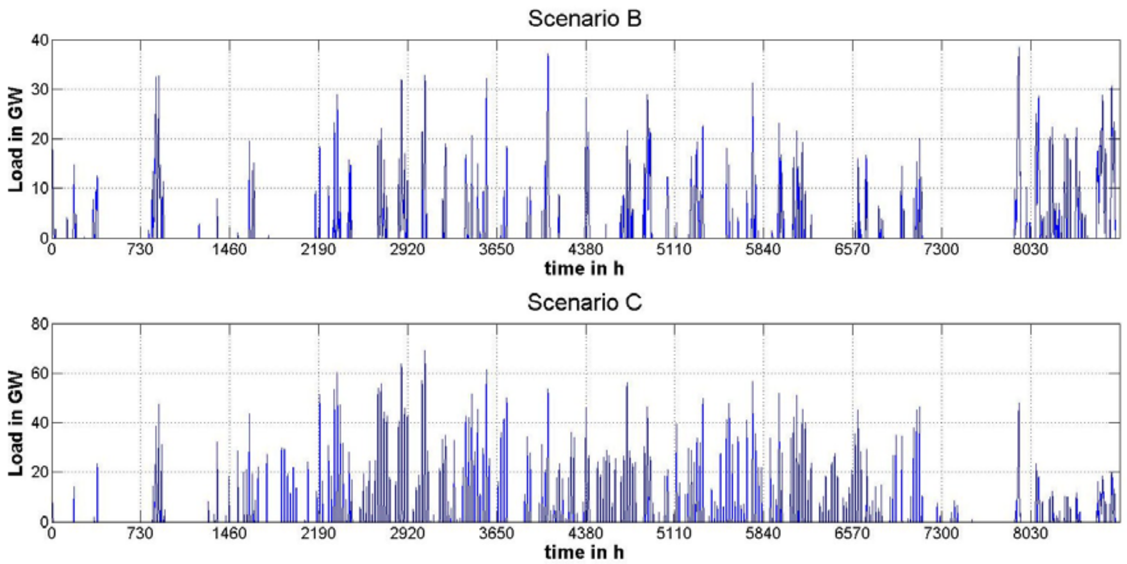

Figure 28: Rejected energy from intermittent renewable sources w/o use of energy storage for scneario B (above) and C (below)

The variation of the residual load increases for the 80% scenario again. As shown in figure 29 the spread of the variation is by far bigger than it is in the reference scenario. Variations of more than 50 GW/8h are summarized at the marks at +/- 50 GW. The higher installed power of intermittent renewable sources produces correspondingly higher fluctuations. The maximum variation of the

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load demand is less than 40 GW/8h whereas the RL shows load changes of more than 50 GW/8h that occur more than 100 times a year. This will be an enormous challenge for the future power plant mix.

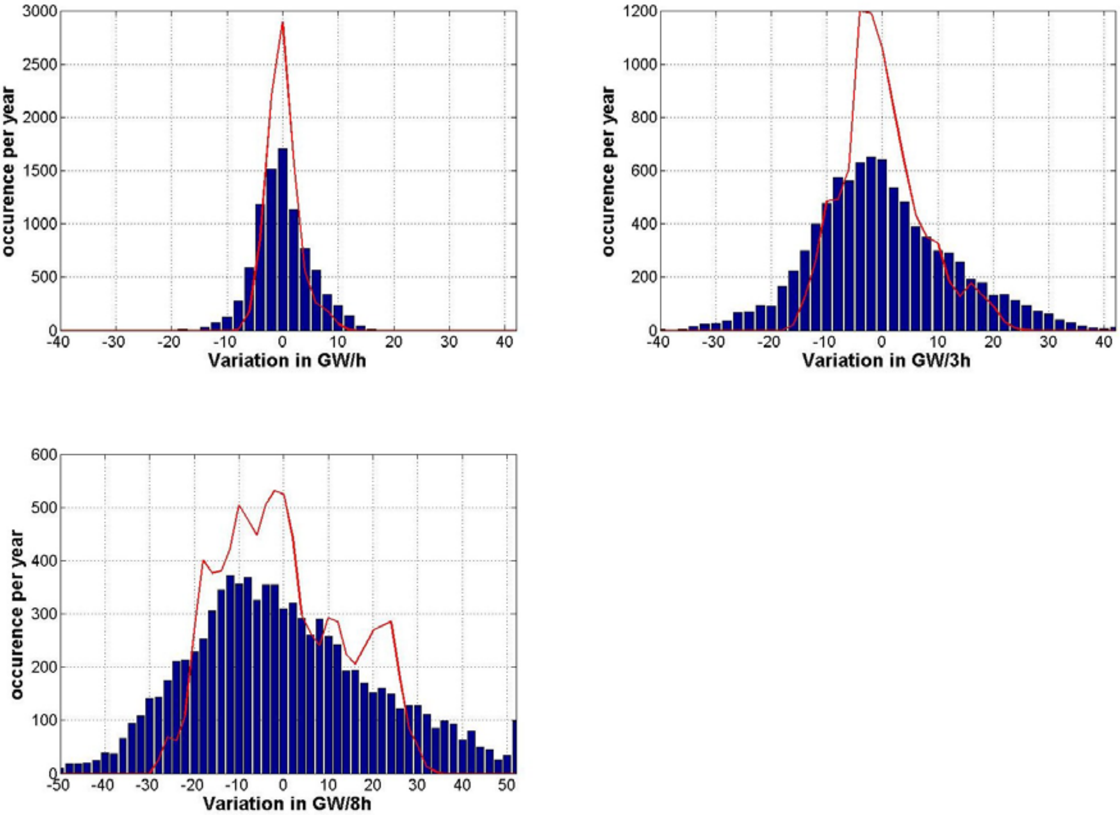

Figure 29: Variation of the load (red line) and the residual load (blue bars) in the scenario 80% A

Same as in 2.1 the variation in scenario C is the highest one, see also figure 30. Variations of +50 GW/8h occur more than 500 times per year. In contrast theses variations occur just around 10 times at scenario B. Even more difficult for the operation of the leftover power plant mix are the fluctuations within 3 hours because some older power plants and base load units have starting times of more than 3 hours (cold as well as warm start-up). For scenario B there are almost no fluctuations of more than +/- 30 GW/3h. Again, scenario C gives an opposite image. Here fluctuations of more than + 40 GWH/3h occur more than 150 times are year and variations of more than –40 GW/3h still more than 50 times. This is again due to the day-night characteristic of PV installations. With high installed PV power the variations of the residual load between day and night will rise accordingly to the installed power. This is especially the reason for the high occurrence of variations of more than 50 GW/8h. Between morning and noon, PV can go from producing no electricity to almost peak power within less than 8 hours. The advantage of this characteristic is the predictability, e.g. PV will never produce energy during night. Wind in contrast can blow with no 100% forecast accuracy and has no clear characteristic like PV. E.g. there can be long periods with strong penetration of wind energy (see fig. 10, scenario B, after hour 8030) or long lasting calms. This characteristic complicates the energy storage capacity issues. This will be discussed in more detail in chapter 3.

All outcomes are again summarized in table 10.

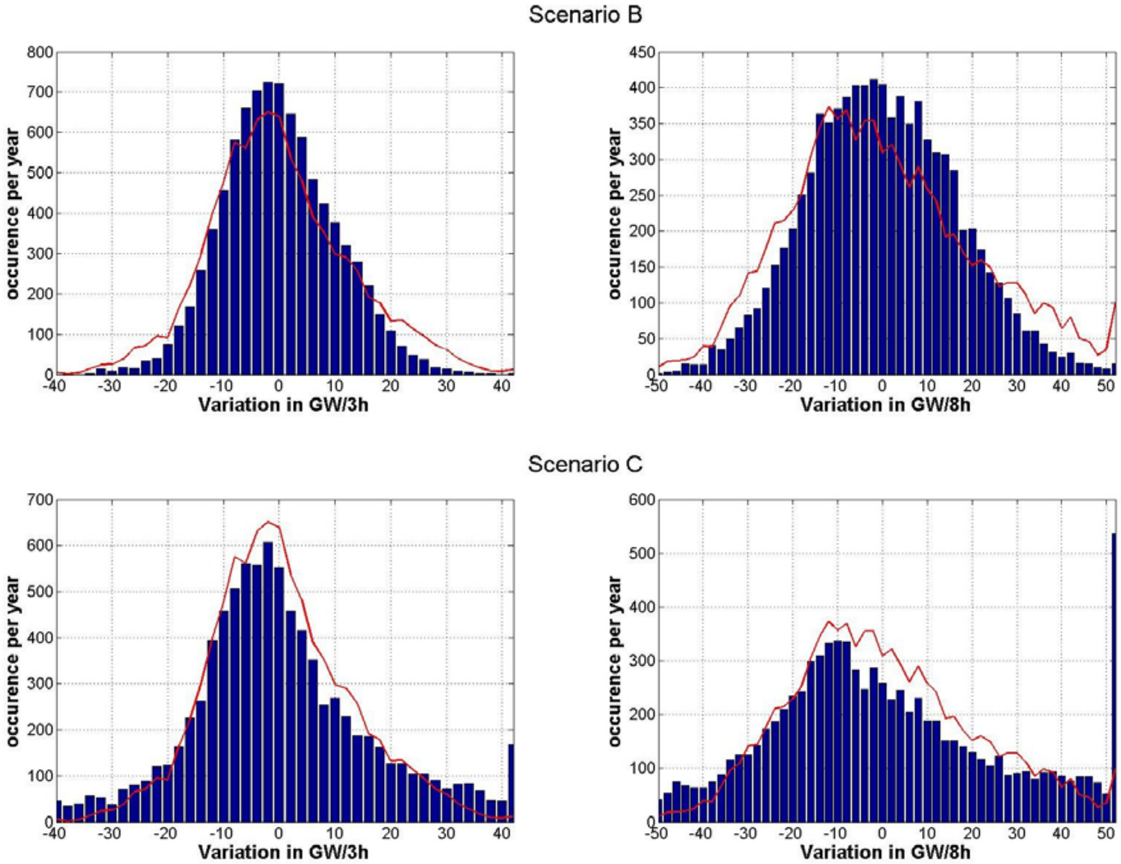

Figure 30: Variation of the residual load with favored development of wind (above), favored development of PV (below) and equal development (red line) as reference

TABLE 12 OVERVIEW OF THE MAIN OUTCOMES ANALYZING THE RESIDUAL LOAD

Scenario	Max. negative Power	Rejected energy w/o storage
A	51.15 GW	21.72 TWh
B	38.85 GW	15.85 TWh
C	69.09 GW	29.04 Wh

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4 Energy storage needs for future RE development scenarios

In the following the 7 scenarios described above are investigated in respect to their energy storage needs for the complete integration of all energy from intermittent renewable energy sources. For that purpose an algorithm was developed to calculate the energy storage needs from an electricity system point of view. This implies that there are no market models or economic considerations made within the algorithm. When considering economic issues the storage needs mostly increase because in many cases it is cheaper to store the energy than to shut down base load units. The aim of the operation of the energy storage system is the smoothening of the residual load as far as possible to allow an easier and safer planning of the operation of the left over power plants. A detailed explanation about the operation of the algorithm can be found in Annex 1. For the further proceeding it is important to now that the target value for the operation of the ESS is a 24 hours average (m24). If m24 or the residual load is below a penetration limit (0, 10 GW etc.), m24 is set to this penetration limit, see Fig. 31.

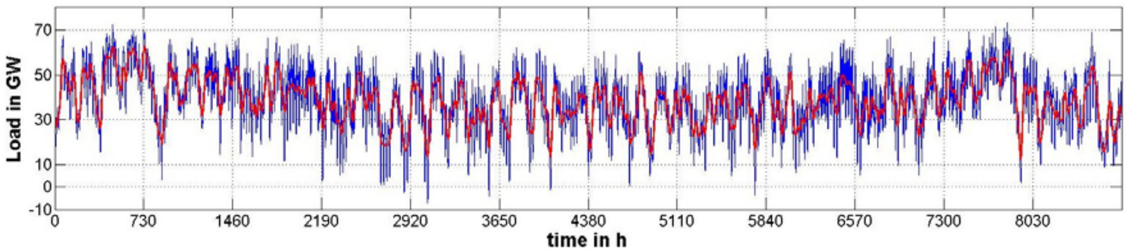

Figure 31: Residual load (blue) and modified 24 h average curve (red) for scenario 2020 A

4.1 2020 Scenario

For the 2020 scenario only actual existing and approved PHES facilities in Germany have been taken into account. That means a rated turbine/pump power of 8 GW and a storage capacity of 60 GWh. The facilities taken into account are all listed in table 11. For simplification all facilities with an installed power of less than 200 MW are summarized as one big ESS. Huntorf, as the only CAES plant is also taken into account. The ADELE project, the first AA-CAES facility, will be taken into account for the 80%, because operation will most likely start after the year 2020. The NREAP of Germany foresees a share of 38.6 % of renewable energies on the net energy consumption. For this scenario it is assumed that this share will be reached. The installed power of the different technologies in the different development scenarios are listed in table 11. In the following Scenario A (equal development) will be investigated in more detail whereas Scenarios B and C are just examined in respect to the changes to Scenario A.

TABLE 13 OVERVIEW OF EXISTING AND PLANED PHES FACILITIES IN GERMANY

Facility	Installed power in MW	Capacity in GWh
Goldisthal	1,060	8,480
Markersbach	1,050	4,018
Hornbergstufe	980	6,073
Waldeck II	480	3,428
Unterstufe Säckingen	370	2,064
Hohenwarte II	320	2,087
Erzhausen	220	940

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Mittelstufe Witznau	220	626
PHES < 200 MW $P_{inst.}$	~ 1,800	~ 7,000
Under construction (planned completion before 2020)		
Atdorf	1,400	13,000
Schmalwasser	500-1,000	?
Riedl	300	?
Total	**~ 8,000**	**~ 60,000**

4.1.1 Equal development

The residual load without any use of storage technologies is shown in the top part of Fig. 32 whereas the two lower plots show the RL with the future PHES system. The graphic is furthermore divided into the smoothened residual load with and without a penetration limit of 10 GW. The penetration limit is marked as a red line in the figure. Due to the penetration limit, the target value (m24) for the ESS operation changes and thus the outcome of the simulation changes as well. As it can be seen there are almost no rejections of renewable energy for scenario A even with a penetration limit of 10 GW. In total there are just 204 GWh that would have to be down regulated. When finishing the approved PHES projects before 2020, it will be possible to fully integrate the installed wind turbines and PV power plants.

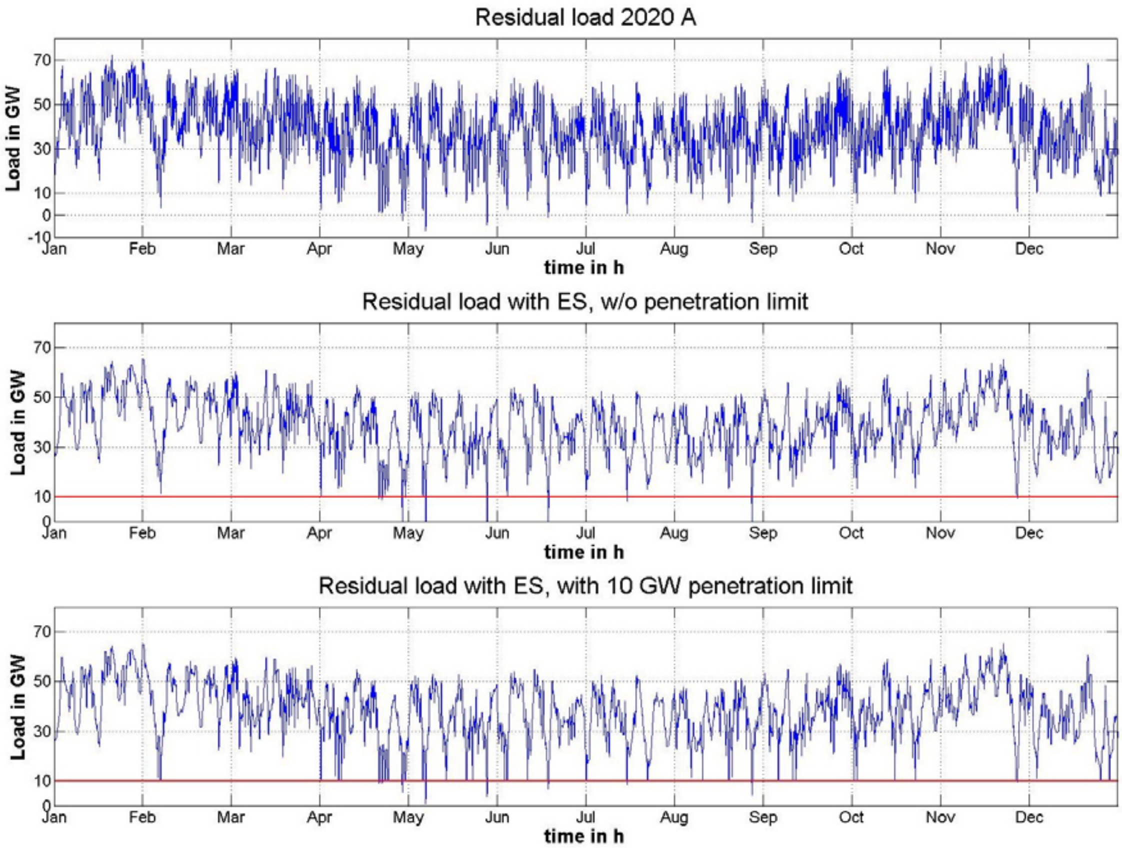

Figure 32: Residual load before and after the use of ESS

Still, the problem with overloads in distribution systems in rural areas especially in the north and east of Germany is not considered. Here there is still potential for optimization, but this is not part of the investigation. There are investigations ongoing nationwide so that it can be assumed that the problem will be solved partly or even in total until the year 2020. The load smoothing potential of

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the PHES system for scenario A is shown in Fig. 33. The high fluctuations of more than 20 GW/h and 30 GW/3h are filtered-out almost completely. This, in addition to a 10 GW penetration limit, enables the left over power plants to react more flexible to load changes. Furthermore the ESS can help to balance out the difference between forecast and actual feed from intermittent renewable sources and thus also improve the operation planning of the power plant dispatch to meet the residual load.

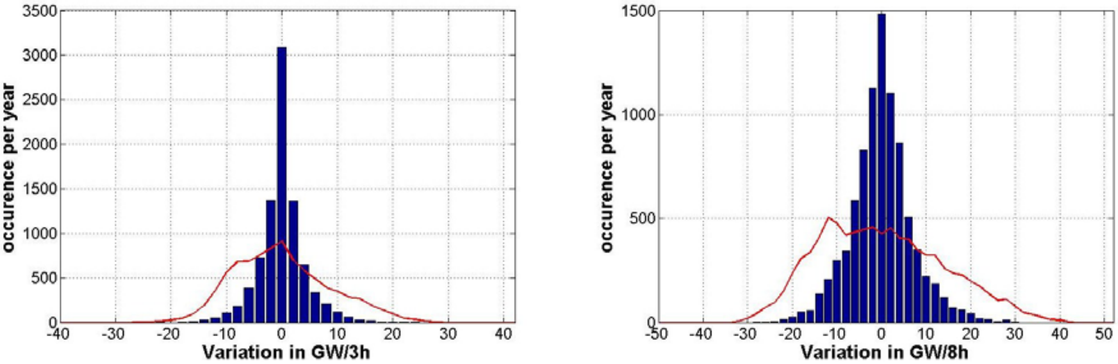

Figure 33: Variation of the smoothened residual load (blue bars) and residual load befor ESS (red line), Scenario 2020 A, 10 GW penetration limit

4.1.2 Favored development of wind energy or photovoltaic

Figure 34 shows the residual load with a penetration limit of 10 GW (marked as red line) after the use of the above defined ESS for the scenarios B and C. As can be seen there are practically no RE rejections in scenario B (44.44 GWh) even with a 10 GW penetration limit. The residual load curve is smoothened and fast load changes can be filtered out very well. Due to the more constant nature of wind, surpluses or shortages appear over a longer period of time. Due to the limit storage capacity the ESS is often filled and emptied completely and cannot store/produce any more energy, even if needed for the smoothening of the residual load. This results in the end in lower capacity factors for the ESS in scenario B than in scenario A.

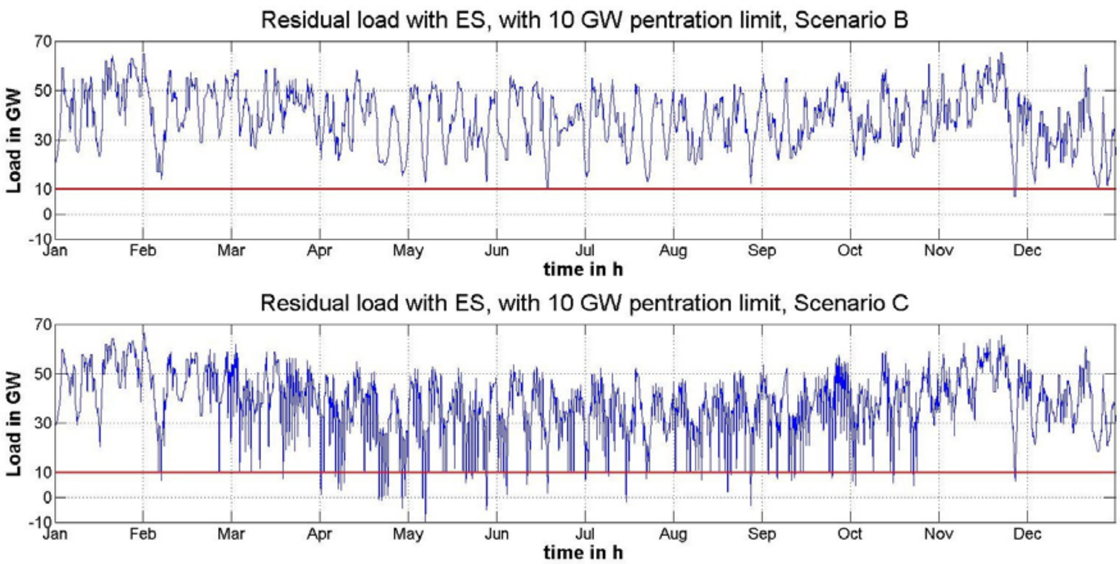

Figure 34: Residual load with 10 GW penetration limit after use of ESS, scenarios B and C

The smoothened residual load of scenario C (Fig. 34, below) has still high fluctuations that appear especially during summer with a high feed in from PV power plants. Due to the higher installed overall RE power in scenario C the power of the surpluses increases and thus more rejections appear than in the two other scenarios. The rejections in scenario C reach almost 1 TWh (965.76 GWh) which is already on the edge of being too high to just down regulate it. Here new storage facilities could be a good and also economical solution. This can be assumed because the capacity factor of the ESS in scenario C is very high (55.50 %) and could therefore grant the economic operation of an additional energy storage facility. This topic is discussed in more detail in chapter 3.3 where reasonable energy storage extension is investigated. The capacity factor is high because of the daily fluctuations of PV (day-night characteristic). Like this the ESS can be charged and discharged almost daily. The actual operation of the ESS regarding pump, turbine power and charging level can be found in Annex 2, plotted in hourly values.

The above mentioned aspects can also be observed when looking at the variations of the resulting residual load after the use of energy storage, see figure 35. In comparison to scenario A the variations in GW/3h as well as in GW/8h are decreasing for scenario B and increasing for scenario C. The reasons for this are discussed in the passage before.

All results are again summarized in table 12.

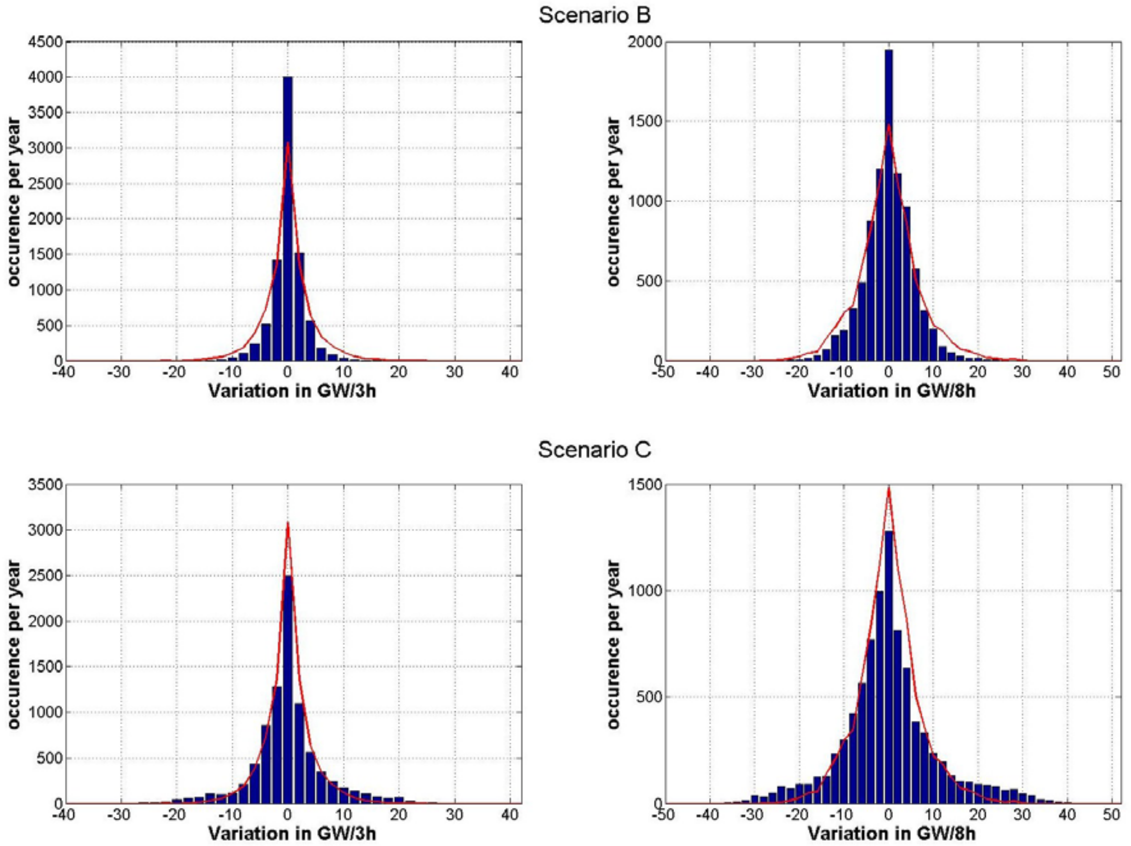

Figure 35: Variation of the residual load after use of ESS, scenarios B and C (blue bars), and comparison to scenario A (red line)

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TABLE 14 OVERVIEW OF THE OUTCOME, SCENARIOS 2020 A TO C

Scenario	Rejected Energy from RE after use of ESS					
	w/o penetration limit			with 10 GW penetration limit		
A	0 GWh			204.20 GWh		
B	0 GWh			44.44 GWh		
C	68.99 GWh			965.76 GWh		
Capacity factor of ESS						
	w/o penetration limit			with 10 GW penetration limit		
	Charge	Disch.	Total	Charge	Disch.	Total
A	29.51 %	24.01 %	53.52 %	27.23 %	22.71 %	49.94 %
B	27.15 %	22.04 %	49.19 %	22.43 %	20.45 %	42.88 %
C	30.38 %	25.12 %	55,50 %	27.57 %	24.42 %	51.99 %

4.2 80% Scenario

Like for the year 2020 Scenario 3 different development scenarios for RE are investigated. The first scenario, the equal development of both, wind and solar energy, will be investigated and described in more detail. For the other 2 scenarios only remarkable changes to scenario A are highlighted. For the following investigation a second technology is added to the simulation program representing the non-existing but needed storage capacity. Technology 1 combines all energy storage facilities used in the simulation of the 2020 scenarios. Technology 2 has now an unlimited capacity as well as an unlimited available power. Like this the computer algorithm will use the power and capacity needed to fully integrate all renewable energies. The finally used power and capacity of technology 2 is the indicator for the needed size of the future energy storage system. Technology 2 does not imply a certain energy storage technology. Which technology will be best to overcome the storage needs determined in this report will be a question of feasibility, cost effectiveness and many other framework conditions and is not part of this report. The calculated storage needs are only from a system point of view. With a full market model and electricity market based price model, the storage needs will most definitely be higher because in many situations it will be more economical to store the energy than to shut down slow starting base load power plants. Nonetheless it is assumed in the following simulation that the power plant mix as well as the transmission and distribution gird is flexible and strong enough to manage an interim load coverage of 100 % renewables.

4.2.1 Equal development

The results of the simulation with the future PHES system and the unlimited technology 2 are shown in figure 37. As it can be seen the residual load is smoothened and any dumping of renewable energies is avoided. This is due to the characteristic of technology 2 in the simulation.

As the second ES-technology has an unlimited power and capacity, it can absorb the total surplus of renewable energies and thus no rejections from RE appear. The residual load and the modified 24 hours average curve (m24) are shown in figure 36. As can be seen the regular 24 hour average curve would be below zero several times a year and thus has to be modified (set to zero).

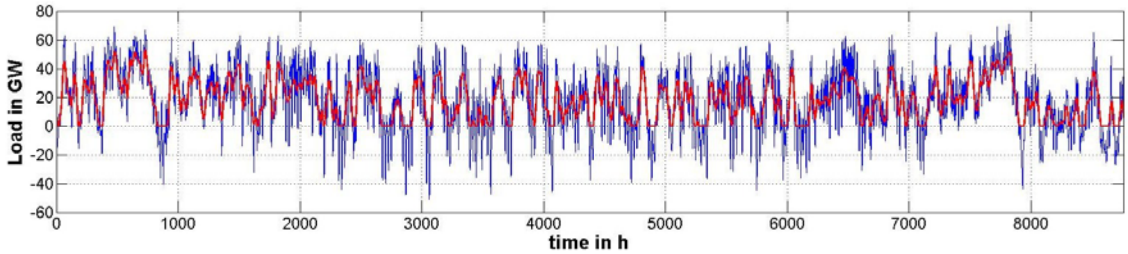


Figure 36: Residual load (blue) and modified 24 h average curve (red) for scenario 80% A

As can be seen in Fig. 37 below, even with the use of technology 2 the peaks of the residual load are still very high. The load that has to be covered by the left over power plants still reaches 60 GW two times in the investigated year. That implies that the backup capacity of controllable power plants has to exceed 60 GW. This power can be provided by fossil fired power plants but also by controllable RE production units like hydropower, geothermal power or biomass. Another possibility is the use of single gas turbines that use gas produced by the methanation of RE surpluses (Power2gas).

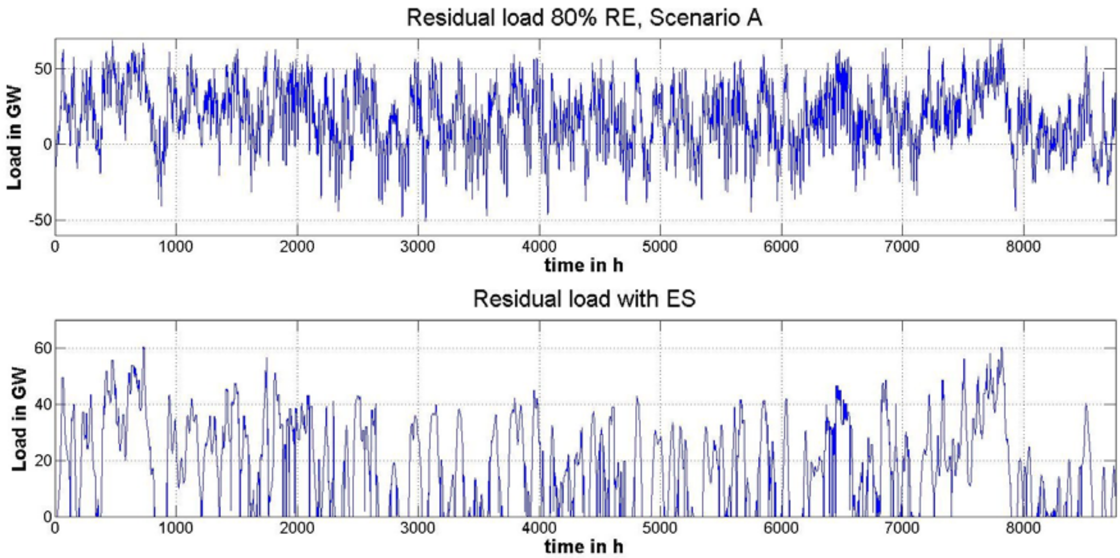
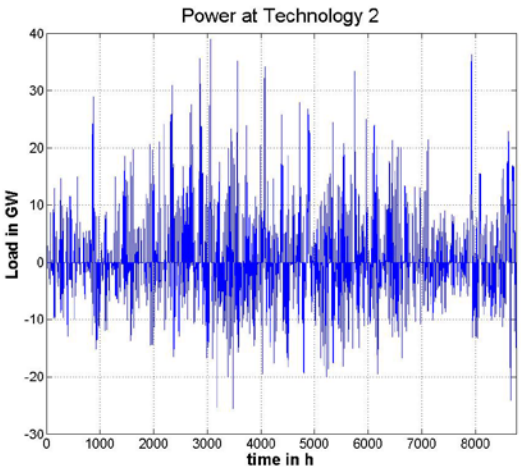


Figure 37: Residual load w/o (above) and with (below) energy storage, Scenario 80% A

Figure 38 is now showing the used power and capacity of technology 2 for scenario A. The maximum charging power is 38.79 GW whereas the maximum discharging power is just 25.17 GW. This difference is due to the target value (24 hour average) and the aim of the operation defined in the algorithm. Discharging is not done only to smoothen the residual load but primarily to be able to integrate the maximum of renewable energy. That means the main goal is to provide the maximum capacity of energy storage when there is a high surplus of renewable energies expected. For that reason discharging power does not necessarily have to be the same as the charging one. When using symmetric installed power for charging and discharging the RL curve would change and the maximum peaks of the smoothened residual load would be lowered. As can be seen in figure 38 on the right side the storage needs of scenario A are very high in comparison to the 2020 scenarios. The charging level of technology 2 reaches 1,308 GWh around hour 3000. This is more than 30 times the size of the actual PHES system (~40 GWh). This surplus is due to a long period of sunny days and additional constant feed in from wind. This effect can also be observed in the residual load curve in figure 37. Around hour 3000 the highest negative peaks of the residual load appear and thus produce this high surplus of energy that cannot be discharged right away because there residual load does not turn positive often enough. The same effect can be observed when looking at the used power. Some few hundred hours before hour 3000, the storage system is almost continuously in charging mode. The last peak that appears at the end of the year is mainly due to strong wind energy penetration. This strong wind energy penetration is constant almost from hour 8000 to the end of the year which can also be observed in the low residual load and the needed charging power. Overall the needed storage capacity is more a long term storage. Long term energy storage is seen as an energy storage facility that is filled and emptied only a few times a year like a seasonal energy storage facility in the Alps of Austria. The fluctuations of less than 100 GWh in capacity and with periods of maximum 24 hours could be handled by regular short term storage systems like PHES and CAES. The long term storage needs will be much higher than the short term storage needs, which is shown by the trend of the charging level curve. This is due to periods of “good” and “bad” weather conditions for renewable energies. The separation of long and short term storage can be reached by making a Fourier transformation of the charging level curve. Like this all fluctuations of less than 24 hours can be filtered out and be declared as short term storage needs. The left over curve can be seen as long term energy storage needs. This will be discussed in more detail in future reports.



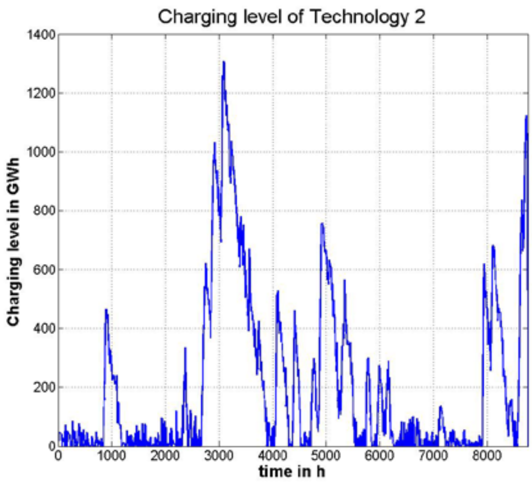


Figure 38: Power at and capacity of Energy storage system 2

The operation of the energy storage system 1 (see table 13) regarding used power in charging and discharging mode as well as charging level is shown in Annex 2, Fig. 8 ESS 1 is used to a very high degree which is reconfirmed by the high capacity factor of 49.59 %, see table 13. The system is filled and emptied completely very often and can therefore be operated economically feasible.

Due to the nature of technology 2, the load variations in the different scenarios decrease to a very high amount. This can be seen as prove for the effect energy storage systems can have on the residual load and the advantages for the operation of the left over power plants. An example for scenario A is shown in figure 39. Other results for the load variations e.g. for scenarios B and C can be found in Annex 2. As the size of the storage system is not necessarily the most economic one, this should just be seen as an indicator for the positive effects of energy storage not only for the integration of renewable energies but also for the system reliability.

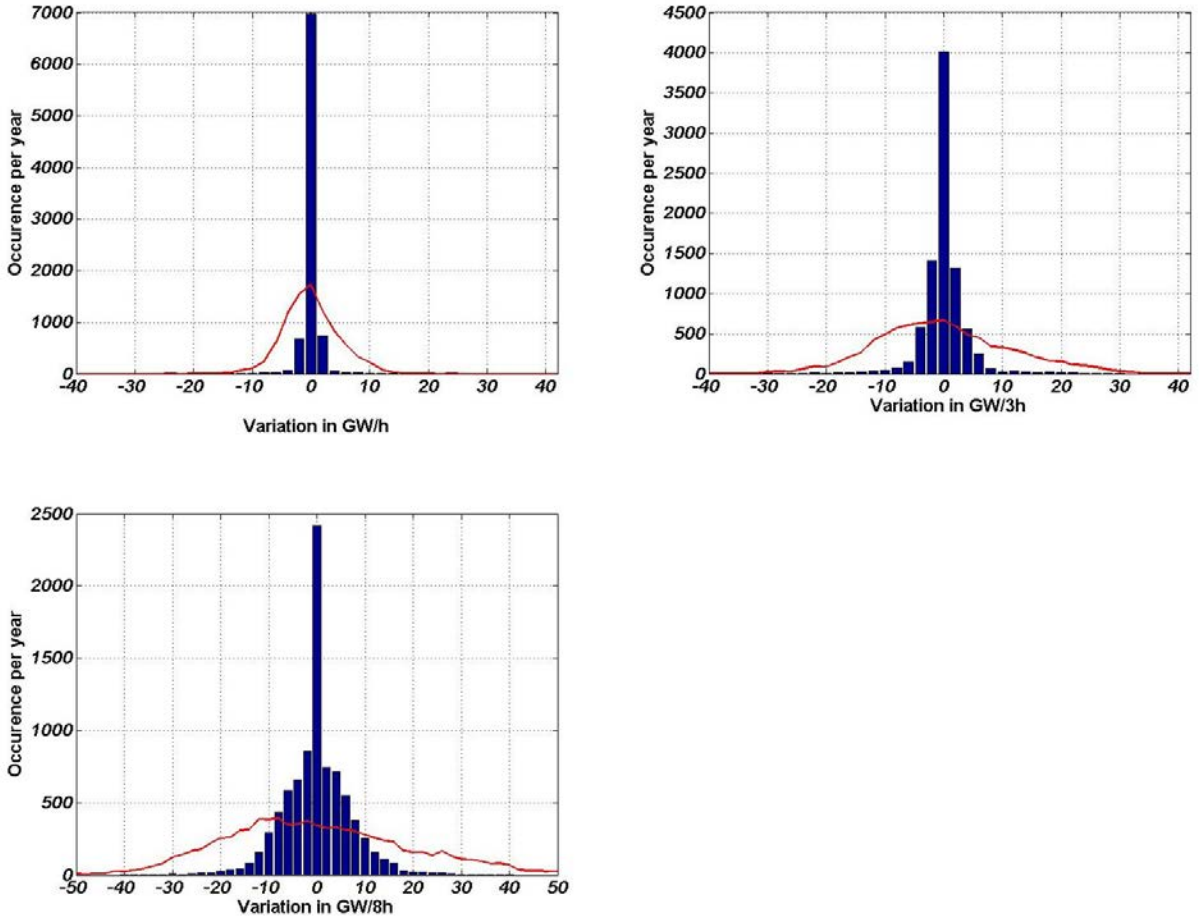


Figure 39: Variation of the Residual load with (blue bars) and w/o (red line) the use of energy storage systems

4.2.2 Favored development of wind energy or photovoltaic

In figures 40 and 41 the outcome of the simulation regarding future needed energy storage power and capacity of scenarios B and C is shown. All other results, like residual load curves before and after the use of energy storage, power and charging level of ESS 1 and load variations of these two scenarios, are listed in Annex 2, plotted in hourly values.

The peak of the storage needs is higher in scenario B than in scenario C although the overall altitude of the fluctuations is higher in scenario C. This is due to the very high penetration of wind in December in the investigated year. This can also be seen when looking at the needed power in both scenarios. At the end of the time series the needed charging power is very low at scenario C whereas it is constantly on a high level in scenario B. The highest peak in scenario C appears around hour 3000 like in scenario A. This arises from a combination of constant feed in from wind energy and a very high amount of PV power that is fed in over a long an sunny period. The needed power in charging mode is 24 GW higher in scenario C than it is in B (see table 13). This can be derived directly from the overall higher installed RE power (see table 7).

Regarding the capacity of the long and short term storage needs, the long term storage needs will be equal or higher in scenario B. The short term storage needs will be higher in scenario C because of the daily fluctuations in PV power production. Estimations about the reasonable extension of the energy storage system will be made in the next chapter. For a more precise outlook on the long and short term storage needs, more investigations will have to be made regarding the frequency of the fluctuations and possible development potential of future energy storage technologies. Furthermore, there are verifiable big differences in the storage needs (capacity and power) in the different scenarios. This proves that the future storage needs will strongly depend on the development of the renewable energy sources wind and sun.

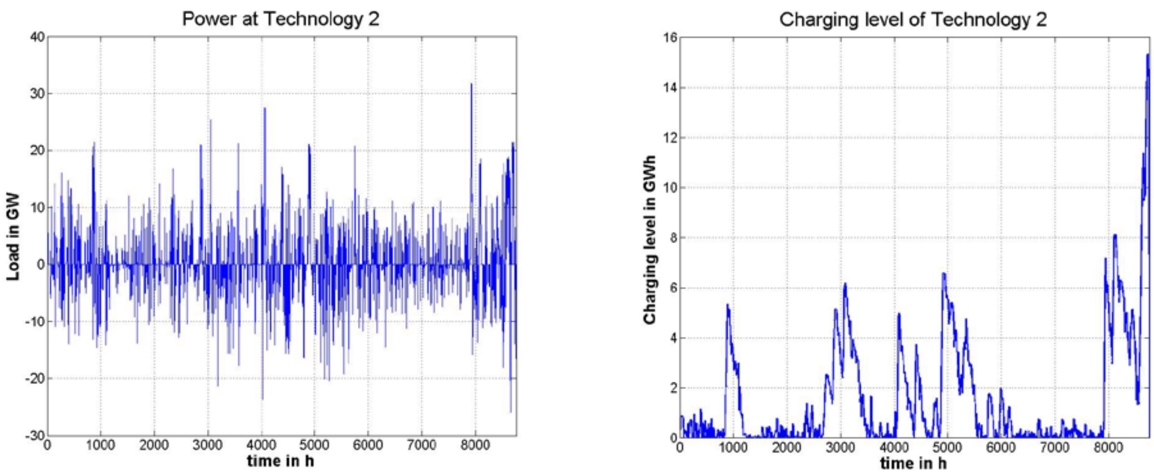


Figure 40: Additionally needed storage power and capacity, Scenario 80% B

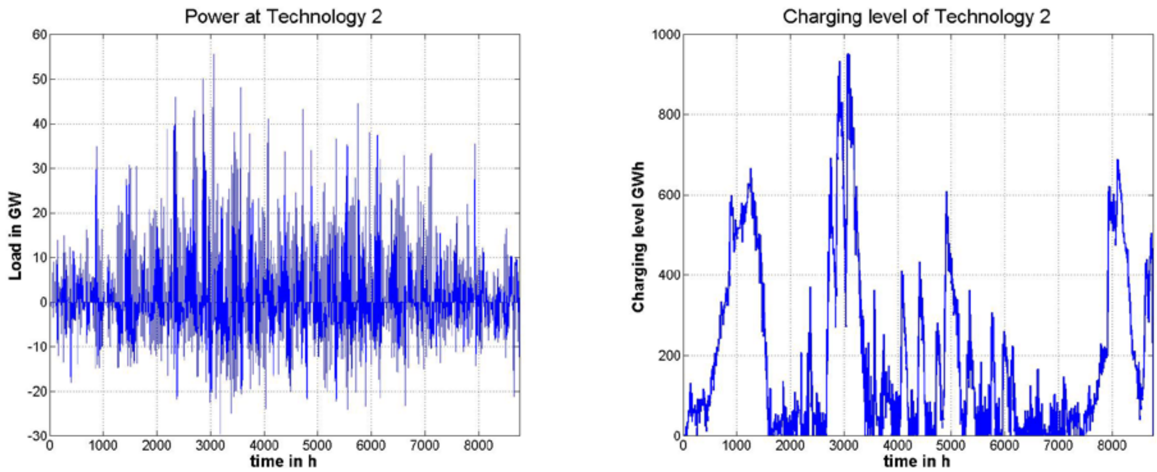


Figure 41: Additionally needed storage power and capacity, Scenario 80% B

TABLE 15 OVERVIEW OF THE OUTCOME, SCENARIOS 80% A TO C

Scenario	**Needed power (Tech. 2) in GW**		**Needed capacity (Tech. 2) in GWh**
	Charging	Discharging	
A	38.79	25.17	1,308
B	31.85	25.74	1,534
C	55.16	29.04	950

Capacity factor						
	Tech. 1			**Tech. 2**		
	Charge	Disch.	Total	Charge	Disch.	Total
A	27.17%	22.42 %	49.59 %	5.43 %	6.39 %	11.82 %
B	24.99 %	20.32 %	45.31 %	4.97 %	4.48 %	9.45 %
C	30.03 %	24.59 %	54.62 %	5.36 %	8.07 %	13,43 %

5 Conclusion

To reach the ambitious target of renewable energies until 2050, set by the German government, energy storage will be needed. In 2020 the storage needs will strongly depend on the flexibility of the electricity supply system and the resulting penetration limit for renewable energies. Without any penetration limit the existing and the planed extension of the German PHES system will be enough to integrated almost all surpluses from renewable energies. With a penetration limit of 10 GW the rejected energy is high enough to enable the economic operation of an additional energy storage facility.

This however implies that the planned facilities will be completed before 2020. For scenarios of 80% share of RE on the net electricity consumption energy storage systems of 950 GWh to 1,534 GWh will be needed, depending on the particular scenario. The needed installed charging power reaches from 38.79 GW in scenario A to 55.16 GW in scenario C. The discharging power is lower in all scenarios but still an additional needed power of 25 GW in scenarios A and B and 29 GW in scenario C is needed

After 2020 the storage needs will rise very fast. When looking at the results of the simulation of the scenarios with an 80 % share of renewable energies on the net electricity consumption, additional energy storage facilities are needed. The size regarding needed charging and discharging power as well as storage capacity is strongly depended on installed technology of renewable energies. There is a big difference between the scenarios with a favoured development of wind and a favoured development of photovoltaic respectively. The needed power is higher with a stronger development of PV whereas the needed capacity increased with a favoured development of wind power.

Therefore it will be important to define an optimal share amongst renewable energies to minimize the additionally needed energy storage systems. Furthermore the combination of the electricity systems of different countries can bring a lot of benefits. As has been shown in report D5.1 of the stoRE project for Austria, the Austrian PHES system has enough capacity to fully cover the surpluses produced by renewable energies in Germany. However this would result in the need of transmission capacity extension as well as a high extension of the installed pumping and turbine power of the Austrian PHES facilities.

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List of figures

Annex

Annex 1: Description of the computation algorithm

For the above made calculations an algorithm was developed to provide an optimized use of the energy storage system only from a system point of view. The aim was to cut the peaks of the residual load to an optimum, achievable with available storage technologies. First a 24 hour average value (A) for each point of investigation of the residual load is determined. For this purpose all values until 12 hours before and after the given point are taking into account, see Fig. 1. The aim of the algorithm is now to approach the residual load to the 24 hour average as much as possible with the provided energy storage facilities. Is A smaller than the residual load, the load has to be raised, if A is higher than the residual load, the load has to be lowered.

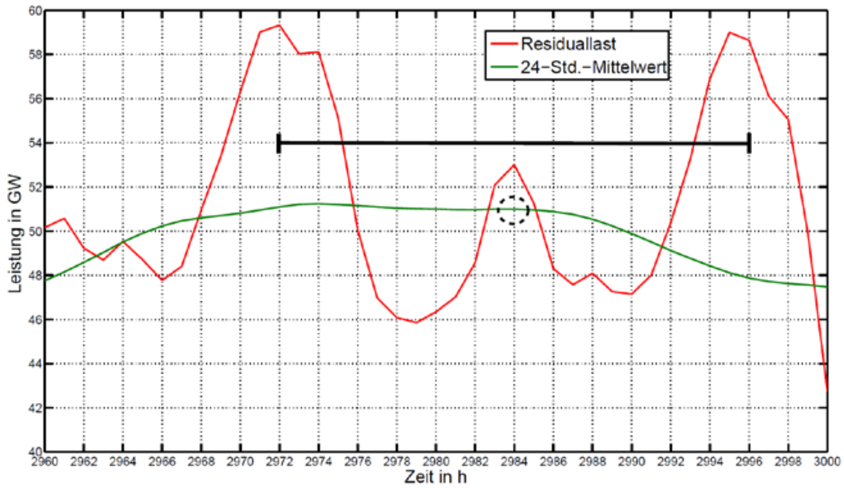

Fig. 1 Calculation of the floating 24 hour average

When the residual load is negative for a longer period, so that the 24 hour average would be negative too, the value for A is set to zero. This can also be implemented for RE penetration limits. If A would be below the penetration limit (flexible or static), A is set to the penetration limit. Like this it is granted that – with enough storage capacity – the energy from renewable sources could be integrated in total and the resulting load can be handled by the left over thermal power plants. To maximize the accuracy of the simulation, the area between the measured values is interpolated with the factor 100. Thus there are now 876000 points instead of 8760 for one year. Furthermore for each charging and discharging cycle the maximum needed energy is determined by a simple integration between the particular intersections of the residual load and A. During a charging cycle the capacity of the particular ESS is calculated. After that a lower boundary for the interval is declared which is the minimum value of the residual load of this cycle, see Fig. 2. The actual storage capacity is divided by the time of the interval. That leads to the power the ESS could provide during the whole interval. When subtracting this amount of power from the lower boundary the upper boundary is obtained. When the upper boundary is lower than the residual load, the boundary is the residual load for that interval, see Fig. 2. For the other case the maximum power of the ESS is important. If the difference between upper and lower boundary is higher than the rated power of the Energy Storage technology the boundaries have to be adapted, see Fig. 2. That was the first cycle of the first storage technology for this interval. Now the storage capacity of the technology under investigation is reduced by the before stored energy. With this new storage capacity the cycle starts over again. This is just for the energy purpose; the already used power is hereby already taken into account. These loops finish either when the left over storage capacity is less than 0,01 MWh or when the EES already stored all the requested or storable energy. The latest can be found when looking at difference of the storage capacity after each cycle. When the capacity doesn't change either the requested energy is fully stored or the ESS can't store any more energy due to power limitations. When this is finished, the algorithm starts with the next technology that has a lower priority. Overall 6 different technologies can be investigated. The clear prioritization is made because of the investigation from an energy system point of view. Thus the technology with the highest efficiency is used first and then rest. The algorithm works in a similar way for the discharging cycles.

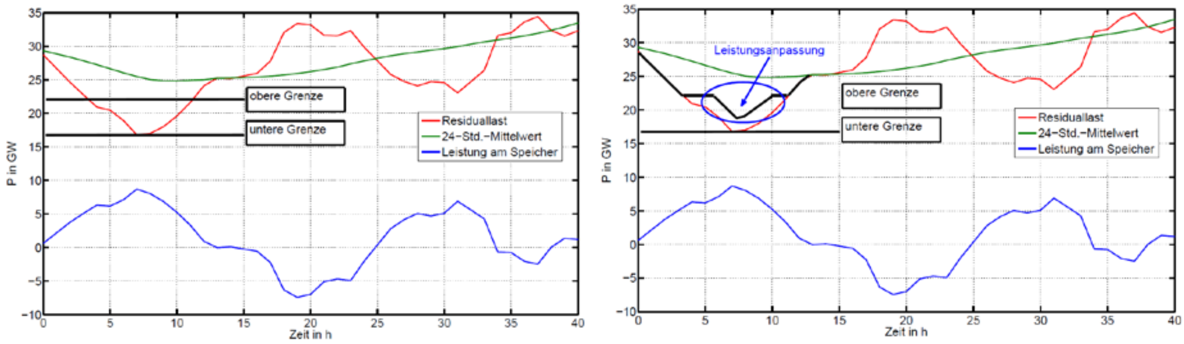

Fig. 2 Definition of the bounderies for the optimization of the ESS operation (left) and actual boundaries and power limitation (right)

As the goal of the ESS operation in this report is the maximum integration of a surplus of renewable energy production a further optimization of the EES operation was implemented. The optimization process starts when the residual load is below the penetration limit or below zero. When the residual load is below these limits the left over power plant mix cannot handle it any more. For that purpose it is important to integrate the maximum of these surpluses. If the surplus is higher than the actual storage capacity and the EES is not empty, the 5-10 (depending on the load situation) cycles before are optimized in a way that the EES is empty at the moment where the full storage capacity is needed to integrate RE that would have to shut down otherwise.

To determine the storage needs of the different scenarios, the actual energy storage system was implemented first and for the reference scenario. For the 2020 scenario all the already approved and planned facilities where also taken into account. Now, to determine the storage needs an additional storage technology is introduced with unlimited power and unlimited storage capacity. Like this the algorithm computes how much new installations would be needed to fully integrate all energy from renewables (with regard to the negative residual load or a certain penetration limit). After looking at the used power and the used capacity of the unlimited storage technology, a realistic amount of new installations can be estimated as well as the rejected energy from renewable sources caused by this limitations.

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Annex 2: Plots

Plots for all residual loads and technologies 2020 scenarios

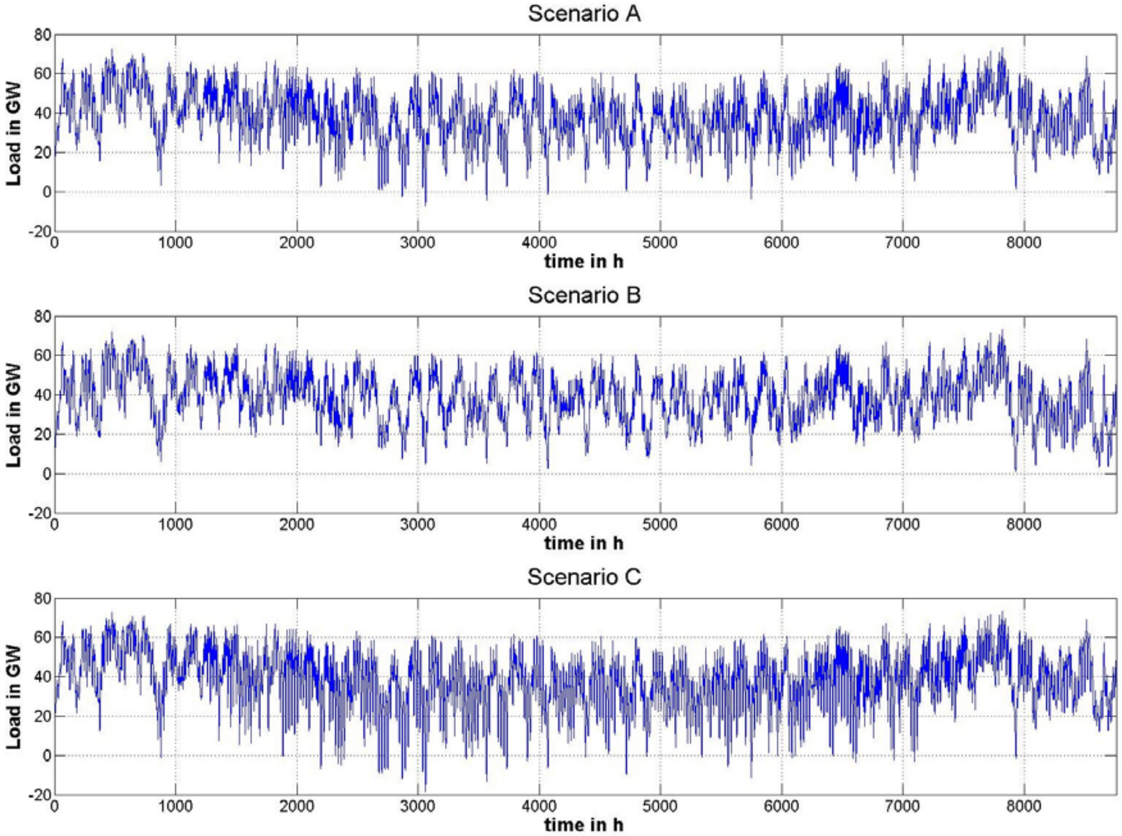

Fig. 3 Residual loads for the 2020 scenario

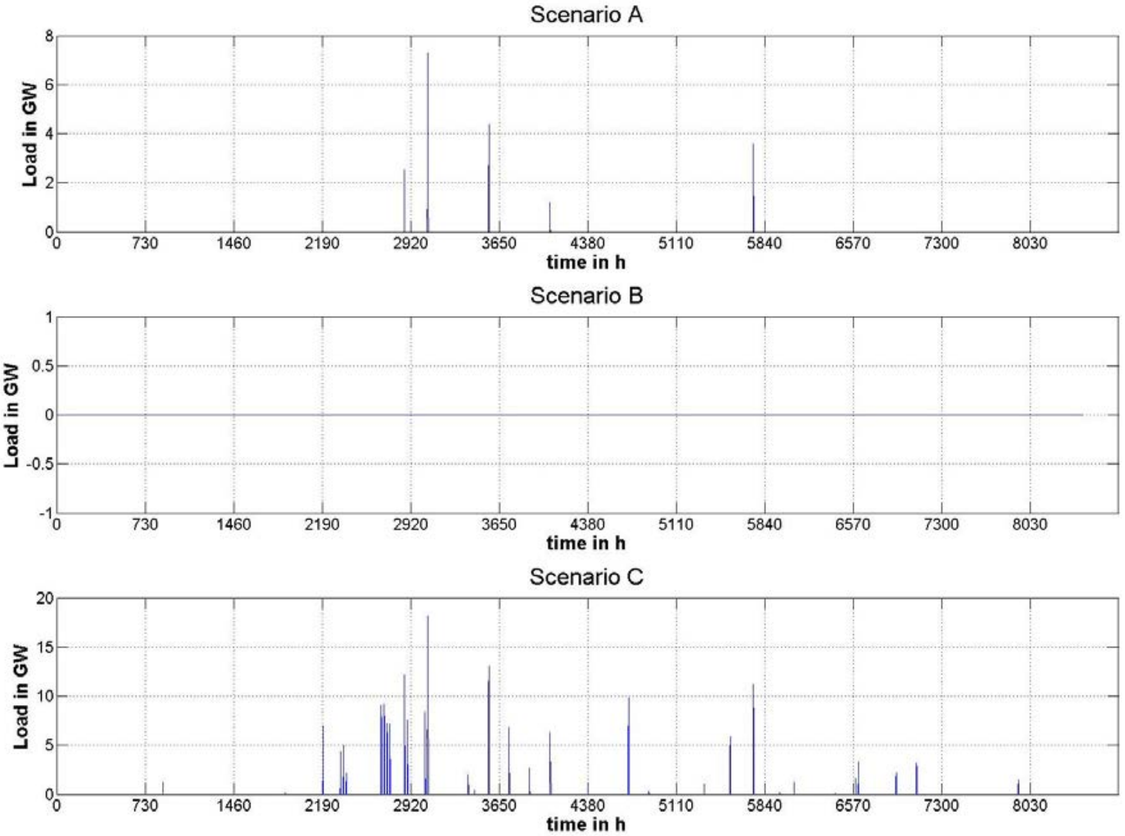

Fig. 4 rejected energy 2020, no penetration limit

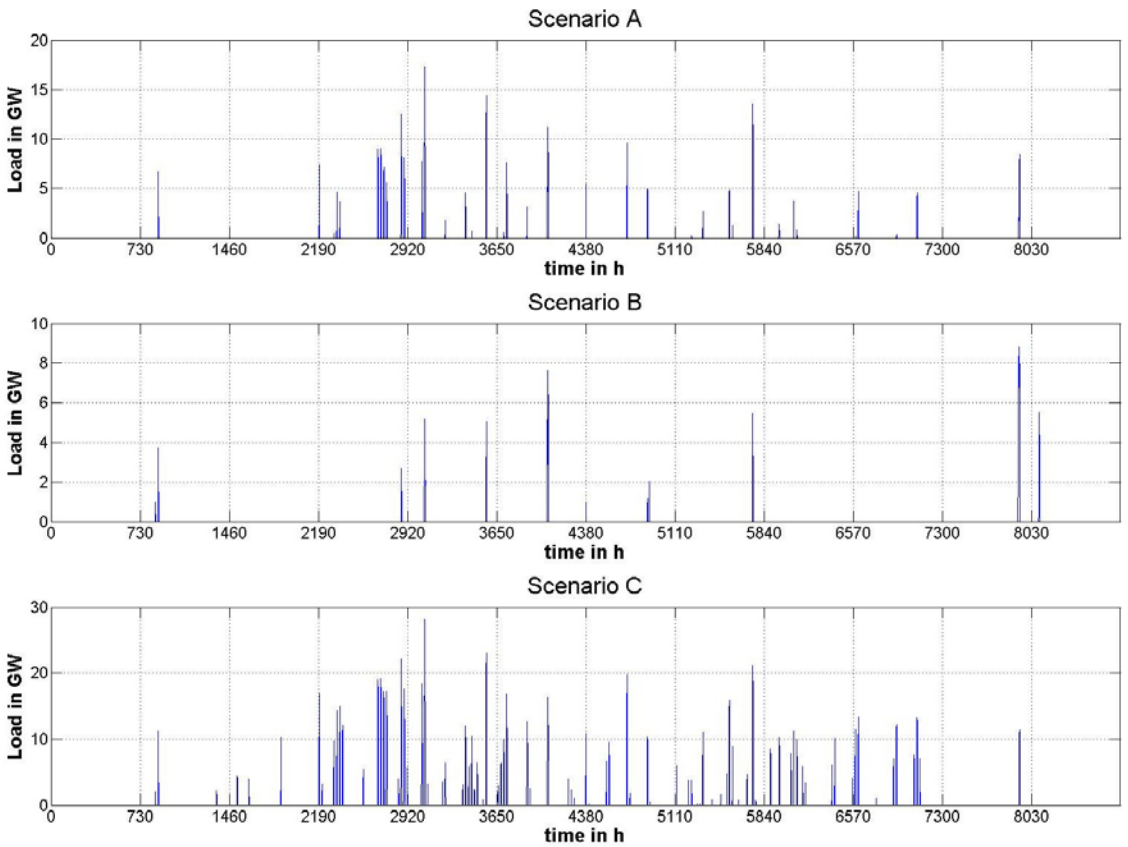

Fig. 5 rejected energy 2020, 10GW penetration limit

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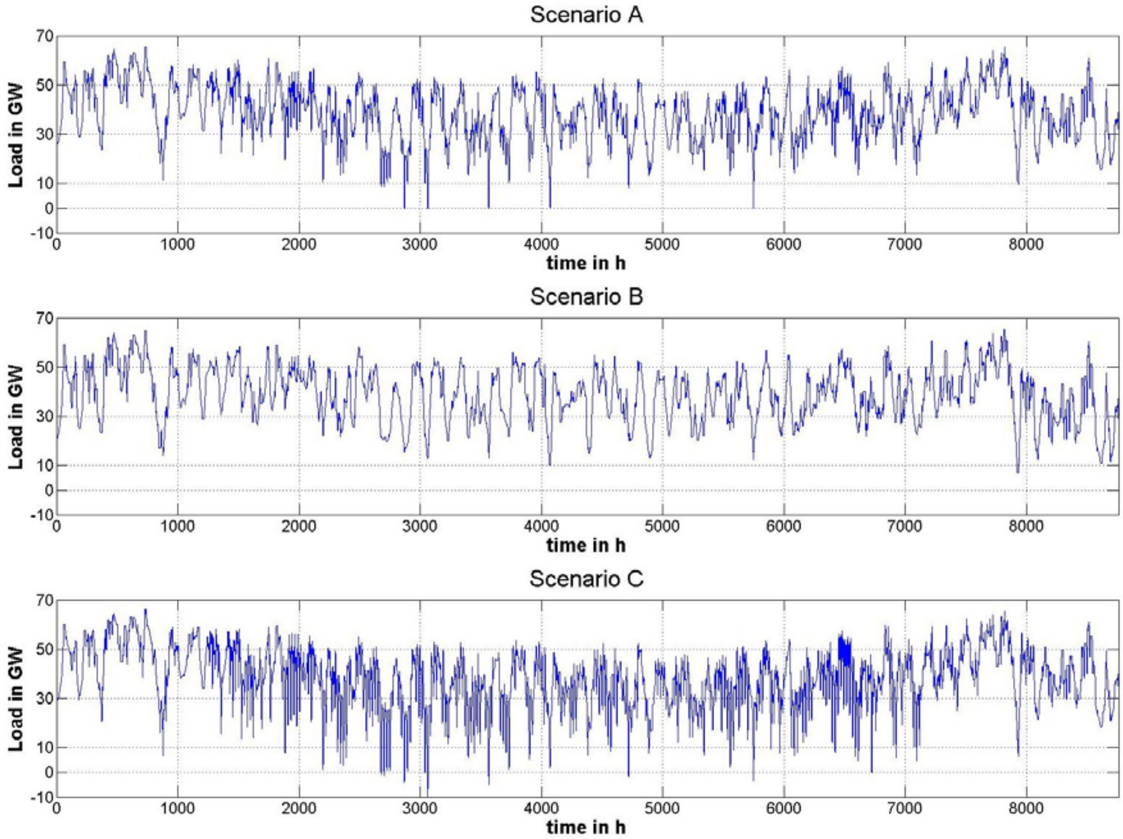

Fig. 6 Residual load after use of ESS (no penetration limit)

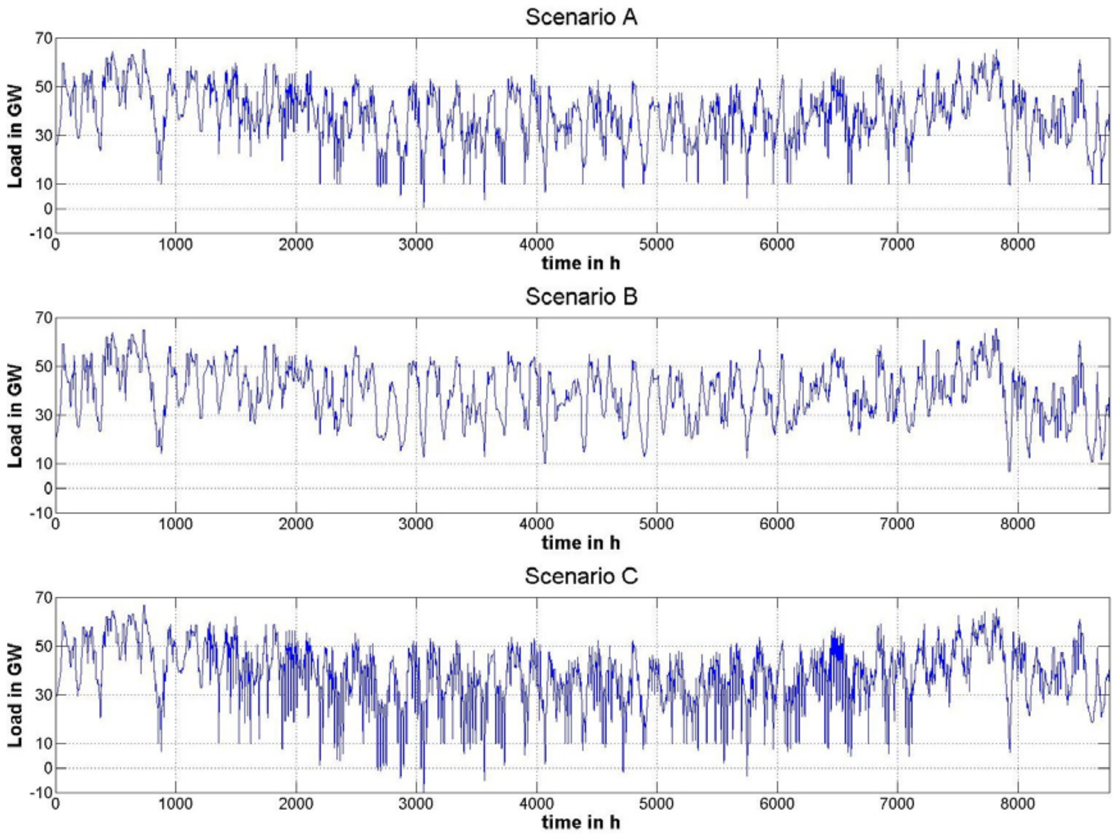

Fig. 7 Residual load after use of ESS (10 GW penetration limit)

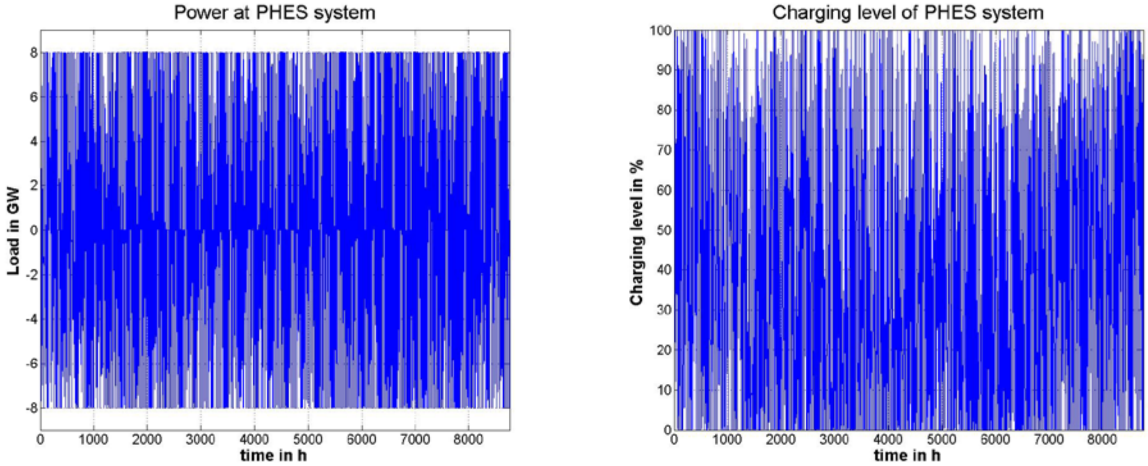

Fig. 8 Power and charging level of PHES system, scenario 2020 A

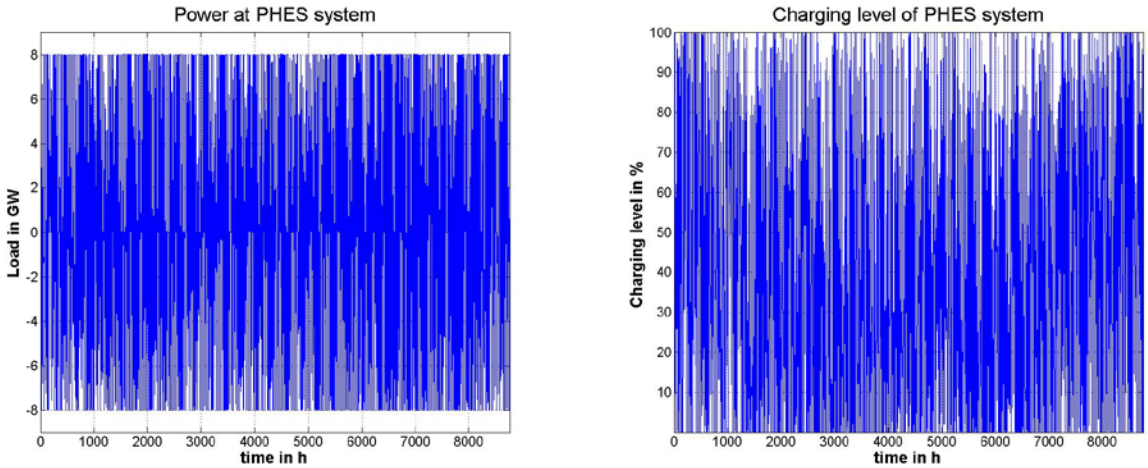

Fig. 9 Power and charging level of PHES system, scenario 2020 A, with 10 GW penetration limit

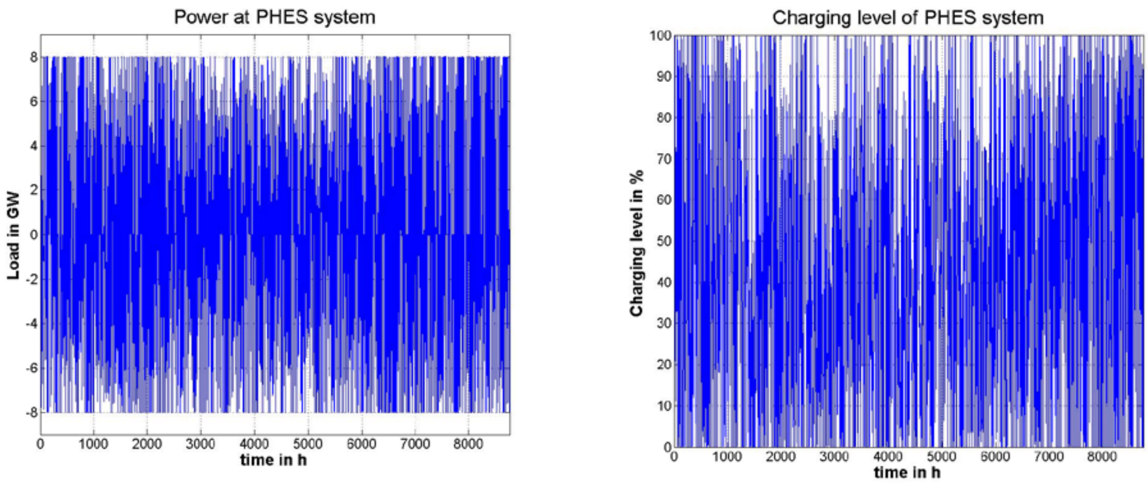

Fig. 10 Power and charging level of PHES system, scenario 2020 C

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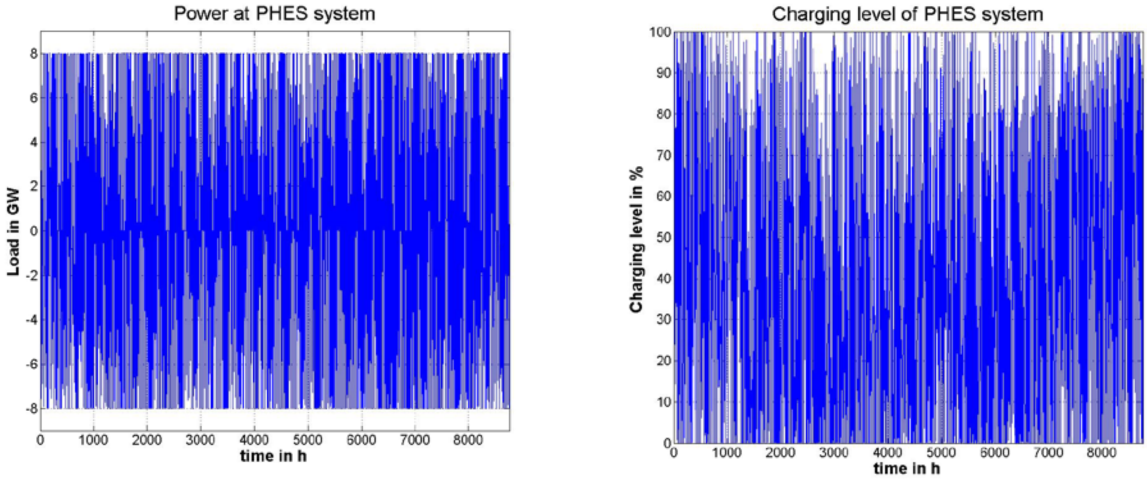

Fig. 11 Power and charging level of PHES system, scenario 2020 C with 10 GW penetration limit

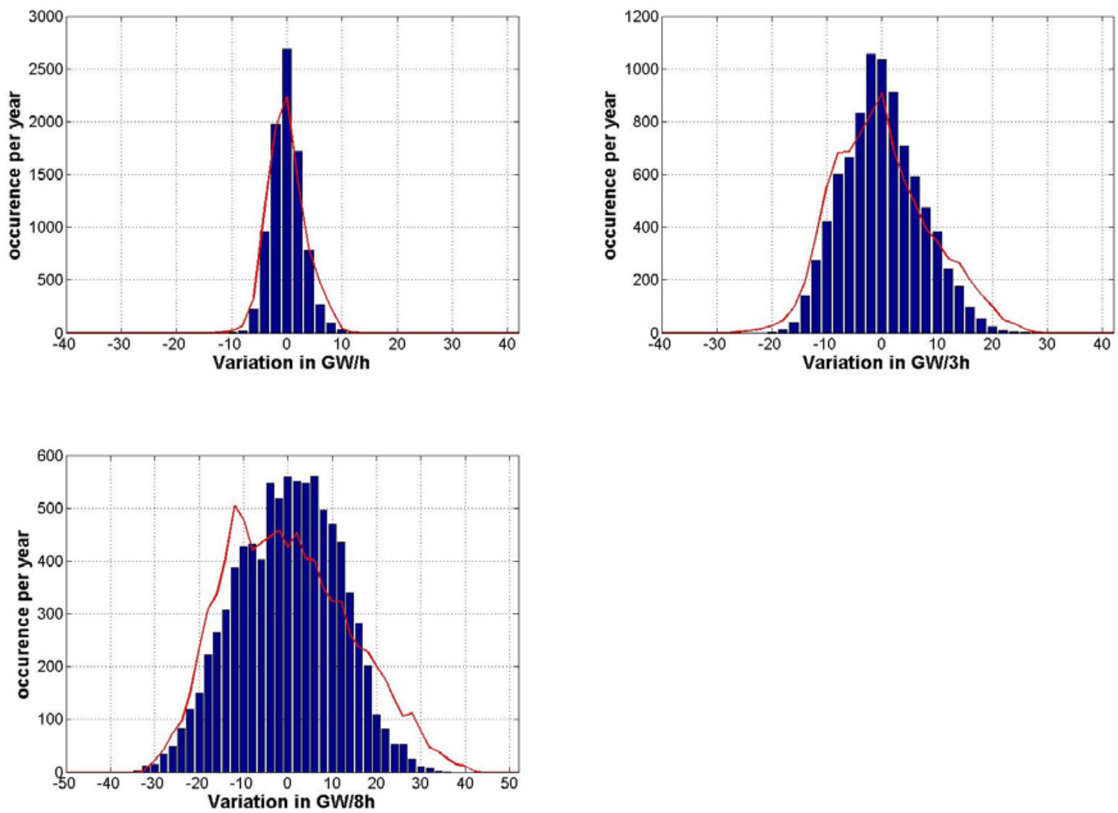

Fig. 12 Scenario 2020 B (blue bars) and Scenario 2020 A (red line)

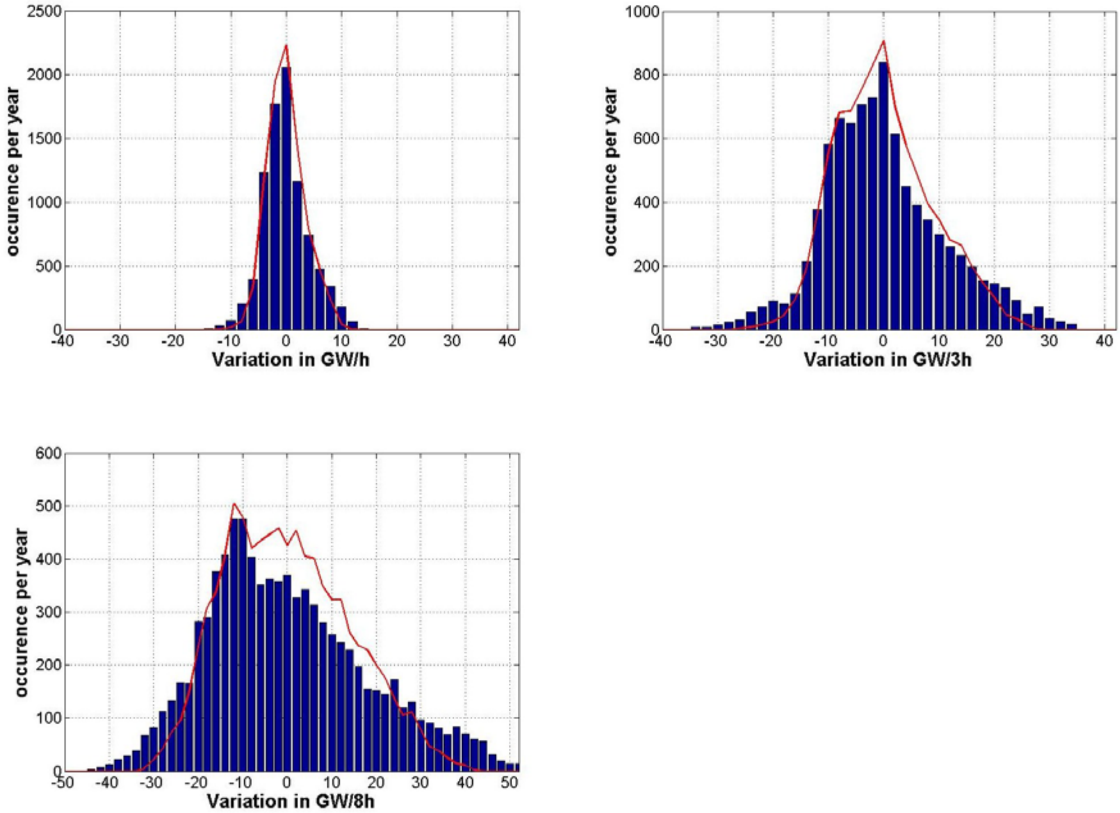

Fig. 13 Scenario 2020 C (blue bars) and Scenario 2020 A (red line)

Plots for all residual loads and technologies 80% scenarios

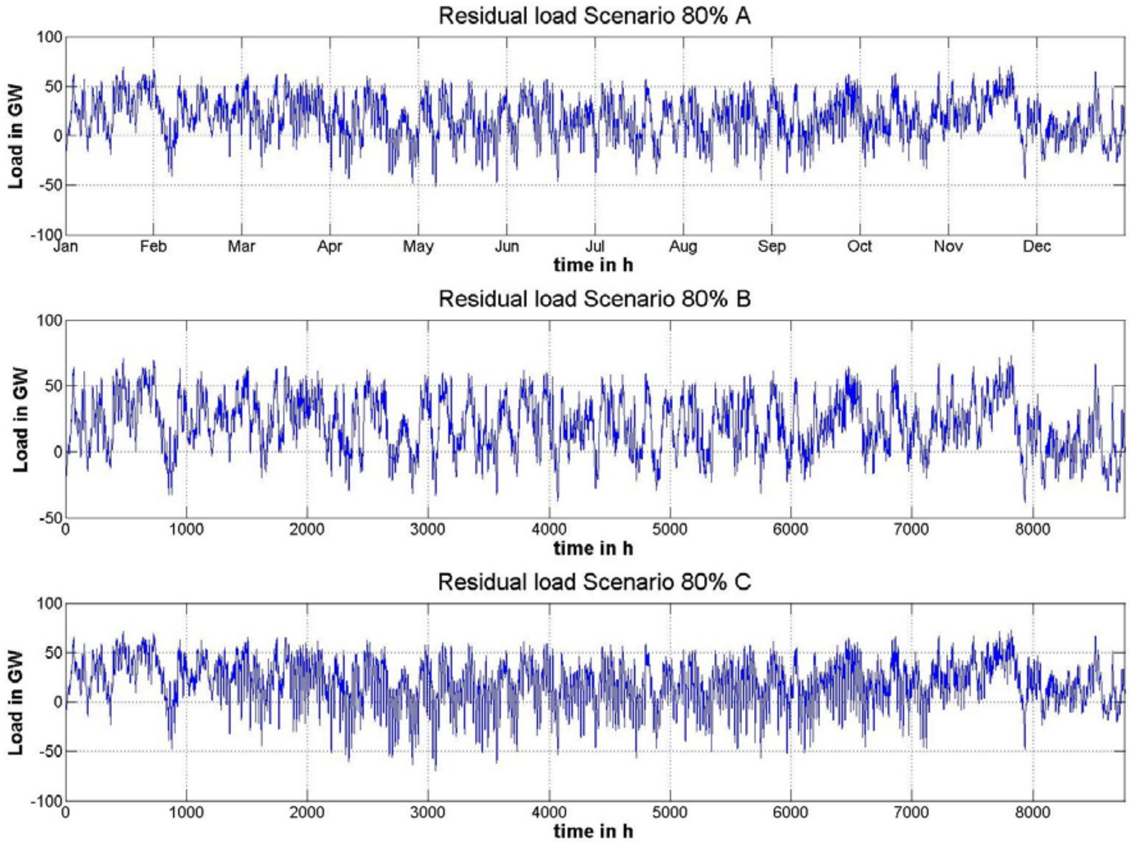

Fig. 14 Residual loads for the 80% scenarios

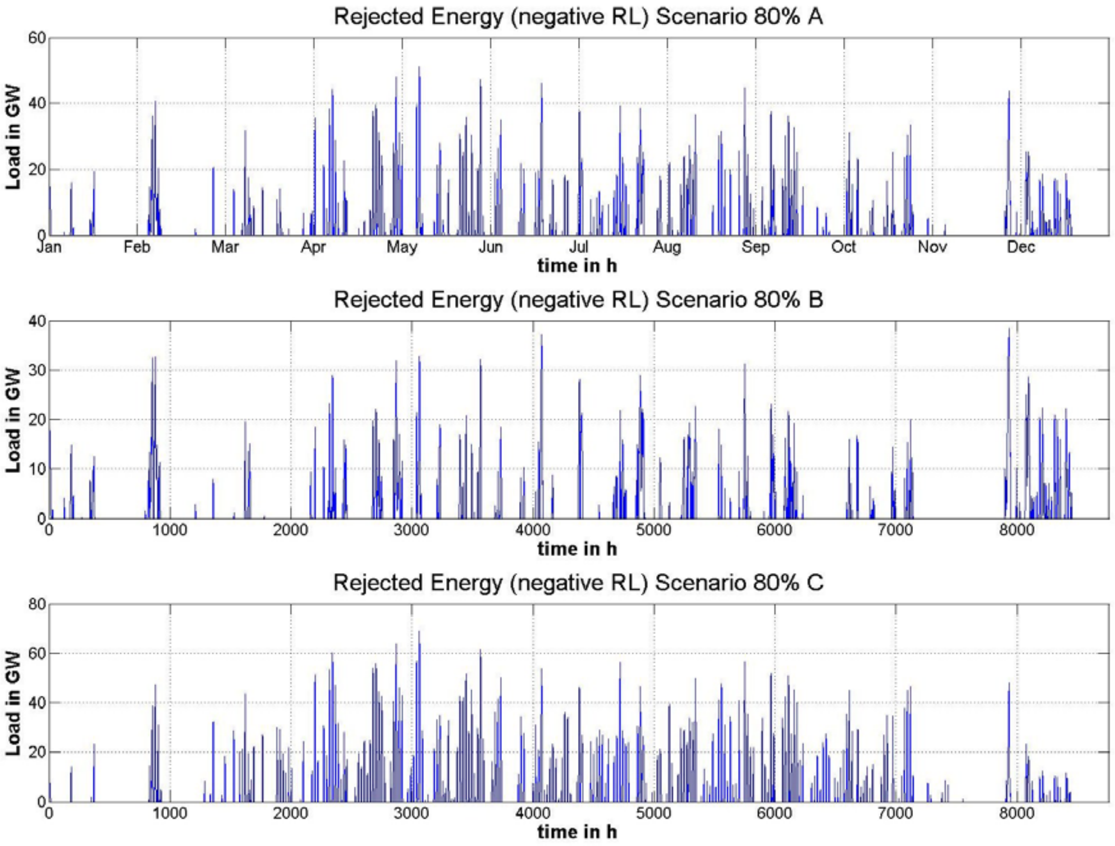

Fig. 15 rejected energy from RE without ES

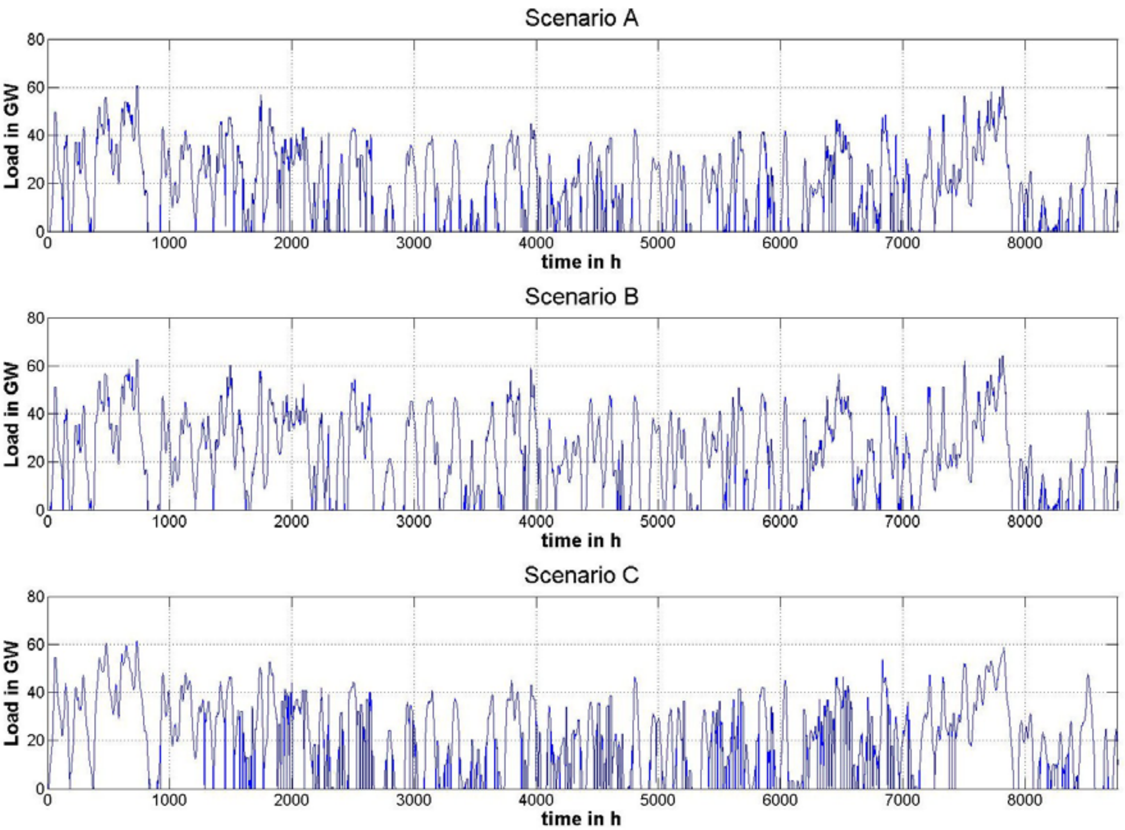

Fig. 16 Residual load after use of ESS

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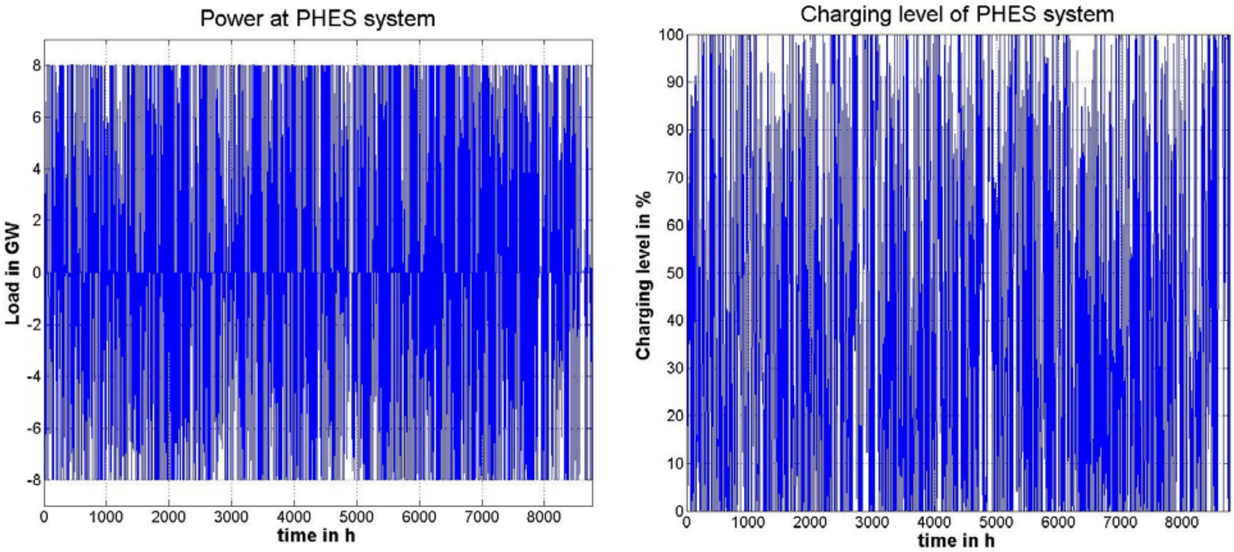

Fig. 17 Power and charging level of PHES system, scenario 80% A

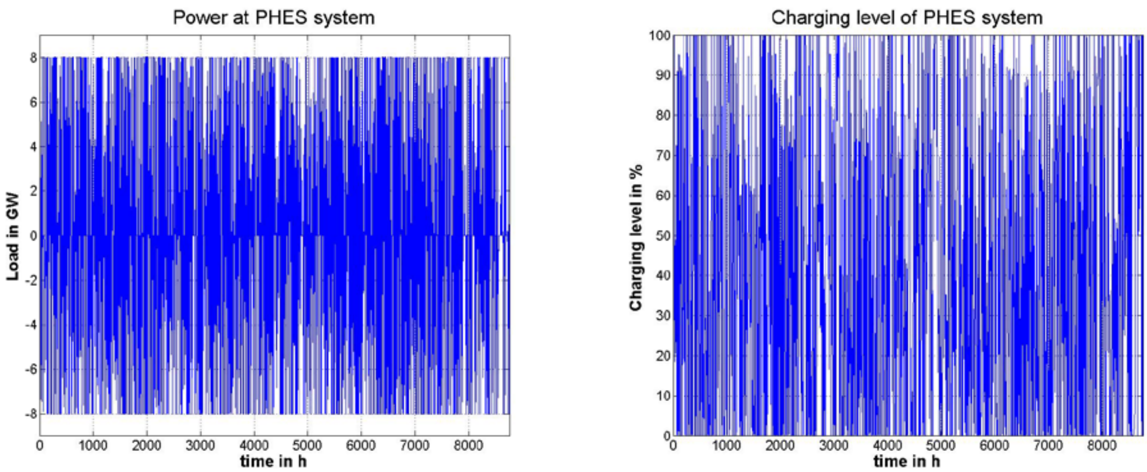

Fig. 18 Power and charging level of PHES system, scenario 80% B

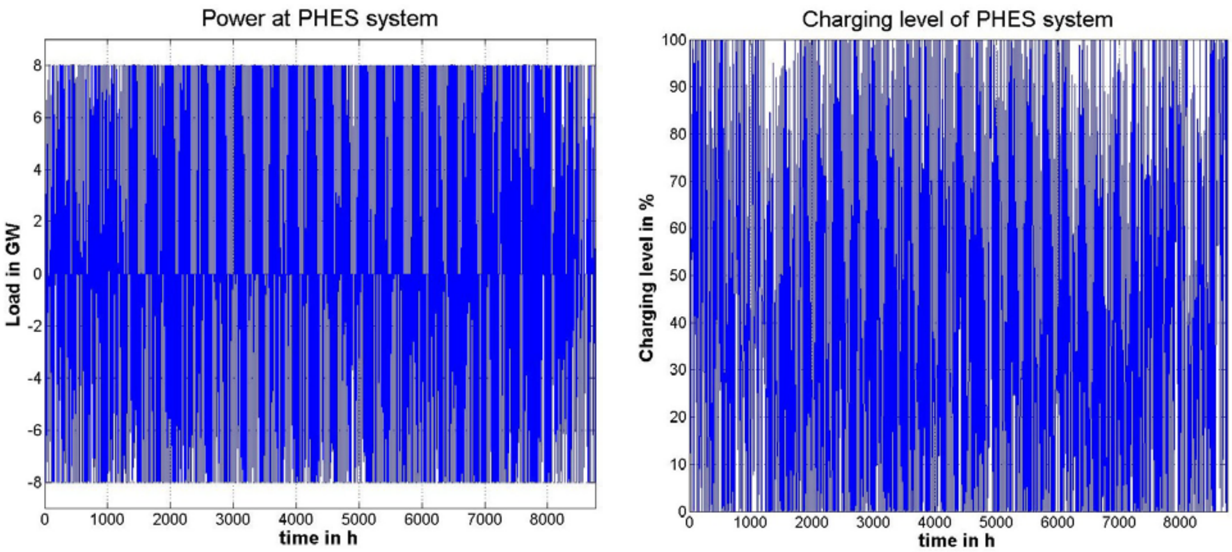

Fig. 19 Power and charging level of PHES system, scenario 80% C