Storage plants – a solution to the residual load challenge of the power sector?

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Abstract

We formulate the concept of a multi-functional energy system, called *storage plant*, as a possible solution to cover the variable residual load that appears in most countries after introducing renewables in the power sector. A storage plant consists of a photovoltaic power plant, a heat storage system with electric heater to transform solar power, a steam power cycle to convert stored heat to dispatchable power, a backup heating unit for the storage based on the combustion of biomass or other renewable hydrocarbons, and a gas turbine with waste heat recovery for peak loads. After explaining the storage plant concept, the paper describes a simulation model of the German power sector and its transformation from the year 2020 with roughly 40% renewable electricity share to 2040 with a hypothetic 90% renewable electricity share. Multi-indicator benchmarking over that period shows that storage plants can have a key role to achieve emission goals and at the same time sustain full supply security within the German power sector.

Keywords: thermal energy storage, flexible power, firm capacity, renewable electricity

1. Introduction

A key challenge of transforming the power sector from fossil fuel based to renewable energy based generation is the residual load curve, which is basically the result of subtracting fluctuating renewable power production from power demand, and tracking that difference over a specific period of time [Schill 2014], [Vahlenkamp et al. 2019], [CAISO 2016]. The residual load curve can vary greatly over time between a maximum, when no renewables are available, and zero, when renewables work at maximum supply [Jessen-Thiessen et al. 2019]. The objective of the present paper is to introduce a novel energy conversion and storage concept that turns out to be affordable, flexible and secure and therefore appears to be suited as one solution for overcoming the residual-load problem.

Residual load requires covering the gaps left vacant by wind and solar power production providing highly flexible and at the same time renewable power [Weber et al. 2018], [Cebulla et al. 2018], [Kondziellaa and Bruckner 2016]. In future, thermal power plants will still be needed to provide firm capacity, but at the same time they will face highly variable load and reduced utilization in terms of full load operating hours, both affecting their technical and economic performance. Another challenge is that in the long-term the residual load – left over by renewable power production – must be covered by renewable energy as well.

Up to now, thermal power plants using fossil and nuclear fuel have been the only available options to securely cover the adversely fluctuating residual load, and up to now it is controversially discussed if there is any other solution to that at all. On the other hand, the storage concept of Carnot Batteries [Hermann et al. 2017], [Thess 2013], [Roskoscha and Atakan 2017], [Laughlin 2017], [Steinmann 2019 et al.], also referred to as pumped heat electricity storage (PHES) paves the ground for large-scale energy storage based on inexpensive thermal energy storage materials. In the present work we demonstrate how a combination of available power plant technologies and Carnot Battery concepts can be used to solve the residual-load problem.

The paper is organized as follows: In the following chapter we shall formulate our concept and explain its basic features. Chapter 3 presents the model instrument used for multi-indicator benchmarking the transformation of power supply systems. Chapter 4 is devoted to applying our concept to the specific case of the German power sector. We shall demonstrate, using available transformation scenarios, how the concept of the storage plant is capable of providing affordable coverage of the residual load. In chapter 5 we summarize our conclusions.

2. Storage plants for high supply flexibility

The following presents an innovative thermal power plant concept that could become a key to a fast transition towards renewable electricity supply world wide, as it solves the challenges related to the residual load curve. The storage plant proposed here uses photovoltaic power, solid biomass and biogas (or temporarily natural gas) as primary energy sources to supply renewable electricity just as required by the residual demand. Depending on availability, synthetic hydrocarbons and liquid biofuels could also be used as alternatives for backup supply.

As shown in Figure 1, a storage plant consists of the following elements:

1. Rankine cycle including steam turbine, condenser, feed pump and steam generator for intermediate and base load supply with typically 4000 and more full load hours per year.
2. Brayton cycle with gas turbine, compressor and combustion chamber used to cover short-term peak load – on top of the Rankine cycle – with 1000 or less full load hours per year.
3. Thermal energy storage consisting of two tanks that contain molten nitrate salts just like those used in solar thermal power plants [Fritsch et al. 2019], [Turchi 2019]. Heat is stored when pumping salt from a cold tank (≈280°C) to a hot tank (≈560°C) while heating it up with one of the below mentioned alternatives. Heat is delivered to the Rankine cycle for on-demand power generation, pumping hot salt through its steam generator and subsequently back to the cold tank.
4. Large scale photovoltaic plant that provides electricity in the form of a regular daily production cycle that can be effectively absorbed by the short term heat storage, with a nominal power capacity several times higher than that of the Rankine cycle.
5. Heater unit that allows for three alternative ways to charge the thermal energy storage:
    a. an electric heater serves to feed electricity from the PV plant,
    b. a co-firing unit using solid biomass or waste as backup heat source, and
    c. a heat recovery unit (recuperator) using waste heat from the gas turbine.

The configuration of the plants and the installed capacities of their components can be flexibly configured in order to optimally match annual demand. During operation, all elements can be flexibly adapted to the varying residual load.

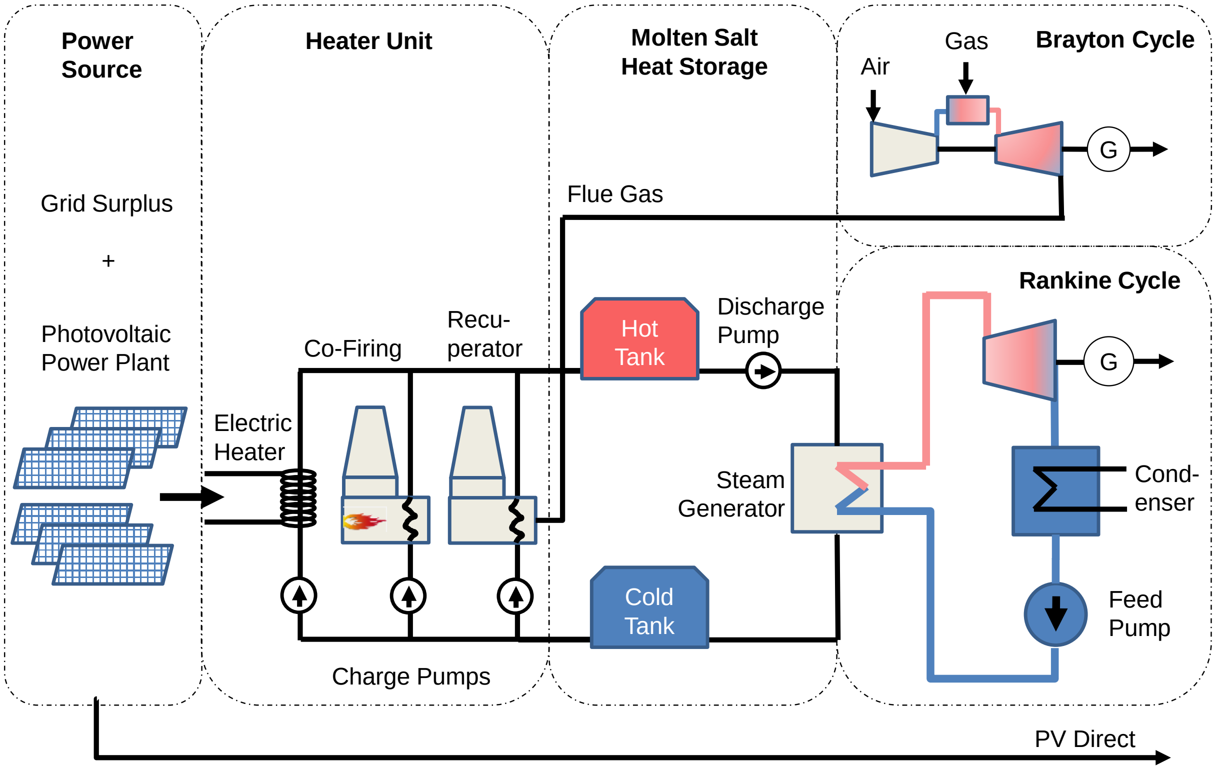

Figure 1: Schematic of a storage plant: renewable power source, molten salt heat storage with electric heater and co-firing (solid biomass), steam turbine and additional gas turbine (fired by natural gas or biogas) with waste heat recovery.

The storage plants have different operation modes to cope with dynamic residual load transients (Figure 2):

1. Electricity from a large photovoltaic plant flows directly to the consumers, while surplus (negative residual load) is fed to the heat storage until it is fully charged. In that case the steam turbine goes off or standby (hours 1-3 and hours 9-10).
2. If direct power from the PV plant does not suffice to cover the load, the steam turbine goes online, in the first instance powered by the heat storage (hours 4-5).
3. If the energy contained in the heat storage sinks to a critical level, backup co-firing of solid biomass is used to secure capacity for firm power generation (hours 6-8). Flexibility of combustion or fuel quality is not critical due to indirect steam generation through the storage. Co-firing could alternatively be integrated to the Rankine cycle.
4. If the load exceeds the maximum capacity of the steam turbine, a peaking gas turbine fired by natural gas, biogas or synthetic natural gas is added and its waste heat fed to the storage (hours 5-6). Waste heat recovery could alternatively be integrated to the Rankine cycle.

Due to the use of fuels, the full capacity of the power plant (steam turbine plus gas turbine) can be guaranteed at any time, and supply can be flexibly adapted to any load situation. At the same time, significant amounts of biomass, biogas or natural gas are saved by photovoltaic electricity either delivered directly to consumers or stored in the heat storage and delivered later. The size of storage plants is defined by the capacity of the steam and gas turbines on the output side and by the size of the electric heater at the input side. The heater will usually have a higher capacity than the steam turbine in order to allow for a high number of operating hours. As an example, a plant according to Figure 1 could be composed of a 500 MW electric heater, a 150 MW steam turbine, a 350 MW gas turbine for peaking and a 750 MW PV plant as main heat source for the storage. Conversion of electricity to heat is close to 100% efficient. Due to its size, losses from heat storage are below 5% per cycle. However, due to the limited efficiency of steam turbines, the roundtrip efficiency of storage plants is limited to an order of magnitude of 35 to 40%. Using future high temperature heat pumps during charging may increase roundtrip efficiencies of future systems to about 70%.

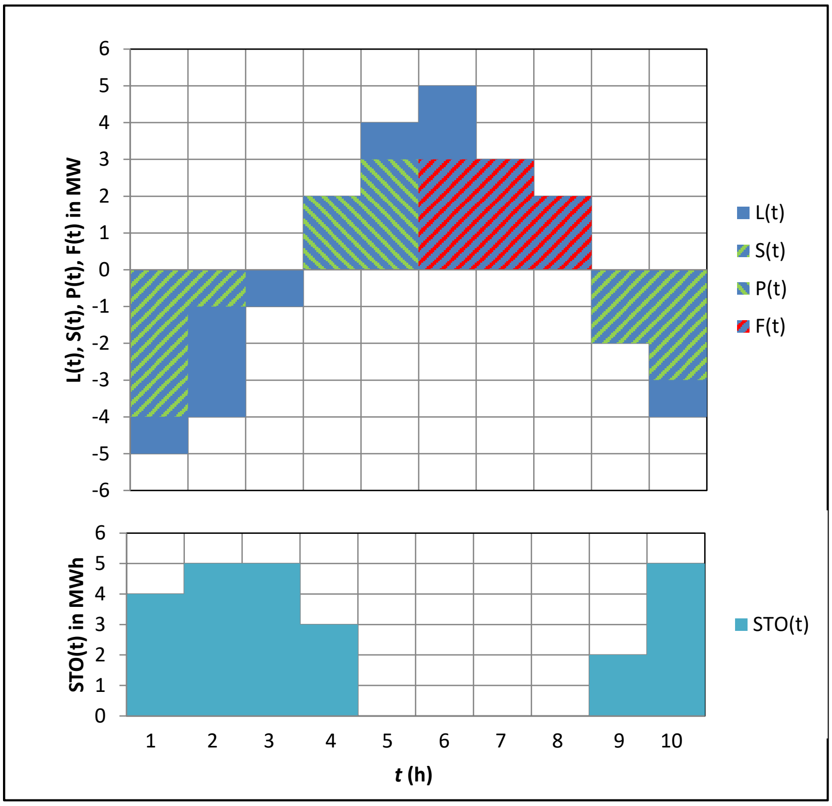

Figure 2: Simplified illustration of storage plant operation. Top graph shows 10 hour time series of the residual load L(t), electric heater input S(t), steam turbine output P(t) powered by the heat storage and steam turbine output powered by backup fuel F(t). Lower graph shows state of charge of the heat storage STO(t). A roundtrip efficiency of 100% and no waste heat recovery from the gas turbine is assumed for simplicity. Negative residual load means surplus. Installed heater capacity S = -4 MW. Installed turbine capacity P = 3 MW. Installed heat storage capacity STO = 5 MWh. Please note that directly delivered photovoltaic power is not included in the residual load and thus not displayed here.

The equations related to the storage plant model are given in the following. Time steps are given in hours t. The modelling starts in the first hour of the year, with a preset state of charge of the storage, e.g. $STO(t = 1) = STO/2$ (in MWh). In case of a positive residual load we calculate the required power output of the turbine $P(t)$ that is limited by the residual load $L(t)$, by the installed turbine capacity P and by the state of charge of the heat storage $STO(t)$ corrected by the roundtrip efficiency η of the storage cycle.

$$P(t) = \min\{P; L(t); STO(t) \cdot \eta\} \qquad \text{Eq.1}$$

In case the storage is empty, power that has to be served via fuel backup is calculated by:

$$F(t) = \min\{P; L(t) - P(t)\} \qquad \text{Eq.2}$$

In case of a negative residual load – which indicates power surplus – the amount of electricity $S(t)$ can be charged to the heat storage. It is limited by the installed heater capacity S, by the available surplus power $L(t)$, and by the available free storage capacity $STO(t) - STO$.

$$S(t) = \max\{S; L(t); STO(t) - STO\} \qquad \text{Eq.3}$$

Finally, the state of charge of the heat storage is calculated for the next time step:

$$STO(t+1) = \min\left\{STO; STO(t) - \frac{P(t)}{\eta} + |S(t)|\right\} \qquad \text{Eq.4}$$

The calculation is then repeated for the next time step starting with Eq.1. The storage plant model was embedded in the power sector simulation model presented in the following.

3. Power system simulation and multi-indicator benchmarking

The simulation tool ELCALC balances hourly time series of electricity demand and supply by renewable and conventional power stations, electricity storage and grid interconnections for selected model years for a selected country or region [Trieb 2017]. The tool allows for benchmarking selected indicators of the power supply system and tracking their change over a defined transformation period.

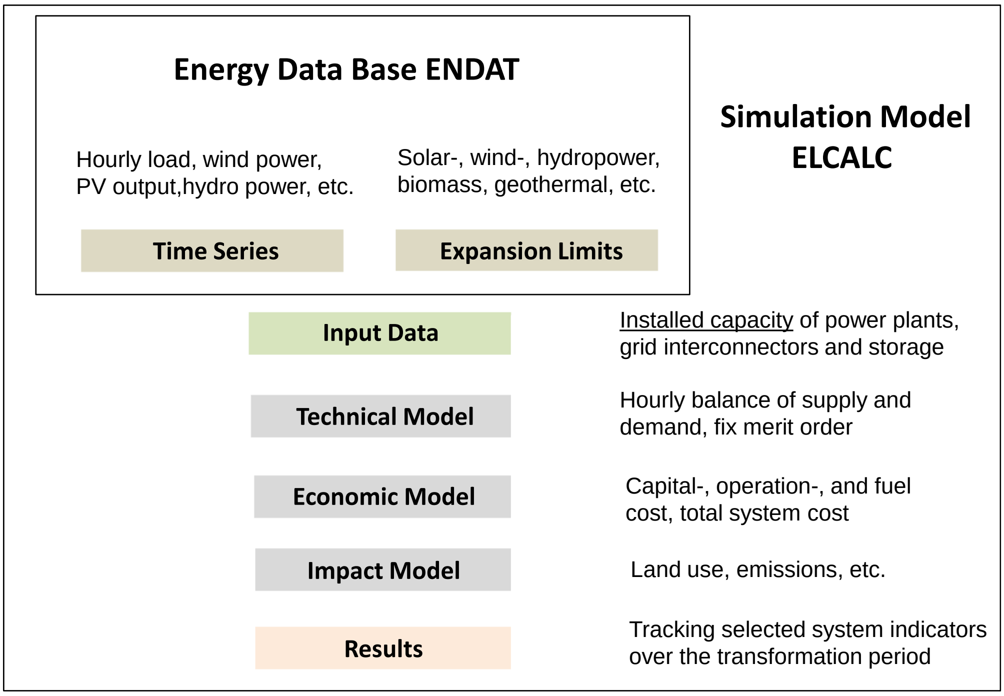

Figure 3: Basic setup of simulation tool ELCALC

The simulation model ELCALC (Figure 3) for electricity sector calculation makes use of an energy data base ENDAT developed by Stetter (2014) that contains average hourly load curves and potential limiters for variable renewable production from onshore and offshore wind power, PV and CSP systems for a region or country of choice. In this case we have selected representative values for Germany and complemented the database by river runoff hydropower production and the country's hourly demand curve. All hourly values in the database are given in relative numbers that can be freely scaled up and down by the user when defining installed capacities and peak load of the supply system. The model then calculates the balance of demand and supply assuming a fix merit order of the power plants as indicated in Table 1. Total system cost, environmental impacts and other freely selectable system indictors are finally calculated from the annual balance.

ELCALC does not include a market dispatch model. It calculates a simple hourly balance of electricity demand and supply for one model year, and from that it derives the overall cost of supply. Dispatch is simply defined by physical demand and availability of power, considering a fix merit order that sets the dispatch sequence of each plant category (Table 1). Storage devices of any kind are only filled if there is physical electricity surplus available and only emptied if there is a physical supply gap, independently from any hypothetic market mechanisms and price spreads.

Table 1: Numbering (*i*) of power plant categories used in the simulation model ELCALC indicating their fix merit order.

1	Photovoltaic power	9	Power-to-gas-to-power	17	CSP fuel backup
2	Onshore wind power	10	Lithium-ion batteries	18	Lignite plants
3	Offshore wind power	11	Redox batteries	19	Nuclear power
4	River runoff hydropower	12	Storage plants	20	Hard coal plants
5	Stored hydropower	13	Geothermal power	21	Combined cycle plants (NG, LNG)
6	Concentrating Solar Power	14	Solid biomass, waste energy	22	Combustion engines (gas & oil derivatives)
7	Pumped hydro storage	15	Biogas, energy crops	23	Grid import
8	Compressed air energy storage	16	Storage plants fuel backup	24	Gas turbines (NG, LNG)

Core of the ELCALC simulation model is the calculation of the residual load $L_i(t)$ that has to be covered by each plant category i.

$$L_i(t) = D(t) - \sum_{j=1}^{i-1} P_j(t) + \sum_{j=1}^{i-1} S_j(t) \qquad t = 1,2,\dots 8760 \qquad Eq. 5$$

With hourly power demand $D(t)$, hourly power production $P_j(t)$ and hourly power absorption into a storage $S_j(t)$ of the plant categories prior to category i. A positive result of this equation quantifies the remaining residual load after operating all prior plant categories $i \le j$, while negative values show the amount of electricity surplus. This calculation is repeated for each hour of the year.

The fix merit order takes into account firstly variable renewable electricity production that is given by nature rather than controlled by demand (categories 1-7). Next come storage technologies, including stored hydropower as well as storage plants (categories 5-12). Power from CSP and stored hydropower partially stem from storage and partially from variable sources. Next in the merit order follows dispatchable renewable electricity from geothermal heat and biomass (categories 13-15). Finally, as last resort to guarantee power on demand, fossil fuel based power production is activated, sorted by cost (categories 16-24). Categories (16) and 17 are inserted before the following ones although using expensive biomass or natural gas for backup, because in order to deliver firm power capacity at any time they only need an additional burner and heat exchanger, but not a complete power plant like the categories sorted later.

4. Role of storage plants in the German power sector

In the following we present a possible transition pathway of German electricity supply up to the year 2040. ELCALC simulates the installation of 70 GW storage plants until 2040, consisting of 21 GW steam turbines and 49 GW gas turbines, 105 GW photovoltaics and heat storage with 600 GWh_{th} storage capacity that is equivalent to about 12 hours of maximum power output of the steam turbines. The storage plants are assumed to be part of the German national power supply system described in Table 2. The storage plants operate with co-firing of biomass and use natural gas for the connected peaking gas turbines. Transition modelling starts in the year 2020 with 40% renewable energy share. For simplicity and comparability, net electricity consumption (551 TWh/a), peak load (83 GW) and the hourly shape of the load curve are assumed to remain constant in all model years.

Model year 2020 (Figure 4, top graph) is characterized by 60% residual load that is still covered by conventional (fossil) power plants. The fact that most of those plants are relatively inflexible base-load plants leads to significant curtailment and export surplus, as the penetrability of the load curve for fluctuating renewable power from wind farms and PV installations is rather limited. It can also be observed that the charge-discharge-cycles of existing pumped hydro storage are scarce, irregular and incomplete. This affects the technical and economic performance of this storage, as it would likewise affect any other buffer storage option like e.g. batteries and also heat storage.

This is one of the reasons why the installation of storage plants must go hand in hand with the installation of photovoltaics as energy source: the installation of storage plants composed of 11 GW steam turbines, 25 GW gas turbines and 53 GW photovoltaics until 2030 leads to a visible reestablishment of regular storage cycles for pumped hydro storage as well as for heat storage, as can be seen in Figure 4, center graph. Due to the decommissioning of some inflexible base load plants (mainly nuclear) by that time, export overhead and curtailment are significantly reduced in comparison to 2020.

The different operation modes of the storage plants in the model year 2040 can be observed in Figure 4, bottom graph. During the night of the hypothetical September 7, storage plants take over a small gap of a few hours of residual load, using heat from the storage and some co-firing. From September 7 to 14 the storage plants mainly operate on stored surplus power from PV plants. Such behavior is typical for the summer months. From September 16 to 18 a longer, two-day residual load gap appears that is mainly covered by co-firing. When the load exceeds steam turbine capacity, peaking gas turbines are added and provide waste heat for the storage, while steam turbines continue operating in base-load. Such situation occurs more frequently and over longer periods in winter.

On most other days, steam turbines, eventually complemented by gas turbines, alternate with direct supply from photovoltaic power production. It can be seen how regular electricity surplus from photovoltaic generation can be effectively stored in pumped hydro and heat storage facilities, and how the likewise regular supply gaps of the residual load curve can be easily filled by the storage plants including steam and gas turbines.

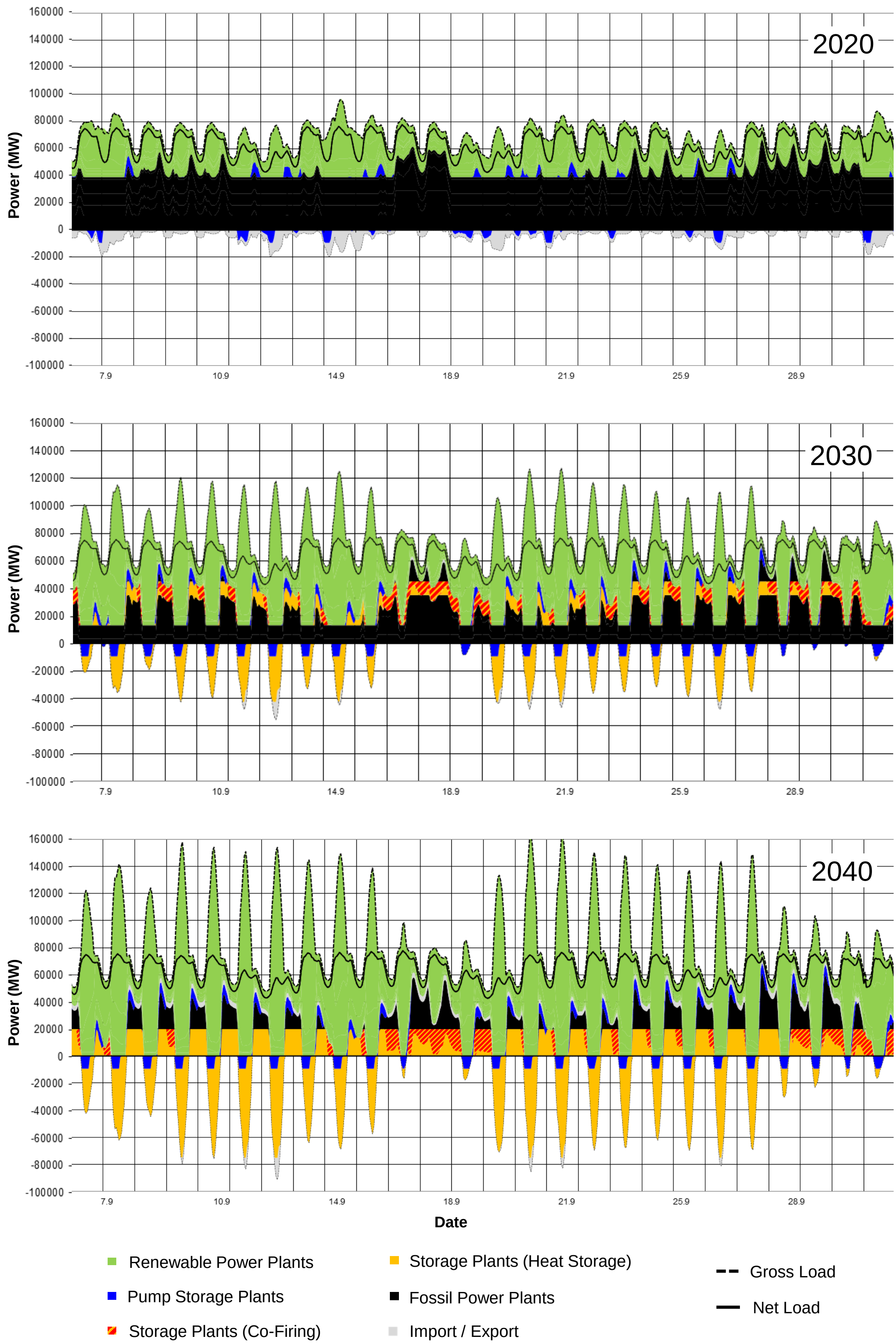

Figure 4: Twenty-six-day sequence of an annual hourly model time series of the German power supply system for the years 2020, 2030 and 2040 with 40%, 65% and 90% renewable electricity share, respectively. Positive values indicate load, power production and imports. Negative values indicate power exported or fed to storage. Gross load includes power production used for system management as well as for power transmission and storage.

Table 2: Installed capacity, annual electricity generation and indicators of the power supply model

Model Year	2020	2030	2040
Renewable Capacity (MW)			
Photovoltaic	48500	107500	135000
Wind Onshore	56500	70000	75000
Wind Offshore	8400	12500	14000
Hydropower	5700	5640	5640
Solid Biomass, Wood, Waste	3000	1800	0
Biogas, Energy Crops	4700	0	0
Geothermal Power	38	250	1000
Hydropower Imports	0	250	1000
Storage Plant Capacity (MW)			
SP Photovoltaic	0	52500	105000
SP Steam Turbines	0	10500	21000
SP Gas turbines	0	24500	49000
Fossil Power Capacity (MW)			
Gas Turbines	1390	17200	19300
Hard Coal Power Plants	22000	14500	0
Combined Cycles and Combined Heat and Power	28700	15500	0
Other	5700	0	0
Nuclear Plants	9400	0	0
Lignite Plants	21200	7000	0
Storage and Grid Capacity (MW)			
Pump Storage	9850	9850	9850
Net Transfer Capacity Import	27000	27000	27000
Net Transfer Capacity Export	23000	27000	27000
Renewable Power Production (TWh/a)			
Photovoltaic	47.9	105.0	139.0
Wind Onshore	105.6	146.0	162.0
Wind Offshore	24.7	40.3	47.6
Hydropower	21.5	22.3	22.3
Solid Biomass, Wood, Waste	22.2	12.9	0.0
Biogas, Energy Crops	27.8	0.0	0.0
Geothermal Power	0.3	1.9	7.8
Hydropower Imports	0.0	1.2	5.2
Storage Plants Power Production (TWh/a)			
SP Photovoltaic Total	0.0	53.0	105.0
SP Photovoltaic Direct	0.0	22.5	45.0
SP Steam Turbine through Storage	0.0	13.9	52.1
SP Steam Turbine through Co-Firing	0.0	37.2	50.8
SP Gas Turbines	0.0	10.2	65.3
Fossil Power Production (TWh/a)			
Gas Turbines	0.0	0.1	0.1
Hard Coal Power Plants	87.0	76.8	0.0
Combined Cycles and Combined Heat and Power	90.8	63.6	0.0
Other	18.0	0.0	0.0
Nuclear Plants	69.9	0.0	0.0
Lignite Plants	130.7	45.1	0.0
Storage and Grid Transfer (TWh/a)			
Pump Storage	5.7	9.6	11.2
Grid Import	17.0	18.7	29.7
Grid Export	60.9	24.1	23.1
Gross Power Production (TWh/a)	646	619	605
Net Power Consumption (TWh/a)	551	551	551
Peak Load (GW)	83	83	83
Firm Capacity / Peak Load	106%	102%	102%
Power Supply System Indicators			
Carbon Emissions (million t/a)	307	180	66
Land transformation (km²)	25433	26188	26910
System Cost (billion €/a)	61.1	59.1	66.1
Installed Power Capacity (GW)	225	349	436
Curtailment (TWh/a)	6.0	2.4	5.1
Import (%)	44%	29%	27%
Grid Extension (TW×km)	75	83	85
Particulate Matter (t/a)	15123	13125	9006
Power from Biomass (TWh/a)	50	50	51
Power from Natural Gas (TWh/a)	91	74	65

Until 2040, about 70 GW of conventional power plant capacity is replaced by storage plants. Under our assumptions storage plants contribute 213 TWh/a equivalent to 35% of German electricity supply. The related steam turbines (21 GW) produce 103 TWh/a equivalent to 4950 full load hours, of which 23 TWh/a stem from stored photovoltaic energy, 51 TWh/a from co-firing with biomass and 30 TWh/a from waste heat recovery of the gas turbines. Gas turbines (49 GW) produce 65 TWh/a equivalent to about 1300 full load hours per year, while photovoltaic power directly delivered to consumers contributes with 45 TWh/a (Table 3). Together with other renewable power plants and pumped hydro storage, a share of 90% of renewable electricity is achieved in the German electricity supply system by that year.

Storage plants as defined here would require a total investment of 176 Billion Euro (or about 9 Billion Euro per year) until 2040 (Table 4). The average electricity cost of the storage plants lies in the range of 140 €/MWh as summarized in Table 5Table 5. This is fairly low considering the challenge of completely covering the adversely fluctuating residual load. Main technical and economic parameters for the model are displayed in Table 6.

As a consequence, the total system cost for German power supply, as obtained from our analysis, is not significantly increased when following the transition described here. Table 2 and Figure 5 show the development of several system indicators during the transformation of the German power sector from 2020 to 2040 according to our model calculation. While carbon emissions are reduced from 307 to 66 Million tons per year, the annual cost of the total German electricity supply system in our model increases slightly from 61 to 66 Billion Euro per year, respectively, resulting in a carbon avoidance cost of 21 €/ton for this specific system transformation pathway. Land use and power generation from biomass remain approximately constant. Power from natural gas is reduced to the amount produced by the storage plants' gas turbines. Massive expansion of grid transfer capacity towards neighboring countries is not required. Installed capacity of power plants nearly doubles.

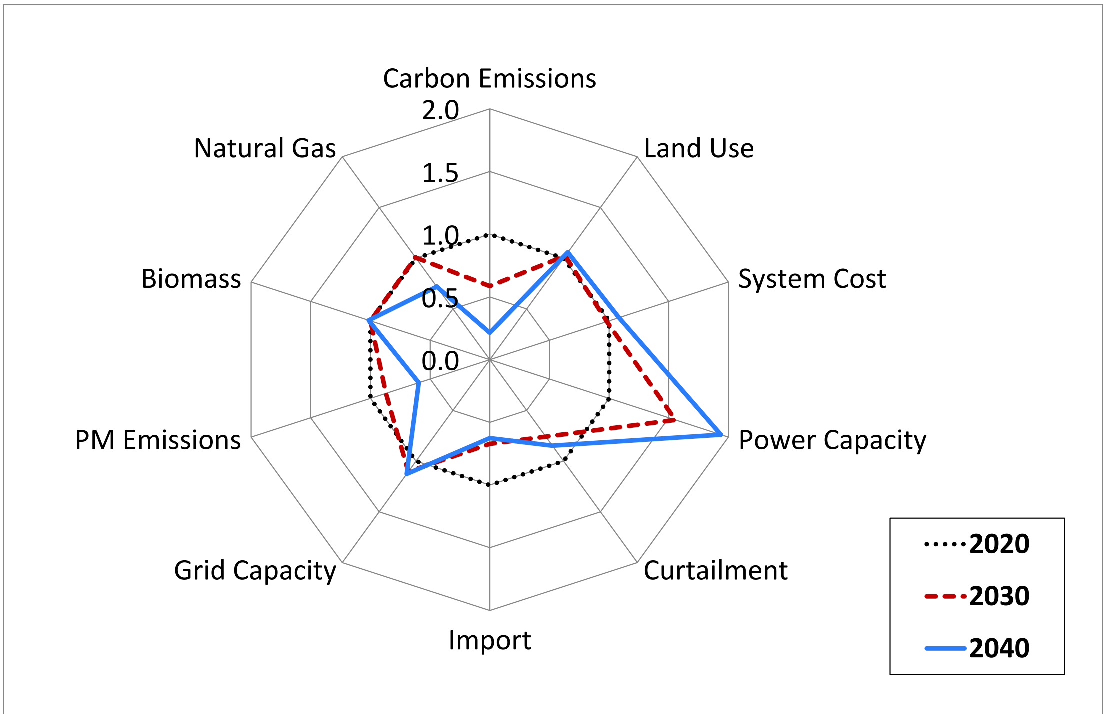

Figure 5: Selected power supply system indicators for the model years 2020, 2030 and 2040 (Table 2).

4. Conclusions

Covering the increasingly fluctuating residual electrical load with renewable energy is a global challenge of energy transition that up to now has not been answered with satisfying solutions. The paper at hand sets the hypothesis that storage plants can take over this task using existing commercial technology.

Storage plants, as defined in this paper, consist of an energy source with fairly regular production cycles such as photovoltaics, a buffer storage, preferably a molten-salt heat storage, a steam cycle that is powered by heat from that storage, a gas turbine that takes over extreme demand peaks, an electric heater and a backup heating unit of the storage as well as a waste heat recovery unit for the gas turbine's exhaust gas. The generated electricity stems by one third from PV, one third from co-firing with biomass and one third from the gas turbines fired by natural gas. In the long-term also the gas turbines could be fired by biogas or synthetic natural gas from renewable production.

We have demonstrated that storage plants are extremely flexible and can cover all kinds of load situations ranging from peak load to intermediate load and base load. In spite of covering short load peaks, gas turbines of storage plants can recover waste heat into the heat storage and thus achieve efficiencies close to those of conventional combined cycle gas turbines.

About half of the electricity stemming from the photovoltaic power plant is delivered directly to consumers without any losses, while the other half is stored in form of heat, suffering significant losses of about 60% before being reconverted to electricity. Nevertheless, the overall efficiency of 65% of transforming fluctuating PV power to dispatchable PV power is relatively high, representing the weighted average of stored and directly delivered solar power.

Thanks to the solar share and to waste heat recovery from the peaking gas turbines that together make up for almost half of electricity supply, the consumption of fuel, that is ultimately required for firm capacity, is significantly reduced to values that allow for the use of scarce biomass for that purpose. The plant's configuration and the fuels used can be adapted to any situation world wide, providing a possible key element of a global transition towards renewable energy in the power sector. Finally, stored heat or heat from combined generation could also be used as process heat for industry.

Acknowledgements

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Table 3: Electricity yield of storage plants for the model year 2040

Photovoltaic Power Supplied Directly	45	TWh/a
Steam Turbines via Biomass Backup	51	TWh/a
Steam Turbines via Stored PV	22	TWh/a
Steam Turbines via Heat Recovery	30	TWh/a
Gas Turbines	65	TWh/a
Total Electricity Supplied	**213**	**TWh/a**

Table 4: Installed capacity and investment cost of storage plant components until 2040

	Capacity	**spec. Inv.**	**Investment**
	GW or GWh_{th} *	€/kW or €/kWh_{th} *	Billion €
Steam Turbines	21	800	17
Gas Turbines	49	400	20
Photovoltaic Plants	105	650	68
Heat Storage *	600	25	15
Electric Heater	69	100	7
Backup Heater	69	105	7
Recuperator	69	100	7
Contingencies	25%		35
Total Investment			176

Table 5: Annual operation cost and electricity cost of storage plants for the model year 2040

Capital Cost	14.1	Mrd. €/a
Fuel Cost	12.1	Mrd. €/a
Operation Cost	3.5	Mrd. €/a
Total Annual Cost	**29.8**	**Mrd. €/a**
Average Electricity Cost	**140**	**€/MWh**

Table 6: Technical and economic parameters used for storage plant modelling

Fuel Cost	40.0	€/MWh_{th}
Operation Cost (% of Investment)	2.0%	/a
Discount Rate	5.0%	/a
Discount Period	20	a
Fix Charge Rate	8.0%	/a
Steam Cycle Efficiency	40.0%	
Gas Turbine Efficiency	37.0%	
Recuperator Efficiency	50.0%	
Heat Storage Efficiency	95.0%	
Self-Discharge Heat Storage	0.05%	/h

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