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Review

The perspective of energy storage systems advancements and challenges for electric vehicle applications; metric, mechanism, mode, and mitigation framework

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A B S T R A C T

New advancements in the automobile industry require greater demonstration of the role of energy storage in EVs. More effective energy production and storage require an in-depth look at the recent advancements and challenges of energy storage systems (ESS). This paper presents a holistic and hierarchical framework of metric, mechanism, mode, and mitigation of ESSs recent advancements and challenges, including a) Evaluation metrics for advancements, b) Identification of mechanisms and most important challenges, c) Mode and effects analysis, d) Mitigation through material optimization/system design. A comprehensive review was conducted by comparing different batteries, fuel cells, and supercapacitors' efficiencies, performance, advantages, and disadvantages.

1. Introduction

In the last decade, increased environmental concerns, rapid technological advancements, and transmission into electrification in the automobile industry have put energy storage systems (ESS) at the center of attention. Among different ESSs for EVs, batteries, fuel cells, and supercapacitors exhibit the potential to shape EV applications thanks to each technology's new advancements and advantages to address required energy/power density, lifetime, cost, and safety [1]. Despite global efforts to enhance energy density, improve power capability, and reduce costs, challenges remain in ensuring the cyclability and safe operation of high-energy-density ESSs. Electrochemical and thermal stability, material development, and system design remain major concerns, particularly following their mass adoption in the coming decades [2]. Figure 1 demonstrates the global electric car stock trends in the 2010-2023 timespan. These trends indicate that battery electric cars accounted for 70% of the electric car stock in 2023 [3]. This paper aims to review the application of energy storage systems (ESS) in EVs with specific attention to battery technologies, fuel cells, and Supercapacitors. ESSs have long played a pivotal role in improving the system's performance in-vehicle applications by delivering energy into the system or saving energy produced by the system. Fuel cells, supercapacitors, ultra-capacitors (UCs), and various battery technologies have been widely adopted in EV applications and have shown promising results in terms of improving fuel economy [4]. The recovered energy is stored in an ESS reservoir for later use when acceleration. Two of the most important indicators of total energy and power per unit weight are introduced as specific power and specific energy. These two parameters are considered the most determinative factors in EES systems in transportation applications, for they directly influence the travel range and weight of the vehicle.

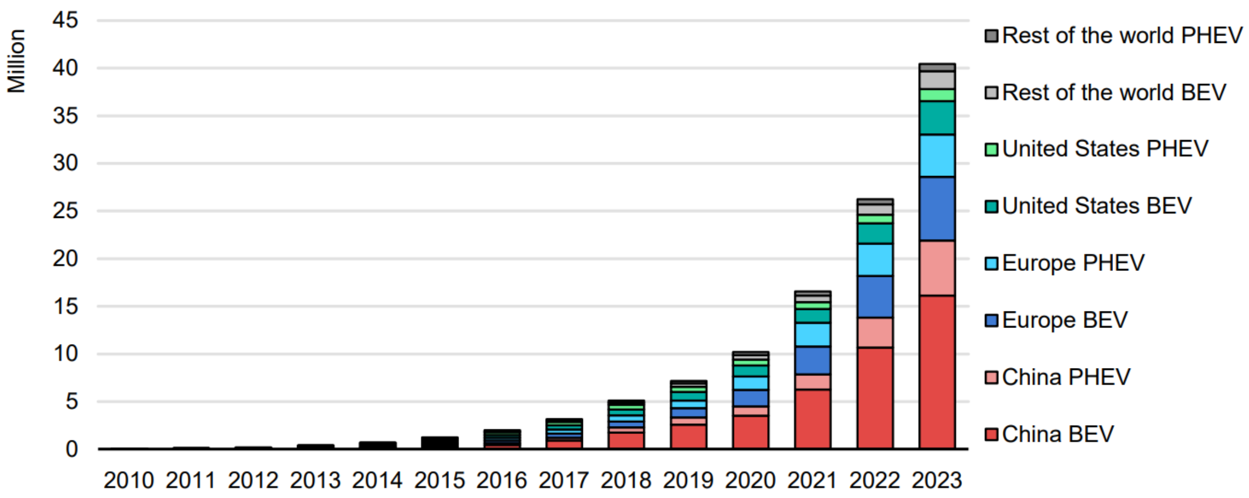

Figure 1. Global electric car stock trends 2010-2023 [3]

The result of the specific power and energy comparison in different EES technologies is illustrated in Table 1 [5]. Supercapacitors, also known as ultra-capacitors, can produce considerable energy at low voltage. They stand in an advantageous position in ESSs due to their high-power density and fast charging and discharging. Nonetheless, UCs are only completely well suited for EV applications once low energy density is addressed [6]. On the other hand, batteries are considered the most promising ESS technology in transportation technologies and have been widely accepted by manufacturers because they offer substantially higher energy storage capabilities. Annual predictions show a steep growth in Li-ion battery demands in the upcoming years [3]. Nevertheless, Li-ion batteries come with their challenges. Safety issues in Li-ion batteries remain a concerning challenge. Increased temperature in Li-ion batteries can cause a series of chain reactions, leading to battery fire and explosion [7]. Complexities in different ESSs can rise from different scales, from material development to system integration [8]. Developing new nanostructured electrodes for increasing the energy density of UCs and designing flow fields in PEM flow fields are some trending research that targets the current ESS constraints [9]. This paper presents a holistic and hierarchical framework of metric, mechanism, mode, and mitigation of Ess's recent advancements and challenges, including a) Evaluation metrics, b) Identification of mechanisms and causes, c) Mode and effects analysis, d) Mitigation through material optimization/system design. A Brief Comparison of ESS technologies is presented in Table 1 [5].

2. Energy storage systems

2.1 Batteries

As one of the most prevalent energy storage and propulsion systems in the transportation industry, batteries can be a perfect fit for vehicle powertrains due to their high energy density, fast response, high efficiency, and zero tailpipe emission as a crucial aspect in future mobility. Moreover, integrating batteries into the vehicle powertrain will bring more flexibility in the electrification of ancillary units, system modularity, better regenerative break, and less maintenance for less mowing parts into the electric vehicles.

Introducing batteries in electrified vehicles will bring about zero-tailpipe emission benefits and improve urban air quality. While existing hurdles in the way of EV battery advancements, such as raw material supply constraints, burdensome cost, and safety threats in higher density chemistries, are proposing challenges for EV battery industries, exceptional advantages of EV batteries call for an increase in the number of research in this area since the annual global demand for EV batteries would reach 1925 GWh by 2030 by a 688% increase from 2021. New regulations also impose net zero tailpipe emission, facilitating vehicle electrification and leading to further market growth. As a result, many research institutions and automotive manufacturers are investing in the integration of EV batteries and the development of batteries for EVs. A group of battery cells forms battery modules, and battery packs comprise battery modules designed with EVs of the desired capacity. Battery pack design complexities bring numerous challenges due to the control of cell voltage, state of charge, and thermal issues throughout the operation.

Table 1. Comparison of ESS technologies

	Battery	Supercapacitors	Fuel cells
Specific Energy (Wh/Kg)	30-300	0.05-15	100-450
Specific Power (W/Kg)	<2000	<10000	<200
Power rating MW	0.005-100	0.0001-0.1	0.005-50
Energy capital cost ($/kWh)	100-150	300-2000	230-330
efficiency (%)	70-100	84-97	60-80
Charge Time	1-5 h	0.3-30 S	3-5 min
Discharge Time	0.3-3 h	0.3-30 S	0.3-3 h
Daily self-discharge (% per day)	<0.03-0.3	Oct-20	-
Lifetime (years)	2-20	10-12	1-10

Battery cells group together and form modules. Several modules also group to form battery packs. Battery management systems handle the interconnection between cells and modules. BMSs monitor and control the batteries efficiently and safely through numerous tasks such as monitoring, protection, charging and discharging management, communication, diagnosis, and data management. Critical states of batteries, such as state of power, health, charge, energy, power, temperature, and safety, are required for effective charging, thermal management, and health management. Batteries produce heat as a result of electrochemical reactions. Very high and low temperatures adversely affect battery performance, life, and safety and might impose degradation and even overheating if not handled properly. This comes to the importance of thermal management. It has been reported that higher temperatures can be very problematic for EV batteries. Higher temperatures lead to the accumulation of heat and trigger chains of exothermic reactions, which lead to combustion and even the explosion of batteries. This phenomenon is called Thermal runaway (TR) and is more extreme in higher energy density materials, owing to more chemically active materials. The TR behavior calls for additional countermeasures for thermal management for safety [7]. The design of BTMS calls for attention, and numerous investigations were focused on leveraging heat transfer mechanisms for keeping the batteries in the optimal range, including active methods (Air cooling and liquid cooling), passive methods (Phase change materials and Heat pipes) and hybrid methods (Integration of active methods with passive methods) [1, 9]. Performance indexes such as energy efficiency, maximum temperature, and temperature difference are satisfied with BTMS designers as the temperature has the most effect on the aging mechanism and threads' lifetime of batteries. The importance of BTMS comes into play in terms of safety implications as well. This is due to the thermal runaway concerns in the accumulation of heat and raised temperature, which leads to further exoteric chained reactions and finally combustion or even explosion of batteries. In the core of battery systems in EVs, there are numerous interconnected battery cells. Battery cells correspond to more than 75% of battery overall costs and determine the characteristics of the system. Energy density, power density, cost, safety, and lifetime are the main critical factors for EV battery selection [10]. Improvements in the energy density of batteries have been greatly focused as one of the main critical factors in EV batteries since the shift from the ICE market requires batteries to deliver a comparable driving range and lower cost, which leads to an exploration of new batteries for higher energy densities. Early EV batteries, such as Pb-acid batteries, offered competitive prices in the market but suffered from low energy density. NiCd batteries showed promising lifespan, while destructive materials impeded their commercialization. NiMH was also utilized in hybrid-electric passenger cars (Toyota Prius) and resolved previous challenges, but still was hindered by low storage capacity and self-discharging. Li-ion batteries revolutionized the EV market owing to their exceptional energy density, lifecycle, and low self-discharge, which is highly important in transportation applications. Higher energy density expands the range as one of the main obstacles to EVs. The reported 80 Wh kg-1 has seen a steep growth from 1991 to 2020 and reached a satisfactory number of 400 Wh kg-1 [7]. Li-ion batteries also propose great energy efficiency and boost EV performance (Up to 95% compared to 70% and 65% in lead-acid and NiMH batteries) [11]. Li-ion batteries come in many characteristics in terms of chemistries. An overview of battery chemistries is provided in the review of Chemali et al. [12]. The cell chemistry selection is a great design choice for EV battery designers since pure EVs require high energy storage, and hybrid electric vehicles call for power [13]. In addition to the main two factors of energy and power density, cells should operate safely in different loads, overcome complex mechanical, electrical, and thermal loads in various working conditions, and offer a high life cycle to work for many years. Therefore, exploring new chemistries and material advancements is the research direction for manufacturing high-energy, safe, and affordable EV batteries with increased lifespan. A comparison of battery characteristics in EV battery evolution is presented in Table 2. The US advanced Battery consortium target is also presented in the table to highlight the target goals in the battery technology advancements [14]. In addition to the promising characteristics of new cell chemistries, battery materials correspond to more than 70% of battery cell cost. Hence, breakthroughs in cell materials will facilitate the market penetration of battery EVs [11].

Different battery technologies arise from various types of cathodes, anodes, and electrolytes. Currently, lithium cobalt oxide (LCO) dominates the market and is the mature cathode chemistry. Other cathode technologies such as lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA), and lithium manganese oxide (LMO) are advancing and tracking the place of LCO in the market by offering more stable crystal structures, lower price, and more abundant materials. LFP offers fast charging and low volumetric energy density and fits better in public transport and heavy-duty applications. However, it has reached its theoretical limit (170Wh/kg) and cannot satisfy the expectations of the next generation of EV batteries. Despite the low energy density and lifetime, LFP battery EVs dominate the commercial EV section due to lower material cost (50% less material cost than NCA). LMO offers high power but low energy density. Battery types can be blended to other high energy density chemistries like NMC to take advantage of both types (e.g. LMO/NMC composite for BMW i3 and Nissan leaf). NMC takes advantage of low internal resistance from manganese, high capacity from nickel, and low cost from less cobalt by combining Ni, LMO, and LCO). It is estimated that NMC will grow its share in the market due to higher energy density than LFP, while others (NCA and LMO) remain constant. The energy density of the cell level has reached 250 Wh/kg, reaching the promising 300 km range [10]. A comparison of Li-ion battery technology across energy/power density, safety, lifespan, and cost is presented in Figure 2. A. Comparison of Li-ion cathode chemistries and the effect of chemistries on the characteristics of the cells is also elucidated in Figure 2. B, C and D. [1, 10, 11].

Anode materials are also under development with the Si integration breakthrough. Si offers exceptionally higher energy density but comes with thorny issues such as material swell and huge volume explanation during lithiation, leading to capacity loss (The calendar life of Si-anode batteries is still only 20–30 months, against the EV requirement of 100–140 months [15]).

Table 2. Comparison of different battery characteristics in EVs

Battery type	Energy density (Wh/kg)	Specific power (W/kg)	Life cycle	Energy Efficiency (%)	Production cost ($/kWh)	Advantages	Disadvantages
USAB goal	350	700	1000		100		
Lead acid (Pb-acid)	35	180	1000	70-90	60	+ Low initial cost + Maturity in technology + Good network of manufacturing infrastructure + Abundant and affordable raw materials	- Low specific energy and power - Short life cycle - Temperature-sensitive performance - Charging time - Safety concerns due to gas release and hazardous lead
Nickel-cadmium (Ni-Cd)	50-80	200	2000	60-70	250-300	+ Good cycle lives + Wide operating temperature range + Good safety + Low charging time + Mature technology	- Memory effect - Reliance on hazardous cadmium
Nickel-metal hydride (Ni-MH)	70-95	200-300	<3000	50-80	200-250	+ Good specific energy and power + Eco-friendly materials + Extensive operating temperature range + Good safety	- High Self discharging - Memory effect
ZEBRA (Na-NiCL)	90-120	155	>1200	80	230-345	+ Low self-discharging and no memory effect	- Extremely high temperature range - Thermal management and safety issues
Lithium-ion (Li-ion)	118-250	200-430	2000	70-80	150	+ Outstanding specific energy and power + Long cycle lives + Satisfactory operating temperature ranges + Chemistry diversity + Eco-friendly material technologies + Fast charging	- High initial cost - Sophisticated BMS technology required - Safety concern for thermal runaway - Material depletion concerns
Lithium-ion polymer (LiPo)	130-225	260-450	>1200	70	150	+ Better packaging optimization compared to Li-ion	
Lithium-iron phosphate ($LiFePO_4$)	120	2000-4500	>2000	90	350	+ High power density than Li-ion + Better safety compared to Li-ion	- Lower energy density compared to Li-ion
Zinc-air (Zn-air)	460	80-140	200	60	90-120	+ Relatively high energy density	- Low power density - Short life cycle
Lithium-sulfur (Li-S)	350-650	-	300		100-150	+ Relatively high energy density + Low cost	- High discharge rate - Short life cycle
Lithium-air (Li-air)	1300-2000	-	100		-	+ Exceptionally higher energy density (Comparable to those of ICEs)	- Short life cycle - Sill in prototype stage

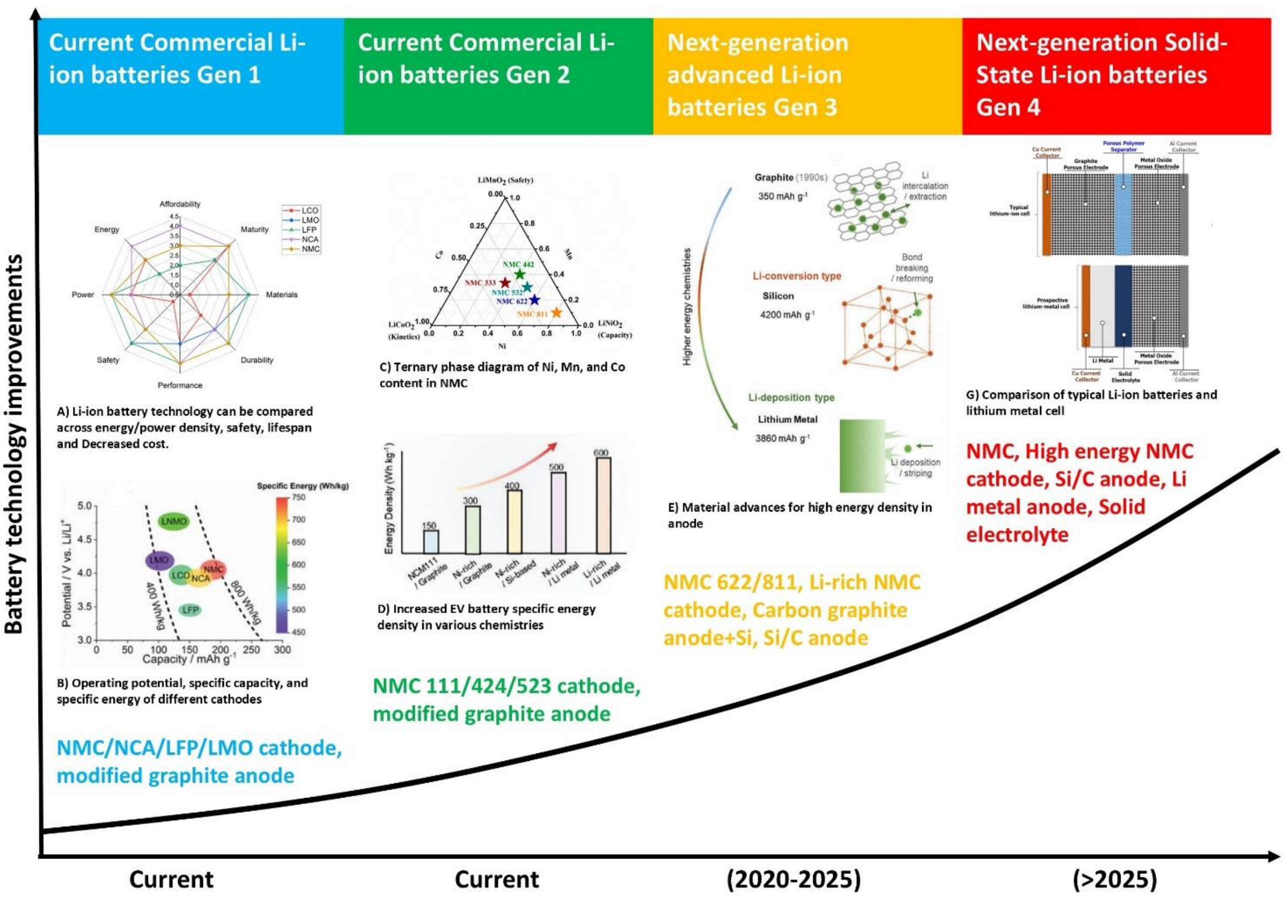

Figure 2. Overview of Short- and long-term research directions for Li-ion battery developments A) Comparison of the Li-ion battery technology across energy/power density, safety, lifespan and cost. B) Comparison of Li-ion cathode chemistries by specific capacity and specific energy. C) Comparison of Mn, Co and Ni content in NMC, D) Increased EV battery specific energy density in Ni and Li rich cathodes, E) Integration of Si for high energy density Li-ion anodes, G) Comparison of typical Li-ion batteries and lithium metal cell

Si-C composition and electrolyte additives for stabilization are known as the target solutions. Today, only 10% Si composition is viable, but Si can offer up to 4200 mAh/g theoretical capacity. Another breakthrough in anode material development is lithium metal, which has a specific capacity that is 10 times higher. Li metal development is hindered by high reactivity, Lithium deuteride growth, and thermal runaway caused by short circuit concerns. The abovementioned issues can be handled by applying protective layers or embedding Solid-state electrolytes. Solid-state electrolytes will be the next generation of Li-ion batteries and resolve the bottleneck. Li foil anodes unlock the energy capacity of graphite anodes, pushing the 280 Wh/kg to ≈ 500 Wh/kg. The lithium metal foil supply chain should be addressed in the next generation of batteries to meet the market demand for SSBs. Figures 2 E and G illustrate the integration of Si for high energy density Li-ion anodes and compare typical Li-ion batteries with lithium metal cells. It is expected that the battery market will heavily rely on currently matured technologies such as NCA, NMC, and higher energy NMCs. EV battery technology also depends on the application. Heavy-duty applications require longer cycle lives, and NMC/LFP batteries are more favorable in commercial EVs than Ni-rich and lithium metals. SSBs are the dominant technology in the long term from 2025 onward, with Li dendrite suppression for safety and high-performance anode material uptake for high energy density being the main incentives. The cost of the battery is highly dependent on the material supply, investment in research and development for developing new cell chemistries, cell manufacturing process, battery pack design, optimizing the BMSs, and battery second life and recycling. Costs have continuously decreased since the early introduction of EV batteries. Reports show that Li-ion EV battery pack cost dropped by approximately 90% in the 2010-2021 timespan and will fall below $100/kWh in 2024 [16]. There are other factors in EV batteries that must be focused on in order to achieve market dominance. Capacity decay occurs in the battery cells every time it is charged and discharged, reducing driving range and service life. The effect of aging is greatly dependent on the battery type, reaction stage, and operating condition, and battery health monitoring and aging diagnostic is one of the main targets of battery management systems, along with the investigation of battery aging mechanisms and proposing prevention methods. Temperature adverse effects are known to have the most aggressive effect on battery aging, which further highlights the importance of effective battery thermal management systems. Fast charging is another technological advancement in the EV battery industry that has further assisted the EV's competitiveness by addressing the range anxiety in the decreased charge time. This also helps the raw material extraction limits since a 120kWh battery charged in one hour can be replaced by a 60kWh battery with 10 min charge time. The fast charging should also be evaluated by the number of cycles since it causes degradation and low cycle life is also a downside in battery life. The ideal target is set by DOE as 240 Wh kg−1 acquired energy after a 5 min charge with a more than 2,000 cycle lifetime. Different power levels in AC charging from 3 to 22 kW, and DC fast chargers from 40 kW to 120 kW are now permitted in the EV batteries [17]. Embedded fast chargers also bring other design aspects, such as redesign of vehicle electronics and thermal management, implementation of charging stations, and grid stability challenges [18]. Employing the fast-charging methods requires more aggressive BTMSs that cannot be handled by air cooling or even liquid cooling. Nonetheless, the implementation of fast charging station cooling for less weather independence, investigation of new BTMS for high heat transfer efficiency (Immersion and jet cooling), and cell design for lower temperature variation inside the cell due to high heat generation are some of the thermal considerations that should be addressed in this aspect. Graphite anode batteries are the first to unlock the fast-charging potential since conventional Li-ion batteries have undergone rapid capacity loss and safety hazards in fast charging due to heightened lithium plating risks [15]. The development of EV batteries calls for a huge value chain improvement. Despite the zero-emission tailpipe standards, the production and process of materials for manufacturing cells impose substantial carbon emissions. Therefore, to alleviate the environmental burden of the whole battery lifecycle, the lifecycle analysis of battery production and recycling of used batteries play a crucial role. The production emissions of batteries are mainly caused by battery cell manufacturing and mostly by positive electrodes, which further highlights the importance of electrode material design. Battery cooling systems, BMS, and packaging constitute components and subsystems in the battery system, as observed in the life cycle analysis. Safely disposing of batteries with less than 80% of their nominal capacity will not only minimize the overall carbon footprint but also reduce the cost since batteries in EVs account for almost 40% of the total cost of vehicles [19]. Figure 3 elucidates the most current solutions in EV batteries with their promises and challenges based on the main design metrics.

2.2 Supercapacitor

Supercapacitors or Ultracapacitors are some of the most attractive ESSs that contribute to the growth of low to high-power applications. UCs can store and recover energy in EV applications and improve the overall performance of the system in terms of energy efficiency. UCs come into play when batteries cannot meet the energy demand in EV systems. Moreover, the ever-changing and erratic inherent energy consumption with changes during battery charge and discharge is very harmful to the electrochemical process of the battery. This can be resolved by utilizing UCs as a high-rate ESS accompanied by the battery to provide the excess energy demand of EVs. A fuel reduction of 10% is reported by the manufacturers of passenger cars when exploiting UCs to store breaking energy [20]. Supercapacitors offer extremely higher specific power density (up to 100 times) but suffer from lower energy density when compared to batteries. In an electric double-layer capacitor (EDLC), a double-layered conductor with equal and opposite electric charges allows the UCs to store energy by electrostatic charge accumulation. EDLC is the most commonly used SC.

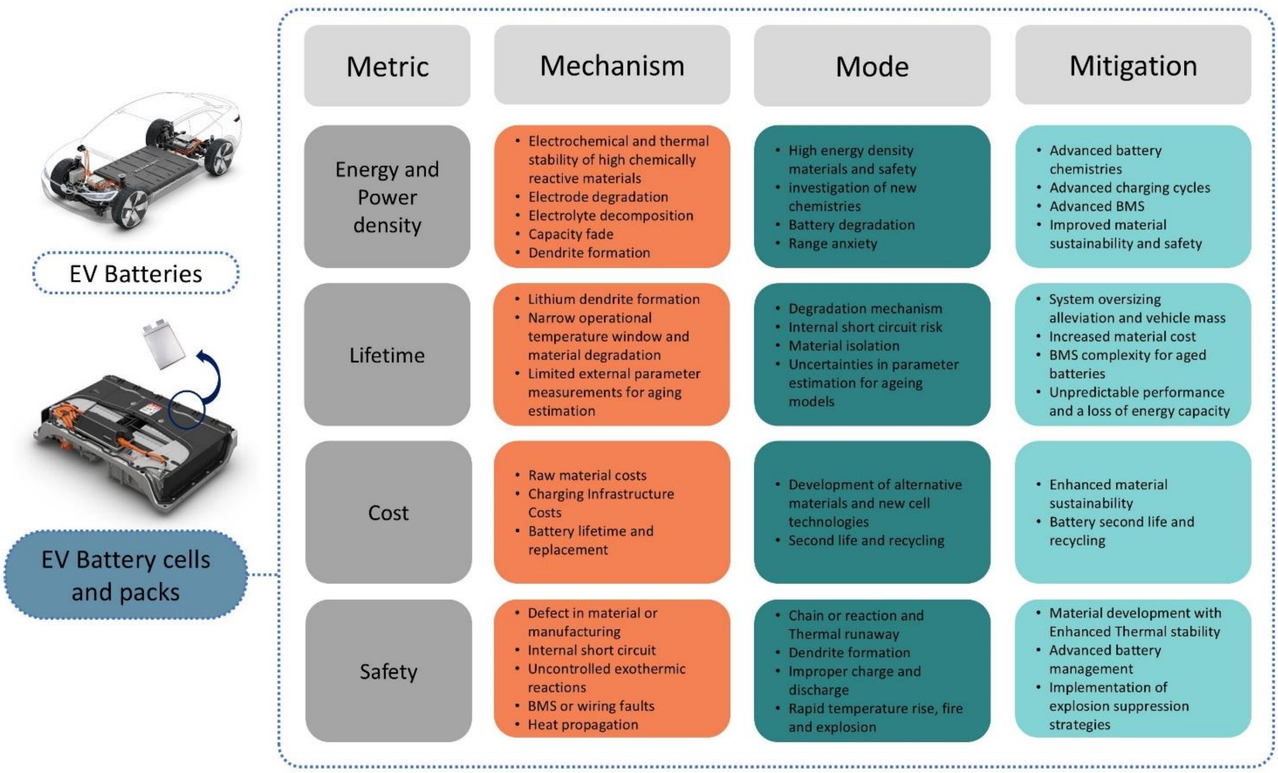

Figure 3. Recent progress in EV batteries with their mechanism, mode, and mitigation challenges based on the principal design metrics

Phosphoric capacitors (PC) offer higher energy densities at the expense of power density and cycling stability by storing charge via the faradic process. Hybrid supercapacitors (HSC) combine the characteristics of EDLC and PC and offer a good combination of power and energy density, and cycling stability. Li-ion capacitors are one example of HSE [14]. Table 1 illustrates different supercapacitor technologies' energy and power density [21]. Supercapacitors guarantee a long life due to the lack of chemical reaction in the electrodes, which is in contrast to batteries, and offer a much faster storage capability, which is appealing to mobile machinery. Recent developments in electrode materials have been trying to enhance the charge stability, cyclability, and energy density of UCs in EV ESSs. Compared to aqueous electrolytes, non-aqueous electrolytes show a higher energy density due to the high voltage window, enabling the use of high-voltage active materials in the supercapacitor. Non-aqueous electrolytes also offer better stability and longer cycle life. However, challenges such as cost, toxicity, and flammability stay ahead of non-aqueous electrolytes despite their advantages. Exploring new materials for SC electrolytes, such as NASICON-type materials, is the future of SC development. The advantages of new electrolyte materials, such as high conductivity, good cyclic stability, and enhanced energy and power density, will play an important role in commercializing SCs in EV applications [22]. Figure 4 elucidates the most current solutions in EV SCs with their promises and challenges based on the main design metrics.

2.3 Fuel cells

The advent of fuel cells has been considered a technological marvel in energy and transportation systems due to their capability to provide zero carbon, efficient, and adaptable power sources. Fuel cells have been at the center of increased attention in recent decades owing to their well-competent characteristics and better performance in terms of range and efficiency in the automotive industry. Compared to the ICEs and BEVs, fuel cells can take advantage of their exceptional characteristics by offering higher energy efficiency than ICEs, as a matter of direct conversion of chemical energy to electricity, and maintain a longer driving range than BEVs by cutting out charging time. Fuel cells owe these interesting features to the generation of emission-free (green) electricity and not to the storage, allowing them to enjoy the high range capability of IC engines without sacrificing the clean and sustainable power supply of BEVs. Implementing FCEVs in the transportation industry offers many other advantages, such as modular structure, silent operation, and flexible power ratings, turning FCs into an appealing choice for vehicles ranging from passenger cars to buses and trucks. The attractive lifetime range of FCs (20-25 years) is another interesting factor in the vehicle industry that needs to be considered [23]. Fuel cells are not heat engines; hence, their efficiency is not limited by the Carnot limit as in the IC engines. Therefore, the FCEVs can enjoy a sustainable power supply to run the system if the cells are maintained fuel and oxidant. This inherited nature of FCs can also extend the BEV capabilities by charging batteries while operating. Notwithstanding the wide variety of fuel cells, which are classified into six classes, including proton exchange membrane fuel cells (PEMFCs), alkaline fuel cells (AFCs), phosphoric acid fuel cells (PAFCs), molten carbonate fuel cells (MCFCs), solid oxide fuel cells (SOFCs), and direct methanol fuel cells (DMFCs), each type of fuel cells can cover a specific application depending on their limits and advantages. Among all types of different fuel cells, PEMFCs can be a perfect fit in EV applications by maintaining a proper operating temperature range and high-power density, which leads to a fast startup time required in the transportation industry and a lightweight load to carry for its smaller size, respectively. PEMFCs, by exploiting the zero-carbon and high energy density hydrogen gas, can stand out in EV applications and are in progress. However, the challenges of commercialization in FCEVs are steep [24]. The very first challenge of FCEVs is fuel supply. There are currently two practical ways of storing hydrogen: high-pressure gas or cryogenic tanks. Each of them faces important challenges that need to be addressed. Pressurizing hydrogen can be very costly or even hazardous. Energy per liter of H2 is equivalent to 0.1 liter of gasoline (~1kWh) at the pressure of 350 bar. Something in the margin of 25% of its energy should also be consumed to compress the gas into that high pressure, let alone the weight of such a strong tank to tolerate this pressure and safety issues if a dangerous tank is used in transportation applications. Liquid hydrogen stored in cryogenic tanks also faces important challenges.

Facilities to keep the low temperature (-259.2 °C) can add to the weight of the vehicle, liquefying hydrogen is costly, and in case of dropping the temperature and boil-off, the tank is susceptible to highly pressured liquid-gas mixture or even explosion in a vase of using safety valves [24]. The power transmission structure of FCEVs includes an FC stack to supply energy, a hydrogen tank, a unidirectional DC-DC converter for FC, a motor drive converter, and an electric motor. Additionally, different energy storage and/or generation units can integrate with fuel cells and hybridize FCEVs. Batteries, Supercapacitors, Photovoltaic panels, and flywheels are some hybridization units that can offer a variety of hybrid FC designs, with FC-battery hybridization being the most popular topology. A general schematic of FCEVs and hybrid FCEVs power transmission structure is depicted in Figure 5.

There are more than 34,800 FCEVs and 540 hydrogen refueling stations worldwide, with passenger cars dominating the vehicle market (~75%) [25]. Announced targets are also set to reach 10-15 million and 400 million FCEVs by 2030 and 2050, respectively. Samsun et al. [26] conducted detailed statistical analysis and perspectives on the development of FCEVs and hydrogen refueling station infrastructure. Even though the fuel supply in FCEVs can be problematic and PEMFCs are still expensive, FCEVs interest automotive companies and researchers to solve unresolved issues and make perfect use of fuel cells in EV applications. Expensive catalyst cost, hydrogen purity and production challenges, fuel station accessibility, and safe built-in storage are some challenging issues in the face of FCEV advancements underway to meet transportation needs. Almost 40% of an FCEV's total cost comes from the stack, and 60% of it comes from the cell itself. More than 45% of the cost in the cell is the catalyst, which shows the importance of reducing Platinum loading in the catalyst or utilizing new catalysts [27]. Some studies have tried to investigate new catalysts that are much more affordable than precious metals. New FCs with efficient iron-based catalysts have even exceeded the DOE's 2025 target for current density [28, 29]. New investigations are also focused on safer and more affordable hydrogen storage methods and putting behind conventional compressed gas storage systems that have stalled the commercialization of the FCEV market. Solid hydrogen storage or metal hydride hydrogen storage technology can store the hydrogen for an extended period; however, charging time is still a problem.

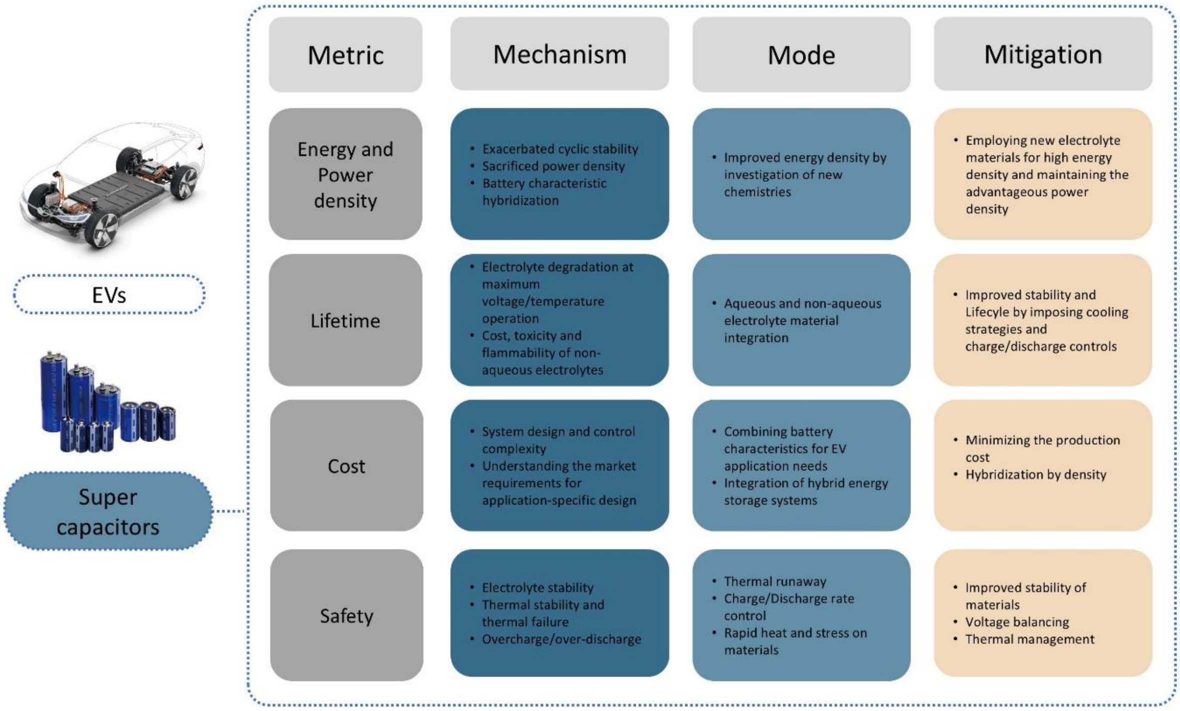

Figure 4. Recent progress in EV UCs with their mechanism, mode, and mitigation challenges based on the principal design metrics

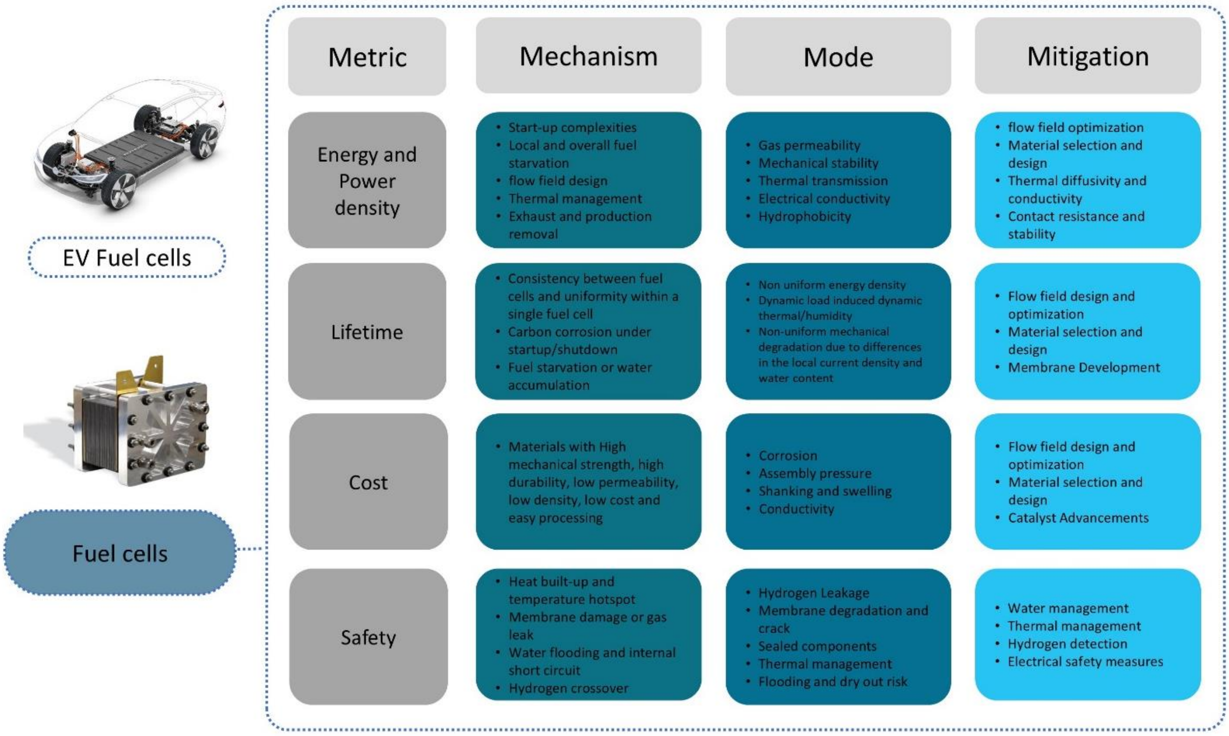

Figure 5. Recent progress in EV Fuel cells with their mechanism, mode, and mitigation challenges based on the principal design metrics

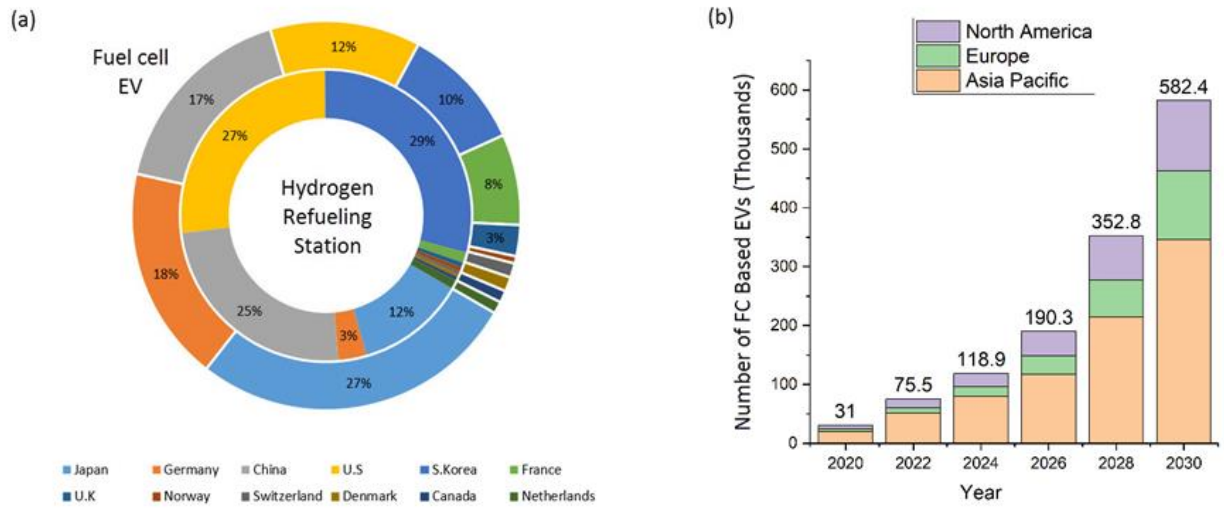

Figure 6. (a) FCEV and hydrogen refueling station share in different countries. (b) Number of FCEVs [34]

Recent investigations tackle this issue by designing new internal heat exchangers to address the low thermal conductivity of hydrogen and reduce the charging time by up to 59% [30]. Economically, scale can also unleash the FCEVs' market potential. Estimates show that fuel cell prices will drop 70 to 80% as production volume scales, according to Ballard, one of the biggest FC manufacturers. The ultimate DOE cost target is 30 $/kW. Component cost breakdown and cost reduction measure analysis are conducted in different studies [31, 32]. The cost of passenger light-duty vehicles in the US will be cut almost in half from 2030 to 2050, according to the International Energy Agency technology roadmap, and cost parity with ICEs will be reached by 2040 by the rapid ramp-up of fuel cell sales [33]. Also, the WtW emission of FCEVs will dramatically decrease by 2050, whereas it is currently almost comparable to ICE's well-to-wheel CO_2 emission. It is expected that the vehicle industry will see a surge in FCEVs running on roads. Figure 6 illustrates the share of FCEVs and hydrogen refueling stations for different countries.

3. Conclusion

This study presents a holistic and hierarchical framework of metric, mechanism, mode, and mitigation of ESS recent advancements and challenges for Lithium-ion batteries, PEM fuel cells, and supercapacitors as three major potent candidates in EV ESS. Complexities in different ESSs can rise from different scales, from material development to system integration. Nonetheless, each technology poses its unique challenges and promises. Li-ion batteries are bound to reach higher energy and power densities and extended lifetime by advancements in new chemistries, solid-state batteries, and methods for suppressing dendrite formation for improved cyclability. However, safety concerns in Lithium-ion batteries remain a challenge due to increased energy density. Still, they can be controlled by investigation of more stable cell components and system-level safety integration. Furthermore, supercapacitors will continue to grow in EV applications by hybridizing materials with battery characteristics to improve energy density. PEM fuel cells will continue growing as interesting candidates for EV ESS. However, the design of flow field channels, improved performance, and optimized thermal and mechanical properties of the cells for better cyclability will remain important research directions for PEM fuel cells.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding authors.

Conflict of interest

The authors declare no potential conflict of interest.

References

[1] A. Gharehghani et al., "Progress in battery thermal management systems technologies for electric vehicles," Renewable and Sustainable Energy Reviews, vol. 202, p. 114654, Sep. 2024, doi: 10.1016/j.rser.2024.114654.

[2] J. Zhao et al., "Battery engineering safety technologies (BEST): M5 framework of mechanisms, modes, metrics, modeling, and mitigation," eTransportation, vol. 22, p. 100364, Dec. 2024, doi: 10.1016/j.etran.2024.100364.

[3] "IEA (2024), Global EV Outlook 2024, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2024, Licence: CC BY 4.0."

[4] A. Parikh, M. Shah, and M. Prajapati, "Fuelling the sustainable future: a comparative analysis between battery electrical vehicles (BEV) and fuel cell electrical vehicles (FCEV)," Environ Sci Pollut Res, vol. 30, no. 20, pp. 57236–57252, Apr. 2023, doi: 10.1007/s11356-023-26241-9.

[5] S. Sabihuddin, A. E. Kiprakis, and M. Mueller, "A numerical and graphical review of energy storage

technologies," Energies, vol. 8, no. 1, pp. 172–216, 2014.
[6] M. Yaseen et al., "A review of supercapacitors: materials design, modification, and applications," Energies, vol. 14, no. 22, p. 7779, 2021.
[7] Y. Wang, X. Feng, W. Huang, X. He, L. Wang, and M. Ouyang, "Challenges and Opportunities to Mitigate the Catastrophic Thermal Runaway of High-Energy Batteries," Advanced Energy Materials, vol. 13, no. 15, p. 2203841, 2023, doi: 10.1002/aenm.202203841.
[8] I. Banagar, A. Mahmoudzadeh Andwari, S. Mehranfar, J. Könnö, and E. Kurvinen, "Electric vehicles' powertrain systems architectures design complexity," 2023, Accessed: Oct. 28, 2024. [Online]. Available: https://oulurepo.oulu.fi/handle/10024/44739
[9] S. Rashidi, N. Karimi, B. Sunden, K. C. Kim, A. G. Olabi, and O. Mahian, "Progress and challenges on the thermal management of electrochemical energy conversion and storage technologies: Fuel cells, electrolysers, and supercapacitors," Progress in Energy and Combustion Science, vol. 88, p. 100966, 2022.
[10] M. S. Houache, C.-H. Yim, Z. Karkar, and Y. Abu-Lebdeh, "On the current and future outlook of battery chemistries for electric vehicles—mini review," Batteries, vol. 8, no. 7, p. 70, 2022.
[11] Bin Ahmad MS, Pesyridis A, Sphicas P, Mahmoudzadeh Andwari A, Gharehghani A, Vaglieco BM. Electric vehicle modelling for future technology and market penetration analysis. Front Mech Eng 2022;8:896547. https://doi.org/10.3389/ fmech.2022.896547.
[12] E. Chemali, M. Preindl, P. Malysz, and A. Emadi, "Electrochemical and electrostatic energy storage and management systems for electric drive vehicles: State-of-the-art review and future trends," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 3, pp. 1117–1134, 2016.
[13] M. Rabiei, A. Gharehghani, A.M. Andwari, Enhancement of battery thermal management system using a novel structure of hybrid liquid cold plate, Appl. Therm. Eng. 232 (2023), 121051. https://doi.org/10.1016/j.est.2023.110273.
[14] M. B. F. Ahsan, S. Mekhilef, T. K. Soon, M. B. Mubin, P. Shrivastava, and M. Seyedmahmoudian, "Lithium-ion battery and supercapacitor-based hybrid energy storage system for electric vehicle applications: A review," Intl J of Energy Research, vol. 46, no. 14, pp. 19826–19854, Nov. 2022, doi: 10.1002/er.8439.
[15] C.-Y. Wang et al., "Fast charging of energy-dense lithium-ion batteries," Nature, vol. 611, no. 7936, pp. 485–490, 2022.
[16] "Breaking Down the Cost of an EV Battery Cell. Available online: https://elements.visualcapitalist.com/breaking-down-the-cost-of-an-ev-battery-cell/".
[17] A. Cardenas, C. Guzman, and W. Martinez, "Ev overnight charging strategy in residential sector: Case of winter season in quebec," Vehicles, vol. 3, no. 3, pp. 557–577, 2021.
[18] Y. Liu, Y. Zhu, and Y. Cui, "Challenges and opportunities towards fast-charging battery materials," Nature Energy, vol. 4, no. 7, pp. 540–550, 2019.
[19] M. Shahjalal et al., "A review on second-life of Li-ion batteries: Prospects, challenges, and issues," Energy, vol. 241, p. 122881, 2022.
[20] C. Chellaswamy and R. Ramesh, "Future renewable energy option for recharging full electric vehicles," Renewable and Sustainable Energy Reviews, vol. 76, pp. 824–838, Sep. 2017, doi: 10.1016/j.rser.2017.03.032.
[21] P. Forouzandeh, V. Kumaravel, and S. C. Pillai, "Electrode materials for supercapacitors: a review of recent advances," Catalysts, vol. 10, no. 9, p. 969, 2020.
[22] S. Samantaray, D. Mohanty, I.-M. Hung, M. Moniruzzaman, and S. K. Satpathy, "Unleashing recent electrolyte materials for next-generation supercapacitor applications: a comprehensive review," Journal of Energy Storage, vol. 72, p. 108352, 2023.
[23] M. İnci, M. Büyük, M. H. Demir, and G. İlbey, "A review and research on fuel cell electric vehicles: Topologies, power electronic converters, energy management methods, technical challenges, marketing and future aspects," Renewable and Sustainable Energy Reviews, vol. 137, p. 110648, 2021.
[24] "Modern Electric, Hybrid Electric, and Fuel Cell Vehicles | Mehrdad Ehs." Accessed: Oct. 28, 2024. [Online]. Available: https://www.taylorfrancis.com/books/mono/10.1201/9780429504884/modern-electric-hybrid-electric-fuel-cell-vehicles-mehrdad-ehsani-yimin-gao-stefano-longo-kambiz-ebrahimi
[25] Remzi Can Samsun, Laurent Antoni, Michael Rex, Detlef Stolten, "Deployment Status of Fuel Cells in Road Transport: 2021 Update."
[26] R. C. Samsun, M. Rex, L. Antoni, and D. Stolten, "Deployment of fuel cell vehicles and hydrogen refueling station infrastructure: a global overview and perspectives," Energies, vol. 15, no. 14, p. 4975, 2022.
[27] S. Ma et al., "Fuel cell-battery hybrid systems for mobility and off-grid applications: A review," Renewable and Sustainable Energy Reviews, vol. 135, p. 110119, 2021.
[28] C. Li et al., "Fe-NC PGM-Free ORR Catalysts: An Investigation of the Source of Observed Redox Peaks and Their Significance to Catalysis," in ECS Meeting Abstracts, 2022, pp. 1487–1487. Accessed: Oct. 28, 2024. [Online]. Available: https://ui.adsabs.harvard.edu/abs/2022ECSMA2022.1487L/abstract
[29] C. Li et al., "Rationally Designed PGM-Free Catalyst MEA with Extraordinary Performance," in Electrochemical Society Meeting Abstracts 242, The Electrochemical Society, Inc., 2022, pp. 1487–1487. Accessed: Oct. 28, 2024. [Online]. Available: https://iopscience.iop.org/article/10.1149/MA2022-02401487mtgabs/meta

[30] P. Larpruenrudee, N. S. Bennett, Y. Gu, R. Fitch, and M. S. Islam, "Design optimization of a magnesium-based metal hydride hydrogen energy storage system," Scientific Reports, vol. 12, no. 1, p. 13436, 2022.

[31] B. D. James, J. M. Huya-Kouadio, C. Houchins, and D. A. DeSantis, "Mass production cost estimation of direct H2 PEM fuel cell systems for transportation applications: 2012 update," report by Strategic Analysis, Inc., under Award Number DEEE0005236 for the US Department of Energy, vol. 18, 2012, Accessed: Oct. 28, 2024. [Online]. Available: https://www.researchgate.net/profile/Brian-James-5/publication/341407810_Final_SA_2018_Transportation_Fuel_Cell_Cost_Analysis_-2020-01-23/links/5ebea64ba6fdcc90d675d7b4/Final-SA-2018-Transportation-Fuel-Cell-Cost-Analysis-2020-01-23.pdf

[32] S. T. Thompson et al., "Direct hydrogen fuel cell electric vehicle cost analysis: System and high-volume manufacturing description, validation, and outlook," Journal of Power Sources, vol. 399, pp. 304–313, 2018.

[33] "IEA (2015), Technology Roadmap - Hydrogen and Fuel Cells, IEA, Paris." [Online]. Available: https://www.iea.org/reports/technology-roadmap-hydrogen-and-fuel-cells, License: CC BY 4.0. n.d

[34] "IEA (2021), Global EV Outlook 2021, IEA, Paris." [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2021, License: CC BY 4.0 n.d.