HYDROGEN, FUEL CELL & ENERGY STORAGE

Power Management in Grid-Scale Energy Storage Systems; A Case Study of Trends

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Abstract

The global energy crisis poses a major challenge, driven by the depletion of fossil fuel reserves and the escalating impacts of climate change. In response, the transition to renewable energy sources, particularly solar and wind power, is accelerating to address these pressing issues. However, renewable energy systems require efficient storage solutions to enhance energy utilization and ensure a stable, resilient power grid. Energy storage systems play versatile roles within power grids, including peak shaving, fast frequency response, voltage stability, and power quality enhancement. This study examines the trends and current status of various energy storage technologies, highlighting lithium-ion (Li-ion) batteries as particularly promising. While pumped-hydro storage currently accounts for approximately 95% of total storage capacity, Li-ion batteries demonstrate substantial potential for future applications. A case study highlights utility-scale applications of energy storage systems in Iran's power system, emphasizing peak-shaving, load-leveling, power quality improvement, and energy efficiency enhancement. Energy storage plays a critical role in Iran, particularly for peak shifting and load leveling. In the summer of 2023, Iran's peak energy consumption reached approximately 80,000 MW, with an average demand of 64,000 MW during peak seasons. Diesel generators, with a grid capacity of approximately 1000 MW, serve as Iran's primary emergency power supply system. A comparison of the levelized cost of energy (LCOE) for lithium-ion (Li-ion) batteries, identified as an optimal fast-response system in Iran, revealed that diesel generation is more expensive, even without accounting for CO_2 emission costs. Given Iran's significant lithium reserves, estimated at 8.5 million metric tons, Li-ion batteries have the potential to emerge as the dominant energy storage solution both domestically and globally.

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1 Introduction

Energy has played a vital role in human life since the discovery of fire and the advent of cooking. While solar power was not humanity's first energy source, it has long been utilized for drying and heating. In recent years, the rapid growth of the global population and advancements in technology have intensified the energy crisis, making it one of humanity's most pressing challenges. Global energy consumption increased from 172,629 TWh in 2018 to 183,230 TWh in 2023, partly due to the effects of the coronavirus pandemic. This upward trend is expected to accelerate in the coming years. The industrial sector accounts for the largest share of global energy consumption, using approximately 54% of the world's total delivered energy. The industrial sector can be divided into three categories: energy-intensive, non-energy-intensive, and non-manufacturing industries. In 2023, oil remained the dominant source of primary energy, accounting for 26.7% of total production [1].

The global community is striving to combat climate change by transitioning to an energy infrastructure that minimizes greenhouse gas emissions and pollutants. Consequently, reliance on fossil fuels as traditional energy sources is declining due to their environmental impact and contribution to global warming. This shift prioritizes reducing fossil fuel consumption in cumulative energy production while adopting more eco-friendly production methods. In response, various types of renewable energy (RE) sources have been introduced. Among REs, solar and wind power exhibit the greatest growth potential. However, their intermittent nature means they are not always available to meet consumption demands. As a result, maintaining a balance between energy supply and demand requires the integration of consistent energy production with advanced energy storage solutions. These storage systems support critical functions such as peak shaving, frequency response, voltage stability, and power quality enhancement. With the widespread application of energy storage systems, significant advancements have been made in renewable energy (RE) technologies, particularly in electric vehicles (EVs) [2–5]. Despite challenges such as the stability of energy production and difficulties in energy transportation, the application and utilization methods of these systems have developed rapidly. Energy storage offers a practical solution to these challenges, enabling the storage of large energy reserves for use at optimal times or to compensate for fluctuations in supply and demand [3, 6, 7]. Additionally, the use of renewable energies (REs) in transportation is currently limited, with fuel cells and photovoltaic (PV) prototypes being among the few exceptions. As such, energy storage systems (ESSs), particularly batteries, provide the most effective solution to these challenges [2, 4, 8]. These technologies optimize renewable energy development, enhancing both grid stability and the practical application of produced energy for transportation. The growing integration of coupled devices in energy systems, such as power-to-gas (P2G) and combined heat and power (CHP) technologies, as well as integrated energy systems (IESs) and energy hub concepts, underscores the critical role of ESSs in these frameworks [9, 10].

One of the key challenges Iran faces in power supply is maintaining production stability during peak summer periods. This study aims to assess the stability of the energy supply during these times and explore various storage solutions. The objective is to identify the most cost-effective energy storage system (ESS) for Iran, specifically comparing Li-ion batteries with diesel generators. This paper reviews current trends and the status of various ESS technologies, with a focus on the potential of Li-ion batteries in Iran's energy sector. Additionally, it emphasizes the importance of strengthening local research capabilities and infrastructure to advance these technologies within the country.

2 Review of Energy Storage Systems

The global installed storage capacity has been growing annually, with projections reaching approximately 1,000 GW by 2030 [11]. As previously mentioned, grid flexibility and the stability of renewable energies are the primary drivers behind this growth. Historically, ancient civilizations used primitive energy storage systems (ESS), and this practice has evolved into the development of state-of-the-art technologies. The main types of ESSs include [5, 12]:

- Pumped-hydroelectricity storage (PHS);
- Electromechanical storage: Compressed air energy storage (CAES), flywheel;
- Thermal storage: Chilled water thermal storage, heat thermal storage ice, molten salt thermal storage, etc;
- Electrochemical storage: Batteries (Li-ion, Lead Acid, Na-based, Flow, etc.) and electrochemical capacitors;
- Chemical: Hydrogen storage and synthetic natural gas (SNG).

Each system has distinct characteristics based on its application. For example, pumped-storage hydroelectricity (PSH) is typically deployed at high power levels, requiring large land areas and careful environmental considerations. In contrast, batteries are suited for low-capacity applications and serve as distributed energy providers. While batteries are more expensive to manufacture than PSH, their response time is significantly faster, typically measured in seconds compared to the minutes required for PSH [13, 14]. The share of various ESS technologies, including thermal, electrical, mechanical, chemical, and electrochemical batteries, is illustrated in Figure 1.

Mechanical energy storage, including pumped-hydro storage (PHS) and CAES, accounts for 97% of the total storage capacity for PHS. Excluding PHS, CAES represents about half of global energy storage, followed by sensible heat storage, which accounts for 0.79% of the total. Additionally, batteries, particularly lithium-ion (Li-ion) batteries, represent the next stage ofESSs, comprising 0.24% of the total energy storage capacity, as shown in Figure 2.

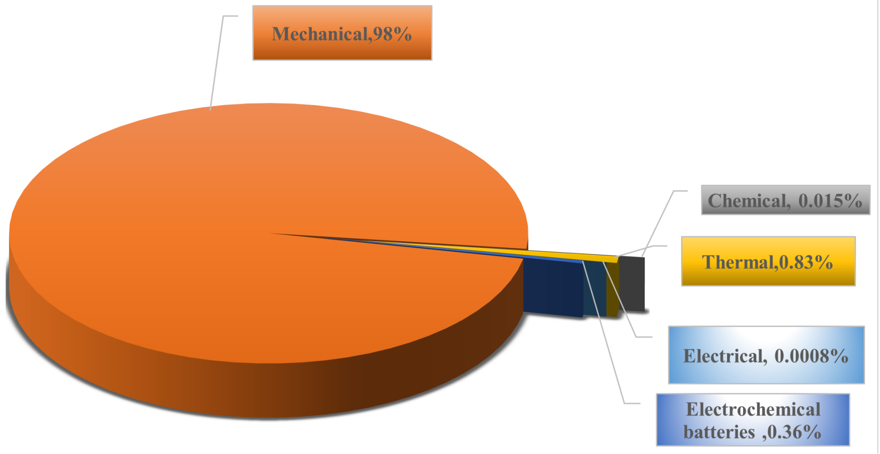

Fig. 1. The global share of different energy storage technologies by 2023.

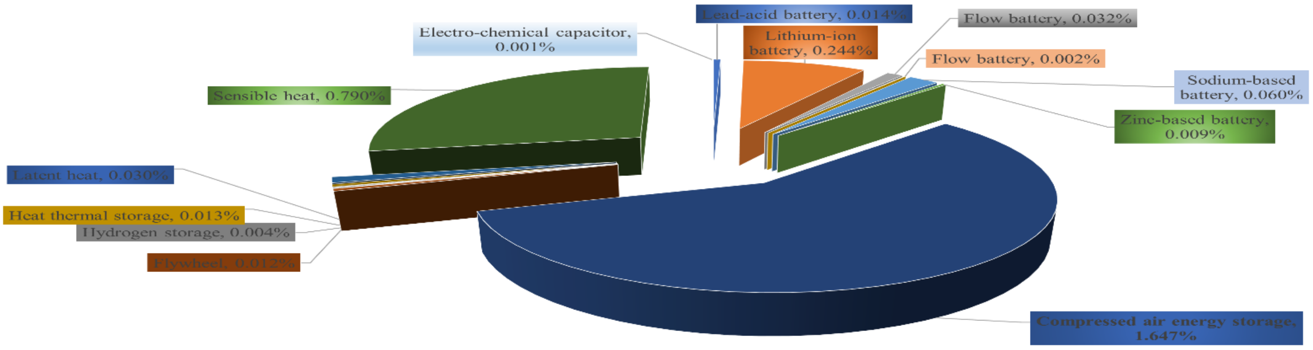

Fig. 2. Share of different energy storage technologies by 2023.

Another important point to note is the recent development trend, as shown in Figure 3. It is evident that there has been a shift towards thermal storage systems and Li-ion batteries from 2020 to 2023. Due to certain limitations of PHS, the development of this type of ESS has been restricted. In contrast, batteries, particularly Li-ion batteries, show significant potential to become the dominant energy storage technology in the future. Battery storage capacity has increased by 50% (5 GW), setting a record with systems implemented in China and the United States. Utility-scale projects have been the primary driver in the market, accounting for about two-thirds of the total added capacity. Recent policies and projects focused on reducing greenhouse gas emissions and achieving Net Zero by 2050 have led to substantial investments in this sector. Additionally, the growth of EVs has created a large market for batteries, further fueling significant research and development in battery technologies. A new generation of batteries with enhanced energy storage capabilities and lower costs is being developed to meet the growing demand for energy storage. Most recent projects rely on these advanced batteries, with predictions indicating a growth of 600 GW in capacity by 2030. This growth may be influenced by events like Russia's invasion of Ukraine, which disrupted the gas supply to Europe, prompting European countries to progressively replace traditional gas power plants with renewable energy plants. China is leading the way in developing batteries for energy storage applications, with forecasts predicting 30 GW of capacity by 2025. In the United States, capacity additions from utility-scale projects more than quadrupled in 2020, driven by two large projects in California [15,16].

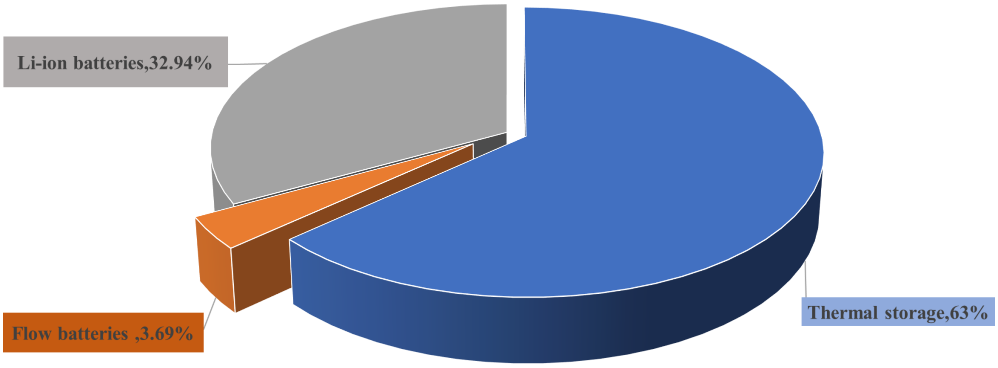

Fig. 3. Share of different energy storage technologies from 2020 to 2023.

2.1 Type of energy storage systems

2.1.1 Mechanical energy storage systems

Mechanical energy storage systems. CAES is a method that involves two main processes: charging and discharging. During the charging process, electricity from the grid powers a motor, which drives a turbine or a series of turbines. This compresses air into a large underground cavern, with the heat generated during compression being rejected into the environment [17,18]. In the second process, when needed, the high-pressure air is mixed with gas and combusted to drive turbines. The result is electricity supplied to the grid or consumers. This storage system is exemplified by the Huntorf plant in Germany, built in 1978, and the McIntosh plant in Alabama, USA, which has been operational since 1991 [19,20]. In this method, energy is stored as compressed air in a reservoir through the charging and discharging processes. Additionally, CAES has other applications, particularly in pneumatic equipment and instrumentation. Pneumatic systems offer advantages over other technologies due to their lower cost and greater flexibility.

It is noticeable that some vehicle designs based on the CAES concept still require commercialization [17,20–22]. Although CAES offers certain advantages over batteries, its cost is higher in mass production due to the expensive storage reservoirs required. Currently, six CAES facilities are operational worldwide, with a combined storage capacity of 609 MW. This includes a 317 MW plant in Texas, USA, used for renewable energy time-shifting, and a 290 MW plant in Germany used for energy arbitration. Additionally, research has been conducted on utilizing CAES energy and hybridizing it with other systems to enhance efficiency and flexibility [23,24].

Flywheels. For over a century, this kind of energy storage has been utilized, storing energy in a rotational form within a flywheel. The FES system comprises a rotor, bearings, power electronics, a vacuum pump, and housing. The flywheel itself is typically made of carbon fibers and supported by magnetic bearings, spinning at speeds ranging from 20,000 to 50,000 revolutions per minute in a vacuum chamber to minimize energy loss. A major milestone in the development of flywheel technology was its adoption in steam engines, marking a significant advancement in energy storage and utilization [25]. During energy production, the rotational speed of the flywheel decreases, releasing stored energy, which is then converted to electricity. Flywheels have the potential to store energy with high output power, achieving an energy density of approximately 100 Wh/kg and an efficiency of 90%. They are available in sizes ranging from 3 kWh to 133 kWh [25–27]. This energy storage method is independent of the environment's temperature and has fewer fault modes compared to batteries. Additionally, flywheels offer an exceptionally long lifespan, with some systems operating reliably for over 200 years. However, the primary drawbacks of this technology include its rigid design and space requirements, which can limit its versatility.

Flywheels can also be used to enhance grid resilience and for peak shaving. The oldest known flywheel energy storage system, located at the Max Planck Institute in Germany, was established in 1973 and has a nominal capacity of 387 MW. The most recent system, China's first grid-level flywheel energy storage facility, was commissioned in June 2024 in the city of Changzhi, Shanxi Province. The market for flywheel energy storage was valued at USD 339.92 million in 2023 and is projected to grow from USD 366.37 million in 2024 to USD 713.57 million by 2032 [3, 25, 27, 28].

Pumped storage hydroelectricity. Another type of mechanical ESSs is pumped storage hydropower. This system involves infrastructure where water is pumped into a storage reservoir during periods of low energy demand. When energy is needed, the stored water flows back through turbines to generate electricity, which is then injected into the grid. PSH represents the largest capacity for energy storage worldwide [13, 29]. The capacity of pumped storage hydropower (PSH) systems experienced significant growth in Europe, the USA, and Japan during the 1970s and 1980s, driven by the expansion of nuclear and coal-fired power plants. However, the 1990s saw a decline in PSH installations due to the low cost and widespread availability of natural gas. By 2023, China leads in PSH capacity with more than 50 GW, followed by Japan and the United States, with capacities of 21.8 GW and 16.7 GW, respectively [30]. The open circuit type has broader applications, with 332 projects delivering a combined capacity of approximately 158 GW [31,32]. PSH accounts for 96% of global energy storage capacity, though only 20% of projects are actively involved [6, 33]. Despite challenges such as high initial costs, significant land requirements, and ecological concerns, several PSH plants remain under construction [34]. Recently, Western countries have renewed interest in PSH development, led by initiatives from the US Department of Energy (DOE) and the International Hydropower Association (IHA) [31, 35]. In Iran, the Siah Bisheh PSH station demonstrates local efforts in this domain, offering a capacity of 1040 MW in turbine mode and 960 MW in pump mode.

Gravity potential energy storage. Similar to other storage systems, this method involves two stages: charging and discharging. It utilizes solid, locally available materials and low-cost composite blocks or mobile masses for energy storage [34]. These materials can include local soil, mine tailings, coal combustion residuals (such as coal ash), and decommissioned wind turbine blades. During the charging phase, energy is used to lift weights, storing it as gravitational potential energy. During the discharging phase, the stored energy is released as electricity to the grid during peak demand periods. This technique, like previous storage systems, uses solid materials instead of water for energy storage [36–39]. An example of its implementation is the Advanced Rail Energy Storage (ARES) project in Nevada, constructed in 2013 and operational since 2019. This project relies on train movements, utilizing a combination of energy storage and gravity methods. With a cost of $46 million, the system has a power output of 50 MW, deliverable within 15 minutes [39, 40]. The latest development in this field is the Energy Vault (EV), which constructed the first commercial gravity-based energy storage system for the grid in China, offering a capacity of 468 MWh [41].

2.1.2 Electrical energy storage systems

Capacitors. Capacitors store energy by using a dielectric material sandwiched between two conductive plates. They are commonly used in applications such as energy sources for camera flashes, audio equipment, uninterruptible power supplies, and pulsed loads. Capacitors help manage battery fluctuations but are not yet suitable for large-scale energy storage. However, advancements in supercapacitors, which will be discussed later, show promise for broader applications [42, 43].

Superconducting Magnetic Energy Storage (SMES). In this system, direct current is passed through a superconducting coil, which, due to the absence of resistance, allows energy to be stored efficiently. The choice of superconducting materials is crucial, as their lack of resistance enables effective energy storage. However, this method has some drawbacks, such as the low operating temperature requirements and the high cost of materials [44]. Recent studies have focused on developing new materials that exhibit superconductivity at higher temperatures, offering the potential for improved performance and reduced costs [45, 46]. The main advantage of this technology is its round-trip efficiency which is the highest among all ESSs. Some smaller SMES (Superconducting Magnetic Energy Storage) systems have been developed for grid applications, typically with capacities less than 1 MW. However, large-scale SMES systems, capable of storing up to 1000 MW, are still not economically viable and face technological challenges, particularly due to the enormous magnetic forces involved [47, 48].

2.1.3 Electrochemical energy storage systems

The most common method for electrical energy storage is the electrochemical method, which relies on rechargeable batteries.

Rechargeable batteries. There are different types of batteries, each suited for various applications. Lead-acid batteries, for example, are widely used due to their low cost, especially in applications requiring relatively low energy and power density. Despite their cost-effectiveness, lead-acid batteries have some limitations, including a short lifespan and lower energy and power density compared to other advanced battery technologies. However, the technology behind lead-acid batteries is mature, and ongoing research is focused on optimizing the electrolytes, electrodes, and the balance of system (BOS) to address these limitations and enhance their performance. It should be noted that several types of batteries, including Li-ion, lead-acid, molten salt, and flow batteries, hold significant potential as ESSs. With the advancement of technology, rechargeable batteries, particularly Li-ion, have seen notable development. However, certain types of nickel-based batteries, such as Ni-Cd and Ni-MH, have encountered challenges. Ni-Cd batteries have largely been replaced due to the environmental and health concerns related to cadmium, while Ni-MH batteries have fallen out of favor due to economic and technical limitations [8, 49]. Despite advancements in raw materials, value chains, and technical knowledge, the development of appropriate infrastructure remains a substantial challenge that needs to be addressed for widespread adoption of these energy storage technologies. In Iran, for instance, lead-acid batteries have been produced for over 50 years, resulting in the development of new generations of batteries, a refined value chain, raw material sources, and well-established infrastructure. However, for other types of batteries, such as Li-ion batteries, there is limited experience, mainly focused on cell production and system packing. Therefore, there is a need for a research center dedicated to Li-ion batteries in Iran to advance this technology. Rechargeable batteries can be classified into the following categories:

Flow batteries. These types of batteries have caused a stir in recent years. The traditional version is the vanadium redox flow battery (VRFB), while more advanced versions, based on iron, are still in the early stages of development. The main advantage of these batteries is their flexible charge-discharge rate, made possible by their low-cost technology. The global flow battery market was valued at USD 297 million in 2022 and is projected to reach USD 2,382.81 million by 2032 [28, 35]. Although research has been conducted to improve flow batteries, the concept of using an active electrochemical fluid is relatively new compared to other technologies. However, a new type of iron-redox flow battery has been introduced by MIT, which produced a modeling framework to enhance the progress of flow batteries for large-scale applications with long-life electricity storage [50–52]. On June 29, 2024, PetroChina completed its first zinc-bromine flow battery energy storage system. Another recently completed project is the largest hybrid energy storage power station in Jiangsu Province, which features a 190 MW/380 MWh liquid-cooled lithium iron phosphate storage system and a 10 MW/20 MWh vanadium flow storage system, capable of storing up to 400,000 kWh of electricity [53,54]. The main application of these systems is the storage of renewable energy sources such as wind and solar [34, 49]. Another application for this type of battery is load shedding and frequency control. There are other types of flow batteries, such as zinc-nickel oxide, iron-chromium, hydrogen-bromine, and zinc-iron, which are less popular than zinc-bromine and vanadium-redox batteries. In summary, flow batteries have significant potential for the future of energy storage and, with further developments, could become a strong option for peak shaving and frequency control [51, 54, 55].

Li-ion batteries. A significant percentage of projects related to ESSs is focused on this type of battery. Studies indicate that Li-ion batteries will dominate the market for the next 15 years, driven by advancements in new electrodes and solid electrolytes that make them more reliable, longer-lasting (up to 20 years for some types), lower in cost, and safer [12, 14, 16, 56, 57]. In recent years, there has been a growing trend toward Li-ion batteries, leading to a significant increase in investment in research and development. Li-ion batteries have gained widespread attention due to their high energy-to-weight ratio, absence of memory effect, and low self-discharge, making them ideal for use in electronic devices, especially portable ones. However, challenges remain, including their cost, cycle life, and safety. To address these issues, solutions such as alternative electrode materials and solid electrolytes are being explored [58–60]. On the one hand, several projects have been carried out to develop new anode and cathode materials for Li-ion batteries. These studies have analyzed the impact of size, morphology, and processing parameters on the performance of Li-ion batteries [61–64]. On the other hand, some research has focused on the safety of Li-ion batteries, particularly addressing the safety concerns related to the electrolyte [19, 59, 64]. Li-ion batteries are also utilized in various applications, such as EVs. In Iran, different scenarios regarding fuel and electricity prices were investigated. The results indicated that the final lifecycle cost (LCO) of an EV and a fuel cell electric vehicle (FCEV) would be nearly the same. However, the development of both Li-ion batteries and fuel cells in the near future is crucial. Additionally, the powertrain topology of both types was reviewed for further development in Iran [65].

Other rechargeable batteries. Other types of rechargeable batteries comprise Metal-air batteries, Ni-based batteries, Sodium- based batteries, Na-ion batteries, Na-NiCl batteries, Na-S batteries, and Lead-acid Batteries.

Metal-air batteries. Metal-air batteries have the potential to meet future energy storage needs and can be categorized into two types: lithium-air (Li-Air) and zinc-air (Zn-Air). The advantages of Li-Air batteries include higher capacity, power, and energy density compared to Zn-Air batteries, which are widely used for various applications. The market for Zn-Air batteries was valued at USD 112.2 million in 2020, with an anticipated growth from USD 117.0 million in 2021 to USD 196.7 million by 2028. Several companies, particularly in the USA, are actively researching and developing this type of battery. Zn-Air batteries have a storage duration ranging from 2 to 48 hours, with power capacities ranging between 250 and 10,000 kW. This technology is particularly well-suited for integration with solar energy networks and microgrids. Research indicates that metal-air batteries have a promising future, especially in terms of storage duration and lifespan [64–66].

Ni-based batteries. Ni-based batteries are divided into Ni-Fe, Ni-Cd, nickel-metal-hydride (Ni-MH), Ni-Zn, and nickel hydrogen (NiH). These batteries have been used in various applications, such as Ni-Fe batteries in railroad signaling in the past and Ni-Cd batteries in aircraft. However, one significant drawback of Ni-Cd batteries is the toxic nature of cadmium (Cd). These batteries were commonly used to supply energy during the night or under low solar irradiation in solar systems, with capacities ranging from 17 to 27,000 kW. With the rapid growth of Li-ion batteries, Ni-based technologies have been largely phased out [14, 49, 67].

Sodium-based batteries. Sodium, being in the same group of the periodic table as lithium, has long been considered an alternative to lithium. It is the most abundant alkali metal on Earth and shares similar physicochemical properties with lithium, making it suitable for large-scaleESSs. An ancient type of Na-based battery, such as Na/S, has been introduced and used for several decades. Other types of sodium batteries, including Na-ion and Na-NiCl, have gained more attention for grid applications due to their similar physicochemical properties to lithium , making them suitable for large-scale storage systems [66, 68–71].

Na-ion batteries. Na-ion batteries are one of the state- of-the-art battery technologies, offering good cycle life and high capacity. The advantages of these batteries include cost savings, safety, cycling stability, and a wide temperature range. Recent advancements have focused on improving electrode materials to enhance performance, particularly in terms of high energy density and stable cycling [72]. Currently, Na-ion batteries are still in the research and development stage and have a low technology readiness level (TRL). There are several projects worldwide, with most of them located in the USA. The power capacity for these projects is 10 kW, lasting 4-10 hours, primarily for microgrids and renewable energy storage systems. Al-ion and Mg-ion batteries are still at the conceptual stage and will take a longer time to commercialize [68, 73]. Several companies, such as HiNa Battery Technology Co., Ltd., Faradion Ltd., and Aquion Energy, Inc., have worked on Ni-ion batteries and developed products for light vehicles like scooters and motorbikes. However, challenges related to cycle life and energy density still need to be addressed [74].

Na-NiCl batteries. Na-NiCl batteries offer higher cell voltage compared to NaS batteries, with an operating temperature range of 250-350 °C. The main advantages of Na-NiCl batteries include their safety characteristics, lower corrosive properties, and longer cycle life. However, their drawbacks include lower power density and energy density compared to NaS batteries. Despite these limitations, this technology has garnered significant attention, with over 30 ongoing projects. FIAMM and GE Energy Storage are two prominent companies leading the development in this field. This type of battery can be integrated with renewable energy sources such as wind and solar for energy storage. In addition to microgrids, they can be used for load capping, frequency control, military applications, and electric vehicles. Despite the broad range of potential applications, very few companies have successfully developed this technology, limiting its widespread adoption [75, 76].

Lead-acid Batteries. Lead-acid batteries, the first type of rechargeable battery, are known for their low energy density and high maintenance requirements. Despite these drawbacks, they hold the largest share in the transportation industry, particularly for starting car engines. Newer generations of lead-acid batteries have been introduced, offering longer lifespans and lower costs, making them more economical. These batteries typically have coulombic efficiencies of around 85%. As a result, lead-acid batteries have a wide range of applications, including uninterruptible power supplies (UPS), though they are not commonly used in grid applications. Recently, valve-regulated lead-acid (VRLA) batteries and advanced types such as absorbent glass mat (AGM) and gel batteries have been developed for use in renewable energy systems and for enhancing grid stability [49, 77–79].

Supercapacitors. Another notable electrochemical storage system is supercapacitors (SC), which have gained attention in recent years due to their exceptional properties, including fast charge-discharge capability, low cost, and long lifespan. Supercapacitors can be categorized into three groups: Electric Double Layer Capacitors (EDLC), Hybrid Supercapacitors, and Pseudocapacitors [80]. This technology has various applications in the electricity grid, such as power smoothing during current fluctuations and harmonics, regulating power oscillations, frequency regulation, capacity firming, stabilizing voltage for PV and wind energy systems, reducing energy consumption and CO_2 emissions, and time-shifting. South Korea, the USA, and Spain are leading countries in the development and application of this technology [12,42,81,82]. Additionally, supercapacitors (SCs) are primarily used in transportation applications, especially for railway systems, rather than grid applications. Some projects in South Korea involve the use of supercapacitors for subway stations, with power capacities ranging from 500 to 2400 kW and storage times exceeding one minute. This technology offers advantages over lead-acid batteries, which has led to its adoption in EVs and power electronics applications. For example, a wireless screwdriver using supercapacitors can retain 85% of its charged energy for up to three months. Although there is rapid growth in rechargeable battery research, several studies have also focused on improving the efficiency of supercapacitor electrodes by developing new materials [32, 81, 83–86].

2.1.4 Thermal energy storage systems

These ESSs store energy through different methods and then release it for heating and cooling applications when required. This technique can be integrated with renewable sources, such as solar farms, to store energy during low-demand periods and provide it later. They can be categorized into three groups: sensitive heat storage (SHS), which involves storing heat in solid or liquid media (such as water, molten salt, sand, gravel, etc.) without changing the physical state of the materials; latent heat storage (LHS), which uses phase change materials; and thermochemical storage methods. When materials undergo state transformation, a system can store a larger amount of thermal energy compared to SHSs. Typically, water, steam, oil, or phase change materials are used as the storage medium in this type of system. Numerous projects have been conducted worldwide in this field and continue to progress. Additionally, the "Design and Integration of Thermo-chemical Energy Storage (TCES) into Buildings for Load Shedding/Shifting" project began on January 1, 2024, by Georgia Tech Research Corporation. The applications of thermal energy storage systems enhance the reliability of renewable energy grids and solar farms [2, 4, 32, 87, 88].

Molten salt energy storage systems. There is an urgent need to transition to renewable energy sources. Solar and wind power can be harnessed, but their energy production is inconsistent due to fluctuations in weather conditions. As a result, storing energy during off-peak hours becomes essential. Methods such as molten salt energy storage systems (MOSAS) can help stabilize the grid, enhance load management, improve the reliability of renewable energy grids, and facilitate peak shifting control. Molten salts have been used for decades in nuclear reactors to transfer heat. Unlike water, which vaporizes at 100 °C, molten salts can be used at higher temperatures, making them ideal for energy storage applications. One of the main applications of MOSAS is in concentrated solar power plants. These systems typically operate with capacities of several tens of megawatts (MW) for multiple hours, both during the day and night. In this technique, liquid salt is pumped into heaters, where it is heated to temperatures as high as 570 °C. The heated salt is then used to produce superheated steam to power turbines. The heat is stored in insulated tanks for several days, providing a reliable energy source when needed. When needed, the thermal energy stored in molten salts is converted into electricity by a steam turbine, with the salt being cooled to around 290 °C. Spain is a key user of this technology, with 13 molten salt storage plants having a combined capacity of 550 MW and a storage duration of up to 7 hours. Germany has also developed MOSAS with a 200 MW turbine capacity and a 700 MW output, all within a relatively small area of just $1.5\,\mathrm{km}^2$. This demonstrates the efficiency and compact nature of the technology [2, 45, 75, 89].

Chilled water. Chilled water is one of the simplest technologies for thermal energy storage, relying on the principle of density differences between cooled and warm water in a tank. Warm water, being lighter, rises to the top, while cooler, denser water stays at the bottom. The warmer water is then pumped out of the tank, typically to be used in a chiller system to cool the surrounding environment. Meanwhile, the cooled water is pumped back into the bottom of the tank.

This technology is commonly used in public buildings such as hospitals, universities, and military facilities. This method is effective for peak shifting, helping to decrease energy demand during peak times and reduce energy costs for end users. The typical capacity of these systems ranges from 2 to 3 MW, and they are most commonly used in North America. One of the main challenges of this system is designing the cooling tank to optimize efficiency. However, it is a cost-effective solution that offers significant economic advantages over ice storage systems [6, 90].

Ice storage. In this technology, energy storage relies on the transformation of the physical state of water, specifically using ice as the storage medium, which falls under the category of Latent Heat Storage (LHS). Similar to chilled water systems, this method uses a loop, but instead of just circulating water, a glycol solution circulates through the system to create ice on coils within the tanks. One advantage of ice storage systems over chilled water systems is that ice has a higher energy density per unit area, allowing for greater energy storage capacity in a smaller space. However, this also means that ice storage systems typically require more specialized equipment and space than chilled water systems. Ice storage systems, like other thermal energy storage methods, are designed to store ice during off-peak hours when energy demand is lower. This ice is then used to provide cooling during peak hours, helping to reduce energy costs and alleviate stress on the grid. Although this technology faces challenges that require improvements, it has gained attention due to its potential applications. Prominent companies like Ice Energy and CALMAC have been leading in the development of this technology, with several projects ranging from tens of kW to several hundred kW in high-energy consumption areas. These systems are primarily used in malls, public buildings, and residential complexes, where they can store energy for up to 4 hours, offering a reliable and cost-effective solution for peak shaving and cooling needs [4, 38].

2.2 Chemical energy storage systems

In chemical storage methods, energy is typically stored as gas or liquid fuels through chemical reactions and processes, depending on their physical and chemical properties, as well as power electronic devices. There are various ongoing projects in this area.

Fuel storage systems. The leading gases used in these external storage systems are as follows:

Hydrogen. This gas can be produced from natural gas, oil, coal, and electrolysis of water which allows for the storage of both oxygen and hydrogen. Hydrogen storage is considered a promising option due to its low-carbon production methods and versatile end-use applications [6, 75, 78]. It can be used as fuel for rockets and jet engines and plays a crucial role in fuel cells as a source of energy. There are several projects worldwide with a combined capacity of 18 MW, with 14 MW currently under production in Germany, which is the only country with more than one operational unit [91].

Methane. Using the Sabatier process to produce methane CH_4 from hydrogen and carbon dioxide has its drawbacks, as does the Fischer-Tropsch process, which involves hydrogen and carbon monoxide (Biogas) [92].

One of the countries that has performed the highest number of projects is Germany. The integration of this type of energy storage strategy with fuel cells is both attractive and applicable. For instance, Audi is running a project that converts CO_2 from biomass into pure methane for CNG cars, while simultaneously producing hydrogen in situ, which is used in fuel cell cars. As a result, the need for hydrogen transportation infrastructure is eliminated. Hydrogen is widely recognized for its broad range of applications. Several projects worldwide are utilizing hydrogen storage as a form of chemical energy storage. Germany plans to store 1 GW of energy in hydrogen form by 2025, with an expected capacity of less than 100 MW by 2022 [4]. It is notable that this type of storage, known as E-Gas, helps reduce global warming and air pollution by converting electricity into fuels such as hydrogen, methane, or methanol. Both renewable and traditional power plants can be used for electricity supply [93, 94]. Other types of storage, such as gas, thermal, battery, and P2G systems, can enhance the operation and planning of IESs more efficiently and economically. For instance, Hydrogenics used a P2G system to deliver 2 MW of storage capacity and provided PEM electrolyzers in the Toronto area. Various studies have focused on improving solid oxide fuel cell electrodes to directly use natural gas without reforming [85, 95]. Additionally, a 1 MW hydrogen storage system has been installed in a 140 MW wind farm in Germany [85, 90].

Liquid fuel storage systems. Liquid fuels include methanol and biofuels. Methanol: Methanol can be produced from hydrogen generated by wind and solar renewable energy sources. This fuel offers several advantages compared to others: it has a high volumetric energy density, and its physical state is liquid at ambient temperature and atmospheric pressure. Like methane, carbon dioxide is required for methanol production, which is considered a disadvantage. However, there are methods to produce clean fuels by using hydrogen from water electrolysis and carbon dioxide for combustion.

Biofuels. Biodiesel, alcoholic fuels, or biomass can be substituted by fossil fuels. The oil price of more than $76 makes this method economical [4, 94].

2.3 Application in grid

Storage applications in the power grid is presented as follows:

- Decreasing the need for power generation by using PHS for time shifting, which stores energy in peak off and delivers it at peak hours;
- Keeping power quality, voltage, and frequency using stored energy in the needed time;
- Providing stable power for off-grid systems;
- Providing power in an emergency condition;
- PHS for time shift and power quality;
- CAES for time shift and power quality;

There are two commercial diabatic systems worldwide. One is located in Germany (built in 1978) with a capacity of 290 MW, and the other is in the USA (built in 1991) with a capacity of 226 MW. Both systems compress air during off-peak hours, store the energy, and then discharge it during peak hours by mixing the compressed air with natural gas and combusting the mixture. The remaining systems are in the adiabatic installation stage [17,25]. The compressed air is stored in underground caverns. Li-ion batteries can provide the highest efficiency for grid applications. Additionally, the TotalEnergies company began operating 129 MWh of battery-based storage capacity in mainland France starting in 2020. In 2023, TotalEnergies launched the largest battery-based energy storage project in Europe, located in Belgium, with a capacity of 75 MWh, which provides daily energy for nearly 10,000 homes. The battery system helps reduce costs and improves the response time of the grid [16, 57, 96, 97]. Vital infrastructure, such as power stations, communication stations, and distribution networks, requires reliable energy sources. Therefore, DC power sources with batteries are commonly used in these types of applications. Lead-acid batteries are typically chosen for their cost-effectiveness, established technology, and availability. Some challenges, such as energy density and maintenance requirements, have been addressed with advancements in this technology [3,79,98]. Remote areas, small cities, and villages that are not connected to the electricity grid can benefit from sustainable technology and reliable resources. These areas can use diesel generators and batteries to meet electricity demand. The system size is a key factor in determining the appropriate battery type [2, 4, 99]. Additionally, uninterruptible power supplies (UPS) offer solutions for managing higher electricity costs during peak hours by providing backup power during outages or sudden power disruptions. UPS systems improve power quality for organizations and commercial buildings, which is critical in certain locations [25, 73]. These applications are categorized into four classes:

RESs. RESs like wind and solar have been used to address environmental problems. The main challenge with these energy sources is their instability in production due to fluctuations in weather conditions. As a result, other systems can help bridge the energy gap and provide opportunities to minimize these fluctuations. Based on capacity, power production is categorized into kilowatts, megawatts, and gigawatts [10, 100, 101]. Moreover, ESSs are crucial for managing time-shifting. The integration of renewable energies and storage systems can optimize energy production and reduce the levelized cost of storage (LCOS). Batteries, fuel cells, and supercapacitors are leading energy storage devices used for residential applications. Lead-acid and Li-ion batteries are the most commonly used, with the former offering a lower cost per kW and the latter providing the highest efficiency [2, 10]. ESSs, integrated with wind and PV generation, can have MWh capacities. Between 2020 and 2023, 3,673 RES projects worldwide with a total capacity of 12,876 MW were completed, including 2,567 MW from wind energy and 10,309 MW from PVs. The interest in wind stations with batteries has been growing over time. For example, a wind station in Japan with a 51 MW capacity integrates Na-S batteries. With these batteries, the wind generation can be levelized, ensuring that the output power does not exceed 40 MW [4, 73, 102].

Smart grids. Today's grids are usually based on central plants that consist of four main components: energy sources, systems that convert energy sources into thermal energy (typically chilled and hot water), a low- and mid-voltage distribution system to transfer power, and end users. Power dispatch and grid control are generally managed using centralized equipment, with independent control for end-users [99, 103]. An intelligent system can be used to manage both consumption and production, as well as monitor and control residential devices. By regulating the production and consumption sides, efficiency can be improved by controlling devices that are unnecessary during peak hours and reactivating them during non-peak hours. Various technologies are utilized in smart systems, with energy storage being one of the most important [15, 104]. The reasons for using ESSs are as follows:

- With the advent of technology, the share of renewable energy in energy production has been increasing. Along with the integration of renewable energy, ESSs have been developed to enhance the system's ability to manage charge and discharge cycles, balancing power consumption and generation;
- In certain cases, ESSs can help defer and reduce investments in power generation infrastructure, such as transformers, distribution lines, and transmission systems, particularly during peak hours. Additionally, ESSs can enhance the capacity for frequency control;
- Another approach is managing the consumption side, which involves residential users and smart grids. Through smart grid management, incentives can persuade the user to buy electricity in off-peak hours when the energy costs are lower.

Different electrochemical ESSs are used in smart grids, including lead-acid, Na-S, and Li-ion batteries. Moreover, redox batteries show great potential due to their decoupling of energy and power, which enables more effective and efficient storage [7, 15, 104].

Smart microgrids. Smart microgrids can be used to meet the needs of consumers in smart factories, buildings, hospitals, a village community, malls, or other middle-grid users, utilizing electrochemical ESSs. The integration of microgrids is critical for enhancing grid flexibility, providing power when needed in a cost-effective manner. Electrochemical ESSs are key components of a smart microgrid, and they should possess characteristics that enhance capacity, independence, and the potential for seamless connection to other grids. The architecture of a smart microgrid consists of distributed energy resources such as PV and wind energy, storage systems, and loads. A controller can be implemented to enhance capacity based on the size of the storage system within the smart microgrid. Both microgrids and ESSs should be connected to the grid, even in the case of stand-alone or isolated smart microgrids. Additionally, the system should be adaptable, as isolated microgrids can be intelligently contracted or expanded as needed [3, 15, 38].

Smart homes. In smart homes, devices can be automatically controlled to optimize energy usage and increase efficiency. The electrochemical energy storage system plays a crucial role in this process. Additionally, load leveling through electrochemical energy storage can reduce peak demand. However, decreases in cost and discharge can simultaneously lead to increased consumption. Users can lower electricity expenses by optimizing the electrochemical energy storage system and controlling factors such as temperature and lighting. Some users prefer to rely on renewable energy sources. ESS can help balance the gap between demand and generation. In certain exceptional cases, such as with electricity generation, many isolated renewable power plants encounter challenges due to the intermittent nature of their output. ESSs can address this issue [7, 99, 101, 104].

3 Results and Discussion

The share of energy storage projects is illustrated schematically in Figure 4. As can be seen, electrochemical energy storage systems account for the highest percentage, with 60% of the ESSs in the grid utilizing the electrochemical method [35].

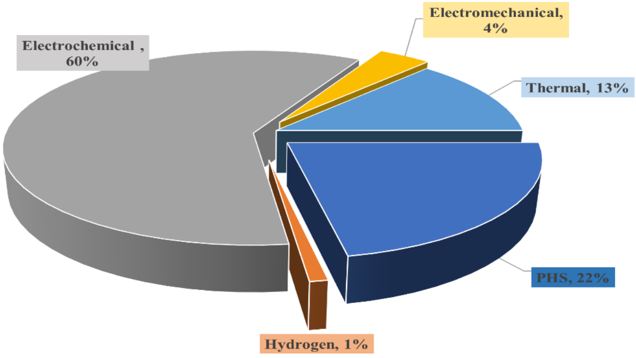

Fig. 4. Share of energy storage projects worldwide.

This behavior can be attributed to the flexibility of batteries in terms of size and capacity. Additionally, maintenance and wear are lower compared to other systems, and the ability of batteries to supply energy to the grid for several hours makes them a favorable choice for energy storage. Among the various types of batteries, Li-ion batteries hold the largest share. Figure 5 illustrates the percentage distribution of different electrochemical energy storage systems. It can be observed that 66% of all projects are associated with Li-ion batteries [35, 49, 96].

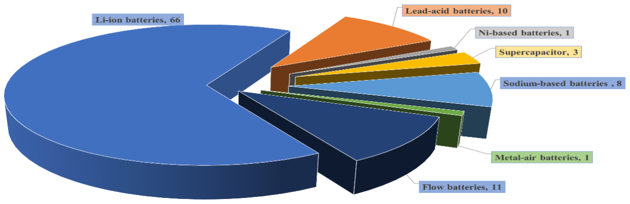

Fig. 5. Electrochemical energy storage systems share.

These data refer to the number of projects, not the capacity. As previously mentioned, when considering capacity, electrochemical energy storage systems represent a small share of the total energy storage. The largest share is held by pumped storage hydro (PSH), which accounts for approximately 97% of the installed energy storage capacity worldwide. PHS systems, with an average capacity of 520 MW, have the highest capacity among the systems introduced. The next largest systems are CAES at 175 MW, molten salt at 67 MW, and flywheel systems at 19 MW. Other systems typically have an average capacity of less than 10 MW. Electrical energy storage time and regeneration are critical parameters inESSs. The characteristics of different storage systems are outlined in Table 1.

Table 1. Storage system classification by characteristics.

Storage system	Application	Cycle-life	Life (Year)	Efficiency (%)	Nominal discharge	Power density (W/l)	Energy density (Wh/l)	Response time
PHS	Time shift, Emergency power supply	> 15000	>50	70-80	Hours	0.1-0.2	0.2-2	Minute
CAES	Time shifting	> 10000	>25	41-75	Hours	0.2-0.6	2-6	Minute
FES	Power quality	20000-10000000	15-20	80-90	Seconds	5000	20-80	<Second
Lead-Acid	Emergency power supply, Time shifting, Power quality	250-1500	3-15	75-90	Hours	90-700	50-80	<Second
NiCd	Emergency power supply, Time shifting, Power quality	1500-3000	5-20	60-80	Hours	75-700	15-80	<Second
NiMH	EVs	600-1200	5-10	65-75	Hours	500-3000	80-200	<Second
Li-ion	EVs, Time shifting, Power quality, Network efficiency	500-10000	6-15	85-98	Hours	1300-10000	200-400	<Second
Zn-Air	EVs, Network efficiency	>1000	>1	50-70	Hours	50-100	130-200	<Second
NaS	Time shifting, Network efficiency	2500-4500	10-15	70-85	Hours	120-160	15-300	<Second
Na-NiCl	Time shifting, EVs	1000	10-15	80-90	Hours	250-270	150-200	<Second
VRFB	Time shifting, EVs	> 10000	5-20	60-75	Hours	0.5-2	20-70	Second
HFB	Time shifting, EVs	1000-36500	5-10	65-75	Hours	1-25	65	Second
Hydrogen	Time shifting	1000-10000	10-30	34-44	Hours-Week	0.2-20	600	Second-Minutes
SNG	Time shifting	1000-10000	10-30	30-38	Hours-Week	0.2-2	1800	Minutes
DLC	Power quality	10000-100000	4-12	85-98	Seconds	40000-120000	10-20	<Second
SMES	Time shifting, Power quality	NA	NA	75-80	Seconds	2600	6	<Second

3.1 Technology trends and prospective energy storage solutions for Iran

Energy storage in the Iranian market can be classified into short-term, mid-term, and long-term. Hydroelectric power plants, a mature technology, have the largest share of installations worldwide. The main challenges in developing PHS include geometric, environmental, and funding limitations. In Iran, there are hydroelectric power plants such as the Siahbishe plant, which has a capacity of 1000 MW. The investment cost for the Siahbishe hydroelectric power plant was approximately 120 million dollars, which can offset the 10 million dollars per year depreciation of thermal power plants. The total power production is about 80,000 MW, offering significant potential for energy storage. However, this PHS system is currently the only one in Iran specifically aimed at energy storage. There are other EES in Iran, but they are primarily used for ensuring safe and stable power, rather than for energy storage. Constructing a hydroelectric power plant requires expertise in civil and mechanical engineering. While Iran has advanced capabilities in dam construction, there are limitations in the mechanical sector that could be addressed by companies like MAPNA. However, the primary challenge remains securing adequate funding. Different research institutes and universities are working on ESS topics in Iran. Some strategic plans focus on renewable energy development, with a target capacity of 10 GW for non-hydropower renewables by 2025. Additionally, a roadmap and strategic plan for ESS have been prepared by the Niroo Research Institute in collaboration with various stakeholders for the Ministry of Energy [105]. The outcomes of the ESS strategic plan and subsequent experiences indicate that the main goals for Iran should focus on the following areas:

- Decreasing greenhouse gas emissions and increasing environmental protection;
- Increasing the quality and security of energy;
- Localization of technology knowledge and ESS application;
- Increasing the share of REs along with increasing exporting of electricity.

To address such issues, it is important to consider both the potential and attractiveness of a technology. The potential is evaluated by examining infrastructure, economic factors, and availability, while attractiveness is determined by available funding, research trends, and practical applications. In Iran, research trends are increasingly favoring Li-ion batteries. However, PSH (Pumped Storage Hydro) has the highest potential. It is also worth noting that Li-ion batteries, due to their applications in transportation, are gaining significant attention and are expected to be in high demand in the near future. Research into Li-ion batteries is feasible and could be developed over the next five years in Iran through national laboratories, start-ups, and interested researchers. CAES technology is a flexible system capable of offering various capacities. This technology has garnered significant attention in recent years. Iran has good potential for developing CAES technology, given the country's capabilities in producing components for this type of energy storage system. The application of ESSs in Iran's electricity industry can be summarized as follows:

- Usage in grid-scale; smart grids
- The role of utility; time shift, power quality, more efficient grid, isolated grids, etc;
- Emergency power supply;
- Technical and performance advantages include gas and oil, aviation, transportation, etc.

From another point of view, EES can directly and indirectly affect social welfare. These effects include energy savings, reduced energy service costs, alleviation of poverty, increased net income, improved efficiency in the industrial sector, job creation, and enhanced energy security. Some technologies in Iran have been developed over time, with substantial associated costs. For example, the PHS (Pumped Storage Hydro) system is a nearly mature technology with limited ongoing research and development. In contrast, many research and development projects are focused on newer technologies. However, the development trend must align with upstream regulations and strategic roadmaps. In the plans of the Ministry of Energy in Iran, the addition of 10,000 MW of renewable energy (primarily wind and solar) is included in the three-year development program. It is crucial to minimize the risk of electricity shortages during peak hours [106]. As shown in Figure 6, the share of renewable energy sources in Iran's grid has been increasing. The proportion of electricity generated from hydropower accounts for 87% of the total generated electricity. Furthermore, the annual percentage change in renewable energy generation in Iran was 55.13%, compared to 5.99% globally, which includes energy from hydropower, solar, wind, geothermal, wave and tidal energy, and bioenergy [107].

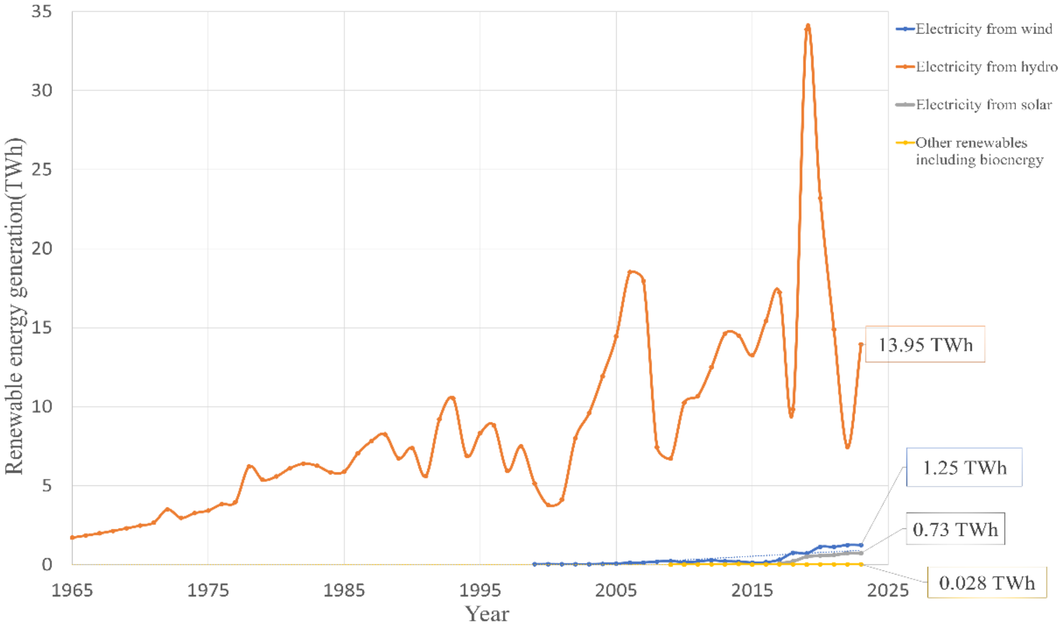

Fig. 6. Statistical review of renewable energies in Iran.

Moreover, there are plans in place to utilize energy storage for peak shaving and renewable energy integration. Significant work has already been done by scientists on energy storage and various systems. Therefore, research should focus on existing technologies to further explore their design, manufacturing, and application in line with previous uses. These applications include frequency control, power quality improvement, peak shaving, grid stability, and increasing the penetration of renewable energy. It is important to note that technical knowledge is crucial for the development of technology in a country and should be pursued with precision. For example, acquiring technical expertise in Li-ion batteries is a costly process that is not easily accessible in Iran due to a lack of infrastructure and limited active research centers and universities. Therefore, a two- or three-year plan is needed to establish research centers, fund universities and startups, and foster the development of this technology and the acquisition of technical knowledge. As this technology is developing rapidly worldwide, technology transfer at this stage may not be the best approach; instead, developing local infrastructure is essential. The same challenge applies to other technologies that still need to mature. While many studies have been conducted in Iran, they are mostly on a laboratory scale. Currently, there are only a few ESSs in the grid, aside from the Siah Bishe PSH Power Plant with a capacity of 1000 MW and some distributed batteries used for solar panels (both portable and stationary). In the next section, some of these studies will be explored in more detail.

3.2 Economic analysis

In recent years, one of the main challenges in Iran's power supply has been maintaining production stability during peak times in the summer. Various methods have been considered to address this issue, including the development of new renewable energy power plants and offering incentives for consumers to reduce their consumption. However, these methods are not always stable, and energy generation security may still be at risk. Another proposal is the establishment of new CHP plants, which could be more economical. On the other hand, industries are required to reduce their usage during peak times in exchange for incentives. One possible solution to this challenge in Iran is the use of diesel generators. Li-ion batteries could serve as an alternative to diesel generators. To compare the levelized cost of energy (LCOE) between diesel generators (DG) and Li-ion batteries, Equation (1) is used [108, 109].

$$\mathrm{LCOE} = \sum \left[\frac{I_t + M_t + F_t}{(1+r)^t} \right] \Big/ \sum \left[\frac{E_t}{(1+d)^t} \right] \tag{1}$$

where:

I : Capital cost
M : Operational and maintenance cost
F : Fuel cost
r : Discount rate
d : Degradation rate
E : Total electricity produced
t : Life cycle

This calculation considered Li-ion batteries with a four-hour duration for a system that includes a 10 MW generator and a 40 MWh daily energy output, with charging provided by a CHP plant and PV power plants. The calculation was conducted for two years, using 2023 and 2030 as reference points. For this purpose, the installation cost of 10 MW of Li-ion batteries was estimated at \$20,000,000 in 2023 and \$16,120,000 on average for 2030 [110, 111]. The parameters for Li-ion batteries included a round-trip efficiency of 86% and 3,500 cycles for 2023, and over 90% round-trip efficiency with 5,000 cycles for 2030, with a discount rate of 10%. The annual operational and maintenance costs were estimated at \$400,000 (2% of capital cost) for the installation of Li-ion batteries in 2023 and \$260,000 in 2030. In comparison, the maintenance cost for the diesel generator was \$23,000 [112]. The installation cost of a 10 MW diesel generator was calculated at \$27,500,000 for 2023 and \$23,500,000 for 2030 [113].

LCOE in 2023. The LCOE of Li-ion batteries charging with PV power plants (consider 6 cents/W as the PV generation cost [114]) is calculated as follows:

$$F_t = 40 \times 60 \times 3500 = 8400000\,\$\,, \tag{2}$$

$$E_t = 40 \times 3500 \times 86\% = 120400\,\mathrm{MWh}\,, \tag{3}$$

$$\mathrm{LCOE} = \left[\frac{20000000 + 400000 + 8400000}{(1+0.1)^{9.58}} \right] \Big/ \left[\frac{120400}{(1+0.1)^{9.58}} \right] = 239.2\,\$/\mathrm{MWh}\,. \tag{4}$$

The LCOE of Li-ion batteries charging with CHP power plants (consider the actual cost of energy in Iran, 2.5 cents/kW) is expressed in Equation (6).

$$F_t = 40 \times 25 \times 3500 = 3500000\,\$\,, \tag{5}$$

$$\mathrm{LCOE} = \left[\frac{20000000 + 400000 + 3500000}{(1+0.1)^{9.58}} \right] \Big/ \left[\frac{120400}{(1+0.1)^{9.58}} \right] = 198.5\,\$/\mathrm{MWh}\,. \tag{6}$$

For a 10 MW diesel generator working 4 hours daily with a cycle life of 15000 hours and an average diesel FOB Persian Gulf cost of 1.52 and 1.62 \$/gallon, the

LCOE can be calculated using Equation (8) and Equation (9), respectively.

$$E_t = 40 \times 3750 = 150000\,\text{MWh}\,, \tag{7}$$

$$\text{LCOE} = \left[\frac{27500000 + 23000 + 19360000}{(1+0.1)^{10.2}}\right] \Bigg/ \left[\frac{150000}{(1+0.08)^{10.2}}\right] = 259\,\$/\text{MWh}\,, \tag{8}$$

$$\text{LCOE} = \left[\frac{27500000 + 23000 + 21000000}{(1+0.1)^{10.2}}\right] \Bigg/ \left[\frac{150000}{(1+0.08)^{10.2}}\right] = 268\,\$/\text{MWh}\,. \tag{9}$$

LCOE forecast for 2030. The LCOE of Li-ion batteries charging with PV power plants (consider 3.5 cents/kW as the PV generation cost [115]) is calculated as follows:

$$F_t = 40 \times 35 \times 5000 = 7000000\,\$\,, \tag{10}$$

$$E_t = 40 \times 5000 \times 90\% = 180000\,\text{MWh}\,, \tag{11}$$

$$\text{LCOE} = \left[\frac{16120000 + 260000 + 7000000}{(1+0.1)^{13.6}}\right] \Bigg/ \left[\frac{180000}{(1+0.1)^{13.6}}\right] = 129.88\,\$/\text{MWh}\,. \tag{12}$$

The LCOE of Li-ion batteries charging with CHP power plants (consider the actual cost of energy in Iran, 3 cents/kW) is expressed in Equation (7).

$$F_t = 40 \times 30 \times 5000 = 6000000\,\$\,, \tag{13}$$

$$\text{LCOE} = \left[\frac{16120000 + 260000 + 6000000}{(1+0.1)^{13.6}}\right] \Bigg/ \left[\frac{180000}{(1+0.1)^{13.6}}\right] = 124.33\,\$/\text{MWh}\,. \tag{14}$$

For a 10 MW diesel generator working 4 hours daily with a cycle life of 15000 hours and an average diesel FOB Persian Gulf cost of 1.72 and 1.92 \$/gallon, the LCOE can be calculated using Equation (15) and Equation (16), respectively.

$$E_t = 40 \times 4500 = 180000\,\text{MWh}\,, \tag{15}$$

$$\text{LCOE} = \left[\frac{23500000 + 23000 + 27000000}{(1+0.1)^{12.3}}\right] \Bigg/ \left[\frac{180000}{(1+0.08)^{12.3}}\right] = 224\,\$/\text{MWh}\,, \tag{16}$$

$$\text{LCOE} = \left[\frac{23500000 + 23000 + 28800000}{(1+0.1)^{12.3}}\right] \Bigg/ \left[\frac{180000}{(1+0.08)^{12.3}}\right] = 232\,\$/\text{MWh}\,. \tag{17}$$

These results demonstrate a comparison between the use of Li-ion batteries and diesel generators. In 2023, Li-ion batteries are not as economical as diesel generators in Iran. However, by 2030, Li-ion batteries become more cost-effective. It is important to note that in this calculation, the cost of CO_2 emissions is not considered. When factoring in the CO_2 emission cost, Li-ion batteries would prove to be significantly more beneficial, as shown in Table 2.

Table 2. LCOE of different technologies with and without considering CO_2 emissions.

System	LCOE (\$/MWh)			
	2023		2030	
	W/O CO_2[1]	W CO_2	W/O CO_2[2]	W CO_2
Li-ion battery (PV charged)	239.2	239.2	129.88	129.88
Li-ion battery (CHP charged)	198.5	198.5	124.33	124.33
Diesel generator (Diesel)	259	266	224	294
Diesel generator (Petrol)	268	273	232	294

As peak consumption in Iran is typically limited to less than ten days in the summer, other methods, such as using ESSs for peak shifting, could be helpful. In the summer of 2023, the peak consumption reached about 70,000 MW, which was managed without any major grid issues and with the lowest outage rate. The average daily peak consumption was approximately 64,000 MW, with a 6,000 MW deviation during peak times. The average daily off-peak consumption was around 58,000 MW. However, these values are close to the limits of production capacity in Iran, and some solutions should be implemented in the coming years. Devel-

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[1] The average cost of CO_2 emission in 2023 considered 7.6 \$/tone.

[2] The average cost of CO_2 emission in 2030 considered 100 \$/tone.

oping around 3,000 MW of Li-ion batteries, charging them during off-peak hours, and utilizing them during peak hours could help create a safe margin for grid stability.

4 Conclusions

This study reviews various energy storage methods, some of which are already in operation, while others have been recently introduced. The choice of energy storage system depends on its intended application, and several factors must be considered. For example, some methods may offer high power density but have a limited storage duration, while others may have a longer storage time but lower power density. In the case of flywheels, the discharge time is typically less than a minute, which makes them suitable for specific applications requiring rapid energy release over short durations. Therefore, the application is the primary factor limiting the selection of an energy storage method. Another crucial consideration is the response time. For example, despite the high capacity and power density of Pumped Storage Hydropower (PHS), its response time is on the order of days, which makes it unsuitable for certain applications like frequency control and peak shaving. Additionally, the life cycle of energy storage systems is another important aspect to consider. Batteries, in particular, have a limited lifespan and require optimization to improve their longevity and efficiency in practical applications. For instance, Ni-Cd batteries offer high power density, but they suffer from a memory effect, meaning they must be completely discharged before recharging. This limitation restricts their applications.

As a result, using rechargeable batteries with memory effects in cases like balancing networks can lead to unnecessary energy loss and higher costs. On the other hand, Li-ion batteries have a wide range of applications due to their favorable properties, such as higher efficiency and longer lifespan. As mentioned earlier, Li-ion batteries account for the largest share of recently installed systems and project numbers, highlighting their growing dominance in energy storage solutions. Recently, in California, the use of Li-ion batteries has become preferable to gas turbine power plants due to the decrease in the cost of Li-ion batteries. It seems that Li-ion batteries will be the preferred choice for fast-response ESSs in the near future. The high power and long duration of Pumped Hydro Storage (PHS) make it unique for certain applications and contribute to its ongoing development. The most important factors for this technology are site location, as well as economic and environmental considerations. It should be noted that PHS is not economical or suitable for low-capacity applications. Therefore, factors such as capital cost, operational cost, revenue, life cycle, electricity price, environmental aspects, and others should be considered when choosing a site. Another important consideration is technology trends and developments. For example, ESSs have been rapidly advancing in China and the USA, with a focus on thermal and electrochemical storage systems. One emerging technology is the molten metal battery, which combines thermal and electrochemical energy. Originally developed in the USA, this technology has the potential to produce both heat and power simultaneously. The first versions of supercapacitors were capable of delivering energy only for short periods.

In Iran, the vision for energy storage technologies is divided into two classifications: potential and attractiveness. The potential is assessed based on factors such as infrastructure, economic viability, and availability, while attractiveness takes into account available funding, research trends, and practical applications. Pumped Storage Hydropower (PSH) has the highest potential, while Li-ion batteries are considered the most attractive technology in Iran. The study highlights the significance of investing in Li-ion battery technology by establishing national laboratories and supporting startups, which is expected to yield substantial benefits in the next five years. Additionally, one of the main ESS used as a backup power source in Iran is the diesel generator, which is anticipated to become less economical in the near future. The LCOE analysis of Li-ion batteries shows that their cost would decrease to 55% of that of diesel generators.

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