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Energy Economics Group

Dissertation

Techno-economic analysis of energy storage systems for electricity and opportunities in the Western Balkan

carried out for the purpose of obtaining the degree of Doctor technicae (Dr. techn.), submitted at TU Wien, Faculty of Electrical Engineering and Information Technology,

by

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Abstract

As an expansion of renewables in the electricity markets continues, variability and volatility in the grids require additional flexibility utensils. Energy storage systems, as they can provide the flexibility needed, are considered a key component for efficient power systems transitioning from fossil fuels to renewable energy sources. In this thesis storage systems for electricity are analyzed from the technical and economic perspective, considering energy storage profitability in the electricity markets. The collected up-to-date research on storage systems for electricity gives a comprehensive review of the current studies regarding all relevant parameters for storage utilization in the electricity markets. From the conducted review, the following research questions arise for the analysis in the research papers. The first question, about the energy storage systems' economic justification in the electricity markets, is answered within the economic assessment of different types of storage for electricity depending on capital-recovery-factors, life cycle costs, full load hours, the price spread of electricity in day-ahead markets, and the Levelized cost of energy storage. Additionally, the mixed-integer optimization model is performed with the subtraction of the total storage costs. The model objective is maximizing profits in price arbitrage for the analyzed electricity markets and is subject to energy storage capacity constraints. The second question, about major prospects and barriers for the implementation of storage for electricity systems in the Western Balkan, is answered within the study case in all three research papers. The third question, regarding the impact of renewables on storage for electricity systems in the Western Balkan countries, is answered with an econometric model, electricity market price distribution, and full load hours. The results from the carried out research show: i) pumped hydro storage with 111 €/MWh is economically justified for arbitrage, unlike lithium-ion batteries with 864 €/MWh of Levelized cost of storage; ii) An average yearly profit of pumped hydro storage for a study case with 83% of electricity generation from renewables, is 70% lower compared to the case highly dependent on fossil generation when 2000 full load hours considered; iii) The ultimate profitability of energy storage systems, when used as flexibility measures in the electricity markets, depends on the full load hours, electricity market price spreads and investment costs of technology;
iv) With the development of renewables in the Western Balkan region, energy storage price arbitrage prospects are promising.

Kurzfassung

Mit dem Ausbau erneuerbarer Energien in den Stromsystemen ist eine Flexibilität von Stormspeichersystemen erforderlich, um die in den Netzen auftretenden Schwankungen und Volatilität auszugleichen. Speichersysteme für Strom gelten als Schlüsselkomponente für den effizienten Übergang von Energiesystemen von fossilen Brennstoffen zu erneuerbaren Quellen. In dieser Dissertation werden Stormspeichersysteme aus technischer und wirtschaftlicher Sicht analysiert, wobei die Rentabilität der Energiespeicherung auf den Strommärkten eine wichtige Randbedingung ist. Die Beschreibung der wissenschaftlichen Literatur zu Stromspeichern gibt einen umfassenden Überblick über die aktuellen Studien zu allen relevanten Parametern für die Speichernutzung in Strommärkten. Aus dieser Literaturanalyse ergeben sich die folgenden Forschungsfragen für die Analyse in dieser Arbeit. Die erste Frage über die Stormspeichersysteme wird aufgrund der wirtschaftlichen Bewertung verschiedener Stromspeichersysteme in Abhängigkeit von Annuitätenfaktoren, Lebenszykluskosten, Volllaststunden, der Strompreisspanne und die „Levelized Kosten der Speichersysteme“ beantwortet. Darüber hinaus wird das Gemischt-Ganzzahlige Lineare Optimierung mit der Subtraktion der Gesamtspeicherkosten durchgeführt. Das Ziel des Modells ist die Gewinnmaximierung bei der Preisarbitrage für die analysierten Stormmärkte und unterliegt den Kapazitätsbeschränkungen der Stormspeichersysteme. Die zweite Frage zu den wichtigsten Aussichten und Hindernissen für die Umsetzung von Stormspeichersystemen am Westbalkan wird in allen drei Forschungsarbeiten beantwortet. Die dritte Frage bezüglich der Auswirkungen erneuerbarer Erzeugung auf Stormspeichersysteme in der Westbalkan wird bei einen ökonometrischen Modell, Strommarktpreisverteilung und Volllaststunden beantwortet. Die Ergebnisse der durchgeführten Forschung zeigen dass: i) Pumpspeicher mit 111 €/MWh „Levelized Kosten der Speichersysteme“ sind im Gegensatz zu Lithium-Ionen-Batterien mit 864 €/MWh für Arbitrage wirtschaftlich gerechtfertigt; ii) Der durchschnittliche jährliche Gewinn von Pumpspeicher ist für einen Studienfall mit 83 aus erneuerbaren Erzeugung, um 70 % niedriger als für den Studienfall der stark von der fossilen Erzeugung abhängt, wenn 2000 Volllaststunden berücksichtigt werden; iii) Die letztendliche Rentabilität von Stormspeichersystemen, wenn sie als Flexibilitätsmaßnahmen auf den Strommärkten eingesetzt werden, hängt von den Volllaststunden, den Strompreisspannen und den Investitionskosten der Technologie ab; iv) Mit der Entwicklung erneuerbarer Energien in der Westbalkan Region sind die Aussichten für eine Preisarbitrage der Stormspeichersysteme vielversprechend.

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List of Abbreviations and Symbols

ALPEX	Albanian Power Exchange
ARX	Autoregressive exogenous model
AT	Austria
BESS	Battery Energy Storage System
CAES	Compressed Air Energy Storage Systems
CAP	Capacitors
CAPEX	Capital Expenditure
CEM	Capacity Expension Model
CBAM	Carbon Border Adjustment Mechanism
CO_2	Carbon-dioxide
DIETER	name of the model
EDLC	ultra-capacitors
EPEX	European Power Exchange
ESS	Energy Storage Systems
EU	European Union
EU-28	European Union consisting of 28 countries
EU ETS	European Union Emission Trading Scheme
EXAA	Energy Exchange Austria
FESS	Flywheel Energy Storage System
FW	Flywheels
HUPX	Hungarian Power Exchange
IRR	Internal Rate of Return
LAES	Liquid Air Energy Storage
LCOC	Levelized Cost of Capacity
LCOE	Levelized Cost of Electricity
LCOS	Levelized Cost of Storage
Li-ion	Lithium-ion
MEMO	Electricty Market in North Macedonia
MEPEX	Montenegro Power Exchange
MILP	Mixed Integer Linear Programming

MoU	Memorandum of Understanding
n/a	not applicable
NaS	Sodium Sulfur
NECPs	National Energy and Climate Action Plans
Ni-Cd	Nickel Cadmium
NOSBIH	Independent System Operator in Bosnia
NPV	Net Present Value
OCAES	Offshore Compressed Air Energy Storage
OPEX	Operation Expenditure
P2G	Power to Gas
Pb	Lead acid battery
PHS	Pumped Hydro Storage
PTES	Pumped Thermal Energy Storage
PV	Photovoltaic
RES	Renewable Energy Sources
SEEPEX	Serbian Energy Exchange
SMES	Superconducting Magnetic Energy Storage
TES	Thermal Energy Storage
UK	United Kingdom
VrB	Vanadium Redox Flow
WB	Western Balkan
WBC	Western Balkan countries
WB6	Western Balkan six contracting parties of Energy Community

Symbols and units

kW	Kilowatt
kWh	Kilowatt hours
GW	Gigawatt
GWh	Gigawatt hours
MW	Megawatt
MWh	Megawatt hours
TW	Terrawatt
$\forall_t$	Mathematical symbol “for every”

1 Introduction

1.1 Motivation

Over the last decade electricity sector has changed significantly with the increase of electricity generation from variable sources such as wind and solar photovoltaic (PV), distributed energy sources, and new market players. When compared to the previous systems, the shares of renewables in the final energy consumption in Europe significantly increased from 6.8% in 1990 to 19.9% in 2020 (Energy Statistics Data Browser, 2023). This increase resulted from lower technology costs, government subsidies for energy policies, and feed-in tariffs. The Paris Agreement, as an international treaty on climate change to limit the temperature increase to 1.5 °C above pre-industrial levels, ensures that the development of renewables continues. Renewables' target shares are determined within National Energy and Climate Action Plans (NECPs), defined by the signatory countries. As the new International Energy Agency's outlook predicts, "renewables are set to contribute 80% of new power capacity to 2030 in the Stated Policies Scenario"(World Energy Outlook, 2023), underlining future changes in the energy sector. The transition to the decarbonized energy system in Europe has been determined by the Green Deal, which aims to achieve zero net emissions of greenhouse gasses by 2050, making it the first climate-neutral continent. This has been determined within the set of proposals regarding the climate, energy, transport, and taxation policies adopted by the European Commission in 2024. The set target for reducing greenhouse gas emissions by 55% by 2030 has recently been increased, as one of the goals of the 28th conference of the Convention on Climate Change. The participants signed the Global Renewables and Energy Efficiency Pledge, which committed to triple the world's installed renewable energy generation capacity to at least 11 terawatts by 2030 (Energy Community, 2023). The Western Balkan countries (WBC), as signatory countries of the Paris Agreement and Green Deal are following in contribution of renewable development, but at a slower pace. This is due to the political, economic, and environmental aspects and high dependency on fossil power plants for the generation of electricity. Over the years there has been a development of energy policies and legislation as Western Balkan countries are six Contracting Parties of the Energy Community (Albania, Bosnia and Herzegovina, Kosovo, North Macedonia, Montenegro, and Serbia) obliged to establish and develop an integrated pan-European energy market with the European Union (EU). A Declaration on Energy Security and Green Transition (Energy Community Report, 2023) has been signed by the leaders of WBC as an additional pledge to align energy sectors with the international commitments established within the Paris Agreement and The Energy Deal. The WB region has been heavily dependent on coal with inadequate regulation and underinvestment in renewable energy sources. Historic renewables' development in the

Western Balkan countries (Fig.1.1) and in Austria for comparison (Fig.1.2), shows differences in their energy portfolios.

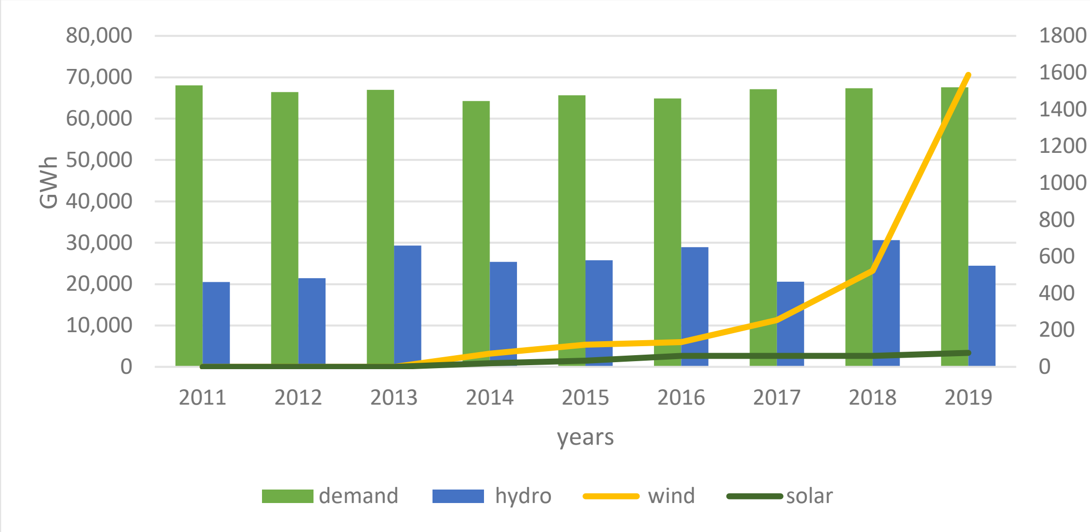

Fig. 1.1 Total generation of selected renewables in the total electricity demand over the years for the Western Balkan with wind and solar on the secondary axis (Bankwatch, 2023)

Owing to the strong renewable generation in Austria and the daily balancing of the demand-supply curve, the operation of the energy system is challenging and requires additional flexibility. While renewable generation in all WBC covers 39%, wind and solar generation is still scarce with 2.5 % of the total demand in 2019 (Fig.1.1.). Austria is going towards set plans of reaching 100% renewable electricity system by 2030 with 79% of RES generation, with wind and solar amounting to the 14% of the total demand in 2019 (Fig. 1.2).

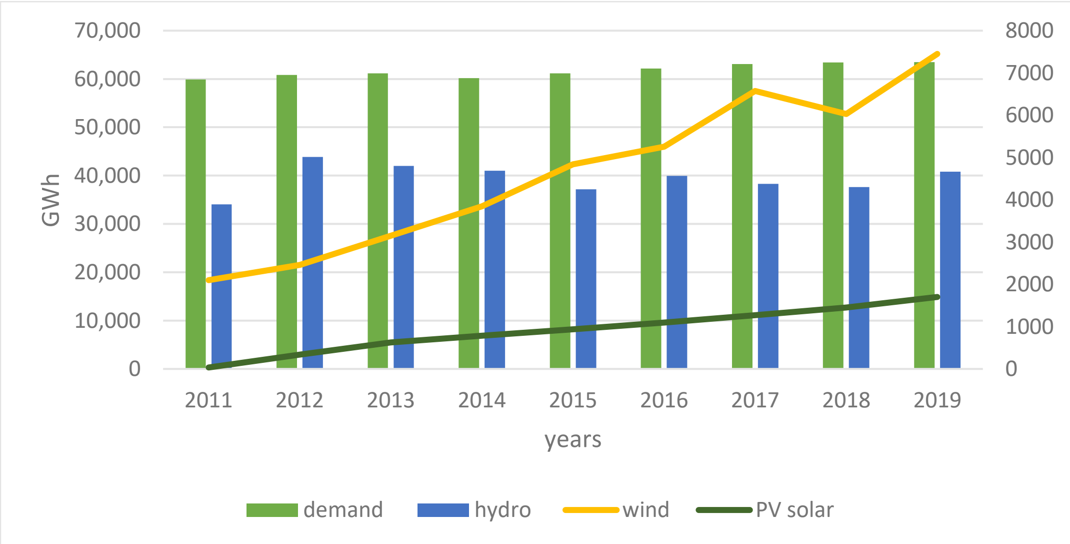

Fig. 1.2 Total generation of selected renewables in the total electricity demand over the years for Austria with wind and solar on the secondary axis (IRENA, 2022), (Statistik Austria, 2024)

Considering assumed obligations from the signed documents towards future integration of the regional electricity market, sustainable and emission-free energy systems, and mitigation of greenhouse emissions from fossil power plants, high shares of renewables are expected also in the WBC. There are different methods for managing shares of renewable energy sources (RES) in the grids such as demand side management, usage of electric vehicles, or grid support services. Energy storage systems, among other applications, also provide flexibility that has been traditionally utilized with pumped hydropower plants. These plants were first used for storing excess electricity in large water reservoirs during the night and generating it at the time of supply scarcity during the day. Today, energy storage systems are again in focus of research, especially already installed pumped hydro plants (as they can be revitalized) or new battery storage technology, that now with the technology improvement can be used even for large-scale applications. According to the (Global Energy Storage Database, 2020) other storage technologies are still lagging behind historical installations of pumped hydro storage with an installed power capacity of 181.91 Gigawatt (GW) globally (Table 1).

Table 1 Installed capacities of energy storage technologies globally (Global Energy Storage Database, 2020)

Technology Category	Rated power (GW)
Lead-Carbon	0.0004
Liquid Air Energy Storage	0.0054
Compressed Air Energy Storage	0.0084
Hydrogen Storage	0.02
Electro-chemical	0.34
Lithium-Ion Battery	0.75
Thermal Storage	1.86
Electro-mechanical	1.92
Pumped-hydro storage	181.91

Despite energy storage systems' flexibility advantages and technical maturity, other factors impact their utilization in the electricity grids, especially profitability. Considering the energy systems in which they operate, investment costs of technology, and electricity market conditions, energy storage systems' economic feasibility is questionable and in some cases inefficient. In light of future events such as the integration of large-scale energy storage systems in the electricity markets, RES investments in the WB region, and increased flexibility needs in the power grids, this thesis gives a detailed techno-economic analysis of storage systems for electricity and their feasible utilization in the electricity markets.

1.2 Major literature

Research about energy storage systems has been intensified recently as the electricity generated by variable renewable energy sources increases. In the detailed technical reviews (Das *et al.*, 2018), (Koohi-Fayegh and Rosen, 2020) the focus is on the capacity of storage, installation in distribution grids, and optimal sizing. These reviews show significant technology advances and developments with the prospects of optimal energy storage placement in the grids. They are valuable for understanding of technical characteristics and constraints of energy storage technologies. Analyses of energy storage from an economics perspective, such as in (AL Shaqsi, Sopian and Al-Hinai, 2020), (Olabi *et al.*, 2021), (Haas *et al.*, 2022), (Schmidt and Staffell, 2023) contribute to the thesis research regarding energy storage economic viability. The previous research about electricity storage profitability, especially modeled as a price-taker approach by (Williams and Green, 2022), (Spodniak, Bertsch and Devine, 2020), (Sioshansi *et al.*, 2022), and (Lamp and Samano, 2022) is extended in this thesis with the comprehensive calculation of the optimal profits when total costs of energy storage systems are included. Considering renewable energy sources development, research so far shows a connection between renewables and energy storage systems in the electricity markets (Zerrahn, Schill and Kemfert, 2018), (López Prol and Schill, 2021), (Mallapragada, Sepulveda and Jenkins, 2020). There is a considerable connection between renewable generation development, the electricity market, and energy storage systems. Mentioned literature provided with the meaningful insight and inspiration for the writing of this thesis.

1.3 Core objective

Storage systems for electricity can be analyzed from different perspectives, such as technical, economic, environmental, and social, hence the conducted research in this thesis covers explicitly defined aspects. The core objective of the thesis is to provide a detailed techno-economic analysis of energy storage systems in the electricity markets, given the rising needs for flexibility of power systems. A comprehensive literature review by (Topalović *et al.*, 2023) serves as a foundation behind the proposed goal as it gives detailed state of the art of energy storage technical and economic parameters. Derived conclusions from the conducted review show prospects for energy storage systems and divide the research into three research questions answered within the publication of three research articles.

First research question: *Under which conditions is the integration of energy storage systems in the electricity market economically feasible?*

The first question is answered within two research papers where economic prospects of electricity storage utilization in the electricity markets are analyzed. In the paper *Economics of electric energy storage. The case of Western Balkans* by (Topalović *et al.*, 2022) is a detailed cost-effectiveness analysis of pumped hydro storage (PHS) in comparison to large-scale battery storage systems. The conducted Levelized storage cost calculation with different full load hours and price spreads of electricity in the day-ahead markets shows the cost-effectiveness of analyzed technologies. The analysis of the storage's profitability is continued with the *Economic benefits of PHS and Li-ion storage. Study cases: Austria and Bosnia and Herzegovina* by (Topalović, Haas and Sayer, 2024) with the linear mixed-integer optimization model. The model uses a price-taker approach to optimize yearly arbitrage profits of PHS and Lithium-ion (Li-ion) energy storage when total costs of storage are subtracted from the arbitrage revenues. The proposed research question is answered within the results that indicate impacting factors on energy storage systems' profitability and provide prospects for further development of energy storage for price arbitrage.

Second research question: *What are the major prospects and barriers to implementing different types of energy storage systems in the Western Balkan countries?*

Considering the lack of research regarding the impact of energy storage in the Western Balkan countries, and the lack of renewable investments when compared to the countries from the European Union, the Western Balkan study case is a valuable addition and novelty case for the thesis analysis. Within all three research papers study case of Western Balkan provides the answers to the second research question. Firstly, prospects for pumped hydro storage installation in comparison to battery storage systems for the Western Balkan region are presented in (Topalović *et al.*, 2022). Secondly, an optimization model of the pumped hydro and Li-ion technology is simulated by (Topalović, Haas and Sayer, 2024) for the study case of Western Balkan country Bosnia and Herzegovina. The study case of Bosnia and Herzegovina is considered a Western Balkan case since the electricity market exchange relevant to the WB region is used for the analysis. Thirdly, an analysis of the energy storage conditions in the proposed study case is continued in the paper *Role of Renewables in Energy Storage Economic Viability in the Western Balkans* by (Topalović and Haas, 2024). Analyzed relationships between energy storage revenues and hydro, wind, and photovoltaics generation and European

Union Emission Trading Scheme (EU ETS) prices show fundamental drivers behind energy storage's economic viability and answer to the proposed research question.

Third research question: *How does future renewable generation influence energy storage development in the Western Balkan countries?*

The role of renewables, given by (Topalović and Haas, 2024), follows in the investigation of the development of energy storage systems in the Western Balkan countries. Using revenues from arbitraging a 10-megawatt (MW) pumped hydro storage system in the Western Balkan, resulting from the electricity market price distribution and the analysis of the total costs of storage, an econometric model is created. This model shows the impacting factors of energy storage development in the context of the rising renewables generation. Levels of the correlation between independent variables and revenues provide the answers to relevant parameters that impact future energy storage development in the region with the upcoming renewables investments.

The mentioned articles serve the purpose of answering the proposed research questions as the main goal of this thesis is to identify possibilities for integration of energy storage systems within their technical developments in the electricity markets as the flexibility in the power systems increases (rising shares of renewables, electrification of transport, heating and cooling sectors and self-consumption). The term "energy storage" in the thesis is considered "storage system for electricity".

1.4 Method of approach

Analysis of the energy storage systems' economic viability in the electricity markets is conducted with three different methods: cost calculation, linear mixed-integer optimization, and linear regression analysis. Before the modeling analyses, a literature review provided significant technical and economic results of the energy storage systems. Given the variety of energy storage systems technologies and application possibilities, there are differences in the calculation of the energy storage system cost-effectiveness. Investment costs can be presented as costs of energy stored €/kWh or costs of energy capacity €/kW. These costs are only one part of the total cost calculation, as presented in the thesis by the "Levelized cost of storage" (LCOS). This cost calculation takes into consideration all costs for a given energy storage system's lifetime: investment costs, operation and maintenance costs, recycling, and disposal costs. The LCOS, as a method is used in the recent literature for comparing storage technologies, similar to the Levelized cost of electricity (LCOE) used for representing the average costs of electricity from the generation technologies. Both terms include a "Levelized cost" as a representation of discounted costs per unit of electricity generated (power plants) or discharged (storage). In the LCOS calculation in this thesis, LCOE is a part of the equation that along with the electricity market price, gives final costs. A detailed description of the mentioned method is given in Chapter 3. The second part of the analysis is based on the mixed-integer optimization model for maximum energy storage profits from price arbitrage. Maximizing these profits with the energy storage capacity constraints and including the LCOE, given from the previously conducted cost calculation, allows for the profitability analysis that results in an operational strategy and storage profits. The resulting profits represent a possibility for energy storage price arbitrage based on the analysis of the electricity market conditions in the analyzed timeframe. This method provides insightful remarks regarding energy storage systems' economic justification and prospects for investment in energy storage systems in the electricity market designs of the study case. Given the strong relationship between energy storage systems and RES, a detailed analysis using linear regression is conducted as the third part of the thesis model. The linear regression model is based on the historic data of hydro, wind, solar generation, and carbon prices as predictors or independent variables, while the response or dependent variable is energy storage price revenue. This revenue is calculated by analyzing the electricity market price distribution regarding the number of full load hours. In the arbitrage application, an energy storage system will discharge at the times of high electricity market prices, and charge at the times of the lowest, hence average costs and revenues of the energy storage system are calculated given the different number of full load hours.

A schematic overview of the methods in the thesis is given in Fig.1.3, showing the connection between all methods from cost calculation, optimization, and finally regression, conducted in the thesis. The life cycle costs divided by the full load hours are used in the final LCOS calculation as well as in the mixed–integer optimization. Full load hours are also input parameters for the optimization analysis, as in the cost-effectiveness analysis. The models and their results continue from one to another, as the first method, cost calculation, shows that full load hours for PHS given the maximum number of cycles and 8-hour discharge time, are around 2000. Since Li-ion technology is considered one of the most promising electrochemical energy storage, with the longest life cycle, it is included in the optimization analysis along with the PHS. The models are based on the study case of Western Balkan and compared to the case of Austria. In the cost calculation, this comparison is done within the LCOS for two different electricity markets: Hungarian Electricity Exchange (HUPX) and Energy Exchange Austria

(EXAA). Along with the price arbitrage, the optimization model uses the same electricity markets within the timeframe from 2011 to 2019, but it compares the country of Austria with Bosnia and Herzegovina for further analysis of the energy storage prospects in two different energy systems. The linear regression model is conducted for the generation of hydro, wind, and solar renewables in the WBC, as single generation analysis for each country is notably lower. The conducted models can be applied to any study case, but some limitations should be mentioned. Firstly, in the cost calculation, the input parameters can differ in the literature, since there is scarce information about costs from energy storage manufacturers. Secondly, the models use perfect foresight of the electricity market prices and assume that the number of energy storage systems is still insignificant to make an impact on the electricity market prices, hence the price-taker approach in the optimization analysis. Thirdly, the renewable generation data of the linear regression model are relatively small for WBC, and in some cases, wind and solar generation was zero at the beginning of the analyzed timeframe. The focal point of the analysis is on finding the impacting factors on energy storage in the electricity markets with rising renewables circumstances, hence the energy storage technology constraints are neglected, and analysis is based on the maximum limits of energy storage capacity.

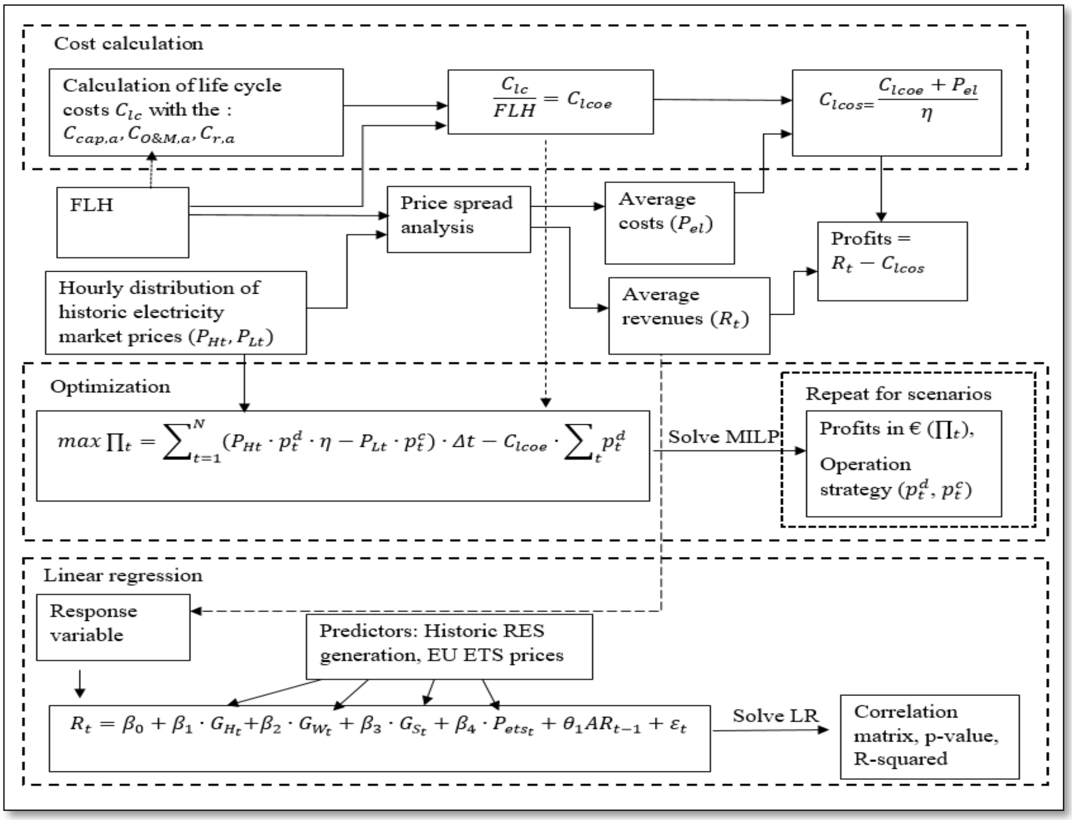

Fig. 1.3 Schematic representation of the methods used for energy storage systems techno-economic analysis as in the papers: (Topalović, Z. et al., 2022), (Topalović, Z., Haas, R. and Sayer, M., 2024), and (Topalović, Z. and Haas, R., 2024)

Each method of approach, from literature review, cost calculation, optimization, to linear regression, is described in detail in Chapter 2, Chapter 3, Chapter 4, and Chapter 5 respectively. Hence, this Chapter provides an overview of all methods, as schematic representation (Fig.1.3) serves only for the description of relationships between the methods in the thesis. The variables, equations, assumptions, and input data from Fig.1.3 are described along with the simulation setup and results of the conducted research in the following chapters.

1.5 Structure of the work

The analysis starts with the comprehensive state-of-the-art energy storage systems considering their technical and economic parameters in Chapter 2 as in the paper by (Topalović, Z. et al., 2023). A detailed categorization of the selected storage technologies and their costs is presented based on the literature review. Chapter 3 gives a detailed cost-effectiveness comparison of the two types of energy storage systems, pumped hydro storage and battery storage. Using Levelized cost of storage, full load hours, and price spreads, currently, the most viable technologies are analyzed and their utilization in the electricity grids is presented in the paper by (Topalović, Z. et al., 2022). Profitability analysis of the selected technologies when used for a price arbitrage in two different electricity markets is given in Chapter 4. The optimization model with a price-taker approach results in the profits of PHS and Li-ion storage in the electricity markets, conducted for the research paper by (Topalović, Z., Haas, R. and Sayer, M., 2024). Following the previous analysis of energy storage profitability, in Chapter 5 impact of renewables on energy storage systems' development is analyzed with the linear regression method, as described in the research paper by (Topalović, Z. and Haas, R., 2024). A summary of the obtained results is given in Chapter 6 along with the conclusions and an outlook on energy storage systems in the electricity markets. The reference list of papers is provided in Chapter 7.

2 Literature review on technology and economics of energy storage systems

Storage for electricity is expected to ensure flexibility in future carbon-free energy systems with high shares of renewables. A comprehensive review of their technical constraints and advantages while considering profitability and economic viability is valuable for understanding of energy storage position in the changing electricity grids. This chapter is based on the literature review article published by (Topalović *et al.*, 2023).

2.1 Core objective

The core objective of the (Topalović *et al.*, 2023) review is to give up-to-date research on the electricity storage systems, provide an economic assessment, and find cost-effective and feasible technology for implementation in the electricity market. Considering the different applications of electricity storage as ancillary services, flexibility measures, and large-scale and distributed installations, a detailed analysis of the total costs and technical maturity of the selected systems is conducted. Opportunities for electricity storage in energy systems with the growing shares of renewable energy sources are analyzed in the next chapters.

2.2 Method of approach

The conducted analysis of energy storage technical and economic characteristics is obtained within the literature provided in the databases of Science Direct, TU Bibliothek, and Scopus. Using highly cited articles based on the storage for electricity utilization in the power grids, an up-to-date review is given. As the focus of the research is to analyze energy storage systems in the current market conditions and their profitability, the most used keywords in a search for the relevant references are energy storage, economics, pumped hydro storage, battery storage, and energy storage profitability. The structure of the review is based on the given references count:

- Energy storage technologies: 47
- Distributed energy storage: 13
- Energy storage economics:19

The conducted review provided the thesis with an overview of the energy storage economics and their technical maturity, from which research questions and further analyses have been developed.

2.3 Energy storage categorization

Installation of the energy storage systems in the 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, for the analyzed storage systems for electricity, these characteristics are selected from the literature and presented in Table 2. Analysis shows that pumped hydro storage and compressed air energy storage systems (CAES) can provide large amounts of energy (up to gigawatts) in a couple of minutes, with an average efficiency of 70%, and once installed, they can be operable for more than 40 years with a range from 5 to 5000 MW power capacity. Contrary to these, flywheel energy storage systems (FESS) and batteries are responsive in less than seconds, but are limited with high power density and power ranges up to 100 MW. Highly responsive technologies such as capacitors and magnetic storage systems can provide up to 10 MW, but they can have a power density of up to 120 000 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 in the energy transition towards renewables, is hydrogen (Töpler, 2016),(Hassan *et al.*, 2023) and (Ajanovic, Sayer and Haas, 2024). A disadvantage of hydrogen is low efficiency of 50% on average due to the conversion methods and current technical maturity which impacts high investment costs. Their application in hybrid mode with battery energy storage, as analyzed by (Yang *et al.*, 2024), improves the overall effects of large-scale storage. Hence, depending on the technical characteristics from Table 2, application and utilization of the selected storage systems in the electricity grids (PHS, CAES, FESS, Li-ion, lead-acid (Pb), nickel-cadmium (Ni-Cd), sodium-sulfur (NaS), vanadium redox flow battery (VrB)) are analyzed in the next chapters.

Table 2 Electricity storage technical characteristics

Storage type	Power Range MW	Power density volumetric (kW/m^3)	Energy density volumetric (kWh/m^3)	Energy density (mass) (kWh/kg)	Efficiency %	Response time	Lifetime years (cycles)	Source
PHS	10-5000	-	-	-	75-85	s-min	40-60 (>13,000)	Das, C. K. *et al.* (2018)
	-	0.1-0.2	0.2-2	0.2-2	70-80	-	(>5000)	Koohi-Fayegh, S. *et al.* (2020)
	10-1000	-	-	0.1-0.4	65-80	min	30-50	Olabi, A. G. *et al.* (2021)
CAES	5-1000	-	-	-	70-89	1-15min	20-40 (>13,000)	Das, C. K. *et al.* (2018)
	-	0.2-0.6	2-6	3-60	41-75	-	(>10,000)	Koohi-Fayegh, S. *et al.* (2020)
	50-300	-	-	0.0032-0.0055	70-73	-	30-40	Olabi, A. G. *et al.* (2021)
FESS	0.1-20	-	-	-	93-95	< 4ms-s	15+ (>10^5)	Das, C. K. *et al.* (2018)
	-	5000	20-80	5-30	80-90	-	(2x10^4-10^7)	Koohi-Fayegh, S. *et al.* (2020)
	0.1-20	-	-	0.005-0.1	85	-	20	Olabi, A. G. *et al.* (2021)
Li-ion	0-100	-	-	-	85-90	20 ms-s	5-15 (1000-20,000)	Das, C. K. *et al.* (2018)

	-	1300-10,000	200-400	60-200	85-98	-	(500-10,000)	Koohi-Fayegh, S. *et al.* (2020)
	0.1-50	-	-	0.08-0.15	78-88	-	14-16	Olabi, A. G. *et al.* (2021)
Pb	0-40	-	-	-	70-90	5-10 ms	3-15 (2000)	Das, C. K. *et al.* (2018)
	-	90-700	50-80	30-45	75-90	-	(250-1500)	Koohi-Fayegh, S. *et al.* (2020)
	0.005-10	-	-	0.03-0.05	75-80	-	15	Olabi, A. G. *et al.* (2021)
Ni-Cd	0-40	-	-	-	60-65	ms	10-20 (2000-3500)	Das, C. K. *et al.* (2018)
	-	75-700	15-110	15-45	60-80	-	(1500-3000)	Koohi-Fayegh, S. *et al.* (2020)
	45	-	-	0.03-0.05	72	-	13-20	Olabi, A. G. *et al.* (2021)
NaS	0.05-34	-	-	-	80-90	1ms	10-15 (2500-4500)	Das, C. K. *et al.* (2018)
	-	120-160	150-300	100-250	70-85	-	(2500-4500)	Koohi-Fayegh, S. *et al.* (2020)
	0.05-34	-	-	0.1-0.175	75-87	-	12-20	Olabi, A. G. *et al.* (2021)
Vrb	0.03-3	-	-	-	~85	< 1ms	5-10 (12,000+)	Das, C. K. *et al.* (2018)

	-	0.5-2	20-70	15-50	60-75	-	(>10,000)	Koohi-Fayegh, S. *et al.* (2020)
Hydrgoen Fuel Cell	0-58.8	-	-	-	25-58	< 1s	5-20+ (10^3-20,000+)	Das, C. K. *et al.* (2018)
	-	>500	500-3000	800-10,000	20-50	-	(>1000)	Koohi-Fayegh, S. *et al.* (2020)
	0.1-50	-	-	-	35-42	-	15	Olabi, A. G. *et al.* (2021)
Capacitor	0-0.05	-	-	-	60-65	ms	~5 (>50 000)	Das, C. K. *et al.* (2018)
	-	>100,000	2-10	0.05-5	60-70	-	(>50,000)	Koohi-Fayegh, S. *et al.* (2020)
Super-capacitor	0-0.3+	-	-	-	90-95	8 ms	20+ (>10^5)	Das, C. K. *et al.* (2018)
	-	40,000-120,000	10-20	1-15	85-98	-	(10^4-10^5)	Koohi-Fayegh, S. *et al.* (2020)
SMES	0.1-10	-	-	-	95-98	< 100 ms	20+ (> 10^5)	Das, C. K. *et al.* (2018)
	-	2600	6	-	75-80	-	(> 10^5)	Koohi-Fayegh, S. *et al.* (2020)
	0.05-0.25	-	-	0.002-0.069	80-95	-	20	Olabi, A. G. *et al.* (2021)

2.3.1 Pumped hydro storage

Energy storage systems can be categorized by the form of energy used to produce electricity, therefore potential energy of the water or kinetic energy presents the basics of mechanical energy storage systems. Pumped hydro storage systems were developed in the early 1900s, yet planning and construction began after the end of the Second World War (IHA, 2018). 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, as presented by (Barbour *et al.*, 2016). The authors (Barbour *et al.*, 2016) 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. They conclude that new investments of energy storage systems (EES) in the 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 (Table 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 2.1.

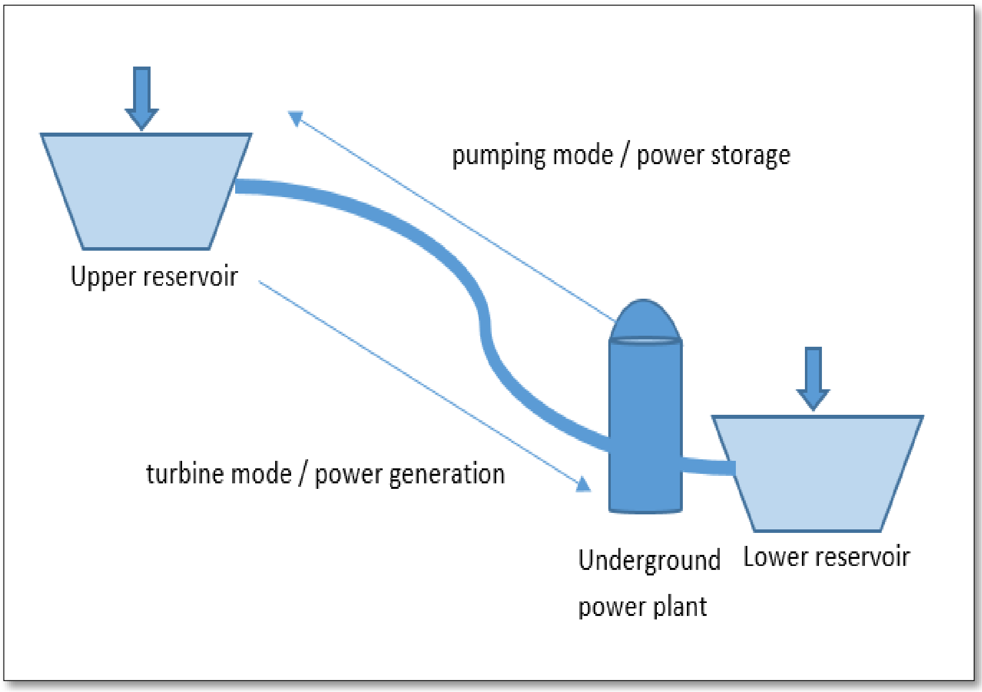

Fig. 2.1 Pumped hydro storage working scheme

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 system balances and adjusts the demand and supply, thus providing the stability of the power grids. The paper by (Al-hadhrami and Alam, 2015) presents 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 research analysis by (Hunt *et al.*, 2020) 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 as seen in the research by (Blakers *et al.*, 2018), (Lu *et al.*, 2021). 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 the 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, as analyzed by (Barbaros, Aydin and Celebioglu, 2021).

2.3.2 Compressed air energy storage

Identical to pumped hydro storage systems, compressed air energy storage systems depend on the 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 by (King *et al.*, 2021). A conducted study case shows high potential for CAES that can exceed the storage requirements in the United Kingdom (UK), given the findings of the salt caverns as methods for using underground formation, while comparison with India shows scarce geographical locations for CAES. 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 as presented by (Habibi *et al.*, 2020). The authors show 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 loads. 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 powerplant coupled with offshore compressed air energy storage (OCAES) proves to be non–feasible for such a system, as analyzed by (Li and Decarolis, 2015). 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 (Table 2) show similar characteristics of PHS and CAES. Because of their robustness, they can provide a large power range for a longer period, hence they are needed for bulk energy storage applications. Nevertheless, CAES technology requires more research, as research by (Zhang *et al.*, 2024) shows that only a couple of plants were constructed for commercial use.

2.3.3 Flywheels

Flywheels, disk-shaped systems that rotate and store surplus electricity, examined from a techno-economic point of view by (Rahman *et al.*, 2021), are considered an alternative to electrochemical energy storage systems because of the equal characteristics of short-duration time. A detailed principle of flywheel technology, application, development, and system practice is given by (Arabkoohsar and Sadi, 2021). Flywheel 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 features of FESS for different charging demands of electric vehicles are analyzed by (Thormann, Puchbauer and Kienberger, 2021). 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 cost reduction or power grid fee increase. Using FESS as a complementary to electric vehicles allows for 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, which is replaced by fast response and high energy density needed for additional services such as reserves or peak shaving. Nevertheless, FESS is still an expensive technology, which can be utilized in specific conditions, at least until technology costs decrease.

2.3.4 Electrochemical Energy Storage

Regardless of the 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 for transportation applications, are given by (Miao *et al.*, 2019), (Fang *et al.*, 2020), and (Zubi *et al.*, 2018). Energy storage technologies reviews by (Behabtu *et al.*, 2020) and (Yang *et al.*, 2018) 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 (Table 2), of up to 15 years or 20,000 cycles. Yet, calendar life, as the main constraint for the batteries, is being analyzed in the literature to assure longer profitability. A new approach to extending the lifetime of Li-ion batteries used as energy storage systems in household applications, is found by (Alimardani and Narimani, 2021). Such an approach proposes a hybrid energy storage system 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 by (Münderlein *et al.*, 2020) 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 Pb batteries have a lower market price, but lower cycle life when compared to the other batteries (Table 2), analysis by (Fares and Webber, 2018) 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 shaving applications. Installation of batteries alongside pumped hydro storage can also provide effective management of the energy grid variation, especially for off-grid renewable systems. Pumped hydro and battery storage have complementary characteristics, complementing each other in the low state of charge periods, as analyzed by (Javed *et al.*, 2020), thus this type of storage combination is desirable and recommended. The battery energy storage system's implementation in the 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 battery energy storage system (BESS) size, given by (Kelly and Leahy, 2020) results with the conclusion 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 by (Yang *et al.*, 2018) provides new insights into the most appropriate optimization technique for BESS sizing with a focus on the energy application and the type of renewable energy sources. Since renewable energy system applications 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, as showed by (Deguenon *et al.*, 2023) that Li-ion, NaS, and VrB in grid applications can provide 40-50% of RES penetration rates. Batteries with high power capacity, energy densities, and high efficiency (Table 2), are limited by high production costs, but NaS, flow batteries, and vanadium redox flow batteries are applicable as ancillary services as they can rapidly provide energy and ensure grid stabilization. Because of the fast response time and high energy density, BESS has been used in electric vehicles, contributing to their integration as an 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 by (Balali and Stegen, 2021). Along with the electromobility spread, self-consumption is increasing as well. A comparison of large-scale, industrial, and home energy storage systems in Germany by (Figgener *et al.*, 2021), 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. 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 possibilities for utilization as fast response measures.

2.3.5 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 (Breeze, 2018), hence they have high capital costs, but a recent analysis by (Cui and Aziz, 2024) shows that a 10% reduction of their total costs is achievable with the 20%

of an increase in their efficiency. Similar to other unattainable storage systems, challenges in technology and costs can be reduced in hybrid systems such as wind-hydrogen storage, where the wind would be otherwise curtailed. A developed renewables-hydrogen model by (Ruhnau and Schiele, 2023) shows that optimal dispatch that allows for flexible hydrogen usage with the market interaction reduces the levelized cost of hydrogen.

With the technical revolution in the late 1970s and the expansion of new 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 by (Chang and Hang Hu, 2018). 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 (Wang *et al.*, 2021). 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 methods for optimally utilizing electricity storage performance is installation alongside different renewable energy sources, such as in hybrid power systems.

2.3.6 Hybrid power systems with storage

Between 2009 and 2022, the technology cost of solar PV modules fell by 91% in Europe (IRENA, 2023), therefore photovoltaics have become desirable in households as installations for self-consumption. The problem with self-consumption is a high peak demand during the afternoon hours and oversupply during the noon hours. Thus, home storage systems that store excess electricity generation during the day can make roof-top solars feasible, especially when there is a decrease in battery technology that is boosting the economic effects for end-users. These effects are seen especially in Germany, a country with rapid deployment of PV home storage with 60,000 new installations in 2019, a total of 250 MW battery power and 490 MWh battery capacity (Figgener *et al.*, 2021). With the high penetration of photovoltaics in distribution grids in recent years, maintaining a balance of demand and supply for grid operators has become challenging. Energy storage systems can reduce the variability effects and the curtailment of RES generation when employed in hybrid systems. One of the key issues for utilizing hybrid systems is the optimal sizing of the installed technologies. A techno-economic analysis of the optimal capacity sizing for PHS, thermal energy storage (TES), hydrogen, and BESS technologies in wind-solar-storage hybrid systems by (He, Y. *et al.*, 2021), shows that battery storage systems prove to be the most cost-effective besides thermal energy storage systems for such multi-optimization strategy. Various factors should be considered when modeling hybrid storage systems, such as technical, economic, and environmental, hence multi-criteria decision-making should be considered as proposed by (Panda *et al.*, 2023), (Emrani and Berrada, 2024). Different hybrid storage designs researched so far, as by (Atawi *et al.*, 2024) and (Psarros and Papathanassiou, 2022), prove the importance of combining different renewables or storage technologies to improve the overall economic viability. The economic aspect of storage systems for electricity, especially the high initial investment cost, is considered the major barrier to wider storage integration. Given the examined research so far, it is evident that this barrier can be overcome with the proposed methods of mixing energy storage systems in specific applications with variable renewable energy sources and with the consideration of the optimal sizing of the technology.

2.4 Distributed energy storage

Due to the decrease in solar technology costs, prosumers have emerged as a new group of storage users, who are slowly becoming local energy market players, seldomly called prosumages. The word "prosumage" by (Green and Staffell, 2017) 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. An economic feasibility analysis by (de Doile *et al.*, 2023) indicates that smaller battery storage systems are economically justified for residential PV systems contrary to the large-scale ones, while an analysis by (Nguyen *et al.*, 2017) confirms the maturity of the batteries and thermal energy storage systems for small scale application. Battery energy storage systems with PVs, with a viable business model as proposed by (Resch *et al.*, 2021), can significantly reduce the inevitable grid expansion costs when compared to the traditional distribution grids. The importance of future growth of prosumages is presented through a simulation model by (Say, Schill and John, 2020). The conducted analysis shows that PV-battery prosumage households impact wholesale electricity market prices. As their energy demand is reduced during the day by PV generation and at the evening peak by battery storage, with the industrial demand decreasing in the evening, electricity prices decrease and the peak is shifted to the mid-morning. This way average electricity prices for prosumage households decrease as they benefit from the decrease in prices in the early evening peak, while prices for industrial demand increase. Results of the simulation brought the conclusion that regulators should promote battery flexibility in the energy transition, but investors and power system planners of large-scale renewable generation should prevent possible prosumage overinvestment. An economic assessment of energy storage systems developed for trading electricity between local households, as researched by (Liu *et al.*, 2021), 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 (Li, Cao and Zhang, 2022). A presented framework by (Schram *et al.*, 2020) indicates that households can be co-owners of community storage, but also decision-makers in a trade-off between costs and emissions. Nevertheless, for distributed storage operational charging and discharging impact degradation costs of the storage, hence optimal strategy is vital for systems' profitable utilization. Economic analyses of distributed energy storage systems by (Ding *et al.*, 2021) and (Al Khafaf *et al.*, 2022) maximize profits with the proposed models that determine optimal dispatch strategies. Analysis of the distributed storage shows the technical maturity of the technology used as a tool for the implementation of renewable generation in the grids and for mitigating carbon dioxide (CO_2) emissions while reducing electricity bills for end-users. Nonetheless, for the wider development of distributed storage in the upcoming years, government incentives are needed. Since energy policies for storage development are still not effectively addressed in a long-term effect, some of the presented mechanisms for promoting energy storage growth are direct subsidies and price floors, as proposed by (Lai and Locatelli, 2021). 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 research by (Haji Bashi *et al.*, 2022), 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. The new role of EES would require changes in market rules and regulations by implementing a capacity-based market and fast response segment, as shown in the case of Australia (Martin and Rice, 2021).

As seen, an application of energy storage systems as 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 Chapter.

2.5 Economic assessments

Most of the recent storage literature covers modeling renewable generation with energy storage systems as analyzed by (Santos *et al.*, 2021), (Mohandes *et al.*, 2021), (Mazzoni *et al.*, 2019), and (Soini, Parra and Patel, 2020). These analyses provide important technical overviews, that expended with the cost calculations, can result in final assumptions for wider electricity storage utilization. Along with the renewables' further development, the variable nature of PV generation impacts the grid stability and influences an imbalance between demand and supply. This imbalance, graphically presented as a duck-shaped load curve, as explained by (Hou *et al.*, 2019), can be solved with flexible resources. Changing patterns of demand and supply because of the high PV and wind generation, changes in the transportation and heating sector with the emergence of electric vehicles and heat pumps, and an increase in self-consumption, are expected to continue in the further electricification. Historical supply from the flexible fossil power plants is being replaced by renewable energy sources from variable PV and wind generation to mitigate greenhouse emissions, hence additional flexibility is required to balance these changes in the power systems. There are different methods for balancing systems depending on the time requirements as changes in the demand/supply are categorized by seconds (unexpected changes in the frequency) to hours (during the day a peak and off-peak demand) and seasons (higher demand in summer and winter due to the cooling and heating). Among flexibility options such as demand response, power generators, or interconnection is energy storage. Within the variety of energy storage systems technologies developed, their application is determined by their technical characteristics (Table 2) given the power system requirements. Flywheels and supercapacitors given their fast response time are best suitable for frequency regulation, while PHS and CAES with longer duration time for seasonal storage, batteries as complementary to self-consumption (prosumagers) are also suitable for peak capacity and energy arbitrage together with PHS. An economic analysis of the selected energy storage technologies for load shifting is conducted by (Frate, Ferrari and Desideri, 2021), showing that PHS and CAES are the most promising technologies given the cost-efficiency combination, but there isn't an economic justification for any ESS technology without government subsidies. Contrary to the analyzed research, (Aguiar and Gupta, 2021) show that ESS are viable in today's electricity markets by proposing a hedging mechanism with insurance contracts between a renewable producer and a 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. The profitability study of PHS plants by

(Dallinger *et al.*, 2019) for study case Austria, shows a reduction of reserve capacity and investments in peaking units in Europe, as the storage capacities increase. Other benefits of operating with large-scale storage systems can be seen with the mitigation of the costs for operating volatile wind generation. 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 (de Boer *et al.*, 2014). 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. Energy storage systems can also improve profitability of the conventional power plants, as analysis by (Sheibani, Yousefi and Latify, 2021) shows, but they are expected to provide decarbonization of the future energy systems. Contrary to the assumption that storage limits the further expansion of variable energy generation (Sinn, 2017), an economic assessment of energy storage technologies by (Zerrahn, W. P. Schill and Kemfert, 2018) shows that energy storage needs are lower when renewable capacity expansion and the level of renewable curtailment is considered. Hence application of economically viable storage technologies is highly recommended for an increase of renewable shares in the power grids. This can be achieved with large-scale long-duration energy storage applications, as an overview of different types of ESS by (He, W. *et al.*, 2021) shows, or with the combination of PV-battery storage systems as they can be developed for covering peak-demand growth as substitutes for coal-fired plants (Kahrl and Lin, 2024). Trends in the spreading of stationary batteries in the United States of America (Telaretti and Dusonchet, 2017) have shown that the profitability of ESS depends on 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 as examined by (Junge, Mallapragada and Schmalensee, 2022). Still, regardless of the application and duration type (short-term, medium-term, and long-term), storage implementation in smart grids is conditioned by the number of full-load hours as concluded in the analysis by (Ajanovic, Hiesl and Haas, 2020). Implementation of economically viable storage systems in the electricity markets can be achieved with a future decrease in technology costs or an increase in electricity market prices. In this thesis, a detailed economic analysis of the energy storage systems is conducted with the capital costs, charge and discharge time, and environmental impact, as shown in Table 3. 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).

Table 3 Comparison of the analyzed energy storage systems, given the economic parameters in the selected literature

Storage type	Capital cost (power-based) €/kW	Capital cost (energy-based) €/kWh	Charge time	Discharge time	Environ-mental impact	Source
PHS	1700-2550	4.25-85	hr-months	1-24hr+	Large	Das, C. K. *et al.* (2018)
	510-1700	4.25-85	-	-	-	Koohi-Fayegh, S. *et al.* (2020)
	-	10-70	-	-	-	Olabi, A. G. *et al.* (2021)
CAES	340-850	1.7-102	hr-months	1-24hr+	Large	Das, C. K. *et al.* (2018)
	340-680	1.7-42.5	-	-	-	Koohi-Fayegh, S. *et al.* (2020)
	-	3-70	-	-	-	Olabi, A. G. *et al.* (2021)
FESS	212.5- 297.5	850-11,900	s-min	ms-15min	Almost none	Das, C. K. *et al.* (2018)
	255-850	2550-5100	-	-	-	Koohi-Fayegh, S. *et al.* (2020)
	-	340-680	-	-	-	Olabi, A. G. *et al.* (2021)
Li-ion	765-3400	510-3230	min-days	min-hr	Moderate	Das, C. K. *et al.* (2018)
	1020-3400	85-2125	-	-	-	Koohi-Fayegh, S. *et al.* (2020)

	-	765-1105	-	-	-	Olabi, A. G. *et al.* (2021)
Pb	255-510	170-340	min-days	s-hr	Moderate	Das, C. K. *et al.* (2018)
	255-510	170-340	-	-	-	Koohi-Fayegh, S. *et al.* (2020)
	-	50-100	-	-	-	Olabi, A. G. *et al.* (2021)
Ni-Cd	425-1275	340-2040	min-days	s-hr	Moderate	Das, C. K. *et al.* (2018)
	425-1275	680-1275	-	-	-	Koohi-Fayegh, S. *et al.* (2020)
	-	340-2040	-	-	-	Olabi, A. G. *et al.* (2021)
NaS	850-2550	255-425	s-hr	s-hr	Moderate	Das, C. K. *et al.* (2018)
	850-2550	255-425	-	-	-	Koohi-Fayegh, S. *et al.* (2020)
	-	210-450	-	-	-	Olabi, A. G. *et al.* (2021)
VrB	510-1275	127.5-850	hr-months	s-24hr+	Moderate	Das, C. K. *et al.* (2018)
	510-1275	127.5-850	-	-	-	Koohi-Fayegh, S. *et al.* (2020)
Hydrogen Fuel Cell	425-8500	12.75	hr-months	s-24hr+	Small	Das, C. K. *et al.* (2018)
	425-8500	-	-	-	-	Koohi-Fayegh, S. *et al.* (2020)
	-	12-15	-	-	-	Olabi, A. G. *et al.* (2021)

Capacitor	170-340	425-850	s-hr	ms-1hr	Small	Das, C. K. *et al.* (2018)
	170-340	425-850	-	-	-	Koohi-Fayegh, S. *et al.* (2020)
Supercapacitor	85-382.5	255-1700	s-hr	ms-1hr	None	Das, C. K. *et al.* (2018)
	111-438	8500	-	-	-	Koohi-Fayegh, S. *et al.* (2020)
SMES	170-415.65	850-61,200	min-hr	ms-8s	Moderate	Das, C. K. *et al.* (2018)
	111-438	850-8500	-	-	-	Koohi-Fayegh, S. *et al.* (2020)
	-	6800-17,000	-	-	-	Olabi, A. G. *et al.* (2021)

Note: the conversion course for $ to € is from the 16.8.2021.

As there are significant differences in the energy storage technology characteristics, and in a wide range of applications they can be applied, capital cost comparison differs depending on the size, location, or time of construction for plants used in the estimation from the literature. They are presented as capital cost per power capacity €/kW (accounting for the costs for turbine, and power connection) or energy-based capital cost per energy €/kWh (including costs depending on size such as PHS reservoirs, or tanks in batteries). Capital costs for PHS are the highest, contrary to the capital costs of supercapacitors. Still, depending on the other factors, for large-scale application, PHS is the most cost-effective technology, 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 (Ajanovic and Haas, 2019). 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 a 15-year calendar life and due to the decreasing trend in their production costs. Detailed analysis of the total energy storage costs represented as "Levelized cost of storage" of PHS and BESS, conducted for the study case of Western Balkan countries, is given in the next Chapter.

3 Economics of storage for electricity: the case of Western Balkan countries

Research of the energy storage systems' technical constraints has been long underway, but the economics are still the major issue for wider utilization of these systems. Integration of ESS is economically justified if the costs of energy storage systems do not exceed the costs of energy from the market. This chapter presents an analysis of the cost-effectiveness of pumped hydro storage and large-scale battery storage systems based on the research article by (Topalović *et al.*, 2022).

3.1 State of the art

Pumped hydro storage depends mainly on the geographical area where two reservoirs are at 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. Originally, pumped hydro plants were installed as a complement to nuclear power plants. The economic driver of the pumped hydro storage technology is the flexibility of demand-supply. With the high integration of variable renewable energy sources, the operation of power grids requires additional flexibility. Operating pumped and thermal plants in the most cost-efficient way as described in detail by (Crampes and Moreaux, 2010), shows that optimal dispatch of a PHS is efficient whether it is coupled with inflexible thermal generation or variable generation of wind and solar renewable sources. Recently, there has been renewed interest in pumped hydro energy storage systems, especially because of electricity market deregulation and increased renewable generation, as these storage technologies assist renewables in replacing dispatchable power production, as analyzed by (Soini, Parra and Patel, 2020). Countries with rapid economic development, like China, invest in pumped hydro storage systems as the main measure for ensuring stability in the power grids with its regulation policies that provide different models for payment and tariff systems with the majority of the PHS facilities being owned by transmission companies (Nibbi, Sospiro and De Lucia, 2021). Capital costs for the proposed PHS are affecting energy operation and flexibility. A feasibility study by (Strang, 2017) shows that the conversion of one form of energy that is not storable to another form of storable energy can have a more valuable economic impact. Besides the most installed capacities of pumped hydro storage systems, new emerging storage technologies such as batteries are still under research of cost-effectiveness. Batteries are used to meet demand when wind and solar cannot provide enough electricity. Still, battery storage has limited capacity. Environmental consequences of battery storage when compared to hydro storage, are much higher. Because of the hydrokinetic energy, PHS systems have 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. As the disposal of batteries' materials impacts the environment significantly, especially given the exponential growth of electric vehicles in recent years, these costs should be considered in the costs analysis. An overview of the existing battery storage optimization techniques is presented by (Yang *et al.*, 2018), according to the storage application type for the specific renewable energy systems. As BESS are inevitable part of the future systems with the consideration of the environmental criteria and despite technical and financial indicators, methods for their utilization depend on the size and characteristics of the renewable energy system they are applied in. Large-scale battery storage systems, reviewed by (Poullikkas, 2013), are used as ancillary services competent for balancing supply-demand, as well as for the support of extensive grid integration of wind and solar generation technologies. Battery participation in the electricity markets as an instrument for operating the electricity grid has been appealing from an economic perspective. The economic viability of grid-scale battery integration in the electricity markets is still being researched due to the limited cycle life and calendar life of batteries. An analysis by (Fares and Webber, 2018) indicates that energy storage systems' lifetime is not dependent 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 to wider utility-scale battery 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 going to be used further due to CO_2 emission mitigations, as concluded in the research by (Kear and Chapman, 2013). 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. The economic top-down approach by (Zerrahn, W. Schill and Kemfert, 2018) shows how energy storage costs depend on the user's economic environment, the annual number of storage cycles, and used storage technologies (higher costs for short-term storage systems). A different approach to the volatility of energy generation and market prices is described by (Rathgeber, Lävemann and Hauer, 2015). The analysis compares the arbitrage benefits of the 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. An investment and management analysis of the ESS by (Newbery, 2018), shows that higher effectiveness is achieved with ancillary services. Hence, further research in terms of feasibility and economics is conducted by (Topalović *et al.*, 2022) for this thesis, using the Levelized cost of energy storage, as presented in the next chapters.

3.2 Core objective

A detailed cost-effectiveness analysis is conducted with the Levelized storage cost calculation with the full load hours and the price spread of electricity in the day-ahead markets. Taking into calculation all costs that an energy storage system can hold and discharge over its lifetime allows for a comprehensive economic analysis. Presented information about the prospects for pumped hydro storage installation in comparison to the large-scale battery storage systems, given the study case of the Western Balkan region, is included in the research of energy storage economics in the thesis.

3.3 Method of approach

For the comparison of the economic viability of pumped hydro storage and battery storage systems, all costs are considered in the next equation:

$$C_{tot} = C_{pcs} + C_{bop} + C_{sto} \cdot t_d \tag{1}$$

Where:

C_{tot} ....total capital costs (or investment costs) for a storage system expressed in (€/kW),

C_{pcs} ....power conversion system costs expressed in (€/kW),

C_{bop} ....balance of plant costs expressed in (€/kW),

C_{sto} ....storage costs related to energy capacity expressed in (€/kWh),

t_d .... 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. Balance of plant considers costs for project engineering, grid connection, and system integration (Zakeri and Syri, 2015). Costs for battery banks, reservoirs, or electrolytes are related to energy capacity and represent construction costs. Storage costs are related to energy capacity in kWh as a function of discharge time. When analyzing storage costs, life cycle costs are an inevitable part of the calculation, as in the next equation:

$$C_{lc} = C_{cap,a} + C_{O\&M,a} + C_{r,a} + C_{dr,a} \quad (2)$$

Life cycle costs C_{lc}, expressed in (€/kW-annual), represent the sum of annualized capital costs for storage systems $C_{cap,a}$, (€/kW-annual), fixed and variable operation and maintenance costs $C_{O\&M,a}$, (€/kW-annual), replacement costs of energy storage systems $C_{r,a}$ (€/kW-annual), and costs for disposal and recycling $C_{dr,a}$ (€/kW-annual). Annualized capital costs of the storage system are total capital costs C_{tot} calculated with a capital recovery factor α, which considers interest rate (i) during the lifetime (T) of the storage system:

$$C_{cap,a} = C_{tot} \cdot \alpha \quad (3)$$

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

Operation and maintenance variable costs consider both fixed annual costs for energy storage system $C_{f,a}$ in (€/kW) and variable annual costs $C_{v,a}$(€/ kWh), which depend on the hours of charging/discharging energy storage systems i.e. full load hours of operating energy storage systems FLH.

$$C_{O\&M,a} = C_{f,a} + C_{v,a} \cdot FLH \quad (5)$$

Future replacement costs of battery storage systems C_r in €/kWh and replacement period p in years are calculated as in Eq. (6), resulting with the annualized replacement costs $C_{r,a}$ in (€/kW) during battery calendar life, where t_d is the discharged battery time (hours), as in Eq.(1), k is the number of replacements and η is the overall efficiency, which takes in considerable losses of charging/ discharging during the life cycle of the energy storage system.

$$C_{r,a} = \alpha \cdot \sum_{k=1}^{r}(1+i)^{-kp} \cdot \frac{C_r \cdot t_d}{\eta} \quad (6)$$

Disposal and replacement costs C_{dr} in €/kW are annualized with the interest rate i for battery lifetime period T. These costs are rather omitted in storage costs calculations, but they are included in this costs calculation.

$$C_{dr,a} = C_{dr} \cdot \frac{i}{(1+i)^T - 1} \tag{7}$$

Given Equation (2), the life cycle costs of the energy storage system when divided by full load hours are equal to the Levelized cost of electricity C_{lcoe} (€/kWh) that is discharged when the energy storage system is operating:

$$C_{lcoe} = \frac{C_{lc}}{FLH} \tag{8}$$

Given research on storage technologies from a technical viewpoint in Chapter 2.3, shows technical maturity and possible applications for storage grid integration with higher shares of renewable energy sources. Nonetheless, the main indicator for the profitability of projects is economic assessment. All studies in recent years that consider cost calculations use a method of Levelized cost of storage (Klumpp, 2016), (Rahman *et al.*, 2020), (Mostafa *et al.*, 2020) and (Mayyas *et al.*, 2022). The levelized cost of storage considers all technical and economic parameters for utilizing the storage system, including costs for charging the system. 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 LCOS is reduced. Assumptions are usually based on several cycles, hence comparison of technologies can differ. The levelized cost of storage C_{lcos} (€/kWh) is the internal average price at which electricity can be sold for the investment's net present value to be zero (Schmidt *et al.*, 2019), as in the next equation:

$$C_{lcos} = \frac{C_{lcoe} + P_{el}}{\eta} = \frac{C_{lc}}{FLH \cdot \eta} + \frac{P_{el}}{\eta} \tag{9}$$

The sum of the Levelized cost of electricity C_{lcoe} and the electricity market price P_{el} (€/kWh) for the assumed full load hours, is divided by the energy storage system's overall efficiency η. The efficiency factor represents the efficiency of the input and output of the energy storage system, which shows that $\frac{P_{el}}{\eta}$ are costs of charging the storage system from the grid. This method allows for the analysis of energy storage economics for the Western Balkan study case as shown in the following chapters.

3.4 Study case

Western Balkan is a region in southeast Europe, referred to by the EU as WB6 with the next contracting parties of the Energy Community: Albania, Bosnia and Herzegovina, Kosovo, Montenegro, North Macedonia, and Serbia. Only Albania among these countries has 100% renewable generation of electricity, while others are still highly dependent on fossil energy sources (Fig.3.1). All countries are interconnected and have high potential in wind and solar renewables (Balkan Energy Prospect, 2023), but hydro is still dominant. This is due to the historic installments of hydro and thermal powerplants, used together allowing flexibility and security of the electricity supply. The total demand of 70.4 TWh in the WB6 from 2021., is covered by hydro/thermal generation with only 3% of generation from other renewables (Fig.3.2). Besides hydro generation there is a mix of wind, solar, and biofuels, which is expected to increase in the future with the implementation of the measures taken for reaching proposed targets from NECPs.

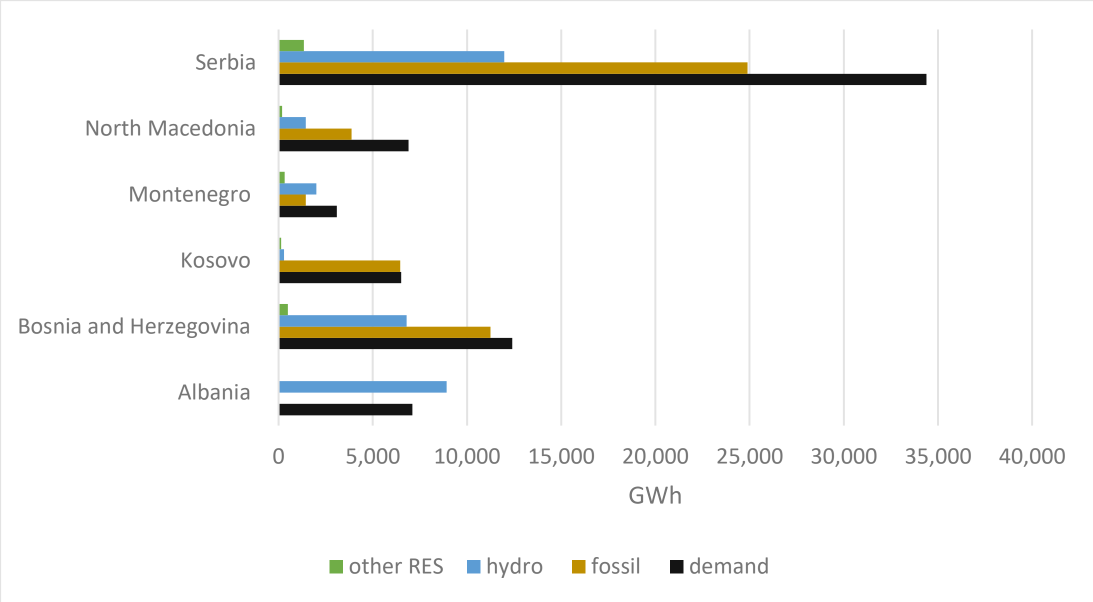

Fig. 3.1 Electricity consumption and electricity generation by source in the Western Balkan countries in 2021. (IEA, 2023)

In recent years, investment in renewable energy sources has increased with a total of 9.5 GWs of installed capacity from renewables in 2021. (Fig. 3.3), as indicated by the commitments from the signed agreements such as the Paris Agreement, Green Deal, and Sofia Declaration. All documents impose a significant increase in renewables as well as phasing out thermal power plants by 2050., which will also be accelerated with the imposition of the Carbon Border Adjustment Mechanism (CBAM).

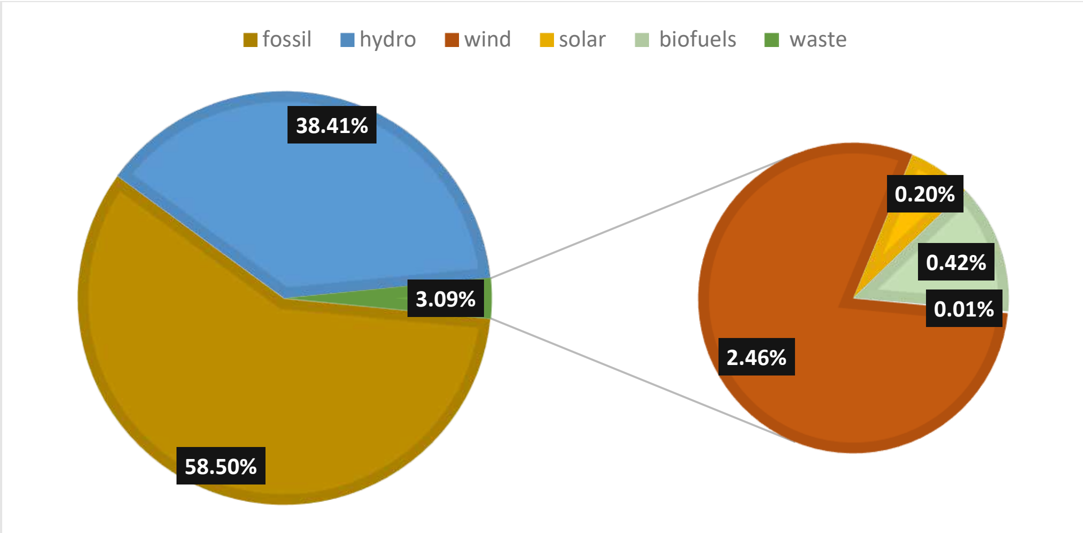

Fig. 3.2 Cumulative generation of electricity by source in the Western Balkans in 2021. (IEA, 2023)

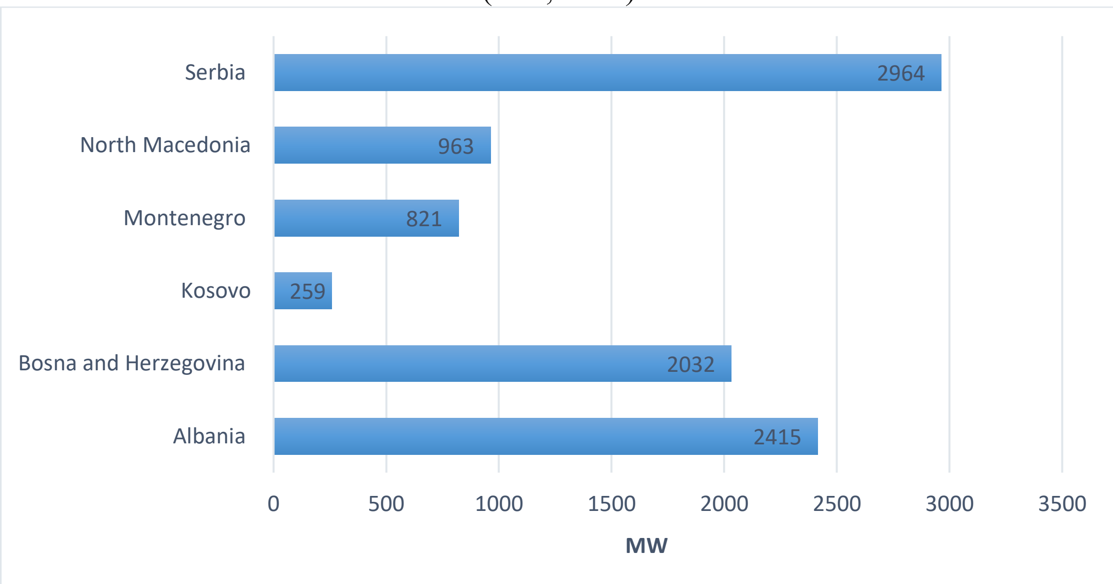

Fig. 3.3 Installed capacity of renewables in 2021. in the Western Balkan (IRENA, 2022)

The energy storage systems in the WB6 are scarce (Fig. 3.4.), with the 1 GW capacity of the two operational pumped hydro power plants in Serbia and Bosnia and Herzegovina (Table 4).

Table 4 Installed PHS in the Western Balkans, (Global Energy Storage Database, 2020)

Country	Project name	Location	Technology	Capacity output MW	Status
Bosnia and Herzegovina	PHS Čapljina	Čapljina, Svitava	Open-loop pumped hydro storage	420	Operational
Serbia	PHS Bajina Bašta	Perućac Zlatibor	Open-loop pumped hydro storage	614	Operational

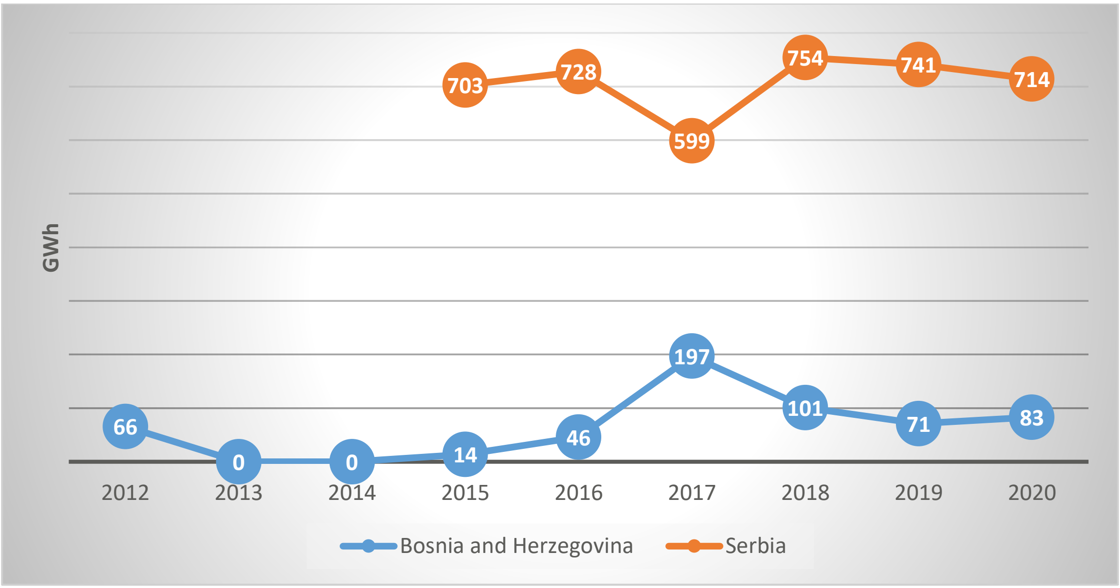

Fig. 3.4 Pumped hydro in GWh over the years in the Western Balkan, (IRENA, 2022)

Western Balkan countries signed a Memorandum of Understanding (MoU) in 2016., as a commitment towards establishing a regional electricity market that is expected to be integrated into the pan-European one (MoU, 2016). Currently, there is only one functional day-ahead market, that is Serbian Energy Exchange (SEEPEX), with soon-to-be-established Albanian Power Exchange (ALPEX), MEPX in Montenegro, and MEMO in North Macedonia (Energy Transition Tracker, 2022). Hence, for the study case's economic assessment of the energy storage systems, a HUPX is used as a liquid and representative electricity exchange that depicts the conditions of the electricity trade in the Western Balkan. As for the comparison to the other electricity markets, and since Austria is used as a comparable case in the further research of the thesis, an analysis is conducted for EXAA.

3.5 Results

A detailed cost-effectiveness analysis of selected technologies: PHS, Li-ion, Pb, NaS, and Ni-Cd allows for a comparison of the large-scale storage systems for electricity and their integration in the electricity markets. The selected electrochemical energy storage systems have a longer duration time and are dominantly used for electricity arbitrage, unlike lithium-ion batteries that have a medium duration time, but as their production has been rising, and given their high number of cycles, they are considered in the cost evaluation as well. Data for cost calculation of bulk energy storage systems are presented in Table 5 (Zakeri and Syri, 2015). The main difference between these technologies is that pumped hydro energy storage systems have the lowest energy-related costs and zero replacement costs, but they demand specific construction and hydro conditions. Contrarly, batteries do not require specific geographic areas, and have fast response time, but when used as large-scale storage systems, they have higher energy-related costs. When comparing PHS and BESS, environmental constraints are also subject to discussion, since batteries dispose toxic materials, and eventually need replacement.

Table 5 Data for the cost calculation of large-scale energy storage systems (Zakeri and Syri, 2015).

Cost	PHS	Pb	NaS	Ni-Cd	Li-ion
C_{pcs} (€/kW)	513	378	366	239	463
C_{bop} (€/kW)	15	87	-	-	-
C_{sto} (€/kWh)	68	618	298	780	795
$C_{f,a}$ Fixed O&M (€/kW-yr)	4.6	3.4	3.6	11	6.9
$C_{v,a}$ Variable O&M (€/MWh)	0.22	0.37	1.8	-	2.1
$C_{r,a}$ 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

Considering the assumption, that all technologies from Table 5 have the same discharge time of eight hours, the total capital costs are calculated based on Eq.(1) and shown in Fig. 3.5 and Fig.3.6. The lowest total capital costs of 1072 €/kW has PHS, followed by total capital costs of 2750 €/kW for sodium-sulfur, lead-acid with 5409 €/kW, nickel-cadmium 6479 €/kW and the most expensive investment costs for large storage systems of 6823 €/kW are for lithium-ion.

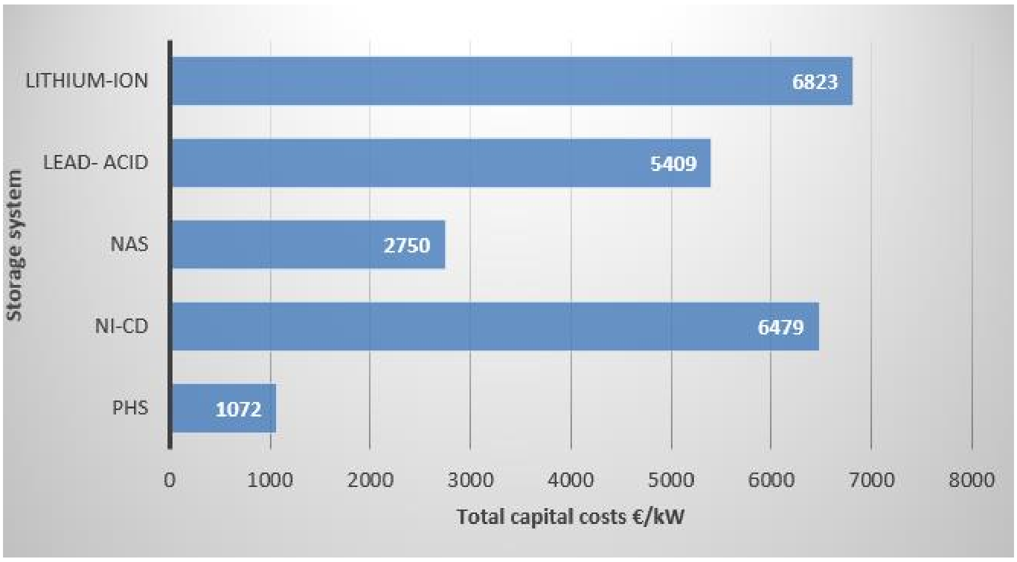

Fig. 3.5 Comparison of the investment costs for PHS and large-scale BESS, expressed in €/kW

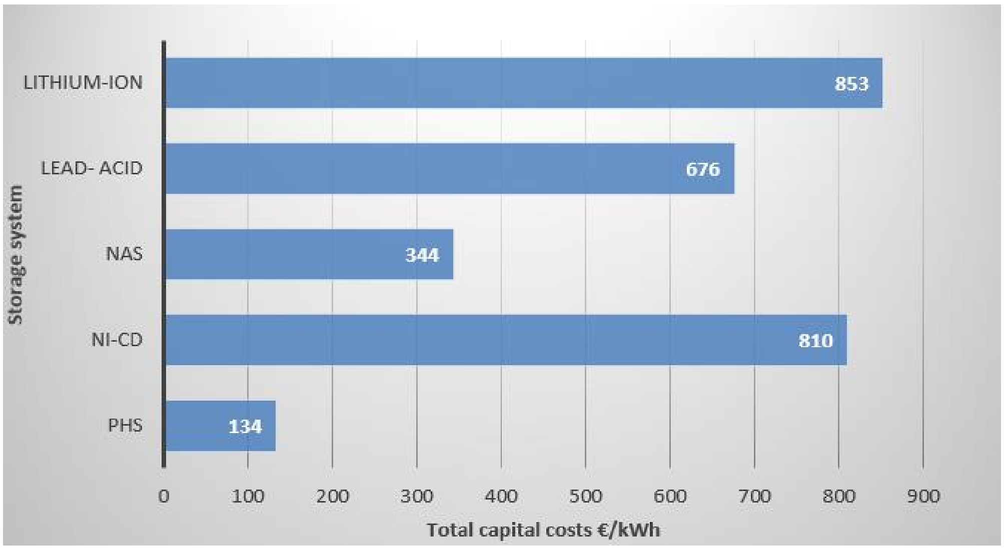

Fig. 3.6 Comparison of the investment costs for PHS and large-scale BESS given the 8-hour discharged time, expressed in €/kWh

Calendar life for PHS is 50 years, lead-acid and lithium-ion 10, NaS 17, and Ni-Cd 15 years, hence analysis of the annualized capital costs as in Eq. (3) and Eq.(4) provide more details of the ESS feasibility (Fig. 3.7).

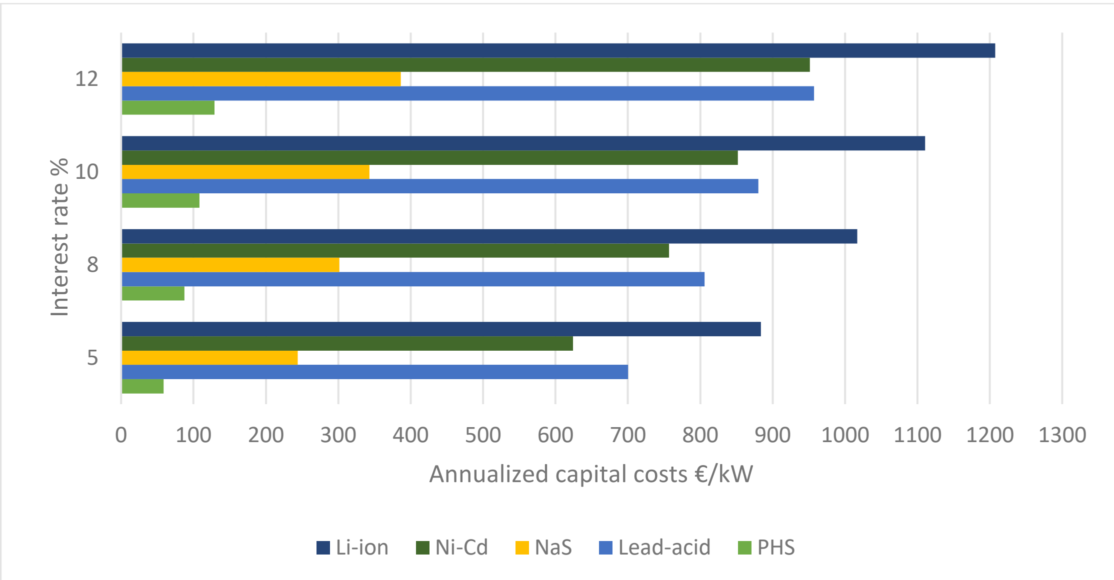

Fig. 3.7 Comparison of the annualized capital costs of the ESS, for different interest rate in the capital recovery factor calculation

Given the Eq.(2) life cycle costs are presented in Fig. 3.8 with different interest rates, the replacement costs from Table 5, 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, due to the unavailability of the data from the manufacturers. Full load hours for variable and maintenance cost calculation are chosen from a range of 150 to 4000 hours, taking into consideration an average number of cycles for bulk energy systems ranging from 250-300 per year (Global Energy Storage Database, 2020).

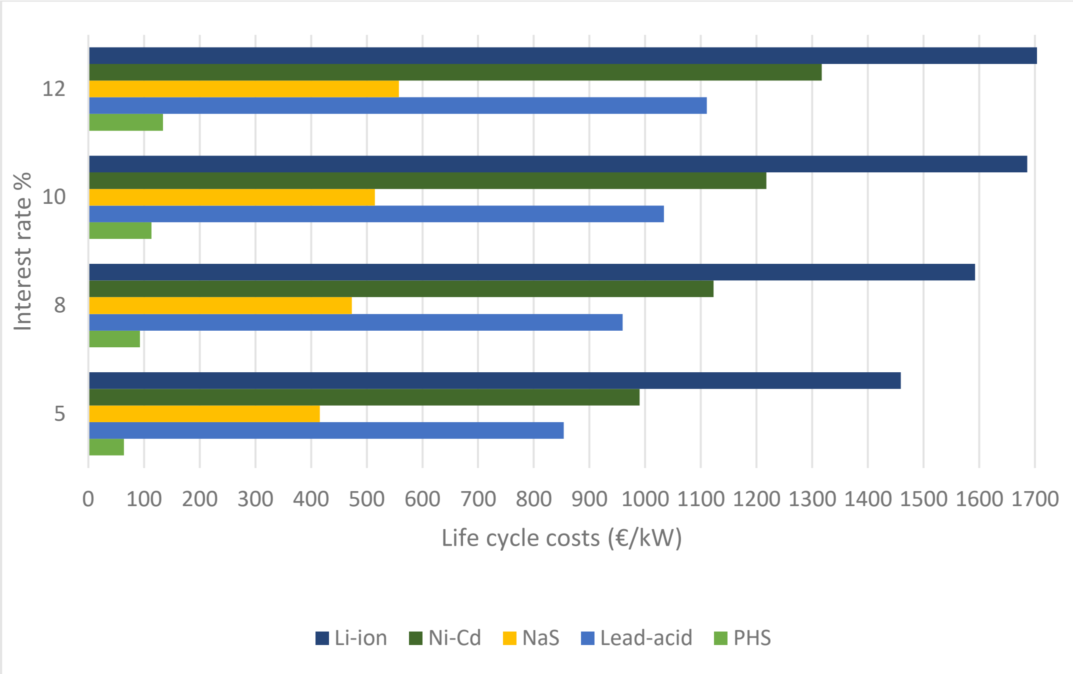

Fig. 3.8 Life cycle costs for storage systems concerning different capital recovery factors

Levelized cost of electricity and the LCOS are calculated with the number of annual hours of operating storage, i.e. full load hours (see Eq. (8), Eq. (9)). The Levelized costs of electricity from operating analyzed storage systems in one year given the interest rate of 10% are illustrated in Fig. 3.9. As interest rate impacts the life cycle cost of PHS more because of a higher lifetime, the assumption of a higher interest rate is chosen, to analyze the costs when the conditions are at the upper level of the range (i.e. maximum cycles, maximum discharge hours from batteries, and higher interest rate, and lower efficiency). With the lower full load hours, costs are increasing, indicating that energy storage systems in the electricity market should be optimally utilized not just for their size and efficiency, but as well as to their operational hours. The results follow the same order as investment costs Fig. 3.5., highlighting the impact of the initial costs of energy storage technology.

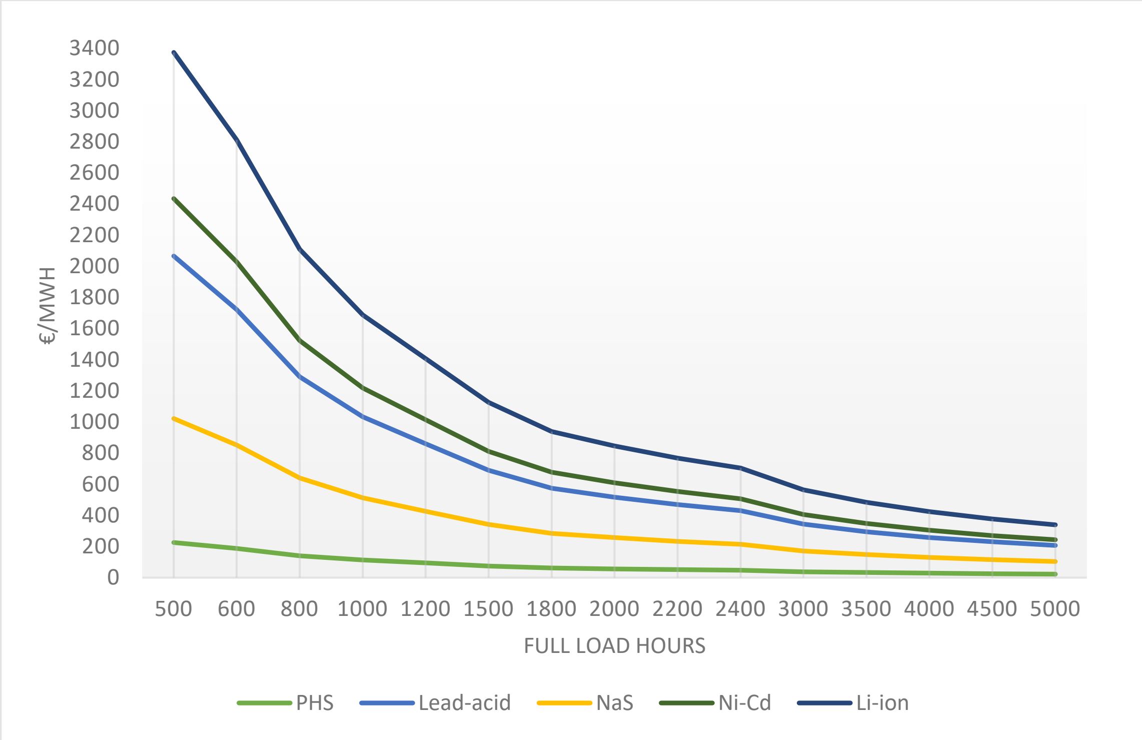

Fig. 3.9 Levelized costs of electricity delivered by different energy storage systems

Analyzing life cycle costs and full load hours isn't enough, since electricity market prices influence overall costs of storage systems. This analysis takes into consideration market-specific factors and calculates the LCOS considering electricity prices from HUPX and EXAA (Fig.3.10).

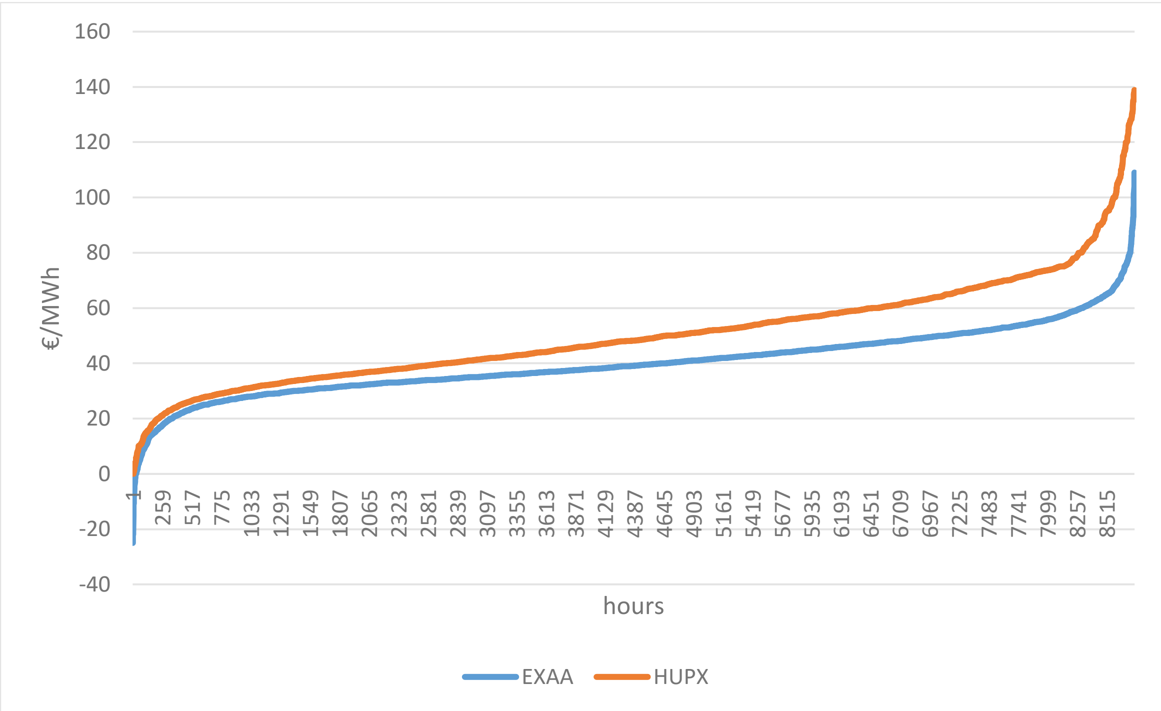

Fig. 3.10 Price spread of the electricity prices in the day-ahead EXAA and HUPX electricity markets in 2019.

Electricity market prices in HUPX are higher than in EXAA, given the differences in the energy systems of Western Balkan countries and Austria. Hence, LCOS shows the impacts of different markets in which the energy storage system will be integrated. Contrary to the LCOE, which only considers technical parameters when employed in the analysis of the generation technologies, LCOS calculation reflects the effects of electricity markets, thus the feasibility of energy storage systems will depend on the market conditions in the analyzed energy systems.

Levelized storage costs represent the full amount of energy a storage system can hold and discharge over its lifetime. These results confirm the cost-effectiveness of pumped hydro storage systems, followed by NaS batteries and Lead-acid batteries (Fig.3.11). If a maximum number of cycles is considered for comparison of LCOS for different technologies, with the assumption of the same 8 hours of discharge time, this equals to 2400 full load hours, while the minimum overall efficiency is assumed. Results, given the interest rate of 10% and considering the costs from price spreads in the HUPX electricity market for 2400 full load hours, are the lowest for PHS (111 €/MWh), followed by 326 €/MWh for NaS and 659 €/MWh for lead-acid, while higher costs are 864 €/MWh for Li-ion, and 896 €/MWh for Ni-Cd. Finally the difference in the LCOS order, where Li-ion is lower than Ni-Cd, when compared to the previously calculated investment costs and LCOE, is due to the higher efficiency of the Li-ion batteries (see Eq.(9), Table 5).

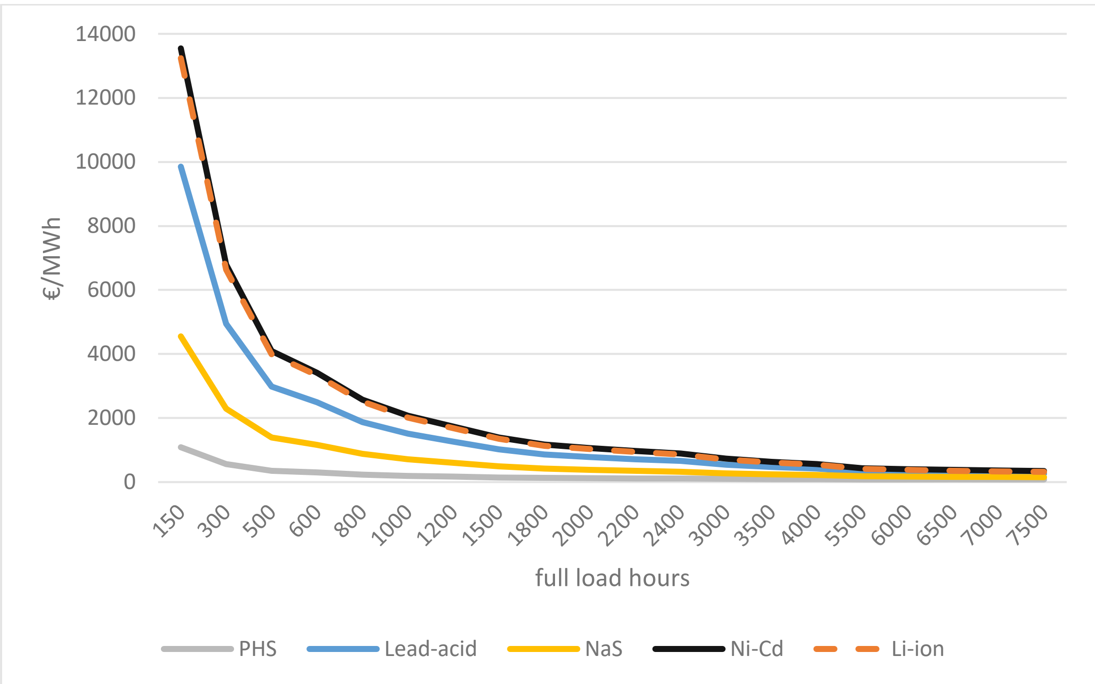

Fig. 3.11 Levelized costs of energy storage given the price spread from the day-ahead HUPX market in 2019.

The efficiency of Li-ion is the highest among other analyzed storage technologies, reflecting the current state of the accelerated technology development and research interest in Li-ion. Regardless of the fact that this technology is used in many electric appliances and for different applications, especially in the transportation sector with the rising electric vehicle production, the cost-effectiveness of Li-ion energy storage systems in the electricity markets is well behind other electrochemical storage. These findings, together with the shortage of Li-ion materials, provide insights into the future development of energy storage systems, as there is an inevitable need for progress in the development of other technologies and their materials. To compare the HUPX electricity market price spread to the EXAA electricity market price spread in 2019., the same calculation resulted in a slightly lower LCOS: 105 €/MWh for PHS, followed by 321 €/MWh for NaS and 653 €/MWh for lead-acid, while costs for Li-ion are 860 €/MWh and 890 €/MWh for Ni-Cd. The results show the differences in the LCOS calculation, given the price spreads and full load hours as signals for energy storage economics. Electricity market prices have been subject to significant changes since 2019. until the conducted research is finished, hence an additional calculation of the Levelized storage costs is given. Since 2019., price spreads in the electricity markets have changed from falling prices in 2020. with the Coronavirus disease in 2019, to high spikes later in 2021. during the energy crisis. The scarcity of gas supply impacted electricity market conditions with different fluctuations, eventually with an average increase of 112% (Fig. 3.12). Given the new circumstances and higher electricity market prices, additional results regarding storage costs are analyzed.

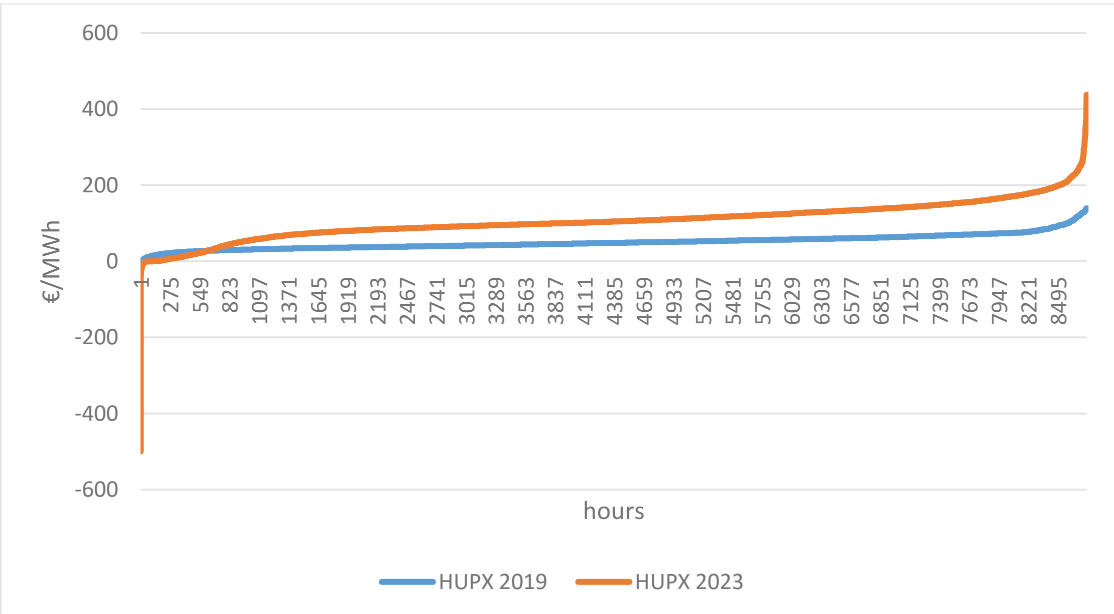

Fig. 3.12 Price spread of the electricity prices in the day-ahead HUPX electricity market in 2019 compared to 2023.

Analysis shows that the difference in the Levelized storage costs will depend on the total investment costs, full load hours and efficiency, and later electricity market prices. With the higher efficiency and full load hours, the LCOS will be lower, hence even if the average electricity market prices are higher, as in the HUPX electricity market in 2023., the LCOS remain almost the same until 2000 full load hours (Fig.3.13). The total percentage of change in LCOS for PHS for 2400 hours is 36.47%, while for batteries percentage ranges from 3.64% to 11.07% (Fig.3.14).

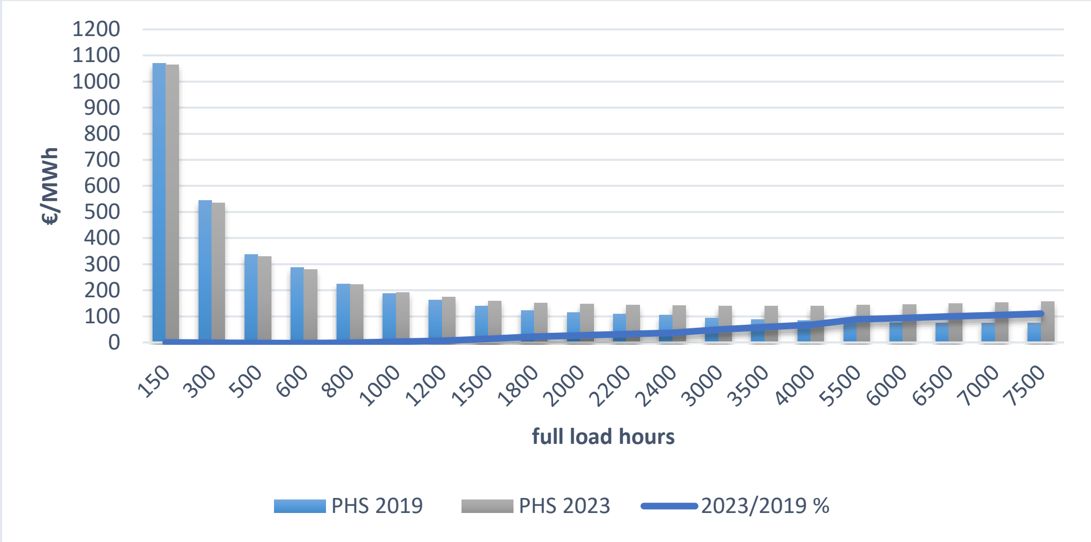

Fig. 3.13 Comparison of the Levelized storage costs for PHS for HUPX electricity market price spread in 2019. and in 2023.

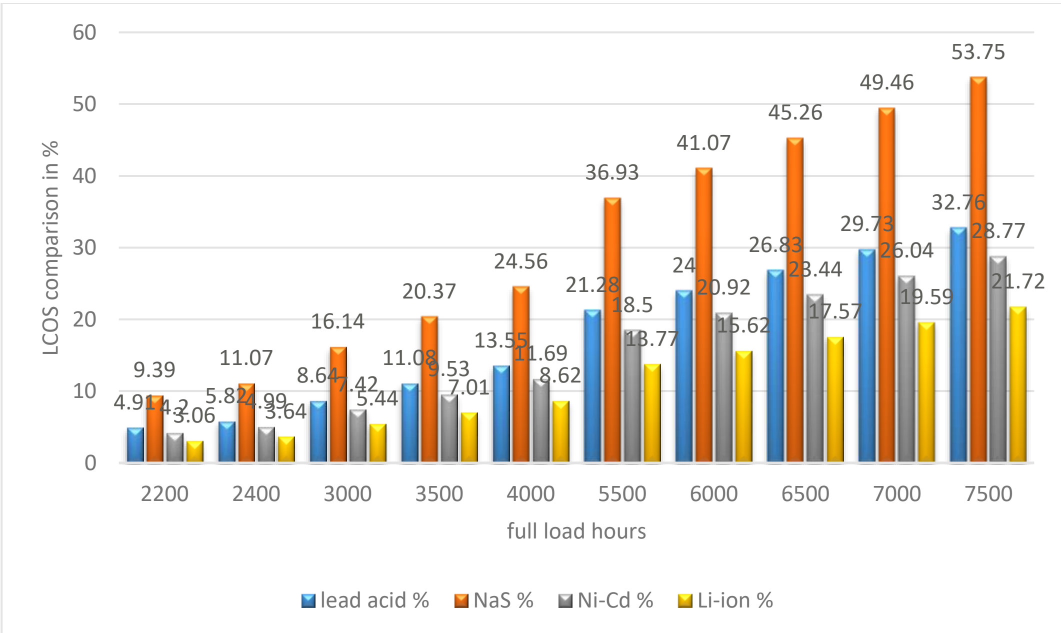

Fig. 3.14 Percentage difference in the Levelized storage costs for batteries given the HUPX electricity market prices in 2019. and 2023.

If the electricity market prices from Eq.(9) are lower, LCOS will be lower, but there is a more important role of the technical characteristics as efficiency of storage, and number of annual cycles given the discharge time, that represent full load hours. Hence, energy storage systems cannot be compared to their total capital costs or capacity costs, but to the costs that impact the final utilization of the energy storage systems over their technical characteristics, and their calendar life. The proposed analysis gives a valuable comparison of storage costs, indicating that the ultimate profitability of the energy storage systems as integrated parts of the power grids, depends on the energy storage application. One energy storage system will prove profitable over the other if they are optimally used for the application where it can provide a maximum of its technical characteristics. Over the years, energy storage systems, mostly PHS have been used in arbitrage, but recently other technologies have been followed, hence the optimization model with the dispatching strategy of PHS and Li-ion battery is developed in the next Chapter.

4 The economic benefits of pumped hydro and lithium-ion storage: Austria vs Bosnia and Herzegovina

This Chapter presents an economic profitability analysis of PHS and Li-ion energy storage systems, as in the research article by (Topalović, Haas and Sayer, 2024). Energy storage profits are analyzed using the mixed-integer optimization model with the subtraction of total storage costs, given the two different energy systems as study cases: one with high generation of renewables and the other with high shares of fossil generation.

4.1 State of the art

The economics of energy storage systems in the electricity market are still analyzed in the recent literature in terms of profitability. The summarized literature regarding the economics of energy storage systems and their integration into the electricity markets is given in Table 6. As predicted by (He *et al.*, 2020), the annual profit of arbitraging electrochemical energy storage systems would decrease due to performance degradation. Other research on energy arbitrage of batteries in most European electricity markets as analyzed by (Hu, Armada and Jesús Sánchez, 2022), proves unprofitability. Considering renewable energy sources development, research so far shows a connection between renewables and energy storage systems in the electricity markets (Schill and Zerrahn, 2018), (Haas et al., 2022), (Mallapragada, Sepulveda and Jenkins, 2020). There is a considerable connection between renewable generation development, the electricity market, and storage systems for electricity. For arbitraging electricity market prices with energy storage dispatch, mixed-integer linear programming is used for the study case of Italy by (Frate, Ferrari and Desideri, 2019) where predictions of energy storage viability are given only if the average maximum daily energy prices increase from 150 €/MWh. This research emphasizes that energy storage grid profitability would be achieved through the energy storage costs decrease or increase of electricity market prices. The conducted model finds optimal revenue first, and then compares it to the annualized costs of storage. A linear optimization model, as in (McConnell, Forcey and Sandiford, 2015), is constrained by the storage power capacity and the hours of storage, also excluding costs in the model. The conclusions of the research show that storage systems profitability depends on extreme prices rather than round trip-efficiency. How the electricity market outlook impacts energy storage systems development is researched by (Spodniak, Bertsch and Devine, 2020). Optimization is also conducted with a linear model, where the ultimate profitability isn't analyzed but the effects of the electricity market designs on energy storage. Hence, Net Present Value (NPV) is used for the calculation of the discounted costs. Similarly, the economic analysis of different battery storage systems by (Gaspar, Castro and Sousa, 2021) and (Núñez, Canca and Arcos-Vargas, 2022) is conducted using the NPV along with the Internal Rate of Return (IRR), which is a discounted rate for the net present value of the investment to be zero. The analysis of the battery's economic feasibility is based on the extra profit that is generated due to the battery storage implementation. The storage profitability for price arbitrage by (Bradbury, Pratson and Patiño-Echeverri, 2014) is modeled also with the IRR. Firstly, a linear optimization for arbitraging storage profits is calculated considering storage capacity constraints, only to be later used in the nonlinear equation of IRR, as the total revenue that the energy storage would provide over the lifetime. Meanwhile, an analysis by (McPherson *et al.*, 2020) shows that the storage profits depend on price profiles in each market, but it considers only storage that has been selected for the dispatch without further cost analysis of such systems. Different modeling techniques for energy storage, among them the price-taker approach, are given in detail by (Sioshansi *et al.*, 2022). In the research by (Mercier, Olivier and De Jaeger, 2023) the price-taker approach is conducted using mixed-integer linear programming, but the model is solved for varying round-trip efficiencies and storage durations. The agent-based model by (Mason, Qadrdan and Jenkins, 2021) examines large-scale battery integration by 2050., but results indicate that the costs of batteries are still the biggest issue for economic utilization in the electricity markets.

Table 6 Literature on the economics of energy storage systems in electricity markets

Reference	Storage technology	Electricity market	Modeling technique	Cost calculation	Storage duration h
(Bradbury, Pratson and Patiño-Echeverri, 2014)	PHS, CAES, FW, CAP, EDLC, SMES, batteries	USA	Linear Optimization Programing	IRR	1-4

(Frate, Ferrari and Desideri, 2019)	PHS, CAES, LAES, PTES, NaS, flow batteries	Italy	MILP	power and capacity costs	4
(Gaspar, Castro and Sousa, 2021)	batteries	Iberian wholesale electricity market	Long Short-Term Memory	NPV, IRR	n/a
(He et al., 2020)	batteries	California	short-term optimization	fixed costs	4
(Hu, Armada and Jesús Sánchez, 2022)	batteries	Europe	payoff-model	OPEX,IRR	1.2, 2, 4
(Lamp et al., 2022)	large- scale battery	California	price- taker	n/a	0.5-7
(Mallapragada, Sepulveda and Jenkins, 2020)	Li-ion	USA	CEM	CAPEX	4
(Mason et al., 2021)	large- scale battery	Great Britain	agent-based modeling	NPV	n/a
(McConnell, Forcey and Sandiford, 2015)	PHS	South Australia	Linear Program	LCOC	5
(McPherson et al., 2020)	n/a	n/a	price- taker	production cost model	2
(Mercier et al., 2023)	n/a	bidding zone in EU-28	MILP	n/a	1-10
(Nunez et al., 2022)	Li-ion	EU	MILP	NPV, IRR	n/a
(Schill and Zerrahn, 2018)	batteries, PHS, P2G	Germany	DIETER	fixed, marginal	4
Spodniak, Bertsch and Devine, 2020).	n/a	Germany, UK, Nordic	Linear Optimization Programing	IRR	1-13
(Williams et al., 2022)	n/a	Great Britain	price- taker	n/a	n/a

Note: PTES represents pumped thermal electricity storage that stores electricity as thermal energy and later converts it electricity; LCOC represents the annual revenue required per kW of capacity for the economical viability of the technology

All of the mentioned models focus on calculating revenues first, then on comparing them to the costs of electricity storage and later calculating the internal rate of return. This approach doesn't allow for an ultimate optimization strategy. Hence, the previous research about electricity storage profitability when used as price arbitrage, especially modeled with a price-taker approach as by (Williams and Green, 2022) and (Lamp and Samano, 2022), is extended with the comprehensive calculation of the optimal profits when different full load hours of energy storage systems are applied. The modeling optimization approach in the thesis considers all the impacting factors on the energy storage profitability other than electricity market prices (as analyzed before by (Frate, Ferrari and Desideri, 2019), (McConnell, Forcey and Sandiford, 2015), and (Spodniak, Bertsch and Devine, 2020)), allowing for the calculation of storage profits depending on the different full load hours with costs included.

4.2 Core objective

The goal of this analysis is the calculation of the optimal profits using a mixed-integer linear optimization method. Study cases for the analysis provide insights into the electricity storage economic viability of the Western Balkan country, highly dependent on fossil power plants, and the country such as Austria which has high shares of renewable generation in the energy portfolio. A comparison of both cases is valuable for deriving conclusions about energy storage development and the impact of price arbitrage in different electricity markets, and it is contributes to the previous research on energy storage profitability.

4.3 Method of approach

Profits from energy storage systems arbitrage are gained by buying the electricity from the market when prices are lower and selling it from the storage when prices are higher. An operational optimization strategy with the objective to maximize the profits of energy storage arbitrage is presented in this Chapter. The model is subject to energy storage capacity constraints. Electricity market input data are in the hourly resolution from the period of 1.1.2011. to 31.12.2019., EXAA (study case Austria) and HUPX (electricity exchange used for Bosnia and Herzegovina's wholesale market and WB6). The generic price-taking approach gives a maximum of the objective function without representing balancing equations of the power systems with the assumption that energy storage is small to have an impact on the electricity market and power system. The ultimate energy storage profitability, based on the maximization of profits $\prod_t$ with the total costs of operating energy storage for one year C_t (in €) being subtracted from the revenues R_t, is defined in the next equations:

$$max \prod_t = \sum R_t - C_t \tag{10}$$

Revenues R_t in € are defined as:

$$\sum R_t = \sum_{t=1}^{N} (P_{Ht} \cdot D_t \cdot \eta - P_{Lt} \cdot D_t) \tag{11},$$

Where:

P_{Ht} .... selling (high) price of electricity in the market at hour *t* in €/MWh,

D_t .... the demand of energy in MWh at hour *t*,

η ....storage efficiency (round-trip efficiency of storage device),

P_{Lt}...........buying (low) price of electricity in the market at hour *t* in €/MWh,

N.............hours in a year, assuming there isn't any repair or overhaul for the energy system

Considering other constraints besides technical, the model can be expanded. Energy storage power limitations are presented in the next equations:

$$0 \leq p_t^c \leq p^{c,max}, \forall_t \tag{12}$$

$$0 \leq p_t^d \leq p^{d,max} \ , \forall_t \tag{13}$$

$$\sigma^{min} \leq \sigma_t \leq \sigma^{max} \ , \forall_t \tag{14}$$

$$\sigma_t = \sigma_{t-1} + (p_t^c - p_t^d) \cdot \Delta t \ \ , \forall_t \tag{15},$$

Where:

p_t^c...........charging power capacity at time *t* in MW

p_t^d ....discharging power capacity at time *t* in MW

$p^{c,max}$......maximum charging power capacity in MW

$p^{d,max}$ ......maximum discharge power capacity in MW

σ_t..........stored energy (state of energy storage system has already used) in MWh,

Δt.......... time difference in hours

With these constraints and total costs of operating energy storage, i.e. Levelized costs of electricity C_{lcoe} as in Eq. (1-8), but in €/MWh, Eq. (10) is modified:

$$max \prod_t = \sum_{t=1}^{N}(P_{Ht} \cdot p_t^d \cdot \eta - P_{Lt} \cdot p_t^c) \cdot \Delta t - C_{lcoe} \cdot \sum_t p_t^d \quad (16)$$

The model assumes full load hours for the calculation of the Levelized costs of electricity, thus an input parameter FLH is defined. As an energy storage system cannot discharge and charge at the same time, a number of times energy storage discharges is defined with the binary variable z(t) within the lower and upper power limit of energy storage as:

$$0 \leq p_t^d \leq p^{d,max} \cdot z(t) \quad (17)$$

$$\sum_t z(t) = FLH \quad (18)$$

This optimization model is the extension of the previous cost analysis in Chapter 3, where detailed input parameters from Table 7 are described. Assumptions regarding energy storage technologies are used for the purpose of deriving price arbitrage conclusions as opposed to the real market volume of energy storage. Utility-level storage technologies are analyzed with the capacity of eight discharging hours for PHS and two for Li-ion storage.

Table 7 Input data for the investment, operation and maintenance, and replacement costs calculation (Topalović et al., 2022)

Costs	PHS	Li-ion
Calendar life T (years)	50	10
Overall efficiency η (%)	80	85
Discharge time t_d (hours)	8	2
Interest rate i (%)	5	5
Capital recovery factor α	0.0548	0.1295
Replacement period p (years)	-	5
C_{pcs} (€/kW) Power conversion costs	513	463
C_{bop} (€/kW) Balance of plant costs	15	-
C_{sto} (€/kWh) Storage costs related to energy capacity	68	795
$C_{f,a}$ Fixed O&M (€/kW-yr)	4.6	7.9
$C_{v,a}$ Variable O&M (€/MWh)	0.22	2.1

C_r Replacement costs in (€/kWh)	-	369
C_{tot}(€/kW) Total capital costs /Investment costs	1072	2053
Cr, a (€/kW) Annualized replacement costs	0	157
C_{lcoe} (€/MWh) for 500 FLH	127	862
C_{lcoe} (€/MWh) for 1000 FLH	64	432
C_{lcoe} (€/MWh) for 2000 FLH	32	217

The model calculates the profits of the companies with the described energy storage technologies and historic electricity prices from 2011 to 2019 in two different electricity markets and for different full load hours. The analysis is conducted assuming the same charging and discharging power capacity with a lower limitation of 1 MW and a maximum of 100 MW for PHS, and 1 kW minimum to 500 kW maximum for Li-ion storage. The maximum state of charge declared as MWh/MW ratio is assumed for both storage technologies at the beginning and the end of the dispatching process for each analyzed year. The depth of discharge for a Li-ion battery is 80%, and overall efficiency is 85%, while efficiency for the PHS is 80%. The method considers only revenue streams from the arbitrage storage in the wholesale markets while neglecting other possibilities. The storage systems can enhance their revenues from price arbitrage by providing additional flexibility as ancillary services or being a part of the capacity markets. This revenue stacking, when profits are gained from the multiple storage applications represents the storage mechanism, as opposed to the possible revenue cannibalization when the facility (in this case storage) during the period makes a significant impact on the markets and decreases price spreads, eventually leading to lower revenues and changes in the patterns of peak and off-peak prices. As the current storage capacity integrated into the markets isn't significant, the price-taker approach is justified.

4.4 Study case

Effects of different electricity markets for integration of energy storage systems, are analyzed with the case of Austria, and a Western Balkan country, Bosnia and Herzegovina. Because of its favorable geographical position in the center of Europe, Austria has substantial technical interconnection capacity with neighboring countries. Cross-border interconnections with the Czech Republic, Hungary, Slovenia, Switzerland, Germany, and Italy (Fig.4.1), indicate a strong interest in improving the integration and taking part in an integrated wholesale market (e-control, 2023). Liberalization of the electricity market in Austria finished in 2001. with the model of Independent System Operators and Independent Transmission Operators, dividing the market into generators, Transmission System Operators, Distribution System Operators, and suppliers. The balance group model has been implemented, while e-control represents Austrian regulation authority (CMS, 2023). Austria has been using its geographical advantages for the utilization of pumped hydro storage power plants since the beginning of technological developments in the early 19th century. Currently, there are eighteen operational pumped hydropower plants with an average rated power of 246 MW (Global Energy Storage Database, 2020*)*. In 2021. Austria has generated 2,7 TWh of electricity through pumped hydropower plants, which is 9% of the total electricity generation (ENTSO-E, 2023). Regarding electrochemical energy storage in Austria, a Zinc Iron Flow Battery, with a rated power of 64 kW, has been developed by a private company in Frankenburg in late 2013. The goal of the battery is to maximize the solar reserves by providing onsite renewable shifting and renewable capacity firming which is a significant improvement for the Austrian community.

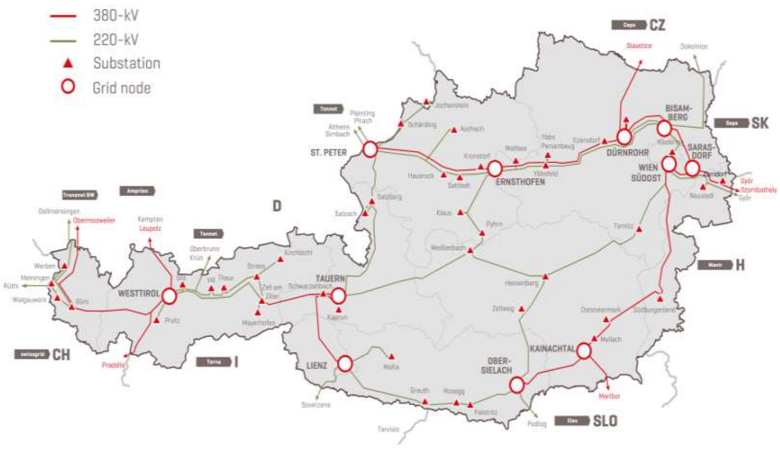

Fig. 4.1 Austrian transmission grid scheme (APG, 2023)

In comparison to such a strong deployment of renewable energy sources, a study case of a Western Balkan country with a history of fossil dominance, Bosnia and Herzegovina, is chosen. The conducted method of approach can be applied to any study case, and the compared electricity markets are representative of Austria and Western Balkans, hence the effects of energy storage systems in analyzed countries provide additional insights into the economics of storage systems for electricity.

In addition to Austria, Bosnia and Herzegovina has valuable interconnections and competitive advantages with an energy generation mix consisting of thermal and hydropower plants. The energy system is divided between three utility state-owned electric power generation and distribution companies (in the text: utility companies): *JP Elektroprivreda d.d.- Sarajevo*, *Elektroprivreda Republike Srpske* and *Elektroprivreda Hrvatske Zajednice Herceg Bosne*. The electricity market in the country was officially opened in 2015., but the unbundling of the power activities, a functional separation of the distribution and supply sector, hasn't been finished yet. State-owned utility companies, as the largest suppliers in the country, managed to operate on the companies' distribution lines and keep their consumers, hence retail market as formally opened, is still lacking valuable competition inside the country. Three Electricity Regulatory Commissions influence prices for households, and they are mostly dependent on the energy portfolio of the provider (Derk, 2023). As the wholesale electricity market opened, end-consumers were offered to change their suppliers, but all consumers from the category households kept their previous retail providers and continued with regulated electricity prices supply. Electricity prices for households are still below the electricity market prices due to the socioeconomic status in the country and administrative problems in implementing distinctive electricity prices for the socially vulnerable categories. This large disparity between prices for generating electricity and regulated retail electricity prices for households endangers the economic viability of utility companies. Taking into consideration that investments in renewable energy sources are expected to reach decarbonization targets by 2050., it is currently economically unsustainable to operate the described energy system. Balancing the electricity market is controlled by the Independent System Operator in Bosnia (NOSBIH) which defines a system of Ancillary Service and maintains a continuous balance of supply and demand in real-time. Because of the systematic combination of thermal and hydropower plants, the electricity industry is one of the key sectors of the country's economy. Given the generation mix in Bosnia and Herzegovina, there are possibilities for trading and exporting electricity. Regional transmission of electricity is achieved with the cross-border transmission capacity allowances with Croatia and Montenegro through the Coordinated Auction Office in Southeast Europe or bilateral auctions with Serbia (Fig. 4.2).

Fig. 4.2 Cross-border transmission lines in Bosnia and Herzegovina (NOSBIH, 2023)

4 The economic benefis of pumped hydro and lithium-ion storage: Austria vs Bosnia and Herzegovina.

Despite the high generation from hydro, accounting for 66% of the total energy generation in 2021. (Fig.4.3(a)), the Austrian power system is still dependent on fossil gas power plants. Nevertheless, moderate renewables development with wind installations covering 13% and solar 1% of total generation in 2021., Austria plans on reaching 100% renewable energy by 2030. as a decarbonization and energy efficiency strategy of the National Energy and Climate Plan (NECP, 2023). Currently, power grids are dispatched with fossil gas power plants that cover peak demand, but with further renewable generation increases, and CO_2 mitigation plans, it is expected that additional flexibility for balancing grid supply will be needed.

Natural sources of coal and hydro have secured electricity supply in Bosnia and Herzegovina, but there is potential for renewable generation from wind, solar, and biomass as well. The combination of thermal and hydropower plants has given adequate seasonal energy generation and provided additional economic activity for the country through the net export of electricity (Fig.4.3(b)). Owing to the highest shares of CO_2 emissions from the energy sector (IRENA and CPI (2020)), Bosnia and Herzegovina as a signatory to the Paris Agreement, Sofia Declaration, and Energy Community Treaty obligations, is in the process of changing its generation portfolio in the upcoming years. Recently, as part of the developing NECP, Bosnia and Herzegovina has been obliged to follow European Regulations and to put coal-fired thermal plants in an opt-out phase, eventually shutting them down by 2050. and finding a way for new investments in generation from renewable energy sources. Renewable generation in the country comes from hydropower plants with a slight improvement in shares of wind generation, but with only one pumped hydro storage power plant of 420 MW rated power. Incentives for renewable generation are coordinated by two state operators, with a feed-in tariff model, premiums, and net metering. With the solar panels' technology costs decreasing, more end-users have been researching ways to integrate roof-top solar. Because of the previous lack of legal framework in Bosnia and Herzegovina, such investments are still scarce. Net metering, prosumers, and renewable energy communities are part of the new energy law reforms. In the Federation of Bosnia and Herzegovina, net metering and net billing are recently envisaged within the new energy reforms, allowing the maximum installed power capacity up to 150 kW. In the other entity, existing law allows net metering for installations up to 50 kW, but new reforms should allow for net billing as well, as a means to increase the number of prosumers.

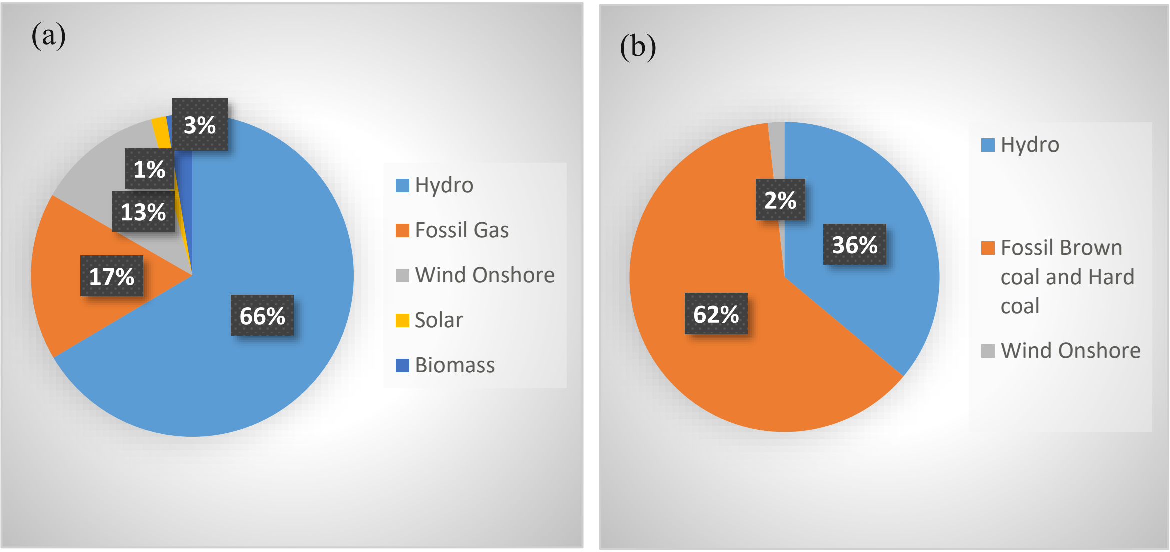

Fig. 4.3 Shares of total electricity generation per production for Austria (a) and for Bosnia and Herzegovina (b) in 2021., (ENTSO-E, 2023)

Austrian wholesale trading market has been providing trading products such as Day-Ahead, Intraday, and capacity auctions since 2001. Average electricity market prices from 2011 to 2019 range from 33 €/MWh to 53 €/MWh, with a decreasing trend for the analyzed timeframe of the optimization model (Fig. 4.4.).

Fig. 4.4 Electricity market prices over the years at EXAA

As for compared country Bosnia and Herzegovina, power exchange isn't established in the country yet, thus the transactions on the wholesale electricity market are carried out bilaterally. Hence, for the electricity market day-ahead prices, HUPX is used as referent exchange as in previously conducted cost-effectiveness analysis for Western Balkan in Chapter 3. The hourly resolution is the input parameter of the optimization model for the analyzed timeframe, while the average prices, with a range from 35 €/MWh to 55 €/MWh, are given in Fig. 4.5.

Fig. 4.5 Average yearly prices of hourly distribution at HUPX

An operational strategy and profits, that result from Equation (16), explain the relations between the electricity market prices and energy storage in addition to different full load hours and energy systems of the described study case, as it is presented in the next Chapter.

4.5 Results

The profitability analysis of selected storage systems for electricity, when used for price arbitrage in the electricity markets, is conducted with different full load hours. This allows for the analysis of the impact of energy storage costs on arbitrage profits. The model resulted in yearly arbitrage revenues, with the costs of operating analyzed energy storage systems considered.

4.5.1 Simulation setup

In the optimization analysis, calculated Levelized costs of electricity C_{lcoe} are set as scalar data and used in the objective function for each scenario. Profits are calculated based on the day-ahead market prices in hourly resolution from EXAA and HUPX. Each simulation uses around 8760 sets of data (exceptions are: 8762 in 2011, 8785 in 2012, and 8784 in 2016) which represent day-ahead market prices for each year. The objective function is constrained with the temporal variable state of charge, which is used in the energy capacity equation for limiting energy storage discharge. Iteration starts assuming a full state of charge and assuming a depth of discharge of 80% for Li-ion battery and zero for PHS. The number of full load hours that is available for the operational strategy is constrained by the binary variable z(t) [see Eq. (17), Eq.(18)]. Since large-scale energy storage systems operate around 2000 FLH, as presented in Chapter 3, the sensitivity analysis for the optimization model is done with 2000, 1000, and 500 full load hours, and the linearity of the model is saved as opposed to the calculation of the FLH. Simulation is done using GAMS 24.7.1 version on a computer with a 2.4 GHz Intel Core i3 processor and 8 GB of RAM. Programmed optimization for described study cases is finished in less than a minute.

4.5.2 Optimization results

The output of the conducted research, besides yearly profits of energy storage, is operational strategy. Using predefined full load hours, operational, replacement, and finally total costs for operating energy storage, the optimization is modeled. For both study cases, an arbitrage of the pumped hydro storage with 2000 full load hours has positive profits, while for 500 full load hours results in negative profits. Contrary, Li-ion technology shows higher total costs than arbitrage profits for all full load hours. Different trends of pumped hydro storage profits, given the study case of Austria and Bosnia and Herzegovina, follow conditions of the respecting electricity markets of the analysis (Fig.4.6), (Fig. 4.7). Beneficial to understand the relations between profits of energy storage, renewable generation and the driving factors of storage's profitability, the electricity market as a whole has to be examined. Hence, a comparison of the two study cases allows for a detailed analysis. The electricity market price spread depends on different factors such as generation portfolio, weather conditions, and merit order curve. From 2013. the merit order curve of EXAA has changed significantly. High shares of the renewables in the grids changed the relations of prices in the merit order curve, as zero marginal costs of renewables pushed higher costs of fossil generation to the right side of the curve. Consequently, high shares of renewables with lower demand managed to lower electricity market prices, but influenced Austrian market design with negative electricity prices at the time. The same happened in Germany at the European Power Exchange (EPEX) with the distinction in single prices being lower due to the market conditions influenced by the high generation of roof-top PV solar installations. Incentives for the implementation of renewables in the countries that use the HUPX market have been developing at a slower rate than in Austria, hence there is a difference in profits for Bosnia and Herzegovina when comparing the same period. Despite high shares of wind generation in Europe in 2017., leading to renewables generation reaching historically 30% of total electricity production (Jones *et al.*, 2018), price spikes occurred in both exchanges. Due to the low hydro generation in the same year, electricity market disruptions occurred impacting an increase in storage profits. Looking at the results for the Bosnia and Herzegovina study case (Fig.4.7), the difference in profits is due to the analyzed electricity exchange. A relevant electricity exchange for the Western Balkan countries, HUPX, is highly dependent on hydro generation and influenced by weather conditions, which is one of the reasons for the price difference in the electricity markets. Another reason for the higher prices of HUPX exchange is due to the energy portfolio of the Western Balkan countries, consisting of fossil power plants, which have higher marginal costs and are influenced by material costs and ore production for their operation.

The price spread in the EXAA electricity market, was between 0.03 €/kWh and 0.05 €/kWh, with an average of 0.04 €/kWh, given the analyzed timeframe and 2000 full load hours, while the range for HUPX was 0.03-0.06 €/kWh, with an average of 0.05 €/kWh. The minimum price spread that resulted in profits of energy storage arbitrage was 0.03 €/kWh in both markets in 2016. This year has been characterized by lower electricity market prices, higher shares of renewables in the grids impacting the EXAA market, and severe weather conditions impacting hydro dependent HUPX market. One of the many energy storage systems advantages is in using these spreads: buying the electricity when prices are higher and selling it when they are lower.

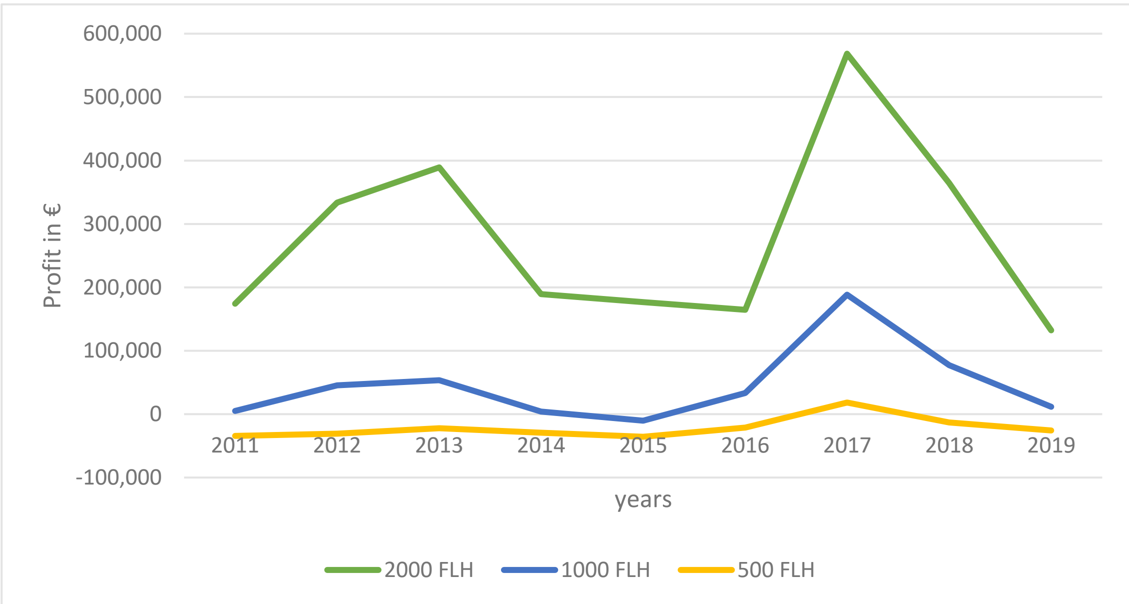

Fig. 4.6 Impact of different full load hours on pumped hydro profits given the conditions of the EXAA in the analyzed timeframe

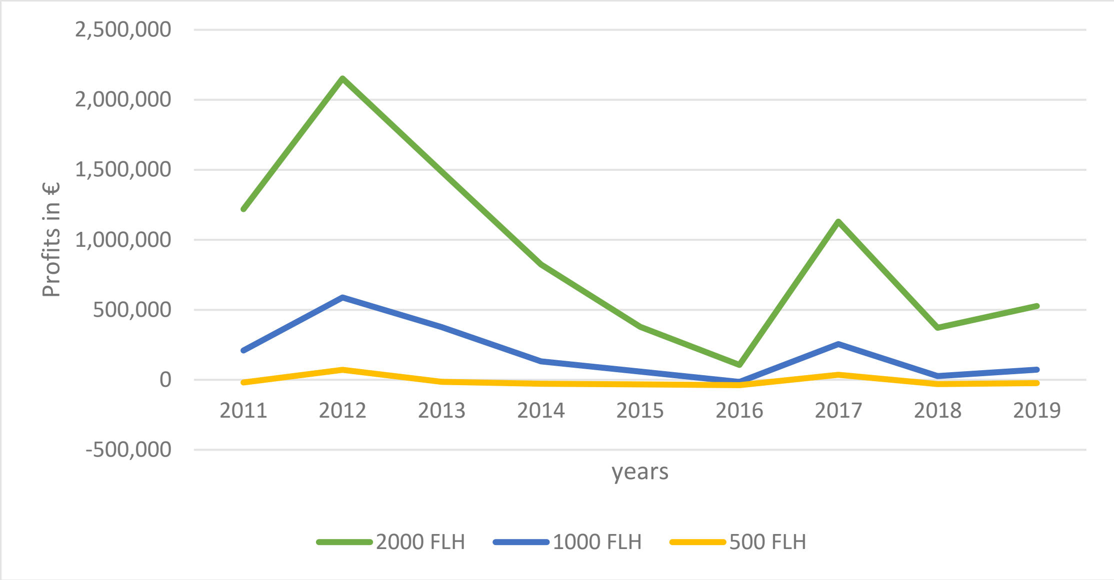

Fig. 4.7 Impact of different full load hours on pumped hydro profits given the conditions of the HUPX electricity market in the analyzed timeframe

The optimization moded provided the profits highest in 2017 and 2012 for EXAA and HUPX respectively.The results from the analysis indicate that these years had the best market conditions for arbitraging PHS. Given the data from Table 7, an optimization model resulted with the optimization strategies. A visual representation of the energy storage systems dispatch during the weeks with the highest (Fig. 4.8), (Fig . 4.9) and the lowest electricity market prices (Fig. 4.10), (Fig.4.11) for both exchanges reflect the conditions for energy storage arbitrage in these markets. The energy storage system will discharge at times of high electricity prices, and charge at times of lower electricity prices while it manages the state of energy [see Eq. (15)]. Considering the year 2017 when energy storage profits were optimal for Austria, the spread of discharging and charging electricity prices was 0.04 €/kWh (range of spread during analyzed timeframe is 0.03-0.05 €/kWh). The average discharge price was 48.82 €/MWh while the average charging price was 5.77 €/MWh. Interestingly, the highest EXAA price spread was in 2018 in the years investigated here, but the maximum profits are for the year 2017, which implies that the highest price spread isn't the main factor that impacts energy storage profits. Ultimately, it is a combination of different factors that indicate energy storage arbitrage potential: price spread, available flexibility options for the analyzed study case, and full load hours of energy storage. For the study case of Bosnia and Herzegovina, in 2012 spread of discharging and charging electricity prices was 0.06 €/kWh (the range of spread during the analyzed timeframe is 0.03-0.06 €/kWh). This is the year when arbitrage profits and HUPX price spread were maximum, given the analyzed timeframe. The average discharge price for

2012 was 81.1 €/MWh while the average charging price was 22.91 €/MWh. Although electricity price spreads indicate the possibility for price arbitrage, the analysis in terms of optimal results should be conducted with a broad approach. The optimization strategy, that is conducted in the model, provides the optimal energy storage arbitrage, given the described assumptions.

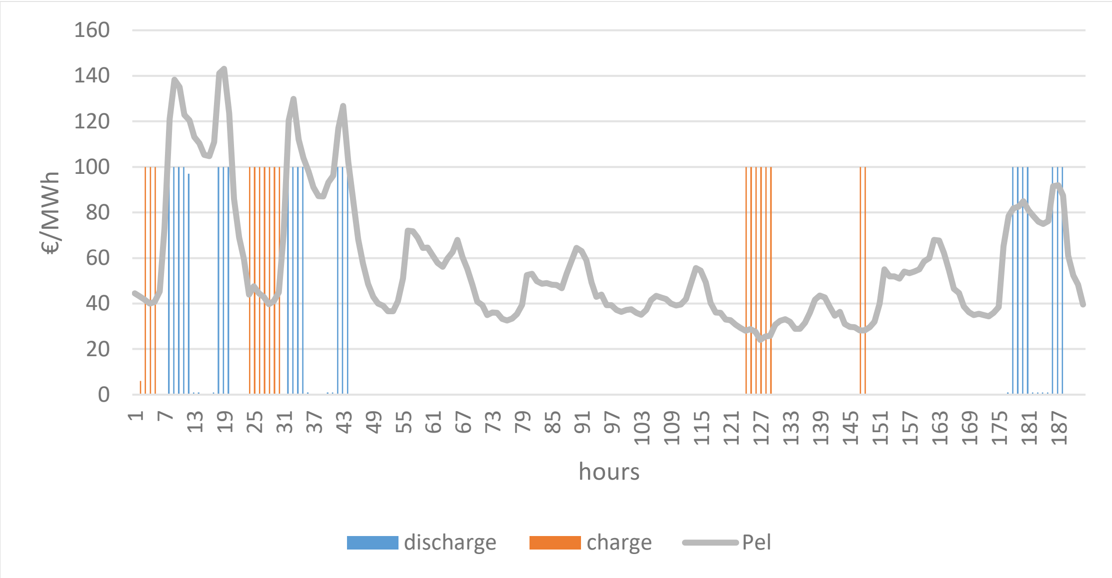

Fig. 4.8 Hourly optimization strategy for PHS in EXAA electricity market for week 24.1.2017.-31.1.2017.

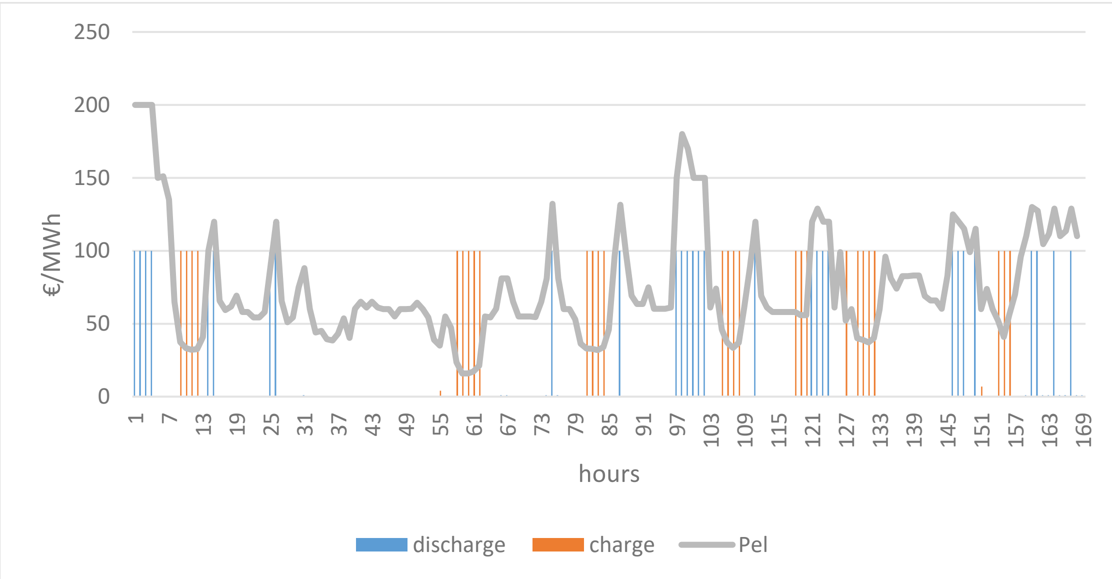

Fig. 4.9 Hourly optimization strategy for PHS in HUPX electricity market for week 16.2.2012.-23.2.2012.

During the same year, in the week with the lowest electricity market prices, the energy storage system was charging with the minimum electricity price of 83 €/MWh in EXAA and 113.67 €/MWh in HUPX. In the analyzed week, the optimization strategy shows, that at some hours the energy storage system was also discharging. This is due to the requirements of energy storage systems that need to be met at any time. The optimization strategy finds the optimum regarding the state of charge and energy and power constraints, while costs of storage are included.

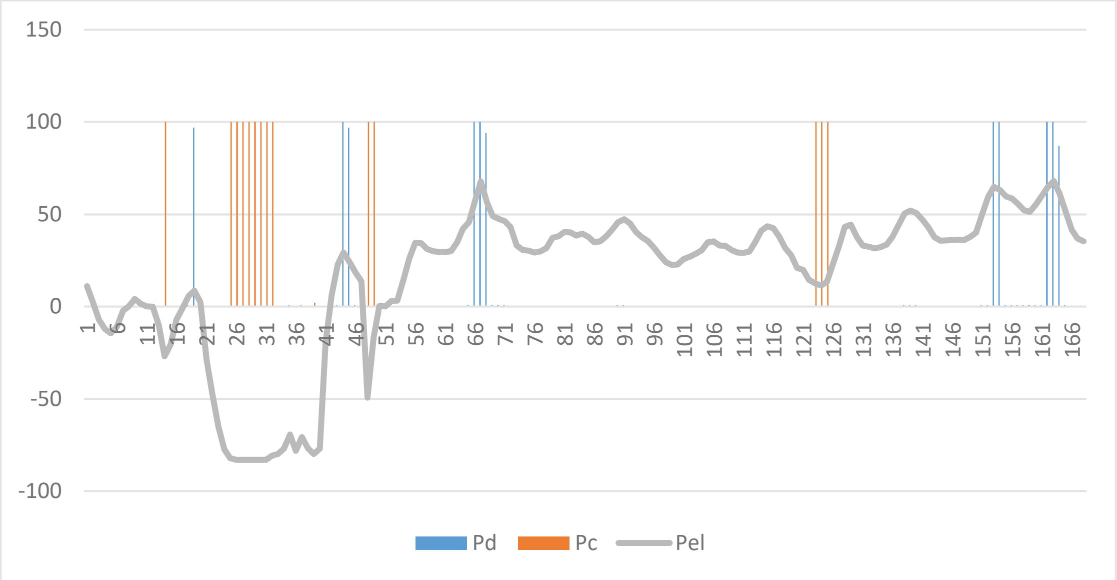

Fig. 4.10 Optimization strategy for EXAA electricity market for week 17.3.2017.-24.3.2017.

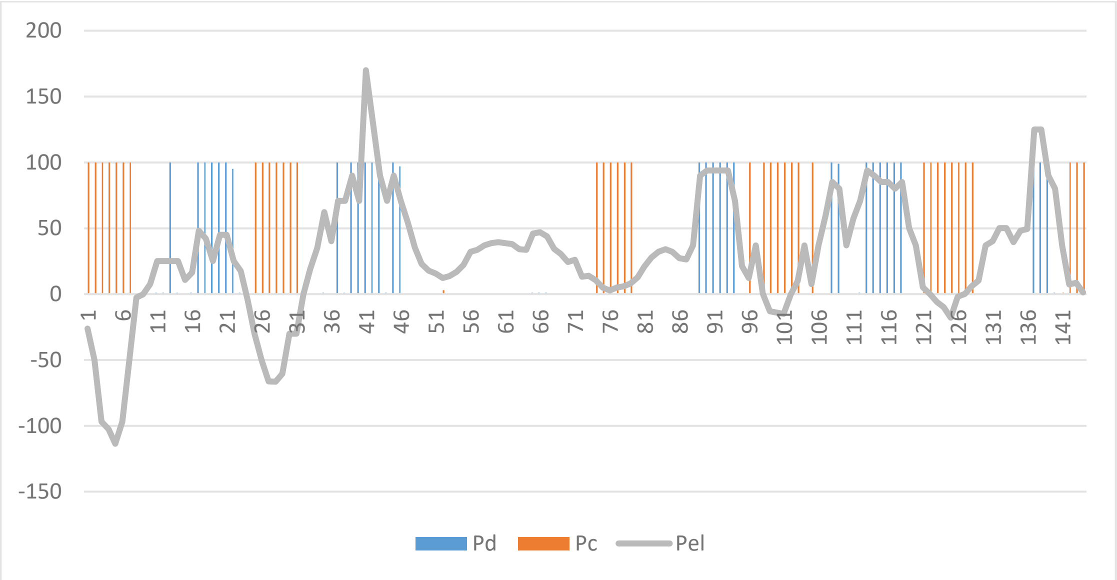

Fig. 4.11 Optimization strategy for HUPX electricity market for week 26.12.-31.12.2012.

The optimization analysis shows that pumped hydro storage is operational and profitable for both analyzed countries, but Li-ion storage analysis is yet to be proven profitable as technology continues to develop in the upcoming years. Arbitraging Li-ion batteries with an assumed operational strategy results in negative profits since the costs of operating such technology are still high to compete for the analyzed electricity markets (Fig.4.12), (Fig.4.13). Even with the 2000 FLH used, profits from arbitraging Li-ion energy storage in EXAA and HUPX remain negative.

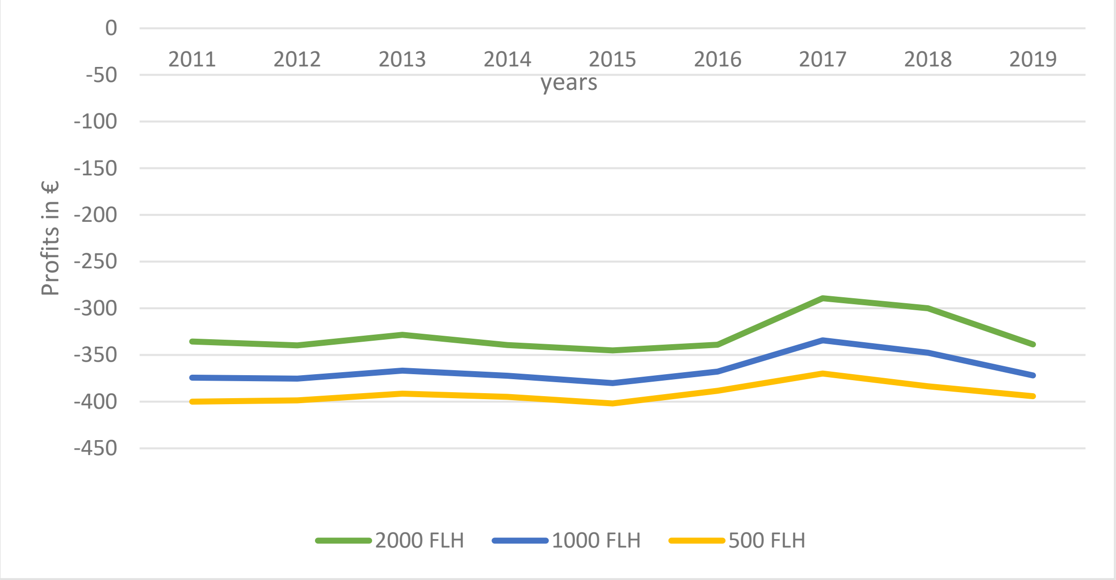

Fig. 4.12 Impact of different full load hours Li-ion profits for the Austria study case

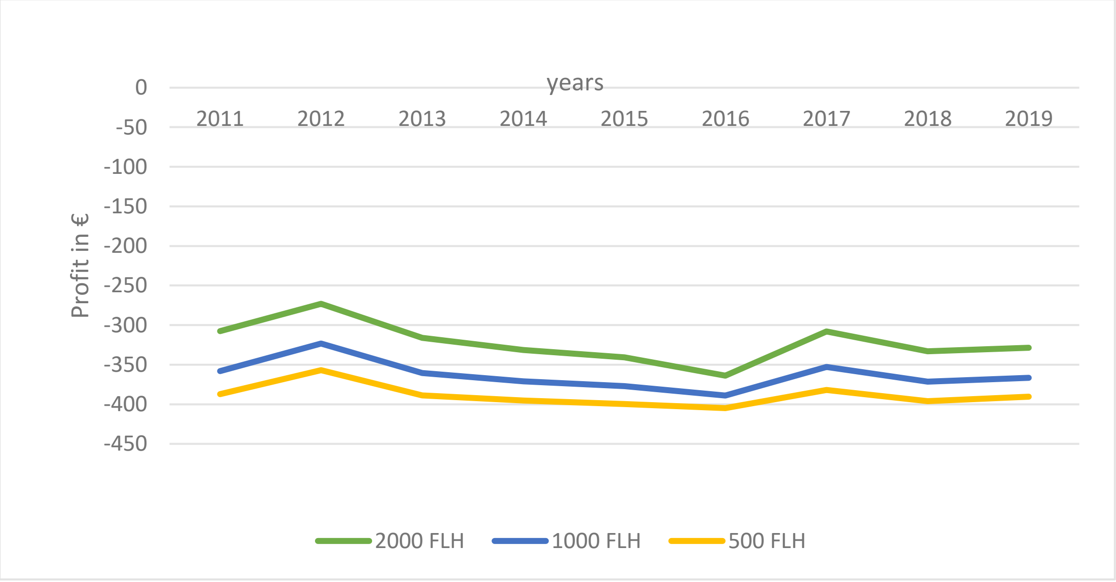

Fig. 4.13 Impact of different full load hours on Li-ion profits for the Bosnia and Herzegovina study case

Despite Li-ion technology developing only recently, and since it is still not deployed for the analyzed study case, the optimization analysis uses historic electricity market conditions and includes total costs that both provide significant insights for energy storage prospects. As results show, Li-ion technology for large-scale storage applications is still unprofitable, regardless of the technology development throughout the analyzed timeframe. In this period, renewable generation along with the development of electric vehicles changed the electricity market with the decline of electricity market prices and with the emergence of new market players. Over the years, improvements in battery technology have led to dramatic changes in the transportation sector allowing for the mitigation of greenhouse emissions. Another valuable application of electric vehicles is the additional flexibility they provide, especially with the possibility to charge during the night when electricity demand is lower. Nevertheless, the impact of electric vehicles in this period was still insignificant, as their extensive application in the transport sector and power grids is developing (global electric car sales reached 2.5 % in 2019. (Ajanovic, 2022)). During the analyzed timeframe, the value of pumped hydropower plants increased. Their functionality as a flexible mechanism for dispatch in previous energy systems consisting of nuclear and fossil power plants continued after the liberalization of electricity markets. Already installed plants are revitalized and used again for covering not only peak and off-peak prices, but also a disparity that happens with high generation of photovoltaics during the day and lack of generation in the evening or the variability that occurs with volatile wind generation. For Western Balkan countries, PVs and wind power plant investments started later with significant installations from 2017, which consequently led to higher electricity market prices and energy storage profits, among other factors. Nevertheless, pumped hydro storage technologies gain a competitive advantage in these circumstances of later liberalization of the electricity markets in the Western Balkan region. With more shares of unreliable renewable generation in the grids and energy transition from fossil-oriented generation, the value of pumped hydropower plants increases. They are seen as valuable electricity trading tools within price arbitrage applications or as ancillary services for allowing demand-supply balance in the power grids.

4.5.3 Impact on the study case

The economic benefits of energy storage integration in the wholesale electricity markets of Austria and Bosnia and Herzegovina are compared as both countries have high hydro potential, but different energy mixes, gross domestic product, and legislative frameworks of the energy sector. The vast majority of the recent research regarding energy storage profitability (Table 6) covers study cases of European countries where high shares of renewables are already implemented, hence comparison with one of the Western Balkan countries with high shares of fossil generation is valuable for the analysis of the arbitraging opportunities. Although it could have been expected that in Austria, a country with 66% of electricity generation from renewable energy sources, and installed pumped hydro storage power plants, energy storage flexibility characteristics would provide additional profits higher than in the compared study case, results show the significance of the electricity market conditions and price spreads that occur given the other impacting factors. Differences between PHS profits for 2000 full load hours are shown in Fig. 4.14, where significant events that occurred in EXAA and HUPX electricity markets are explicitly seen. A decreasing trend of storage profits ended in 2016. for both countries when the price spikes occurred in 2017. due to the lower hydro potential in Europe and colder than usual winter that influenced longer working hours of fossil and gas powerplants. Strong dependence on weather conditions of Western Balkan countries that influence HUPX exchange can be seen as an opportunity for storage arbitrage. If renewable generation increases in the upcoming years in the Western Balkan countries, would electricity prices in the HUPX electricity market remain higher than in EXAA, is yet to be seen. Nevertheless, the price difference is the investment signal for utilities and storage operators to gain profits from arbitraging pumped hydro storage in the HUPX electricity market, given the analyzed investment costs and operational hours.

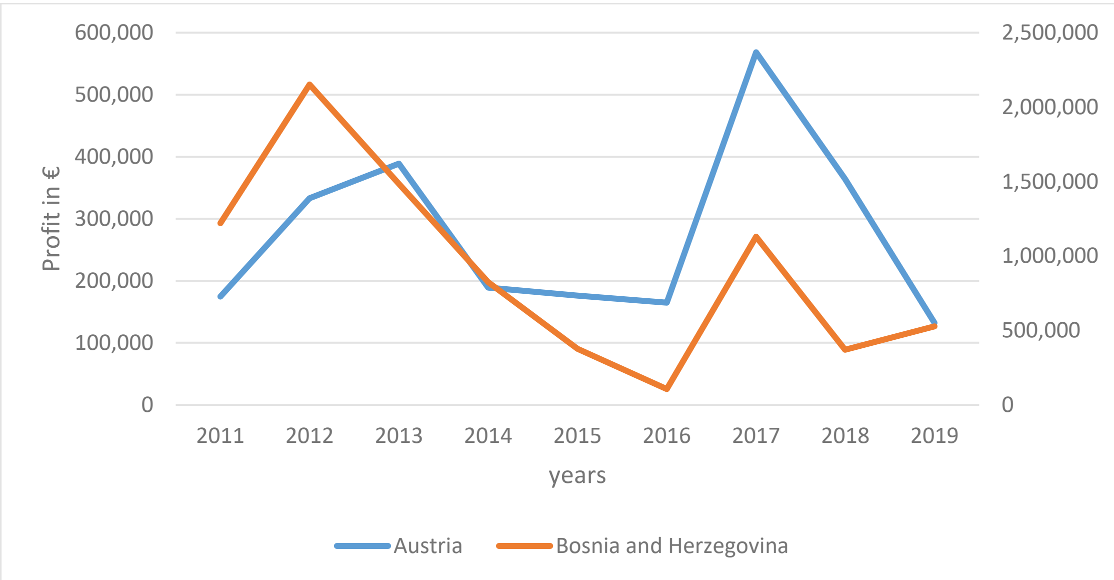

Fig. 4.14 Comparison of pumped hydro storage profits for 2000 full load hours in two different electricity markets for study case of Austria (primary axis) and Bosnia and Herzegovina (secondary axis).

When comparing Li-ion batteries, profits are negative for both countries (Fig.4.15). Despite the recent improvement in the production of Li-ion batteries, as presented in the review by (Balali and Stegen, 2021), for the analyzed markets price arbitrage with Li-ion isn't economically viable. Pumped hydro energy storage is technically and operationally more mature than Li-ion batteries. Although Li-ion is the most mature among electrochemical storage and has higher efficiency than PHS, since it is a new technology, investment, and replacement costs are higher leading to accordingly higher total costs of storage. Taking into the account replacement costs of Li-ion batteries, their marginal costs are higher than PHS, especially when considering the influence of material waste on CO_2 emissions. Results from the profitability analysis of price arbitrage indicate that even with 2000 full load hours, technical characteristics of energy storage systems influence final profits. Since in Austria, new locations for pumped hydro storage power plants are scarce, Li-ion batteries could only be a substitute for other flexibility measures if the prices of technology decrease.

Utility companies in Bosnia and Herzegovina, a country with one pumped hydro storage that is operated from one of the three state-owned companies only, should use maximum potential for investment in arbitraging opportunities with pumped hydro energy storage and in finding new locations for profitable renewable sources, given the challenging future of energy transition. Especially, with the European Union's plans for a carbon-neutral continent by 2050. and closing fossil power plants, an increase in renewable shares is inevitable for Bosnia and Herzegovina, as well as for other countries in WB6, still dependent on fossils. Along with the changes in generation portfolios of other Western Balkan countries, power peaks would occur as consequences of new variable renewable energy, making price spikes in the electricity market that are signals for price arbitrage. Finally, analysis of profits shows that either usage of energy storage as a flexibility measure for ensuring the future stability of electricity supply in Bosnia and Herzegovina, or as a new source of income for utility companies, there is an economic justification for pumped hydro energy storage systems.

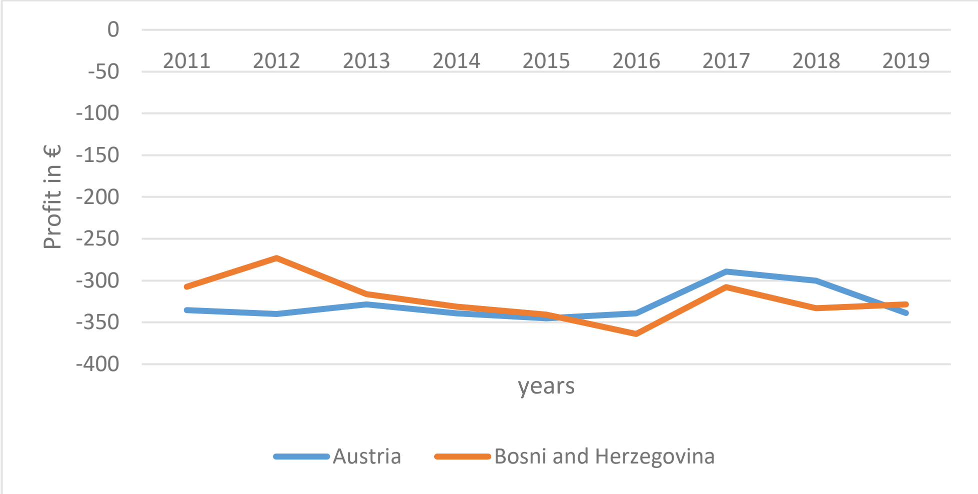

Fig. 4.15 Comparison of Li-ion profits for 2000 full load hours in two different electricity markets.

Given the first analysis of the cost-effectiveness in Chapter 3, it is evident that PHS has the lowest LCOS when compared to the other electrochemical technologies. Still, the profitability of energy storage systems should be considered from two aspects: application and energy system. As much as the Li-ion technology is efficient in the transportation sector, their employment in price arbitrage isn't economically justified yet. The conducted optimization analysis shows the impacts of the electricity markets and energy portfolios on the profitability of energy storage in price arbitrage, as well as prospects for energy storage for given study cases. As the HUPX electricity market is used for the Bosnia and Herzegovina study case, the optimization model can be applied to other countries of the Western Balkan or any other electricity market. The comparison of the two entirely different energy systems serves for the analysis of all significant factors for the energy storage economic justification. Analysis of the energy storage profitability can not be one-sided, with only cost calculation or analysis of investment costs. The possibilities and economic justification of energy storage systems in price arbitrage will depend on other factors of the energy system in which they will operate, that is electricity market conditions, energy portfolios, and flexibility systems available.

4.5.4 Price- taker approach

The conducted research based on a price-taker approach provides an analysis of the storage for electricity profitability with insignificant impact on the electricity market prices, with full load hours of storage included in the optimization model. This approach represents an estimation of energy storage value in the markets with the assumption that energy storage is insignificantly small enough to have an impact on the electricity market prices or power system. Since development of the energy storage systems is yet emerging, their costs decreasing and they are yet to be analyzed for the benefits of the electricity market integration, they don't influence electricity market prices. The price-taker approach is used in this thesis, as it allows for simplifications of the maximum objective function in the optimization model, without the representation of the power systems balancing. Considering new deployments of energy storage systems in the electricity markets, energy storage will soon have a higher impact on electricity prices, as predicted by (Zhao *et al.*, 2022). An arbitrage profit is achieved for only pumped hydro energy storage systems, since PHS operational costs for 2000 full load hours, and given the energy storage constraints, are lower than revenues. Another analyzed storage technology, Li-ion, proves unprofitable considering any of the analyzed full load hours since investment costs are considerably higher than arbitraging revenues. The yearly approach of the analyzed profitability gives an indication that energy storage profitability depends strongly on the electricity market conditions and installations of renewable generation in the grids. Price spreads in the electricity markets, that occur due to different factors such as high generation of renewables, demand-supply imbalance, weather conditions, or dependency on fossil power peaks, impact arbitraging opportunities. The profitability of energy storage is achieved in these price spreads, indicating that storage systems could be the stabilizing factor, similarly as gas power plants are mitigating power peaks currently. Overall energy storage profitability and optimization when costs are included for predefined full load hours, proves that justified flexibility can be achieved for pumped hydro storage, but for Li-ion, costs must decrease further. Other impacting factors of energy storage's wider integration in the power grids are analyzed in the following Chapter.

5 Role of renewables in energy storage economic viability in the Western Balkan countries

As optimization analysis in the previous Chapter shows, energy storage systems‘ profitability depends on many factors other than electricity market prices. Hence, the impacting factors of energy storage economic viability in the electricity markets are analyzed, taking into account electricity market price distribution, full load hours, total costs of energy storage, and linear regression analysis. This research is a part of the published article by (Topalović and Haas, 2024). The results from the proposed model, provide the effects and driving factors of storage for electricity utilization.

5.1 State of the art

Given the current state of the art, energy storage systems and renewable energy sources have been closely related and considered as key factors in future carbon-free systems. Among many services of energy storage systems for support of RES integration in the power grids, described in detail by (Koeva, Kutkarska and Zinoviev, 2023), (Hossain *et al.*, 2020), (Tan *et al.*, 2021), are flexibility and solving RES variability. As more renewables are in the grid, more energy storage is needed. This hypothesis is questioned in various papers given different methods of analysis. In (Cárdenas *et al.*, 2021), an assessment of energy storage capacity for up to 100% renewable generation in the analyzed study case is based on the net-demand profiles which are the result of subtracting the wind and solar profiles from the profile of electricity demand. The algorithm calculates the capacity of energy storage based on these profiles as they present periods of negative demand, when renewables exceed the electricity demand, and periods of positive demand when additional energy is required. Results show that energy storage systems' rated power would increase with the penetration of renewables in the grids. Similarly, the optimization analysis by (Auguadra, Ribó-Pérez and Gómez-Navarro, 2023), which minimizes operational and replacement costs of the energy systems used to cover demand with a specified share of RES, finds that optimal capacity for dealing with variable RES exponentially increases as the decarbonization targets increase. If renewables development is expected, then development of the energy storage technology and a decrease in their costs is also expected, as highlighted by (Wang *et al.*, 2022). Research by (Jafari, Korpås and Botterud, 2020) with the cost-based capacity study, finds that a decarbonized power system for the analyzed study case of Italy can be reached with lower costs if energy storage is implemented. Decision layers of the power system are optimized in the model with the objective function of minimizing the planning and operation costs of the power system based on the input parameters, such as available generation technologies and load requirements. If batteries were installed, total costs of energy generation would increase by 20% instead of 40%, since system operation is less expensive with ESS because it allows for more RES generation. Similarly, the expansion model by (López Prol and Schill, 2021) is based on the cost-minimal generation and storage capacities of pumped hydro storage allowing for their optimal dispatch when different shares of RES are considered. Analysis shows RES and ESS complementarity, but they can also be substitutes as ESS can be replaced by RES curtailment. Ultimately, it is shown that 100% of RES shares will increase the role of long-term storage. Considering the geographical locations of PHS as their main constraints, there is an acceleration of research regarding short-term storage, especially Li-ion batteries for large-scale applications. Cost-optimal generation and storage analysis (Mallapragada, Sepulveda and Jenkins, 2020) finds Li-ion batteries still expensive, as they cover only 4% of peak demand when there is an increase of 40-60% of renewables. The value of storage is estimated on the changes in transmission and generation costs of energy systems when additional units of storage are added. The optimization and regression analysis of large-scale batteries for price arbitrage by (Lamp and Samano, 2022), also finds negative profits at current electricity market conditions. All the relevant research agrees that energy storage is a vital element for reaching set targets for the implementation of RES, but a decrease in energy storage costs would influence a faster transition towards a sustainable energy sector as concluded by (Haas, Auer and Resch, 2022). For further development of renewables, research by (Kebede *et al.*, 2022) and (Haas *et al.*, 2022) highlight that it is important to plan the installation of new energy storage systems along with renewable energy sources, considering relevant application and storage capabilities. As concluded by (Child *et al.*, 2019), PV prosumers with batteries can lower costs and reduce dependency on large-scale centralized grids. Because of the variable nature of RES, higher shares impact electricity market conditions and prices significantly, hence price arbitrage is considered a valuable tool for mitigation of those effects. Arbitrage is a profitable and effective method for managing demand and supply. When prices are higher ESSs discharge and sell electricity, while when prices are lower ESSs charge and buy electricity from the market. This analysis follows in the investigation of the relationships between energy storage systems for price arbitrage and renewable energy sources.

5.2 Core objective

Aiming to find the fundamental drivers behind energy storage economic viability, the relationships between energy storage revenues and hydro, wind, photovoltaics generation, and EU ETS prices are analyzed. The selected renewables represent the future substitute for fossil generation in the Western Balkan. Using revenues for arbitraging a 10 MW pumped hydro storage system, resulting from the electricity market price distribution and total costs of storage analysis, an econometric model is conducted resulting in the impacting factors of energy storage development in the rising renewables circumstances.

5.3 Method of approach

Renewables' impact on energy storage development in the WBC is based on the econometric model and revenues/costs analysis. Given the hourly spread of the day-ahead HUPX electricity market prices in the period from 2011 to 2019, average revenues and average costs are calculated depending on a certain number of full load hours. The Levelized costs of energy storage C_{lcos} in €/kWh, are calculated as in the proposed method in Chapter 3, equations (1-9), and given the assumptions from Table 7. For the graphical representation as conducted by (Hiesl, Ajanovic and Haas, 2020), Eq. (9) is written in the following form:

$$C_{lcos} = \frac{C_{lcoe}+P_{el}}{\eta} = \frac{C_{cap,a}}{FLH \cdot \eta} + \frac{C_{O\&M,a}}{FLH \cdot \eta} + \frac{P_{el}}{\eta} = C_{capital} + C_{operational} + C_{energy} \quad (19),$$

Where:

$C_{capital}$……… annualized capital costs $C_{cap,a}$ in €/kW divided by full load hours and storage efficiency η,

$C_{operational}$………annualized operation and maintenance costs in €/kWh divided by full load hours and efficiency,

C_{energy}………average energy costs based on the full load hours of day-ahead market price in €/kWh divided by the energy storage efficiency.

Given the price distribution of the electricity markets during the analyzed timeframe, average energy storage revenues based on the full load hours are represented as dependent (response) variables in the econometric analysis. Independent variables (predictors) are the yearly generation of hydro, wind, and solar PV as in Table 8, and EU ETS carbon price from Fig. 5.1.

Table 8 Generation of renewables over the years in the Western Balkan countries (Bankwatch, 2023)

years	hydro GWh	wind GWh	PV solar GWh
2011	20,504	0	0
2012	20,774	1	9
2013	28,629	2	18
2014	24,772	72	32
2015	25,008	123	48
2016	28,154	136	65
2017	19,781	255	64
2018	29,787	523	66
2019	23,753	1588	107

The regression model allows for the analysis of the relationships between renewable generation and storage revenues. The next equation describes the proposed method:

$$R_t = \beta_0 + \beta_1 \cdot G_{H_t} + \beta_2 \cdot G_{W_t} + \beta_3 \cdot G_{S_t} + \beta_4 \cdot P_{ets_t} + \theta_1 AR_{t-1} + \varepsilon_t \qquad (20)$$

Where:

R_t…………………revenues in € for the year t, (resulting from the price spread analysis)

β_0…………………intercept

β_1, β_2, β_3, β_4………regression coefficients

G_{H_t}, G_{W_t} G_{S_t}………..yearly hydro, wind, and solar generation in GWh

P_{ets_t}….the average price of the EU ETS emission trading system allowances in € for a year t

$\theta_1 AR_{t-1}$…………first lag of the autoregressive term

ε_t is an error in each iteration of t

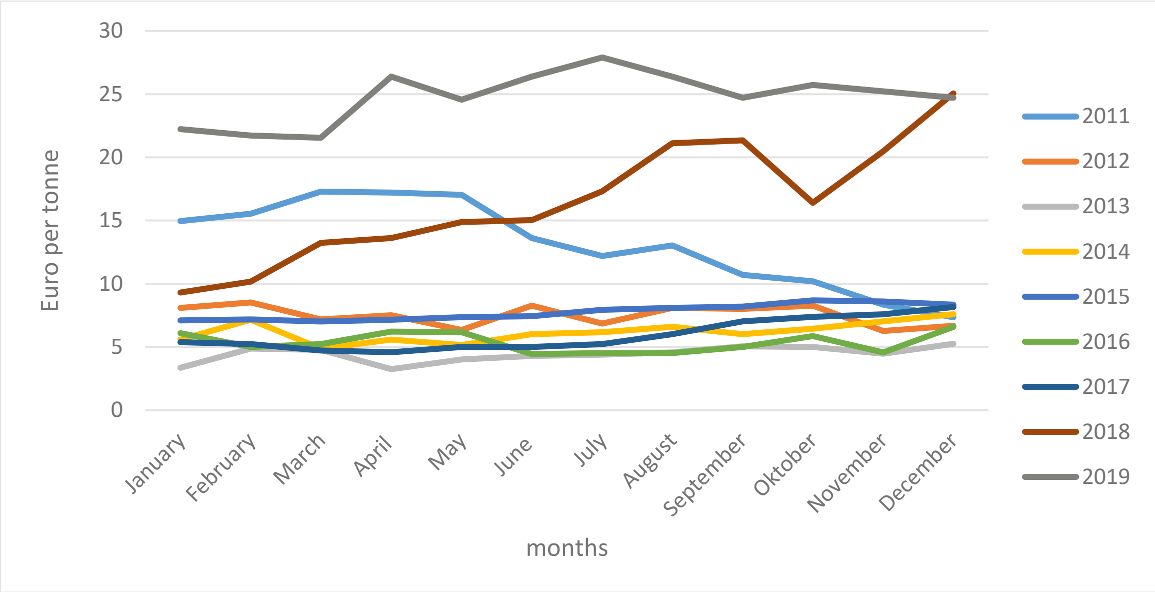

Fig. 5.1 Prices of EU carbon emission allowances over the years for the analyzed timeframe (Trading Economics, 2023)

Analyzing the electricity market day-ahead prices it can be assumed that for the optimal price arbitrage, the energy storage would discharge when the prices are highest, hence the revenues represent the highest average market prices for different full load hours. Since optimal price arbitrage calls for buying the electricity (charging energy storage) at the time of the lowest electricity market price, these costs are represented as energy storage costs C_{energy}. In this model, the complexity behind the operation of real storage operators, and dynamics behind daily storage discharge/charge are neglected as the previous chapter in the thesis shows an optimizational strategy for energy storage price arbitrage. The average revenues resulting from the hourly day-ahead electricity market prices spread and historic renewables generation are sufficient for the scope of the empirical research. Durbin-Wattson test, applied in the regression model, shows the effects of autocorrelation, hence the first lag term of the dependent variable is included. The mentioned statistic test uses residuals from the least squares regression set of data to find the best fit and see if there is autocorrelation among the residuals. A detailed description of the autoregressive terms and autoregressive exogenous models (ARX) is given in the work by (Montgomery D.C *et al*., 2012) and (Weron, 2014). The conducted analysis assumes perfect foresight, as historical data on electricity prices are available. At the time of the analysis, there wasn't an additional dataset, hence model captures the period from 2011 to 2019, but the general patterns can be derived from the analyzed timeframe regardless. Similarly, the model is simplified with the assumption of using pumped hydro storage of 10 MW power capacity given the assumed full load hours, instead of using individual storage power plant's historic outputs.The selected full load hours mean to answer whether there are some implications concerning an average number of cycles being 250-300, with 8-hr discharge, as previously determined in Chapter 4.These simplifications allow for the analysis of the impacting factors on storage revenues and the understanding of patterns behind the economics of energy storage.The presented approach has some limitations, such as representing the profitability analysis using average revenues from the electricity market price distribution. In the dispatching optimization model, as in Chapter 4, these prices are actual electricity day-ahead market prices which along with the energy storage capacity constraints give more precise arbitrage profits. But, as the goal of the third research question in the thesis is to find impacting factors behind storage arbitrage value, the analysis uses maximum limits of energy storage capacity for the given full load hours while the energy storage technology constraints are neglected.

5.4 Renewables in the Western Balkan countries

Understanding the dynamics between the growing shares of renewables in the electricity market and energy storage revenues is crucial for future investments in the energy sector, given the obligations stemming from agreed energy and climate targets. Almost half of the demand in the Western Balkan countries is covered by hydro run-of-river or accumulation, with modest generation from wind and solar sources, which is almost non-existent when compared to hydro. The share of hydro in total electricity generation represents 38%, while the shares of wind and solar are less than 3% (Fig. 3.2). This scarcity of generation from PVs and wind is due to the high dependency on fossil generation in the WB region, as previously noted. The WB region has been heavily dependent on coal, with inadequate regulation and underinvestment in renewable energy sources. The implementation of day-ahead and intraday coupling is an inevitable requirement for integrating WBC into the EU's internal electricity market. The energy transition has been long underway, but not as effectively as expected. With the energy crisis, when gas shortages in Europe imposed high electricity prices in 2021 and 2022, countries dependent on fossil power plants continued to generate electricity, despite technical and mining problems. These problems are direct consequences of the powerplants' age, with the installations dating back to the fifties, and of the decrease in coal quality. The unfavorable weather conditions, when hydro generation was scarce, and the increased imports, combined with the soaring electricity prices, have amplified these effects. Higher electricity prices impact the usage of fossil power plants and delay their phasing out, although wind and PV investments have been simultaneously increasing (Ciuta I., Gallop P., 2022). Taking into account the above-mentioned effects of the energy crisis, despite committing to the achievement targets by 2030 (Table 9), the Western Balkan countries continue using fossil power plants to their maximum extent, hence, prolonging the committed development of the RES, even at the expense of the environmental and social consequences.

Table 9 Targets for share of energy from RES in gross final energy consumption (Energy Community, 2022)

Western Balkan country	Targets by 2020	Targets by 2030
Albania	38 %	52.0 %
Bosnia and Herzegovina	40 %	43.6 %
Kosovo	25 %	32.0 %
Montenegro	33 %	50.0 %
North Macedonia	21 %	38.0 %
Serbia	27 %	40.7 %

Although these targets are well established, aligning with the NECPs, countries are still lagging behind the RES investments. The main constraints are regulatory uncertainties and limited regional market integration, as analyzed by (Đurašković,2021). As of 2023, the Energy Community reports that Albania and Montenegro have managed to surpass the 2020 RES targets; Serbia and Bosnia and Herzegovina came close to reaching them, while North Macedonia and Kosovo stayed below the set targets (Energy Community CBAM, 2023). The biggest share for reaching the set targets comes from hydro generation as renewable hydropower, accounting for 92% of the total renewable energy production in 2019 (IRENA, 2022). All countries, except for Albania, are dependent on coal and are continuing to use it despite their high wind and solar potential. The European Union's planned CBAM is expected to minimize this coal dependency, as it will apply imposing charges on electricity imports from carbon-intensive industries in the upcoming years. The price of EU carbon emission allowances has been increasing over the years, as free allocations have been reduced (Fig. 5.1). Decarbonization will lead to the replacement of fossil power plants with PVs and wind, as hydropower expanding potential is limited. This increase in renewable shares in the electricity markets will create flexibility requirements for storage, which can regulate the variable nature of renewables. The region currently employs only two energy storage facilities, that is pumped hydropower plants with 1 GW capacity (Table 4). Other possible technologies for the future economically viable integration of RES are lithium-ion batteries, thermal storage, and hydrogen, which can reduce the natural gas demand by 50 percent by 2050, as a study (Enervis, 2022) shows. Despite the technical advantages of the aforementioned technologies, they are still new, with higher levelized storage costs when compared to pumped hydro storage. Because of the cost-effectiveness and historical installations of PHS in the WB region, as future installations of RES also indicate prospects for energy storage development, their effects are analyzed. The next section covers empirical observations of the optimal PHS revenues, based on the distribution of hourly day-ahead electricity market prices, to understand the impacting patterns for future storage operators and investors in the region.

5.5 Results

The given results bring forth a meaningful understanding of the economics behind the energy storage systems and their relationship with the growing shares of renewables in the grids. The proposed method gives valuable insights as future trends of energy storage development can be derived for any study case. To compare the results for the WB region with the energy system consisting of higher shares of renewables installed, profitability analysis is conducted for the Austria study case as well.

5.5.1 Price spread effects on the storage profitability

Given the price spread of HUPX and EXAA electricity markets from 2011-2019, average revenues and average costs are calculated for different full load hours (Fig.5.2). This approach allows for the analysis of the energy storage profitability as average revenues are representation of the electricity market prices for a number of full load hours in which the energy storage is discharging electricity, while average costs represent the electricity market costs for charging the energy storage for a number of full load hours (Fig.5.3). Actual day-ahead hourly price spread of the analyzed electricity markets is given in the Appendix A of the thesis. Over the years, different factors have influenced price spreads in these markets. With the renewables boom from the late 2000s, EXAA electricity market conditions have changed significantly. The zero marginal costs of fluctuating photovoltaics and wind power plants impose a merit-order effect by pushing out the inflexible fossil power plants and thus decreasing electricity market prices. This decrease can lead to negative electricity market prices affecting the stability of energy systems. Energy operators are challenged with the higher generation of renewables in the grids, especially at times of lower demand. When an oversupply of generation from RES collides with low demand, there are different options for managing this imbalance. Consumers are either paid to buy electricity or are asked to ramp up demand by power suppliers or power operators. These methods are used to avoid turning off inflexible generation units by systems operators, as they provide stability to the system, and cannot be easily unplugged because of technical but also economic reasons. For energy storage suppliers there is an option for curtailment of renewable energy sources to avoid further unsteadiness, despite the economics and resources waste. The effects of the negative prices, as analyzed by (Prokhorov and Dreisbach, 2022), can be minimized using different methods, such as adjustments in the electricity market design, improvements in the cross-border capacity, and the development of system flexibility. One of the advantages of energy storage systems is their flexible application in the grids, which is considered a highly effective method for dispatching volatile and variable RES generation, but this method should be analyzed from the economic point of view as well. Analyzing solely revenues to determine energy storage's economic viability is not enough, as final profitability also depends on the costs of the operating storage systems. The average revenues and the Levelized costs of storage (as in eq. (19)) regarding full load hours for a given timeframe are shown in Table 10. Higher electricity market prices in the HUPX market are a reflection of energy conditions and energy mixes, which are coal and hydro-dependent. Hence, the revenues are higher as well, which eventually shows an indication of profits for the HUPX market when compared to the Levelized costs of storage (Fig.5.4). For the Austrian scenario, electricity market conditions are impacted by higher shares of renewables installed over the years (Fig.1.2) at a faster rate than in the WB region, hence lower electricity market prices, which are in some cases negative (Fig.5.5). Thus, the average revenues and costs when compared to the HUPX are lower, as seen in Fig.5.6, for 26% and 12% respectively, given the 2000 full load hours. As Austria has a high generation of hydro, which is dependent on weather conditions, mitigation of peak demand is covered by gas power plants, consequently leading to lower arbitrage opportunities (Fig.5.7). It is evident that in HUPX electricity market, costs are lower than revenues in a range from 1000 to 4000 full load hours (exceptions being in 2015 and 2016 year) indicating profit potential, which is not the case for the Austrian scenario, with profits being positive only above 2000 full load hours threshold and only in exceptional cases during the analyzed timeframe (2013 and 2018). Hence, revenues, as changing factors that reflect the electricity market conditions, are used further in the econometric analysis for the WBC study case, with the objective of analyzing the effects of renewable generation and EU ETS carbon prices on the economic viability of storage for electricity.

Table 10 Profitability analysis of 10 MW PHS for HUPX and EXAA

Year	Full load hours	HUPX			EXAA		
		LCOS	Revenues	Profit	LCOS	Revenues	Profit
		€/kWh	€/kWh	€	€/kWh	€/kWh	€
2011	500	0.1831	0.1080	-375,506	0.1867	0.0746	-560,734
	1000	0.1124	0.0939	-184,850	0.1154	0.0713	-440,900
	2000	0.0811	0.0816	9,606	0.0832	0.0676	-312,223
	3000	0.0731	0.0756	75,449	0.0745	0.0649	-287,519
	4000	0.0706	0.0714	31,443	0.0712	0.0625	-349,441
2012	500	0.1705	0.1165	-269,964	0.1739	0.0732	-503,892
	1000	0.1000	0.1025	25,564	0.1018	0.0672	-346,134
	2000	0.0691	0.0861	339,958	0.0697	0.0616	-161,892
	3000	0.0613	0.0773	481,766	0.0611	0.0580	-92,709
	4000	0.0592	0.0715	489,670	0.0581	0.0552	-116,256
2013	500	0.1670	0.0917	-376,269	0.1671	0.0709	-480,868
	1000	0.0941	0.0809	-131,597	0.0942	0.0655	-287,539
	2000	0.0624	0.0707	165,930	0.0621	0.0593	-55,459
	3000	0.0545	0.0645	300,091	0.0536	0.0545	26,800
	4000	0.0520	0.0595	302,799	0.0506	0.0507	6,932
2014	500	0.1718	0.0819	-449,687	0.1686	0.0592	-546,801
	1000	0.0982	0.0724	-258,789	0.0954	0.0545	-408,835
	2000	0.0648	0.0638	-21,070	0.0621	0.0492	-257,796
	3000	0.0556	0.0589	96,960	0.0526	0.0457	-207,887
	4000	0.0526	0.0551	101,049	0.0487	0.0430	-230,972
2015	500	0.1743	0.0741	-500,756	0.1668	0.0558	-554,814
	1000	0.1007	0.0664	-343,439	0.0939	0.0519	-420,092
	2000	0.0669	0.0602	-135,594	0.0606	0.0474	-263,962
	3000	0.0577	0.0565	-37,340	0.0512	0.0442	-208,710
	4000	0.0546	0.0535	-45,034	0.0474	0.0416	-229,994
2016	500	0.1729	0.0641	-544,057	0.1664	0.0557	-553,512
	1000	0.0986	0.0589	-397,151	0.0933	0.0500	-433,512
	2000	0.0638	0.0528	-220,945	0.0594	0.0440	-306,923

	3000	0.0540	0.0490	-150,657	0.0493	0.0407	-258,572
	4000	0.0506	0.0463	-173,061	0.0451	0.0382	-274,934
2017	500	0.1770	0.1175	-297,564	0.1591	0.0780	-405,672
	1000	0.1046	0.1002	-44,508	0.0894	0.0655	-238,999
	2000	0.0716	0.0837	242,347	0.0596	0.0550	-91,751
	3000	0.0630	0.0751	365,388	0.0517	0.0500	-52,814
	4000	0.0603	0.0692	356,103	0.0487	0.0466	-82,531
2018	500	0.1760	0.0916	-422,135	0.1670	0.0818	-425,901
	1000	0.1044	0.0841	-202,922	0.0980	0.0763	-217,880
	2000	0.0732	0.0765	67,020	0.0684	0.0697	25,405
	3000	0.0656	0.0716	180,630	0.0612	0.0650	115,853
	4000	0.0635	0.0675	160,075	0.0591	0.0614	92,194
2019	500	0.1822	0.0981	-420,807	0.1772	0.0676	-547,893
	1000	0.1092	0.0861	-231,661	0.1049	0.0618	-430,496
	2000	0.0760	0.0762	4,213	0.0714	0.0564	-300,937
	3000	0.0669	0.0704	103,186	0.0617	0.0530	-261,170
	4000	0.0639	0.0660	83,748	0.0577	0.0503	-296,648

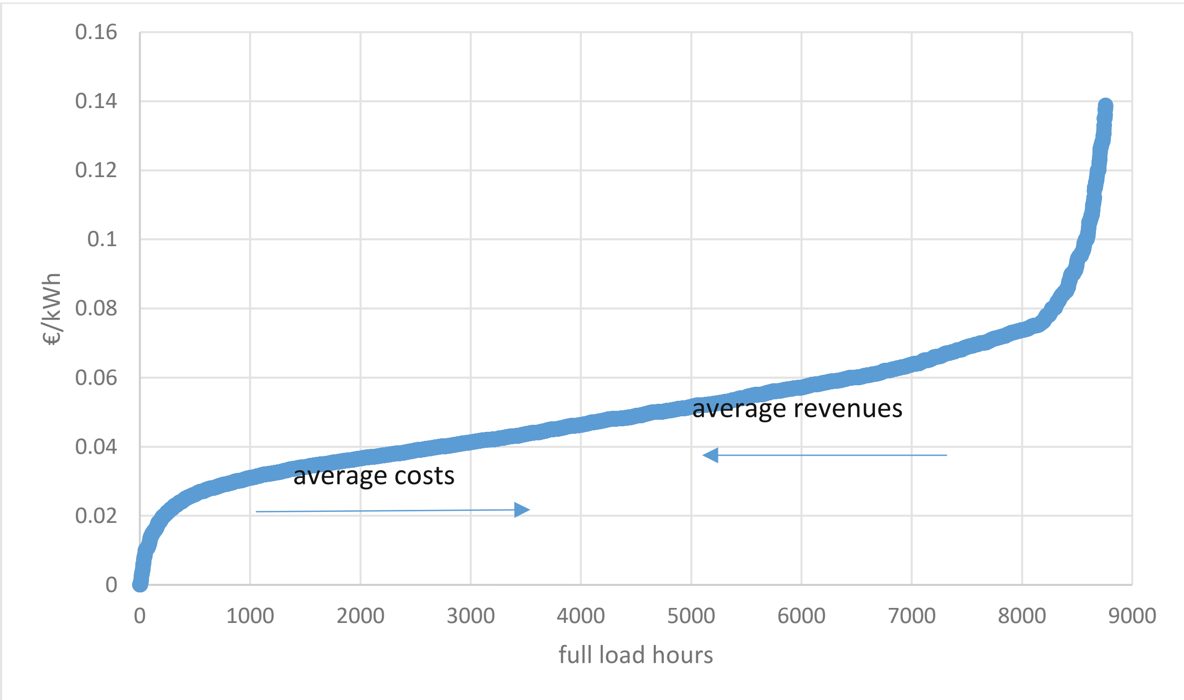

Fig. 5.2 Hourly distribution of the day-ahead electricity prices from HUPX in 2019

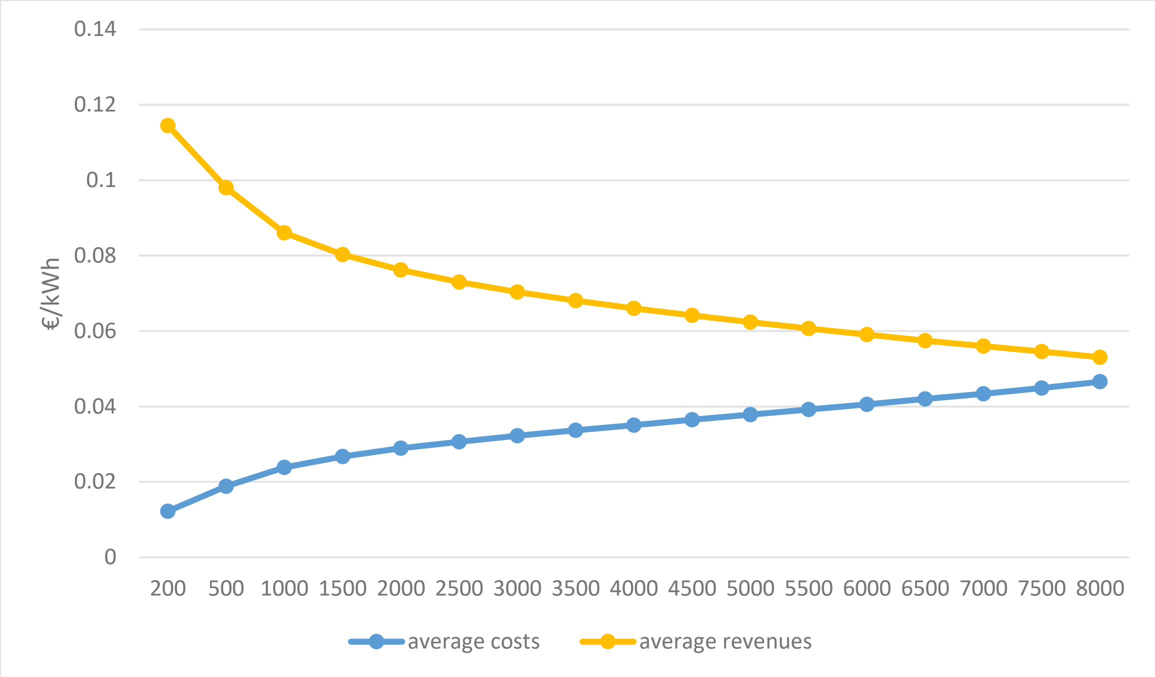

Fig. 5.3 Average revenues and average costs in the day-ahead HUPX electricity market in 2019

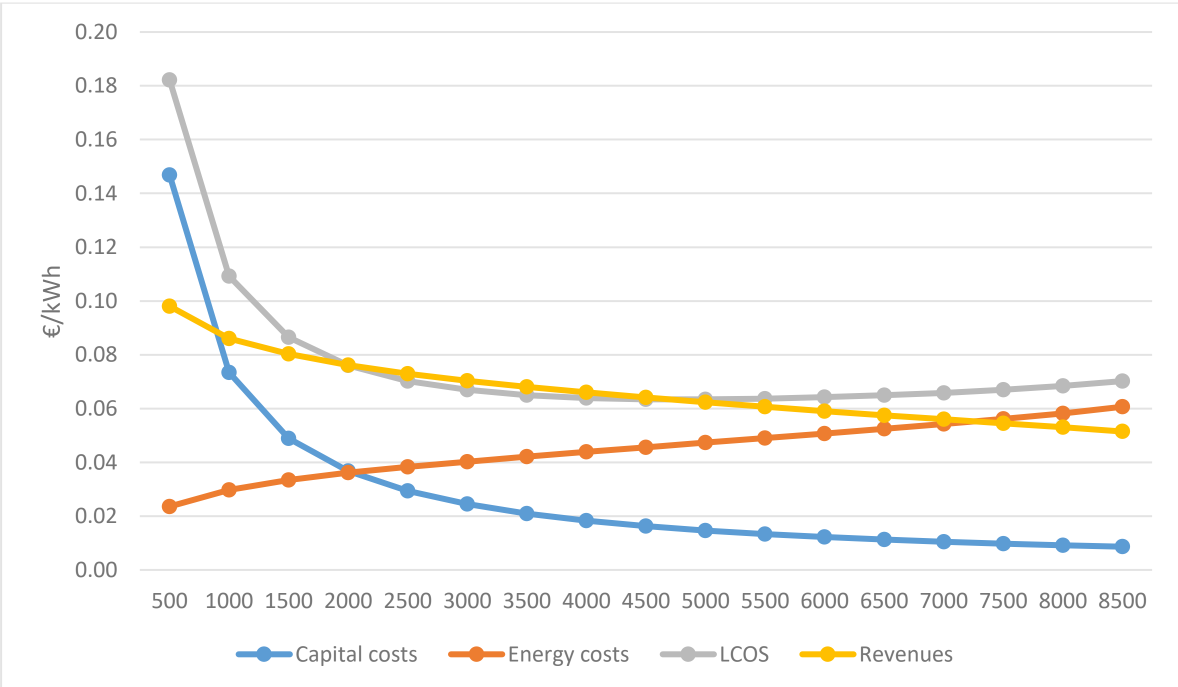

Fig. 5.4 Profitability analysis depending on the different full load hours for day-ahead HUPX electricity market prices in 2019

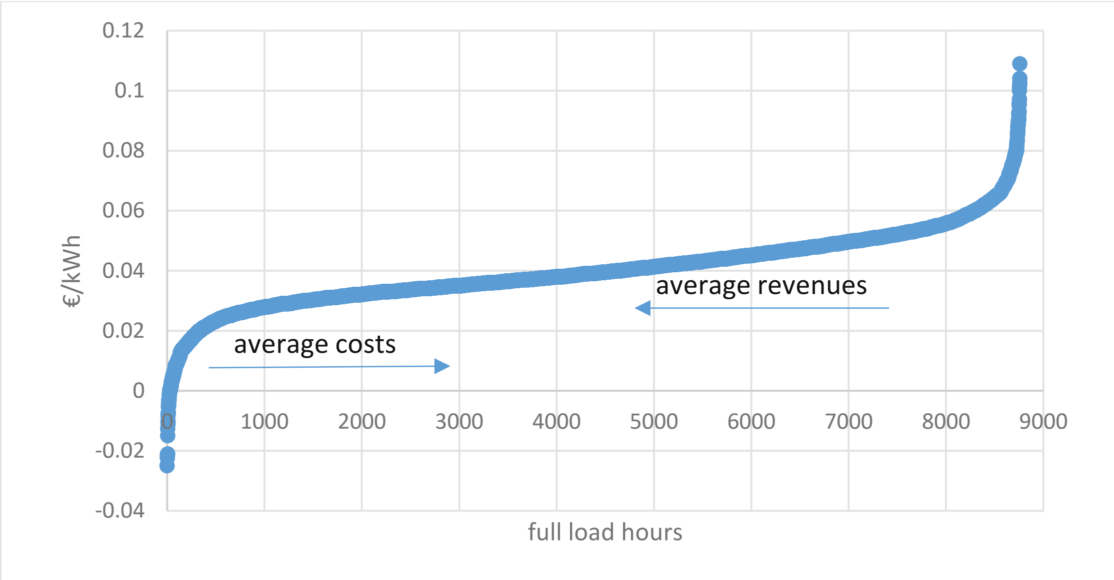

Fig. 5.5 Hourly distribution of the day-ahead electricity prices from EXAA in 2019

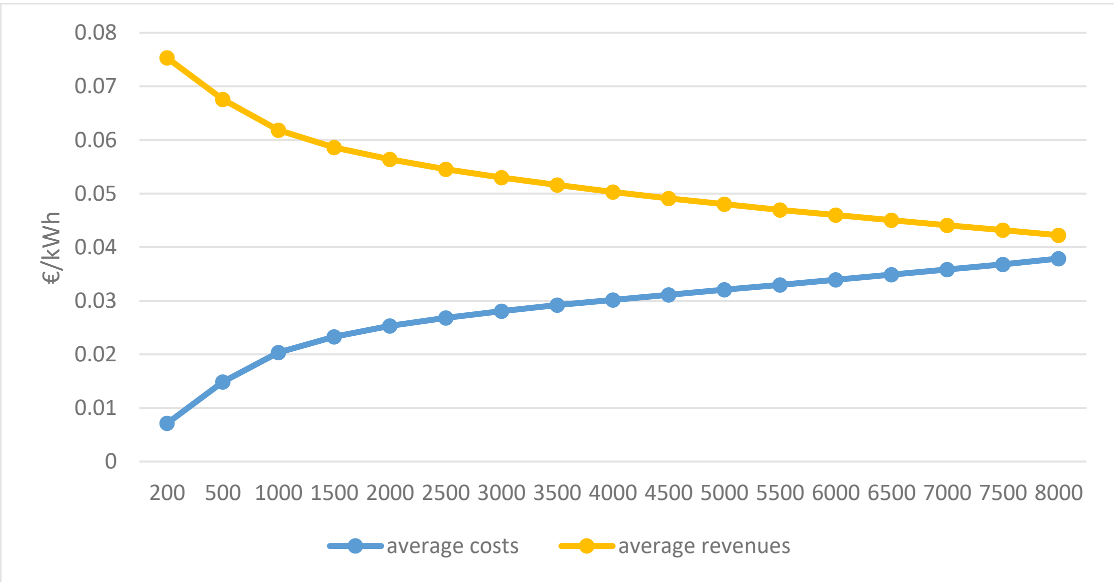

Fig. 5.6 Average revenues and average costs in the day-ahead EXAA electricity market in 2019

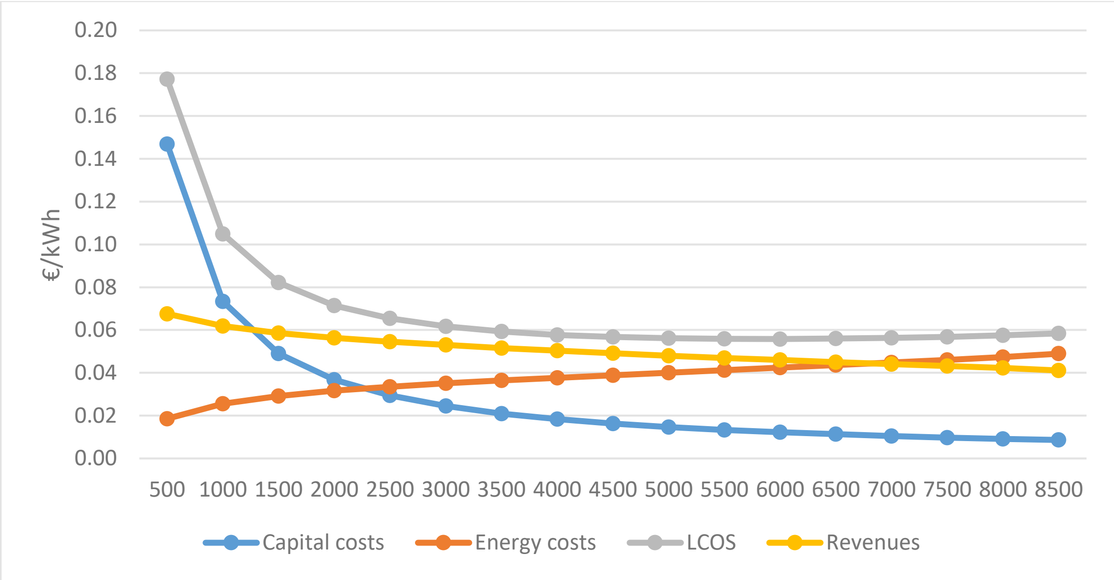

Fig. 5.7 Profitability analysis depending on the different full load hours for day-ahead EXAA electricity market prices in 2019

When compared to the optimization analysis in Chapter 4, it should be noted that this approximation of the optimal results when price distribution is analyzed, serves as an indication of the electricity market's conditions for possible price arbitrage, rather than an optimization strategy. The market prices replicate the possibilities for storage and provide an insight into the division of the costs.

5.5.2 Impacting factors on energy storage revenues

The implementation of the Durbin-Wattson test for the linear regression model proved autocorrelation in the time-series dependent variable, revenue. With the first lagged terms defined, the linear regression analysis shows signs of strong correlation among some variables. The correlation matrix resulting from the Matlab calculation (Table 11) presents degrees of linear relationships between all variables. The maximum value of the coefficient is 1 representing a very strong positive linear correlation among variables, while values closer to -1 indicate the opposite. Value zero shows no signs of correlation among analyzed variables. Signs from the correlation matrix indicate if the two variables change together (positive sign) or reversely (negative sign). Almost all coefficients show positive correlations with each other, except for the hydro and solar variables when correlated to the dependent variable revenue. The hydro-revenue correlation coefficient value of -0.72 indicates that there is a strong possibility that with the increase of hydro generation, revenue for storage price arbitrage decreases. Given the described energy system of the Western Balkan countries, with hydro-fossil generation (except Albania), it can be expected that if hydro increases, market conditions would change and lead to lower possibilities for arbitrage revenue due to the changes in the price spreads. As for the solar–wind correlation, a coefficient of 0.827 indicates that if solar generation increases or decreases, wind generation will increase or decrease as well. This reflects the dynamics of the solar and wind investments in the Western Balkan countries, as they have been developing simultaneously given the higher historic installments of the hydropower plants. The EU ETS variable is positively correlated to the wind (ETS-wind 0.827) and solar generation (ETS-solar 0.557), as a reflection of the decarbonization underway. With the number of available allowances reducing over the years, their prices increase, which corresponds to an increase in generation from wind and solar. It is expected that countries in the WB region will implement the CBAM, as only Montenegro has done so far. With carbon taxes, electricity market prices will increase, as generation from fossil power plants will be more expensive. This increase will provide opportunities for investing in RES and energy storage. The energy power systems in the WBC consist of mostly fossil and hydro energy sources. Hence, stronger development of hydro can cover peak demands instead of expensive but inflexible fossil power plants, lowering the electricity market prices, and with the fossil out of the way, storage value decreases. The lower values of other coefficients from Table 11 indicate a weak correlation which reflects the rate at which wind and solar installations have been developing in the Western Balkan countries during the time investigated in the model. The significance of the model is represented with a *p*-value, showing whether the null hypothesis can be rejected, while the signs of coefficients represent the impact of independent variables on the dependent variable revenue, as in Table 12. The independent variables wind, solar, and EU ETS changed their signs in the final output of the linear regression model. This is due to the so-called “suppressor effect" (Falk and Miller, 1992), which occurs in this case because the original relationship between the two variables (wind- revenue, solar-revenue and EU ETS- revenue) is close to zero. Hence, the different signs from the output model (Table 12) when compared to the correlation matrix, represent random variation around zero and they should be neglected. Thus, the explanation of the model lies within the original signs, as in Table 11, which confirms the dynamics of the electricity market and energy mix of the WBC. The assumed full load hours used in the analyses reflect the current storage conditions, as the significance of the model for 3000 and 4000 full load hours, cannot be approved. Accordingly, the model shows that increased renewable generation doesn’t increase large-scale energy storage requirements for the WB region at the same rate, as grid balance is maintained within the current flexibility options and with the smaller storage(fossil power generators, interconnections) from the analyzed timeframe. These findings indicate that the analyzed market design doesn't propose energy storage incentives and that storage systems will have to compete with other flexibility options while the requirements for large-scale storage will have to be carefully analyzed given the installed shares of variable renewable energy sources. The future development of renewables along with the closing of the fossil power plants, as a means for future decarbonized systems is going to provide flexibility requirements, that will also require a shift towards different market designs as proposed by (Haas, R. et al. 2022) and energy policies to increase storage value in the markets (Lai and Locatelli, 2021). The future developments of these changes that will be inflicted on the fossil-dependent WBC and the investment cost of battery storage should be monitored closely.

Table 11 Correlation coefficients for of the WB linear regression analysis

Coefficients	Revenue	Hydro	Wind	Solar	ETS
Revenue	1	0	0	0	0
Hydro	-0.72451	1	0	0	0
Wind	0.060548	0.049868	1	0	0
Solar	-0.24519	0.244404	0.827332	1	0
ETS	0.180287	-0.01469	0.875327	0.557031	1

Note: +1 very strong positive linear correlation, -1 very strong negative correlation

Table 12 Resulting parameters of the WBC linear regression analysis

Full load hours	*p*-value				R-squared
	Hydro	Wind	Solar	EU ETS	
500	-0.000356***	-0.032874**	0.001063**	-0.001831**	0.9995
1000	-0.000511***	-0.00354**	0.001368**	-0.005242*	0.9993
2000	-0.03415**	-0.085058*	0.070501*	-0.271771	0.9565
3000	-0.17314	-0.309321	0.330888	-0.831425	0.8098
4000	-0.268517	-0.450408	0.543159	0.831335	0.7323

Note: significance of the p-value test: p<*0.1, p<**0.05, p<*** 0.001, + indicates positive effects, - negative effects

Linear regression analysis, conducted in Matlab provides the added variable plots (partial regression leverage plots) that allow for the interpretation of the variable when other variables are held constant. These plots show the significance of the model if the horizontal line can not be drawn between the confidence bounds. Added variable plots serve as an illustrative method for additional explanation of the impact of the fitted values (from the whole model) on the x-axis on the residuals of revenue on the y-axis (i.e. adjusted revenue). The model behind the presented plot is known as Frisch- Waugh-Lovell Theorem, with further details described by (Davidson, 2024). The narrower the fit, the greater the significance of the model, as it yields R-squared factors greater than 95% for 500, 1000 and 2000 full load hours (Fig. 5.8, Fig. 5.9, and Fig.5.10, respectively), harmonizing with the resulting *p*-value from the Table 12.

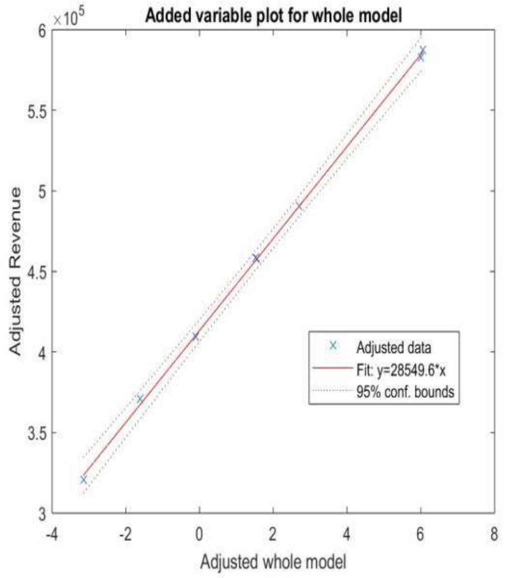

Fig. 5.8 Linear regression analysis for WBC for 500 full load hours

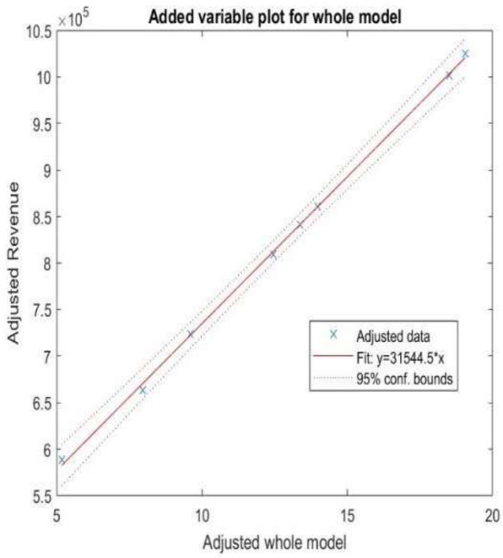

Fig. 5.9 Linear regression analysis for WBC for 1000 full load hours

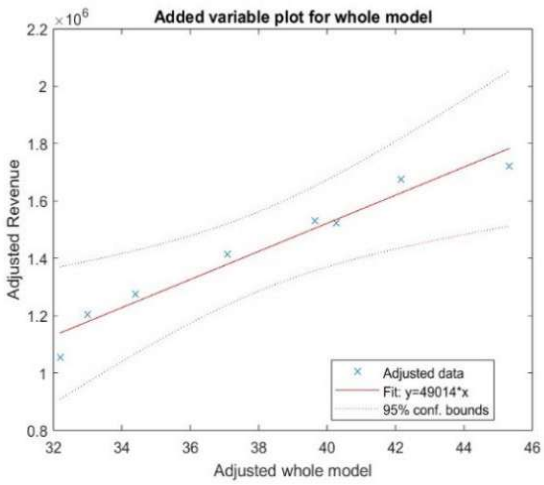

Fig. 5.8 Linear regression analysis for WBC for 2000 full load hours

A strong correlation of revenues to hydro generation reflects the market design and energy systems in the WBC. A further increase in the hydro generation can impact market conditions and opportunities for storage revenues, but given their characteristics, they can provide the systems with a significant peak covering in the transitional period together with solar generation, until the fossil power plants are fully closed. For the analyzed case study, EU ETS prices correlate to wind and solar generation as their development in the WBC is interconnected, meaning that carbon prices will lead to more wind and solar investments. Although lower values of correlation among other predictors to revenue (Table 11), due to the analyzed timeframe, the positive sign of wind generation and EU ETS prices on the revenues can be seen in the context of the future closing of fossil power plants, but further analysis would require a larger dataset. These results with the mentioned limitation of the approximation of average revenues and costs from the price distribution can serve as signals for storage investors as a future increase in wind generation is expected in the WB region, along with the imposition of carbon taxes. Further discussion on the future development of energy storage is provided in the next chapter.

5.5.3 Prospects for storage in the Western Balkan countries

The previous paradigm of the one-way route of electricity (from the inflexible fossil or nuclear power plants in combination with hydro to the consumers) has changed due to the replacement of the production from fossil fuels with renewable energy sources for the mitigation of greenhouse emissions. To avoid possible curtailments and allow for larger shares of RES from wind and PV, the consumer side becomes variable as demand increases. This shift where demand can dictate the changes in the supply comes from the electrification of the transport sector (electric vehicles), heating and cooling, and industry. With variable generation from one side and variable demand on the other, the balance of the power systems is attained with flexibility options such as demand response, interconnections, and generating power plants (which should be decommissioned as carbon-intensive technologies) and energy storage systems. Thus, pumped hydro systems, as matured and cost-effective technology, have recently been revitalized due to their storage capacity and duration characteristics suitable for storing large amounts of electricity over longer periods (weeks, seasons). As technical development of batteries proposes possibilities for large-scale application, because of their higher capital costs, replacements cost, and deterioration over a shorter lifetime, their viability is in the short-term applications when electricity storage is required within seconds. The highlighted differences between technologies should be analyzed given the systems requirements, and application needed, and given the cost-effectiveness of these technologies, they should be compared to other flexibility options available. As the future flexibility needs increase, the storage requirements increase as well, but by 2030 90% of global storage capacity (1600 GW) will be for battery storage, with 10% for other storage (PHS, CAES, and FESS), as predicted by (IEA, 2024). Given the energy transition in the WBC and the gradual phasing of the fossil power plants as they reach the end of their life, an increase from renewable energy sources other than hydro, and already developed hydro infrastructure, the prospects for large-scale storage to balance these changes depend on the market conditions.

The HUPX electricity market, used as a reference electricity exchange in the Western Balkan region, is highly dependent on fossil generation. In 2019. 72% of electricity generation for the total electricity demand came from fossil fuels (coal, gas, and oil generation) (Bankwatch, 2023), which illustrates the effects of this generation on the electricity market prices. Hydro generation is also highly dominant in the WB region (Fig.3.2), used for dispatching processes, with fossil generation, providing a dose of certainty to the prediction and operation of power grids. It can be expected that these large-scale run-of-river power plants continue their role in the transitional period until the wind and solar shares increase at a higher rate. The advantage of hydro generation in the WBC is their flexibility when used together with fossil power plants, they can cover a high peak demand. That is also the advantage of solar generation, but given the current state of the solar installation, and results from the empirical analysis, they can't pose a significant impact on the market. The characteristics of wind generation, which hit the EXAA electricity market, with high shares over the last decade, have influenced the overall dynamics of price spreads differently. For wind generation, variability, and residual demand can be expected, initiating coverage with higher marginal-cost plants such as gas power plants in Austria. The results from the analysis reflect the slow implementation of wind and solar renewable energy sources in the Western Balkan countries over the analyzed period, hence predictions regarding their effects on the future market conditions and storage opportunities will require a wider dataset. As fossil power plants are phasing out, it can be expected that market conditions change in the future. Until then, resulting from the conducted model, the economic value of storage depends on the hydro generation and carbon prices. The future wind and solar generation development corresponds with the increase in the EU ETS prices. Higher carbon prices are driving factors for wind and solar development, with the increase in costs of electricity from the fossil power plants and ultimately they will pose different effects on the storage opportunities. The future effects, provided with the conducted analysis, correspond to the predictive results of RES development in the WBC by 2050, as analyzed by (Szabó *et al.*, 2019), as it says: *"After the initial increase in the electricity prices because of CBAM, effects of RES installment will impact merit order curve after 2040 and lower electricity prices"*. The modeled approach predicts the highest increase in wind generation, followed by small-scale PVs. Additionally, it is predicted by (Falcan *et al.*, 2022) that by 2050, the Contracting Parties of the Energy Community have to achieve an increase of renewables by a factor of four, while the highest increase will be from the PVs. These predictions show potential in wind and PV investments that is strongly related to EU ETS prices, as the linear regression model shows. The future impact of these investments depends on other factors as well, hence the model can be expended in the future analysis with an additional dataset. The analysis shows that the higher hydro generation for the WB region can decrease revenue opportunities for storage given the analyzed market conditions and energy systems. An increase in EU ETS prices will impose the increase of electricity costs from fossil generation in the transitional period, and higher wind and solar investments, consequently leading to higher price spreads. It can be expected that hydro generation will remain their leading renewable energy source role in the Western Balkan with current installations, hence, possibilities for price arbitrage of energy storage systems are justified. Compared to the EXAA electricity market, an increase in RES generation, which has marginal costs of zero, has displaced gas power plants, which cover peak demand in the merit order curve, leading to lower electricity market prices. The case of Austria, with more than 80% renewable generation (IRENA, 2022) and 24% fossil generation (Bankwatch, 2023), does not demonstrate the economic justification of storage, given the analyzed model and market conditions. This is because the costs given the analyzed timeframe were higher than revenues for most full load hours for Austria, but considering other events that affect prices, such as a decrease in gas supply or weather conditions, future price spreads cannot be excluded, despite the lower prices. Austria plans to reach 100% renewable generation by 2030, hence, incorporating energy storage or other flexibility options, such as demand-response or imports of electricity, will be required.

As WBC are still fossil-dependent, the economic viability of storage systems depends on the future market conditions (impact of the RES on the merit order curve in the conditions of closed fossil power plants) and other flexibility options available. The conducted research finds positive market signals in the WBC for 500, 1000, and 2000 full-load hours of PHS arbitrage. The future development of RES will impose a stronger need for flexibility, but the integration of long-duration storage systems is at a pace with the costs, other flexibility options, and market incentives. Revenue stacking is one of the proposed market mechanisms for storage owners to increase their profitability (Parra and Mauger, 2022), or long-term policy mechanisms such as price floor or subsidies as proposed by (Lai and Locatelli, 2021). The required future storage capacities will be provided with a different application of storage and in different locations, possibly near generation sites to avoid transmission costs (Cárdenas et al., 2021), as grid fees can decrease arbitrage value (Mercier, Olivier and De Jaeger, 2023). The storage remuneration policies and the involvement of energy storage in the capacity and ancillary markets can increase energy storage revenues. The analysis from the thesis is limited to the energy storage values in the wholesale markets, hence the effects of the energy storage in the other markets can be analyzed in future research. Regardless of large-scale storage challenges, energy storage systems are inevitable parts of the carbon-neutral future within their applications in all parts of the power systems from generation (complementing variable renewables or as peak capacity), grids (as frequency regulation or congestion management) and behind-the-meter (self-consumption). The speed of the energy transition is an issue of different political and environmental concerns. Nevertheless, the potential investors and utility companies have economic justification for energy storage systems implementation in the Western Balkan region. The obtained results within the presented Chapters, provide the thesis with universal conclusions regarding the economics of storage for electricity and their prospects in the electricity markets.

6 Summary and conclusion

This thesis contributes to the growing research on storage systems for electricity and their value given the rising flexibility needs in the circumstances of decarbonization that is underway. A literature review of storage systems discloses technological characteristics that impose different modeling options for their implementation in the grids, with scarce economic justification analyses. Energy storage will play a crucial role in securing a balance in the demand-supply curve, as electrification in the transport and heating sector continues and proposes unpredictable demand, as opposed to the increasing variable RES supply. Hence, the core objective of this thesis is to provide a detailed techno-economic analysis of storage systems for electricity in the changing conditions of the electricity markets and increased flexibility requirements. The answer to **the first research question**: *"Under which conditions is the integration of energy storage systems in the electricity market economically feasible?"* lies in the characteristics of the relevant energy systems and the Levelized costs of storage. These costs strongly differ depending on the storage application characterized by discharge hours and number of cycles, capital costs, and electricity market price. Hence, despite the technical development of the analyzed batteries, they can't compete with PHS for large-scale applications, but their fast response time allows them to be more applicable as ancillary services. The LCOS would need to decrease for NaS three times, for Pb batteries six times, and for Ni-Cd and Li-ion eight times to be competitive with the new PHS (111 €/MWh for HUPX and 105 €/MWh for EXAA in 2019), given the 300 cycles per year and 8-hour discharge time. A technological improvement of the Li-ion batteries with the highest efficiency (>95%) among other electrochemical storage, doesn't impose requirements for large-scale application, as their high life cycle costs can't be covered by revenues given the effects of the analyzed market conditions (Chapter 4). The modeled optimization results in the average profits for PHS being 70% lower in the EXAA market for 2000 full load hours, and 76% lower for 1000 full load hours, when compared to the HUPX market, while negative for 500 full load hours. Driving factors of energy storage economic value as flexibility measures in the electricity markets are price spread in the electricity markets (which is a matter of fossil dependency and installed shares of renewables) and the number of full load hours. Considering the described features of the Western Balkan countries used as a novelty study case in the thesis**, the second research question:** *What are the major prospects and barriers to implementing different types of energy storage systems in the Western Balkan countries?* finds PHS investing potential among analyzed battery technologies for large-scale storage. The dependency of storage revenues on the price spreads from the systems that cover off-peak prices with inflexible generation from fossil power plants benefits the PHS implementation in the WBC. The prospects of using PHS for energy arbitrage, or as ancillary services will benefit utility companies as they can gain competitiveness in the wholesale markets. Besides revenues, reaching national targets for decarbonized systems, while phasing out the fossil power plants, inflicts a challenging energy transition for WBC, thus the prospects of PHS are promising in the future flexibility requirements, while battery storage integration depends on the further decrease of costs. For **the third research question**: *How does future renewable generation influence energy storage development in the Western Balkan countries?*, the empirical results from Chapter 5 indicate that with higher hydro generation, revenues from price arbitrage in the WBC will decrease, while a positively strong correlation between EU ETS prices and wind and solar generation shows the effects of higher carbon prices and imposition of the CBAM mechanism as an accelerating measure for wind and solar generation increase. The future of energy storage systems in the WBC depends on the rate of wind and solar investments, the closing of fossil power plants, and EU ETS prices. In the short run of the energy transition in the WBC, until proposed targets from the NECPs are reached, there is a high potential for PHS arbitrage. In the long run, there is the possibility that storage becomes subject to revenue cannibalization, hence the future storage implementation will depend on the decrease in battery costs and other flexibility options.

The results from the conducted techno-economic analysis in this thesis propose that flexibility achieved with large-scale electricity storage is still reached dominantly with PHS. Despite the accelerated research in electrochemical storage and technical development, the batteries for large-scale applications don't meet economic requirements yet (negative arbitrage value in Chapter 4). As storage systems are inevitable parts of the future systems (complementing RES development and avoiding their curtailment, decreasing transmission congestions or behind-the-meter allowing self-consumption), they require incentives to gain competitiveness in the current market designs. These findings correspond to the recent research by (Lamp and Samano, 2022), (Williams and Green, 2022), (Haas, R. et al. 2022). The prospects of battery storage are in other applications, especially in transport, frequency regulation, or ancillary services, given their fast response time, or as a complement to PV self-consumption. Taking into consideration the fluctuations of the material costs of batteries, because of the mining and exploitation conditions, the obtained results are subject to future analysis that depends on the development of the batteries until they reach a status of mature technology. Contrary, the maturity of the PHS technology is already in the third generation, with zero replacement or disposal costs, but finding new locations and meeting all environmental requirements, could impact changes in future investment costs (site specific), though this wouldn't inflict significant changes to the overall conclusions obtained in this thesis. The results from the thesis demonstrate that besides technical requirements, temporal and geographical conditions strongly impact storage values in arbitrage with prospects in the energy systems where off-peak electricity generation is attained from fossil sources. The arbitrage value of storage is lower in the systems with higher RES generation (lower profits for the Austria case) while an increase in RES will provide lower arbitrage opportunities in the fossil-dominant systems (negative correlation with hydro-revenue). These results indicate negligible effects of the higher full load hours (insignificant model for 3000 and 4000 full load hours in Chapter 5) on the storage revenues given the higher generation of wind and PV over the analyzed timeframe, which reflects the effects of other flexibility options used in analyzed market conditions (WBC countries). The storage arbitrage revenues for PHS in the WBC conditions didn't follow an increase in the PV and wind generation from the analyzed timeframe, as flexibility could have been maintained with the 2000 full load hours. Hence, the analysis from this thesis indicates that energy storage systems are in pace with a decrease in investment costs (batteries), market incentives, and other flexibility options (interconnection, power generators), rather than just higher shares of RES. Deployment of the storage systems requires analysis of the entire power system. Depending on the generation mix, shares of RES, gas and oil prices, and other global factors such as weather conditions, fossil fuels supply, and unexpected events, market conditions for storage arbitrage will differ. The effects of the future decarbonized systems without fossil fuels, with higher shares of variable wind and solar generation impacting the merit order curve and decreasing price spreads for storage revenues while increasing the storage capacity requirements, are the subject of future research. New storage added to the market is at risk of "revenue cannibalization", (decreasing peak prices with discharge and increasing the off-peak prices) and it will be analyzed with further storage development (Schmidt, O. and Staffell, I., 2023). These future challenges for storage systems in the electricity markets will propose a combination of revenue streams for gaining storage benefits. Utility companies or storage investors can increase storage value by using it in different applications during their lifetime, i.e. "revenue stacking" such as using PHS for arbitrage and as ancillary service, or as congestion management for allowing the surplus electricity to be managed. The future RES development will undoubtedly accelerate an increase of energy storage capacity, but how the markets respond and provide adequate pricing signals depends on the regulatory framework and energy policies that are subject to further research.

For energy storage, a technology with rapid development, it can be expected that a large disparity in costs for PHS and batteries will decrease in the future. As the thesis model can be applied to any study case, the input parameter *Clcoe* is subject to changes, along with the input parameters for the electricity market conditions (with the updated market prices using perfect foresight as in the thesis model or with the prices forecasting models). Given the further RES development, decommissioning of the fossil power plants, electrification of transport and heating sectors, and the emergence of self-consumption, storage systems are inevitable parts of the future. Prospects for their integration in markets will depend on other flexibility options (i.e development of demand response, stronger interconnections, or power generators if they aren't decommissioned as they are fossil-fueled) unless they decrease investment costs (batteries), provide hybrid systems (combining the PHS and battery storage or PHS with PV and wind plants) or expand their applications by participating in other markets (providing ancillary or capacity services). These implications are subject to future analysis, as the model in the thesis only captures the effects of the large-scale storage integration in the wholesale markets. Higher arbitrage values in the conditions of fossil-dependent systems and already installed hydroelectric infrastructure indicate prospects for PHS investments in the WBC. These findings can be considered from the two aspects- until the WBC reaches their proposed targets for the mitigation of greenhouse emissions and when it reaches. During the transitional period, significant changes can be expected that will affect changes in the market conditions, hence the obtained results should be further analyzed. One of the first is the imposition of CBAM which will be reflected in the market prices and investments in wind and PV installations. Thus, as the previous historic installations served for the empirical analysis, the obtained results can be further analyzed given the rate of the future development of RES and the closing of fossil power plants. A HUPX exchange used in this thesis can be substituted in the future analysis given the establishment of the required internal electricity market in the WB, attached to the pan-European. The changes in the prospects for energy storage systems in the long run of the energy transition in the WBC, when there is a significant increase in wind and PVs, depend on the level of the substitute technology for off-peak prices. These implications will be confirmed throughout the scope of the RES development in the Western Balkan countries, along with the accelerated closing of the fossil power plants, and investment in the flexibility systems.

7 List of papers

Topalović, Z. et al. (2022) 'Economics of electric energy storage . The case of Western Balkans', Energy Journal, 238. doi: 10.1016/j.energy.2021.121669.

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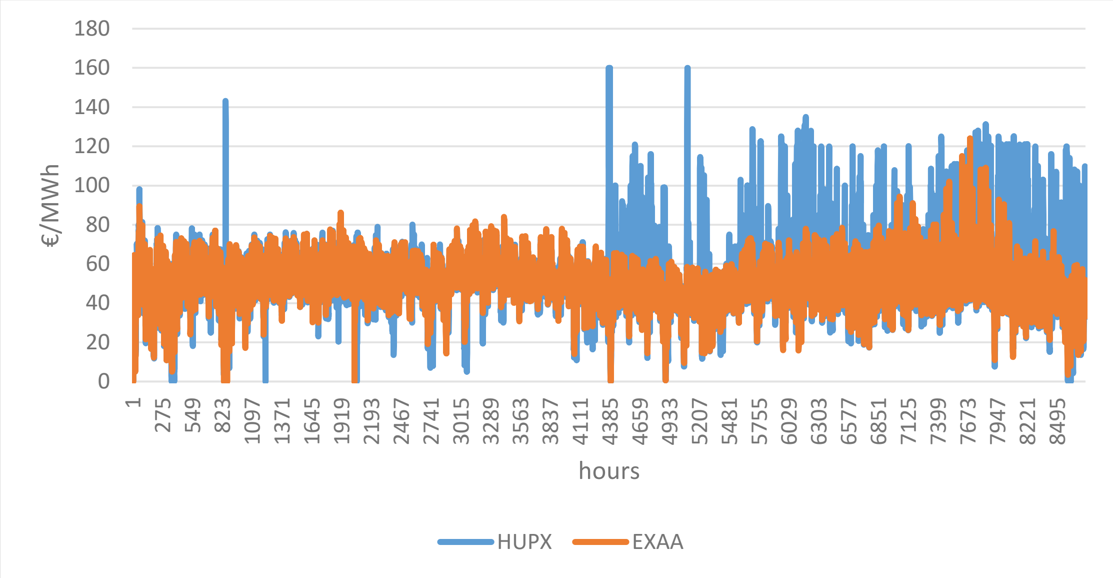
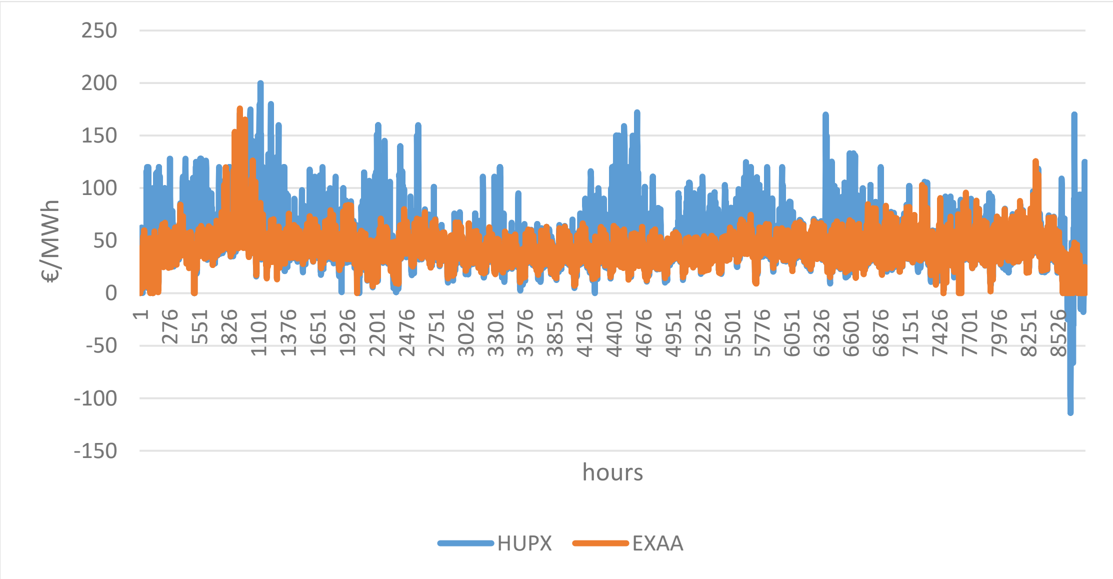
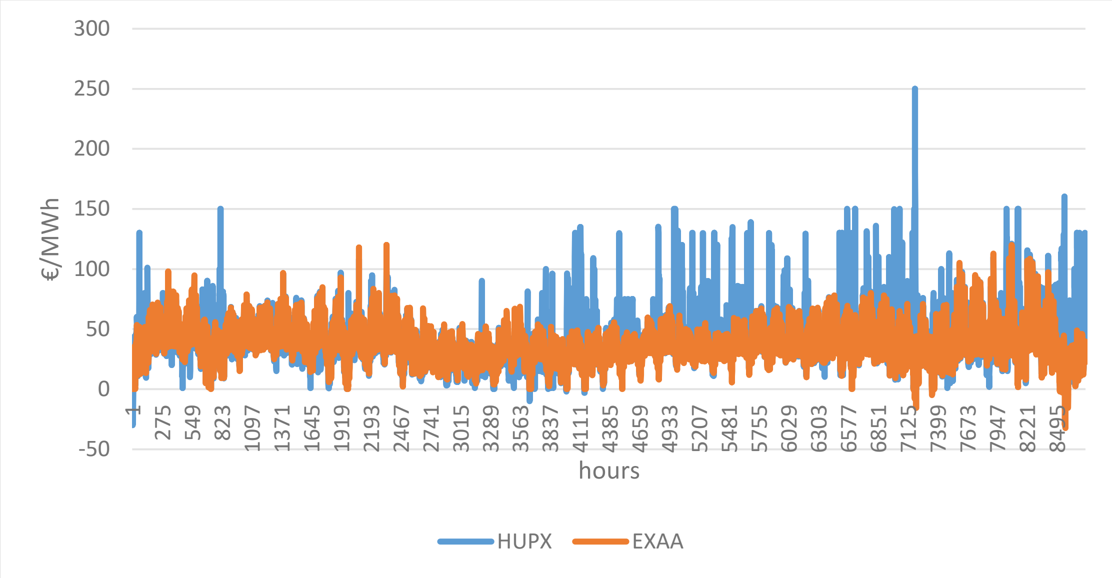
Appendix A



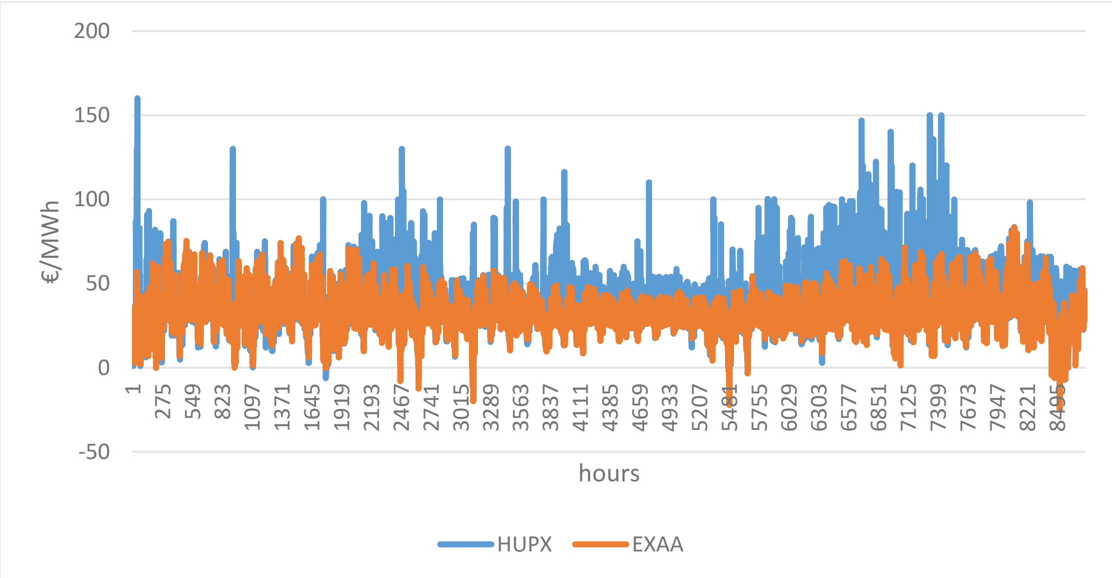
Appendix A 1 Day-Ahead electricity market prices in hourly distribution from HUPX and EXAA electricity exchanges in 2011.



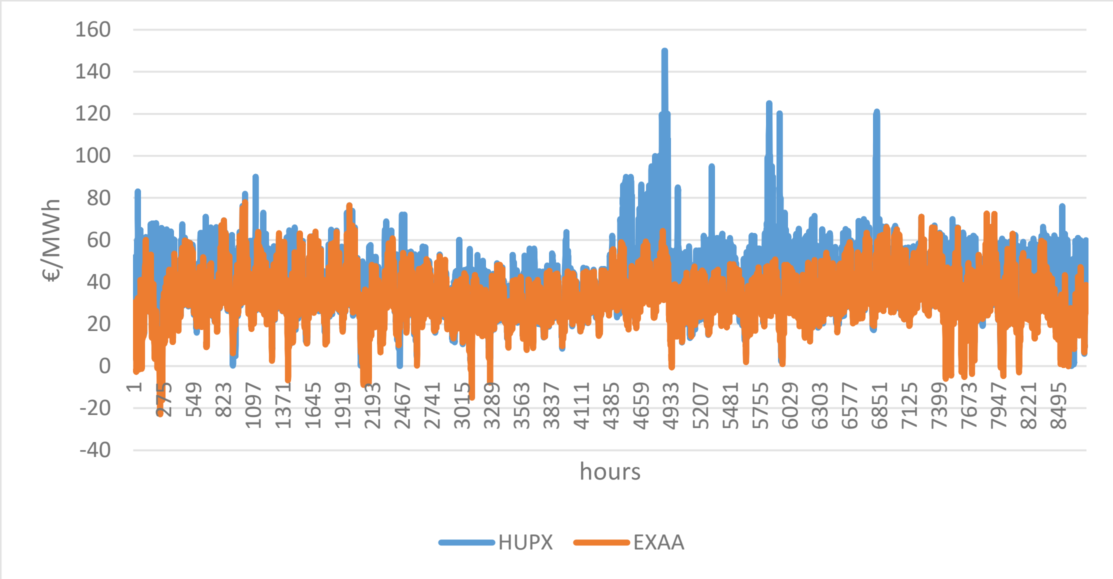
Appendix A 2 Day-Ahead electricity market prices in hourly distribution from HUPX and EXAA electricity exchanges in 2012.



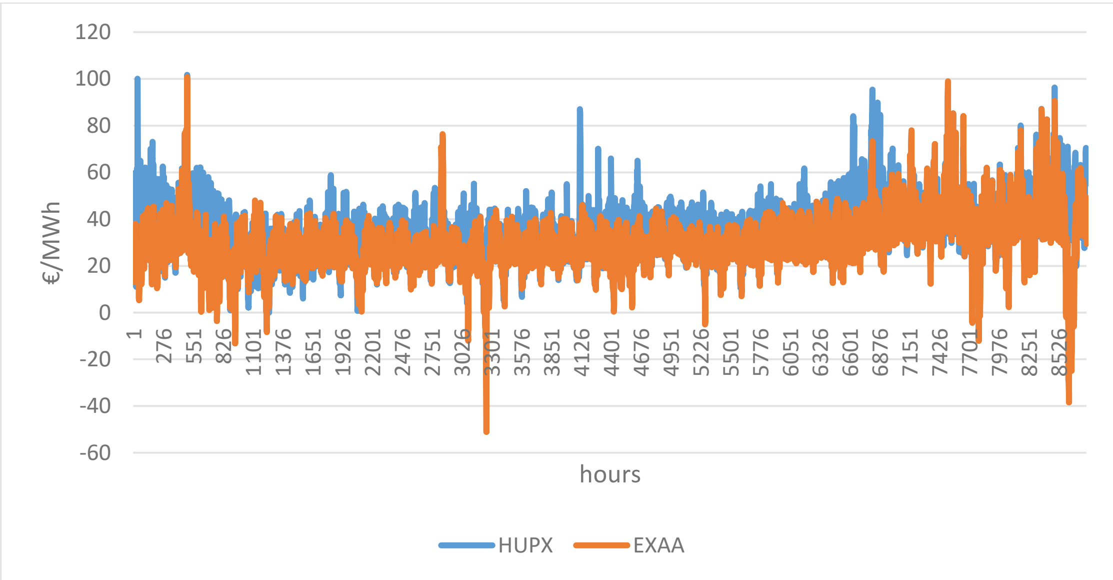
Appendix A 3 Day-Ahead electricity market prices in hourly distribution from HUPX and EXAA electricity exchanges in 2013.



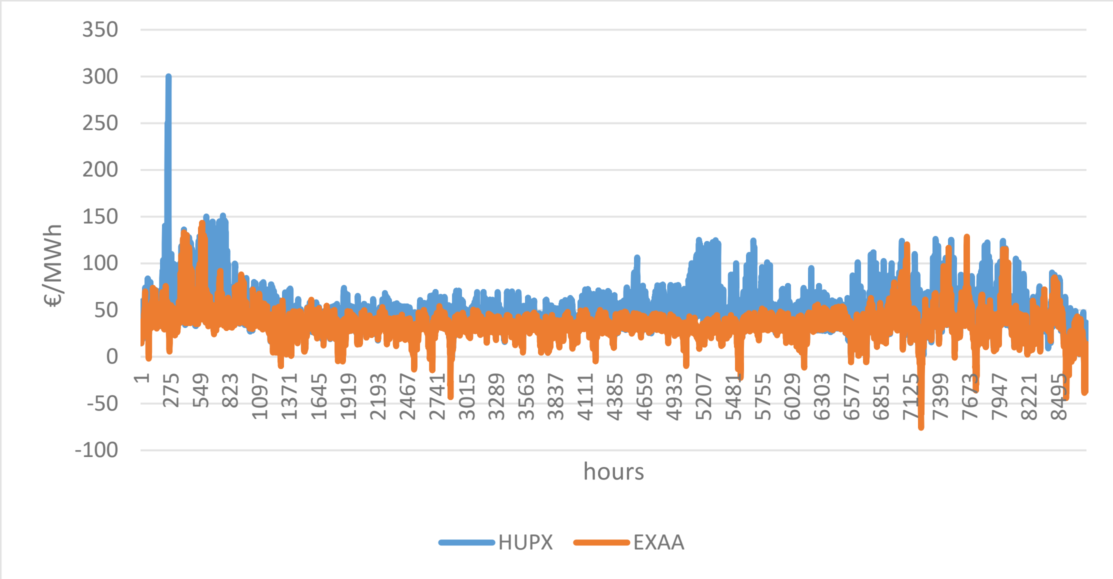
Appendix A 4 Day-Ahead electricity market prices in hourly distribution from HUPX and EXAA electricity exchanges in 2014.



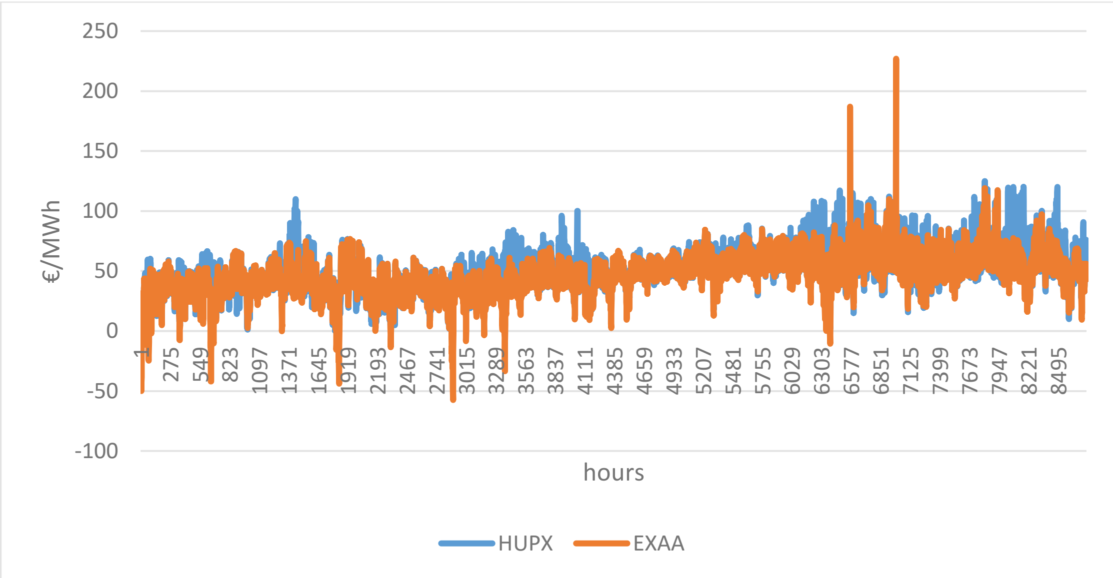
Appendix A 5 Day-Ahead electricity market prices in hourly distribution from HUPX and EXAA electricity exchanges in 2015.



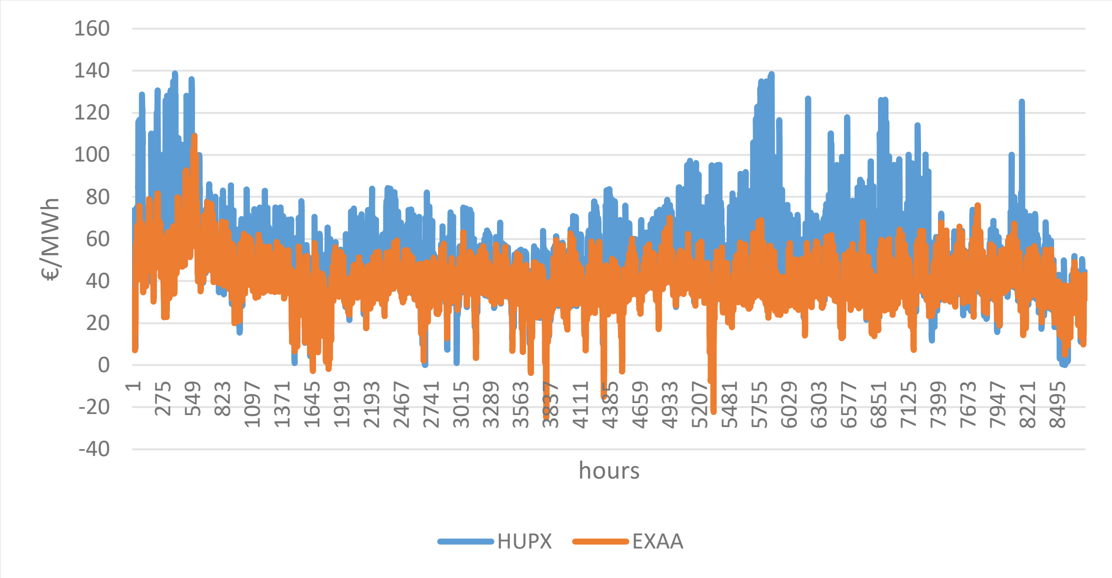
Appendix A 6 Day-Ahead electricity market prices in hourly distribution from HUPX and EXAA electricity exchanges in 2016.



Appendix A 7 Day-Ahead electricity market prices in hourly distribution from HUPX and EXAA electricity exchanges in 2017.



Appendix A 8 Day-Ahead electricity market prices in hourly distribution from HUPX and EXAA electricity exchanges in 2018.



Appendix A 9 Day-Ahead electricity market prices in hourly distribution from HUPX and EXAA electricity exchanges in 2019.