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Emerging Energy Storage Solutions for Transportation Electrification – A Review

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Abstract

Energy storages have caught the attention of transportation community for the past several years. Rsecent developments in hybrid and plug-in electric vehicles together with novel concepts in transportation such as electric highways are the reasons for raising the role of energy storages in transportation to such a significant level. Performance demands for energy storage solutions vary significantly from one transportation application to the other, making it difficult for the scientific community to converge to a single energy storage solution that caters all. This paper reviews the key performance demands of the major transportation applications. It also investigates the characteristics of emerging energy storage solutions and assess their suitability for those reviewed transportation applications.

Keywords: batteries, capacitors, chemistry, energy management, energy storage, flywheels

1. Introduction

Researchers have been reviewing energy storage systems continuously by looking at them from different points of view. Use of energy storage systems in automotive applications is thoroughly discussed in [1]. As per battery technologies, the paper reviews Lead Acid (LA), Lithium Ion (Li-ion), Nickel Metal Hydride (NiMH), Nickel Cadmium (NiCd), Sodium Nickel Chloride (NaNiCl2) and flow batteries. In this work, Fuel Cells (FCs), Ultra-Capacitors (UCs) and flywheels are also considered as alternative energy storages used in transportation applications. A detailed discussion on Energy storage systems in transportation and grid applications can be found in [2]. In this work, several battery technologies such as LA, Li-Ion, NiMH, NiCd, NaNiCl2, Flow Batteries (FB) together with alternative energy storage solutions such as Compressed Air Energy Storage (CAES), Fuel Cells (FCs), Electrochemical Double-Layer Capacitors (EDLC), Superconductive Magnetic Energy Storage (SMES), Flywheel Energy Storage Systems (FESS), and Thermo-Electric Energy Storage (TESS) are reviewed in detail. As per applications in transport, authors mainly focus on road and rail transport in this work. Applications of electrical energy storage systems for vehicular transportation is broadly discussed in [3]. In this work, energy storages such as battery, FESS, SMES, UC energy storage technology are reviewed. The authors give special emphasis on hybrid energy storage technologies, where a detailed discussion on the use of combined energy storage systems such as UC/Battery, FC/Battery, FC/UC etc. can also be found in this work.

There have been several energy storage applications in rail sector. These will be addressed later in the paper. A more detailed discussion on application of LA and Li-Ion energy storages as well as UC and FESS in Hybrid Railway Vehicles (HRV) is presented in [4].

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Similar to rail applications, it is possible to locate several scientific publications in the area of energy storage applications in maritime transportation. More fundamental mathematical insight into optimization of the efficiency and reduction of emission of the propulsion system of ships can be found in [5-8]. The potential of using hybrid energy storage technology in ships, while incorporating different battery storage technologies is presented in [9]. Some other publications detailing the application of some specific energy storages in maritime transportation applications will also be cited at a later stage in this paper.

Researchers have never forgotten aircrafts when it comes to using energy storages. Applications of energy storages in aircrafts specifically in relation to particular technologies will be discussed later in this paper.

Sustainability aspect in using more and more energy storages is an important aspect to be addressed when it comes to carbon footprint in the manufacturing process of batteries and also in recycling of chemical compounds used in batteries. This sustainability aspect of energy storages is addressed in detail in [10-11]. The incorporation of energy storages has now been identified as an essential requirement not only in transportation, but also in modern power networks. This has become essential due to the fact that more and more renewable energy sources are being integrated into the power grid today. Energy storage have been identified as a very useful component in power system stability, voltage regulation, unbalance compensation, renewable energy integration, realization of SMART grid features and making use of "Gridable Vehicles" (GVs) as power system components etc. [2, 10-18].

In order to understand the capability of various energy storage devices, one very important feature to look at is the available energy from the storage device for constant active power request. Analyzing the energy storage devices in this way leads to determine the most suitable energy storage devices for various applications. The general theory of Ragone plots for energy storage devices is a very helpful tool for the researchers to do this comparison [19]. Optimizing energy storage devices using Ragone plots is discussed in [20], while [21] details how energy management and sizing of a hybrid locomotive application can be done using the Ragone plot approach. Fig. 1 shows a typical Ragone plane [19]. Ragone plots present available energy of an energy storage device for fixed power. Different types of energy storage devices are typically located in different regions. The locations of some of the energy storage devices on the Ragone plane elaborate how the performance comparison can be done.

Emerging energy storage solutions for road, railway, maritime and air transport applications are the emphasis in this paper. This work is an expanded version of a previous conference article published by the authors [22]. While appreciating the existence of other technologies, this paper also gives more emphasis on battery energy storage technologies as the energy storage solution for the applications mentioned above. Stationery energy storages connected at grid level have also gained a lot of interest of the researchers in parallel to the emergence of plug in electric vehicles. This is combined with other major challenges such as solar PV penetration together with voltage regulation. This paper also emphasizes the significance of further investigation into this aspect in future due to its relevance.

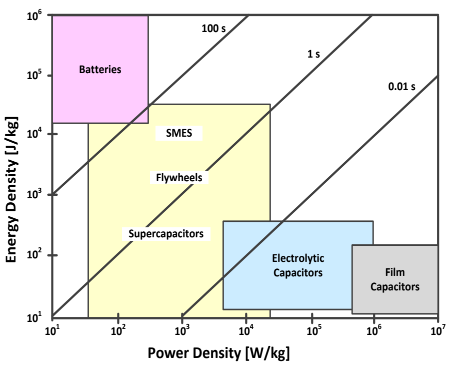

Fig. 1 Ragone plane

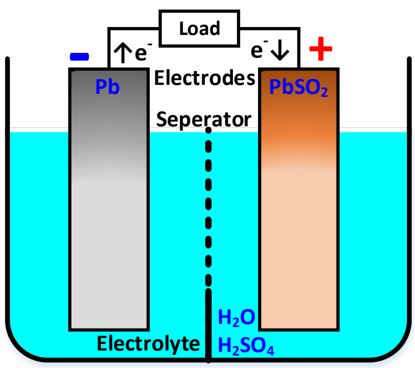

Fig. 2 Lead-Acid battery chemistry

Some of the more recent scientific contributions related to the coverage of this paper are worth mentioning here. Economic performance of electric vehicle to grid and building integration and how it is influenced by driver behavior and building category is addressed in [23]. The optimization of energy sharing between Electric Vehicle (EV) charging stations, commercial buildings and power grid is addressed in [24]. A review of application of energy storages applied to railway can be found in [25]. The significance of energy storages in the future power networks in general has been reviewed in [26]. A detailed review study on energy storage systems applied in various transportation sectors as presented in this paper has not been published in the recent past according to the knowledge of the authors. This work also presents a global classification of different energy storage solutions for different transportation applications, which is a novel contribution. Hence, it is believed that this work will make a significant contribution to the research community working in the area of transportation electrification.

2. Energy Storages in Automotive Applications

The use of energy storage systems in automotive applications is the most widely researched area among the scientific community that is within the scope of this paper.

2.1. Key attributes of battery technologies

Several key attributes exist that can be used to characterize different battery energy storage solutions for automotive applications. Some of the key attributes mentioned also in [1] are; Energy density of battery, Power density of battery, Operating temperature range of battery, Charge retainment capability, Cell voltage of battery, Cyclability of battery, Cost per kilowatt (kW), Cost per kilowatt hour (kWh), Safety of battery and Recyclability of battery.

Technical characteristics of electrical energy storage technologies are broadly and comprehensively compared in [12]. The main focus in that work is their usage in power system operation. Some of the attributes mentioned above of a range of battery technologies are compared in Table 1 [2-3, 23].

2.2. Widely used battery technologies

Work presented in [1-3, 13, 27-29] reveal a lot of valuable information on widely used battery technologies in case of automotive applications. The key battery technologies that have been identified are Li-Ion, LA, NiCd, NiMH and NaNiCl2 and Flow batteries.

Table 1 Comparison of key attributes for battery technologies

Battery Technology	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle Efficiency (%)	Cyclability (Cycles)	Energy capital cost ($/kWh)	Power capital cost ($/kW)
Lead-Acid (LA)	30 - 50	75 - 300	70 - 80	200 - 2000	200 - 400	300 - 600
Lithium-Ion (Li-Ion)	100 - 200	150 - 315	75 - 90	500 - 2000	600 - 2500	1200 - 4000
Nickel Metal Hydride (NiMH)	60 - 80	80 - 300	66	< 3000	360	180
Nickel Cadmium (NiCd)	50 - 75	150 - 300	60 - 83	500 - 2000	800 - 1500	500 - 1500
Vanadium Redox (VRB)	10 - 30	80 - 150	75 - 85	> 16000	150 - 1000	600 - 1500
Zinc-Bromine (ZnBr)	30 - 50	100	66 - 80	> 2000	150 - 1000	700 - 2500

(1) Lead-Acid battery chemistry:

Lead-acid batteries can be nominated as the most widely used rechargeable batteries. It comprises a cathode made of PbO2 and the anode is made of Pb. Sulfuric acid is the electrolyte medium used in these batteries as indicated in Fig. 2. They have fast response times and the daily self-discharge rates are small. These batteries have comparatively high cycle efficiencies. The capital costs incurred by these batteries are low [2, 16, 14-17]. Battery chemistry of Lead-Acid technology is illustrated in Fig. 2.

(2) Lithium-Ion battery chemistry:

Lithium metal oxide ($LiCoO_2$, $LiMO_2$, etc) is used to construct the cathode in a Li-Ion battery. Graphitic carbon is used to construct the anode. The electrolyte is a non-aqueous organic liquid containing dissolved lithium salts (such as $LiClO_4$) [18]. Li-Ion batteries are considered to be performing well in applications that require short response times. Li-Ion batteries are also suitable for applications that require smaller physical dimensions and overall weight (meaning higher power per volume). The cycle efficiencies of Li-Ion batteries are also high [2, 12, 14, 16]. Li-Ion battery chemistry is illustrated in Fig. 3.

(3) NiMH battery chemistry:

Nickel hydroxide is used to construct the positive electrode of a NiMH battery. Negative electrode is an engineered alloy with multi-components. Vanadium, titanium, nickel, and some other metals are the usual ingredients of this alloy. Past 20 years saw a significant development in NiMH battery technology. During this period, NiMH battery technology underwent a threefold increment in energy capacity together with ten times increase in the specific power [1]. According to [1-2, 12, 30], major advantages of NiMH batteries are; Safety in operating at high voltages, Excellent energy and power per a unit volume, Ability to tolerate overcharge and over discharge and Excellent thermal properties. NiMH battery chemistry is demonstrated in Fig. 4.

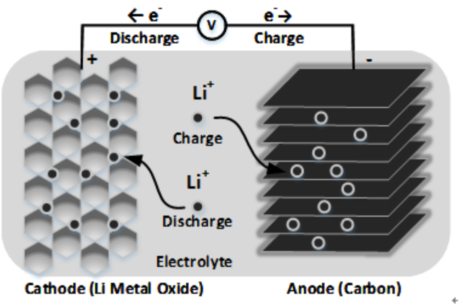

Fig. 3 Li-Ion battery chemistry

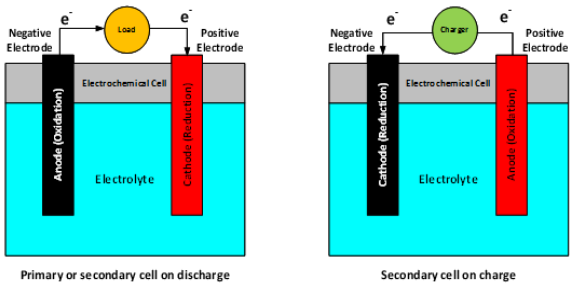

Fig. 4 NiMH battery chemistry

(4) NiCD battery chemistry:

Nickel hydroxide together with metallic cadmium are used to construct the two electrodes of a NiCd battery. An aqueous alkali solution is the electrolyte. NiCd batteries are very robust and known to have relatively higher reliabilities. Low maintenance requirement is another attractive feature of NiCd batteries. However, the usage of NiCd batteries today is limited due to the fact that cadmium and nickel being toxic heavy metals, which can cause possible environmental hazard. This can be highlighted as one weakness of NiCd batteries. The memory effect, which is defined as the significant reduction of maximum capacity, when the battery is subjected to repeated recharges after only being discharged partially is another drawback of this technology [12, 25, 31-32].

(5) NaNiCl2 battery chemistry:

The $NaNiCl_2$ batteries have a liquid Na electrode. They also have a β"-alumina solid electrolyte. The positive electrode is made out of a secondary electrolyte made of molten sodium tetrachloroaluminate ($NaAlCl_4$). Insoluble nickel chloride is the active material. The Na ions from the β"-alumina electrolyte are conducted to the nickel electrode reaction by $NaAlCl_4$ electrolyte [33]. Some of the highlights of Sodium Nickel chloride Technology according to [34] are, high specific density, temperature agnostic, long life and long shelf/storage life, no memory effect, maintenance free and zero ambient emission, 100% recyclability and availability of raw material. They are successfully used in electric as well as plug-in hybrid vehicles [34]. These batteries are also known as ZEBRA (Zeolite Battery Research Africa) batteries [35]. $NaNiCl_2$ battery chemistry is illustrated in Fig. 5.

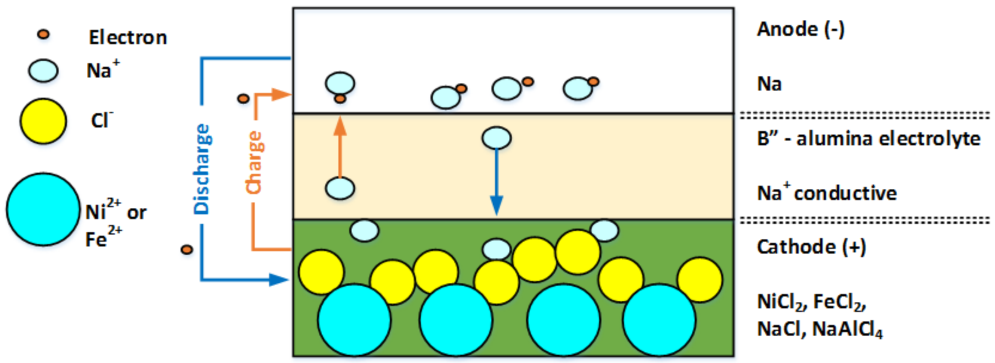

Fig. 5 NaNiCl2 battery chemistry

(6) Flaw batteries:

Vanadium sulphate - Vanadiuomoxide sulphate battery is the most common form of flow battery [36]. In one cell of this battery, the oxidation of V2+ to V3+ takes place, while a reduction of V5+ to V4+ takes place in the other and vice versa. These reactions take place at carbon or graphite electrodes without engaging them in the actual reaction. H+ is also formed, which are transferred from one cell half to the other through a semipermeable membrane. However, other ions such as SO4 are not passed through this membrane. This creates a difference in pH between one cell half and the other. Use of flow batteries in heavy vehicle applications is discussed in detail in [36]. Flow battery chemistry is illustrated in Fig. 6.

Each of the battery technologies described has different properties in relation to various attributes such as response time, storage capacity, power and cost etc. As such, it is difficult to determine which single battery technology is the most suitable one for all automotive applications. Increasing the energy capacity, power etc. is the general focus of the current state-of-the-art research and development in relation to these battery technologies [3]. This is also confirmed by the "spider web" graph, which compares some of the key attributes of the battery technologies discussed in this paper shown in Fig. 7 [37].

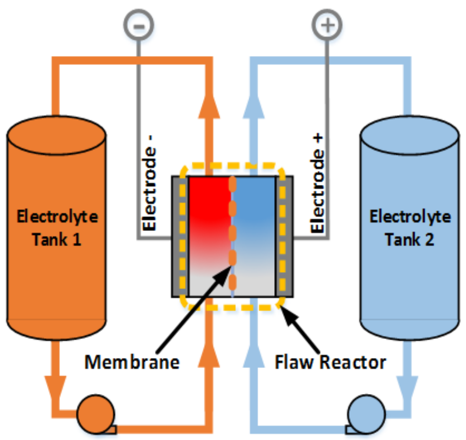

Fig. 6 Flow battery chemistry

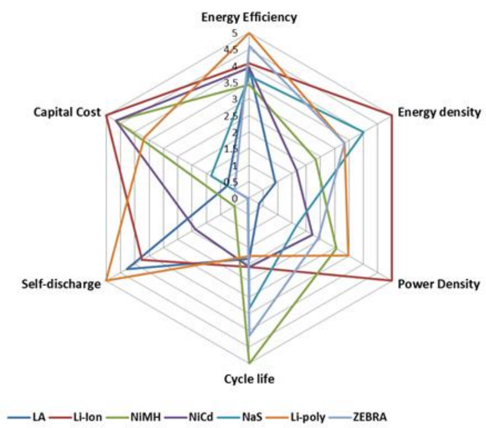

Fig. 7 Comparison of some of the key attributes of widely used battery technologies

In addition to the battery technologies reviewed so far, it is of importance to make a special mention on Lithium Titanate battery technology, which is another emerging energy storage solution. Lithium Titanate battery technology may be widely used in transportation applications in the near future. Extended research in the area of Li-Ion battery technology has resulted in Lithium Titanate battery technology. Lithium Titanate battery technology has higher energy density, more than 2000 cycles at 100% depth-of-discharge. The life expectancy of those batteries are 10–15 years, which will yield a good return for investment. They also have better thermal characteristics as compared to Li-Ion batteries [38-39].

2.3. Alternate energy storage solutions

Other energy storage solutions used in automotive applications are; FCs, UCs, FESS and hybrid energy solutions in addition to energy storages based on batteries.

(1) Ultracapacitor technologies:

Significant amount of energy can be stored in UCs at low voltage levels and hence they are considered as special capacitors [40]. High permittivity dielectric together with a high surface area is used to achieve this. Currently, five different UC technologies are in development [1]; Carbon and metal fibre composites, Aerogel (Foamed) carbon, Particulate Carbon with a binder, Conducting polymer films (Doped) on carbon cloth, Coatings of mixed metal oxide on metal foil.

The development of hardware interface electronics that is capable of allowing the UCs to perform across a variable voltage range is one of the major challenges in incorporating UCs in automotive applications [1]. Researchers are now trying to combine the properties of UCs and batteries into a single hybrid energy storage module, which obviously is better suited in case of automotive applications [41].

(2) Fuel cell technology:

Internal Combustion Engine (ICE) which has been operating as the primary source of power in automotive applications can potentially be fully replaced by FCs in the years to come. To power FCs, Hydrogen, which could be produced remotely is used. This is a new development as a part of the hydrogen economy [42]. A process such as electrolysis of water can be used to produce hydrogen, which is termed as the concept of “Hydrogen Economy” [42]. Hydrogen produced is then used as fuel. The most important attributes for FCs are characteristics of Cell voltage and power density vs current density [43]. A detailed elaboration of the FC technology can be found in [44-45]. Another attribute of FC is the polarization curve [46]. The current vs voltage characteristics for various working temperatures of the cell is another important factor [47-48]. There are six different types of fuel cells available [49], namely; PEMFC - Proton Exchange Membrane Fuel Cell, AFC - Alkaline Fuel Cell, PAFC - Phosphoric Acid Fuel Cell, MCFC - Molten Carbonate Fuel Cell, SOFC - Solid Oxide Fuel Cell, DMFC - Direct Methanol FC.

A range extension technique for electric vehicles using Fuel Cells is presented in [50]. A good comparative study of the performance of different FC technologies is presented in [49]. Large scale commercialization of FC powered vehicles is currently challenged by high costs and durability of the systems. However, plans are underway to open 400 hydrogen stations in Germany by the year 2023 by a consortium of six partners (Air Liquide, Daimler, Linde, OMV, Shell and Total) in “H2 Mobility” program. This initiative really can change the conditions for commercialization.

(3) Flywheel energy storage system:

Use of FESS in the automotive sector is a novel approach. Kinetic energy is the form of energy stored in a flywheel [51]. When required, this stored kinetic energy is transformed into electricity. Essentially, a flywheel is a large rotating disk, which stores kinetic energy. A motor/generator set coupled to the flywheel is used for converting kinetic energy into electrical energy and vice versa as required. The electric motor can be used to raise the rotational speed of the flywheel, which in turn increases the stored energy in the flywheel. On the other hand, the generator is used to supply energy to the load thereby absorbing the stored energy from the flywheel. High power density together with high energy density are the main features of FESS [52-53]. Most important feature in FESS is that they are capable of undergoing an infinite number of charge-discharge cycles unlike any battery technology. Applications that require a large number of charge-discharge cycles in automotive and power quality areas are the ideal applications for using FESS [52-53]. To ensure that the losses due to wind effects are minimum, FESSs must be operated at a partially vacuum environment. Frictional losses in bearings are another form of losses in FESS. Active magnetic bearings, which are noncontact type bearings, are used in some situations as a solution [54]. Initially, FESS which are associated with high costs, are considered for large vehicles that require large expensive battery systems [55].

(4) Flywheel energy storage system:

The Lithium Ion Capacitor is a new arrival to the energy storage market, which has some innovative technology. They are said to fill the application gap between Lithium Ion batteries and super capacitors [56]. It can also be called as a hybrid capacitor. Similar to a Lithium Ion battery, the anode of a Lithium Ion Capacitor is made of carbon materials. However, they are pre-doped with Lithium. The material used in the cathode side is activated carbon, which is similar to an Electrochemical Double Layer Capacitor (EDLC). A high cell operation voltage can be achieved by using this design. These capacitors are used in electric vehicle quick charging stations according to [56-57], which detail their use in hybrid vehicles, hybrid excavators, forklifts, harbor cranes and many others.

(5) Hybrid energy storage system:

Combining two energy storage systems to achieve better characteristics by complementing each other is another emerging approach in automotive sector also. One such example is the urban electric mini-bus application presented in [35]. This work presents a hybrid energy storage made by combining ZEBRA batteries and supercapacitors. The advantage of combining these two energy storages is the ability of the hybrid system to better handle electric power peaks and the regenerative breaking operations [35].

3. Energy Storages in Rail Applications

Some of the critical constrains associated with automotive applications such as lower weight, lower volume etc. are not effective in case of energy storages for rail applications to a certain extent. On the contrary, rail applications demand higher power and energy density with special requirements being the high load cycling capability [58] and large peak power demand for a short time [59] etc. A couple of other critical factors associated with selecting the suitable energy storage method for rail applications [59] are; the ratio between peak traction power demand and mean traction power demand, the duty cycle, optimization of the prime mover, downsizing, handling braking energy capture and release, driving style, optimizing to maximize the usage of energy regenerated etc.

An overview of energy saving techniques for the power feeding network of electric railways can be found in [60]. Introducing energy storages to railway applications has several advantages. Some of the key advantages [61-62] are; Energy consumption reduction, reduction of the peak power of the rail vehicle, catenary free operation (autonomous operation), even if electric power fails train is able to continue to the next station, tractive/braking characteristics are substantially improved in the high-speed region, reduced burden to the power feeding system.

Another point of view on the rail application is to distinguish the difference between electric railway and diesel traction. For electric railway systems, it is possible to use regenerative braking and recuperate energy back to the power grid. This eliminates the need for having on-board batteries. However, in such situations, the use of stationery battery banks could reduce the energy consumption. This is more prominent in DC electric rail systems, which are popular for urban mass transit applications [63-69]. Stationery energy storage for a DC electric rail system using double layer capacitors is presented in [70-71].

Energy saving by the introduction of on-board energy storages together with the added benefit of reduced environment pollution is more significant in case of diesel traction applications. This is demonstrated by the PLATHEE project, which details a hybrid locomotive that uses a diesel engine together with three different energy storages, namely; ultra-capacitor, fuel cell and NiCd battery [72]. The hybrid locomotive concept becomes even more meaningful and also practical when it is applied for shunting locomotives, which operate in a much more frequent acceleration and deceleration cycles. Fuel-Cell hybrid shunt locomotive is presented in [73], while a plug-in hybrid architecture with deep discharge batteries is presented in [74] confirming this claim.

A detailed overview of the energy storage solutions used commonly in hybrid railway systems can be found in [59]. They are [59, 75-76]; Lead-Acid (LA) batteries, Li-Ion batteries, Flywheel Energy Storage Systems (FESS), Ultra-Capacitors (UC).

Electric Double Layer Capacitors (EDLC) also known as UC or Super Capacitors (SC) are the most widely reported energy storage systems for railway applications according to the literature [58, 61, 77-84].

4. Energy Storages in Sea Transport Applications

A broad analysis on reducing exhaust emissions from global shipping using the potential of hybrid energy storage technology is the key contribution in [85]. Another important thing to mention here is the wide range of marine applications in terms of vessel capacity that can have a huge impact on the most applicable energy storage technology to be used. It is well known that the ships are huge floating structures having relatively higher demand on the capacity of the energy storage. Optimum location of the energy storage system within the structure of the ship plays an important role on its stability. A more mathematical approach to address this issue can be found in [86]. Optimal power management, when energy storage is introduced [87], and optimal capacity of the energy storage system [88-89] on board a ship are two other aspects that have been dealt with in literature from the point of view of optimization.

The key energy storage solutions used in ships are; FESS-Flywheel Energy Storage Systems [90-92], Li-Ion based battery energy storages [93], SCMS - Super Conducting Magnet Systems [94] and FC-Fuel Cells [95].

Hybrid energy storage systems on board the ships is another emerging technology. Battery/UC hybrid [96-98] systems seem to be the most widely used methodology among hybrid energy storage solutions.

Use of electric thrusters for storing energy in the form of kinetic and potential energy of the ship presented in [99] is a unique approach of positioning the ship dynamically. There is no physical energy storage system on board the ship in this method. Instead, the dynamic positioning is done such that the ship stores the energy it receives through various disturbances such as winds, waves and other external forces. Photovoltaic (PV) and Diesel hybrid vessels based on battery energy storages reported in [100] is another work worth mentioning here. In this application, there is additional energy generation by means of a PV system on top of the diesel engine.

5. Energy Storages in Air Transport Applications

Light weight, very high reliability and safety are key attributes of energy storage systems used for air transport. The energy storage system used in air transport applications must be free from other disastrous issues such as overheating also. One famous example on this aspect is the range of overheated battery incidents that Boeing 787 Dreamliner underwent since its inception [101].

Sizing and locating the energy storage system in an aircraft also plays a significant role when it comes to overall stability of the body similar to energy storage applications in ships. In addition to safety, stability and economic issues are the other related aspects in case of using an energy storage in an aircraft. Due to this background, more mathematical approaches can be found addressing the issues such as sizing the energy storage system and physically locating the energy storage system within the structure of the aircraft [102-103].

The energy storage systems most widely used in aircraft industry are; Sealed Lead-Acid (LA) [104-105], Li-Ion based battery energy storages [101] and FC-Fuel Cells [106-110].

Use of hybrid energy storage systems on board the aircrafts is another emerging technology. Some examples to mention here are; hybridization of FC/Li-Ion [111] and hybridization of battery/SC [112].

Application of solar power in aircrafts is another widely used technology; mainly in case of light aircraft applications [113-115]. The work in [116] presents a detailed discussion on using PV cells for solar-powered aircrafts.

6. Study of Key Related Aspects of Energy Storage Solutions

The purpose of this section is to present some brief studies of a couple of key related aspects to energy storage solutions.

6.1. Electric vehicles as energy storage solutions

In the modern SMART grid concepts, the use of electric vehicles as energy storage solutions is seriously being considered and studied. Hybrid Electric Vehicles (HEV), Plug-in Hybrid Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV) can be made use of in these systems. Some of the key aspects that have been researched in relation to this strategy of using EVs as energy storages are; smart charging of electric vehicles, effects of EV charging to global load characteristics, fast charging stations for the voltage control of electricity distribution networks and viability of vehicle-to-grid operations from a battery technology and policy perspective. More detailed information on these research initiatives can be found in [117-130].

Technical characteristics of electrical energy storage technologies are broadly and comprehensively compared in [12]. The main focus in that work is their usage in power system operation. Some of the attributes mentioned above of a range of battery technologies are compared in Table 1 [2-3, 23].

6.2. State of Charge and State of Health for as energy storage solutions

State of Charge (SOC) and State of Health (SOH) are two key factors to consider when it comes to energy storage solutions. Both these address the long term usage of a given energy storage. SoC can be explained as the equivalent of a fuel gauge of a conventional car, when it comes to the battery pack in a BEV, HEV, or PHEV. An alternate indicator of the same measure is the depth of discharge (DoD), which can be interpreted as the inverse of SoC. As an example, an SOC of 100% = empty battery; while SOC of 0% = fully charged battery. On the other hand, SoH of a battery energy storage is defined as a figure of merit of the condition of a battery (or a cell, or a battery pack), compared to its ideal conditions. This figure is normally given as a percentage. Various estimation methods based on basic instrumentation around battery systems have been developed and reported by researchers on SOC and SOH. Among these methods, nonlinear observers, enhanced coulomb counting, extended Kalman filter based methods, are more prominent [131-136].

6.3. Improving battery safety and reducing costs

Improving battery safety is another important aspect in order to ensure the transportation safety, when using energy storages in all mediums of transportation. Recent advances in battery health monitoring and prognostics technologies for electric vehicle (EV) safety and mobility has been reviewed in [137], which provides valuable information on this aspect. Improving safety of Li-ion batteries used in transportation applications has been an important research area for quite some time due to the fact that several safety concerns raised over the performance of Li-ion batteries. Improved electrolytes [138], use of bi-functional separators for early detection of internal shorting [139], use of flame-retardant additives [140] are some of the widely reported techniques of improving safety.

Cost reduction is another aspect of using energy storages in transportation. In [141], a comprehensive analysis of using plug-in vehicles and renewable energy sources for cost and emission reductions can be found. The authors of this work present valuable information about intelligent scheduling and control of “Gridable Vehicles” (GVs) as loads and/or sources. They also confirm the great potential for evolving a sustainable integrated electricity and transportation infrastructure through the introduction of GVs.

7. Conclusions

Emerging energy storage technologies used in transportation were reviewed in detail in this paper. The emphasis was given to road, railway, maritime and air transportation applications. Energy storage technologies that have been used in each of those areas of application were reviewed. In relation to automotive applications, Lithium-Ion, Lead-Acid, Nickel Metal

Hydride, Nickel Cadmium and Sodium Sulphur battery technologies were identified as the most widely used technologies. As alternatives, at the fore front are fuel cells, ultra-capacitors and fly wheel energy storage systems.

Electric Double Layer Capacitors also known as Ultra-capacitors or Super Capacitors were found to be dominating the energy storage systems used for rail applications. In shipping applications, flywheels, batteries and hybrid energy storage systems are widely used. In case of aircraft applications, still battery based energy storages are the most promising technology. However, hybrid solutions and fuel cells are also often being considered.

With the extensive review done on reported on-board energy storage solutions in transportation sector, it is possible to present a global classification of different energy storage solutions for different transportation modes, which is illustrated graphically in Fig. 8.

As it was mentioned in the beginning of this review, one thing to emphasize here is the important fact that it is not possible to nominate a single energy storage technology that addresses all the requirements of diverse transportation applications considered in this paper. As such, it is required to analyze each application problem in detail to be able to choose the most suitable energy storage solution, particularly taking into consideration the future predictions of price.

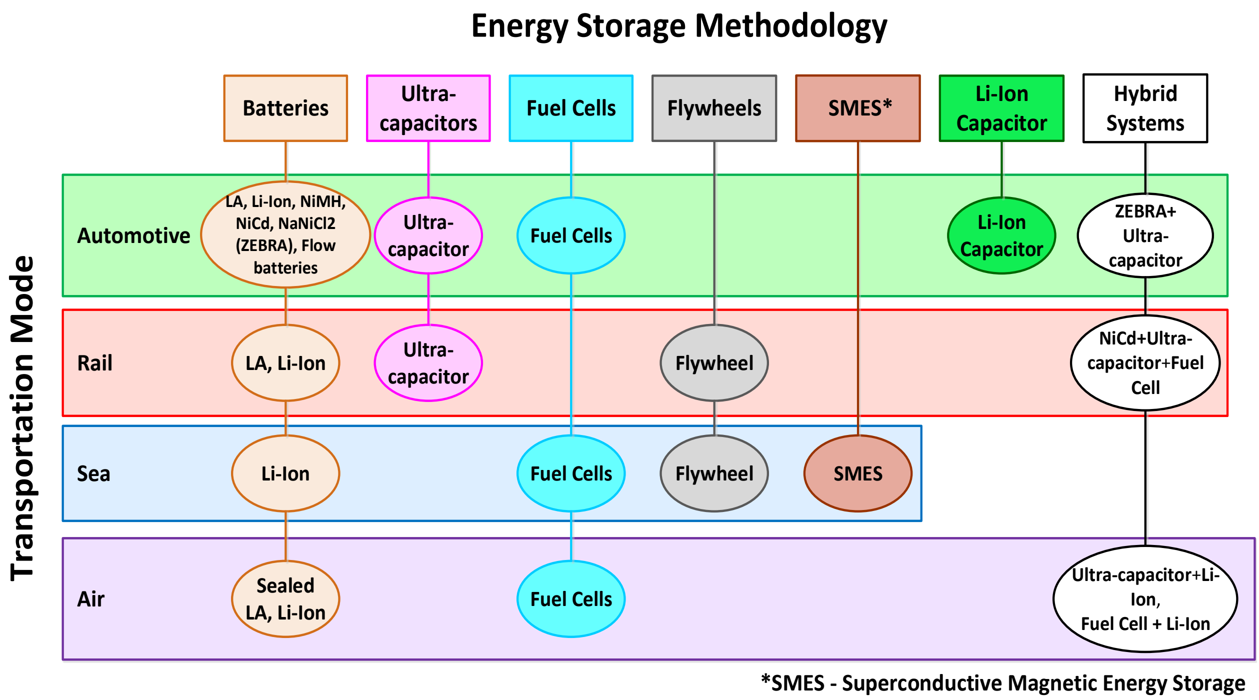

Fig. 8 Global classification of different energy storage solutions for different transportation applications

Conflicts of Interest

The authors declare no conflict of interest.

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