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On the role of storage for electricity in smart energy systems

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ABSTRACT

In recent years the electricity system has started to undergo significant changes. Three major developments are underpinning these changes: (i) the rapid digitalization of the energy system leading to smart grids and increasing flexibility in the system; (ii) the increasing electricity generation from variable renewable energy sources, such as wind and solar; and (iii) the continuing decentralization of electricity generation leading to more and more prosumagers (consumers, which also produce energy and store it) instead of former consumers. Among other necessary changes these developments have led to calls for additional storage capacities. The core objective of this paper is to investigate the possible role of electricity storage in such smart energy systems. We consider all relevant types of storage: short-term ones such as pumped hydro storage, small and large stationary battery and the battery of electric vehicles as well as long-term storage such as hydrogen and methane from power-to-gas conversion technologies and compressed air energy storage. The major conclusions of this analysis are: In recent years the options for placing storage in smart energy systems as well as types of storage have been increasing significantly. However, low number of full-load hours is still the major problem of all electricity storage options.

1. Introduction

In recent years the electricity system has started to undergo significant changes. In Europe these developments were mainly motivated by policies implemented and targets set by the European Commission (e.g. Energy & Climate package, Renewable Energy Directive, the Internal Electricity Market Directive, etc.) [1–3].

These changes are underpinned by three major developments: (i) the increasing electricity generation from variable renewable energy sources such as wind and solar; (ii) the rapid digitalization of the energy system leading to smart grids and increasing flexibility in the system, and (iii) the continuing decentralization of electricity generation leading to more and more prosumers and prosumagers (consumers, which also produce energy and store it) instead of former consumers. In the ongoing energy transition the role of electricity storage is becoming more crucial.

In recent years especially electricity generation from variable renewable sources such as wind and solar has increased remarkably. Between 1990 and 2018 in the EU-28 "new" renewables excluding hydro grew from less than 1% to about 20%, mainly from wind. In total, since about 2013 renewables are the major energy source for electricity generation in the EU, see Fig. 1.

With the increasing share of variable renewables in electricity generation, the electricity system will require larger flexibility. To balance electricity supply and demand over time, electricity will need to be stored over days, weeks or months. Due to variability of electricity generation from renewable energy sources (RES) also over longer periods – months, years – long-term electricity storages are also of interest. In the transition towards carbon-neutral economy energy storage addresses several of the European climate and energy principles. By balancing power grids and saving surplus energy, it represents a concrete means of improving energy efficiency and allowing the integration of more renewable energy sources into electricity systems, but as argued in Ref. [4] it may also help to enhance European energy security and create a well-functioning internal market.

Accordingly, the development and deployment of energy storage is placed at the top of the Energy Union's priorities [5], and gained the attention of major European countries and industrial sectors. Given the ambitious targets for the further development and deployment of renewable energy the potential position of energy storage in the future energy industry could be particularly

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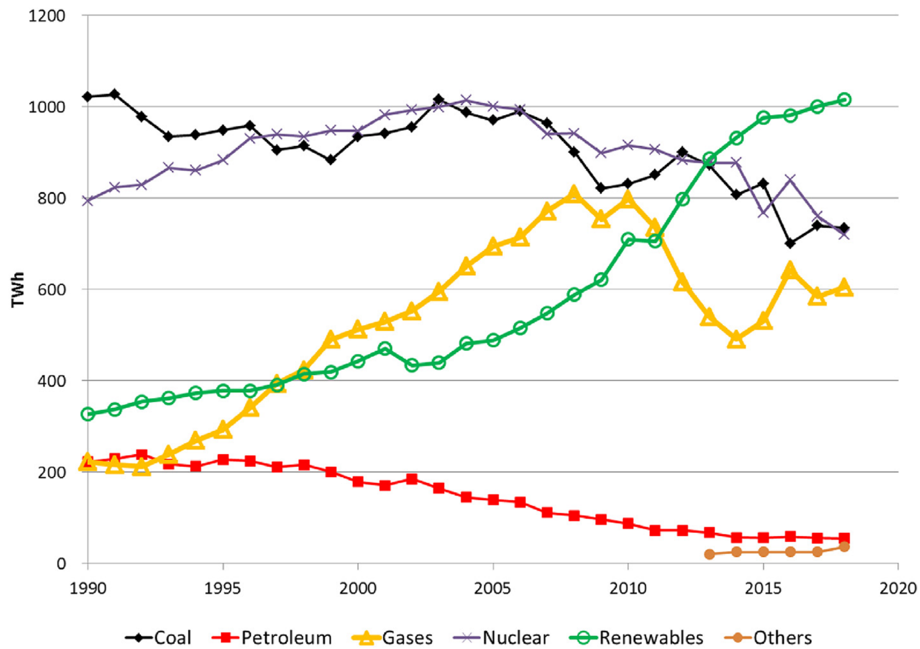

Fig. 1. Development of electricity from different energy sources in EU-28 between 1990 and 2018, in TWh ([6], own estimations).

significant.

The core objective of this paper is to investigate the possible role of storage for electricity in smart energy systems. The major new contribution of this paper is that it provides a very comprehensive and up-to-date analysis of the state-of-the-art of the relevance of all currently discussed storage technologies. In addition, this paper compiles a survey on the most relevant and recent literature.

We consider all relevant types of storage: short-term storage such as small and large stationary batteries and the battery of electric vehicles, as well as long-term storage options such as pumped hydro storage, hydrogen (H2) and methane (CH4) from power-to-gas (PtG) conversion technologies, and compressed air energy storage. In this context, we analyse the systemic, the energetic and economic perspectives for these technologies. We do not consider heat storage as it is virtually impossible to re-convert low-temperature into electricity.

There are in principle many different storage categories depending on the voltage level, as well as different storage types (e.g. pumped hydro, batteries, chemical storage) in a smart energy system as shown in Fig. 2. This figure depicts the possible placement of various types of storage in a smart energy system. On the level of the transmission grid pumped hydro storage is the classical option pumping at times of excess electricity and turbining at times of scarcity. In addition, it is possible to store excess electricity in chemical storage by producing hydrogen, methane or other chemical products with PtG-technologies. Either these products are re-electrified or they are used in other sectors, e.g. industry or transport.

On distribution grid level, grid-scale large batteries are discussed, mainly for shaving peaks in the distribution grid and for ensuring supply security. Finally, at former customer level – now called “prosumager” – there are storage options such as battery of electric vehicles (EV) or a stationary storage “behind the meter”.

Many recent studies have analysed challenges for the distributed grid caused by increasing use of renewable energy sources in electricity generation [7–11]. To balance electricity supply and demand different storage options are considered as well as smart grid technologies [12,13]. In a number of studies storage is identified as a key technological component for the transformation of the current operation of the power grid [14,15]. Cross energy solutions such as power-to-gas (hydrogen or methane) could also provide additional flexibility to the system [16–18]. The integration of large amounts of variable renewable energy poses fundamental challenges to the operation and governance of the energy system [19,20] and requires policy support [21]. Already in 1986 the concept of a regulation hierarchy was discussed in order to manage distributed generation without causing feedback in the system [22,23]. A relevant set of regulatory and financial policies is required to support realization of the full benefits of different storage options in combination with smart grid technologies [24–26]. To face the challenges of global climate change many countries have started to restructure their electricity system [27] and are heading towards smarter energy systems.

2. The problem of balancing electricity supply and demand

Larger use of RES is considered as a pre-condition for heading towards smart and sustainable energy systems. Due to the supporting policy measures in the EU at least since 1990 the share of RES in total energy supply has been continuously increasing, see Fig. 1. In the last years, especially high photovoltaic (PV) and wind penetration in some regions has been noticed. However, the increasing quantities of variable RES have led to additional needs for balancing electricity supply and demand. Usually, all electricity generation technologies have profiles different from customers load profiles, and so do variable RES, see Fig. 3.

In the future, both distributed and centralised renewable electricity generation are expected to increase. Moreover, also consumers will increasingly participate in the energy markets as 'prosumers' and ‘prosumagers’. In general, an increase in electricity demand can be expected. All this leads to increasing need for flexibilities in the electricity system (e.g. demand response, flexible generation and grid extension (including interconnections)).

In the case of increasing use of variable RES in electricity generation, energy storage could bring benefits to the balancing of the electricity system. It can shave the peaks and provide flexible

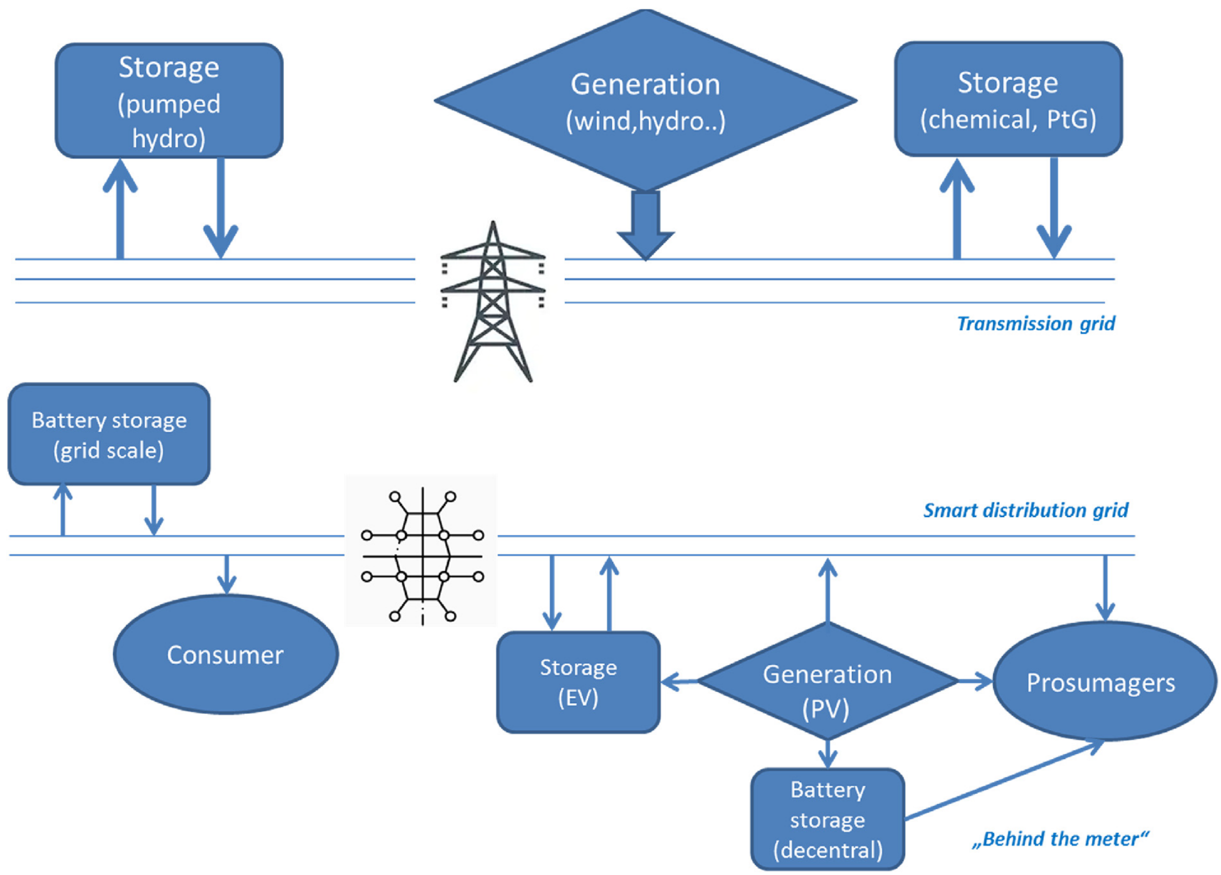

Fig. 2. Different storage options at different grid level in a smart energy system.

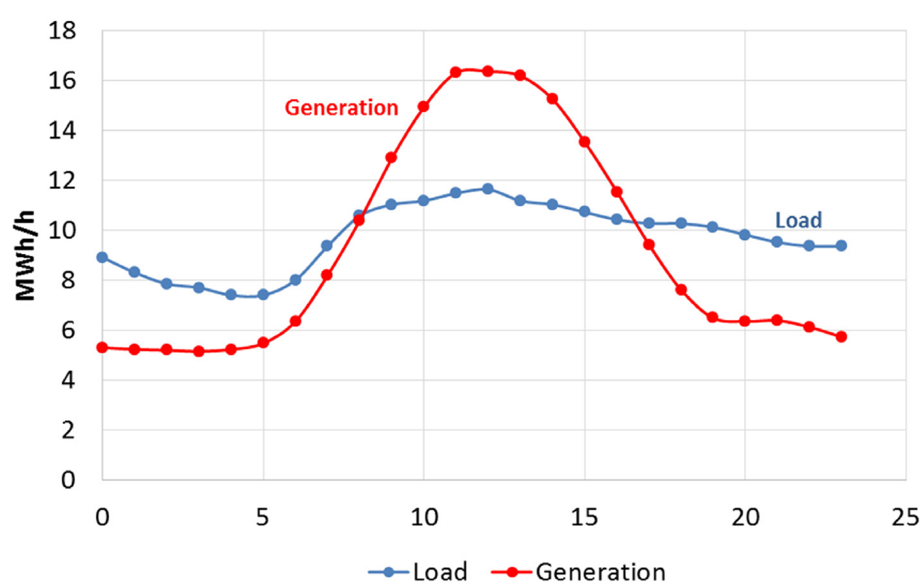

Fig. 3. The problem of balancing electricity supply and demand.

solutions to market participants. Moreover, energy storage can help in emission reductions by facilitating a more efficient use of the existing assets and by reducing the carbon content of the fuels (e.g. blending of the natural gas with renewable hydrogen and synthetic methane).

The need for balancing activities between supply and demand with the goal to meet the so-called residual load is depicted in Fig. 4 and Fig. 5. Fig. 4 shows an example of electricity generation using synthetic hourly data for an average year in Austria in a hypothetical scenario up to 2030 with very high quantities of variable renewables (6.5 GW wind, 11.4 GW PV, 7 GW run-of-river hydro and 8 GW hydro storage power) over a summer and winter week on an

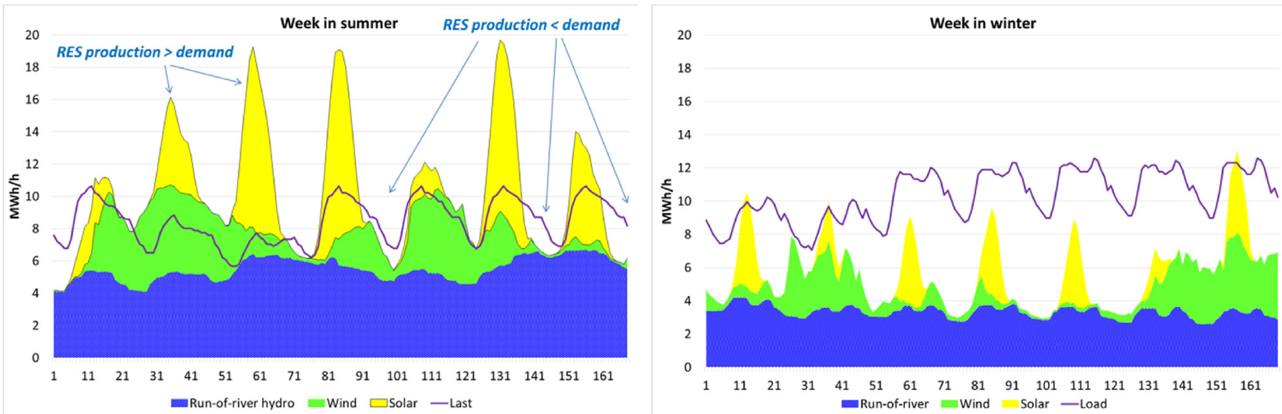

Fig. 4. Example: Electricity generation from variable renewables (wind, PV and run-of-river hydro) over a summer and winter week on an hourly base in comparison to demand for Austria in a scenario for 2030 (own modeling analysis).

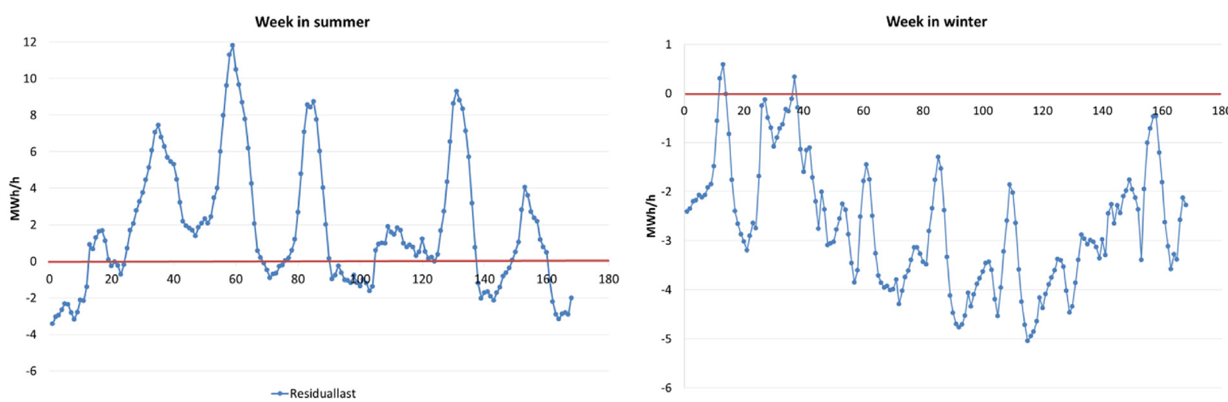

Fig. 5. Example: Residual load over a summer and over a winter week on an hourly base. Related to generation and demand pattern in Fig. 4.

hourly base in comparison to demand. Yet, of relevance in this context is mainly residual load which is the difference between the over-all variable generation and the demand at every hour. Hence, in Fig. 5 the residual loads on an hourly base corresponding to the two weeks shown in Fig. 4 are depicted. The fluctuations over hours and days can clearly be recognized, as well as the fluctuating differences between electricity supply and demand. In addition, Fig. 5 illustrates clearly that in summer excess electricity prevails while in winter under coverage is dominating.

These fluctuations exist over days and weeks but also over the months of a year, see Fig. 6. This figure shows the distribution of electricity generation from variable RES (PV, wind, run-of-river hydro power, and hydro storage, excluding pumped hydro), as well as load (demand) over the months of an average year for Austria in the described scenario with high shares of electricity from variable RES. Fig. 6 is the result of own modelling approaches as described above for the illustrations in Fig. 4. For the fluctuation over a year, as depicted in Fig. 6, long term electricity storage options such as pumped hydro storage, compressed air energy storage (CAES) as well as PtG-storage for hydrogen and methane would be required.

3. Types of storage and recent developments

Storage has played an important role in balancing electricity supply and demand since the beginning of electricity systems. Depending on the characteristics of a specific type of electricity storage, it can be used for different purposes and provides various services. Storage can be used to support uninterruptible power supply and power quality, for transmission and distribution grid support and load shifting, as well as for bulk power management. Currently, there are different storage technologies, which can be classified in short-term and long-term storage options depending on their average storage capacity and storage time, see Fig. 7.

The major characteristics of different storage options for electricity are given in Table 1. It documents power rating, energy range, response time, efficiency, self-discharge, lifetime and energy density for major types of storage technologies.

3.1. Pumped hydro storage

Pumped hydro storage is one of the oldest and mostly used electricity storage technologies. In pumped hydro storage, water is pumped from lower to higher reservoir during low-cost energy periods and high renewable energy generation periods, and, when electricity is needed, water is released back to lower reservoir, generating electricity. This storage technology is usually used on a large scale and within the wholesale market. Use of pumped hydro storage is mainly determined by geographical and geological characteristics, and most of suitable locations are already in use. In the EU pumped hydro storage accounted for 97% of electricity storage capacities in 2017 [38]. However, due to the ongoing changes in the electricity system, need for local flexibility is increasing. Due to this decentralized electricity storage options are

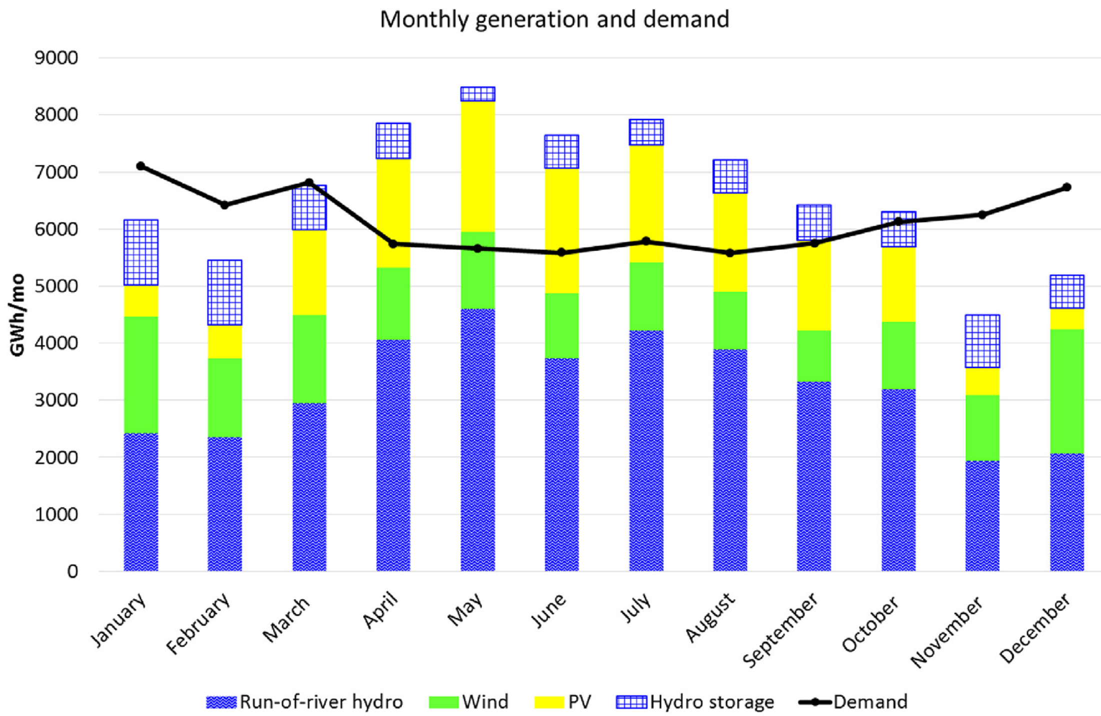

Fig. 6. Distribution of electricity generation from variable RES as well as demand over the months of an average year for Austria with high quantities of PV, hydro storage, wind and hydro power (results of own modeling analysis).

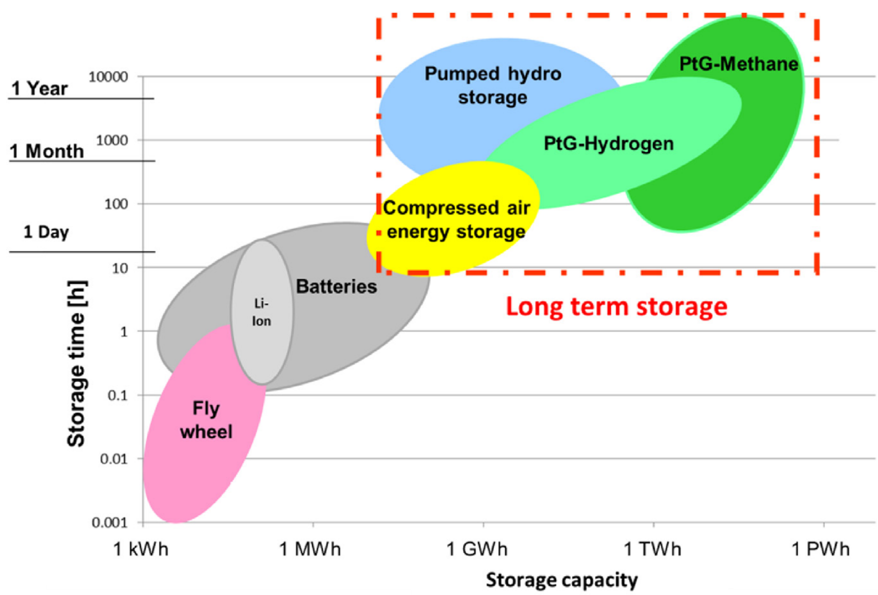

Fig. 7. Typical storage time of various storage technologies as a function of installed storage capacity [28,29].

becoming increasingly attractive [16].

However, in comparison to other types of energy storage, pumped hydro storage can be cheaper, especially for very large storage capacity. Despite this advantage, the challenge of this energy storage is need for long-term investment. Permitting and construction can take 3–5 years each [35]. This can be significant problem, especially in a fast-changing market.

Besides balancing the peak and off-peak periods, pumped hydro storage provides ancillary services such as: frequency, primary and voltage control to the power grid. In order to fulfil the power system control, pumped hydro storage can switch within seconds to different operation modes [36]. The balance with hydro pumped storage can be done over short periods, e.g. hours and days, as well as over longer periods, e.g. months and year.

Currently, worldwide there are over 170 GW of pumped storage capacity in operation. Europe is the second biggest zone, with 57 GW, accounting for approximately 33% of the market. Opportunities are mostly focused on mountainous regions in Switzerland, Austria, Germany, Spain and Portugal [36].

Table 1
Survey on different types of storage options for electricity [30–37].

	Power rating	Energy range	*Response time*	*Efficiency (%)*	*Self-discharge (%)*	*Cycles* or lifetime	Energy density (Wh/l)
Mechanical storage							
Pumped hydro	10 MW - 3 GW	Up to some 100 GWh	sec-min	70–85	negligible	30–80 years	0.2–2
Compressed air	100 MW- 1 GW	100 MWh-10 GWh	sec-min	40–75	negligible	20–50 years	2–6
Flywheel	100 kW–20 MW	10 -100 kWh	10–20 ms	70–95	1.3–100	*20,000 – 100,000*	20–80
Electrochemical storage							
Li-ion battery	1 kW-100 MW	Up to 10 MWh	10–20 ms	85–98	0.1–0.3	*1000 – 10,000*	200–400
Lead-acid battery	Some kW – 100 MW	Up to 10 MWh	<sec	75–90	0.1–0.3	500-3000 cycles	50–80
Flow battery	Several kW- 100 MW	100 kWh- some MWh	10–20 ms	60–85	0.2	*12,000 – 14,000*	20–70
Chemical storage							
Hydrogen	1kW-1GW	ca. 10 kWh-several GWh	sec-min	25–45	0–4	5–30 years	600
Methane	1MW-1GW	1 MWh-several GWh	sec-min	25–50	negligible	30 years	1800

3.2. Compressed air energy storage

Using this storage technology, air is pumped into an underground hole (e.g. salt cavern) during off-peak hours with cheap electricity. When energy is needed, the air from the underground cave is released back up into the facility, where it is heated and the resulting expansion turns an electricity generator. This heating process usually uses natural gas, which releases carbon [35]. This type of storage is suitable for daily/weekly balancing, for arbitrage, reserve, demand service and other standard ancillary services.

Currently, there are only two operating compressed air energy storage facilities. One plant is located in the USA (110 MW), and one in Germany (320 MW) [36].

3.3. Flywheel

A flywheel is a high speed spinning mechanical device designed to store energy which is released by slowing down the flywheel's spin.

Flywheels are not suitable for long-term energy storage, but are very effective for load-leveling and load-shifting applications. They have long-life cycle, high-energy density, low maintenance costs, and quick response speeds. Their major applications are to ensure uninterrupted power supply, increase efficiency and reduce load peaks.

Most important advantages of this storage technology are fast power response, high number of life cycles, flexible power/energy ratio, and high efficiency. Major barriers are materials cost, mechanical complexity, and self-discharge power losses.

The first commercial use of flywheel technology (20 MW) used to regulate the grid in the United States was demonstrated in 2011. Since then several other flywheel facilities are in use [35].

3.4. Li-Ion battery

A Lithium Ion (Li-Ion) Battery System is an energy storage system based on electrochemical charge/discharge reactions utilizing flow of lithium ions from negative to positive electrode to produce energy and vice versa for charging.

The use of Li-Ion batteries in the stationary field has significantly increased since 2010. Already in 2015, more than 500 MW of stationary Li-Ion batteries were operating worldwide in grid-connected systems. Moreover, Li-Ion battery systems for grid support with voltages up to 1 kV have been designed and successfully tested [36].

Lithium-ion batteries are by far the most popular battery storage option today and control more than 90% of the global grid battery storage market. Compared to other battery options, lithium-ion batteries have high energy density and are lightweight [35].

Although, most suppliers of Li-Ion batteries are from Asia (Korea, China or Japan), Europe is one of the leading continents in utilization of Li-Ion batteries in different applications, such as stationary energy storage, rail, marine, truck and automotive. For the energy storage market in particular, the leading countries for the deployment of Li-Ion batteries are: Italy for transmission and distribution grid support, Germany for PV self-consumption, and France in the island grids [36].

Huge advantage of Li-Ion batteries is their high scalability and flexibility in power and energy, as well as usability in a large variety of applications (e.g. time shifting and self-consumption of locally produced PV energy, voltage, capacity and contingency support of smart grids, ancillary services and frequency regulation, support to better integration of large renewable plants into the electricity system) [36].

3.5. Lead-acid battery

Although, lead-acid batteries were among the first battery technologies used as energy storage, they are not popular for grid storage due to their low-energy density and short cycle and calendar life [40]. However, the batteries' inherent advantage of efficient performance at low investment cost is expected to encourage their widespread adoption across Europe in grid-connected and off-grid applications [36].

This battery system utilizes reaction between lead and sulphuric acid to generate electrons that move from negative to positive electrode to produce energy and vice versa for charging.

Although, lead-acid batteries are mostly used in cars, they can be also used as grid-connected energy storage, and off-grid household or residential electric power systems.

3.6. Flow battery

Flow batteries are rechargeable batteries which use two liquid electrolytes, separated using an ion-selective membrane, as energy carriers. The characteristic of this storage technology is the total decoupling between power and energy ratings.

Flow batteries are in use since 1970s. However, they make up less than 5% of the battery market [35]. They have relatively low energy densities and have long life cycles, which make them well-suited for supplying continuous power. Currently, the development of these batteries is mostly done in Asia (Japan and China), Australia and in the USA. In Europe, the development is ongoing and products are available in the class of 10 kW and 200 kW [36].

Flow batteries offer a high flexibility to independently tailored power and energy ratings for storing electrical energy. However, due to the relatively low energy density of the vanadium electrolyte, big storage tanks are necessary leading to the limited number of applications for flow battery technology. Most important applications are large-scale non-mobile energy storage applications, peak shaving and energy time shifting [36].

3.7. Hydrogen

Hydrogen energy storage is form of chemical energy storage in which electrical power is converted into hydrogen. Electricity is stored by electrolyzing water to produce oxygen, which is released, and hydrogen, which is compressed and stored. According to electricity demand, hydrogen can be re-electrified via fuel cells. Alternatively also gas turbines or engines can reconvert hydrogen into electricity.

Hydrogen energy storage systems are characterized by the high volumetric energy density of compressed hydrogen. However, the efficiency of the conversion chain is also very low, i.e. below 40% for one charge-discharge cycle [36].

Currently, there are many power-to-gas projects emerging in Germany and other European countries. It has been demonstrated that the different electrolyser types can follow the load changes produced by the output of a wind farm very quickly. This means that electrolysers could be used as negative, or, in continuous operation, also as positive operating reserve for the grid system [36].

Most of these demonstration projects envisage the use of hydrogen in the transport sector or wholesale via the gas grid (with direct hydrogen injection or with methanation step). Only a few of them have large scale storage and re-electrification in its scope [36]. However, large scale hydrogen storage has already been operated for several years at two locations in the UK and the USA.

Hydrogen energy storage is suitable for different applications such as balancing seasonal and weekly fluctuations, ancillary services, and they can be an alternative for grid extension and grid reinforcements [36].

3.8. Methane

An alternative to the storage of hydrogen is the storage of methane. It can be produced from hydrogen and carbon dioxide by the so called methanation. Huge advantage of methane is that it can be injected into the natural gas grid without restriction and could be used for medium- and long-term storage purposes.

The major advantage of methanation over direct use of hydrogen is exactly the full compatibility with the existing value chain of natural gas. Methanation provides the possibility to connect the electricity system with the heat and fuel market. However, disadvantages are the additional loss in efficiency and the added cost [39].

3.9. Advantages and disadvantages of energy storage technologies

Major advantages and disadvantages of energy storage technologies discussed above are summarized in Table 2.

The share of total electricity storage capacity of various storage technologies is shown in Fig. 8. It is obvious that by far the largest shares are still provided by hydro pumped storage. On the second place is electrochemical storage. Among the later, especially high shares have lithium-Ion batteries, about 86%.

In the contrary to pumped hydro storage which is already mature technology, other forms of electricity storage are mainly under development and increasing in capacity. Especially batteries are expected to play an increasing role in the future electricity system [38].

Investment in grid-scale battery storage by country/region as well as global behind-the-meter battery storage over the last few years is depicted in Fig. 9. Since 2013, global investment in behind-the-meter battery storage is continuously increasing.

Electricity storage capacity is growing rapidly worldwide but the largest growth is coming from batteries, especially lithium-ion batteries. The largest amount of total capacity-based investment in battery storage technology is currently coming from electric companies, see Fig. 10. They are critical partners for advancing a robust, sustainable energy storage industry given their unique ability to maximize the value of energy storage for the benefit of all customers [44].

4. The costs of electricity storage

To make a realistic appraisal of the market perspectives of different types of storage it is important to calculate and to compare their costs. Our method of approach is based on levelized calculation of electricity storage costs, see Refs. [17,46]. For analysing the total cost per kWh of different types of storage we have to consider investment costs, operation and maintenance costs, as well as the cost of electricity. Important parameters in this context are the full-load hours, the storage efficiency and the price of electricity. In the following the total electricity storage costs, are calculated as:

$$C_{sto} = \frac{I_{sto} . \alpha}{T . \eta_{sto}} + C_{O\&M} + \frac{P_{ele}}{\eta_{sto}} \qquad [EUR/\text{kWh}] \tag{1}$$

with:

C_{sto} Total storage costs per kWh of electricity [EUR/kWh]
$C_{O\&M}$ Operation & maintenance costs [EUR/kWh]
I_{sto} Total investment costs [EUR/kW]
T Full-load hours [h/a]
α Capital recovery factor [1/a]
η_{sto} Efficiency of storage [%]
P_{ele} Price of electricity [EUR/kWh]

Based on equation (1) the average costs of different storage technologies are depicted in Fig. 11. As seen the battery storage costs are still highest. However, in real life the stationary batteries have the major advantage that they do no compete with the low price spreads in the wholesale markets but with the considerably higher retail prices for electricity (between 20 and 30 EUR/kWh in Western Europe).

A very important parameter for the costs of storing electricity is the number of full-load hours, [17]. For example, 500 full-load hours per year the costs are four times higher than at 2000 full-load hours per year, see Fig. 12. To answer the core question we use a dynamic framework to model supply from various quantities of electricity from variable RES and the load profiles based on Western European conditions. An interesting paper in this context is Mehrjerdi (2019) [47]. They analyse the optimal correlation of non-renewable and renewable generating systems for producing hydrogen and methane by power-to-gas processes.

The most important results of our investigations are: The major reason for the currently high costs of electricity storage is their low number of full-load hours. Currently, a figure of about 2000 h per year is considered to be the minimum. As Fig. 12 shows costs at current price spreads of about 3–5 cents/kWh in the German/French market no type of storage is economically attractive at full-load hours below 4000 h per year. Also in the long run the economic prospects of storage technologies do not look much brighter, see Section 9.

5. Storing every peak? The role of flexibility

In Fig. 5 we have presented the residual load curve over a week. If the residual load curve is analysed over a year and classified by

Table 2
Advantages and disadvantages of energy storage technologies [39,41].

Storage	Advantages	Disadvantages
Pumped hydro	• Mature and established technology • Very long lifetime • Low self-discharge • Good efficiency • High power density	o Geographical restriction o Expensive to site and build o Long construction time o High investments costs and long return of investments o Only large plants connected to the transmission grid are economical.
Compressed air	• Relatively low costs • Long life • Low self-discharge	o Geological restrictions o High investments costs and long return of investments o Long construction time. o Only large plants connected to the transmission grid are economical.
Flywheel	• High power density • Long life time • Very fast recharge • Low maintenance requirements	o Low energy density o Large standby losses o Vacuum chamber needed o Mechanical complexity
Li-ion battery	• High power density • High energy density • High efficiency	o Early-stage technology o High investment costs o Sustainability of lithium mining
Lead-acid battery	• Mature technology • Familiar, experience with large storage • Inexpensive • Acceptable energy and power density for stationary applications • No complex cell management needed	o High maintenance requirements o Short cycle life o Environmental hazards o High voltage of deep discharging o Ventilation requirement o Capacity depend on temperature increasing
Flow battery	• Energy and power independently scalable • High cycle life • Variety of possible redox couples possible	o Leakage caused by acidic fluids o Costs for vanadium-based redox solution is too high o Pumps and valves are prone to errors c o Costly maintenance
Hydrogen	• Low footprint in the case of underground storage • Sufficient experience with hydrogen storage in caverns • Large amount of energy can be stored	o High costs for electrolyzers o Storage density is about one-third lower than for methane o Operation costs very dependent on electricity price
Methane	• Technology for long term storage of electricity • Additional buffer storage in the gas system • Full compatibility with the existing value chain of natural gas	o Low efficiency o External source of CO2 necessary or extraction from the air – resulting in further reduction in efficiency) o High costs

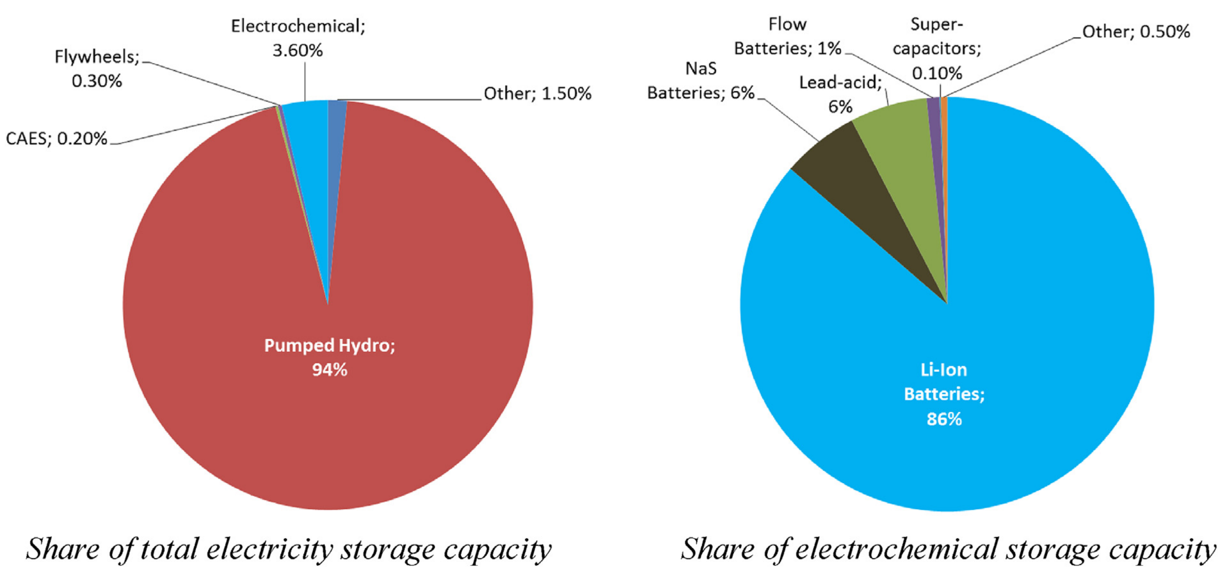

Fig. 8. Share of total electricity storage capacity worldwide by storage technologies (Data source [42]).

magnitude a pattern as shown in Fig. 13 emerges. These curves apply for the example of Austria for the years 2016 vs 2030, given significantly higher quantities of variable renewables in 2030.

From this classified residual load curve scenario for 2030 as shown in Fig. 13 it can be seen that there are more than 2000 h with surplus electricity due to excess generation mainly from variable renewable energy. It is also clearly indicated that there is a pronounced steep peak. That is to say, high excess capacity exists only at very few hours. From this graph the question arises whether really all surplus electricity shown in this figure should be stored to be used latter at times of scarce electricity.

More precisely, the most important question is whether even the unique peak possibly produced from variable RES should eventually be stored.

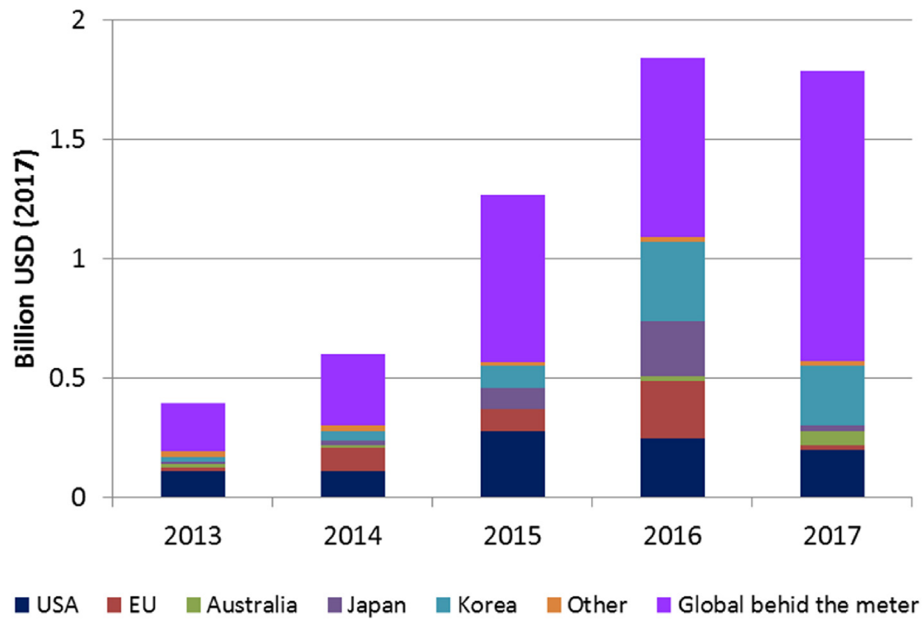

Fig. 9. Investment in grid-scale battery storage by country/region and global behind-the-meter battery storage (data source [43]).

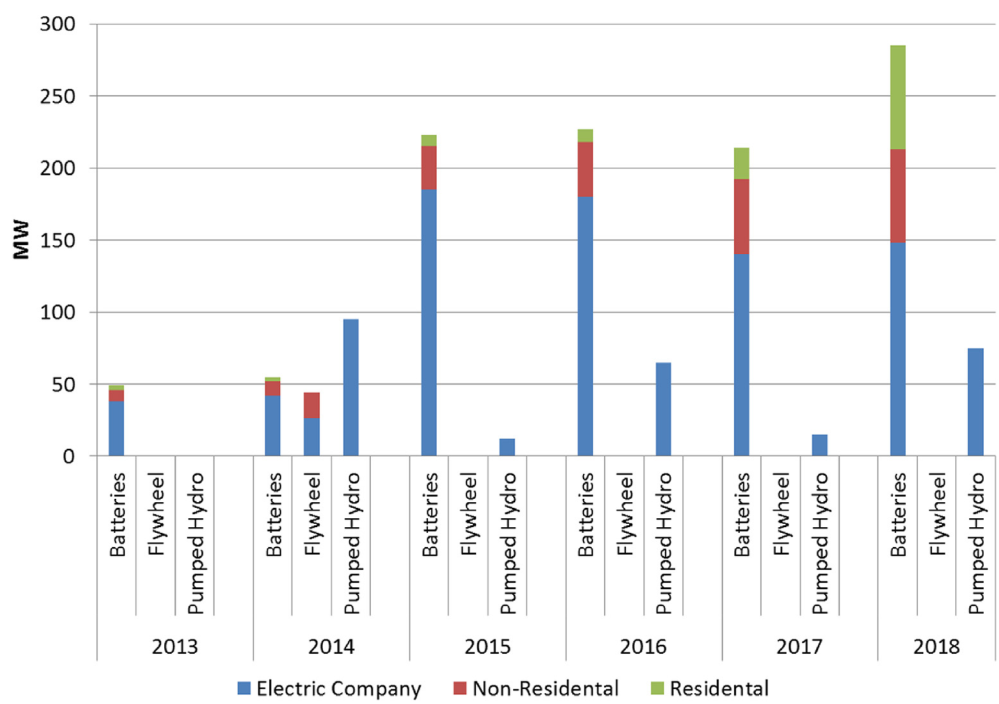

Fig. 10. Annual electricity storage capacity additions by segment and type of storage technology (Data source [44,45]).

Aside from the unfavorable economics due to the high costs there are other major reasons for storing only part of the excess electricity. One major reason is, that all types of storage are in competition with other flexibility options, such as economic demand response, technical demand–side management, and grid extension, see Fig. 14. This figure refers to the right lower corner in Fig. 13, and finally the extreme peaks occurring will be shredded. The different storage options will be put into practice only at economically reasonable number of full-load hours. For a comprehensive analysis of flexibility options see Lund [48].

6. The role of stationary decentralized storage

In recent years, in addition to the classical pumped hydro storage plants, stationary batteries have become more and more popular. There are two major motivations: (i) to store decentral generated excess electricity, e.g. from PV; and (ii) to help to keep the system in balance with respect to supply security. Here we solely focus on the first aspect.

In 2018, the worldwide expansion of storage capacity again increased rapidly. Above all, the "behind the meter" sector, i.e. mainly for decentralized coupling with photovoltaics, see also

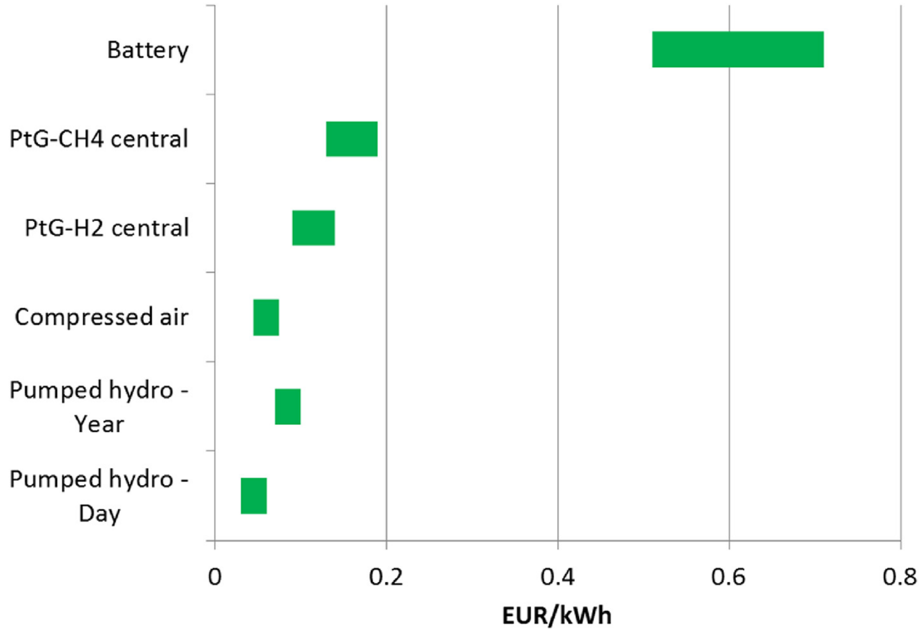

Fig. 11. Average cost ranges of different storage technologies.

Fig. 2, has increased significantly. In the area of decentralized use, it is mainly battery storage systems that are used here. In 2018, around 1.9 GW of battery storage capacity was added "behind the meter", compared to 1.2 GW in the grid scale area, see Fig. 15. This trend, in which "behind the meter" is being strongly expanded, was already clearly evident in 2017, and according to forecasts this trend will also continue in the future.

Basically, there are many different battery types of cell-types, but as it can be seen from Fig. 8 only a few have played an important role in recent years. These technologies are lithium based batteries, lead-acid batteries, flow batteries, sodium sulphur batteries [50]. Most decentralized stationary battery storage systems are either lead-based or lithium-based systems, but as shown in Fig. 8 lithium-based systems clearly dominate today.

The lead acid battery is one of the most proven and widely used battery in many applications. This battery is known as a classic car battery and most UPS (Uninterruptible Power Supply) systems are still based on this cell type.

Lead acid batteries are inexpensive, but also have low cycle stability, especially at high discharge depths. This fact, as well as the fact that lithium-based batteries have significantly higher energy and power densities, has also made them interesting for the prosumer market in recent years [51]. Driven by the construction of immense capacities for battery storage construction for e-mobility, prices have fallen significantly, especially for battery modules.

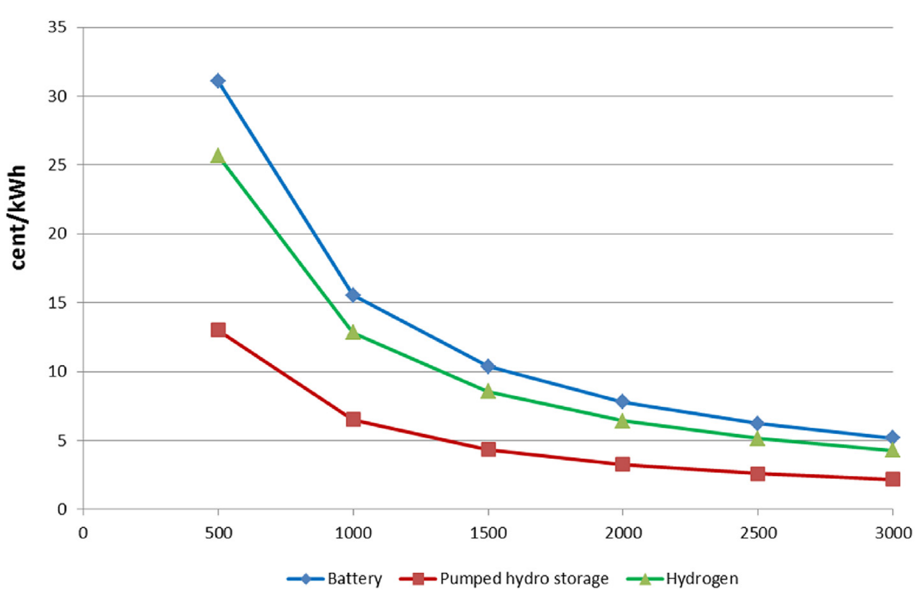

Fig. 12. Costs of storing electricity for different technologies depending on the full-load hours per year (as of 2018).

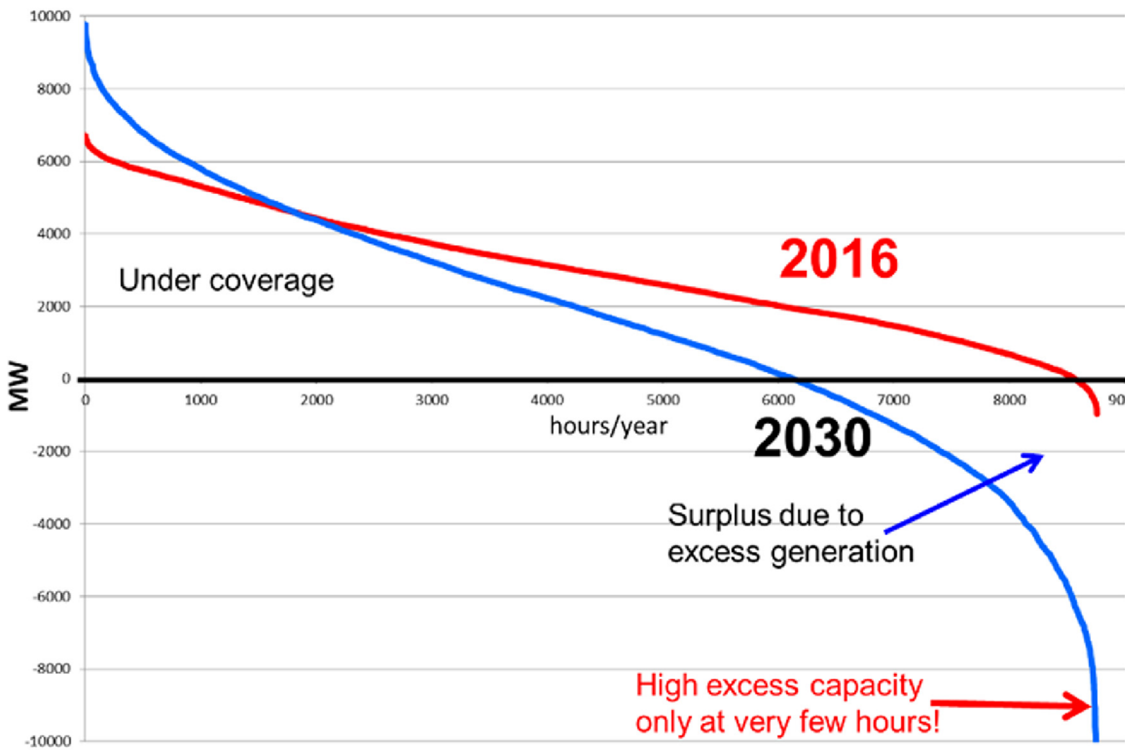

Fig. 13. Classified residual load curve for the years 2016 (historical data) vs 2030, given high quantities of variable renewables in 2030.

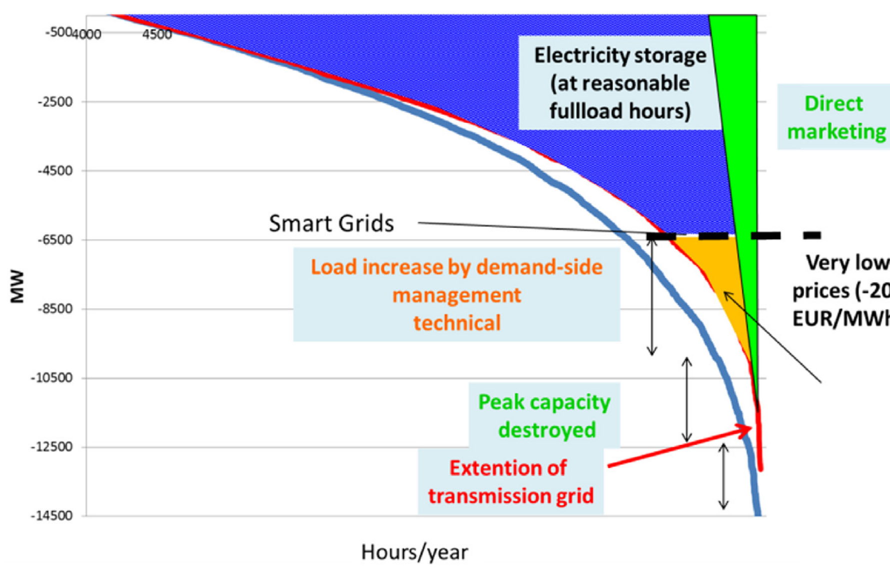

Fig. 14. Flexibility options competing with storage technologies for more excess electricity.

6.1. Full-load hours vs. number of cycles

For the calculation and above all for the comparability of storage costs, it is important to define the levelized costs of electricity of the stored energy. For battery storage systems this definition of costs can be based on the number of full-load hours, as it is common in other power plants/storage facilities, or on the number of full cycles. The number of full-load hours is defined as the total energy stored divided by the maximum discharge capacity. In other words, if a battery with a nominal capacity of 20 kWh and a maximum discharge capacity of 20 kW is discharged 1000 times per year, this would mean 1000 full-load hours. Of course, the efficiency of the battery must also be taken into account here. The full-load hours are therefore quite easy to estimate. The costs of the stored energy (without operating costs) are now calculated by dividing the annual investment costs per kW by the annual full-load hours. The problem with this calculation for batteries is that the investment costs of this storage option are mostly given in €/kWh capacity and not in €/kW. In addition, it is not possible to determine the lifetime of the storage unit, i.e. how much energy can be stored per lifetime.

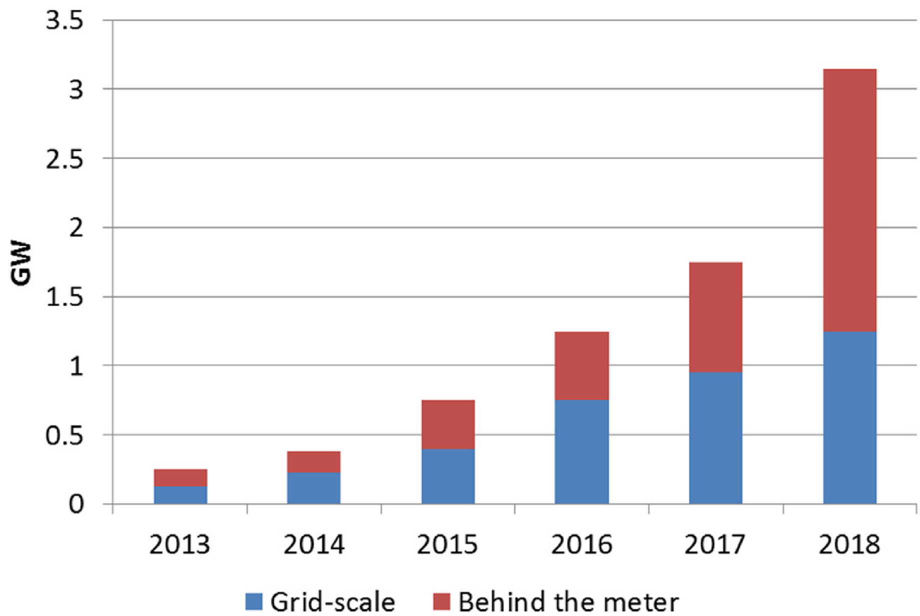

Fig. 15. World-wide yearly new installed battery storage capacity for grid-connected and "behind the meter" (data source: [49]).

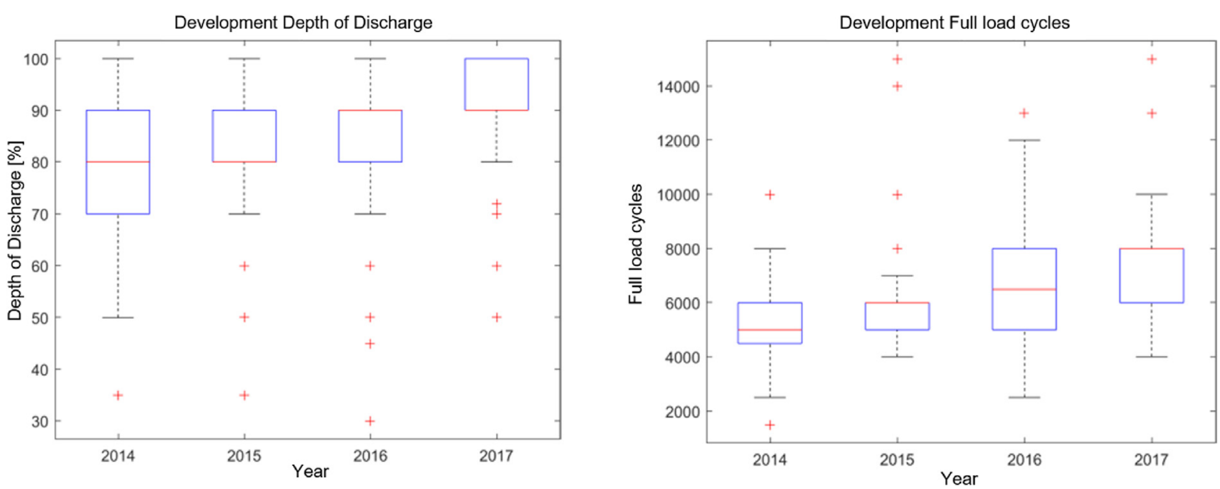

Fig. 16. Recent development of average depth of discharge and full load cycle stability, (data source: [53], own analysis).

An alternative calculation of the levelized costs of electricity is based on the number of full cycles. The number of full cycles is defined as the complete discharge and charge cycle of the battery in relation to its capacity. The number of full cycles is also one indicator of the battery life, which is also specified by the manufacturers, and the cycle stability increases as the depth of discharge decreases. An exemplary lithium accumulator can run about 3000 cycles at 80% discharge depth, but at a discharge depth of 50% it can already run 9000 cycles. This corresponds to a useable total capacity of 48 MWh or 90 MWh over the cyclical life and thus also makes a significant difference to the cost of the stored energy over the lifetime. The levelized costs of electricity are calculated here from the annuity of the investment costs divided by the capacity of the battery, the depth of discharge, the efficiency and the number of cycles. The difficulty in this methodology lies in the estimation of the annual cycles.

However, if the full-load hours and all parameters such as depth of discharge, efficiency and capacity of the battery are known, it is relatively easy to convert from full-load hours to cycles. Conversely, if you know the cycles instead of the full-load hours, it is relatively easy to deduce the full-load hours.

Both types of calculation have their advantages and disadvantages. To make the different energy production technologies comparable, the methodology of full-load hours is definitely useful. For the calculation of the levelized costs of electricity and for estimating the lifetime of the storage unit, the calculation of full cycles per year makes sense.

Even if e-mobility can certainly be considered a major driver or enabler for stationary battery storage systems, developments in storage costs in the automotive sector cannot always be allocated one-to-one to stationary operation. It strongly depends on what is directly considered in the costs (cells, packaging, charge control, thermal management, installation, inverter etc.) and what is left out. This is of course not only true for the comparison between stationary systems and batteries for the automotive sector, but also among the stationary systems there are big differences which

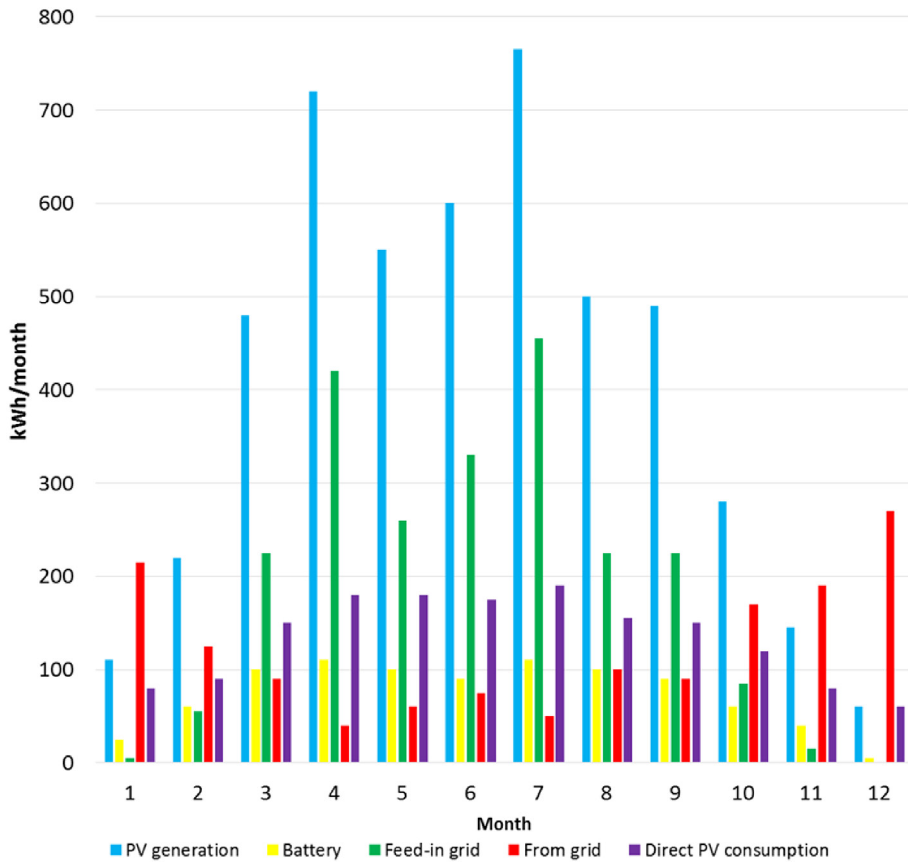

Fig. 17. Monthly data for a PV-system with battery storage for own consumption, grid supply, battery charge, battery discharge and grid feed-in (own analysis).

components are included in the costs [52].

In addition, large differences in storage costs can be found in the various literature sources. There are several reasons for these differences: Firstly, because of the many different technologies (even within lithium-based batteries) it is difficult to make a valid comparison. On the other hand, as mentioned before, different components are taken into account. In the automotive sector, the cells are usually taken into account. Other studies also include modules and battery management system but mostly enclosure costs and other balance of system components are omitted. In the case of stationary batteries, the inverter costs are usually included and the profit margin, which is shown in the automotive sector on the entire vehicle, is also added. In addition, the comparison between batteries in the automotive sector and the stationary behind-the-meter comparison is a bit misleading because the latter sector has yet to develop, whereas the automotive sector is already mature. If all these aspects were correctly priced in the studies, the cost difference shown in the studies would be significantly lower. It can also be concluded that stationary battery systems in long-run will be cheaper than batteries in the automotive sector, as the latter have to meet higher requirements for safety, durability and discharge power.

With respect to the development of batteries over time, in addition to the cost digression of recent years, also the cycle stability and the average discharge depth have been improved further, see Fig. 16. Both parameters are important indicators of durability and useable capacity over the lifetime. The higher the number of cycles with a large discharge depth, the more capacity is available for a longer period of time, which straightforward has a direct effect on the economic viability of battery storage systems. Fig. 16 is based on surveys conducted by C.A.R.M.E.N eV [53], which also collected data on the cycle stability and discharge depth of battery storage systems from the manufacturers in the respective years. It can be seen that the median of the surveyed systems increased from 80% to 90% between 2014 and 2017. In addition, the outliers downwards can be classified as significantly lower, which makes a significant difference in the overall systems considered. At the same time, the median of the full load cycles has risen from about 5000 in 2014 to about 8000 in 2017. Overall, this means that battery storage systems have become significantly more durable at a higher depth of discharge.

The following figures, Fig. 17, Fig. 18 and Fig. 19, depict the problem from the perspective of decentralized storage linked to a residential PV-system. A comparison of own consumption of a residential PV system, grid supply, battery charge, battery discharge and grid feed-in for an example over the months of a year in Austria is depicted in Fig. 17.

The economic performance of such a systems depends highly on its share of own consumption of the electricity generated. The share of own consumption depends essentially on the irradiation as well as on the dimensioning of the system compared to the overall load profile. Fig. 17 shows monthly balances for a typical single-family building with an annual electricity consumption of 4000 kWh/a and a 5 kWp PV system facing south. This system is supplemented by a 5 kWh battery storage. In practice only a part of the electricity generated is consumed by the generator itself, see the violet bars in Fig. 17. On contrary the blue bars show over-all direct electricity generation from the PV system and yellow is the electricity discharged from the battery. The green bars depict the electricity fed into the grid, the red ones depict electricity taken from the

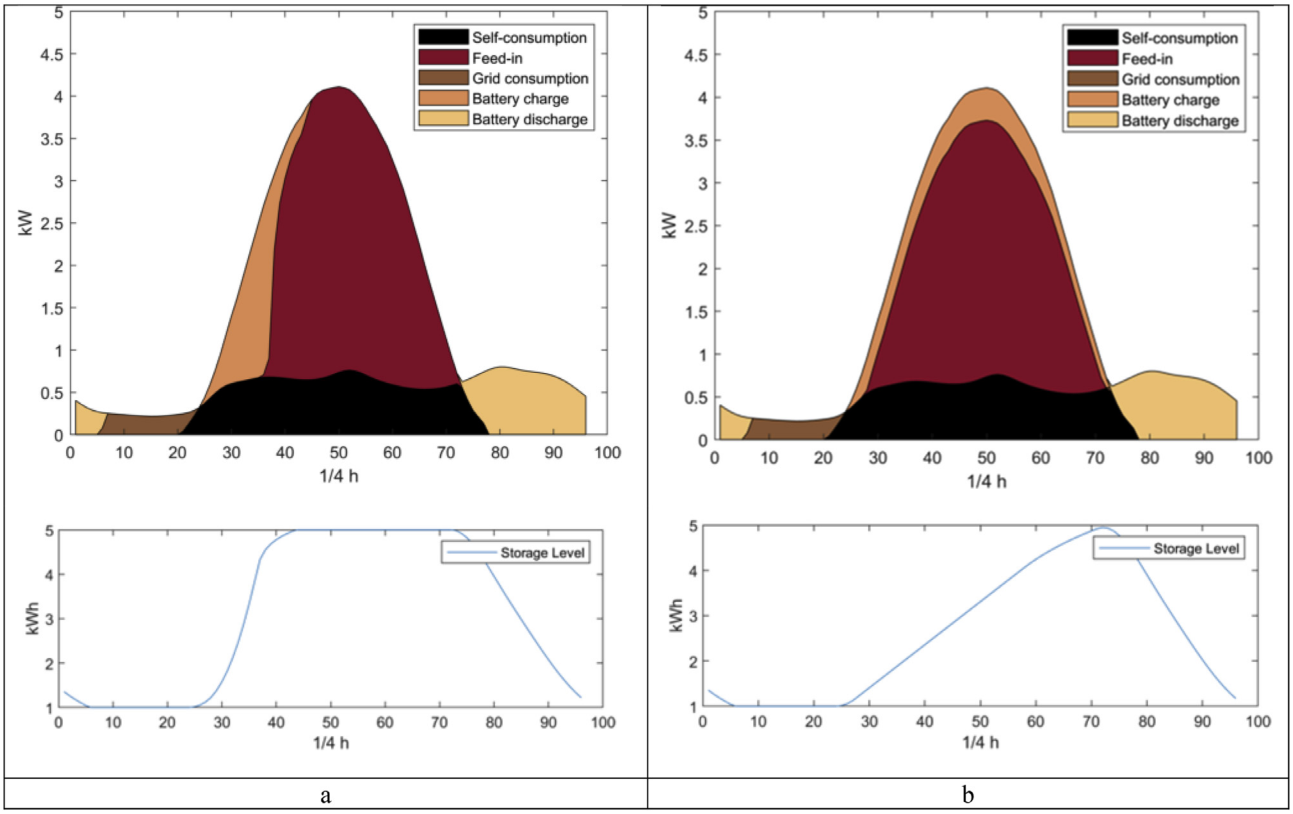

Fig. 18. **a** Comparison of own consumption, grid supply, battery charge, battery discharge and grid feed-in on a summer day without any strategy for optimal charging (own analysis) **b** Comparison of own consumption, grid supply, battery charge, battery discharge and grid feed-in on a summer day with a strategy for optimal charging from the distribution grid's point-of-view (own analysis).

network.

Figs. 18 and 19 provide an exemplary comparison of PV generation, grid connection, own consumption and the battery charge state for a typical household in Austria for both a winter and a summer day. The system configuration is the same as already defined in the analysis in Fig. 17. As can also be seen here, the load profile is implemented as a standard load profile.

Two strategies for charging the battery are considered in this analysis. Figs. 18a and 19a show how the energy consumption would behave if the battery is charged uncontrolled. If we look at the summer day in Fig. 18a, we can see that the battery is fully charged around noon and then the full PV output (minus own consumption) is fed into the grid. This high gradient of the feed-in peak must be avoided as far as possible in the interests of grid service. An example of this is shown in Fig. 18b, where the battery storage is continuously charged during the day so that it is fully charged at the end of the day. The advantage is that the feed-in gradient is more continuous than in the first case and thus high power peaks are not transmitted to the grid within a very short time. On a winter day, as shown in Fig. 19a and b, this question does not really arise because only on a few days is surplus energy actually generated, which could then be stored in the battery storage or fed into the grid.

7. The role of electric vehicles as decentralized storage

Another decentralized option is to use the battery of the electric vehicles as storage for electricity from the grid and to use it especially for delivering electricity in times of scarcity. With the increasing number of rechargeable electric vehicles interest in this storing option is increasing, as well as a number of studies dealing with this issue [54–56].

Having this perspective in mind, policy makers, utilities, and grid operators have begun to work on integration of electric vehicles into the energy system. Since electric vehicles (as all types of cars) are parked most of the time, the batteries in electric vehicles could be used as storage for surplus electricity and as an energy source in times of scarcity. Moreover, in combination with the smart grid, electric vehicles could be also used to allow electricity flow from the car to the electric distribution network. In such a system, called Vehicle-to-Grid (V2G), electric vehicles communicate with power grid. The V2G concept is a crossover of electric vehicles, power system and information technology. In this concept, electric vehicles are not just a transportation means. They serve as storage, as well as mobile power plants giving electricity to the power grid when necessary. With the increasing use of RES, V2G storage capacities can enable electric vehicles to contribute to balancing electricity supply and demand.

The V2G concept relies on a smart power grid, which involves smart metering, dynamic pricing, automated control and real-time information exchange. With the increasing number of electric vehicles, the V2G concept could become an energy arbitrage between the power utilities and the EV drivers, and have a significant impact on a balanced power system operation.

As discussed in literature [57], there are three necessary conditions for V2G deployment: (i) the penetration of electric vehicles needs to be high enough to offer enough agents participating in V2G and thus a high enough parked ratio of electric vehicles, (ii) there must be a need for decentralized storage, and (iii) the cost of V2G must be low enough to compete with other decentralized

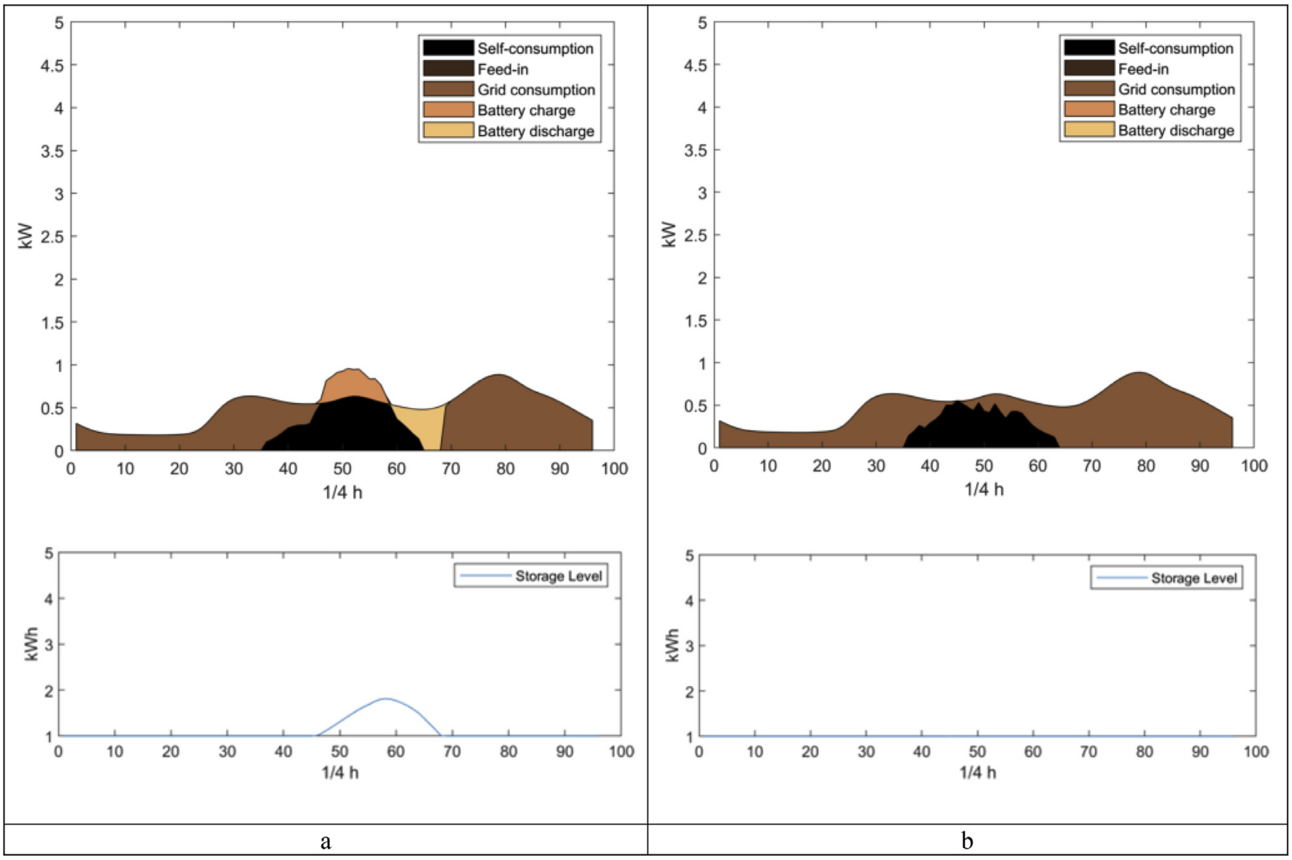

Fig. 19. **a** Comparison of own consumption, grid supply, battery charge, battery discharge and grid feed-in on a winter day with excess PV and without any strategy for optimal charging (own analysis) **b** Comparison of own consumption, grid supply, battery charge, battery discharge and grid feed-in on a winter day without excess PV and with strategy for optimal charging (own analysis).

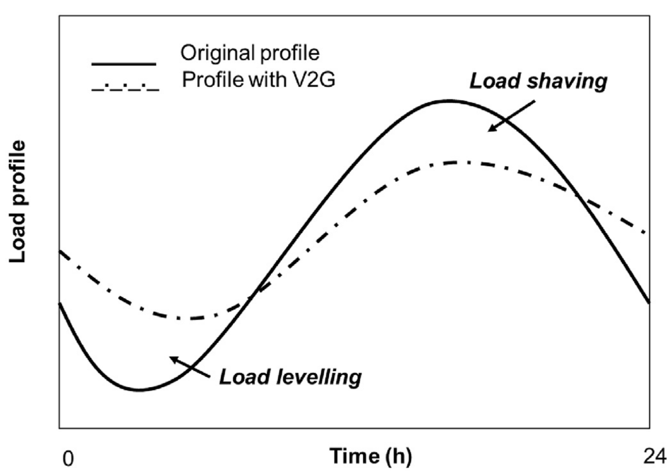

Fig. 20. Load shifting: levelling and shaving (adapted from Ref. [59]).

storage technologies.

However, an individual V2G set-up of each EV with the power grid is ineffective and inefficient. Since an electric vehicle can store relatively small amount of electricity, about 10–60 kWh, an aggregator should be introduced which is responsible for gathering a number of EVs and communicating with the power grid. Based on willingness of EV drivers and available battery capacities, the aggregator controls smart charging and discharging of EVs [58]. The aggregator coordinates the intragrid power flow, minimize the total power demand and total power loss, optimize the voltage deviation, calculates prices, etc. Since the power generation capacity has to be in balance with the load demand, a large fluctuation of load demand will significantly increase the capital- and operation costs of the power system. The V2G operation can contribute to load leveling (EV batteries take electricity from the grid during the off-peak periods) and load shaving (electricity flow from EVs to the grid during peak periods), see Fig. 20.

The charging and discharging processes in V2G applications are

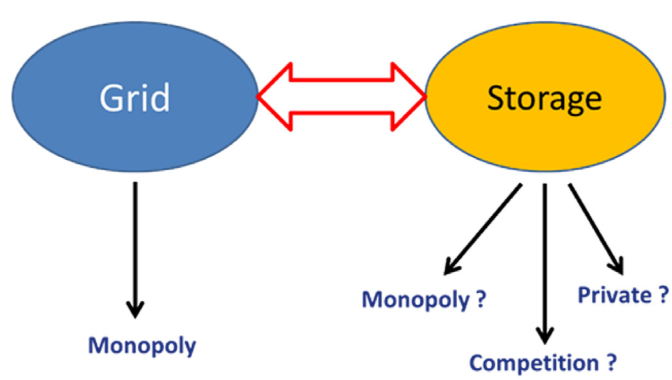

Fig. 21. Interaction of grid extension and new storage.

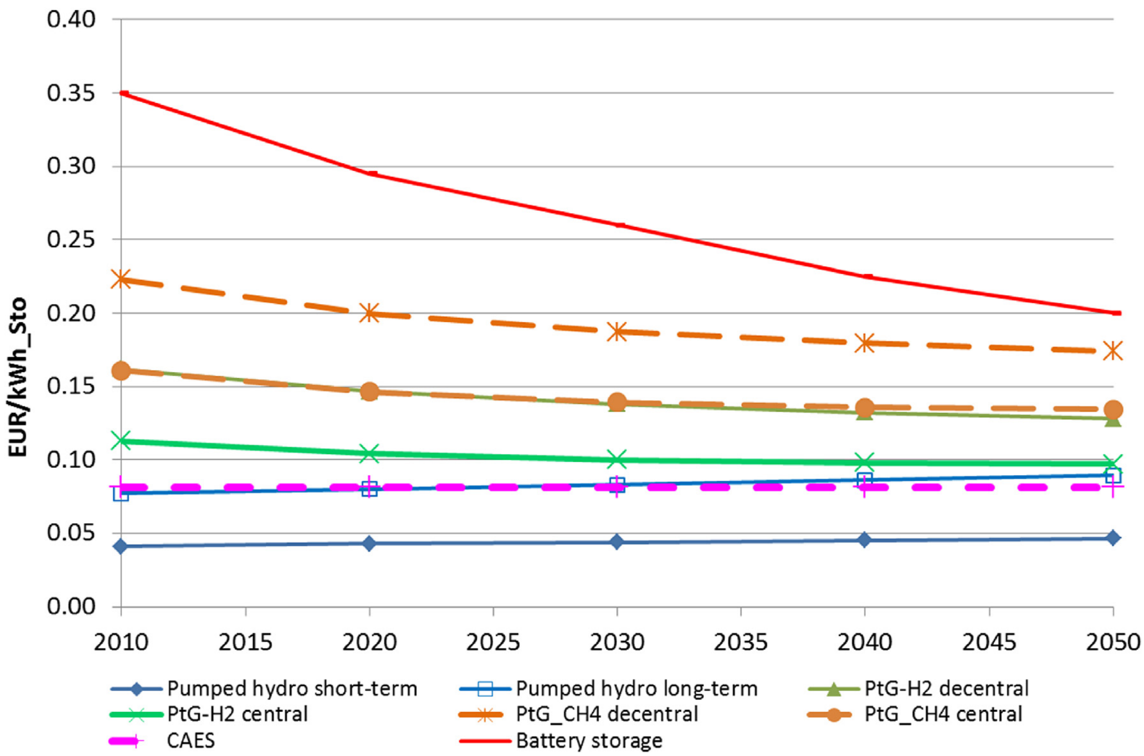

Fig. 22. Development of costs of several technologies for long-term storage of electricity depending on technological learning over time up to 2050 (own analysis).

much faster than the shutoff and startup processes of standby generators. However, V2G services could provide useful support to the power system in the future. Currently, V2G is challenged by high costs due to lack of standards and scale. For example, car manufacturers in Europe, Japan and China use different charging protocols. European manufactures use mostly the Combined Charging System which das not enable V2G.

Another important challenge is battery lifetime. Currently used EV batteries suffer from a limited cycle life. The V2G operation additionally degrades their life. Since V2G systems are currently represented just in pilot studies, the full impact of V2G operation on battery lifetime is still subject of research.

Moreover, in the assessment of the benefits of the V2G systems it is important to consider efficiency. The charging efficiency from the grid to the battery is 70–80%, battery to grid discharging efficiency is 80–90%, so that overall charging/discharging efficiency of V2G operation is about 60–70% [59].

Currently, many supply authorities are experimenting with V2G systems. However, all current applications are small-scale trials.

8. Interactions between storage and the grid

One very important issue is the interaction of storage for electricity with grid services and grid extension. In principle, both storage and grid are flexibility measures. The situation is as follows: Every extension of the transmission or the distributed grid leads to a reduction of the demand for storage. Vice versa additional storage capacity leads to a reduction in required grid capacity. The interaction takes place on every grid level – the transmission grid as well as the distribution grid level. As seen from Fig. 14 the most important measure for enhancing flexibility and electricity supply security is the extension of the electricity transmission grid. Extensions of the grid lead to flatter demand profiles and evened out generation of variable renewables. That is to say, the larger the area of generation of variable renewables is the flatter will finally be the residual load profile.

Hence, the extension of storage and grid has to be done in lockstep and carefully tuned. But the major crucial issue in this context is the issue of regulation vs market, see Fig. 21. It is without discussion that the grid is considered to be a natural monopoly. However, from the energy economic point-of-view, excluding the grid security issue, storage is actually considered to be a market-based option and could also be in competition with other storage or other flexibility options, such as demand-side management. But from the above stated request of extending storage and grid in lockstep some contradiction may emerge. However, in Europe currently there are clear regulated plans for grid extention in the so-called Ten-Year Network Development Plans (TYNDP) including both, national grid extention and cross-border interconnections, see Ref. [60]. That leads to the conclusion that the deployment of any new storage has to take into account the planned new transmission lines.

9. Future prospects

The analysis of future prospects is based on technological learning regarding the future development of investment costs of long-term storages. Quantities for the single technologies are modeled based on International Energy Agency [61]. Note that for hydro storage, due to the maturity level, we do not consider further technological learning.

Fig. 22 depicts the possible development of costs of several technologies for long-term storage of electricity depending on technological learning over time up to 2050, see also [62]. As seen over the period up to 2050 decreases in the prices of PtG-technologies will take place mainly due to learning effects. For long-term hydro pump storages (over a year) further prices will rather increase mainly due to a lack of sites with reasonable costs and lack of acceptance. In a dynamic market framework the costs of all centralized long-term storage technologies will finally be too high to become competitive. By 2030 under most favorable learning conditions the costs of hydrogen and methane for 2000 full-load hours per year will be between 0.10 EUR/kWh and 0.18 EUR/kWh.

10. Conclusions

The major conclusions of this analysis are:

The options for placing storage in smart energy systems have increased significantly in recent years, as well as the diversity of storage types: (i) we still have the classical pumped hydro storage mainly placed on the transmission grid level and also operating in cross-border exchange; (ii) there are battery storage options which may be placed either on grid-level or in decentralized applications, i.e. connected to the grid (e.g. V2G) or "behind the meter", and (iii) there is the option of long-term chemical storage e.g. of hydrogen and methane, which may in future also connect different sectors e.g. the electricity sector and the transport system.

Regarding these different opportunities the major findings are:

(i) with respect to pumped hydro storage, significant decrease of investment costs cannot be expected in the future because no meaningful further learning effects are expected and the cheapest site options are already in use; (ii) stationary, decentralized batteries connected to PV systems increase household independency from grid electricity; However, they have the major disadvantage that despite decreasing battery prices in recent years, their very low full-load hours still lead to a poor economic performance; (iii) regarding V2G options, it is not yet clear how car owners would benefit. It seems that the increase in charging cycles and limited flexibility of vehicle use are rather discouraging for the car owner; (iv) for PtG-technologies such as hydrogen and methane, it will be difficult to compete in the electricity markets despite the high technological learning potential. The major reason for this is the low round-trip efficiency and the resulting high electricity generation costs.

However, as also indicated e.g. by Lund [48], excess electricity must not necessarily be stored in electricity storage. There are further attractive solutions such as storing electricity in thermal storage, in the district heating network or in chemical storage i.e. hydrogen and methane. In addition, for hydrogen and methane there are prospects for their use in the transport sector. In recent years, gasoline and diesel prices have increased as compared to the stagnation or even decreases in electricity spot markets. In addition, due to the lack of environmentally benign fuels for mobility, hydrogen and methane produced from renewable electricity may become economically feasible alternatives.

For the practical use of storage technologies, it is essential to identify options for cheaper electricity (e.g from depreciated wind power plants not receiving any further subsidies) and to increase full-load hours, e.g. by using only a part of the production profile of wind power plants without peaks and with high number of full-load hours. However, new storage options will only make sense if they are constructed in coordination with grid extensions and if new excess production, particularly from variable RES, seems likely.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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