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Economics of electric energy storage. The case of Western Balkans

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ABSTRACT

Paris Agreement has influenced a higher generation of renewable systems that impact energy balancing costs and question future energy supply stability. Energy storage could be the key component for efficient power systems transition from fossil fuels to renewable sources. The core objective of this paper is to investigate the cost-effectiveness of pumped hydro storage and large-scale battery storage systems. This paper provides prospects for pumped hydro storage installation in comparison to battery storage with an overview of installed capacities in the Western Balkan countries due to renewed interest in already installed pumped hydro plants. The method of approach is based on an economic assessment of the different types of storage depending on capital-recovery-factors for the capital costs, life cycle costs, full load hours, the price spread of electricity in the day-ahead markets, and Levelized costs of energy storage. Sensitivity analysis of the market prices is conducted. The major results of these investigations show the economic justification of pumped hydro storage systems implementation, their role in grid flexibility, and their influence on electricity market competitiveness. Levelized storage costs of 339 €/MWh for sodium-sulfur batteries show considerable potential for new installations, as compared to 125 €/MWh for pumped hydro storage.

1. Introduction

1.1. State of the art

The European Commission has set ambitious targets for increasing the share of electricity from renewable energy sources (RES-E). In recent years, electricity generation from variable sources such as wind and solar PV has increased remarkably. Between 1990 and 2017 in the EU- 27, "new" renewables (excluding hydro, mainly from wind and PV) grew from less than 1% to about 20%. With extended penetration of renewable energy sources in electricity grids, due to the Paris Agreement, energy storage systems could play a crucial role in the energy transition by enhancing reliability, flexibility, and security of the European energy industry supply. Still, operating energy storage systems in the deregulated electricity market is challenging, especially when surplus energy is not properly used. This is evident particularly for solar technologies when maximum energy output is not at the time of peak demand. But for difficult weather conditions, lack of required generation must be compensated. Generation from wind is also fluctuant. When wind drops or the energy demand is high, energy storage systems are the solution for delivering energy to consumers. In these times, appropriate energy storage systems are used to operate and balance energy generation and consumption. Overview of existing energy storage systems in distribution grids, recommendation of adequate size, operation, and energy storage system selection is given in Refs. [1,2].

The high integration of renewable energy sources in power systems has led to electricity market prices imbalance. Generation from photovoltaics is at a peak during the day when consumption for many households is low. Peak demand occurs in evening hours when solar generation is deficient, and grid operators must use other sources for the generation of electricity to meet demand. This type of imbalance between demand and generation from photovoltaics creates a duck-shaped load curve called the "Duck curve" [3]. California Independent Operator first addressed the Duck curve problem, by analyzing high penetration generation of solar power and late afternoon ramping when peak demand begins and solar generation ends. Electricity market prices are higher in peak demand and lower in evening hours. This large disparity between midday and evening energy prices impacts the Duck curve and makes the difference between expected load and anticipated renewable generation more noticeable. Over the years, the price of photovoltaic technologies has decreased and influenced greater

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photovoltaic systems implementation. For meeting demand at night time, and starting the generation in the morning, other dispatched plants were used before introducing energy storage systems. With energy storage, idea is to store surplus energy produced in the daytime and use it later at night. Optimal usage of thermal generation plants and energy storage systems such as PHS is considered to solve the duck curve problem, with possible low costs.

Pumped hydro storage depends mainly on the geographical area where two reservoirs are in high and low heights. This combination allows hydro potential energy to be converted into kinetic energy and produce electricity in peak hours. Stored energy is pumped back to the upper level when demand is low, especially during the night. Overview of installed capacities shows how this method of storage has been used for many years. Originally, pumped hydro plants were installed as a complement to nuclear power plants. When consumption is low and turning off nuclear units is risky, pumping water can enhance the global efficiency of nuclear units [4]. Pumped hydro storage is used to cut and raise off-peak load demand in an optimization program, reducing the fuel costs of thermal generation plants [5]. The economic driver of the pumped hydro storage technology is the flexibility of demand-supply. With the high integration of renewable systems, the operating of the power systems should be managed efficiently. In Ref. [6], operating pumped and thermal plants in the most cost-efficient way is described in detail, and a model for optimal storage dispatching is developed. In Ref. [7], battery storage systems are compared to the thermal energy storage technology for a specific case study. Results show that compared systems are subject to high investment and operation costs, but with thermal storage systems, total system costs are reduced, contrary to battery energy storage systems, which increase overall costs.

There has been renewed interest in pumped hydro energy storage systems, especially because of electricity market deregulation and increased renewable generation, so these storage technologies assist renewables in replacing dispatchable power production [8].

Countries with rapid economic development, like China, invest in pumped hydro storage systems as the main measure for ensuring stability in the power grids. Development and exploitation of pumped hydro storage systems in China are given in Ref. [9], where is stated that by the end of 2014. China had 22 GW of installed PHS capacity, with plans for reaching 70 GW by 2020. These plans weren't reached, as the regulations regarding ownership and operation of storage systems, were reviewed in China in 2019. As a result, storage costs are excluded from transportation and distribution fees, which led to the falling of installations throughout the year by one-third and the announcements of new projects being stopped [10].

Due to the regulations that consider PHS part of the transmission system rather than a generating asset, investments in PHS depend on the network investment. Capital costs for the proposed PHS are affecting energy operation and flexibility. These costs, with a technical and economical review of installed and proposed capacities in Europe, the USA, and Japan are listed in Ref. [11].

Besides the most installed capacities of pumped hydro storage systems, new emerging storage technologies such as batteries are still under the research of cost-effectiveness. Batteries are used for meeting demand when wind and solar cannot provide enough electricity. Still, battery storage has limited capacity. Some feasibility studies proved that conversion of one form of energy that is not storable to another form of storable energy can have a more valuable economic impact than battery storage [12]. Environmental consequences of battery storage when compared to hydro storage, are much higher. As stated in Ref. [12], solar, wind, and hydro are the most economical clean and renewable energy generation sources. Because of the kinetic energy of hydro, these storage systems remain the cheapest, having zero replacement costs. Batteries have a fast response and are a great source of storage, but when analyzing their application as bulk energy storage, for assumed cycle life, replacement costs are higher than for PHS. Hence, disposal of material and recycling costs of batteries impact the environment in a way that requires detailed research, especially with the exponential growth of electric vehicles in recent years. Overview of existing battery storage optimization techniques is presented according to energy application type of renewable energy systems and it is going to be more important in the future, considering environmental criteria despite technical and financial indicators [13].

Large-scale battery storage systems are used as ancillary services competent for balancing energy demand-supply, as well as for the support of extensive grid integration of wind and solar generation technologies [14]. Battery participation in electricity markets as an instrument for operating electricity grid has been appealing from an economic perspective. The economic viability of grid-scale batteries integration in electricity markets is still being researched due to the limited cycle life and calendar life of batteries. Analysis in Ref. [15] indicates that energy storage systems' lifetime is not dependable on the life cycle of batteries, meaning batteries already have enough cycle life to charge and discharge more than one time per day during their lifetime. A barrier for wider utility-scale batteries integration is cost-effectiveness. These storage costs are higher than any other storage technologies, but because of batteries' fast time response, they can be used as a reserve. As much as pumped hydro storage has technical advantages as a reserve, batteries have advantages as fast reserves. Nevertheless, these technologies are likely to be used further due to CO2 emission mitigations [16]. Energy transition has influenced the wide scope of renewable generation, but still many countries have not implemented EU Directive 2020 and 2030 targets. Detailed analysis of possible scenarios for policies implementation [17] shows that marginal electricity cost would decrease with increased renewable installations, hence energy storage technologies need to be properly considered. With a decrease in technology costs, it can be assumed that their feasibility would improve and they can be utilized at a higher level than currently.

1.2. Motivation

There has been much research in terms of technology and mechanical limits of energy storage, but costs are still a major barrier for wider integration. Limitations for wider energy storage integration are not just technical, physical, but also economical. Integration of energy storage systems is economically justified if the costs of energy storage systems do not exceed the costs of energy from the market. The economic top-down approach in Ref. [18] shows how energy storage costs depend on the user's economic environment, an annual number of storage cycles, and on storage technologies used (higher costs for short-term storage systems). In Ref. [19], a different approach to the volatility of energy generation and market prices is described. It compares arbitrage benefits of energy storage systems (using market price data) with alternative technologies such as backup generation and interconnection costs to show different solutions for shifting demand-supply over time. In Ref. [20], there have been investment and management analyses of energy storage systems, but there is still a need for further research in terms of feasibility and economics using the Levelized cost of energy storage as in Ref. [21].

In the light of the recent wider integration of renewables and battery storage systems costs decrease, this paper provides an up-

to-date analysis of energy storage economics. Due to the lack of recent research, the main contribution of this paper is a detailed cost-effectiveness analysis of pumped hydro storage in comparison to large-scale battery storage systems. Presented information about the prospects for pumped hydro storage installation in comparison to battery storage systems, especially for the Western Balkan region, is included in energy storage research. Since the cost data of energy storage systems are obscure and varying in different literature, cost calculation is as well scattered through different methods. This paper applies Levelized storage cost calculation for comparison between storage technologies and shows the importance of analyzing full load hours and the price spread of electricity in the day-ahead markets. Sensitivity analysis of the market prices is conducted. The major result of these investigations shows the economic justification of pumped hydro storage systems implementation, their role in grid flexibility, and their influence on electricity market competitiveness, which is of importance for future investors.

Section 2 presents an overview of electric storage technologies. The calculation method is given in Section 3, while results of the techno-economic analysis are presented in Section 4. The Paper is concluded with the main aspects of comparison in Section 5.

2. Energy storage technologies

Pumped hydro plants have been used for energy generation and dispatching for many years, but constructing has always been challenging due to the required geographical position. These plants consist of two connecting accumulation reservoirs. Water from the upper reservoir serves for generating electricity and water from the lower reservoir is pumped back up the hill, at times of low demand. Some countries in Western Balkan have a specific geographical position, and installed capacities of pumped hydro storage are still operating in this region. With the renewed interest in technologies for grid flexibility, it is expected for pumped hydro plants to be revitalized and used more in the light of new storage needs, developed as consequences to EU directives for renewable energy generation and mitigation of CO2 emissions. Two types of pumped hydro storage can be constructed. Depending on the water flow, there are closed-loop plants and open-loop or pumped back plants. Closed-loop plants pump water from a lower reservoir, a river or sea, to an upper reservoir. Pumped back plants rely on natural water flow and pumped water to produce electricity. This type of storage uses mechanical water energy, contrary to battery storage systems which use electrochemical conversion.

There are various types of batteries developed: lead-acid (Le-a), lithium-ion (Li-ion), sodium-sulfur (NaS), flow batteries, and nickel-cadmium (Ni–Cd). International Energy Agency Tracking report [22] gives an optimistic prediction for future battery storage development, while technology costs for battery storage are dropping due to the growth of manufacturing for electric vehicles. Lithium-ion battery automotive production was 160 GWh in 2020, up 33% from 2019 [23]. This is mostly due to stimulating policies and measures taken for the wider integration of electric vehicles in the transportation sector. China is still a leader in battery production, accounting for over 70% of global battery cell production capacity, as well as in battery demand, reaching almost 80 GWh in 2020. An increase of 110% occurred in Europe, with 52 GWh, but in the United States, demand has not changed significantly from 19 GWh.[†] These results show strong energy storage deployment in recent years, which is expected to continue. Lithium-ion batteries can be used in grid-scale energy storage systems due to their high round-trip efficiency and energy density, but these batteries are an issue to the environment regarding their disposal. As seen in Ref. [24], batteries have a relatively short life because of cell degradation. When compared to other batteries, lithium-ion have the highest efficiency rates, but as well high capital costs. Economic, feasibility, and technology characteristics are presented in Refs. [24,25]. Comparison of generation integrated with energy storage systems and non-energy storage systems indicates that energy storage costs impact total costs, which shows that study case with wind-only systems without energy storage is the most profitable investment. Energy storage systems provide other services for grid flexibility, during peak hours or when there is scarce generation due to weather conditions. Generation integrated with energy storage systems is an adequate method for storing large-scale grid energy, but policymakers need to provide mechanisms for the wider integration of energy storage systems.

Regardless of high battery development, pumped hydro storage is still the most dominant storage technology as given in Table 1, which presents global energy storage data provided by the National Technology & Engineering Sciences of Sandia (NTSS). All installed storage capacities and energy storage projects registered in the Global Energy Storage Database (DOE) are presented. This overview shows that pumped hydro storage technology, with 350 single projects documented, in comparison to other storage technologies, has the most installed capacities of 181 GW worldwide since it has been developed and used for many years. The total installed battery capacity is 4 GW. Batteries are used so far in different applications: mobile applications, technical equipment, electric vehicles, distributed storage, and as well as large-scale systems. A review of energy storage systems [26] shows the latest technologies in terms of battery energy systems, describing lead-acid batteries as one of the most durable batteries. Lithium-ion storage systems are mostly used for portable applications, but lately, they have been on top of the development due to an increase in electric vehicles production. The limitation of lithium-ion batteries is a short discharge time, which affects their durability. Recent research has proven that lithium-ion batteries are suitable for micro-grid storage, rather than large-scale storage systems, for which lead-acid batteries are mostly used [26]. Large-scale battery systems provide ancillary services, grid stabilization, frequency regulation, voltage support, power quality, load shifting, transmission line stability, energy arbitrage, peak, and load shaving. When compared to pumped hydro storage, which has a power rating around 100–4000 MW, large-scale batteries have a smaller power rating with less than 50 MW for lead-acid and Ni–Cd systems, a lower than 350 MW for NaS. A detailed battery overview is provided in Ref. [27]. An in-depth study of lead-acid and lithium-ion batteries in Ref. [28] has given an economic overview of these technologies, concluding that despite lead-acid being the most popular in off-grid applications, lithium-ion batteries are a powerful competitor due to the nowadays increase in their production, hence decrease in costs.

Pumped hydro plants have been installed in the Western Balkan region in the late 1970s. Currently, with higher integration of renewables in transmission grids, energy stability puts these plants again in focus with a possibility of revitalization. Table 2 provides a detailed overview of installed capacities of pumped hydro storage and battery storage systems in Western Balkan countries. Only one battery storage construction is announced, other installed capacities are operational pumped hydro storage systems. The next section describes methods for cost calculation, therefore the economic viability of these systems is analyzed.

[†] Data from International Energy Agency.

Table 1
Installed capacities of different energy storage technologies [29].

Technology Broad Category	Number of installed projects	Sum of Rated Power (MW)
Compressed Air Energy Storage	4	8,4
Electro-chemical	991	3.297
Electro-mechanical	74	2.601
Hydrogen Storage	13	20,4
Liquid Air Energy Storage	2	5,3
lithium-ion battery	32	754
Pumped Hydro Storage	350	181.191
Thermal Storage	220	3.275
Total	**1.686**	**191.152**

Table 2
Installed pumped hydro storage and battery storage in the Western Balkan region [29].

Country	Project name	Location	Technology	Capacity output generation regime MW	Status
Bosnia and Herzegovina	PHS Čapljina	Čapljina, Svitava,	Open-loop pumped hydro storage	420	Operational
Croatia	PHS Velebit	Obrovac, Zadar	Open-loop pumped hydro storage	276	Operational
	PHS Lepenica	Primorje, Gorski Kotar	Open-loop pumped hydro storage	1,14	Operational
	PHS Fužine	Primorje, Gorski Kotar	Open-loop pumped hydro storage	4,60	Operational
Serbia	PHS Bajina Bašta	Perućac, Zlatibor	Open-loop pumped hydro storage	614	Operational
Slovenia	PHS Avče	Avče, Littoral	Open-loop pumped hydro storage	185	Operational
	BS Imergy Trojane	Trojane, Lukovica	Vanadium Redox Flow Battery	0,01	Announced

3. Methods for cost calculation

Installed capacities in the Western Balkan region and global energy storage capacities overview reveal dominant pumped hydro plants, built before electricity market liberalization, but revitalized now and used in electricity trading because of electricity price arbitrage opportunities. Decrease in battery technology costs influences new projects implementation. Batteries such as lead-acid, sodium-sulfur, and nickel-cadmium can be applicable for price arbitrage and bulk storage, besides other applications, as in distributed storage, mobile applications, and besides having shorter calendar life as compared to pumped hydro storage systems. Nevertheless, these battery systems are going to be analyzed to provide a comparison to pumped hydro storage systems and to provide a premise for using one of these technologies in bulk energy storage applications. Although lithium-ion batteries have an advantage due to their performance in mobile applications, especially the rising trend in electric vehicles, they are still feasibility issues to be addressed and they are of interest in the analysis as well. Lithium-ion batteries need to be properly recycled if they are to be used in bulk energy storage systems. Batteries recycling adds up to the costs and it should be improved to meet current requirements. Overview of these technologies, proving lead-acid batteries are still predominantly used in utility energy storage, is in Ref. [30]. Batteries require cost-effectiveness and economic justification, besides technology capabilities, if they are to be considered in bulk energy storage applications. Even if future predictions of a decrease in technology costs of lithium-ion batteries come true, they will be used firstly as distributed storage rather than a centralized one. These future perspectives are given in more detail in Refs. [30,31].

Revenue from price arbitrage is compared to investment costs for bulk energy storage systems. Considering all costs for both pumped hydro storage and battery storage purchase and installation, a comparison is given in this section. For calculating total capital costs, all costs should be considered:

$$Ct = Cpcs + Coh + Csto \times t \tag{1}$$

where Ct is total capital cost for a storage system, expressed in (€/kW), $Cpcs$ power conversion system costs (€/kW), Coh overhead costs (€/kW) and $Csto$ are storage costs related to energy capacity (€/kWh), t represents storage discharge time in hours (h). Power conversion system costs are related to power rate and these represent costs for a turbine, pump, or converter. Overhead costs consider costs for project engineering, grid connection, and installation. Costs for battery banks, reservoirs, or electrolytes are related to energy capacity and are a representation of construction costs. Storage costs represent costs for available capacity in kWh as a function of discharge time.

When analyzing storage costs, life cycle costs should also be considered:

$$Clc = Ccap, a + CO\&M, a + Cr, a + Cdr, a \tag{2}$$

Life cycle costs are the sum of annualized capital costs for storage system $Ccap,\ a$, expressed in (€/kW-annual), fixed and variable operation and maintenance costs $CO\&M,\ a$, (€/kW-annual), replacement costs of energy storage systems $Cr,\ a$ (€/kW-annual), and costs for disposal and recycling $Cdr,\ a$ (€/kW-annual). Annualized capital costs of the storage system are total capital costs Ct calculated with a capital recovery factor α, which considers interest rate (i) during the lifetime (T) of the storage system:

$$Ccap,\ a = Ct \times \alpha \tag{3}$$

$$\alpha = \frac{i(1+i)^T}{(1+i)^T - 1} \tag{4}$$

Operation and maintenance variable costs consider both fixed annual costs for energy storage system Cf, a in (€/kW) and variable annual costs $Cv,\ a$ (€/kWh), which depend on hours of charging/discharging energy storage systems tf. In this analysis, this time is presented as full load hours of operating storage systems.

$$CO\&M, a = Cf, a + Cv, a \times tf \tag{5}$$

Most of the literature gives an overview of investment costs of energy storage systems regarding eq. (1). In Ref. [22], comparative life cycle cost analysis shows costs for different storage systems. Future replacement costs of battery storage systems Cr, in €/kWh

and replacement period p in years, calculated as in eq (6), results in annualized replacement costs $Cr,\ a$ in (€/kW) during battery calendar life, where t is the discharged battery time (hours), as in eq. (1), k is the number of replacements, and ηs the overall battery efficiency, which takes in considerable losses of charging/discharging battery during the life cycle.

$$Cr,\ a = \alpha \times \sum_{k=1}^{r} (1+i)^{-kp} \times \frac{Cr \times t}{\eta s} \tag{6}$$

Disposal and replacement costs Cdr in €/kW are annualized with interest rate i for battery lifetime period T. These costs are rather omitted in storage costs calculations, but some argue that they are concerning environmental issues for bulk battery storage systems development and they should be included in calculations [12].

$$Cdr,\ a = Cdr \times \frac{i}{(1+i)^T - 1} \tag{7}$$

Given eq. (2), life cycle costs of energy storage system when divided with full load hours ($FLH\ hrs$), amount to Levelized cost of electricity $Clcoe$ (€/kWh) that is discharged when the energy storage system is operating:

$$Clcoe = \frac{Clc}{FLH} \tag{8}$$

Constant or Levelized cost of energy storage considers the full amount of energy a storage system can hold and discharge over a lifespan, unlike Levelized cost of electricity which only considers discharged energy. Levelized cost of storage considers all technical and economic parameters for utilizing the storage system, including costs for the charging system, which makes it market-dependent. It is used for costs comparison between different storage systems. In the literature, there are different cost parameters included in the calculation of the Levelized cost of storage, since some studies exclude replacements or disposal costs, due to lack of data from technology producers. Some methods take into consideration performance characteristics as self-discharge and capacity degradation [22]. When describing electricity storage costs, some take a different approach, and often define the net Levelized cost of storage as net internal costs of storing electricity, which excludes electricity price and storage efficiency. Cost per unit of discharged electricity includes both and is named Levelized cost of electricity in Refs. [32,33]. Due to different definitions of Levelized storage costs, in literature different terms can be found as: Levelized cost of stored energy, Levelized cost added by storage, Levelized cost of electricity delivered by EES systems, Levelized cost of delivery, life cycle cost, and even Levelized cost of electricity. In this analysis, Levelized cost of storage is defined, as in the most recent literature, as the internal average price at which electricity can be sold for the investment's net present value to be zero, which makes it useful for comparing to other storage technologies, analogous to the Levelized cost of electricity for generation technologies. This definition of the Levelized cost of storage $Clcos$ (€ /kWh) is presented in eq. (9) and it accounts for all technical and economic parameters affecting the lifetime cost of discharging stored electricity [22]. In other words, the Levelized cost of energy storage is a sum of the Levelized cost of electricity discharged $Clcoe$ and electricity market price Pel (€/kWh), divided by energy storage system efficiency factor ηs. This factor represents the efficiency of input and output of the energy storage system, which shows that $\frac{Pel}{\eta s}$ represents costs for charging storage system from the grid:

$$Clcos = \frac{Clcoe + Pel}{\eta s} = \frac{Clc}{FLH^{*}\eta s} + \frac{Pel}{\eta s} \tag{9}$$

4. Results

This section compares the costs of the analyzed large-scale energy storage systems: pumped hydro, lithium-ion, lead-acid, sodium-sulfur, and nickel-cadmium. These energy storage systems have a long duration time and are dominantly used for electricity arbitrage, unlike lithium-ion batteries that have a medium duration time, but a fast response. Since lithium-ion production is rising, their feasibility is also analyzed. Detailed comparison of bulk energy storage systems provides information for integration of these storage systems in the electricity market. Data for cost calculation of bulk energy storage systems are presented in Table 3 [34]. The main difference between these technologies is that pumped hydro energy storage systems have the lowest energy-related costs and zero replacement costs, but demand specific constructing and hydro conditions. Batteries do not require specific geographic areas, have fast response time, but when used as large-scale storage systems, they have higher energy-related costs. When comparing PHS and BS, environmental constraints are also subject to discussion, since batteries dispose of toxic materials, and eventually need replacement.

Considering the assumption that all technologies given in Table 3 have the same discharge time of 8 h, total capital costs, as in Fig. 1, show the lowest total costs of 1072 €/kW for PHS. Results for batteries show the lowest total costs of 2750 €/kW for sodium-sulfur (NaS). Following is lead-acid with 5409 €/kW, nickel-cadmium 6479 €/kW and the most expensive investment costs for large storage systems of 6823 €/kW is for lithium-ion. Total capital costs in €/kWh are given in Fig. 2.

When evaluating costs for investing in energy storage systems, annualized capital costs give a better overview of different storage systems as they are part of life cycle costs calculation (eq. (2)). The different interest rates for capital recovery factors affect annualized capital costs, hence life cycle costs, as shown in Fig. 3. Annualized capital costs are the lowest for pumped hydro storage systems, given the different capital recovery factors. Different interest rates chosen (5, 8, 10 or 12 years), total costs from Table 3, eq. (3) and eq. (4), give the results in Fig. 3. Calendar life for PHS is 50 years, lead-acid and lithium-ion 10, NaS 17, and Ni–Cd 15 years.

For life cycle cost calculation, different interest rates are considered, replacement costs are calculated given the parameters in Table 3, eq. (2), and taking into account that for lithium-ion batteries replacement time is every 5 years, for lead-acid and NaS replacement is every 8 years, and for Ni–Cd every 10 years. Disposal costs are excluded from the calculation. Full load hours for variable and maintenance costs calculation is chosen from 150 h to

Table 3
Main cost items for bulk energy storage systems [34].

Cost	PHS	lead-acid	NaS	Ni–Cd	Li-ion
Cpcs (€/kW)	513	378	366	239	463
Coh (€/kW)	15	87	–	–	–
Csto (€/kWh)	68	618	298	780	795
Cf,*a* Fixed O&M (€/kW-yr)	4,6	3,4	3,6	11	6,9
Cv,a Variable O&M (€/MWh)	0,22	0,37	1,8	–	2,1
Cr,a Replacement costs (€/kW)	–	172	180	525	369
Replacement period *p* (years)	–	8	8	10	5
Calendar life *T* (years)	50	10	17	15	10
Overall efficiency (%)	70	70	75	60	85

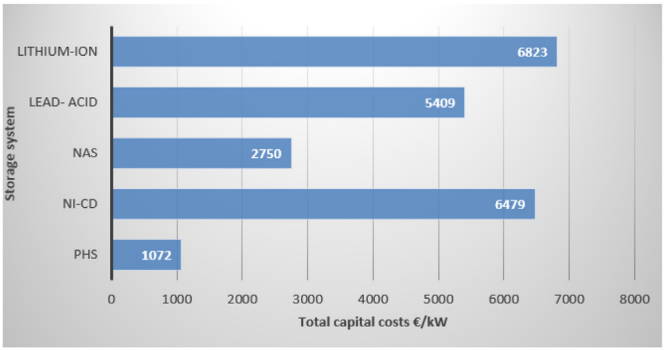

Fig. 1. Total capital costs in €/kW.

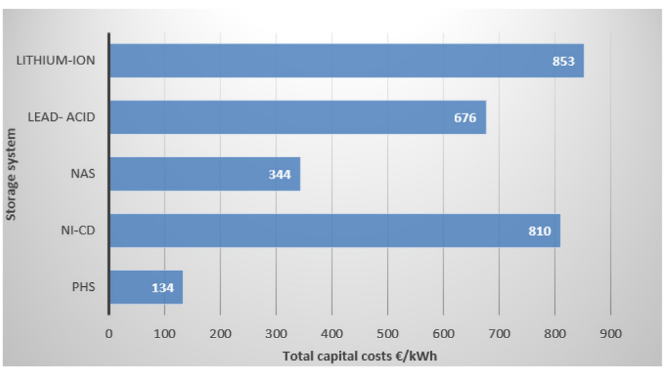

Fig. 2. Total capital costs in €/kWh for 8-h discharged time.

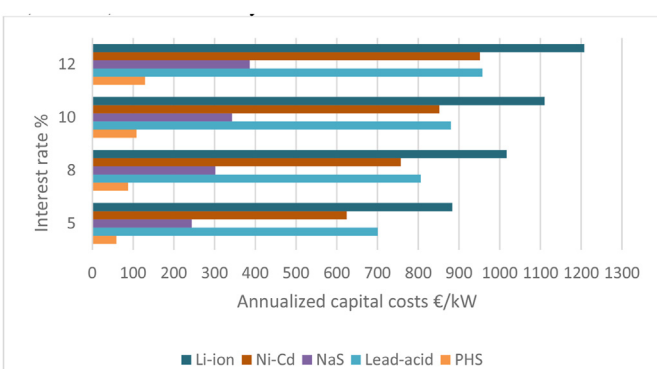

Fig. 3. Annualized capital costs calculation for different interest rate.

4000 h, taking into consideration an average number of cycles for bulk energy systems range from 250 to 300 per year [29]. A maximum number of cycles is used in the calculation, which for the assumption of 8 h discharge time for all storage systems, equals 2400 full load hours. Minimum overall efficiency found in the literature is used since it can take different percentages depending on the given data from manufacturers, as stated in Ref. [34]. Results in Fig. 4 show that life cycle costs change significantly with given capital recovery factors since, in eq. (2), parameter variable cost of storage mostly depends on annual discharge time. Therefore, the annual capitalized cost parameter dominantly influences results. Life cycle costs are the lowest for pumped hydro storage, depending mostly on the different interest rates.

Levelized cost of electricity and the Levelized cost of energy storage systems are calculated with life cycle costs (eq. (8) and eq. (9)), taking into the account number of cycles per year. Depending on cycles per year and discharge time, annual hours of operating storage present full load hours. Fig. 5 illustrates the Levelized cost of discharged electricity from an operating storage system in one year. Pumped hydro storage has the lowest Levelized cost of electricity and is still the most cost-efficient storage technology.

When energy storage systems are in charging mode, electricity market prices influence overall costs. Calculating the Levelized costs of discharged electricity without the price of charging power neglects electricity market influence, which is inevitable for energy storage system implementation. This analysis takes into consideration market-specific factors and calculates the Levelized cost of energy storage, considering electricity prices in EPEX and Hudex electricity markets (Fig. 6).

When calculating the costs of the energy storage system, it is important to consider the costs of electricity needed for the charging system, as seen in eq. (9). Fig. 7 shows that the Levelized cost of electricity discharged is the lowest when PHS is operating in between 1000 and 2000 full load hours per year (eq. (8)). These costs are then compared to hourly prices of electricity on the day-ahead market Hudex, as well as electricity price spread on EPEX. Since Hudex is correspondent electricity market for Western Balkans, a comparison is made, showing that for the year 2019, the average market price in EPEX is 40,06 €/MWh and 50,36 €/MWh in Hudex, for about 4500 full load hours.

The same comparison is given in Fig. 8 for batteries. Life cycle costs, calculated as in eq. (2), are divided into different full load hours (eq. (8)). All batteries are compared using the same discharge time, hence results show that lithium-ion batteries are the least cost-effective technology.

When analyzing the cost efficiency of energy storage systems, it is important to calculate costs given the number of full load hours and electricity costs for charging the storage systems. Figs. 7 and 8 show life cycle costs dependencies of different storage technologies to full load hours and average prices on electricity markets. Finally, Levelized costs of energy storage systems are calculated, considering EPEX average prices for electricity in 2019 divided by storage system efficiency (eq. (9)). These results in Fig. 9 confirm the economic efficiency of pumped hydro storage systems, followed by NaS batteries and lead-acid batteries. Results for 4000 full load hours, considering average electricity price, are the lowest costs of 98 €/MWh for PHS, 226 €/MWh for NaS and 426 €/MWh for lead-acid, following 546 €/MWh for Li-ion and 574 €/MWh for Ni−Cd. In practice these costs are higher, considering the system could operate to a maximum of 300 cycles a year. This equals 2400 maximum full load hours for 8 h of discharge time.

Levelized cost of energy storage is useful for comparing different energy storage systems and providing adequate information for future investors. Since electricity price for charging energy storage systems is an unreliable parameter for investors, because it mostly depends on other factors, sensitivity analysis in Fig. 10 shows how life cycle costs divided by full load hours can be compared to electricity prices spread on markets when considering 10% of market price fluctuations. If prices in the market go higher by 10%, the average price in EPEX would be 44,06 €/MWh, but if prices go by −10%, the average price would be 36,05 €/MWh. These price changes would increase energy storage costs, hence they are important when analyzing the implementation of storage systems that can work to a maximum of 2400 full load hours per year.[‡]

[‡] During the global COVID-19 pandemic in 2020., when this paper was already finished, prices have fallen and influenced the increase of costs that are subject of further research.

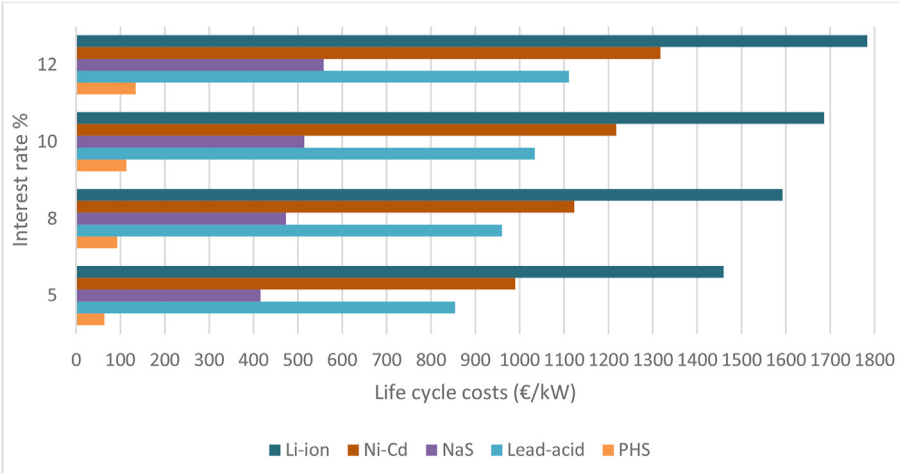

Fig. 4. Life cycle costs for storage systems concerning different capital recovery factors.

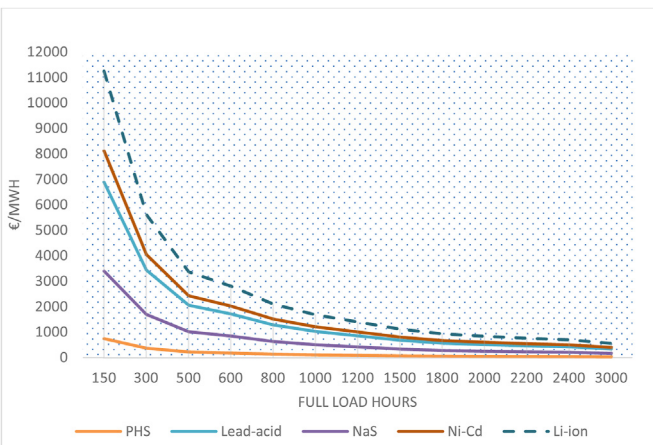

Fig. 5. Levelized costs of electricity delivered by different energy storage systems.

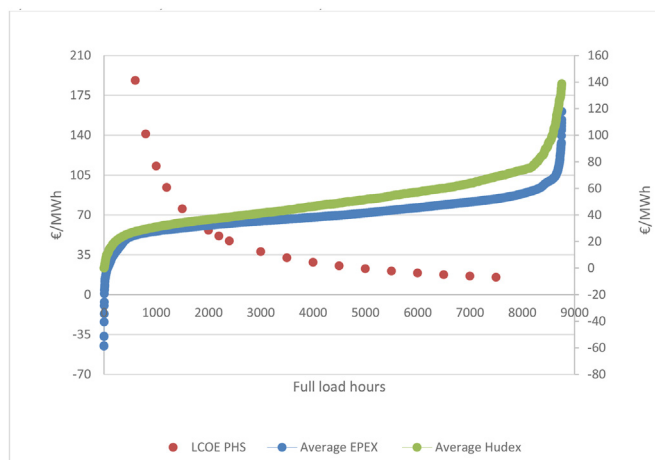

Fig. 7. Levelized cost of discharged electricity for PHS and hourly market price spread over a year for Hudex and EPEX electricity market, 2019.

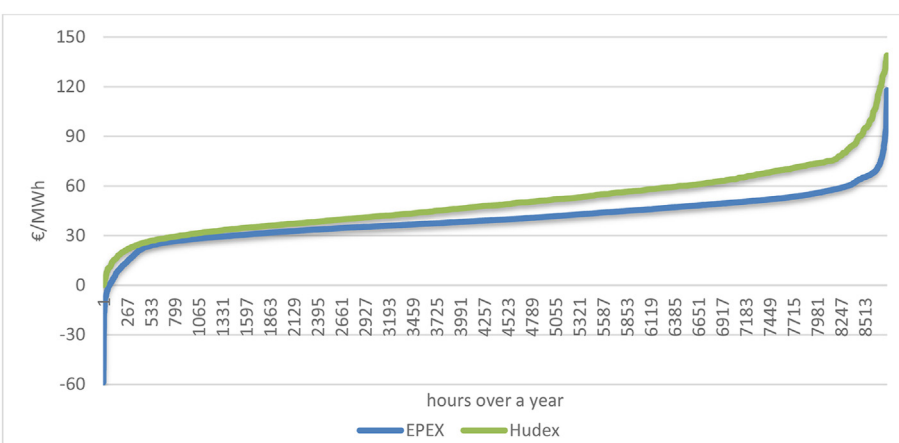

Fig. 6. Electricity markets Epex and Hudex hourly prices (data source: EPEX 2019, Hudex DAM 2019).

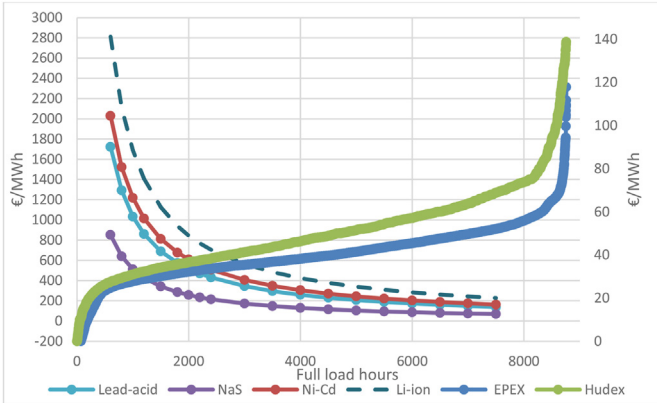

Fig. 8. Levelized cost of discharged electricity for batteries and hourly market price spread over a year for Hudex and EPEX electricity market.

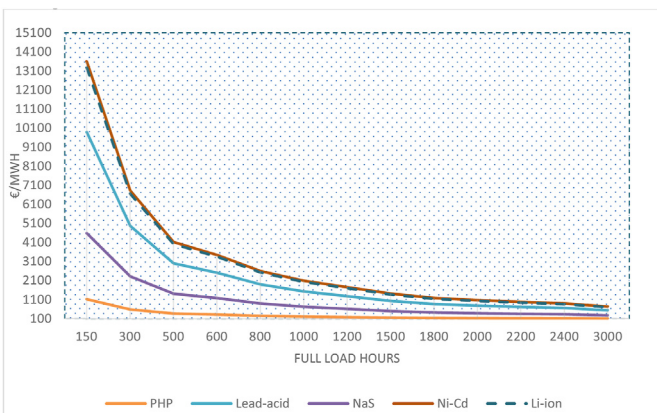

Fig. 9. Levelized costs of energy storage, charged with average electricity price on EPEX market 2019 (data source EPEX 2019).

5. Conclusion

Results show PHS is still the most cost-efficient energy storage technology, which along with analysis of installed plants in the Western Balkan region, presents prospects regardless of their difficult installation and geographical requirements. At least until the life cycle costs of batteries decrease and overall calendar and cycle life duration improve.

The conducted analysis provides valuable information for future investors, showing that pumped hydro storage has the lowest Levelized storage cost of 125 €/MWh when considering 300 cycles per year. The Levelized cost of energy storage for Ni−Cd batteries is 912 €/MWh, for Li-ion batteries is 876 €/MWh, for lead-acid 673 €/MWh and the lowest cost for a battery storage system is for sodium-sulfur 339 €/MWh. Calculation shows the importance of analyzing full load hours of operating storage systems and electricity prices in different markets, as well as the electricity price sensitivity analysis that was carried out.

Market prices influence energy storage system investment, especially for application such as energy arbitrage, since for large utility companies, which are the main market players in the electricity market, electricity arbitrage brings new possibilities for trading. Companies with the highest share of fossil-based power plants in their energy mix have limited options for energy trading and high balancing costs.

Electricity arbitrage provides additional electricity for utilities,

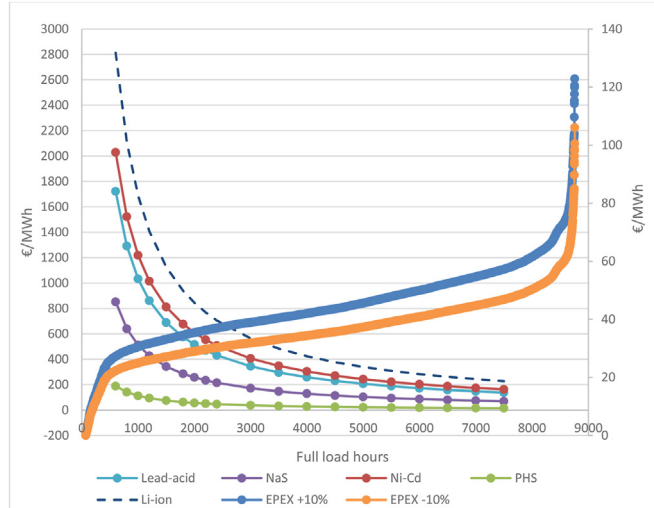

Fig. 10. Levelized costs of discharged electricity and sensitivity analysis of market price over a year (EPEX electricity market).

which can be used as ancillary-services or traded in wholesale markets. Most economical losses in operating energy systems with hydro are due to forecast mistakes, hence energy storage application as energy arbitrage, would consequently improve the competitiveness of companies in the electricity market and provide long-term flexibility. This opens new market possibilities, but for countries with pumped hydro storage potential, it changes the energy mix, especially in Western Balkans, where integration of high share variable generation technologies is still rising and it is below shares of renewables in EU-27 countries.

The flexibility of the power systems is still the main concern for reaching national targets of renewable generation. Considering the stability of the entire demand-supply curve, investors should analyze the cost-effectiveness of all given technologies. Despite a decrease in lithium-ion costs, the Levelized cost of this storage technology is still high when compared to other batteries. Because of the duration time and recycling costs, it is challenging for lithium-ion batteries to compete in utility applications with pumped hydro storage. Analyzing Levelized costs of storage for batteries and considering their fast response time, batteries application as an ancillary service prove to be more economical rather than large-scale energy storage application with a discharge time of 8 h, as assumed in the calculation. Results show that investing in large-scale storage systems is cost-effective for the analyzed region mostly dependent on fossil fuels and one that meets geographical requirements. Given the experience with this technology already and low Levelized storage costs, pumped hydro storage should be a strategic plan for power systems development in Western Balkans.

Future work would likely cover other energy storage technologies and would provide additional calculation considering future production costs decrease for batteries. The impact of the Coronavirus that is spreading around the world at the time of finishing this paper should also be considered. Since sensitivity analysis of electricity prices is conducted in this paper, a drop in electricity prices due to the COVID-19 restriction measures is already taken into the consideration. Consequences on the global energy market will be seen afterward. In the light of the government and policymakers' decisions, the influence of COVID-19 on battery production and costs, as well as further transition to green energy and energy storage development, can be analyzed.

Credit author statement

Zejneba Topalović: Conceived and designed the analysis, Collected the data, Contributed data or analysis tools, Performed analysis Wrote the paper. Reinhard Haas: Contributed data or analysis tools, Amela Ajanović: Other contribution, Albert Hiesl: Other contribution.

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.

Nomenclature

kW	kilowatt
kWh	kilowatt-hour
MW	megawatt
MWh	megawatt-hour
GW	gigawatt
GWh	gigawatt-hour

Abbreviations

RES-E	Renewable Energy Sources
EU-27	27 European Union Countries
PV	Photovoltaic
PHS	Pumped Hydro Storage
EU	European Union
USA	United States of America
CO2	Carbon dioxide
Li-ion	lithium-ion
NaS	sodium-sulfur
Ni−Cd	nickel-cadmium
DOE	Global Energy Storage Database
NTSS	National Technology & Engineering Sciences of Sandia
DAM	Day-Ahead Market
FLH	Full load hours
EPEX	European Power Exchange
HUDEX	Hungarian Derivative Energy Exchange
COVID-19	Corona Virus Disease 2019

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