Storage economy and markets

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Edisson Villa-Ávila[1,2], Paul Arévalo[1,2], Danny Ochoa-Correa[1], Michael Villa-Ávila[1], Juan Leonardo Espinoza[1] and Esteban Albornoz[1]
[1]Faculty of Engineering, Department of Electrical, Electronics and Telecommunications Engineering (DEET), Universidad de Cuenca, Balzay Campus, Cuenca, Azuay, Ecuador,
[2]Department of Electrical Engineering, University of Jaén, Jaén, Spain

Introduction

In recent years, the increasing penetration of renewable electricity has been one of the reasons for the very low electricity prices in electricity markets (Abdon et al., 2017). The growing production of renewable energy has been accompanied by challenging situations for grid operators in terms of transmission and distribution loads, as well as monetary losses for conventional power generation plants due to production curtailment (Wang et al., 2023). This trend is expected to continue in the future as renewable electricity generation continues to grow (Xie et al., 2023). A possible remedy for the temporal mismatch between supply and demand is electricity storage (ES) (Lechón et al., 2023), which has led to increased research efforts in storage technologies over the past few years, as shown by several comprehensive technology reviews (Lechón et al., 2023). Since most new renewable energy sources are distributed and their success is at least partly due to the pursuit of higher levels of self-sufficiency (Newbery, 2023), interest in local storage solutions for districts, communities, and even individual households is growing (Chu et al., 2024). This contrasts with the existence of a large base of conventional large-scale pumped hydroelectric plants and has given rise to a growing market for stationary batteries and the development of new technologies, such as small-scale compressed air energy storage systems (Maghami & Mutambara, 2023).

The levelized cost of stored electricity (LCOES) is a fundamental economic parameter that evaluates both investment and operational costs over the lifespan of ES (Manandhar et al., 2023). It is essential to consider that the variability in the number of operational cycles can significantly influence the economic performance of storage (Manandhar et al., 2023). Additionally, each storage application is linked to a specific charge and discharge pattern, affecting its efficiency in different operational contexts. Regarding the environmental aspect, the use of electricity storage can contribute to reducing dependence on nonrenewable energy sources and mitigating associated carbon emissions (Cisterna et al., 2020). However, it is crucial to recognize that the implementation of these technologies may entail adverse environmental effects, depending on the context and the type of energy they replace. Cisterna et al. (2020) examined how

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large-scale storage technologies affect carbon dioxide emissions in different renewable energy penetration scenarios. Abdon et al. (2017) evaluated the technoeconomic and environmental performance of stationary electricity storage, comparing technologies such as pumped hydro storage (PHS), isothermal and advanced adiabatic compressed air ES (AA-CAES), stationary lithium-ion batteries, and the power-to-gas-to-power (P2G2P) process. The rapid growth of intermittent renewable electricity has generated interest in the economic potential of ES. Kloess and Zach (2014) analyzed the economic performance of storage technologies for load leveling operation in the German and Austrian electricity markets. Kondziella et al. (2023) evaluated four technologies: PHS, AA-CAES, hydrogen storage (H_2), and methane storage (CH_4). There is potential seasonal use for H_2 and CH_4 if costs decrease. The results indicate low incentives for investment in storage, which could hinder the integration of renewable electricity.

The European Union is currently taking an effort to increase the share of renewable electricity (RES-E) in order to reduce carbon emissions in the energy sectors. The expected shares of fluctuating RES-E production will pose a major challenge for the electrical system, requiring greater flexibility from backup power plants to cover the residual load and higher transmission capacities to balance supply and demand over wider areas (McLaughlin et al., 2023). ES is considered a key component in addressing these challenges. García-Miguel et al. (2024) and Maghami et al. (2024) demonstrated the technical and economic benefits of using storage in isolated electrical systems. García-Miguel et al. (2024) showed the benefits of combining wind farms with ES. Palma et al. (2024) indicated that ES increases overall social welfare in the electricity market, and Maghami et al. (2024) found that ES leads to benefits in an electrical system with high wind penetration.

Cóndor (2021) and Gao et al. (2023) showed how electricity storage plants can help reduce transmission costs in an electrical system with wind generation. Benito & Arena (2020) found that storage plants are more viable than thermal power plants as a flexibility option up to a certain installed capacity. This aligns with the results found by Ölmez et al. (2024) and Zhu et al. (2024), who analyzed the optimal economic storage capacity for the German electrical system. Although the economic benefits of ES seem evident at the system level, its economic performance from an investor's perspective remains uncertain. Assareh and Ghafouri (2023) showed that the profitability of CAES remains negative despite the economic benefits it brings to the electrical system. Cetegen et al. (2024) and Saleh-Abadi et al. (2023) analyzed the current and future economic potential of CAES in the European market. Martinez and Iglesias (2024) conducted an economic assessment based on models of ES plants in different European countries according to historical price data. Altea and Yanagihara (2024) and Hadelu et al. (2024) showed that the injection of intermittent renewable energy has reduced the revenues of PHS plants in the German and Austrian electricity markets. In the economic evaluation, Le et al. (2024) analyzed these technologies in the German electricity market, noted for its rapid growth in intermittent RES-E. Hurta et al. (2022) examined the annual revenues of storage technologies in load leveling. Bulut and Özcan (2024) helped to understand the operation of ES and the differences between technologies, including the developing power-to-gas technologies. A focus on the Austrian−German market reveals the effects of increasing RES-E on the operation and revenues of storage.

Fig. 9.1 illustrates the traditional energy market, characterized by the use of conventional sources such as coal, oil, and natural gas for the production, distribution, and consumption of energy. Large utility companies control this market, generating and distributing electricity through a centralized electrical grid (Haji Bashi et al., 2022). Energy production is centralized, with power plants located far from end-users. Electricity is transmitted over long distances via high-voltage transmission lines and distributed to local communities via low-voltage distribution lines. Customers pay a fixed rate based on fuel costs, maintenance, operation, and regulatory requirements, although they often desire more control over their rates or the energy source (Liang et al., 2023). This market has been criticized for its negative environmental impact due to carbon emissions and its inefficiency in transmission and infrastructure construction (Watson et al., 2024).

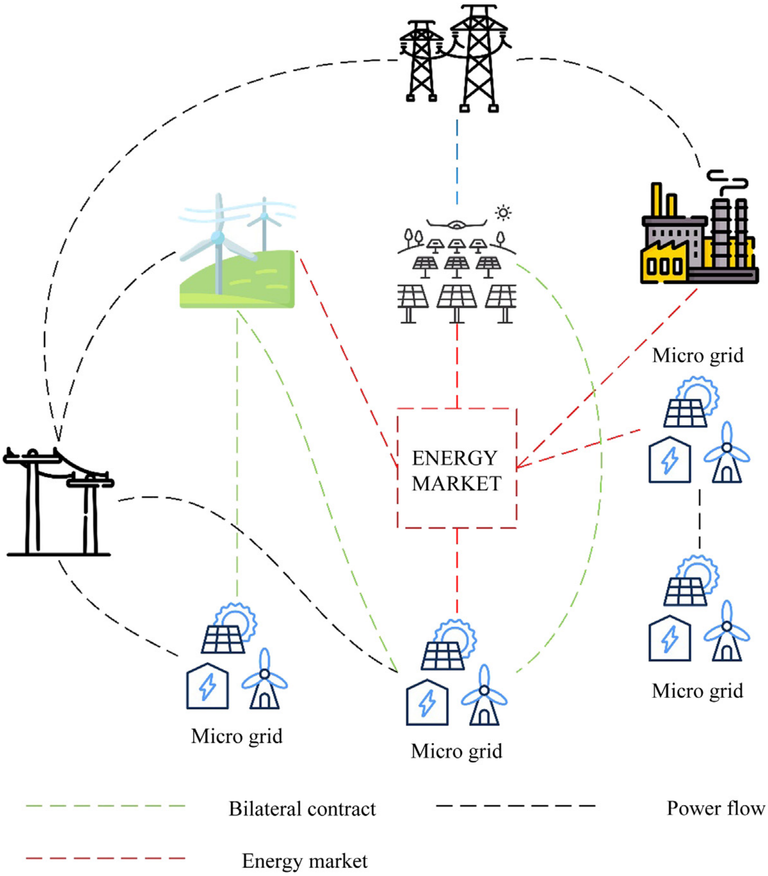

Figure 9.1 Block diagram of the energy market.

Literature review

In recent years, there has been significant interest in research on ES batteries in residential systems (Chreim et al., 2024; Al-Wreikat et al., 2022). This focus is due to their essential role in integrating renewable energies, balancing supply and demand, and allowing for active consumer participation in the electricity market. However, the high capital cost of these batteries remains a significant obstacle to their widespread adoption, even in the form of hybrid photovoltaic battery energy storage system (PV-BESS) installations (Hokmabad et al., 2024). The main research areas focus on optimal system sizing, technoeconomic analysis, and efficient battery management, considering different operational objectives (Cai et al., 2024). Bosu et al. (2023) and Jannesar Niri et al. (2024) addressed these topics from various perspectives. For instance, an overview of ES technologies has been provided, highlighting their importance in managing renewable energy fluctuations and addressing challenges such as frequency control and load management. Other studies have compared the advantages and disadvantages of ES batteries and pumped hydroelectric storage (Haji Bashi et al., 2022), emphasizing their role in improving the grid's capacity to handle intermittent renewable energy generation.

Chatzigeorgiou et al. (2024) examined the feasibility and sizing of PV systems, highlighting the widespread use of simulations for technoeconomic analysis and the growing popularity of PV-BESS systems. Energy management strategies have been proposed to improve the demand profile during peak hours, including the integration of photovoltaic systems with storage batteries in commercial settings (Kebir et al., 2023). In terms of future research, key areas identified include technoeconomic analysis (Lin & Bagnato, 2024), operational control (Yang et al., 2021), system sizing, and demand response (Chatzigeorgiou et al., 2024). The need to improve the economic viability of ES batteries is emphasized, as well as the development of effective demand-side management (DSM) strategies and operations in different application contexts (see Fig. 9.2) (Cha et al., 2023).

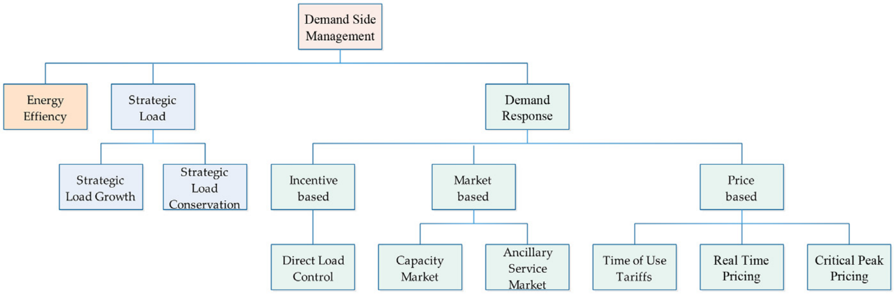

Figure 9.2 DSM techniques based on timing and impact of action. *DSM*, Demand-side management.

Storage technologies

This section presents the four ES technologies analyzed (Cho et al., 2015; Lee et al., 2023), for the integration of intermittent renewable energy into the European electricity market. In addition to PHS, three alternative options are analyzed (Altea & Yanagihara, 2024). Each technology has specific site requirements (Altea & Yanagihara, 2024). A brief description of their operation is provided, and their technical and economic parameters are analyzed, including storage components and the balance of plant (Khan et al., 2024). The storage capacity is decoupled from the discharge power for all technologies, except for stationary lithium-ion batteries and PHS (He et al., 2021).

Combined assessment methodology

Abdon et al. (2017) employed a combined assessment methodology to analyze the economic and environmental performance of electricity storage in various applications and system sizes. Scenarios are defined by considering different applications and sizes, then technologies are chosen, and technical parameters are assigned based on the literature (see Fig. 9.3). The levelized cost (EUR/kWh) and greenhouse gas emissions (CO_2 eq/kWh) are quantified to evaluate the economic and environmental performance of various technologies, including PHS (He et al., 2021), isothermal air energy storage and AA-CAES (Chen, 2023; Javaheri & Shafiei Ghazani, 2023), lithium-ion batteries, and P2G2P (Cruz-Soto et al., 2022;

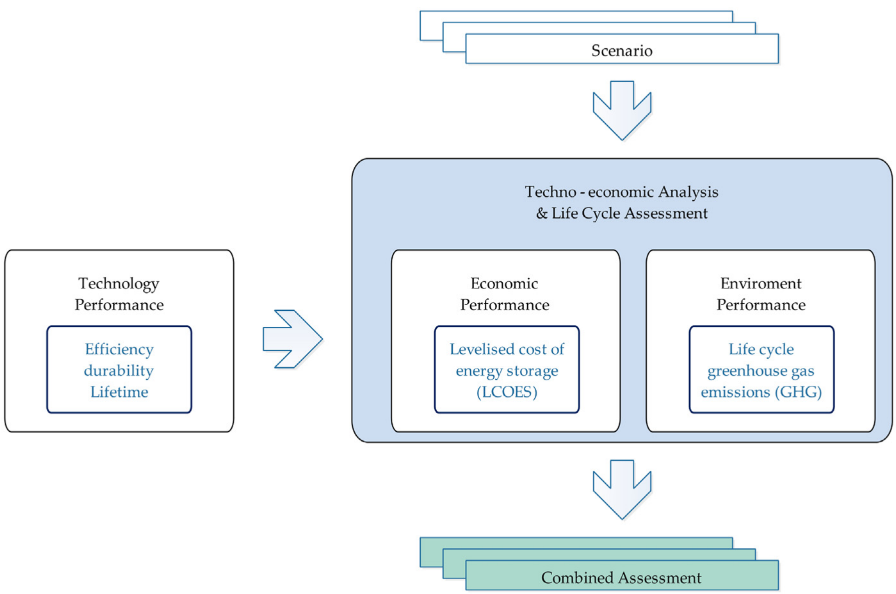

Figure 9.3 Methodology framework for the assessment of electricity storage technologies.

Park et al., 2024). Three generic time scales for stationary ES (short, medium, and long-term) (El-Sayed et al., 2023) are proposed, and two system scales are selected to characterize decentralized and centralized systems (Panda et al., 2023). Jamroen and Vongkoon (2023) and Williams et al. (2023) conducted a sensitivity analysis to understand the variability of the results, considering parameters such as lifespan, efficiency, costs, and prices of stored electricity. The aim is to understand the economic and environmental implications of various combinations of technology, application, and system scale.

Life cycle assessment

Niu et al. (2023a) used a life cycle assessment approach to evaluate the environmental impact of ES technologies. It focuses on climate change, measuring the carbon dioxide equivalent emissions per kWh of electricity supplied from storage. The functional unit is 1 kWh of electricity supplied from storage systems, covering from material production to final disposal. Life cycle inventory data comes from various sources, adjusted to ensure a consistent assessment. Sources of stored electricity include wind turbines, photovoltaic solar panels, and average grid electricity (Altea & Yanagihara, 2024).

Pumped hydro storage

PHS is a mature technology and the most common form of electricity storage, accounting for the majority of installed capacity worldwide. In Switzerland (Mearns & Sornette, 2023), for example, there are PHS plants ranging in size from small installations to large-scale projects under construction. Investment costs for PHS plants can vary significantly depending on local conditions such as topography and geology (Altea & Yanagihara, 2024). In general terms, PHS is widely used in Europe and has proven effective in integrating intermittent energy sources such as wind (Henke et al., 2022). These plants have the capability to provide both load leveling and ancillary services due to their rapid response. The efficiency of PHS varies depending on the technology used and can range between 65% and 87%.

The power capacities of PHS plants can range from a few hundred MW to 1500 MW, with investment costs typically expressed in euros per kW installed, ranging from 500 to 1500 €/kW. Specific investment costs related to ES capacity can range from 5 to 100 €/kWh. To estimate the investment costs of a new PHS project, a two-dimensional approach is considered, taking into account both power capacity and ES capacity. However, it is important to note that finding suitable sites for the construction of new PHS plants can be challenging, especially in regions like Germany and Austria, where suitable sites are often located in remote and mountainous areas (Henke et al., 2022).

Adiabatic compressed air energy storage

CAES plants harness the potential energy of compressed air to store electricity (Connolly et al., 2016). This process involves compressing air at high pressure and storing it in either pressurized containers or suitable geological formations such as salt caverns. When the compressed air is released, it powers turbines that produce electricity. There are two main types of CAES plants: diabatic and adiabatic (AA-CAES) (Kloess & Zach, 2014). Diabatic CAES plants are limited globally, while AA-CAES plants are in a more conceptual phase. Large-scale CAES plants rely on the availability of suitable geological formations for storing compressed air (Bennett et al., 2021).

Bennett et al. (2021) primarily focused on AA-CAES due to their higher efficiency and lack of need for fuels during discharge, unlike diabatic CAES, which require natural gas during this process. Although AA-CAES are still in the planning and demonstration phase, investment costs are estimated based on data found in CAES and thermal storage. Investment costs for CAES reported in the literature vary depending on storage capacity and power, ranging from 5 to 100 €/kWh and from 400 to 800 €/kW, respectively (Comodi et al., 2017). For estimating AA-CAES costs, both storage capacity-related and power-related components are considered. Capacity-related costs are set at 600 €/kW, in line with CAES costs found in the literature. Additionally, capacity-dependent storage costs are set at 70 €/kWh, reflecting the additional thermal storage requirements of AA-CAES compared to conventional CAES (Shabani et al., 2020).

Hydrogen storage

In hydrogen storage systems, electricity is converted into hydrogen through the process of electrolysis. This hydrogen can be stored in pressure vessels or in suitable geological formations such as salt caverns or rock, especially for large-scale central plants. To recover stored energy, hydrogen can be burned in thermal power plants or converted back into electricity through a fuel cell (Lin & Bagnato, 2024). In the context of the electric system, this would involve its use in single-cycle gas turbines (GT) or combined-cycle GT (CCGT), resulting in a storage cycle efficiency of 33%−40%, depending on component efficiencies reported by Li et al. (2024) and Martsinchyk et al. (2024). Since there are currently mostly demonstration plants for hydrogen storage, investment costs are estimated based on system components. According to Haroon Bukhari et al. (2023) and Yue et al. (2021), current electrolysis costs are around 1000 €/kW, with potential short- and medium-term reductions to around 500 €/kW. On the other hand, investment costs for thermal power plants vary depending on the technology applied, ranging from 300 €/kW for GT to 600 €/kW for CCGT plants in Europe (Peng et al., 2023). For hydrogen cavern storage, a cost of approximately 0.5 €/kWh is considered, according to Hassan et al. (2023) (see Table 9.1).

Renewable methane storage

Renewable methane storage (CH_4) offers an alternative for storing electricity through a process involving the conversion of electricity into hydrogen and then into methane by adding CO_2 (Abbas et al., 2023; De Maron et al., 2023). The produced methane can be injected into the natural gas grid or stored in specific facilities for this purpose.

Table 9.1 Efficiency and investment costs of hydrogen and methane storage components.

	Efficiency (%)	Investment costs (€/kW)	Sources
Hydrogen storage electrolyzer	75	500	Le et al. (2024); Lystbæk et al. (2023); Shirizadeh and Quirion (2023)
Compressor	89		Yang et al. (2023)
Thermal power plant (GT or CCGT)	50–60	300–600	Solovey et al. (2023); Mukherjee et al. (2023)
Total	33–40	800–1100	
Methane storage	75	500	Rodriguez et al. (2023); Bhandari et al. (2014)
Electrolyzer	80	500	Lystbæk et al. (2023); Shiva Kumar and Lim (2022); Niu et al. (2023b)
Compressor	97		Chen (2023)
Thermal power plant (GT or CCGT)	50–60	300–600	Abdon et al. (2017); Cruz-Soto et al. (2022); Quarton and Samsatli (2018)
Total	29–35	1300–1600	

CCGT, Combined-cycle gas turbines; GT, gas turbines.

This requires access to the natural gas grid near the production site. Reconversion to electricity can be achieved through conventional power plants fueled by natural gas, such as CCGT or GT (Aubin et al., 2023). This strategy leverages existing natural gas storage and distribution infrastructure, which can mitigate some challenges associated with the intermittency of renewable electricity. However, the storage efficiency of this process is relatively low, estimated between 27% and 32%, depending on the power plant efficiency (Wulf et al., 2020). Investment costs are calculated based on the components involved, with the methanation process being a factor of uncertainty due to the lack of available data. Therefore, investment costs are estimated to be similar to those of electrolysis (see Table 9.1).

Lithium-ion electrochemical battery

Lithium-ion battery technology has stood out due to its technical improvements compared to more traditional technologies. According to Cicconi and Kumar (2023) from IRENA in 2015, this technology represented the majority of installed capacity during that period. The lithium-ion battery is modular, and its available capacity ranges from several kWh up to 400 MWh in the market. In this analysis, the lithium titanate oxide (LTO) battery with nickel cobalt aluminum oxide (NCA) as the cathode material has been considered, known for its long lifespan, safety, and

Table 9.2 Storage technology specification for each application scenario.

	Short term	Medium term	Long term
1 MW	PHS LTO – NCA P2H + H_2 STORAGE + PEMFC	PHS I – CAES LTO – NCA P2H + H_2 STORAGE + PEMFC	PHS P2H + NG NETWORK + PEMFC
100 MW	PHS LTO – NCA P2M + NG NETWORK + CC	PHS AA-CAES LTO – NCA P2M + NG NETWORK + CC	PHS P2M + NG NETWORK + CC

LTO, Lithium titanate oxide; *NCA*, nickel cobalt aluminum oxide; *PHS*, pumped hydro storage.

performance, particularly suitable for stationary applications. Costs have been estimated considering both the upper and lower ranges, based on current and projected costs of the technology (see Table 9.2) (Okazaki et al., 2015).

Economic evaluation

In the evaluation, the perspective of an investor was adopted when analyzing the technologies. This involved operating plants with the aim of maximizing their own economic benefit, without necessarily prioritizing the improvement of the electrical system's efficiency or the energy market, unless contractual agreements stipulated otherwise. This approach aligned with typical framework conditions of liberalized energy markets, where ES plants are privately owned and offer their services in the open market (Amir et al., 2023).

Technological parameters

Alili and Mahmoudimehr (2023), Altea and Yanagihara (2024), and Assareh and Ghafouri (2023) presented a synthesis of the parameters used for the subsequent evaluation in Table 9.3 along with some of their key technical characteristics. Values were selected to reflect technological advancements, particularly for those technologies currently in experimental or demonstration phases. This approach provides a solid basis for comparison and analysis of the different ES technologies considered in the study, allowing for an accurate assessment of their performance and feasibility in various contexts.

Table 9.3 Storage parameters used in the analysis.

			Pumped hydro storage (PHS)	**Adiabatic compr. Air energy storage (AA-CAES)**	**Hydrogen storage (H_2)**	**Methane storage (CH_4)**
Efficiency	Charging	(%)	92	84	67	58
	Discharging	(%)	92	84	60	60
Investment costs						
Capacity specific		\$/kW	500	600	1000	1500
Energy specific		\$/kWh	30	70	0.5	0.15
Depreciation time		Years	25	20	20	20
O&M costs		\$/kW/year	4	20	20	20

Control reserve and intraday market

In some European countries (Cetegen et al., 2024; Green IRENA, 2020; Iribarren et al., 2023), control reserve has been a significant source of revenue for electricity storage systems, especially with the increasing intermittent production of renewable energy. However, the consolidation of control energy markets can lead to improved efficiency in control reserve utilization and, consequently, lower revenues for providers (Schwidtal et al., 2023). Demand and prices for control reserve vary among system operators in Europe, generating uncertainty in potential revenues for power plants. Although control reserve is not considered in this analysis, its provision could enhance economic performance, especially for highly flexible plants like PHS (Altea & Yanagihara, 2024). Intraday markets are expected to gain importance with the continuous integration of intermittent renewable energy, offering an alternative source of revenue for ES plants, thanks to price differences between base load and peak load periods in markets like EPEX SPOT in Germany (Wulf et al., 2020). Although traded volumes in these markets are still low compared to the day-ahead market, their relevance is increasing and expected to continue growing in the coming years.

Market-centric energy scenario

In a market-centric energy scenario (see Fig. 9.4), the goal of achieving zero carbon emissions is accomplished through the implementation of clean power stations, peak shaving, energy conservation, and efficiency improvement (Jamroen & Vongkoon, 2023). In this context, the energy side, the electricity grid side, and the

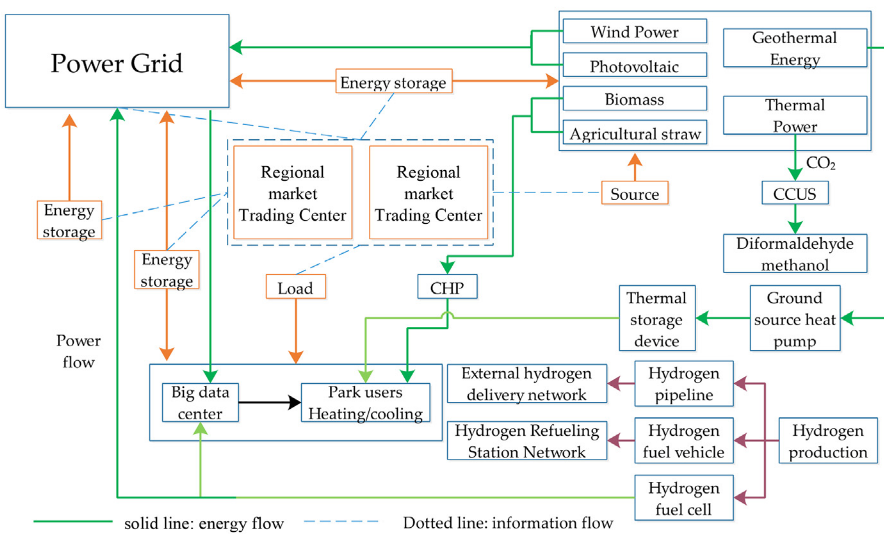

Figure 9.4 Design of market-centric energy scenarios for the industrial park.

load side share the responsibility of investing in, operating, and maintaining the ES station, jointly assuming the costs associated with zero carbon emissions (Fang et al., 2023).

Cost−benefit analysis

The cost of building an ES station is consistent across different scenarios, encompassing initial investment, operational and maintenance expenses, electricity procurement, and carbon-related costs (Yue et al., 2021; Zhu et al., 2024). This cost is directly related to the station's capacity and power. ES stations generate different benefits depending on the scenario. In the first scenario, they benefit from peak shaving, frequency modulation, ancillary services, and deferred device upgrades. In the second scenario, profitability is achieved through differential price arbitrage from peak to off-peak hours. In the third scenario, profitability comes from providing ancillary services and peak-to-off-peak price arbitrage. Hadelu et al. (2024) conducted a cost−benefit analysis, and estimates for each scenario are presented in Table 9.4.

Marketing measures

The application of ES has contributed to mitigating the volatility of renewable sources (Benavides et al., 2024), offering a technical approach to development with zero carbon emissions. However, in industrial parks (Fang et al., 2023), strategic planning and effective coordination of ES with sources, grids, and loads are essential to achieving zero carbon emissions goals. Several

Table 9.4 The cost and income of the three scenarios.

Scenarios	Power grid-centric scenario	Power user-centric scenario	Power market-centric scenario
Cost	One-time investment cost Operation and maintenance cost Electricity purchase cost Carbon emissions treatment cost	One-time investment cost Operation and maintenance cost Electricity purchase cost Carbon emissions treatment cost	One-time investment cost Operation and maintenance cost Electricity purchase cost Carbon emissions treatment cost
Income	Frequency regulation income Benefits of peak reduction Delay the benefits of equipment upgrades	Peak and valley spread arbitrage	Frequency regulation income Benefits of peak reduction Peak and valley spread arbitrage

Table 9.5 Source grid load storage coordination measures.

Subject	Synergistic measure	Synergistic effect	Benefits
Source	Power grid dispatching	Balance of supply and demand, abandon wind and light	Provide low-cost green electricity
	On-demand power supply	Balance of supply and demand, abandon wind and light	
	Smoothing output	Output adjustable	
Grid	Dispatching power	Balance of electricity supply and demand	Supply and demand balance and power quality
	Demand-side response	Dynamic grid power balance	
	Frequency modulation reserve	The system runs safety and reliably	
Load	Interruptible load	Lifting load elasticity	Green energy and elastic load
	Elastic load	Reduce electricity consumption	
	Cut peaks and fill valleys	The load moves with the source	
Storage	Power-side storage	Smooth output and energy storage	Supply and demand balance and power quality
	Grid-side energy storage	Frequency modulation, reserve, delay investment	
	Load-side energy storage	Peak-valley electricity price	

collaborative modes of grid-origin load and storage in industrial parks have been designed, including 4 collaborative subjects and 12 collaborative modes. These modes are classified according to their contribution to zero carbon emissions goals, maximizing the economic value of ES through specific collaboration measures (Fang et al., 2023). Table 9.5 shows collaboration measures and the synergistic effects of different entities. Among them, the electric grid as the main entity offers low-cost green energy and is responsible for grid regulation, energy supply according to demand, and smoothing output. Additionally, load-based synergy seeks to improve load elasticity and reduce fluctuation with energy supply, while synergy with ES aims to balance supply and demand, enhancing energy quality (Xie et al., 2024).

Analysis of trends and future perspectives

Energy storage

The analysis of trends and future perspectives highlights the crucial role that ESSs will play in the smart grid (Cha et al., 2023). The large-scale implementation of these systems will offer a variety of key applications:

- Energy arbitrage: It will enable buying electricity at low prices and storing it for use during periods of higher demand, generating income (Horesh et al., 2021).
- Frequency regulation: It will be vital for maintaining grid stability, especially with the increase in renewable energy sources.
- Peak load shaving: It will help reduce demand peaks, improving grid reliability and efficiency, and reducing costs for customers (Malka et al., 2023).
- Voltage support: It will provide services to keep voltage within safe ranges, ensuring proper operation of electrical equipment.
- Integration into virtual power plant systems: It will be an essential component for enhancing flexibility, reliability, and efficiency of the grid, facilitating the integration of renewable energies (Yu et al., 2024).
- Transient stability: It will play an important role in maintaining grid stability during abrupt changes in demand or supply, avoiding power outages or equipment damage (Kebir et al., 2023).

Future research directions for demand-side management implementation in the smart grid market

Several areas of research could further advance the use of DSM in energy markets:

- Advanced analytics and machine learning: Advanced analytics and machine learning techniques can be applied to extract insights from data generated by DSM programs. For example, predictive algorithms could anticipate changes in energy demand and adjust supply accordingly, improving grid efficiency and reducing the need for costly peak power plants (Kaif et al., 2024; Panda et al., 2023).
- Integration of renewable energy: DSM programs can help more effectively integrate renewable energy sources into the grid. Future research can explore how to manage fluctuations in supply and demand resulting from renewable energy sources and maximize their use (Chatzigeorgiou et al., 2024).
- Coordination of multiple DSM programs: Coordinating multiple DSM programs can enhance efficiency. Research can explore how to integrate and coordinate different programs to achieve optimal outcomes, as well as incentivize collaboration (Chatzigeorgiou et al., 2024).
- Policy and regulation: The design of policies and regulations can influence the adoption of DSM programs. Research can investigate how to design policies to encourage the use of technologies that enhance the effectiveness of DSM programs (Lee et al., 2023).
- Consumer behavior: Understanding how consumers respond to DSM programs is critical. Future research can explore behavioral interventions to promote more sustainable energy consumption (Cai et al., 2024).

Conclusions

This study addresses the evaluation of various electrical storage technologies for load leveling in the current market. It is highlighted that PHS plants exhibit remarkable efficiency and competitive costs, although their viability may be constrained by uncertainty in capital costs and site conditions. On the other hand, AA-CAES with enriched air is presented as a promising option for diurnal storage, although cost reductions are still needed for large-scale viability. Energy conversion technologies such as hydrogen (H_2) and methane (CH_4) are considered economically unviable due to their low storage efficiency, although they could find application as long-term storage plants to balance seasonal supply and demand, especially if integrated into existing natural gas infrastructure. In terms of LCOES, lithium-ion batteries are the most economical option for the short term, while PHS and AA-CAES present lower costs for larger systems. For small-scale seasonal storage, the electricity-to-gas-to-electricity conversion process (P2G2P) could be more cost-effective than PHS. Furthermore, it is highlighted that electricity storage from renewable sources can significantly reduce greenhouse gas emissions, making P2G2P competitive in environmental terms, especially in the short term. There is a need for more detailed analysis of the technoeconomic benefits and life cycle emissions of electrical storage technologies, as well as comparison with other alternatives such as grid expansion, to enhance the overall assessment of stationary electricity storage.

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References

Abbas, Z., Waqas, M., & He, S. (2023). Environmental evaluation of electricity generation from landfill gas by using LEAP and IPCC model: A case study of Karachi. *Energy Systems*. Available from https://doi.org/10.1007/s12667-023-00574-3, https://www.springer.com/journal/12667.

Abdon, A., Zhang, X., Parra, D., Patel, M. K., Bauer, C., & Worlitschek, J. (2017). Techno-economic and environmental assessment of stationary electricity storage technologies for different time scales. *Energy*, *139*. Available from https://doi.org/10.1016/j.energy.2017.07.097, https://www.journals.elsevier.com/energy.

Alili, H., & Mahmoudimehr, J. (2023). Techno-economic assessment of integrating hydrogen energy storage technology with hybrid photovoltaic/pumped storage hydropower energy system. *Energy Conversion and Management*, *294*. Available from https://doi.org/10.1016/j.enconman.2023.117437, https://www.journals.elsevier.com/energy-conversion-and-management.

Altea, C. d M., & Yanagihara, J. I. (2024). Energy, exergy and environmental impacts analyses of pumped hydro storage (PHS) and Hydrogen (H2) energy storage processes. *Journal of Energy Storage*, *76*109713. Available from https://doi.org/10.1016/j.est.2023.109713.

Al-Wreikat, Y., Attfield, E. K., & Sodré, J. R. (2022). Model for payback time of using retired electric vehicle batteries in residential energy storage systems. *Energy*, *259*. Available from https://doi.org/10.1016/j.energy.2022.124975, https://www.journals.elsevier.com/energy.

Amir, M., Deshmukh, R. G., Khalid, H. M., Said, Z., Raza, A., Muyeen, S. M., Nizami, A.-S., Elavarasan, R. M., Saidur, R., & Sopian, K. (2023). Energy storage technologies: An integrated survey of developments, global economical/environmental effects, optimal scheduling model, and sustainable adaption policies. *Journal of Energy Storage*, *72*108694. Available from https://doi.org/10.1016/j.est.2023.108694.

Assareh, E., & Ghafouri, A. (2023). An innovative compressed air energy storage (CAES) using hydrogen energy integrated with geothermal and solar energy technologies: A comprehensive techno-economic analysis—different climate areas- using artificial intelligent (AI). *International Journal of Hydrogen Energy*, *48*(34). Available from https://doi.org/10.1016/j.ijhydene.2022.11.233, http://www.journals.elsevier.com/international-journal-of-hydrogen-energy/.

Aubin, P., Wang, L., & Van herle, J. (2023). Evaporating water-cooled methanation reactor for solid-oxide stack-based power-to-methane systems: Design, experiment and modeling. *Chemical Engineering Journal*, *456*. Available from https://doi.org/10.1016/j.cej.2022.140256, http://www.elsevier.com/inca/publications/store/6/0/1/2/7/3/index.htt.

Benavides, D., Arévalo, P., Villa-Ávila, E., Aguado, J. A., & Jurado, F. (2024). Predictive power fluctuation mitigation in grid-connected PV systems with rapid response to EV charging stations. *Journal of Energy Storage*, *86*. Available from https://doi.org/10.1016/j.est.2024.111230, https://www.sciencedirect.com/science/journal/2352152X.

Benito, A. O,. & Arena, A. P. (2020). Distribuidos de Energía Eléctrica en Sistemas Energéticos Regionales: análisis con el modelo LEAP. *AJEA (Actas De Jornadas Y Eventos Académicos De UTN)*, (5). https://doi.org/10.33414/ajea.5.696.2020.

Bennett, J. A., Simpson, J. G., Qin, C., Fittro, R., Koenig, G. M., Clarens, A. F., & Loth, E. (2021). Techno-economic analysis of offshore isothermal compressed air energy storage in saline aquifers colocated with wind power. *Applied Energy*, *303*117587. Available from https://doi.org/10.1016/j.apenergy.2021.117587.

Bhandari, R., Trudewind, C. A., & Zapp, P. (2014). Life cycle assessment of hydrogen production via electrolysis—A review. *Journal of Cleaner Production*, *85*. Available from https://doi.org/10.1016/j.jclepro.2013.07.048, https://www.journals.elsevier.com/journal-of-cleaner-production.

Bosu, I., Mahmoud, H., & Hassan, H. (2023). Energy audit, techno-economic, and environmental assessment of integrating solar technologies for energy management in a university residential building: A case study. *Applied Energy*, *341*121141. Available from https://doi.org/10.1016/j.apenergy.2023.121141.

Bulut, M., & Özcan, E. (2024). How to build a state-of-the-art battery energy storage market? Challenges, opportunities, and future directions. *Journal of Energy Storage*, *86*. Available from https://doi.org/10.1016/j.est.2024.111174, https://www.sciencedirect.com/science/journal/2352152X.

Cai, Q., Qing, J., Xu, Q., Shi, G., & Liang, Q. M. (2024). Techno-economic impact of electricity price mechanism and demand response on residential rooftop photovoltaic integration. *Renewable and Sustainable Energy Reviews*, *189*. Available from https://doi.org/10.1016/j.rser.2023.113964, https://www.journals.elsevier.com/renewable-and-sustainable-energy-reviews.

Cetegen, S. A., Gundersen, T., & Barton, P. I. (2024). Evaluating economic feasibility of liquid air energy storage systems in US and European markets. *Energy*, *300*. Available from https://doi.org/10.1016/j.energy.2024.131524, https://www.sciencedirect.com/science/journal/03605442.

Cha, M., Enshaei, H., Nguyen, H., & Jayasinghe, S. G. (2023). Towards a future electric ferry using optimisation-based power management strategy in fuel cell and battery vehicle application—A review. *Renewable and Sustainable Energy Reviews*, *183*113470. Available from https://doi.org/10.1016/j.rser.2023.113470.

Chatzigeorgiou, N. G., Theocharides, S., Makrides, G., & Georghiou, G. E. (2024). A review on battery energy storage systems: Applications, developments, and research trends of hybrid installations in the end-user sector. *Journal of Energy Storage*, *86*. Available from https://doi.org/10.1016/j.est.2024.111192, https://www.sciencedirect.com/science/journal/2352152X.

Chen, W. (2023). Optimal design and performance assessment of a proposed constant power operation mode for the constant volume discharging process of advanced adiabatic compressed air energy storage. *Renewable Energy.*, *221*. Available from https://doi.org/10.1016/j.renene.2023.1197282023.

Cho, J., Jeong, S., & Kim, Y. (2015). Commercial and research battery technologies for electrical energy storage applications. *Progress in Energy and Combustion Science*, *48*. Available from https://doi.org/10.1016/j.pecs.2015.01.002, https://www.journals.elsevier.com/progress-in-energy-and-combustion-science.

Chreim, B., Esseghir, M., & Merghem-Boulahia, L. (2024). Recent sizing, placement, and management techniques for individual and shared battery energy storage systems in residential areas: A review. *Energy Reports*, *11*. Available from https://doi.org/10.1016/j.egyr.2023.11.053, https://www.sciencedirect.com/science/journal/23524847.

Chu, W., Duić, N., & Wang, Q. (2024). Recent advances in energy storage and energy saving technologies: SDEWES special issue in 2022. *Energy Storage and Saving*, *3*(1). Available from https://doi.org/10.1016/j.enss.2023.09.001, https://www.sciencedirect.com/science/journal/27726835.

Cicconi, P., & Kumar, P. (2023). Design approaches for Li-ion battery packs: A review. *Journal of Energy Storage*, *73*109197. Available from https://doi.org/10.1016/j.est.2023.109197.

Cisterna, L., Améstica, L., & Piderit, M. (2020). Proyectos fotovoltaicos en generación distribuida ¿Rentabilidad privada o sustentabilidad ambiental? *Revista Politécnica*, *45*(2), 2477−8990. Available from https://doi.org/10.33333/rp.vol45n2.03.

Comodi, G., Carducci, F., Sze, J. Y., Balamurugan, N., & Romagnoli, A. (2017). Storing energy for cooling demand management in tropical climates: A techno-economic comparison between different energy storage technologies. *Energy*, *121*. Available from https://doi.org/10.1016/j.energy.2017.01.038, http://www.elsevier.com/inca/publications/store/4/8/3/.

Cóndor, H. (2021). Generación distribuida con energías renovables en Perú [http://purl.org/pe-repo/renati/type#tesis, Universidad de Piura]. https://hdl.handle.net/11042/4782.

Connolly, D., Lund, H., & Mathiesen, B. V. (2016). Smart energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. *Renewable and Sustainable Energy Reviews*, *60*. Available from https://doi.org/10.1016/j.rser.2016.02.025.

Cruz-Soto, J. de la, Azkona-Bedia, I., Velazquez-Limon, N., & Romero-Castanon, T. (2022). A techno-economic study for a hydrogen storage system in a microgrid located in baja California, Mexico. Levelized cost of energy for power to gas to power scenarios. *International Journal of Hydrogen Energy*, *47*(70). Available from https://doi.org/10.1016/j.ijhydene.2022.03.026.

De Maron, J., Mafessanti, R., Gramazio, P., Orfei, E., Fasolini, A., & Basile, F. (2023). H2 production by methane oxy-reforming: Effect of catalyst pretreatment on the properties and activity of Rh-Ce0.5Zr0.5O2 synthetized by microemulsion. *Nanomaterials*, *13*(1). Available from https://doi.org/10.3390/nano13010053, http://www.mdpi.com/journal/nanomaterials.

El-Sayed, A. H. A., Khalil, A., & Yehia, M. (2023). Modeling alternative scenarios for Egypt 2050 energy mix based on LEAP analysis. *Energy*, *266*. Available from https://doi.org/10.1016/j.energy.2023.126615, https://www.journals.elsevier.com/energy.

Fang, Y., Fan, R., & Liu, Z. (2023). A study on the energy storage scenarios design and the business model analysis for a zero-carbon big data industrial park from the perspective of source-grid-load-storage collaboration. *Energy Reports*, *9*. Available from https://doi.org/10.1016/j.egyr.2023.05.202, http://www.journals.elsevier.com/energy-reports/.

Gao, Q., Yuan, R., Ertugrul, N., Ding, B., Hayward, J. A., & Li, Y. (2023). Analysis of energy variability and costs for offshore wind and hybrid power unit with equivalent energy storage system. *Applied Energy*, *342*. Available from https://doi.org/10.1016/j.apenergy.2023.121192, https://www.journals.elsevier.com/applied-energy.

García-Miguel, P. L. C., Zarilli, D., Alonso-Martinez, J., Plaza, M. G., & Gómez, S. A. (2024). Optimal operation and market integration of a hybrid farm with green hydrogen and energy storage: A Stochastic approach considering wind and electricity price uncertainties. *Sustainability (Switzerland)*, *16*(7). Available from https://doi.org/10.3390/su16072856, http://www.mdpi.com/journal/sustainability/.

Green IRENA (2020). Hydrogen.

Hadelu, L. M., Noorpoor, A., & Boyaghchi, F. A. (2024). Assessment and multiobjective dragonfly optimization of utilizing flash tank vapor injection cycle in a new geothermal assisted-pumped thermal energy storage system based on transcritical CO2 cycle. *Journal of Energy Storage*, *88*. Available from https://doi.org/10.1016/j.est.2024.111628, https://www.sciencedirect.com/science/journal/2352152X.

Haji Bashi, M., De Tommasi, L., & Lyons, P. (2022). Electricity market integration of utility-scale battery energy storage units in Ireland, the status and future regulatory frameworks. *Journal of Energy Storage*, *55*, 105442. Available from https://doi.org/10.1016/j.est.2022.105442.

Haroon Bukhari, M., Javed, A., Ali Abbas Kazmi, S., Ali, M., & Talib Chaudhary, M. (2023). Techno-economic feasibility analysis of hydrogen production by PtG concept and feeding it into a combined cycle power plant leading to sector coupling in future. *Energy Conversion and Management*, *282*. Available from https://doi.org/10.1016/j.enconman.2023.116814, https://www.journals.elsevier.com/energy-conversion-and-management.

Hassan, Q., Abdulrahman, I. S., Salman, H. M., Olapade, O. T., & Jaszczur, M. (2023). Techno-economic assessment of green hydrogen production by an off-grid photovoltaic energy system. *Energies*, *16*(2). Available from https://doi.org/10.3390/en16020744, http://www.mdpi.com/journal/energies/.

He, W., King, M., Luo, X., Dooner, M., Li, D., & Wang, J. (2021). Technologies and economics of electric energy storages in power systems: Review and perspective. *Advances in Applied Energy*, *4*, 100060. Available from https://doi.org/10.1016/j.adapen.2021.100060.

Henke, H. T. J., Gardumi, F., & Howells, M. (2022). The open source electricity Model Base for Europe—An engagement framework for open and transparent European energy modelling. *Energy*, *239*. Available from https://doi.org/10.1016/j.energy.2021.121973, https://www.journals.elsevier.com/energy.

Hokmabad, H. N., Husev, O., Kurnitski, J., & Belikov, J. (2024). Optimizing size and economic feasibility assessment of photovoltaic and energy storage setup in residential applications. *Sustainable Energy, Grids and Networks*, *38*, 101385. Available from https://doi.org/10.1016/j.segan.2024.101385.

Horesh, N., Quinn, C., Wang, H., Zane, R., Ferry, M., Tong, S., & Quinn, J. C. (2021). Driving to the future of energy storage: Techno-economic analysis of a novel method to recondition second life electric vehicle batteries. *Applied Energy*, *295*, 117007. Available from https://doi.org/10.1016/j.apenergy.2021.117007.

Hurta, A., Žilka, M., & Freiberg, F. (2022). Impact of the splitting of the German–Austrian electricity bidding zone on investment in a grid-scale battery energy storage system deployed for price arbitrage with gray and green power in Austrian and German day-ahead power markets. *Energy Reports*, *8*. Available from https://doi.org/10.1016/j.egyr.2022.09.045, http://www.journals.elsevier.com/energy-reports/.

Iribarren, A., Elizondo, D., Barrios, E. L., Ibaiondo, H., Sanchez-Ruiz, A., Arza, J., Sanchis, P., & Ursua, A. (2023). Dynamic modeling of a pressurized alkaline water electrolyzer: A multiphysics approach. *IEEE Transactions on Industry Applications*, *59*(3), 3741–3753. Available from https://ieeexplore.ieee.org/servlet/opac?punumber = 28, 10.1109/TIA.2023.3247405.

Jamroen, C., & Vongkoon, P. (2023). The role of state-of-charge management in optimal techno-economic battery energy storage sizing for off-grid residential photovoltaic systems. *Journal of Energy Storage*, *72*, 108246. Available from https://doi.org/10.1016/j.est.2023.108246.

Jannesar Niri, A., Poelzer, G. A., Zhang, S. E., Rosenkranz, J., Pettersson, M., & Ghorbani, Y. (2024). Sustainability challenges throughout the electric vehicle battery value chain. *Renewable and Sustainable Energy Reviews*, *191*. Available from https://doi.org/10.1016/j.rser.2023.114176, https://www.sciencedirect.com/science/journal/13640321.

Javaheri, M., & Shafiei Ghazani, A. (2023). Energy and exergy analysis of a novel advanced adiabatic compressed air energy storage hybridized with reverse osmosis system. *Journal of Energy Storage*, *73*, 109250. Available from https://doi.org/10.1016/j.est.2023.109250.

Kaif, A. M. A. D., Alam, K. S., & Das, S. K. (2024). Blockchain based sustainable energy transition of a virtual power plant: Conceptual framework design & experimental implementation. *Energy Reports*, *11*. Available from https://doi.org/10.1016/j.egyr.2023.11.061, https://www.sciencedirect.com/science/journal/23524847.

Kebir, N., Leonard, A., Downey, M., Jones, B., Rabie, K., Bhagavathy, S. M., & Hirmer, S. A. (2023). Second-life battery systems for affordable energy access in Kenyan primary schools. *Scientific Reports*, *13*(1). Available from https://doi.org/10.1038/s41598-023-28377-7, https://www.nature.com/srep/.

Khan, M. K., Raza, M., Shahbaz, M., Farooq, U., & Akram, M. U. (2024). Recent advancement in energy storage technologies and their applications. *Journal of Energy Storage*, *92*, 112112. Available from https://doi.org/10.1016/j.est.2024.112112.

Kloess, M., & Zach, K. (2014). Bulk electricity storage technologies for load-leveling operation—An economic assessment for the Austrian and German power market. *International Journal of Electrical Power & Energy Systems*, *59*. Available from https://doi.org/10.1016/j.ijepes.2014.02.002.

Kondziella, H., Specht, K., Lerch, P., Scheller, F., & Bruckner, T. (2023). The techno-economic potential of large-scale hydrogen storage in Germany for a climate-neutral energy system. *Renewable and Sustainable Energy Reviews*, *182*. Available from https://doi.org/10.1016/j.rser.2023.113430, https://www.journals.elsevier.com/renewable-and-sustainable-energy-reviews.

Le, S. T., Nguyen, T. N., Bui, D. K., Teodosio, B., & Ngo, T. D. (2024). Comparative life cycle assessment of renewable energy storage systems for net-zero buildings with varying self-sufficient ratios. *Energy*, *290*. Available from https://doi.org/10.1016/j.energy.2023.130041, https://www.sciencedirect.com/science/journal/03605442.

Lechón, Y., Lago, C., Herrera, I., Gamarra, A. R., & Pérula, A. (2023). Carbon benefits of different energy storage alternative end uses. Application to the Spanish case. *Renewable and Sustainable Energy Reviews*, *171*. Available from https://doi.org/10.1016/j.rser.2022.112985, https://www.journals.elsevier.com/renewable-and-sustainable-energy-reviews.

Lee, J. Y., Ramasamy, A. K., Ong, K. H., Verayiah, R., Mokhlis, H., & Marsadek, M. (2023). Energy storage systems: A review of its progress and outlook, potential benefits, barriers and solutions within the Malaysian distribution network. *Journal of Energy Storage*, *72*. Available from https://doi.org/10.1016/j.est.2023.108360, http://www.journals.elsevier.com/journal-of-energy-storage/.

Li, J., Wang, C., Zhai, G., Li, Q., Lim, S. , H., Abdoli, S., Kook, S., Yeoh, G. H., & Chan, Q. N. (2024). Evaluating the techno-economic feasibility of hydrogen-fuelled reciprocating engines for renewable base-load power generation. *Energy Conversion and Management*, *311*, 118515. Available from https://doi.org/10.1016/j.enconman.2024.118515.

Liang, Y., Galiano, J. C., & Zhou, H. (2023). The environmental impact of stock market capitalization and energy transition: Natural resource dynamics and international trade. *Utilities Policy*, *82*. Available from https://doi.org/10.1016/j.jup.2023.101517, http://www.elsevier.com/inca/publications/store/3/0/4/7/8/index.htt.

Lin, A., & Bagnato, G. (2024). Revolutionising energy storage: The latest breakthrough in liquid organic hydrogen carriers. *International Journal of Hydrogen Energy*, *63*. Available from https://doi.org/10.1016/j.ijhydene.2024.03.146, https://www.sciencedirect.com/science/journal/03603199.

Lystbæk, N., Gregersen, M., & Shaker, H. R. (2023). Review of energy portfolio optimization in energy markets considering flexibility of power-to-X. *Sustainability (Switzerland)*, *15*(5). Available from https://doi.org/10.3390/su15054422, http://www.mdpi.com/journal/sustainability/.

Maghami, M. R., & Mutambara, A. G. O. (2023). Challenges associated with hybrid energy systems: An artificial intelligence solution. *Energy Reports*, *9*. Available from https://doi.org/10.1016/j.egyr.2022.11.195, http://www.journals.elsevier.com/energy-reports/.

Maghami, M. R., Pasupuleti, J., & Ekanayake, J. (2024). Energy storage and demand response as hybrid mitigation technique for photovoltaic grid connection: Challenges and future trends. *Journal of Energy Storage*, *88*. Available from https://doi.org/10.1016/j.est.2024.111680, https://www.sciencedirect.com/science/journal/2352152X.

Malka, L., Bidaj, F., Kuriqi, A., Jaku, A., Roçi, R., & Gebremedhin, A. (2023). Energy system analysis with a focus on future energy demand projections: The case of Norway. *Energy*, *272*127107. Available from https://doi.org/10.1016/j.energy.2023.127107.

Manandhar, P., Rafiq, H., & Rodriguez-Ubinas, E. (2023). Current status, challenges, and prospects of data-driven urban energy modeling: A review of machine learning methods. *Energy Reports*, *9*. Available from https://doi.org/10.1016/j.egyr.2023.01.094, http://www.journals.elsevier.com/energy-reports/.

Martinez, A., & Iglesias, G. (2024). Levelized cost of energy to evaluate the economic viability of floating offshore wind in the European Atlantic and Mediterranean. *e-Prime—Advances in Electrical Engineering, Electronics and Energy*, *8*100562. Available from https://doi.org/10.1016/j.prime.2024.100562.

Martsinchyk, K., Martsinchyk, A., Łazor, M., Shuhayeu, P., Kupecki, J., Niemczyk, A., Błesznowski, M., & Milewski, J. (2024). Feasibility study and techno-economic assessment of power-to-gas (P2G) technology based on solid oxide electrolysis (SOE). *Journal of Environmental Management*, *354*. Available from https://doi.org/10.1016/j.jenvman.2024.120425, https://www.sciencedirect.com/science/journal/03014797.

McLaughlin, H., Littlefield, A. A., Menefee, M., Kinzer, A., Hull, T., Sovacool, B. K., Bazilian, M. D., Kim, J., & Griffiths, S. (2023). Carbon capture utilization and storage in review: Sociotechnical implications for a carbon reliant world. *Renewable and Sustainable Energy Reviews*, *177*113215. Available from https://doi.org/10.1016/j.rser.2023.113215.

Mearns, E., & Sornette, D. (2023). Are 2050 energy transition plans viable? A detailed analysis of projected Swiss electricity supply and demand in 2050. *Energy Policy*, *175*113347. Available from https://doi.org/10.1016/j.enpol.2022.113347.

Mukherjee, S. S., Meshram, H. A., Rakshit, D., & Saha, B. B. (2023). A comparative study of sensible energy storage and hydrogen energy storage apropos to a concentrated solar thermal power plant. *Journal of Energy Storage*, *61*. Available from https://doi.org/10.1016/j.est.2023.106629, http://www.journals.elsevier.com/journal-of-energy-storage/.

Newbery, D. M. (2023). High renewable electricity penetration: Marginal curtailment and market failure under "subsidy-free" entry. *Energy Economics*, *126*. Available from https://doi.org/10.1016/j.eneco.2023.107011, http://www.elsevier.com/inca/publications/store/3/0/4/1/3/.

Niu, D., Fang, J., Yau, W., & Goetz, S. M. (2023a). Comprehensive evaluation of energy storage systems for inertia emulation and frequency regulation improvement. *Energy Reports*, *9*. Available from https://doi.org/10.1016/j.egyr.2023.01.110, http://www.journals.elsevier.com/energy-reports/.

Niu, M., Li, X., Sun, C., Xiu, X., Wang, Y., Hu, M., & Dong, H. (2023b). Operation optimization of wind/battery storage/alkaline electrolyzer system considering dynamic hydrogen production efficiency. *Energies*, *16*(17). Available from https://doi.org/10.3390/en16176132, http://www.mdpi.com/journal/energies/.

Okazaki, T., Shirai, Y., & Nakamura, T. (2015). Concept study of wind power utilizing direct thermal energy conversion and thermal energy storage. *Renewable Energy*, *83*. Available from https://doi.org/10.1016/j.renene.2015.04.027, http://www.journals.elsevier.com/renewable-and-sustainable-energy-reviews/.

Ölmez, M. E., Ari, I., & Tuzkaya, G. (2024). A comprehensive review of the impacts of energy storage on power markets. *Journal of Energy Storage*, *91*. Available from https://doi.org/10.1016/j.est.2024.111935, https://www.sciencedirect.com/science/journal/2352152X.

Palma, G., Guiducci, L., Stentati, M., Rizzo, A., & Paoletti, S. (2024). Reinforcement learning for energy community management: A European-scale study. *Energies*, *17*(5). Available from https://doi.org/10.3390/en17051249, http://www.mdpi.com/journal/energies/.

Panda, S., Mohanty, S., Rout, P. K., Sahu, B. K., Parida, S. M., Samanta, I. S., Bajaj, M., Piecha, M., Blazek, V., & Prokop, L. (2023). A comprehensive review on demand side management and market design for renewable energy support and integration. *Energy Reports*, *10*. Available from https://doi.org/10.1016/j.egyr.2023.09.049, http://www.journals.elsevier.com/energy-reports/.

Park, J., Kang, S., Kim, S., Kim, H., Cho, H. S., & Lee, J. H. (2024). Enhancing the economic viability and reliability of renewables based electricity supply through power-to-gas-to-power with green hydrogen. *Energy Conversion and Management*, *310*. Available from https://doi.org/10.1016/j.enconman.2024.118485, https://www.sciencedirect.com/science/journal/01968904.

Peng, Y., Ma, X., Wang, Y., Li, M., Gao, F., Zhou, K., & Aemixay, V. (2023). Energy performance assessment of photovoltaic greenhouses in summer based on coupled optical-electrical-thermal models and plant growth requirements. *Energy Conversion and Management*, *287*117086. Available from https://doi.org/10.1016/j.enconman.2023.117086.

Quarton, C. J., & Samsatli, S. (2018). Power-to-gas for injection into the gas grid: What can we learn from real-life projects, economic assessments and systems modelling? *Renewable and Sustainable Energy Reviews*, *98*. Available from https://doi.org/10.1016/j.rser.2018.09.007, https://www.journals.elsevier.com/renewable-and-sustainable-energy-reviews.

Rodriguez, E. J. R., Monzer, D., & Bouallou, C. (2023). Study of interest for integrating wind energy with a power-to-methane system based on the Molten Carbonate Electrolyzer. *Journal of Energy Storage*, *63*. Available from https://doi.org/10.1016/j.est.2023.107021, http://www.journals.elsevier.com/journal-of-energy-storage/.

Saleh-Abadi, M., Rostami, M., & Farajollahi, A. (2023). 4-E analysis of a hybrid integrated mechanical/chemical/electrochemical energy storage process based on the CAES, amine-based CO2 capture, SOEC, and CO2 electroreduction cell. *Journal of Energy Storage*, *72*. Available from https://doi.org/10.1016/j.est.2023.108278, http://www.journals.elsevier.com/journal-of-energy-storage/.

Schwidtal, J. M., Piccini, P., Troncia, M., Chitchyan, R., Montakhabi, M., Francis, C., Gorbatcheva, A., Capper, T., Mustafa, M. A., Andoni, M., Robu, V., Bahloul, M., Scott, I. J., Mbavarira, T., España, J. M., & Kiesling, L. (2023). Emerging business models in local energy markets: A systematic review of peer-to-peer, community self-consumption, and transactive energy models. *Renewable and Sustainable Energy Reviews*, *179*113273. Available from https://doi.org/10.1016/j.rser.2023.113273.

Shabani, M., Dahlquist, E., Wallin, F., & Yan, J. (2020). Techno-economic comparison of optimal design of renewable-battery storage and renewable micro pumped hydro storage power supply systems: A case study in Sweden. *Applied Energy*, *279*115830. Available from https://doi.org/10.1016/j.apenergy.2020.115830.

Shirizadeh, B., & Quirion, P. (2023). Long-term optimization of the hydrogen-electricity nexus in France: Green, blue, or pink hydrogen? *Energy Policy*, *181*. Available from https://doi.org/10.1016/j.enpol.2023.113702, http://www.journals.elsevier.com/energy-policy/.

Shiva Kumar, S., & Lim, H. (2022). An overview of water electrolysis technologies for green hydrogen production. *Energy Reports*, *8*. Available from https://doi.org/10.1016/j.egyr.2022.10.127, http://www.journals.elsevier.com/energy-reports/.

Solovey, V., Zipunnikov, M., & Rusanov, R. (2023). Increasing the manoeuvrability of power units of the thermal power plants due to applying the hydrogen-oxygen systems. *Institute of Physics, Ukraine JPhys Energy*, *5*(1). Available from https://doi.org/10.1088/2515-7655/aca9ff, opscience.iop.org/journal/2515-7655.

Wang, S., Li, F., Zhang, G., & Yin, C. (2023). Analysis of energy storage demand for peak shaving and frequency regulation of power systems with high penetration of renewable energy. *Energy*, *267*126586. Available from https://doi.org/10.1016/j.energy.2022.126586.

Watson, N. E., Huebner, G. M., Fell, M. J., & Shipworth, D. (2024). Consumer preferences for business models with multiple electricity suppliers: Online choice experiments in the United Kingdom. *Energy Research and Social Science*, *109*. Available from https://doi.org/10.1016/j.erss.2023.103403, https://www.sciencedirect.com/science/journal/22146296.

Williams, B., Gallardo, P., Bishop, D., & Chase, G. (2023). Impacts of electric vehicle policy on the New Zealand energy system: A retro-analysis. *Energy Reports*, *9*. Available from https://doi.org/10.1016/j.egyr.2023.02.080, http://www.journals.elsevier.com/energy-reports/.

Wulf, C., Zapp, P., & Schreiber, A. (2020). Review of power-to-X demonstration projects in Europe. *Frontiers in Energy Research*, *8*. Available from https://doi.org/10.3389/fenrg.2020.00191, http://www.frontiersin.org/Energy_Research/.

Xie, H., Ahmad, T. R., Zhang, D., Hwang Goh, H., & Wu, T. (2024). Community-based virtual power plants' technology and circular economy models in the energy sector: A techno-economy study. *Renewable and Sustainable Energy Reviews*, *192*114189. Available from https://doi.org/10.1016/j.rser.2023.114189.

Xie, Y., Wu, X., Hou, Z., Li, Z., Luo, J., Lüddeke, C. T., Huang, L., Wu, L., & Liao, J. (2023). Gleaning insights from German energy transition and large-scale underground energy storage for China's carbon neutrality. *International Journal of Mining Science and Technology*, *33*(5). Available from https://doi.org/10.1016/j.ijmst.2023.04.001, http://www.elsevier.com/wps/find/journaldescription.cws_home/727915/description#description.

Yang, Q., Wang, H., Wang, T., Zhang, S., Wu, X., & Wang, H. (2021). Blockchain-based decentralized energy management platform for residential distributed energy resources in a virtual power plant. *Applied Energy*, *294*117026. Available from https://doi.org/10.1016/j.apenergy.2021.117026.

Yang, R., Kweon, H., & Kim, K. (2023). Preliminary study for the commercialization of a electrochemical hydrogen compressor. *Energies*, *16*(7). Available from https://doi.org/10.3390/en16073128, http://www.mdpi.com/journal/energies/.

Yu, S., Wei, Z., Sun, G., Zhou, Y., & Zang, H. (2024). A double auction mechanism for virtual power plants based on blockchain sharding consensus and privacy preservation. *Journal of Cleaner Production*, *436*140285. Available from https://doi.org/10.1016/j.jclepro.2023.140285.

Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews*, *146*111180. Available from https://doi.org/10.1016/j.rser.2021.111180.

Zhu, Y., Wu, S., Li, J., Jia, Q., Zhang, T., Zhang, X., Han, D., & Tan, Y. (2024). Towards a carbon-neutral community: Integrated renewable energy systems (IRES)−sources, storage, optimization, challenges, strategies and opportunities. *Journal of Energy Storage*, *83*110663. Available from https://doi.org/10.1016/j.est.2024.110663.