Renew. Energy Environ. Sustain. **8**, 2 (2023)

https://doi.org/10.1051/rees/2022016

Renewable Energy and Environmental Sustainability

Available online at:
www.rees-journal.org

REVIEW ARTICLE OPEN ACCESS

Prospects of electricity storage

Zejneba Topalović[*], Reinhard Haas, Amela Ajanović, and Marlene Sayer

Vienna University of Technology, Institute of Energy Systems and Electrical Drives, Energy Economics Group, Gußhausstraße 25–29, 1040 Vienna, Austria

Received: 21 May 2022 / Received in final form: 14 December 2022 / Accepted: 15 December 2022

Abstract. With the expansion of renewables in the electricity markets, research on electricity storage economics is needed for a better understanding of the utilization of these systems and for improving the performance of intermittent variable generation. Collected up-to-date research of electricity storage systems published in a wide range of articles with high impact factors gives a comprehensive review of the current studies regarding all relevant parameters for storage utilization in the electricity markets. Valuable research of technical characteristics from the literature is broadened with the electricity storage analyses from an economic point-of-view. Analysis of selected technologies, considering different perspectives such as their profitability, technical maturity, and environmental aspect, is a valuable addition to the previous research on electricity storage systems. Comparing conducted analysis with the selected literature, electricity storage technologies are analyzed concerning their viability in the electricity markets. Given the current outlook of the electricity market, the main problems for storage's wider integration are still energy storage costs. These can be overcome with different applications of energy storage systems, integration of new market players, or a combination of storage technologies along with the implementation of new energy policies for storage.

1 Introduction

The utilization of energy storage systems for electricity has a long history from the beginning of the 20th century when the first pumped-hydro power plants were built. Over the years, new technologies for storing electricity were emerging, which have led to a variety of storage systems today, all differing in the application, costs, and profitability. It is forecasted by International Energy Agency (IEA) that global installed storage capacity will expand by 56% in the upcoming years [1]. Due to the rapid development of the electricity sector, especially in the last two decades, there are environmental concerns for the future if further exploitation of natural energy sources continues. A growing number of countries pledge net-zero emissions agreements towards sustainable and clean energy. With the Paris Agreement's goals for limiting global warming to 1.5 °C, many countries are already going towards carbon neutrality ambitious targets. IEA has built a roadmap for reaching net-zero emissions by 2050, ensuring a clean energy transition in the energy sector. Electricity storage systems are used as means for implementing these targets because of their flexibility characteristics. As measures were taken for the implementation of the set goals, solar photovoltaics and onshore wind are dominating, attracting 46% and 29% respectively, of global renewable energy investments [2]. According to the IEA report [3], China and India are going to lead energy growth in the next years. India is facing extreme changes in the last 10 years, firstly due to the progressing electrification and secondly due to the increase in solar generation. All these future investments in variable renewable energy sources can impact the power system's operating and balancing mechanisms. Hence, using a literature review and considering economic assessments alongside technical characteristics, the viability of the electricity storage systems for ensuring adequate renewables expansion in the power grids, is questioned in the paper.

Considering different aspects of electricity storage systems, such as type of application, economic profitability, energy policies for the implementation of electricity storage, and environmental consequences of utilizing these systems, an analysis of different technologies is conducted. Figure 1 presents a scheme of analyzed technologies in the paper from different perspectives of electricity storage systems.

Selected systems are pumped-hydro storage (PHS), compressed air energy storage (CAES), flywheels (FESS), lithium-ion (Li-ion), lead-acid (Pb), nickel-cadmium (Ni-Cd), sodium-sulfur (NaS), vanadium redox flow battery (Vrb), chemical and electrical storage systems.

* e-mail: zejneba.topalovic@student.tuwien.ac.at

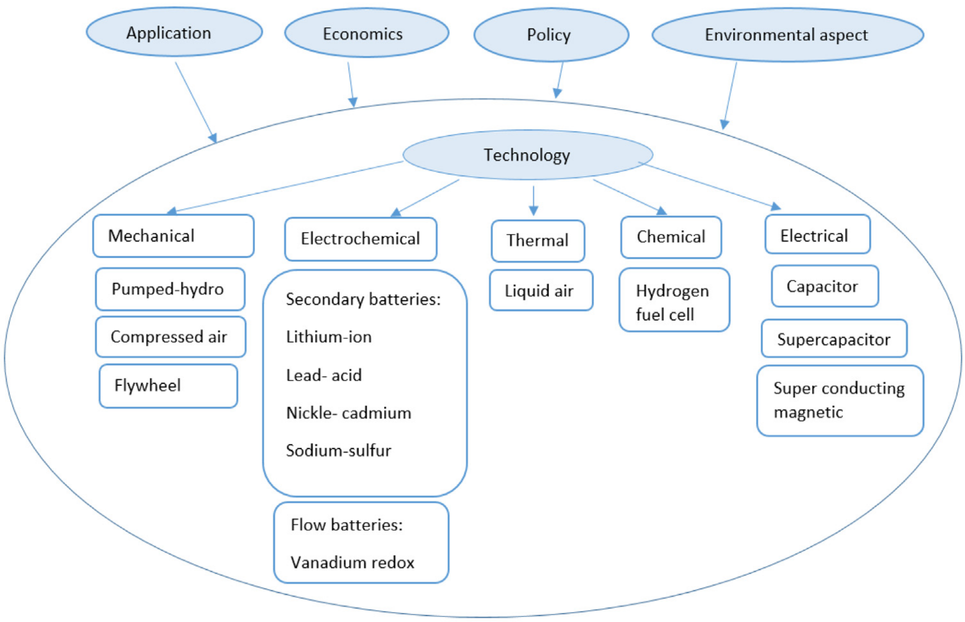

Fig. 1. Selected energy storage technologies for electricity considering different perspectives for the analysis.

1.1 Selected literature

Most of the electricity storage research in the recent literature is based on the storage system's performance, sizing, and operation. Detailed technical reviews [4,5] focus on the capacity of storage, installation in distribution grids, and optimal sizing. They show significant technology advances and developments with prospects of optimal storage placement in the grids. These reviews are valuable for understanding technical characteristics and certain constraints of electricity storage technologies, but they lack analyses of feasibility and economics. Valuable research of technical characteristics is expanded in this paper with electricity storage analysis from an economic point-of-view. With the expansion of renewables, research of electricity storage economics, such as [6–8], is needed for the utilization of these systems and improving performances of intermittent variable generation. Analysis of selected technologies, considering different perspectives such as their profitability, technical maturity, and environmental aspect, is a valuable addition to the previous research on electricity storage systems. Comparing conducted analysis with the selected literature, electricity storage technologies are analyzed regarding their viability in the electricity markets.

The core objective of the paper is to give up-to-date research on electricity storage systems, to provide an economic assessment, and to find what technology is cost-effective and feasible for implementation in the electricity market. Considering the different applications of electricity storage as ancillary services, flexibility measures, large-scale and user-side installations, a detailed analysis of the total costs and technical maturity of the selected systems is conducted. Opportunities for electricity storage to develop alongside growing shares of renewable energy sources in the power grids are analyzed in the next chapters.

Table 1. Installed capacities of different energy storage technologies [DOE]*.

Technology category	Rated power (kW)
Lead-carbon	392
Liquid air energy storage	5,350
Compressed air energy storage	8,410
Hydrogen storage	20,485
Electro-chemical	338,878
Lithium-ion battery	754,610
Thermal storage	1,869,639
Electro-mechanical	1,923,688
Pumped-hydro storage	181,910,506

*Global energy storage Database, National Technology & Engineering Sciences of Sandia, LLC (NTESS), [Accessed: 17th November 2020].

This paper starts with the storage technology's technical categorization in Section 2, followed by an economic analysis in Section 3. In Section 4 new application is discussed, followed by Section 5 where prospects are derived from the presented review.

2 Energy storage categorization

Research about energy storage systems has been intensified recently, as the amount of electricity generated by variable renewable energy sources increases. According to the Global Energy Storage Database (DOE), other storage technologies are still lagging behind historical installations of pumped-hydro storage with an installed power capacity of 182 GW (Tab. 1). Electro-mechanical and thermal storage systems are the categories with the highest sum of installed rated power between categories excluding

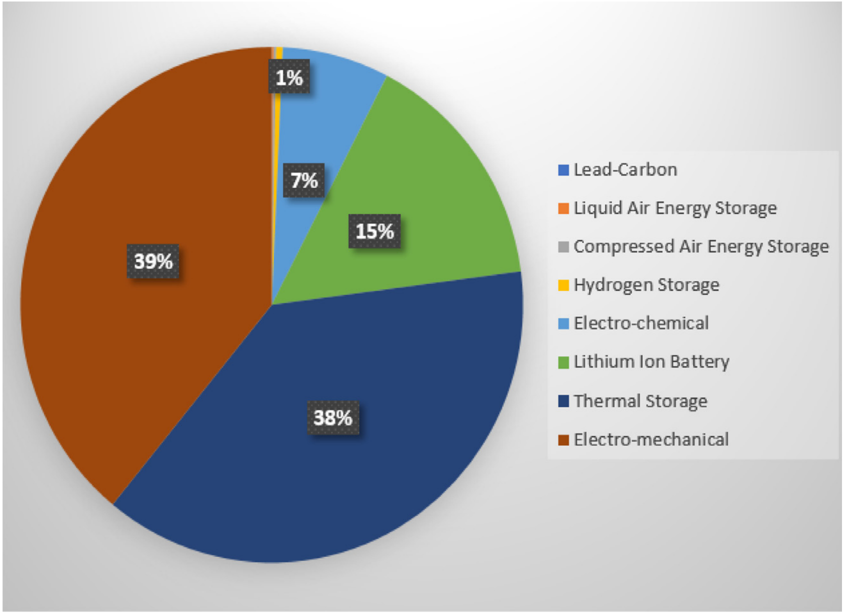

Fig. 2. Rated power of storage technology without pumped-hydro storage.

pumped-hydro systems (Fig. 2). As [1] predicts, stationary storage (excluding electric vehicles) would need to increase from 30 GWh today to 9000 GWh by 2050. These figures should be achieved through proper sizing and installation of energy storage systems, but economically viable as well.

Installation of the energy storage systems in power grids differs depending on the technical parameters. Characteristics such as power and energy capacity, energy density, efficiency, and response time influence energy storage's application and place in the grid, hence these are selected from the literature for the analyzed electricity storage systems in Table 2.

Analysis shows that pumped-hydro storage and compressed air energy storage systems can provide large amounts of energy (up to GWs) in a couple of minutes, with an average efficiency of 70%, and once installed, they can be operable for more than 40 years. Contrary to these, flywheels and batteries are responsive in less than seconds, but are limited with high power density and power ranges up to 100 megawatts. Highly responsive technologies such as capacitors and magnetic storage systems can provide up to 10 MWs, hence they can have a power density of up to $120{,}000\,\mathrm{kW/m^3}$. These technologies are lacking technical maturity for power grid utilization. New emerging technology for long-term storage and for covering a supply gap of fossil generation decrease with the increase of renewables, is hydrogen, as stated in [9]. The problem with this type of storage is the low efficiency of 50% on average because of conversion methods and current technical maturity. Depending on the technical characteristics from Table 2, the application and utilization of storage systems in the electricity grids are analyzed in the next Sections.

2.1 Mechanical storage systems

Energy storage systems can be categorized by the form of energy used to produce electricity, therefore potential energy of the water or kinetic energy present the basics of mechanical energy storage systems.

2.1.1 Pumped-hydro storage

Pumped-hydro storage systems were developed in the early 1900 s, yet planning and construction begin after the end of the Second World War [10]. In Europe, 80% of the PHS capacity was commissioned between 1960. and 1990., with the majority of locations in the mountain region of Austria, France, Germany, Italy, Spain, and Switzerland [11]. The authors present an overview of the historical development of PHS in some of the most important electricity markets and the comparison of mechanisms that reward bulk electric energy systems (EES). They conclude that new investments of EES in liberalized markets are influenced by capital costs, hence bulk EES, if considered the best form of flexibility, should be commissioned by the public sector.

The pumped-hydro storage system works on the principle of two reservoirs and the potential energy of water. Because of their characteristics to store a large amount of energy, pumped-hydro storage systems have become the most used storage technology with installed capacities of 182 GW globally (Tab. 1). When demand is high, electricity is produced by storing the water from the upper to the lower reservoir. At night, when demand is low, electricity from the grid is used to pump back up water, as presented in Figure 3.

This system balances and adjusts the demand and supply, thus providing the stability of the power grids.

In [12] is presented a review of the globally existing PHS systems and hybrid systems such as solar photovoltaic-hydro and wind-hydro, questioning the technology for island grids and bulk storage systems. It concludes that for the analyzed systems, PHS is the best option regarding technical and economical compatibility. Geographical locations are the main constraints for PHS installations, hence [13] proposes a case study with innovative arrangements for PHS, showing possibilities for storage with low topography variations and water availability. Pumped-hydro storage power plants have been revitalized in recent years due to the flexibility mechanism for the operation and dynamic dispatching of power grids. Some countries' main plan for reaching targeted renewable shares, is investing in pumped-hydro storage systems [14]. However, this is challenging to achieve firstly because of location constraints, but also because of electricity market design. In a view of pricing policies on storage schemes that prolong the return of an investment in PHS in some countries, there are options for investors to convert already installed private dams into PHS or to convert public dams into PHS that could also eventually contribute to public welfare in that way [15].

2.1.2 Compressed air energy storage

The same as pumped-hydro storage systems, compressed air electricity storage systems depend on geographical locations. These systems utilize large underground storage caverns for providing large-scale and long-term electricity storage. Analysis of ongoing large-scale CAES projects and possible methods for utilizing these systems is given in [16]. Authors find that salt caverns, promising candidate methods for using underground formations for CAES, are more likely to be found in the United Kingdom (UK) in comparison to India. Utilizing CAES is not just a matter of topology and technical maturity, but of costs and feasibility as well. When considering wind farms and CAES units, the peak- load of the system can be significantly reduced [17]. The authors showed that changes in the prices of electricity and reserves occur in the opposite direction at windy hours. For high loads, CAES units would decrease prices and increase them at low-load hours. This analysis proves that storage units have more preventive dispatches at high-load. The feasibility of the given project of CAES installed beside the wind farm resulted in the conclusion that peak load can be reduced up to 21% along with the reduction of the operational cost. Compared to CAES, offshore wind coupled to offshore compressed air energy storage (OCAES) proves to be non–feasible for such a system [18]. A study proved that OCAES could be the best suited for islands where electricity costs are very high. Despite the analyzed coupled system, CAES is beside PHS systems, proven to be the most cost-efficient technology for large-scale applications, with only constraints of limited geographical positions. Technical parameters (Tab. 2) show similar characteristics of PHS and CAES. Because of their robustness, they can provide a large power range for a long period, hence they are needed for bulk energy storage applications.

2.1.3 Flywheels

These systems store surplus electricity in a disk-shaped flywheel that rotates. Examined from a techno-economic point of view [19], they are considered an alternative to electrochemical energy storage systems because of the same characteristics of short-duration time (Tab. 2). Detailed principle of flywheel technology, application, development, and system practice is given in [20]. Flywheels application in peak shaving proved to be an important factor for future e-mobility development since electric vehicles' peak loads are a concerning issue. The economic and technical suitability of FESS for different charging demands of electric vehicles is analyzed in [21]. As concluded, cost-efficient FESS implementation at technical optimum for electric last-mile delivery trucks and highway fast-charging of passenger electric vehicles should require a flywheel costs reduction or power grid fee increase. Another use case of electric buses supplied by FESS shows a reduction of investment and operational costs with the maximum efficiency of FESS. Contrary to PHS and CAES, flywheels have a relatively lower power range, but a fast response and a high energy density, which is needed for additional services such as reserves or peak shaving. Nevertheless, FESS is still a rather expensive technology, but it can be utilized in specific conditions, at least until technology costs decrease.

2.2 Electrochemical energy storage

Regardless of installed shares of pumped-hydro storage systems worldwide, geographical requirements are still a major constraint for further investment in PHS, a relatively the most used long-term storage technology. Nevertheless, other storage technologies have been developing recently, especially batteries, as a consequence of the improvement in electric vehicle production and decrease in material costs. Progress and the current state of lithium-ion batteries, usually considered supercapacitors' main competitors in transportation applications, are given in [22–24]. Energy storage technologies reviews by [25,26] give a valuable comparison, showing the potential for Li-ion batteries as fully integrated parts of the grid. Lithium-ion batteries have the longest cycle life of all electrochemical storage types analyzed (Tab. 2), of up to 15 years or 20,000 cycles. Yet, calendar life, as the main constraint for batteries, is being analyzed in literature to assure longer profitability. A new approach to extending the lifetime of Li-ion batteries, used as energy storage systems (ESS) in household applications, is found in [27]. Such an approach proposes a hybrid ESS that utilizes the maximum available solar energy. Hybrid battery storage systems can increase the profitability of the system, especially because of the multi-use strategy, as described in [28] for Li-ion and Pb batteries. This study shows that the calendar aging of batteries is a major limit instead of cycle aging. Contrary to this, since lead-acid batteries have a lower market price, but lower cycle life when compared to other batteries (Tab. 2), analysis in [29] shows greater benefit if the life-cycle increases. Because of their characteristics, lead-acid batteries are still operable as a primary reserve or in peak-

Table 2. Electricity storage technical characteristics.

Storage type	Power Range MW	Power density volumetric (kW/m3)	Energy density volumetric (kWh/m3)	Energy density (mass) (kWh/kg)	Efficiency %	Response time	Lifetime years (cycles)	Source
PHS	10-5000	-	-	-	75-85	s-min	40-60 (>13,000)	[4]
	-	0.1-0.2	0.2-2	0.2-2	70-80	-	>0.5 x 10^4	[5]
		0.5-1.5	0.5-1.5	0.5-1.5	70-85		-	
		0.01-0.10	0.5-1.3	0.3-1.3	65-90		10^4-6 x 10^4	
	10-1000	-	-	0.1-0.4	65-80	min	30-50	[7]
CAES	5-1000	-	-	-	70-89	1-15min	20-40 (>13,000)	[4]
	-	0.2-0.6	2-6	-	41-75		> 10^4	[5]
		0.5-2	3-6	30-60	-	-	-	
		0.04-10	0.4-20	3-60	60-90		10^4-3 x 10^4	
	50-300	-	-	0.0032-0.0055	70-73	-	30-40	[7]
FESS	0.1-20	-	-	-	93-95	< 4ms-s	15+ (>100,000)	[4]
	-	5000	20-80	5-30	80-90	-	2 x 10^4-10^7	[5]
		1000-2000	20-80	10-30	90-95		>2 x 10^4	
		40-2000	0.3-400	5-200	70-96		10^4-10^5	
	0.1-20	-	-	0.005-0.1	85	-	20	[7]
Li-ion	0-100	-	-	-	85-90	20 ms-s	5-15 (1000-20,000)	[4]
	-	1300-10,000	200-400	60-200	85-98	-	500-10,000	[5]
		1500-10,000	200-500	75-200	90-97		1000-10,000	
		60-800	90-500	30-300	70-100		250-10,000	
	0.1-50	-	-	0.08-0.15	78-88	-	14-16	[7]
Pb	0-40	-	-	-	70-90	5-10 ms	3-15 (2000)	[4]
	-	90-700	50-80	30-45	75-90	-	250-1500	[5]
		10-400	50-80	30-50	70-80		500-1000	
		10-400	25-90	10-50	60-90		100-2000	
	0.005-10	-	-	0.03-0.05	75-80	-	15	[7]
Ni-Cd	0-40	-	-	-	60-65	ms	10-20 (2000-3500)	[4]
	-	75-700	15-110	15-45	60-80	-	1500-3000	[5]
		80-600	60-150	50-75	60-70			
		40-140	15-150	10-80	60-90		300-10,000	
	45	-	-	0.03-0.05	72	-	13-20	[7]

Table 2. (*Continued*).

NaS	0.05-34	-	-	-	80-90	1ms	10-15 (2500-4500)	[4]
	-	120-160	150-300	100-250	70-85	-	2500-4500	[5]
		140-180	150-250	150-240			2500	
		1-50	150-350	100-240	65-90		1000-4500	
	0.05-0.0534	-	-	0.1-0.175	75-87	-	12-20	[7]
Vrb	0.03-3	-	-	-	~85	< 1ms	5-10 (12,000+)	[4]
	-	0.5-2	20-70	15-50	60-75	-	$> 10^4$	[5]
		< 2	16-33	10-30	75-85		>1.2 x 10^4	
			10-30	10-50	60-90		800-1.6 x 10^4	
	-	-	-	-	-	-	-	[7]
Hydrogen Fuel Cell	0-58.8	-	-	-	25-58	< 1s	5-20+ (1000-20,000+)	[4]
	-					-		[5]
		>500	500-3000	800-10000	20-50		>1000	
			100-370	150-250	75-90			
	0.1-50	-	-	-	35-42	-	15	[7]
Capacitor	0-0.05	-	-	-	60-65	ms	~5 (>50 000)	[4]
	-	>100,000	2-10	0.05-5	60-70	-	>5 x 10^4	[5]
Super-capacitor	0-0.03+	-	-	-	90-95	8 ms	20+ (>100,000)	[4]
	-					-		[5]
		40,000-120,000	10-20	1-15	85-98		$10^4 - 10^5$	
		>100,000	10-30	2.5-15	90-97		$> 10^5$	
Supercond-ucting magnetic	0.1-10	-	-	-	95-98	< 100ms	20+ (> 100,000)	[4]
	-	2600	6		75-80	-	-	[5]
			0.2-2.5	0.5-5	95-97		$> 10^5$	
		300-4000	0.2-14	0.3-75	80-99		$10^4 - 10^6$	
	0.05-0.25	-	-	0.002-0.069	80-95	-	20	[7]

shaving applications. Installation of batteries alongside pumped-hydro storage can also provide effective management of energy grid variation, especially for off-grid renewable systems. PHS and battery storage have complementary characteristics, complementing each other in the low state of charge periods [30], thus this type of storage combination proves to be effective.

When implementing battery storage, strategies that ensure optimal energy and power control in grid-connected systems are challenged and analyzed in [31–33]. One of the storage market-oriented applications is price arbitrage, which shows potential in operation strategy with price differentials. An operational strategy that is based on price differentials to estimate the required price volatility in the German intraday market is given in [34]. Results indicate that there is no profitability because of the high investment costs. Electricity market price jumps (for the 60-min German intraday market) would have to increase by seven times regarding historic values. This study emphasizes the importance of battery storage cost reduction, especially Li-ion. The battery energy storage system's (BESS) implementation in power grids, depends on different decision factors. For the investors, the timing of the investment and the size of the purchased battery capacity should be optimized. A method for optimal BESS size, given in [35] results in the fact that investors can wait seven or eight years to determine BESS capital expenditure costs and then accurately make a decision on how much capacity to purchase. Most of the BESS are chosen based on size optimization, but a different approach [26] provides new insights into the most appropriate optimization technique for BESS sizing where the focus is on the energy application and type of renewable energy source. Since the renewable energy system application can drive the BESS sizing methodology, it also influences the need for large-scale energy storage systems. Power grids with renewables cannot depend only on PHS, hence [36] has compiled a dataset on large-scale battery storage systems showing that Li-ion and NaS batteries with high power capacity, energy densities, and high efficiency (Tab. 2), are limited with high production costs. Smaller BESS, such as NaS, flow batteries, and vanadium redox flow batteries are applicable as ancillary services since they can rapidly provide energy and ensure grid stabilization. Because of the fast response time and high energy density, battery energy storage systems have been used in electric vehicles, contributing to their integration as emission-free means of transport. A detailed review of different solutions for implementing electric vehicles, and a comparison regarding environmental impacts, advantages, and current limitations are given in [37]. Along with the e-mobility spread, self-consumption is increasing as well. Comparison of large-scale, industrial, and home energy storage systems in Germany, indicates further growth of industrial storage systems since the businesses realized the potential of BESS applications in self-consumption, electric vehicle charging, renewable energy sources integration, and peak shaving [38]. Between selected battery technologies, lithium-ion batteries can provide the largest number of 10,000 cycles with high energy efficiency, hence they can store electricity for a longer time. Other analyzed batteries in Table 2 have similar power ranges and energy densities, showing probabilities for utilization as fast response measures.

2.3 Other energy storage technologies

Analyzed technologies in Table 2 such as chemical, and electrical energy storage systems aren't developed in that capacity as pumped-hydro and electrochemical storage systems, mostly because of the technology maturity constraints and high investment costs. Still, because of the importance of conducting different storage technology research for different applications in power systems, they are analyzed in recent literature. For applications in energy arbitrage technology, chemical storage has been analyzed beside its main setback of the round cycle efficiency. Hydrogen's characteristics depend on the conversion method to bring gas back into electrical power [39], hence they can't be competitive with flywheels or electrochemical storage, but if given enough space, they can store a large amount of electricity. Similar to other unattainable storage technologies, a setback can be overcome in hybrid systems such as wind-hydrogen storage, where the wind would be otherwise curtailed. Findings show that pumped-hydro energy storage is the most cost-effective storage technology for short-term and medium-term deployment scenarios, followed by CAES and opposed to hydrogen storage, but for long-term storage, hydrogen cost-effectiveness is behind compressed air storage [40].

With the technical revolution in the late 1970s and the expansion of the new telephone and computer technology, supercapacitors were discovered. Supercapacitors are used as fast charge or backup systems because of their long cycling life, high power density, and reversibility. These systems are described in detail in [41]. Materials for flexible supercapacitors are given in an overview of strategies for improving their performance along with the prospects of supercapacitors considering high costs at the moment [42]. Every electricity storage system can give the best performance if its technology advantages are utilized in fitting applications and if its constraints are optimized. One of the possible methods for optimally utilizing electricity storage performance is installation alongside different renewable energy sources, such as in hybrid power systems.

2.4 Hybrid power systems with storage

With the high penetration of photovoltaics in distribution grids in recent years, maintaining a balance of demand and supply for grid operators can become challenging. In the last decade, electricity costs from utility-scale solar photovoltaics fell by 85% [43], hence photovoltaics became used in households as installations for self-consumption. The problem with self-consumption is high peak demand during the afternoon hours and oversupply during the noon hours. Therefore the usage of home storage systems that store excess electricity generation during the day can make roof-top solars feasible. Decreasing prices in battery technology are boosting economic effects for end-users.

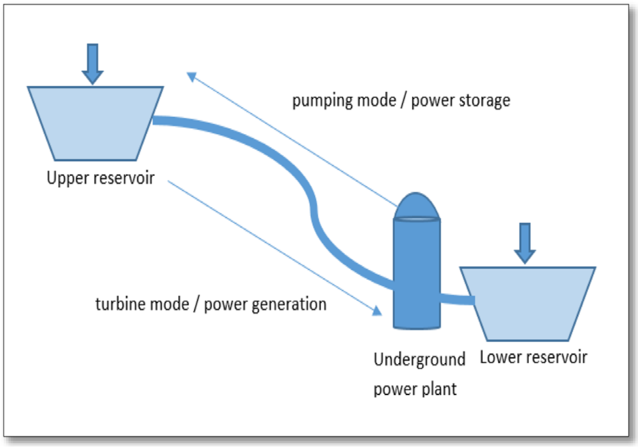

Fig. 3. Pumped-hydro storage working scheme.

Home storage in Germany has grown by more than 50% per year since 2013, which shows a usable storage capacity of about 600 MWh [44]. Another challenge with renewables is wind curtailment, which can be reduced with the application of PHS as a standing reserve, as analyzed for Turkey's electricity energy demand [45]. Study of the Greek power system proved that enough PHS capacity (1500 MW for analyzed scenario) can impact renewable energy curtailments to go below 1.2% for photovoltaics and 0.8% for wind farms [46].

New research on superconducting magnetic energy storage in wind power generation systems shows flexibility potential for planned wind power output [47]. One of the key issues for utilizing hybrid systems is the optimal sizing of the installed technologies. A presented review of different sizing methodologies for hybrid wind/ solar/ storage systems is given in [48]. Optimal capacity sizing and different storage technologies in wind/solar and energy storage hybrid systems, analyzed in [49], find that battery storage systems prove to be the most cost-effective besides thermal energy storage systems in such multi-optimization strategy. All of the given analyzes show that high initial investment costs, as barriers to wider storage grid integration, can be overcome by combining energy storage systems in specific applications with intermittent renewable energy sources. Therefore, energy storage as an additional means of flexibility for avoiding wind curtailment or solar peaks increases the feasibility of such projects, but for a complete analysis, research regarding profitability and economic assessments of storage systems is conducted in the next Section.

3 Economics of energy storage systems

Recent energy storage literature lacks profitability and economic assessments of storage systems. Most of the literature covers dispatching [50], modeling renewable generation with energy storage systems [51–54], or using mobile storage systems for unbalanced distribution grids [55]. These analyses provide important technical overviews, that expended with cost calculations, can result in final assumptions of wider electricity storage utilization.

3.1 Overview of the economic assessment

Along with the renewables' further development, the intermittent nature of photovoltaic generation can impact grid stability and influence an imbalance between demand and supply. This imbalance, graphically presented as a duck-shaped load curve called the "Duck curve" [56] is solved with the application of storage technologies for load shifting, where scarcity of solar generation at the peak time, usually mornings and evenings, is supplemented through storage systems. Economic analysis of selected energy storage technologies [57] suited for load-shifting proved to be uneconomic unless the average maximum daily prices for analysis study case are 100–150 €/MWh, proving that electricity market price plays an important role in energy storage integration. Contrary to previous beliefs that storage limits the further expansion of variable energy generation [58], research shows that energy storage grid integration reduces the inevitable grid expansion costs when compared to traditional distribution grids [59]. The profitability study of PHS plants in Austria shows a reduction of reserve capacity and investments in peaking units in Europe, as the storage capacities increase [60].

Trends in the spreading of stationary batteries in the USA [61] show that the profitability of ESS depends on the revenues, which is an indication for the stakeholders to ensure compensation for storage costs. Hence, technology with the lowest initial costs would be the optimal solution, but sometimes technology such as Li-ion battery, with higher investment costs, can be an optimal solution if that technology has some other advantages, such as high round trip efficiency and lower charge/discharge capacity costs in comparison to Hydrogen [62].

Analyzed economic consequences of the power-to-gas, PHS, and CAES in the electricity grids at different wind power penetration levels, show that the application of large-scale energy storage systems reduces total grid costs [63]. These reductions are higher when using storage systems with higher cycle efficiency, higher storage production capacity, or coupling storage to an energy system with a higher wind penetration. Still, regardless of the application and duration type (short-term, medium-term, and long-term storage), storage implementation in smart grids depends also on the number of full-load hours [64]. Economic assessment of energy storage technologies in [65] proves that energy storage utilization depends on renewable capacity expansion and level of renewable curtailment, hence application of economically viable storage technologies is highly recommended for an increase of renewables shares in the power grids. Implementation of economically viable storage systems in the electricity markets can be achieved with the future decrease in technology costs or increase in electricity market prices. Contrary to many economic assessments that prove electric energy storage systems currently to be unprofitable in today's day-ahead markets, [66] proposes a hedging mechanism with insurance contracts between a renewable producer and storage system. With such a contract, renewable producers can avoid penalties if they are unable to meet day-ahead production because storage reserves are contracted for such renewable shortfalls.

3.2 Energy storage costs

Given research on storage technologies from a technical viewpoint in Section 2, shows technical maturity and possible applications for storage grid integration with renewable energy sources. Nonetheless, the main indicator for the profitability of projects is economic assessment. Cost comparison of three large-scale energy storage technologies (hydro, compressed air, and hydrogen (power-to-gas)), given in [40] uses CAPEX (capital expenditure or investment costs) and OPEX (operational expenditure) as key inputs for Levelized cost of electricity calculation. OPEX consists of costs for operating and maintaining installations, as well as electricity consumed for charging storage. The method for techno-economic analysis in the first economic characterization of offshore compressed air energy storage systems [18] is the Levelized cost of electricity (LCOE). Uniformly, an analysis of Power-to-gas systems generating hydrogen or methane with LCOE and internal rate of return is conducted [67].

In the recent storage literature, the term LCOE is changed to LCOS (Levelized cost of storage), used as a method for the calculation of the storage installation's profitability. The Levelized cost of storage $LCOS$(€/kWh) , as given in equation (1), is the internal average price at which electricity can be sold for the investment's net present value to be zero. That is the sum of the Levelized Cost of electricity discharged $LCOE$ and electricity market price Pel(€/kWh) divided by the energy storage system efficiency factor η(input/output of energy storage system). Detailed Levelized storage costs assessment for chosen technologies, is given in [68].

$$LCOS = \frac{LCOE + Pel}{\eta} = \frac{Clc}{FLH * \eta} + \frac{Pel}{\eta} = \frac{Ct * \alpha + CO\varsigma M, a + Cr, a + Cdr, a}{FLH * \eta} + \frac{Pel}{\eta} \quad (1)$$

where Clc – life cycle costs $\left(\frac{\text{€}}{kW}\right)$; FLH – full load hours (h); Ct – total investment costs $\left(\frac{\text{€}}{kW}\right)$; α- capital recovery factor; $CO\&M$, a- operation and maintenance costs $\left(\frac{\text{€}}{kW}\right)$; Cr, a- recycling costs $\left(\frac{\text{€}}{kW}\right)$; Cdr, a –disposal costs $\left(\frac{\text{€}}{kW}\right)$.

All studies in recent five years that consider cost calculations use a method of Levelized cost of storage [40,69,70]. The main difference between the results found in the given literature is the cost variation due to the proposed assumptions. Depending on the different discharge times, life cycles, efficiency, and market price, the uniformity of the Levelized cost of storage is reduced. These parameters influence final cost results and can give adequate information about storage technology. Assumptions are usually based on several cycles, hence comparison of technologies can differ in literature. For a detailed economic analysis of energy storage systems, Table 3 shows the used parameters: capital costs, charge and discharge time, and environmental impact. Geographical locations, recycling costs, disposal costs, and technology materials influence environmental impact presented as small, moderate, or large (in addition: benign as rather not impacting at all).

As results from Table 3 show, capital costs for PHS are the highest, contrary to the capital costs of supercapacitors. Still, depending on the other factors, Levelized costs of electricity storage show PHS to be the most cost-effective technology, used as large-scale storage, followed by CAES and hydrogen or methane (power-to-gas). Despite the high technological learning potential, power-to-gas is still quite inefficient technology, but its application in the transport sector is promising [71]. Batteries and superconducting magnetic storage systems have a small discharge time, hence their usage can be optimized in applications as reserves or ancillary services. Exceptions are lithium-ion batteries since they are a promising technology for large-scale storage applications because of the possibility of providing 10,000 cycles for 15-year calendar life and due to decreasing trend in their production costs.

3.3 Environmental impact

Electrochemical energy storage's environmental footprint depends on the stationary applications they provide. The main constraints are the life cycle and disposal of materials. Recycling and disposal costs are usually excluded from Levelized storage costs calculations since there is scarce information from production companies. Battery degradation depends on battery efficiency which is a key factor for a possible decrease in costs and emissions. Cumulative degradation of the batteries can be estimated as in [72] and in equation (2):

$$D^m = 20\% * \left(\frac{m}{L} + \right) \sum_{n=1}^{N} \frac{0.5}{Lc * Doc_n^{r-1}} \quad (2)$$

where m – battery age; L – calendar lifetime; N – number of cycles; Doc – depth of the cycle; Lc – number of full equivalent cycles if the depth of the cycle is 100% for every cycle; r – cycle degradation exponent that corrects for actual cycle depth.

Considering different geographical locations for developing storage systems, environmental impact can be divided into three categories: large (PHS, CAES), moderate (for electrochemical storage because of their disposal materials), and small (hydrogen). Technologies such as flywheels and supercapacitors have zero environmental impact, but they have other constraints: technical maturity and high storage costs (Tab. 3).

Degradation of batteries depends on calendar aging and on the relation between charging cycles, where a smaller depth of cycle can lead to reduced aging. Thus, investment in research of battery improvement and calculation of degradation costs in every battery application can reduce the environmental impact.

4 Energy storage outlook

European energy policies are set to promote the reduction of CO_2 emissions, shift towards intermittent renewable power, and ensure grid stability [73]. Since storage systems

Table 3. Economic and environmental parameters of the storage.

Storage type	Capital cost (power-based) €/kWh	Capital cost (energy-based) €/kWh	Charge time	Discharge time	Environmental impact	Source
Pumped-hydro	1700–2550	4.25–85	hr–months	1–24hr+	Large	[4]
	510–1700	4.25–85				[5]
		10.2–71.4				[7]
Compressed air	340–850	1.7–102	hr–months	1–24hr+	Large	[4]
	340–680	1.7–42.5				[5]
		3.4–71.4				[7]
Flywheel	212.5–297.5	850–11900	sec–min	ms–15min	Almost none	[4]
	255–850	2550–5100				[5]
		340–680				[7]
Lithium-ion	765–3400	510–3230	min–days	min–hr	Moderate	[4]
	1020–3400	85–2125				[5]
		765–1105				[7]
Lead–acid	255–510	170–340	min–days	s–hr	Moderate	[4]
	255–510	170–340				[5]
		51–102				[7]
Nickle-Cadmium	425–1275	340–2040	min–days	s–hr	Moderate	[4]
	425–1275	680–1275				[5]
		340–2040				[7]
Natrium-Sulfur	850–2550	255–425	sec–hr	s–hr	Moderate	[4]
	850–2550	255–425				[5]
		212.5–456.45				[7]
Vanadium-Redox	510–1275	127.5–850	hr–months	s–24hr+	Moderate	[4]
	850–2550	255–425				[5]
	–	–				[7]
Hydrogen Fuel Cell	425–850	12.75	hr–months	1–24hr+	Small	[4]
	425–850	–				[5]
		11.9–15.3				[7]
Capacitor	170–340	425–850	sec–hr	ms–60min	Small	[4]
	170–340	425–850				[5]
	–	–				[7]
Supercapacitor	85–382.2	255–1700	sec–hr	ms–60 min	None	[4]
	110.5–437.75	8500				[5]
	–	–				[7]
Superconducting magnetic	170–415.65	850–61200	min–hr	ms–8s	Moderate	[4]
	110.5–437.75	850–8500				[5]
		6083.45–17000				[7]

are recognized as one of the means for reaching set goals, European plans for becoming an emission-free continent by 2050 [74] can be achieved with adequate energy policies. Energy policies for storage development are still not effectively addressed in a long-term effect [75]. Some of the presented mechanisms for promoting energy storage growth are direct subsidies and price floors. The price floor, as the government's regulatory policy, ensures a price limit or how low a price can be charged for some good or commodity. In the [76], for fostering battery storage, policies recommendation are proposed such as pricing mechanism, enabling the participation of storage in the day- ahead and balancing markets, and enabling energy arbitrage. These are all means for allowing more renewable generation with new flexibility of storage battery units.

It is evident that for ensuring the profitability of energy storage systems, policies and regulations are inevitable. The new role of EES would require changes in market rules and regulations by implementing a capacity-based market and fast response segment [77]. In the British capacity market, for example, storage operators are allowed to participate. Still, it is questioned if capacity market rules which include penalties for not delivering electricity, can be a guarantee for precautionary storage if there are arbitrage opportunities available. This can be overcome by keeping out of the market a state of charge until permission was given from the operators [78]. One of the methods for further promotion of energy storage systems is self-consumption, as explained in the next Section.

4.1 New application: user-side energy storage

Retail prices of lithium-ion-based storage systems fell by more than 50% since 2013 and consequently, Li-ion systems became attractive as part of self-consumption photovoltaic systems [44]. Due to the decrease in solar technology costs, prosumers are a new group of storage users, who are slowly becoming local energy market players, seldomly called prosumages [79]. The word “prosumage is conducted from the binding of three words: producer-consumer-storage, hence the new market player can provide a sustainable electricity system for itself, store electricity and give it to the market. Analyzes of prosumage’s different aspects are given in [80–82], whereas [83,84] indicate that modular storage systems are growing faster than large-scale ones. This growth of modular storage shows the need for monitoring and analyzing the mass-market adoption of storage. The importance of future growth of prosumages is presented through a simulation model in [85]. Results of the simulation brought the conclusion that regulators should promote battery flexibility in energy transition, but investors and power system planners of large-scale renewable generation should prevent possible prosumage overinvestment as their behavior can affect power systems.

Besides single prosumages, there is economic potential in shared energy storage systems. Economic assessment of energy storage systems developed for trading electricity between local households, as in [86], shows an electricity purchase cost reduction of up to 8.83% in comparison to the case when each retailer independently plans its energy storage. With such a system as community storage, costs and emissions can be concurrently decreased, as [72] proposes. The presented framework indicates that households can be co-owners of community storage, but also decision-makers in a trade-off between costs and emissions. Nevertheless, for user-side storage operational charging and discharging impact degradation costs of the storage, hence optimal strategy is vital for systems’ profitable utilization. Economic analyses of user-side energy storage systems in [87,88] maximize profits with the proposed models that determine optimal dispatch strategies.

Analysis of user-side storage shows the technical maturity of the technology used as a tool for the implementation of renewable generation in the grids and for mitigating CO_2 emissions while reducing electricity bills for end-users. Though, for user-side storage wider development in the upcoming years, government incentives are needed.

5 Conclusions

Climate changes and emission mitigation plans bring new challenges to the electricity sector. Whereas the shares of variable renewable generation increase, different planning, operating, and flexibility strategies, emerge as well. Energy storage systems play a key role in providing sustainable and flexible power grids. When grids were regional with a small number of interconnections, pumped-hydro plants had one simple regional usage. Today, with new technologies and the intermittent nature of renewable energy sources, the electricity market needs new market instruments to ensure stability. Conducted analysis of energy storage systems profitability and challenges in the electricity markets provided next conclusions:

- Besides the high power range and cost-efficiency of pumped-hydro storage systems, geographical constraints and high investment costs impact the profitability of PHS projects. Nevertheless, with the revitalization of already installed pumped-hydro storage power plants, they will remain their position as leading storage technology in providing a large amount of electricity storage in the recent future, at least until two events occur: electricity storage technology prices decrease or electricity market price increase. Recent events in the European electricity market when prices soared because of gas supply, can serve as a signal for storage investors.
- Similar to PHS, CAES systems have the advantage of large-scale storage applications, but more disadvantages considering constraints for utilizing such projects with current subsidies and energy policies.
- Batteries are promising future storage technology, not just for flexibility applications where they can operate in price spread in today’s electricity markets, but for large-scale energy storage as well.
- Lithium-ion batteries are electrochemical storage technology with the longest lifetime of up to 15 years, or 20,000 cycles. Given the current outlook of Li-ion battery research, its technical characteristics would likely improve further as their production costs continue to decrease.
- Flywheels as fast responsive storage technology would be used as additional battery systems in the future, but they are still expensive, contrary to hydrogen that can easily provide enough storage despite low efficiency. Both technologies prove to be more feasible options for the transport sector.
- Batteries are now at the top of research and exploitation, but these materials are limited and their disposal is questioned. Batteries’ recycling and disposal costs are still omitted in most of the cost calculations, yet they represent indicators of energy storage’s degradation time, which is the battery’s main drawback.
- Considering the lack of energy storage incentives, the installation of ESS in hybrid power systems, especially wind and solar, can increase profitability.
- Another option for future economically viable storage integration is the installation of hybrid storage systems-that is a combination of different batteries or batteries with pumped-hydro storage.

The proposed literature review shows the technical maturity of storage technologies for profitable implementation in the electricity market. New market players such as prosumages or community storage can provide additional local storage at lower costs than single installations. Implementation of these systems at greater scope would consequently increase renewables shares in the grids, but also for end-user-side storage, incentives are inevitable. Historical development of renewable generation and the increase in electric vehicles in transport show positive effects of implemented policies and incentives. Methods for supporting renewables development, such as feed-in tariffs or net metering for prosumers, can be applied to storage as well. Considering the current electricity storage status, already installed shares of renewable energy generation in the power grids, and demand for electric vehicles, it is essential for policymakers to provide subsidies that would allow further and at larger scale storage implementation in the electricity markets.

Given economic assessment shows energy storage opportunities in the electricity markets, especially for price arbitrage. Hence, considering different full load hours and total costs, research can be expended in future work with optimization analysis of electricity storage systems' profits for the application in price arbitrage. Profitability calculations from [34,57] reveal that electricity market prices would have to significantly increase to cover the high investment costs of electricity storage. Therefore, future research would also consider a sensitivity analysis of electricity market prices, given the influence of these prices on the final total costs of electricity storage systems and considering recent spikes of prices in the electricity market.

Implications and influences

Given the current outlook of the electricity market, the main problems for storage's wider integration are still energy storage costs. Analysis of energy storage costs along with the technical parameters provides an entire perspective of electricity storage profitability. Considering technology constraints, new market players and combinations of storage systems emerge as effective utilization possibilities, but only with new energy policies wider storage integration in power grids can be expected. Proposed research shows that there is a technical maturity of storage technologies that can be utilized to bring economic benefits.

Implementation of these systems at greater scope would consequently improve grid operation of the intermittent renewable energy sources in the grids, hence given review of the state-of-art energy storage research provides valuable information for further storage development. The analysis gives valuable indications that electricity storage systems are cost-effective if used as prosumages or as in technologies combination, but for implementation of these systems as economically viable, storage incentives are needed, at least until electricity market prices change or technology costs decrease.

References

1. IEA, How rapidly will the global electricity storage market grow by 2026? IEA, Paris (2021) https://www.iea.org/articles/how-rapidly-will-the-global-electricity-storage-market-grow-by-2026
2. Irena, Global Renewables Outlook: Energy transformation 2050 (2020)
3. IEA, Electricity Market Report (2020)
4. C.K. Das, O. Bass, G. Kothapalli, T.S. Mahmoud, D. Habibi, Overview of energy storage systems in distribution networks: placement, sizing, operation, and power quality, Renew. Sustain. Energy Rev. **91**, 1205–1230 (2018)
5. S. Koohi-Fayegh, M.A. Rosen, A review of energy storage types, applications and recent developments, J. Energy Storage **27**, 101047 (2020)
6. A.Z. AL Shaqsi, K. Sopian, A. Al-Hinai, Review of energy storage services, applications, limitations, and benefits, Energy Rep. **6**, 288–306 (2020)
7. A.G. Olabi, C. Onumaegbu, T. Wilberforce, M. Ramadan, M.A. Abdelkareem, A.H. Al-Alami, Critical review of energy storage systems, Energy **214**, 118987 (2021)
8. R. Haas et al., On the economics of storage for electricity: Current state and future market design prospects, Wiley Interdiscipl. Rev.: Energy Environ. 1–27 (2021)
9. J. Topler, Hydrogen as energy-storage-medium and fuel, Renew. Energy Environ. Sustain. **1**, 31 (2016)
10. I. Hydropower, The world's water battery: Pumped hydropower storage and the clean energy transition (2018), pp. 1–15
11. E. Barbour, I.A.G. Wilson, J. Radcliffe, Y. Ding, Y. Li, A review of pumped hydro energy storage development in signi fi cant international electricity markets, Renew. Sustain. Energy Rev. **61**, 421–432 (2016)
12. L.M. Al-hadhrami. M. Alam, Pumped hydro energy storage system: a technological review, Renew. Sustain. Energy Rev. **44**, 586–598 (2015)
13. J.D. Hunt et al., Existing and new arrangements of pumped-hydro storage plants, Renew. Sustain. Energy Rev. **129** (2020)
14. A. Blakers, B. Lu, M. Stocks, K. Anderson, A. Nadolny, Pumped hydro energy storage to support 100% renewable electricity (2018), pp. 3672–3675
15. E. Barbaros, I. Aydin, K. Celebioglu, Feasibility of pumped storage hydropower with existing pricing policy in Turkey, Renew. Sustain. Energy Rev. **136**, 110449 (2021)
16. M. King, A. Jain, R. Bhakar, J. Mathur, J. Wang, Overview of current compressed air energy storage projects and analysis of the potential underground storage capacity in India and the UK, Renew. Sustain. Energy Rev. **139**, 110705 (2021)
17. M. Habibi, V. Vahidinasab, A. Pirayesh, M. Shafie-khah, J.P.S. Catalao, An enhanced contingency-based model for joint energy and reserve markets operation by considering wind and energy storage systems, IEEE Trans. Ind. Informatics **17**, 1–1 (2020)
18. B. Li, J.F. Decarolis, A techno-economic assessment of offshore wind coupled to offshore compressed air energy storage, Appl. Energy **155**, 315–322 (2015)

19. M.M. Rahman, E. Gemechu, A.O. Oni, A. Kumar, The development of a techno-economic model for the assessment of the cost of flywheel energy storage systems for utility-scale stationary applications, Sustain. Energy Technol. Assessments **47**, 101382 (2021)
20. A. Arabkoohsar, M. Sadi, Flywheel Energy Storage (Elsevier Inc., 2021)
21. B. Thormann, P. Puchbauer, T. Kienberger, Analyzing the suitability of flywheel energy storage systems for supplying high-power charging e-mobility use cases, J. Energy Storage **39**, 102615 (2021)
22. Y. Miao, P. Hynan, A. Von Jouanne, A. Yokochi, Current li-ion battery technologies in electric vehicles and opportunities for advancements, Energies **12**, 1–20 (2019)
23. Z. Fang, J. Wang, H. Wu, Q. Li, S. Fan, J. Wang, Progress and challenges of flexible lithium ion batteries, J. Power Sources **454**, 227932 (2020)
24. G. Zubi, R. Dufo-López, M. Carvalho, G. Pasaoglu, The lithium-ion battery: State of the art and future perspectives, Renew. Sustain. Energy Rev. **89**, 292–308 (2018)
25. H.A. Behabtu et al., A review of energy storage technologies' application potentials in renewable energy sources grid integration, Sustainable **12**, 1–20 (2020)
26. Y. Yang, S. Bremner, C. Menictas, M. Kay, Battery energy storage system size determination in renewable energy systems: a review, Renew. Sustain. Energy Rev. **91**, 109–125 (2018)
27. M. Alimardani, M. Narimani, S. Member, A new energy storage system configuration to extend Li-ion battery lifetime for a household une nouvelle configuration de système de stockage d' énergie pour prolonger la durée de vie de la batterie Li-Ion pour un foyer **44**, 171–178 (2021)
28. J. Münderlein, G. Ipers, M. Steinhoff, S. Zurmühlen, D.U. Sauer, Optimization of a hybrid storage system and evaluation of operation strategies, Int. J. Electr. Power Energy Syst. **119**, 105887 (2020)
29. R.L. Fares, M.E. Webber, What are the tradeoffs between battery energy storage cycle life and calendar life in the energy arbitrage application? J. Energy Storage **16**, 37–45 (2018)
30. M.S. Javed, D. Zhong, T. Ma, A. Song, S. Ahmed, Hybrid pumped hydro and battery storage for renewable energy based power supply system, Appl. Energy **257**, 114026 (2020)
31. P. Malysz, An optimal energy storage control strategy for grid-connected microgrids, IEEE Trans. Smart Grid **5**, 1785–1796 (2014)
32. J. Shi, W. Huang, N. Tai, P. Qiu, Y. Lu, Energy management strategy for microgrids including heat pump air- conditioning and hybrid energy storage systems, J. Eng. **2017**, 2412–2416 (2017)
33. K. Pandžić, H. Pandžić, I. Kuzle, Electrical power and energy systems virtual storage plant offering strategy in the day-ahead electricity market, **104**, 401–413 (2019)
34. D. Metz, J.T. Saraiva, Use of battery storage systems for price arbitrage operations in the 15 - and 60-min German intraday markets, Electr. Power Syst. Res. **160**, 27–36 (2018)
35. J.J. Kelly, P.G. Leahy, Optimal investment timing and sizing for battery energy storage systems, J. Energy Storage **28**, 101272 (2020)
36. A. Poullikkas, A comparative overview of large-scale battery systems for electricity storage, Renew. Sustain. Energy Rev. **27**, 778–788 (2013)
37. Y. Balali, S. Stegen, Review of energy storage systems for vehicles based on technology, environmental impacts, costs, Renew. Sustain. Energy Rev. **135**, 110185 (2021)
38. J. Figgener et al., The development of stationary battery storage systems in Germany – a market review, J. Energy Storage **29**, 101153 (2020)
39. E. Storage, E. Energy, H. Abdi, Learn more about Energy Storage System Energy Storage Systems Introduction to electrical energy systems (2019)
40. F. Klumpp, Comparison of pumped hydro, hydrogen storage and compressed air energy storage for integrating high shares of renewable energies — Potential, cost-comparison and ranking, J. Energy Storage **8**, 119–128 (2016)
41. L. Chang, Y. Hang Hu, Supercapacitors 2–5 (2018)
42. Y. Wang, X. Wu, Y. Han, T. Li, Flexible supercapacitor: overview and outlooks, J. Energy Storage **42**, 103053 (2021)
43. IRENA, Renewable Power Generation Costs in 2020 (2020)
44. K.P. Kairies, J. Figgener, D. Haberschusz, O. Wessels, B. Tepe, D.U. Sauer, Market and technology development of PV home storage systems in Germany, J. Energy Storage **23**, 416–424 (2019)
45. B. Dursun, B. Alboyaci, The contribution of wind-hydro pumped storage systems in meeting Turkey's electric energy demand, Renew. Sustain. Energy Rev. **14**, 1979–1988 (2010)
46. G.N. Psarros, S.A. Papathanassiou, Electricity storage requirements to support the transition towards high renewable penetration levels – application to the Greek power system, J. Energy Storage **55**, 105748 (2022)
47. Y. Xu et al., Research on the application of superconducting magnetic energy storage in microgrids for smoothing power fluctuation caused by operation mode switching, IEEE Trans. Appl. Supercond. **28**, 10–14 (2018)
48. G.J. Rı, Optimal sizing of renewable hybrids energy systems: a review of methodologies, Solar Energy **86**, 1077–1088 (2012)
49. Y. He, S. Guo, J. Zhou, F. Wu, J. Huang, H. Pei, The quantitative techno-economic comparisons and multi-objective capacity optimization of wind-photovoltaic hybrid power system considering different energy storage technologies, Energy Convers. Manag. **229** (2021)
50. Z. Shen, W. Wei, D. Wu, T. Ding, S. Mei, Modeling arbitrage of an energy storage unit without binary variables, CSEE J. Power Energy Syst. **7**, 156–161 (2021)
51. S.F. Santos, M. Gough, D.Z. Fitiwi, A.F.P. Silva, M. Shafie-Khah, J.P.S. Catalao, Influence of battery energy storage systems on transmission grid operation with a significant share of variable renewable energy sources, IEEE Syst. J. 1–12 (2021)
52. B. Mohandes, M. Wahbah, M.S. Elmoursi, T.H. El-Fouly, Renewable energy management system: optimum design & hourly dispatch, IEEE Trans. Sustain. Energy 1–1 (2021)
53. S. Mazzoni, S. Ooi, B. Nastasi, A. Romagnoli, Energy storage technologies as techno-economic parameters for master-planning and optimal dispatch in smart multi energy systems, Appl. Energy **254**, 113682 (2019)
54. M.C. Soini, D. Parra, M.K. Patel, Does bulk electricity storage assist wind and solar in replacing dispatchable power production? Energy Econ. **85**, 104495 (2020)
55. M. Nazemi, S. Member, P. Dehghanian, S. Member, Uncertainty-aware deployment of mobile energy storage systems for distribution grid resilience, IEEE Trans. Smart Grid. **3053**, 1–15 (2021)

56. Q. Hou, N. Zhang, E. Du, M. Miao, F. Peng, C. Kang, Probabilistic duck curve in high PV penetration power system: concept, modeling, and empirical analysis in China, Appl. Energy **242**, 205–215 (2019)
57. G.F. Frate, L. Ferrari, U. Desideri, Critical review and economic feasibility analysis of electric energy storage technologies suited for grid scale applications, E3S Web Conf. **137**, 1–6 (2019)
58. H.W. Sinn, Buffering volatility: a study on the limits of Germany's energy revolution, Eur. Econ. Rev. **99**, 130–150 (2017)
59. M. Resch, J. Buhler, B. Schachler, A. Sumper, Techno-economic assessment of flexibility options versus grid expansion in distribution grids, IEEE Trans. Power Syst. 1–10 (2021)
60. B. Dallinger, D. Schwabeneder, G. Lettner, H. Auer, Socio-economic benefit and profitability analyses of Austrian hydro storage power plants supporting increasing renewable electricity generation in Central Europe, Renew. Sustain. Energy Rev. **107**, 482–496 (2019)
61. E. Telaretti, L. Dusonchet, Stationary battery technologies in the U.S.: development trends and prospects, Renew. Sustain. Energy Rev. **75**, 380–392 (2017)
62. C. Junge, D. Mallapragada, R. Schmalensee, Energy storage investment and operation in efficient electric power systems, Energy J. **43**, 1–24 (2022)
63. H.S. de Boer, L. Grond, H. Moll, R. Benders, The application of power-to-gas, pumped hydro storage and compressed air energy storage in an electricity system at different wind power penetration levels, Energy **72**, 360–370 (2014)
64. A. Ajanovic, A. Hiesl, R. Haas, On the role of storage for electricity in smart energy systems, Energy **200**, 117473 (2020)
65. A. Zerrahn, W. Schill, C. Kemfert, On the economics of electrical storage for variable renewable energy sources, Eur. Econ. Rev. **108**, 259–279 (2018)
66. N. Aguiar, V. Gupta, An insurance contract design to boost storage participation in the electricity market, IEEE Trans. Sustain. Energy **12**, 543–552 (2021)
67. D. Parra, X. Zhang, C. Bauer, M.K. Patel, An integrated techno-economic and life cycle environmental assessment of power-to-gas systems, Appl. Energy **193**, 440–454 (2017)
68. Z. Topalovic, R. Haas, A. Ajanovi, A. Hiesl, Economics of electric energy storage. The case of Western Balkans, Energy **238**, 121669 (2022)
69. M.M. Rahman, A.O. Oni, E. Gemechu, A. Kumar, Assessment of energy storage technologies: a review, Energy Convers. Manag. **223** (2020)
70. M.H. Mostafa, S.H.E. Abdel, S.G. Ali, Z.M. Ali, A.Y. Abdelaziz, Techno-economic assessment of energy storage systems using annualized life cycle cost of storage (LCCOS) and levelized cost of energy (LCOE) metrics, J. Energy Storage **29**, 101345 (2020)
71. A. Ajanovic, R. Haas, On the long-term prospects of power-to-gas technologies, Wiley Interdiscip. Rev. Energy Environ. **8**, 1–16 (2019)
72. W.L. Schram, T. Alskaif, I. Lampropoulos, S. Henein, W.G.J.H.M. Van Sark, On the trade-off between environmental and economic objectives in community energy storage operational optimization, IEEE Trans. Sustain. Energy **11**, 2653–2661 (2020)
73. European Commission, The future role and challenges of Energy Storage, DG ENER Work. Pap. (2013), pp. 1–36
74. European Commission, The European Green Deal, Eur. Comm. **53**, 24 (2019)
75. C.S. Lai, G. Locatelli, Are energy policies for supporting low-carbon power generation killing energy storage? J. Clean. Prod. **280**, 124626 (2021)
76. M. Haji Bashi, L. De Tommasi, P. Lyons, Electricity market integration of utility-scale battery energy storage units in Ireland, the status and future regulatory frameworks, J. Energy Storage **55**, 105442 (2022)
77. N. Martin, J. Rice, Power outages, climate events and renewable energy: Reviewing energy storage policy and regulatory options for Australia, Renew. Sustain. Energy Rev. **137**, 110617 (2021)
78. J. Geske, R. Green, Optimal storage investment and management under uncertainty, in 2016 IEEE 8th Int. Power Electron. Motion Control Conf, IPEMC-ECCE Asia 2016, **41**, 524–529 (2016)
79. R. Green, I. Staffell, 'Prosumage' and the British electricity market, Econ. Energy Environ. Policy **6**, 33–49 (2017)
80. S.A. El-batawy, W.G. Morsi, S. Member, Integration of prosumers with battery storage and electric vehicles via transactive energy, IEEE Trans. Power Del. **5**, 383–394 (2021)
81. Y. Shen, X. Liang, W. Hu, X. Dou, F. Yang, Optimal dispatch of regional integrated energy system based on a generalized energy storage model, IEEE Access **9**, 1546–1555 (2021)
82. R. Dai, S. Member, H. Charkhgard, The utilization of shared energy storage in energy systems: a comprehensive review, IEEE Trans. Smart Grid **3053**, 1–8 (2021)
83. R. Irany, K. Aancha, G. Daniel, G. Arwa, Energy Storage Monitor, World Energy Counc. (2019), pp. 1–32
84. T.-T. Nguyen et al., A review on technology maturity of small scale energy storage technologies, Renew. Energy Environ. Sustain. **2**, 36 (2017)
85. K. Say, W.P. Schill, M. John, Degrees of displacement: the impact of household PV battery prosumage on utility generation and storage, Appl. Energy **276**, 115466 (2020)
86. J. Liu, X. Chen, Y. Xiang, D. Huo, J. Liu, Optimal planning and investment benefit analysis of shared energy storage for electricity retailers, Int. J. Electr. Power Energy Syst. **126**, 106561 (2021)
87. Y. Ding, Q. Xu, Y. Xia, J. Zhao, X. Yuan, J. Yin, Optimal dispatching strategy for user-side integrated energy system considering multiservice of energy storage, Int. J. Electr. Power Energy Syst. **129**, 106810 (2021)
88. N. Al Khafaf et al., Impact of battery storage on residential energy consumption: an Australian case study based on smart meter data, Renew. Energy **182**, 390–400 (2022)

Cite this article as: Zejneba Topalović, Reinhard Haas, Amela Ajanović, Marlene Sayer, Prospects of electricity storage, Renew. Energy Environ. Sustain. **8**, 2 (2023)