

Introduction to Electric Energy Storage Systems

1.1 Introduction

Electric vehicles (EVs) are now recognized as the key technology for decarbonizing road transport, which generates over 15–16% of global CO₂ emissions [1]. EV adoption is surging; global sales reached 14 million units in 2023 and are projected to increase to 70 million units by 2035 [2]. These trends mean that battery packs, the primary energy storage in EVs, are playing a significant role in both transportation and power systems. EV batteries must meet demanding requirements such as extremely high energy density for long driving range, long cycle life, the ability to charge quickly, and rigorous safety and thermal controls [2, 3]. To meet these needs, researchers and manufacturers have rapidly improved lithium (Li)-ion cell chemistries, for example, reducing cobalt (Co) and using nickel (Ni)-rich cathodes and new anode materials, and have driven pack costs steadily downward. For instance, current Li-ion cells now achieve energy densities up to 200–220 Wh/kg and endure thousands of cycles. At the same time, alternative chemistries are being developed, such as sodium (Na)-ion batteries (using abundant Na), which are gaining attention for low-cost, high-cycle storage, and all-solid-state batteries promise yet higher density and improved safety [3, 4].

1.2 Advances in Battery Technologies

Historically, EVs used nickel-metal hydride (NiMH) and even lead-acid batteries, but today Li-ion dominates due to its superior performance. Recent reviews note that modern EV packs typically employ Li nickel-manganese-cobalt oxides (NMC) or Li iron phosphate (LFP) cathodes paired with advanced anodes (often graphite or silicon-based) to maximize energy and power. State-of-the-art automotive Li-ion cells already store about 200–220 Wh/kg and endure well over 2000 cycles.

Research continues to push these limits. For example, silicon-rich anodes and novel solid electrolytes are being investigated to boost capacity and enable 5–10-minute charging. Parallel efforts target cost and sustainability. Na-ion batteries, for instance, leverage inexpensive materials, and emerging recycling processes recover Li, Co, and Ni efficiently. Reviews highlight that next-generation batteries must balance energy density, cost, and lifetime. For example, one recent survey notes that while Ni-based cells once surpassed lead-acid, today's Li-ion chemistries overwhelmingly lead, and future systems like Na-ion, solid-state are being designed to further improve efficiency and resource sustainability [1–4].

EVs also demand high power density for rapid acceleration and fast charging. Advanced battery designs, such as cylindrical, prismatic, or pouch cells, now support extremely high charge/discharge rates, but this in turn places a premium on effective thermal management. Accordingly, much recent work has focused on improving cell stability and heat dissipation. For instance, new electrode materials and electrolytes are optimized for fast-ion transport, and pack designs incorporate advanced cooling (air, liquid, phase-change materials) to prevent overheating during high-rate charging or discharging. These cell- and pack-level innovations, along with economies of scale, have driven the EV battery pack price sharply downward over the last decade, enabling broader adoption [1–4].

1.2.1 Battery Management and Charging Strategies

A battery management system (BMS) is essential for safe and reliable EV operation. The BMS continuously monitors each cell's voltage, current, and temperature and actively controls charging, balancing, and cooling. In practical terms, the BMS prevents thermal runaway and cell imbalance by regulating charge currents, activating cooling loops, and ensuring uniform cell voltages. Reviews emphasize that modern BMS functions include state-of-charge (SOC) and state-of-health (SOH) estimation, often via model-based or data-driven algorithms and real-time fault diagnosis. In addition, the charging strategy is a critical part of system design. Intelligent algorithms adjust the current profile to maximize battery life and accelerate charging when safe. Recent analyses highlight that optimizing the trade-off among fast charging, energy density, and longevity—the so-called “*fast-charging trilemma*”—is a major research theme. In practice, EVs now routinely accept charging rates of more than 150 kW, and ongoing R&D seeks to push this capability to more than 350 kW (providing more than 250 miles of range in approximately 15 minutes) [5].

Large-scale deployment also depends on widespread charging infrastructure and smart charging controls. Home and workplace chargers are the backbone of daily charging, but public and fast-charging networks have expanded rapidly. For example, the IEA reports that public charging points have doubled globally

since 2022, exceeding 5 million by 2024. At the same time, digital “*smart charging*” platforms are being rolled out; these systems use grid signals and AI-based controllers to schedule EV charging for low-cost periods or renewable surpluses. According to recent reviews, such smart strategies allow fleets of EVs to be coordinated as a virtual power plant, with vehicles charging when solar and wind energy are abundant and throttling back charging (or even discharging) during system peaks. In short, modern EV charging integration is becoming an active grid resource, not just a passive load [5–7].

1.2.2 Vehicle-to-grid and Second-life Applications

One of the most promising concepts in EV storage is vehicle-to-grid (V2G) operation. In V2G, bidirectional chargers enable an EV to both draw energy from and feed energy back to the grid. Recent reviews highlight that V2G effectively turns every connected EV into a mobile battery, which can absorb excess renewable generation and later discharge during peak demand. This bidirectional energy flow “*spins*” additional virtual inertia into the grid. EV fleets can rapidly inject power to stabilize frequency or function as a spinning reserve during outages. By spreading storage capacity across millions of vehicles, V2G schemes can improve grid flexibility and reduce curtailment of solar/wind energy. Researchers note that enabling technologies such as advanced inverters, communication protocols, and AI-based energy-management systems are key to realizing these benefits [7, 8].

Beyond grid services, EV batteries also have a second life once their vehicular performance degrades below automotive standards, typically when capacity falls to approximately 70–80%. Instead of recycling at once, these used batteries can be repurposed as stationary storage for homes or utilities. In recent times, second-life EV batteries have emerged as a viable solution by repurposing end-of-life batteries, thereby prolonging their lifespan and optimizing resource use. In practice, retired EV packs keep significant capacity and can serve in less-demanding roles, such as backup power, community storage, etc., delaying recycling or disposal. Studies have shown that using second-life batteries in grid storage can cut life-cycle greenhouse gas emissions by approximately 25–56% (compared with producing all-new storage) and reduce system costs by 30–50%. These economic and environmental dividends, along with emerging business models for refurbishing EV packs, are driving interest in second-life markets. Ultimately, both advanced recycling processes and second-life repurposing are seen as crucial for a sustainable battery ecosystem [7, 8]. Through these advances, energy storage is no longer a peripheral concern but a central enabler of electric mobility. In the words of recent reviews, continued innovation in EV batteries in terms of chemistry, management, and integration is “*a prerequisite for a low-carbon energy future,*” underpinning both transportation decarbonization and grid reliability.

Global trends from climate change mitigation to transportation electrification further underline why storage innovation is vital. International energy agencies and recent review articles all conclude that continued advances in electrical energy storage (EES) are a prerequisite for a low-carbon energy future. Storage is now recognized not just as an optional upgrade, but as a cornerstone of sustainable transportation and electrification. Through these developments, EES has transformed from a niche auxiliary into a central enabling technology. Current literature repeatedly notes that advancing storage technology in terms of capacity, efficiency, cost, and integration is one of the key requirements for a successful clean energy transition [9].

In summary, the confluence of high-performance battery cells, sophisticated BMS/control strategies, and new paradigms such as V2G and battery reuse is rapidly transforming EVs into versatile energy assets for a clean, flexible power system. In addition to the battery storage, other energy storage technologies also play a significant role in e-mobility applications. Therefore, the classification of various energy storage technologies and their detailed explanations are discussed in the following sections.

1.3 Classification of Energy Storage Technologies

EESs can be systematically classified according to the fundamental form in which energy is stored. As depicted conceptually in Figure 1.1, six principal categories are generally recognized: chemical, electrical, electrochemical, electromagnetic, mechanical, and thermal storage [10–12]. This classification reflects the underlying physical mechanisms governing energy conversion, retention, and release, and it provides a useful framework for comparing technologies, particularly in the context of e-mobility, where performance, weight, and responsiveness are critical.

Each category encompasses a range of technologies with distinct operating principles and practical implications. Chemical energy storage relies on storing energy in molecular bonds, typically in fuels or synthetic carriers. In the context of e-mobility, hydrogen-based systems and synthetic fuels have received renewed attention, especially for heavy-duty transport and long-haul applications. Recent studies highlight that hydrogen fuel cell EVs (FCEVs) offer rapid refueling and long driving ranges, although challenges related to energy-storage density, infrastructure, and system cost remain significant.

EES, by contrast, involves the direct storage of charge in electric fields. Technologies such as capacitors and supercapacitors fall into this category. While their energy density is relatively low compared with that of batteries, their extremely high-power density and fast response times make them attractive for specific vehicular functions. Recent literature emphasizes their growing role in

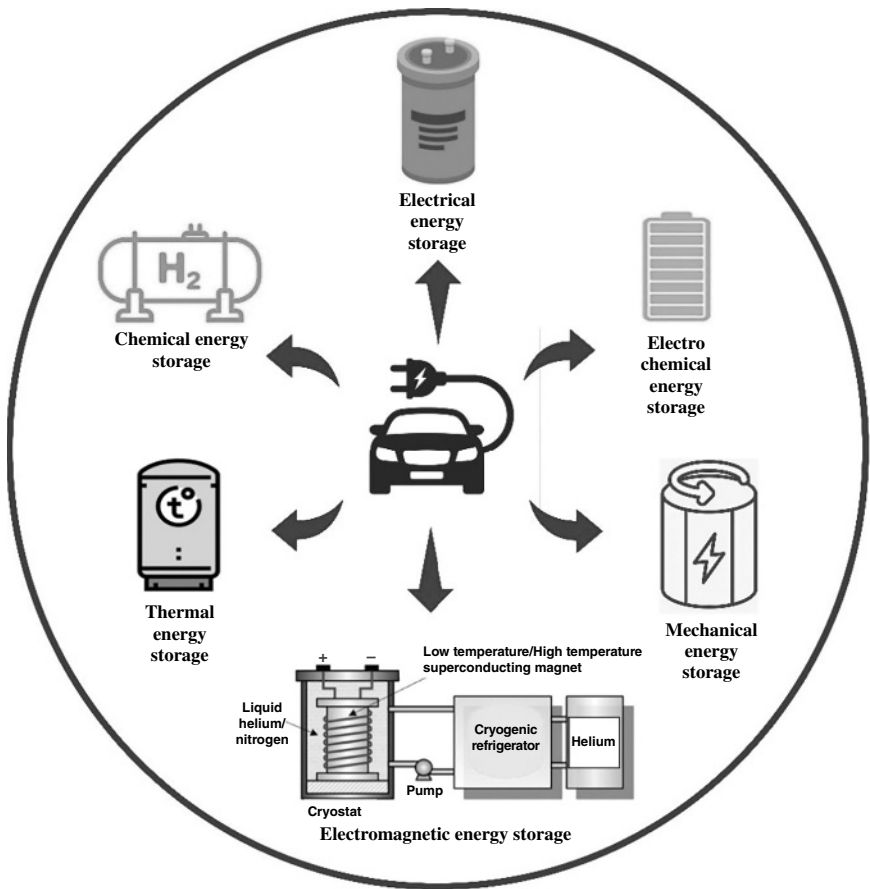


Figure 1.1 Energy storage technologies.

hybrid energy storage systems (HESS), where supercapacitors are paired with Li-ion batteries to handle peak power demands, such as acceleration and regenerative braking, thereby reducing battery degradation and improving overall system lifespan [1–12].

Electrochemical storage represents the cornerstone of modern e-mobility. It is based on reversible redox (reduction–oxidation) reactions, as seen in batteries and flow cells. Li-ion batteries continue to dominate EV applications due to their high-energy density, efficiency, and declining cost. Since 2021, significant advancements have been reported in lithium iron phosphate (LFP), Ni-rich chemistries (nickel manganese cobalt [NMC]/nickel cobalt aluminum [NCA]), and emerging solid-state batteries. These developments aim to enhance safety, extend driving range, and reduce reliance on critical materials. Na-ion batteries have

also gained momentum as a promising alternative for cost-sensitive EV segments, with recent prototypes proving competitive performance for short- to high-range mobility applications.

Electromagnetic energy storage uses magnetic fields to store energy, most notably in superconducting magnetic energy storage (SMES) systems. Although SMES offers near-instantaneous response and extremely high efficiency, its application in e-mobility remains limited due to the need for cryogenic cooling and high costs. However, recent research has explored its potential in niche applications such as high-performance transport systems and grid-vehicle interaction scenarios, particularly where ultra-fast power delivery is needed.

Mechanical energy storage involves storing energy in the form of motion or position. Technologies such as flywheels and elastic (spring-based) systems fall under this category. In e-mobility, flywheel systems have been revisited for regenerative braking in buses, trams, and high-performance vehicles, where their high-power density and long cycle life are helpful. Elastic energy storage, although less mature, has been investigated for micro-mobility applications and auxiliary systems, offering rapid energy release with minimal degradation. These systems are particularly relevant for short-duration, high-power events rather than sustained energy supply.

Thermal energy storage stores energy in the form of heat, either as sensible heat (temperature change), latent heat (phase change), or through thermochemical processes. In the context of EVs, thermal storage has gained importance primarily for battery thermal management and cabin climate control. Additionally, waste heat recovery systems are being explored to improve overall vehicle energy efficiency, especially in cold climates where heating demands significantly impact driving range [10–12].

The detailed classification shown in Figure 1.2 further expands on these categories, illustrating the diversity of technologies within each class. Importantly, these storage options differ significantly in terms of key performance metrics such as energy density, power density, efficiency, lifecycle, cost, and technological maturity. For e-mobility applications, no single technology satisfies all requirements; instead, recent research increasingly supports hybridization strategies, combining complementary storage systems to optimize performance, durability, and cost-effectiveness.

1.3.1 Chemical Energy Storage

Chemical energy storage involves storing energy within the chemical bonds of substances and releasing it later through chemical reactions. In this approach, electricity is often surplus power from renewable sources that is first converted into chemical energy using processes such as electrolysis or chemical synthesis.

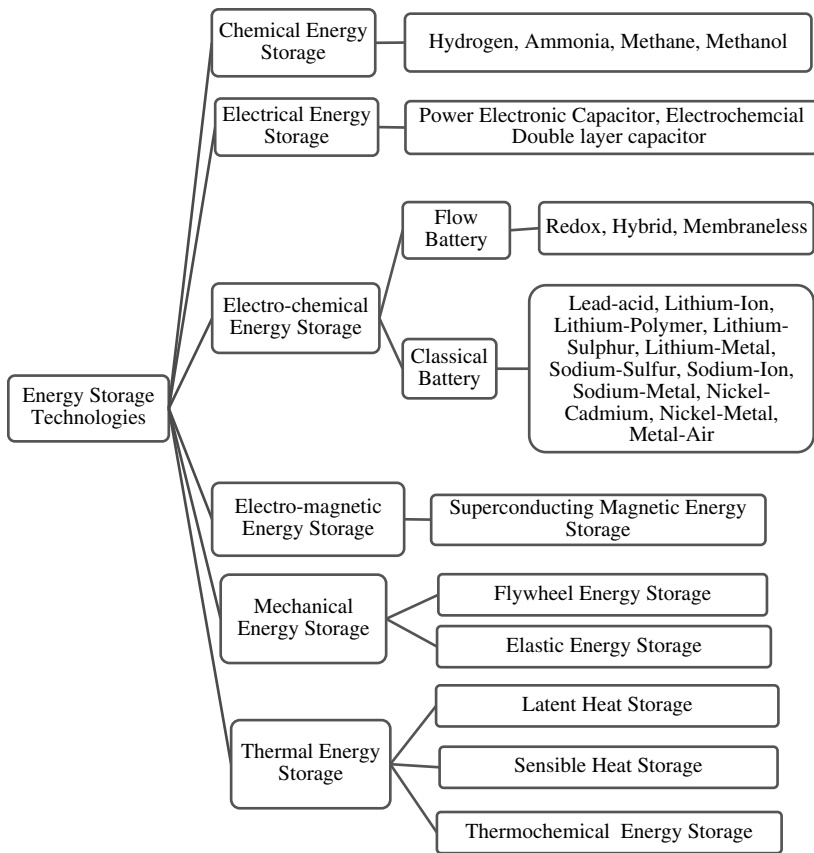


Figure 1.2 Classification of electric energy storage technologies.

The stored energy can then be recovered as electricity or heat through fuel cells, engines, or combustion systems. Common chemical energy carriers discussed in recent literature include hydrogen (H_2), ammonia (NH_3), methane (CH_4), and methanol (CH_3OH). In recent years, energy organizations have highlighted chemical storage as an important solution for long-duration and large-scale energy storage, particularly where batteries are less suitable [13–15].

1.3.1.1 Hydrogen (H_2)

Hydrogen is one of the most widely studied chemical energy carriers. It is mainly produced either by electrolysis of water using electricity or by steam reforming of natural gas. When produced using renewable electricity, hydrogen is considered a low-carbon or “green” fuel. Hydrogen has a very high gravimetric energy density, approximately 33 kWh/kg, based on its lower heating value, which means it stores

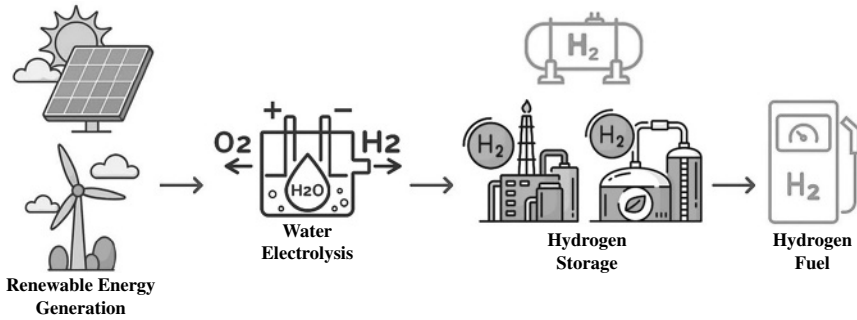


Figure 1.3 Hydrogen storage application.

a large amount of energy per unit mass. However, its volumetric energy density is very low. Even when compressed to high pressures, such as 700 bar, gaseous hydrogen contains only about 5 MJ/L, which is much lower than many liquid fuels. The basic illustration of hydrogen storage is shown in Figure 1.3.

Hydrogen can be stored in several forms, including as a high-pressure gas, a cryogenic liquid, or within solid materials such as metal hydrides. Each of these storage methods presents technical challenges. High-pressure storage requires strong and expensive tanks, liquid hydrogen suffers from boil-off losses due to its very low boiling point, and metal hydrides add weight and cost while facing material degradation issues. Another challenge discussed in recent studies is hydrogen embrittlement, where hydrogen weakens metals used in pipelines and storage vessels. When used for power generation, hydrogen is commonly converted back into electricity using fuel cells, which typically achieve efficiencies of about 50–60%. Hydrogen is considered a strong candidate for long-duration and seasonal energy storage, as well as for long-distance energy transport. However, current research also points out its limitations, including relatively low overall round-trip efficiency and the lack of widespread infrastructure for hydrogen production, storage, and distribution [12, 13].

1.3.1.2 Ammonia (NH₃)

Ammonia is produced by combining nitrogen and hydrogen, usually through the Haber–Bosch process. Because it does not contain carbon, ammonia is considered a carbon-free fuel at the point of use. It has a hydrogen content of about 17.6% by weight and can be stored as a liquid under relatively mild conditions, around 1 MPa at room temperature. This makes ammonia easier to store and transport than hydrogen. Liquid ammonia has a volumetric energy density of about 10.5 MJ/L, which is higher than that of liquid hydrogen (8.49 MJ/L).

Ammonia can be used as an energy carrier in two main ways: it can be cracked back into hydrogen for use in fuel cells, or it can be burned directly in engines or gas turbines. One major advantage of ammonia is its long history of

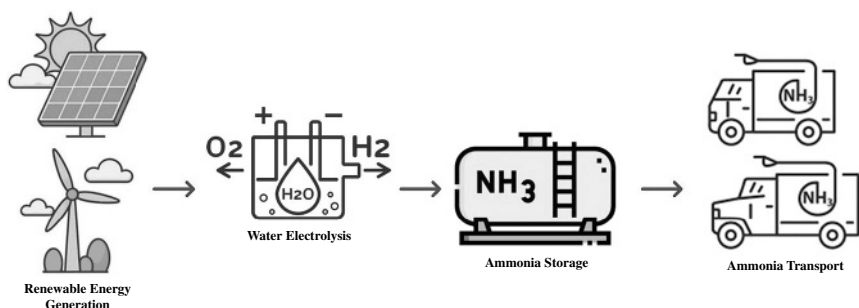


Figure 1.4 Ammonia synthesis and transportation.

large-scale industrial use, particularly in fertilizer production, which has led to the development of well-established storage and transport technologies. The ammonia synthesis and transportation process flow diagram is illustrated in Figure 1.4. Recent literature also highlights its relatively easy liquefaction compared to hydrogen [14].

However, ammonia has several notable disadvantages. It is toxic and must be managed carefully to avoid health and environmental risks. In addition, energy losses occur during its synthesis and during cracking back into hydrogen, leading to lower overall round-trip efficiency. At present, most ammonia-based applications are still at the pilot or demonstration stage. Economic analyses published in recent years suggest that ammonia could become cost-competitive with conventional fuels if low-cost, low-carbon hydrogen becomes widely available.

1.3.1.3 Methane (CH₄)

Methane stores energy in carbon–hydrogen bonds and is commonly used in the form of natural gas. It can also be produced synthetically through “power-to-gas” processes, in which renewable electricity is used to convert carbon dioxide and hydrogen into methane. The methane production and use process is illustrated in Figure 1.5. Methane has a gravimetric energy density of about 38 MJ/kg. On a volumetric basis, compressed methane has an energy density comparable to or slightly lower than that of ammonia; however, it typically requires higher storage pressures.

One advantage of methane is that it can be transported and distributed using existing natural gas pipeline infrastructure. It can also be used efficiently in combined-cycle gas turbines or in certain types of fuel cells. However, methane combustion or reforming releases carbon dioxide unless combined with carbon capture and storage technologies. Recent studies say that producing synthetic methane at a large scale remains expensive, especially when carbon-neutral pathways are used, which limits its current deployment as a clean energy-storage choice [15, 16].

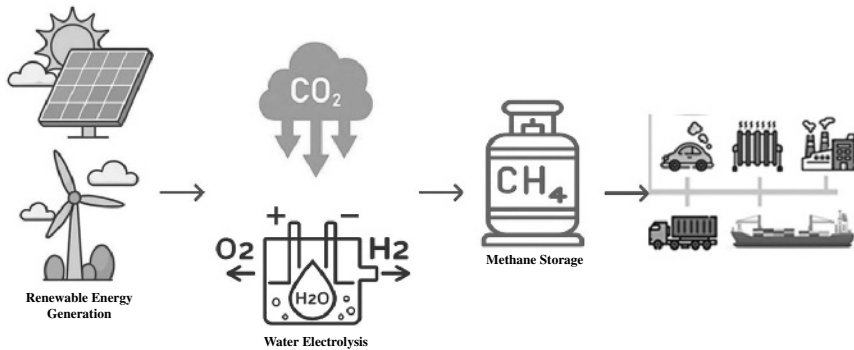


Figure 1.5 Methane production and utilization.

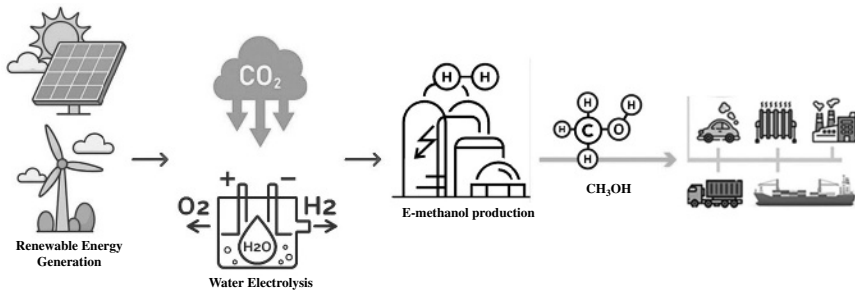


Figure 1.6 Methanol production and utilization.

1.3.1.4 Methanol (CH_3OH)

Methanol is a liquid organic hydrogen carrier and has gained increasing attention in recent research. It has an energy density of about 15.8 MJ/L, or roughly 4.4 kWh/L, which is significantly higher than that of compressed hydrogen. Because methanol is a liquid at ambient conditions, it is easy to store, transport, and handle using existing fuel infrastructure. It can be used directly as a fuel in combustion engines or in direct methanol fuel cells [17]. The process flow of methanol production and utilization is shown in Figure 1.6.

Recent studies highlight that methanol synthesis can consume carbon dioxide, offering a pathway toward carbon-neutral fuels when renewable hydrogen is used. This feature makes methanol attractive for integrating energy storage with carbon recycling. However, methanol is toxic and poses health risks if improperly managed. In addition, methanol fuel cells generally have lower efficiencies compared to hydrogen fuel cells, and some carbon emissions still occur depending on the production and use pathway.

In summary, chemical energy storage systems provide very high energy densities, especially in terms of mass, and are well suited for long-duration and

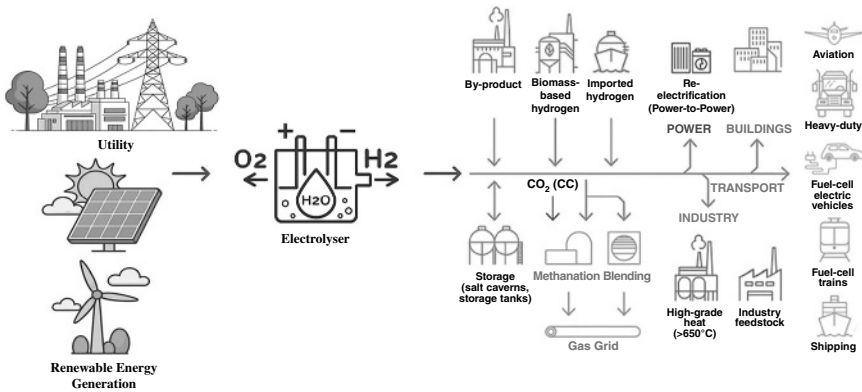


Figure 1.7 Chemical energy storage and utilization. *Source:* Adapted from [13].

seasonal energy storage. These characteristics make them attractive for E-mobility, large-scale grid applications, and energy-intensive industries. However, their overall round-trip efficiencies are typically modest, often ranging from 20% to 50%, depending on the specific conversion processes involved. Capital costs remain high, although ongoing research and pilot projects are steadily improving performance and reducing costs. A detailed overview of chemical energy storage and utilization is shown in Figure 1.7.

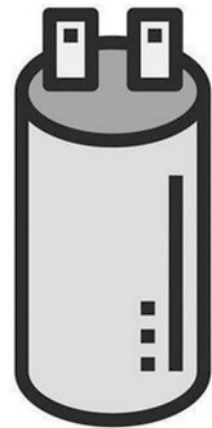
Hydrogen and natural gas are already well established, while ammonia and methanol are at earlier stages of commercialization, mainly demonstrated through research projects and pilot-scale applications. Recent literature consistently identifies chemical energy storage as a critical component of future low-carbon energy systems [13–17].

1.3.2 Electrical Energy Storage

EES devices store charge in electric or electrostatic fields. There are two main categories:

1. Power electronic capacitors (dielectric capacitors used in power electronics)
2. Electrochemical double-layer capacitors (EDLCs), or supercapacitors.

Power Electronic Capacitors: These are conventional film or electrolytic capacitors like DC-link capacitors used in power converters and drives, as illustrated in Figure 1.8.



DC-Link Capacitor for Power Converters

Figure 1.8 DC-link capacitor used in power converters and drives.

They operate at high voltage and can deliver very high-power bursts, short-term buffering of switching transients. However, their energy storage is *negligibly small* (specific energy of about 10^{-5} MJ/kg), so they only smooth out disturbances on micro- to millisecond timescales. In practice, these capacitors are mature, low-cost, and dependable, but they cannot serve as standalone energy storage for more than a brief ride-through or smoothing functions [18, 19].

Electrochemical Double-layer Capacitors (Supercapacitors): These use high-surface-area carbon electrodes in an electrolyte to store charge in the electrical double layer. Supercapacitors have **exceptional power density** and extremely fast charge/discharge (seconds), as well as very long cycle life ($>10^6$ cycles). The basic configuration of an EDLCs is illustrated in Figure 1.9 [19]. For example, they can buffer regenerative braking pulses or ride through short outages. However, their energy density is much lower than batteries, typically about 1–10 Wh/kg (0.004–0.036 MJ/kg) compared to approximately 100–250 Wh/kg for modern Li-ion batteries.

The round-trip efficiency of supercapacitors is very high (often $>98\%$), and their cost is moderate. In summary, EDLCs are commercially mature for high-power, short-duration buffering (transit regenerative braking, uninterruptible power, etc.), but their low energy capacity means they are not used for sustained long-term storage. Many researchers are developing *hybrid* “ultracapacitors” that combine double-layer and pseudocapacitive effects to boost energy density, but

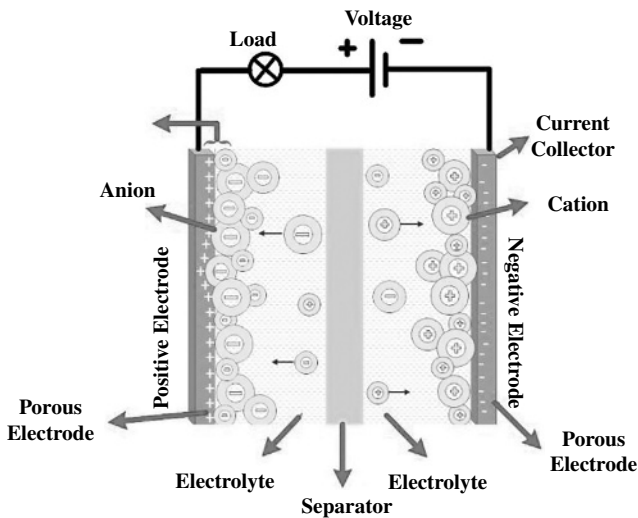
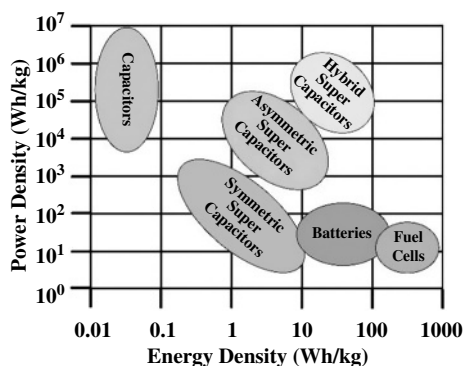


Figure 1.9 Electrochemical double-layer capacitor configuration. *Source:* Adapted from [19].

Figure 1.10 A Ragone plot comparing capacitors, supercapacitors, and batteries.



the basic EDLC is still a power-oriented device. A Ragone plot comparing capacitors, supercapacitors, and batteries, to illustrate energy vs. power density [20], is depicted in Figure 1.10.

1.3.3 Electrochemical Energy Storage

Electrochemical energy storage converts electrical energy via reversible chemical reactions. The two main forms are flow batteries and solid-electrode batteries. The latter are conventional rechargeable batteries [21, 22].

1.3.3.1 Flow Batteries

Flow batteries store energy in liquid electrolytes that circulate through electrochemical cells. The energy capacity is set by the volume and concentration of the active species in external tanks, while the power is decided by the size of the cell stack. Major types include:

- Redox Flow Batteries (RFBs):** A classic example is the vanadium redox flow battery (VRFB), which uses V^{2+}/V^{3+} on one side and V^{4+}/V^{5+} on the other in sulfuric acid [23]. During charge/discharge, the vanadium ions shuttle electrons across the cell as shown in Figure 1.11. RFBs have the advantage of decoupled energy and power (tank size vs. stack area), making them easy to scale. They also have excellent cycle life (>10,000 cycles) and allow deep discharge without damage. Contemporary VRFBs achieve only modest energy densities (typically <25 Wh/kg) due to solubility limits, which corresponds to 20–40 Wh/L for large tank systems. They are inherently safe and nonflammable. The capital cost of VRFB systems is moderate and improves at large scale, though pumps and thermal management add complexity. Commercial VRFB installations (hundreds of kW to MW scale) exist for grid storage, but high vanadium cost and system complexity have

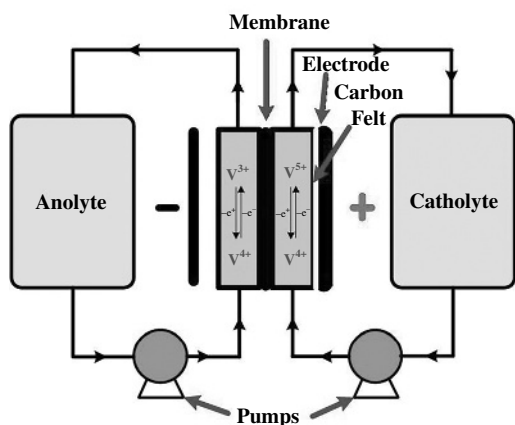


Figure 1.11 Vanadium redox flow battery configuration.

spurred research into alternative chemistries (e.g., iron–chromium, organic redox couples, hybrid designs).

- **Hybrid Flow Batteries:** These combine a circulating electrolyte on one side with a static (often plating) electrode on the other. For example, zinc–bromine or zinc–iron flow batteries use a flowing bromide or iron solution with a zinc metal electrode that plates on charge. Such hybrids can achieve higher energy density (because the plated metal holds more charge), but they introduce challenges, including zinc dendrite formation and require separators. Cutting-edge lab research includes “membraneless” microfluidic flow cells, but these are still experimental [24, 25]. The basic configuration of the zinc–bromine flow battery is shown in Figure 1.12.

Overall, flow batteries are well suited to multi-hour energy storage (tens to hundreds of kWh), providing long service life and flexible scaling. Their main drawback is lower volumetric/gravimetric energy density and higher system cost compared to batteries. VRFBs are the most mature with commercial products available, whereas many alternative flow chemistries are still in demonstration or development stages.

1.3.3.2 Classical Batteries

This category covers “solid-electrode” rechargeable batteries, which use fixed electrodes and internal electrolytes [26, 27]. Key chemistries include:

- **Lead–Acid Batteries:** The oldest rechargeable battery (invented 1859). Lead–acid cells store energy via Pb/PbSO_4 at both electrodes. They have very low specific energy (approximately 35–40 Wh/kg) and low energy density

Figure 1.12 Zinc–bromine flow battery configuration.

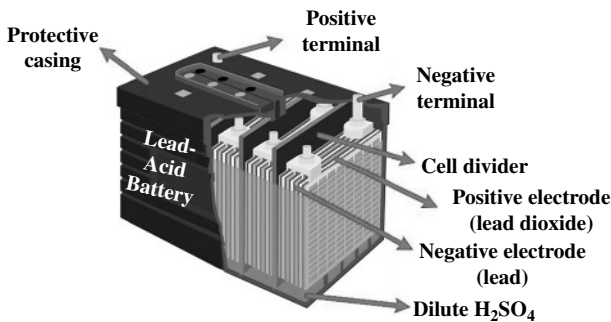
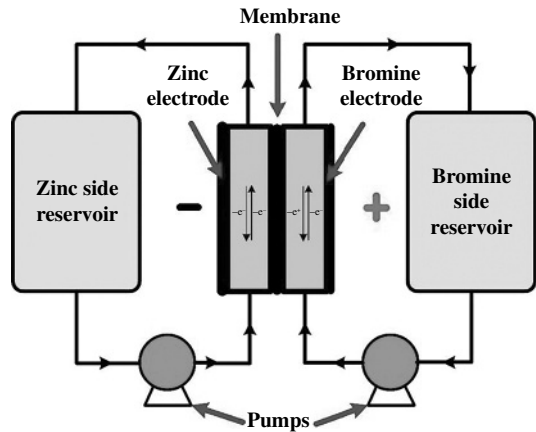


Figure 1.13 Lead–acid battery configuration.

(approximately 80–90 Wh/L), making them heavy for the energy stored. On the plus side, lead–acid batteries are inexpensive, robust, and have mature recycling. They can deliver high surge currents used for engine starters, but only a few hundred deep cycles (≈ 300 –500) and limited calendar life. Efficiency is modest (approximately 75–85%). Because of their low energy density, lead–acid is largely confined to starter, backup, and stationary applications, rather than EV propulsion or portable devices [28]. The basic configuration of lead–acid battery is shown in Figure 1.13.

- **Nickel–Cadmium (Ni–Cd) Batteries:** Ni–Cd batteries use a Ni hydroxide cathode and a cadmium anode with KOH electrolyte. They have moderate energy density (approximately 50–75 Wh/kg) and about 150–300 Wh/L. Ni–Cd cells tolerate abuse (overcharge, deep discharge) well and can sustain high discharge rates; they can last 1500–2500 cycles. However, cadmium is toxic, and Ni–Cd suffers from the “memory effect” and weight issues.

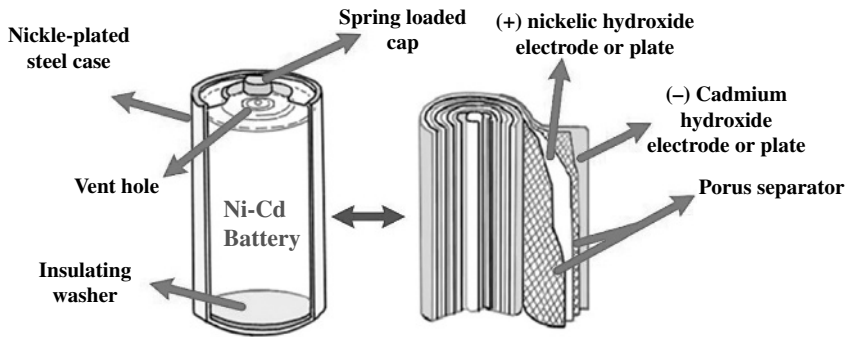


Figure 1.14 Nickel–cadmium battery configuration.

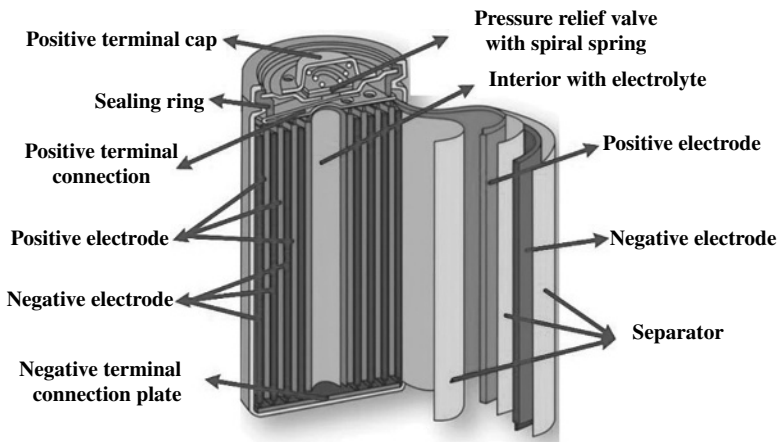


Figure 1.15 Nickel–metal hydride battery configuration.

Consequently, Ni–Cd has largely been replaced by Ni–MH in consumer devices [29]. The Ni–Cd battery configuration is shown in Figure 1.14.

- Nickel–Metal Hydride (Ni–MH) Batteries:** Ni–MH cells (Ni hydroxide cathode, hydrogen-absorbing alloy anode) have higher energy density than Ni–Cd (approximately 70–100 Wh/kg) and 140–300 Wh/L. They achieve a few hundred to approximately 1000 cycles and have better charge retention. Ni–MH was popular in hybrid vehicles (e.g., Toyota Prius) and cordless tools. Today, Ni–MH has been largely superseded by Li-ion, due to Li-ion's much higher energy and lower long-term cost [30]. The Ni–MH battery configuration is illustrated in Figure 1.15.
- Li-ion Batteries:** The Li-ion batteries are the dominant rechargeable battery technology today, with many chemistries (e.g., LiCoO_2 , NMC, LiFePO_4) is

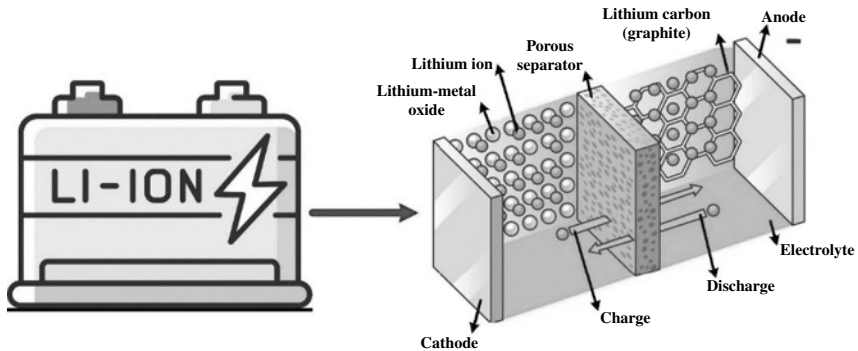


Figure 1.16 Li-ion battery configuration.

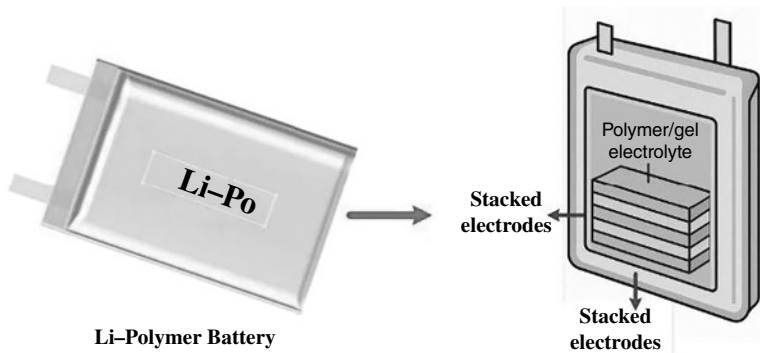


Figure 1.17 Lithium-polymer battery configuration.

Li-ion. The basic configuration of a Li-ion battery is shown in Figure 1.16. Commercial Li-ion cells typically achieve about 100–250 Wh/kg (0.36–0.90 MJ/kg) and 250–700 Wh/L. Coulombic efficiency is very high (approximately 99%), and round-trip efficiencies are approximately 90–95%. Cycle life depends on chemistry and conditions, but is often >1000 cycles; advanced designs now exceed 2000 cycles. Li-ion batteries are relatively expensive and require careful management for safety, as they can undergo thermal runaway. Resource limitations (Li, Co, Ni) are a consideration. Nonetheless, Li-ion batteries are the standard technology for portable electronics, EVs, and utility-scale storage [31].

- **Lithium-Polymer (Li-Po) Batteries:** A variant of Li-ion using a polymer or gel electrolyte. Performance (energy density, power) is like Li-ion, but cells can be made thinner and more flexible [31]. Li-Po is used in drones, wearable devices, and mobile devices where form factor is important. The Li-Po battery has been illustrated in Figure 1.17.

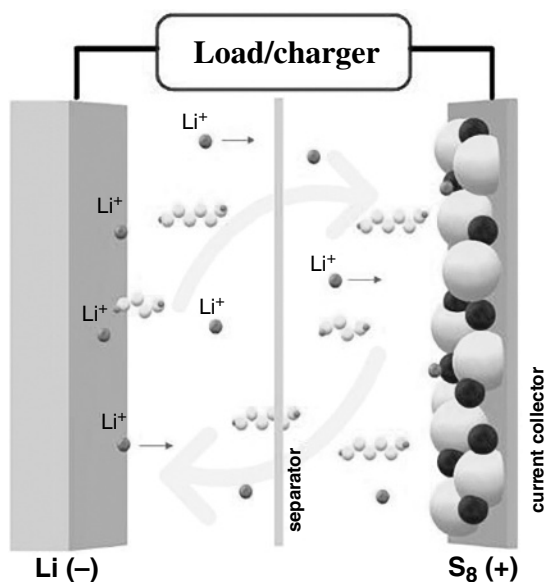


Figure 1.18 Lithium–sulfur battery configuration.

- Lithium–Sulfur (Li–S) Batteries:** These batteries use a Li metal anode and S cathode as illustrated in Figure 1.18. The theoretical specific energy is extremely high (approximately 2600 Wh/kg of Li + S), so practical prototypes aim approximately 500–600 Wh/kg. Lab cells have achieved approximately 250–350 Wh/kg, and S is cheap and abundant. The main challenge is the “polysulfide shuttle” that causes rapid capacity fade, cycle life is currently poor. Li–S technology is still in the research or pilot stage [32].
- Lithium–Metal Batteries:** Using Li metal as the anode (paired with various cathodes) can push the energy density even higher (theoretical cell-level energy densities of up to approximately 500–1000 Wh/kg of cell) because Li metal is lighter than graphite or silicon. Recent R&D (often with novel solid or highly concentrated electrolytes) has produced Li-metal prototypes in the approximately 500 Wh/kg range. Improving cycle life is an active area of research; new electrolytes have demonstrated Li-metal cells surviving hundreds to thousands of cycles (e.g., 483 cycles at 500 Wh/kg, and reports of approximately 3000 cycles at 80% capacity). Commercial Li–metal batteries are not yet available, but this is a “holy grail” for next-generation high-energy cells [32]. The basic configuration of a lithium–metal battery is shown in Figure 1.19.

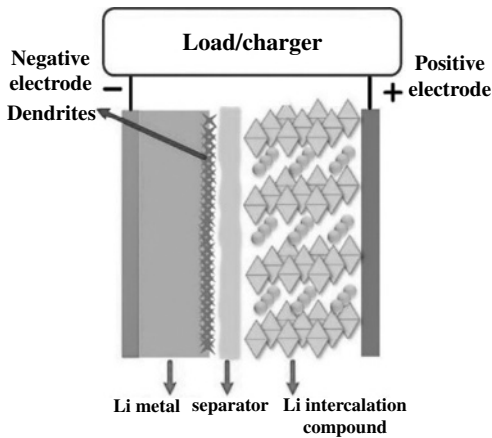


Figure 1.19 Lithium-metal battery configuration.

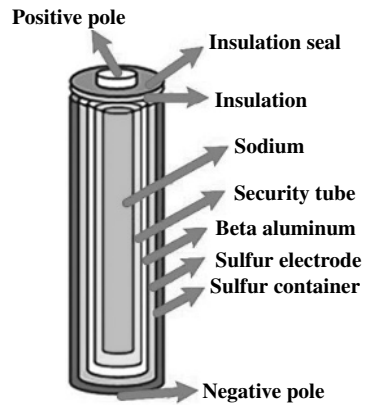


Figure 1.20 Sodium-sulfur battery configuration.

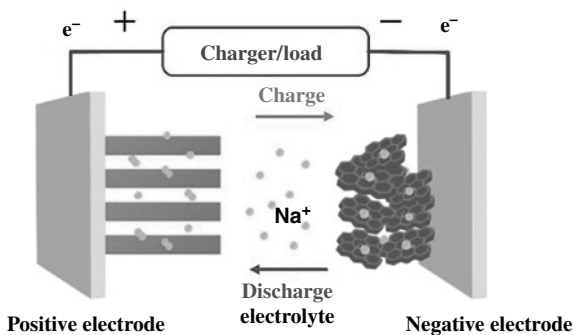


Figure 1.21 Sodium-ion battery configuration.

- Sodium-Sulfur (Na-S) Batteries:** These are high-temperature (300–350 °C) batteries with molten Na and S electrodes and a beta-alumina electrolyte. The basic configuration of a Na-S battery is shown in Figure 1.20. Na-S batteries can reach approximately 150 Wh/kg and have a very long life (>2500 cycles). They have been deployed in grid-scale energy-storage applications. The drawbacks are the high operating temperature and the need for thermal insulation. Owing to their complexity, Na-S batteries are used in large stationary installations rather than EVs [28].
- Sodium-ion Batteries (Na-ion):** An emerging “drop-in” battery using Na⁺ instead of Li⁺. Laboratory Na-ion cells have achieved energy densities of approximately 90–160 Wh/kg (lower than Li-ion but improving). The basic schematic of a Na-ion battery is shown in Figure 1.21.

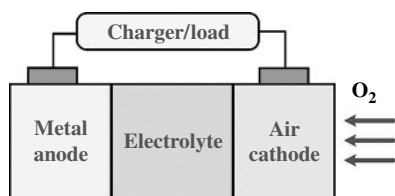


Figure 1.22 Metal–air battery configuration.

Advantages include lower cost and abundant materials such as Na and alumina. Na-ion technology has only recently entered the market, with limited commercialization since 2022, primarily for stationary energy-storage systems and two-wheeler EVs.

- Metal–Air Batteries (Zn–Air, Li–Air, etc.):** These batteries use a metal anode (Zn, Li, Al, etc.) and oxygen from air as the cathode reactant. The theoretical energy densities are extremely high (e.g., Zn–Air theoretical approximately 1086 Wh/kg; Li–Air up to approximately 11,400 Wh/kg). In practice, most metal–air cells are primary (nonrechargeable); for example, Zn–air hearing-aid cells achieve very high energy per weight by venting oxygen. Rechargeable metal–air systems face significant challenges (air electrode catalysis, electrolyte management, dendrites, CO₂ contamination, etc.) [33]. The basic schematic of a metal–air battery is shown in Figure 1.22.

Some technologies such as zinc–air flow batteries and laboratory-scale Li–O₂ cells, are being studied but none are yet practical at scale. Table 1.1 compares key metrics for major battery types.

Advantages and Limitations: Classical battery technologies generally involve trade-offs among energy density for power and cost. Li-ion batteries offer the highest energy density and efficiency of the mature chemistries. Lead-acid and Ni–Cd batteries are well-proven and inexpensive but are heavy with low energy. Ni–MH batteries provide better safety and cycle life than Ni–Cd batteries, but at a higher cost. Na-based (Na–S, Na-ion) and metal–air batteries promise to use abundant materials or ultra-high theoretical energy, but they face technical hurdles (high temperature, limited cyclability, etc.). Modern Li-ion pack costs are about \$100–200 per kWh (e.g., ≈\$115/kWh in 2024). Battery efficiencies are generally high (>80–90%), but all batteries have finite cycle life (hundreds to a few thousand cycles) and require proper management for safety (especially Li-based chemistries). Research continues on advanced chemistries (solid-state, metal anodes, Na systems) to improve energy, life, and cost.

1.3.4 Electromagnetic Energy Storage

Electromagnetic storage uses magnetic fields or magnetization.

Table 1.1 Comparison of selected energy-storage technologies.

Battery type	Specific energy	Energy density	Power density	Cycles	Cost	Status
Lead-Acid	35–40 Wh/kg	80–90 Wh/L	Moderate	<500	Low	Mature (automotive, Uninterruptible Power Supply)
Ni–Cd	40–60 Wh/kg	50–150 Wh/L	High	~2000	Medium	Mature (tools, standby)
Ni–MH	60–120 Wh/kg	140–300 Wh/L	High	500–1000	Medium	Commercial (hybrids, electronics)
Li-ion	100–250 Wh/kg	250–730 Wh/L	High	>1000	Medium–high	Commercial (EVs, portable)
Li-polymer	Same as Li-ion	—	—	—	—	Commercial (consumer electronics)
Li-S (research)	~200 laboratory-scale 300 Wh/kg	—	Moderate	<100 (lab)	Low (materials)	Emerging (pilot)
Li-metal (solid-state) (R&D)	500–600 Wh/kg	—	High	TBD	Low (Li amt.)	Experimental
Na–S (300 °C)	~150 Wh/kg (64 Wh/L)	Moderate	High	>2500	Low	Commercial (grid)
Na-ion	~100–160 Wh/kg	—	High	TBD	Low	Emerging
Zn–air (primary)	≈300 Wh/kg theoretical	(High, depends)	Moderate	1 (nonrechargeable)	Low	Niche (hearing aids)
Supercapacitor	1–10 Wh/kg	3–10 Wh/L	Very high	>100,000	High	Commercial
SMES	~1–11 Wh/kg	~<40 kJ/L (<11 Wh/L)	Extremely high	>10 ⁶	Very high	Demonstration

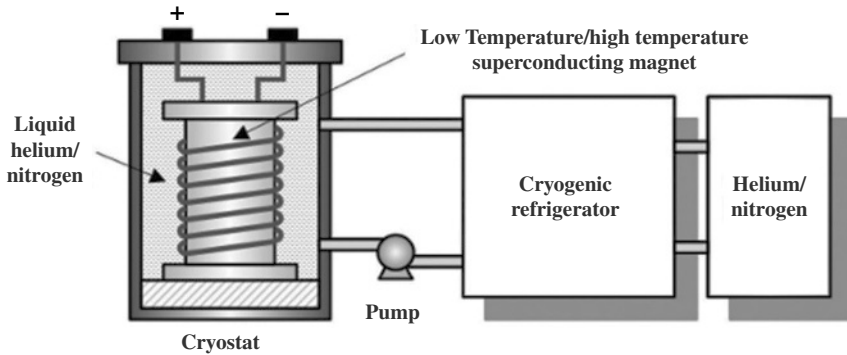


Figure 1.23 Schematic of the SMES system.

1.3.4.1 Superconducting Magnetic Energy Storage

Superconducting magnetic energy-storage (SMES) stores energy in the magnetic field of a superconducting coil. The basic schematic of the SMES system is illustrated in Figure 1.23. Under cryogenic conditions (below T_c), the coil has zero resistance; therefore, power can be exchanged virtually loss-free. SMES systems can release enormous power almost instantaneously (with a power density approximately 10^4 – 10^5 kW/kg) and achieve a high round-trip efficiency (approximately 95%). However, their energy capacity is very low due to the limited coil inductance and cryostat size. The typical SMES energy density is <40 kJ/L (≈ 11 Wh/L). Ongoing advances in high- T_c superconductors aim to reduce costs and refrigeration needs [34].

1.3.5 Mechanical Energy Storage

Mechanical energy storage in vehicles includes high-speed flywheels and elastic devices such as springs [35, 36]. The basic flywheel mechanism is illustrated in Figure 1.24.

Modern flywheel systems spin rotors in a near-vacuum using magnetic bearings, yielding very high-power bursts with minimal wear. In EVs, flywheels have been explored for regenerative braking or hybrid powertrains: they can absorb and release energy almost instantaneously and endure millions of cycles. For example, hybrid locomotives and some heavy vehicles use flywheel modules to capture braking energy. However, flywheels store relatively little energy per mass (tens of Wh/kg at best), so they are suited only to short-duration pulses (seconds to minutes). They complement batteries by smoothing power spikes in UPS, train braking or freight applications. Elastic spring-based storage has also been explored in recent times. Elastic energy storage, particularly spring-based systems, is gaining renewed attention in e-mobility as a lightweight, high-power solution

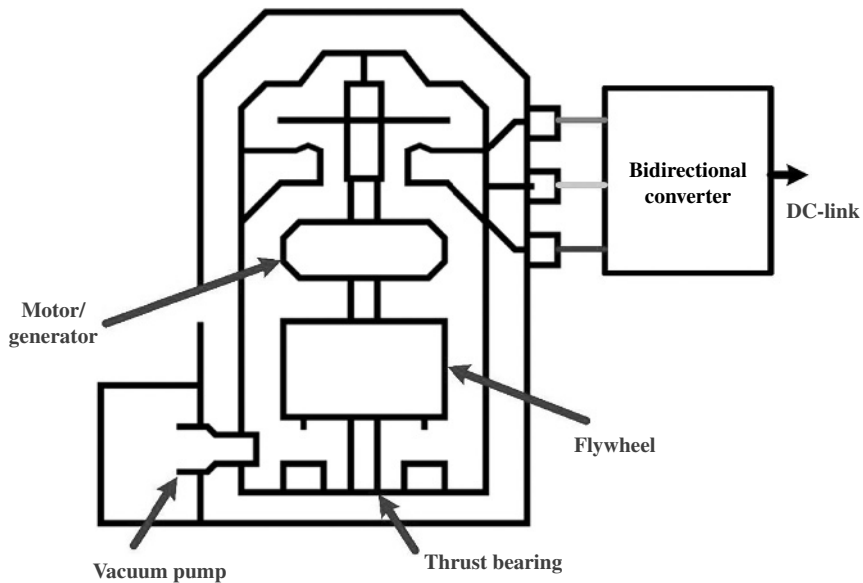


Figure 1.24 Schematic of the flywheel system.

for capturing and releasing energy quickly. Unlike conventional batteries, spring energy storage relies on mechanical deformation to store energy, which can be rapidly discharged to assist in acceleration, regenerative braking, or short bursts of power without chemical degradation. Recent research has explored compact, high-strength composite springs integrated into electric scooters, micro-mobility platforms, and auxiliary systems in larger EVs, showing improved efficiency in energy recapture and reduced load on the main battery. One of the key advantages is durability: spring systems can endure millions of cycles with minimal wear, making them ideal for frequent start-stop applications in urban driving. Additionally, hybrid approaches that combine springs with batteries or supercapacitors are being investigated to smooth peak power demands while supporting overall vehicle range. These approaches offer a promising path toward lighter, more resilient, and efficient energy-storage solutions in next-generation electric mobility [35–37].

1.3.6 Thermal Energy Storage

EVs use thermal storage mainly for managing battery and cabin temperatures. Battery packs employ thermal management systems (liquid cooling, heat pipes, etc.) to keep cells in a safe temperature range of 20–40 °C. Passive thermal storage in EVs often involves phase-change materials (PCMs) integrated into modules.

The latent heat of fusion in a PCM absorbs spikes in battery heat, flattening temperature profiles without active cooling. For example, some EV battery designs include wax or salt-based PCMs that melt at around 40–60 °C, storing heat during heavy discharge and solidifying during idle periods. This passive latent storage can improve safety and efficiency by stabilizing cell temperatures. Sensible heat storage (e.g., water jackets or coolant loops) is limited by low energy density (water stores only approximately 4.2 kJ/kg K); therefore, EV thermal systems rely mostly on circulation rather than bulk heat storage. In cold climates, waste heat from the battery or power electronics can be stored in small heat exchangers to preheat the cabin. Overall, EVs prioritize lightweight, compact thermal management (often with heat pumps) over large-scale thermal storage. In summary, EV thermal storage focuses on heat regulation for performance and safety (e.g., using PCMs and cooling loops) rather than long-term seasonal or grid-level heat storage [37].

1.4 Hybrid Energy-storage Systems

Hybrid energy-storage systems (HESS) combine two (or more) storage technologies to exploit their complementary strengths. A common pairing is a high-energy battery with a high-power supercapacitor. In such hybrids, the battery provides long-duration energy, whereas the supercapacitor oversees rapid power demands and absorbs transient spikes [38, 39]. For example, in an EV powertrain, a Li-ion battery is paralleled with an ultracapacitor (high power). During regenerative braking, the ultracapacitor soaks up the surge of energy, thereby smoothing the load on the battery. During acceleration or peak-load events, the capacitor can deliver a burst of power that the battery alone might struggle to supply. This arrangement protects the battery from extreme currents and can extend its usable life. Advanced energy management strategies ranging from simple rule-based logic to fuzzy controllers or model-predictive control decide how to split the power between the two devices. Typically, a bidirectional DC–DC converter links the battery and supercapacitor, regulating current flow in both directions as shown in Figure 1.25.

Careful design and control of HESS can significantly enhance performance. One recent study found that an optimally designed Li-ion/ultracapacitor hybrid in an EV extended the battery's useful life by roughly 47% and reduced its capacity degradation by about 23% (versus using the battery alone). Hybrid storage has been implemented in various applications beyond cars. For instance, rail transit systems have used battery–capacitor hybrids to handle frequent braking and door cycles, and wind turbines have paired flywheels with batteries for better power smoothing. Toyota has experimented with ultracapacitor-equipped vehicles (e.g., the Toyota Yaris Hybrid R concept used a supercapacitor to improve response).

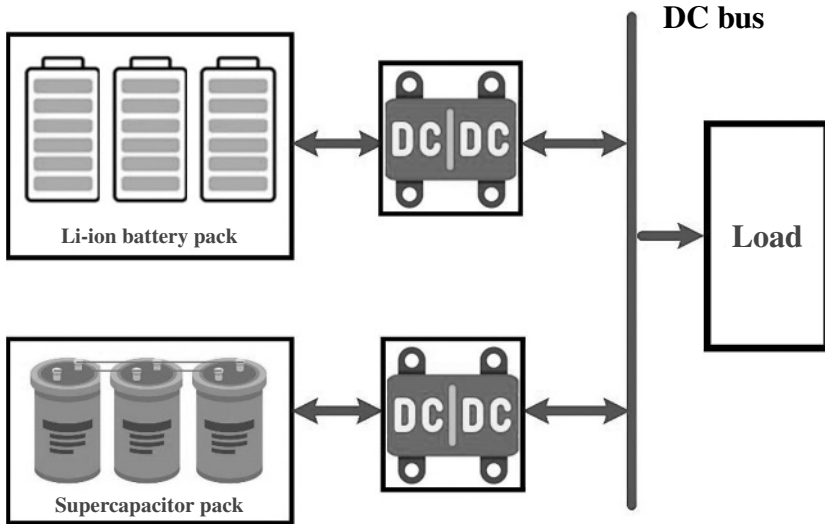


Figure 1.25 Li-ion battery-supercapacitor HESS configuration.

In all HESS designs, the challenge is managing two power sources: dedicated power electronics (e.g., bidirectional DC–DC converters) control the current between them, and an energy-management system decides when each element is used.

The benefits include improved system efficiency and longer lifetime (the supercapacitor shields the battery from large charge/discharge spikes), but these systems also add cost and complexity (extra components and control). To aid their development, specialized design and simulation toolboxes for hybrid energy-storage systems are now emerging, helping engineers to improve the sizing and control of these systems.

1.5 Comparative Analysis and Applications

Different energy-storage technologies tend to excel in different application domains:

- **Passenger EVs:** Modern EVs overwhelmingly use Li-ion batteries for propulsion. Typical packs today achieve approximately 200–250 Wh/kg at the pack level (depending on chemistry). Automakers are pushing next-generation chemistries (solid-state Li-metal, Li-S, high-Ni cathodes) to reach 400–500 Wh/kg or more, enabling much longer range. For short-term energy surges (e.g., rapid acceleration or stop-start operation), some vehicles incorporate ultracapacitors or flywheel auxiliaries. These devices store

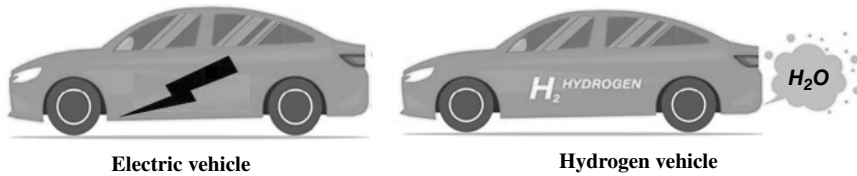


Figure 1.26 Electric and hydrogen-based EVs.

high power but low energy. Ultracapacitors can recapture braking spikes, and small flywheels (or mechanical springs in shocks) have been tested to harvest suspension or brake energy. Such hybrid systems extend battery life by shaving power peaks. Fuel-cell (hydrogen) vehicles offer the potential for longer range but are still rare. By mid-2021, there were only approximately 40,000 hydrogen fuel-cell vehicles worldwide (out of over 1.4 billion total vehicles illustrated in Figure 1.26), i.e., well under 0.1% of the fleet [1–4].

- **Commercial and Heavy Transport:** Electric buses, trucks, and rail systems also rely on Li-ion batteries, often with larger total capacity. Durability and fast charging are emphasized in these applications. Some hybrid locomotives and buses use flywheel modules for regenerative braking because of their long cycle life. For example, a diesel–hybrid train may use a flywheel system with a capacity exceeding 100+ kWh to buffer acceleration loads. In warehouse equipment, both lead–acid and Li-ion batteries are commonly used. In the aerospace and defence sectors, where weight is prioritized, research vehicles use high-energy chemistries (Li–S, Li–polymer) and sometimes ultracapacitors for pulsed-power applications [37].
- **Vehicle-to-Grid (V2G) and Grid Services:** Aggregated EVs can function as distributed storage for the grid. With bidirectional chargers, EV batteries can be charged when renewable energy is abundant and can be discharged during peak demand. Studies have shown that fleets of charging EVs can smooth grid loads and provide frequency regulation. This emerging application treats parked EVs as a “virtual” power plant. In smart-grid pilots, AI and real-time control coordinate EV charging schedules, using both batteries and vehicle auxiliary storage (e.g., heat stored in thermal systems) to optimize energy flow. V2G integration is increasingly seen as a key use case for EV energy storage [37].

1.6 Challenges and Future Directions

Although energy-storage technologies have advanced rapidly, major challenges stay for widespread deployment and scaling:

- **Cost and Materials:** Battery packs remain a major cost driver for EVs, though prices have fallen (approximately \$100–150/kWh in mid-2020s). The need for long-duration storage (e.g., multi-hour reserves) is still costly if based on batteries. Meanwhile, critical minerals (Li, Co, and Ni) have supply constraints. Mining must ramp up to meet EV demand, and reducing reliance on scarce elements is vital. This motivates R&D on low-cost chemistries (e.g., Na-ion, iron-based) and better recycling [37].
- **Safety:** High-energy batteries pose fire risks if abused. Li-ion cells can experience thermal runaway at elevated temperatures or due to internal shorts. Effective thermal management and flame-retardant materials are essential. Similarly, mechanical systems (flywheels) must have containment to safely arrest rotor failures. Ongoing research in solid electrolytes aims to cut flammable liquids altogether.
- **Lifecycle and Degradation:** EV batteries degrade over time. Typical modern batteries may achieve 500–1000 full cycles before falling below approximately 80% capacity. After this, a battery is often unsuitable for automotive use, though as one review notes, spent EV batteries keep significant capacity for secondary use. Enhancing longevity is a focus: advanced BMS, gentler charging profiles, and hybrid systems (battery + capacitor) can extend cycle life. Flow and gravity systems effectively have unlimited cycles but are impractical in vehicles.
- **Recycling and Sustainability:** With millions of EV batteries reaching end-of-life, efficient recycling is critical. Only approximately 5–10% of Li-ion batteries were recycled by 2020, but efforts are accelerating. Current industrial processes (pyrometallurgy, hydrometallurgy) can recover metals but are energy-intensive. Newer “direct regeneration” methods aim to restore cathode materials for reuse, improving circularity. Policy and technology are also pushing digital tracking (battery passports) and automated disassembly to streamline EV battery recycling. Sustainable mobility will require designing batteries for ease of recycling and reusing second-life batteries in stationary storage to offset raw material needs [40].
- **Infrastructure and Scalability:** Deploying EVs at scale hinges on charger availability and grid upgrades. IEA reports over 5 million public chargers exist (doubling since 2022), but more fast-charging stations are needed to meet demand. Standardization (common charging protocols) and smart networks are being developed to avoid grid strain. Likewise, geographic limits mean some storage technologies cannot easily expand. Abundant-material systems (Na-ion, flow batteries using iron/organic materials) are promising for future scale. Ultimately, coordinating EV growth with raw-material supply and charging infrastructure is a major challenge ahead [37–40].

1.7 Emerging Technologies: Looking Forward

Research is pushing the boundaries of storage in several directions:

- **Solid-State Batteries:** Replacing liquid electrolytes with solid ion conductors promises higher energy density and enhanced safety. Many companies and research groups are developing solid-state Li-metal cells. These could potentially reach cell-level energy densities around 400–500 Wh/kg or more while eliminating flammable liquid electrolytes [32, 33]. The basic configuration of a solid-state battery is shown in Figure 1.27.
- **Lithium–Air (Li-O_2) and Other Metal–Air Batteries:** Lithium–air batteries have a very high theoretical specific energy (approximately 1000–1400 Wh/kg depending on design). This is because the cathode uses oxygen from air as the reaction partner, storing only Li and a porous carbon matrix. In practice, Li–air cells have struggled with cycle life, efficiency, and dealing with contaminants (moisture, CO_2) in the air. Recent research has achieved modest cycling (a few dozen cycles) and improved catalysts, but commercialization remains decades away. Other metal–air systems (zinc–air, aluminum–air) are also being studied for niche applications (e.g., long-endurance drones, backup), but none are near parity with Li-ion in portability yet [31–33].
- **Abundant Metal–Ion Batteries (Na^+ , K^+ , Mg^{2+} , etc.):** Na-ion batteries are rapidly maturing. Na-ion cells have lower energy density than Li-ion but use extremely common materials (salt) and cheaper cathode/anode materials. China has already commercialized Na-ion packs, and research suggests Na-ion can be competitive in cost. One analysis projects that Na-ion pack costs could fall to approximately \$40–50/kWh at scale, far below current Li-ion prices. Importantly, Na is about 1000 times more abundant than Li. Potassium-ion and magnesium-ion chemistries are still at earlier

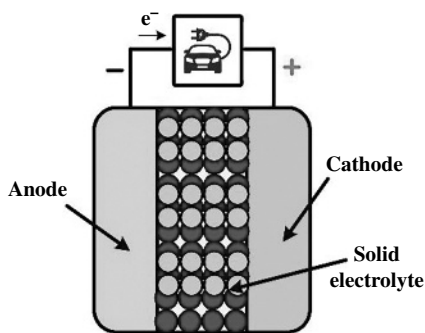


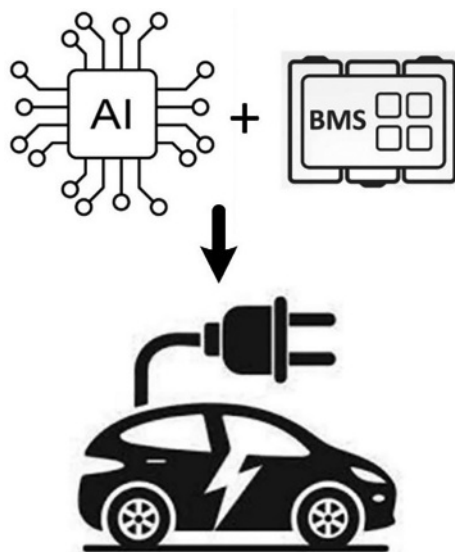
Figure 1.27 Solid-state battery configuration.

R&D stages. Potassium's abundance is like Na's, and K-ion batteries show Li-ion-like behavior but with larger ions. Magnesium (Mg^{2+}) has the appeal of carrying 2 electrons per ion (theoretically higher volumetric energy), but practical Mg batteries have lower voltage and are slower. Advances continue, for example, new electrode materials and electrolytes are improving Na-ion performance (e.g., better cathodes, hard carbon anodes). Some analysts project that future

Na-ion systems might reach extremely low costs (e.g., \$30/kWh by mid-century) due to the cheap raw materials.

- **Next-generation Li Chemistries:** Beyond Na and K, researchers are exploring variants of Li batteries. Lithium–sulfur (Li–S) batteries use S cathodes to potentially reach approximately 500–600 Wh/kg at low cost. (S is very abundant and cheap.) The main challenge is cycle life: Li–S historically suffered from rapid capacity loss, but new electrode designs and electrolytes are extending its life. Researchers also investigate Li–selenium and Li–silicon systems, and even more exotic ideas like Li–chlorine (“memory battery”) cells. A recent prototype Li–Cl₂ battery claimed approximately 362 Wh/kg (at the cell level) by using molten chlorine, but many hurdles remain (operating temperatures, corrosion). These next-generation Li systems aim to push energy density beyond current Li-ion limits, though they often trade off cycle life.
- **Smart Controls and AI:** Finally, the intelligence around EV storage is evolving as shown in Figure 1.28. BMS has undergone a significant transformation in recent years, especially within e-mobility. What was once limited to basic monitoring and protection has evolved into a highly intelligent and interconnected system capable of actively managing battery performance, safety, and longevity. Modern BMS designs increasingly incorporate AI, machine learning, and cloud-based communication, forming what are commonly described as smart or cloud-enabled BMS platforms. One of the most notable developments is the shift toward health-oriented battery management. Rather than focusing only on immediate performance, current

Figure 1.28 Configuration of AI-driven BMS for EVs.



strategies emphasize preserving long-term battery condition. This involves continuous estimation of parameters such as state of charge (SOC), state of health (SOH), state of power (SOP), and remaining useful life (RUL). By leveraging machine learning techniques, including neural networks and other data-driven models, these systems analyze large volumes of real-world operational data to identify early indicators of degradation, such as Li plating, thermal stress, and capacity loss. As a result, the BMS can intelligently regulate charging rates, depth of discharge, and thermal conditions, helping to extend battery life without noticeably affecting user experience.

The introduction of cloud-based BMS has further expanded these capabilities. In such systems, data collected from onboard sensors covering voltage, current, temperature, and impedance are transmitted to remote servers where more advanced computational models can be applied. This approach enables learning at the fleet level, where insights gained from large numbers of vehicles are used to refine predictive models and improve accuracy across the entire network. In addition, these systems support predictive maintenance and allow updates to be deployed remotely, which is particularly advantageous for commercial EV fleets where minimizing downtime is essential. Another area of rapid progress is intelligent charging management. AI-based algorithms can anticipate driving patterns, electricity pricing trends, and the availability of renewable energy sources such as solar and wind. Using these forecasts, the BMS can schedule charging during periods that are both cost-effective and environmentally favorable. Advanced methods, including reinforcement learning, enable real-time optimization of charging decisions while considering user needs such as departure time and required driving range alongside grid constraints. These capabilities are also critical for vehicle-to-grid applications, where EVs function as distributed energy assets. Thermal regulation has similarly benefited from these advancements. Since battery temperature plays a crucial role in performance, safety, and aging, modern systems integrate predictive thermal models with real-time sensor feedback to manage heating and cooling more effectively. Some approaches now employ digital twin models, which replicate the battery system virtually and simulate its behavior under varying conditions. This allows the system to expect and mitigate potential issues before they arise [41–44].

Vehicle-to-grid (V2G) technology is transforming EVs from mere consumers of electricity into active participants in the energy ecosystem. By enabling EVs to discharge stored energy back into the grid during peak demand or periods of renewable intermittency, V2G helps balance supply and demand while reducing strain on power plants. Recent developments have focused on integrating smart software platforms that coordinate fleets of vehicles, allowing them to respond in real time to grid signals and electricity pricing. This capability not only enhances

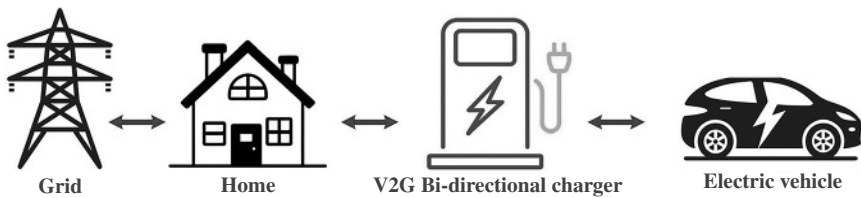


Figure 1.29 V2G configuration.

grid stability but also creates opportunities for owners to earn revenue through energy arbitrage or peer-to-peer trading. Essentially, EVs equipped with V2G act as mobile, distributed energy-storage units, forming the foundation of a more flexible, responsive, and decentralized electricity network (Figure 1.29).

In summary, energy storage has evolved from simple lead-acid batteries to a diverse suite of technologies that blend chemistry and systems engineering. Each technology has trade-offs; some excel at high power (ultracapacitors, flywheels), others at high energy (Li-ion, metal-air), and some at long life (flow batteries). Ongoing research is pushing these frontiers, from high-density solid-state cells to ultra-low-cost Na-ion. The goal is to integrate the right mix of storage solutions to achieve a reliable, affordable, and clean energy system. In practice, this will involve deploying proven technologies today while developing tomorrow's breakthroughs on solid-state, novel chemistries, and smart controls. As storage technologies continue to improve, guided by lessons from real-world pilots and underpinned by abundant new research, they will play a key role in enabling sustainable electric transportation and resilient power grids for the future.

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