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A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration

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ABSTRACT

Currently, the energy grid is changing to fit the increasing energy demands but also to support the rapid penetration of renewable energy sources. As a result, energy storage devices emerge to add buffer capacity and to reinforce residential and commercial usage, as an attempt to improve the overall utilization of the available green energy. Although various research has been conducted in the field including photovoltaic and wind applications, the study on suitability identification of different storage devices for various stationary application types is still the gap observed which needs further study and verification. The review performed fills these gaps by investigating the current status and applicability of energy storage devices, and the most suitable type of storage technologies for grid support applications are identified. Moreover, various technical, economic and environmental impact evaluation criteria's are taken into consideration for the identification of their characteristics and potentials. The comprehensive review shows that, from the electrochemical storage category, the lithium-ion battery fits both low and medium-size applications with high power and energy density requirements. From the electrical storage categories, capacitors, supercapacitors, and superconductive magnetic energy storage devices are identified as appropriate for high power applications. Besides, thermal energy storage is identified as suitable in seasonal and bulk energy application areas. With proper identification of the application's requirement and based on the techno-economic, and environmental impact investigations of energy storage devices, the use of a hybrid solutions with a combination of various storage devices is found to be a viable solution in the sector.

1. Introduction

Currently, the globe is still fronting a challenge in the sector of energy with the lack of reliable energy sources at moderate charges and environmental reparations triggered by polluting energy sources, such as coal. For mitigation of this problem, countries are adopting various types of renewable energy sources (RESs). Wind and solar RESs are predicted to supply 50% of the world's energy demand by 2050 [1] while the electricity demand only from the electric vehicles (EVs) is going to reach a 6% increase i.e. approximately 2 TWh by 2040 of the total electricity produced [2]. According to the BNEF report of the global power generation mix, from 1970 to 2017, compared to renewable sources, fossil fuels have a large share in the generation mix and energy supply system. However, from 2018 onwards, the energy contribution share of fossil fuels including coal and gas gets decreased and will fall to 31% by 2050. Moreover, the expected renewable energy sources (hydro, wind, solar, and others) will have a dominant share accounting for more than 62%. Among these, solar and wind, in particular, will have a large generation mix share of around 48%. This makes an exponential growth of grid support and storage installations around the globe. Consequently, by 2040 (accounting on a 9GW/17 GWh deployed as of 2018) the market will rise to 1095 GW/2, 850 GWh, making a more than 120-times increase, based on a recent study published by Bloomberg new energy finance (BNEF) [3].

Fig. 1 shows the forecast of global cumulative energy storage installations in various countries which illustrates that the need for energy storage devices (ESDs) is dramatically increasing with the increase of renewable energy sources. ESDs can be used for stationary applications in every level of the network such as generation, transmission and, distribution as well as local industrial and commercial customers. Nowadays, in addition to the utilization of existing ESDs in stationary

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List of abbreviations

ESDs	Energy storage devices
EES	Electric energy storage
PV	Photovoltaic
WT	Wind turbine
RESs	Renewable energy sources
TES	Thermal energy storage
EVs	Electric vehicles
BNEF	Bloomberg new energy finance
FBES	Flow battery energy storage
VRFB	Vanadium Redox flow batteries
PSB	Polysulphide Bromine flow batteries
Zn Br	Zinc Bromine flow batteries
SCES	Supercapacitor energy storage
SMES	Superconductive magnetic energy storage
STES	Sensible thermal energy storage
PCM	Latent-phase change material
TCS	Thermochemical storage
PHS	Pumped hydro storage
CAES	Compressed air energy storage
FES	Flywheel energy storage
R&D	Research and development
PHEV	Plugin hybrid electric vehicle
HEV	Hybrid electric vehicle
ETES	Electric Thermal Energy Storage
BTM	Before the meter
FTM	Front the meter
O&M	Operation and maintenance
SGRE	Siemens Gamesa Renewable Energy
CO_2	Carbon dioxide
V2G	Vehicle to grid
G2V	Grid to vehicle
TRL	Technology maturity
MRL	Manufacturing maturity
Li-ion	Lithium-ion
Pb-Acid	Lead-acid
Ni–Cd	Nickel-cadmium
Ni-MH	Nickel-metal hydride
Na–S	Sodium-sulphur
$NaNiCl_2$	Sodium nickel chloride
Li–S	Lithium-Sulphur batteries
M-ion	Metal-ion Batteries
LTO	Lithium-titanate-oxide
ORB	Organic radical batteries
MW	Megawatt
MWh	Megawatt hour
kW	Kilowatt
kWh	Kilowatt hour
Wh/kg	Watthour per kilogram
W/kg	Wattper kilogram
kWh/m_3	Kilowatt hour per cubic meter
kW/m_3	Kilowatt per cubic meter
ms	Milli-second
hr	Hour
Si	Silicon
Sn	Tin

applications, there is an increased motivation in the use of future advanced ESDs (Future Li-ion, solid-state batteries, Lithium-Polymer, Lithium-Sulphur batteries, and Lithium-Metal-Polymer, Metal-ion Batteries, Organic radical batteries, Hybrid Supercapacitors and others [4,5]. According to the study [6,7] it is stated that for bulky power management, thermal storage (TES) is proposed as a possible candidate at the moment. Bulky storage is considered here for higher ranges than several MW. From the electric and electrochemical ESDs, it is provided that only flow batteries, Sodium-Sulphur, and Lead Acid found to be potentially considered to meet these requirements. Besides, for distribution and transmission levels, where the green energy can be integrated as a source, there are various ESDs that can meet the multi-disciplinary needs [6,7]. It is important to analyze the current and future status of the electrical, electrochemical, and thermal ESDs to evaluate why and how various technologies are suitable for the different functions and power applications. The role of ESDs and importance together with their requirements that should be fulfilled are mentioned in Table 1, for the various power levels, but also the interaction among them.

The review conducted is different from previous [4,7,9] reports due to the following reasons. The characteristics study of ESDs is performed with thorough investigation accompanied by updated and reliable data.

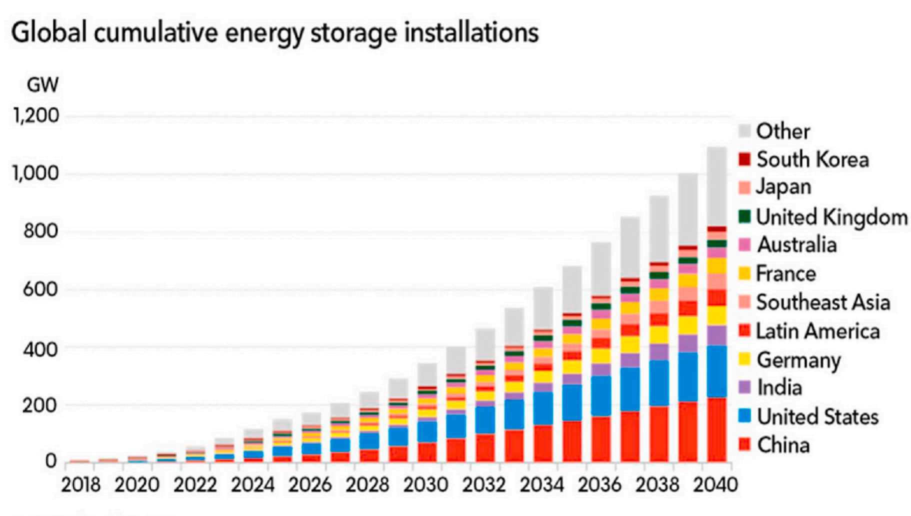


Fig. 1. Prediction of global energy storage installation by 2040 [3].

Table 1
The energy storage role in energy supply scheme [8,9].

Energy storage role				
Function		**Centralized storage and transmission system**	**The distribution system and regional storage**	**Consumer (building and residential level)**
	Balance between supply and demand	Seasonal/ weekly/daily/ hourly variations Large geographical imbalances Variable electricity generation resulted from intermittent nature of wind (WT) and solar (PV)	Daily/hourly variations Peak saving	Daily variations
	Distribution – moving energy	Voltage and frequency control Additional peak production to the classic power plants Power market International market	Voltage and frequency control Power market	Aggregation of small amounts of stored energy to meet distribution needs (capacity problems and loss reduction)
	Energy efficiency improvement	Improved productivity in the globe energy mix with time-shift	Storage and load control for improved performance in distribution system	Augmented value of energy production and utilization, and alteration in behaviors,

Graphic analysis and comparison are performed with efficient and standard performance evaluation parameters considering all economic, technical, and environmental matrices. Regarding the economic aspect, besides the capital cost, the operating and maintenance cost analysis has been performed which is not usually observed in previous reviews. Moreover, advanced features of ESDs are also assessed in the review. The contributions made include the following: Different ESDs requirements for different application types are indicated and more emphasis are given to RESs grid integration application area. The graphical analysis of the most fitting ESDs is performed for respective services. With proper identification of the application's requirement and based on the economic, technical, and environmental impact investigations of storage devices, it is found that the use of the hybrid solution of ESDs is proposed as a feasible solution for RESs and other stationary application areas.

The remaining sections are ordered as follows: Section 2 describes the state-of-the-art review of energy storage devices. Section 3 discussed the graphical analysis of ESDs and their selection for typical applications. Section 4 presented the discussion part including future advances of ESDs, and finally, the conclusion is presented in Section 5.

1.1. Methodology used for selection and categorization of ESDs

With consideration of the types of energy gathered, ESDs can be grouped into five major groups, i.e., electrochemical, electrical, thermal, chemical, and mechanical energy storage systems. From the diverse type of ESDs, electrochemical energy storage including, lithium-ion (Li-ion), lead-acid (Pb-Acid), nickel-metal hydride (Ni-MH), sodium-sulphur (Na–S), nickel-cadmium (Ni–Cd), sodium nickel chloride ($NaNiCl_2$), and flow battery energy storage (FBES) of Polysulphide Bromine flow batteries (PSB), Vanadium Redox flow batteries (VRFB), Zinc Bromine flow batteries (Zn Br) are found. Capacitor, superconducting magnetic energy storage (SMES), supercapacitor energy storage (SCES) are categorized as electric ESDs. On the other hand, sensible thermal storage (STES), latent phase-change material (PCM), thermochemical storage (TCS) are categorized under thermal storage devices. Flywheel energy storage (FES), compressed air energy storage (CAES) and Pumped hydro storage (PHS), are among the common mechanical storage devices. All these storage devices are designated based on the convenience of technical features of the specific power and specific energy, power, and energy density, lifespan, efficiency, cost, technological maturity, discharge time, response time, power rating, and environmental influences, and capital cost in terms of power, energy costs and maintenance & operating costs. Considering the RESs application requirements related to ESDs characteristics, mainly the electrochemical, electrical, and thermal storage technologies are focused on this review.

A review is performed to understand the pros and cons of different ESDs and their respective potentials in grid-scale services. Therefore, the application potentials and characteristics (mainly in terms of economic, technical, and environmental impact) of ESDs have been evaluated by using updated and reliable data with graphic-based comparison of ESDs in terms of their merits and viable selection criteria. Mainly, the following procedures are followed for the selection of the most appropriate type of ESDs in grid-scale RESs applications.

- Collection of the most recent and reliable characteristics data of ESDs from journals, websites, datasheets, etc.
- Selection of reliable performance indices including specific power and specific energy, power and energy density, lifespan, efficiency, cost, technological maturity, discharge time, response time, power rating, and environmental influences, and capital power and energy costs and operating & maintenance costs.
- Use of graphical-based analysis and comparison for evaluation of application potentials of ESDs in grid-scale applications.
- Interpretation of the result analysis
- Identification of ESDs category (application area requirement) using graphical comparison results.

In general, a comprehensive review has been conducted with a thorough investigation of previous studies of storage technologies and collection of reliable and recent data. A state-of-the-art review is done for the understanding of the status and features of each ESDs. Followed by a graphical analysis of reliable data using the standard performance evaluation indices. Based on the graphical analysis, result interpretation is performed, and key findings are summarized. Finally, the most fitting ESDs for RESs integration are identified and a hybrid combination of ESDs is proposed as a viable solution.

For proper selection of the most fitting ESDs, the type of functionalities of each ESDs corresponding to standard requirements, which type of services can be provided, and which type of characteristics the ESDs should possess for every application and functionality should be clearly defined.

The graphical analysis and characteristics of the selected ESDs presented in **section 3.1** facilitate the choice of the most fitting ESDs type for a representative applications sector.

2. State of the art review on energy storage devices

The authors performed an investigation on the requirements that several storage applications for grid support have, as well as the ESDs that can be used to meet them. To begin with, energy storage can have several functions in order to support the grid in all power levels. In the transmission system, supply and demand can be balanced by using a centralized storage system with seasonal to hourly variations and especially can support the intermittent energy production from the green sources. Also, centralized storage in transmission can help with voltage and frequency regulation, and generally for efficiency improvements with time-shift. In lower power levels, in distribution and consumption ranges, ESDs can support with respectively lower energy densities, for daily and hourly variations or peak shaving and improve the system's efficiency. A brief overview of different ESDs and their characteristics are also presented. A complete classification of various ESDs types investigated is presented in Fig. 2.

In the review paper, various types of energy storage devices have been investigated. However, more emphasis is given to the study of the characteristics of electrochemical, electrical, and thermal energy storage systems.

2.1. *Electrochemical technologies*

From the most utilized electrochemical sources (Table 2), Li-ion batteries gain interest in storage installations, accounted for more than 85% of new energy storage distributions in 2016. Regardless of being one of the most preferred storage medium, it is well recognized that a transition to the decarbonized network is requesting more than a single energy storage technology [5,10,11]. Li-ion batteries are accounted for the furthermost of electrochemical storage projects. This is due to the rapid and continuous integration of the Li-ion batteries to various market's power levels, from personal apparatus to electromobility and industrial storage, which also lead to a decrease in the price of the Li-ion battery pack over 85% in the past decade [12]. With the current R&D and the direction of recent investments, novel technologies are about to emerge and support in a more reliable and powerful extend the daily demands, hence the battery pack prices are expected to further decrease and their usage on stationary applications, proportionally, to further increase. However, several challenges still need to be tackled considering the battery integration to energy storage such as the prolonged duration and clean storage, for which a wide range of alternative technologies could offer a cost-effective and reliable solution. Inconsequence, Li-ion based storage devices are limited or overdesigned for certain power and energy density applications. Moreover, the efficient performance of electric and electrochemical energy storage devices are evaluated for a certain type of applications [13]. The main technical features of the electrochemical energy storage devices are described as follows.

2.1.1. *Lithium-ion (Li-ion) batteries*

Li-ion batteries are commonly characterized by possessing high energy and power density which makes it potentially suitable in both transportation and stationary applications [14–18]. These features are dominantly expressed in terms of different performance parameters. The key technical features of Li-ion battery includes the specific energy of 75–250 (Wh/kg), specific power of 150–315 (W/kg), round trip efficiency of 85–95 (%), service life 5–15 (years), and self-discharge rate of 0.1–0.3 (%) [19]. The Li-ion battery possesses high specific energy and power which results in light weight property. This makes the battery suitable in light weight applications [18,19].

2.1.2. *Lead-acid (Pb-Acid) batteries*

Pb-Acid batteries are characterized by moderate round trip efficiency and low cost [14,16,18]. Among the key technical characteristics of Pb-Acid batteries, the following are commonly used measuring indices. The specific energy of 30–50 (Wh/kg), and specific power of 75–300 (W/kg), round trip efficiency of 70–80 (%), service life 5–15 (years), and self-discharge rate of 0.1–0.3 (%) [17–19]. The Pb-Acid is found to be comparable with Li-ion battery in relation to service life and self-discharge rate [18,19] in addition to its low cost. This makes the Pb-Acid battery suitable for stationary applications [14].

2.1.3. *Sodium sulphur (NaS) batteries*

Among the electrochemical storage devices, NaS batteries are found to be more interesting and emerging [13,18]. There are various technical parameters used to evaluate the performance of NaS batteries. These are specific energy of 150–240 (Wh/kg), specific power of 150–230 (W/kg), round trip efficiency of 80–90 (%), service life of 15 (years), and self-discharge rate of ~0 (%) [18,19]. Among the specified parameters, NaS has large specific energy which makes it different from other storage devices. This makes the battery suitable in high specific energy demanding applications [18].

2.1.4. *Sodium nickel chloride ($NaNiCl_2$) batteries*

Electrochemical ESDs like $NaNiCl_2$ batteries can be used in stationary storage applications [15,16]. Similar to previous battery storage technologies, the technical characteristics of NaS batteries are evaluated by different researchers and quantified as follows. The specific energy of 100–120 (Wh/kg), specific power of 150–200 (W/kg), round trip efficiency of 80–90 (%), service life of 10–15 (years), and self-discharge rate of moderate are found [16–18].

2.1.5. *Nickel metal hybrid (Ni-MH) batteries*

Ni-MH storage technologies was among the popular batteries used in the transportation sector of both plugin hybrid electric vehicle (PHEV)

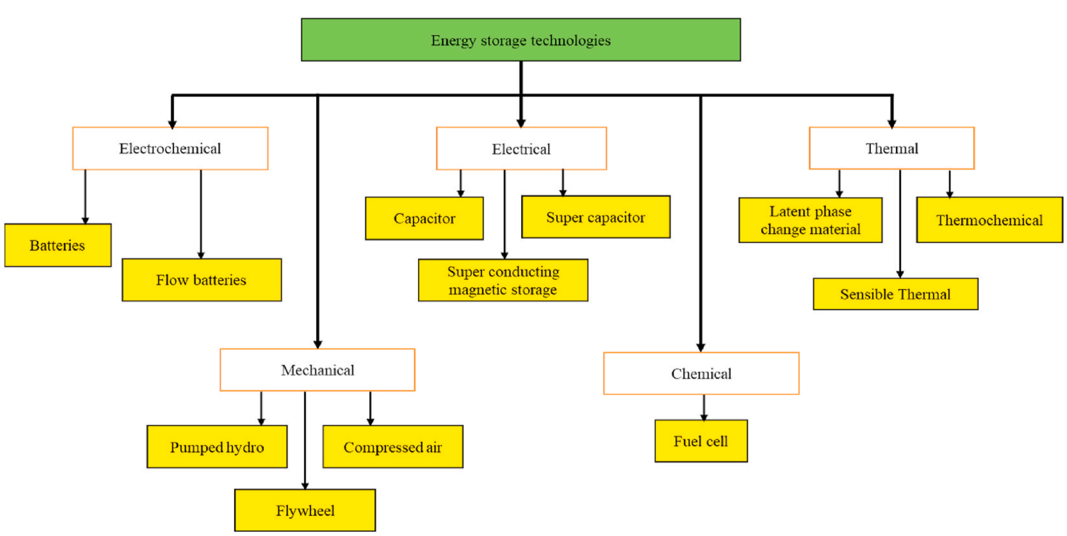


Fig. 2. Classification of storage devices.

Table 2
Present and future status of ESDs, based on [4,5,19,31–34].

Technologies	Sub-technologies	Use	Energy installed capacity	Power installed capacity
Electrochemical	Sodium-Sulphur batteries (RT-NaS* & NaS)	FTM	<100 MWh	<10 MW
	Lead acid batteries (Pb-Acid)	FTM/ BTM	up to 10 MWh	Some MW
	Sodium Nickel Chloride batteries (ZEBRA)	FTM	4 kWh- 10 MWh	Several MW
	Lithium-ion batteries (Li-ion) – Future Li-ions*	FTM/ BTM	up to 100 MWh	Several MW
	Lithium-Sulphur batteries (Li–S)*	FTM/ BTM	–	–
	Lithium-Polymer and Lithium-Metal-Polymer*	FTM/ BTM	–	–
	Metal-Air batteries (M-Air)*	FTM	–	–
	Nickel–Cadmium (Ni–Cd) batteries	–	some MWh	some MW
	Nickel Metal hybrid (Ni-MH) batteries	–	some MWh	some MW
	Sodium-ion (Na-ion) batteries*	FTM/ BTM	–	–
	Redox flow batteries Zn Fe (PSB)	FTM	<100 MWh	<10 MW
	Redox flow batteries Vanadium (VRFB)	FTM	<100 MWh	<10 MW
	Redox flow bromine batteries (Zn Br)	FTM	<100 MWh	<10 MW
	Solid-state Batteries*	FTM/ BTM	–	–
	Silicon (Si) and tin (Sn) anode batteries*	FTM/ BTM	–	–
	Metal-ion Batteries (M-ion)*	FTM/ BTM	–	–
	Organic radical batteries (ORB)*	FTM/ BTM	–	–
Electrical	Superconducting Magnetic Energy Storage (SMES)	FTM	1-10 kWh	100kW-5MW
	Capacitors and Supercapacitor Hybrid Supercapacitors*	FTM	1-5 kWh	100kW-5MW
Thermal	Molten salts	FTM	3 GWh	300 MW
	Sensible Thermal Energy Storage (STES)	FTM	10-50 kWh/t	0,001–10 MW
	Latent- Phase Change Material (PCM)*	FTM	50-150 kWh/t	0,001-1 MW
	Thermochemical Storage (TCS)*	FTM	12-250 kWh/t	0,01-1 MW
	Electric Thermal Energy Storage (ETES)	FTM	130 MWh	50 MW

and hybrid electric vehicle (HEV) [13,17,19]. However, nowadays Li-ion battery gets dominant in the transportation sector with the provision of high power and energy density characteristics as mentioned in section 2.1.1. The technical performance of Ni-MH was investigated by various researchers and their characteristics are summarized as: specific energy of 70–100 (Wh/kg), specific power of 200–300 (W/kg), round trip efficiency of 70 (%), the service life of 5–10 (years), and high self-discharge rate studied by authors [15–17].

2.1.6. Nickel–cadmium (Ni–Cd) batteries

In addition to the aforementioned storage technologies, Ni–Cd batteries have their contributions in stationary energy storage applications. Ni–Cd batteries relatively have a higher specific power, but it is known with a higher self-discharge rate [14,15]. The 50–75 (Wh/kg) of specific energy, and 150–300 (W/kg) of specific power, round trip efficiency of 70 (%), the service life of 10–20 (years), and self-discharge rate of 0.03–0.6 [14–16].

2.1.7. Flow batteries

Next to conventional batteries, flow batteries are another type of electrochemical energy storage devices playing a role in stationary energy storage applications [18,19]. Polysulphide bromine (PSB), Vanadium redox (VRFB), and Zinc bromine (Zn Br) redox flow batteries are among the types of flow batteries [17–19] utilized as stationary energy storage devices. The technical characteristics of these flow batteries are provided in terms of ranges as follows. The specific energy of flow batteries ranges from 10 to 35 (Wh/kg), specific power of 100–166 (W/kg), round trip efficiency of 65–85 (%), service life of 15 (years), and self-discharge rate of ∼0 [17,19]. With these technical features, flow batteries are considered as an advantage in stationary storage applications with low self-discharge as well as high service life and fast response characteristics.

2.2. Thermal energy storage (TES) technologies

TES store the heat energy into insulated repositories and is a technology in the early commercialization phase. It includes several different technologies, as thermal energy can be stored in a wide temperature range from −40 °C to 400 °C, and it is categorized as low-temperature and high-temperature TES. More precisely, the former includes aquiferous and cryogenic energy storage whereas the latter sensible, latent and concrete thermal storage [19]. Cryogenic is under consideration due to its high power and discharge time rates. In the case of sensible heat, the specific heat of the storage medium is of main concern and defines the storage capacity of the TES [20]. A limited storage capacity is obtained if the storage medium is water, and a higher capacity can be obtained if latent-phase change material (PCMs) are used, associated with the latent heat of the PCM [21,22]. Thermochemical technology accumulates and discharges heat and cold on demand utilizing various chemical reactants. Sensible heat is currently commercially available, whereas PCMs and chemicals are mostly under development. According to different scholars' reports, the key performance features of TES technologies are summarized as follows. The power capacity ranges from few to 300 MW, energy range of 20–140 MWh, discharge time of hours to more than a days, unlimited cycle life, some seconds of response time, efficiency of 30–60%, energy density of 80–250 Wh/kg, specific energy of 80–250 Wh/kg, specific power of 10–30 W/kg, service life of 10–30 years, and 0.05–1(%) of self-discharge [5,19,23–25].

One of the most dominant TES technology achieves energy storage by heating the molten salt by concentrating and reflecting the solar energy. Molten salt energy storage (MSES) can be used for both storage medium and heat transfer by incorporating smaller storage tanks and higher temperatures (up to 570 °C) [5]. MSES is exceptional for heat transfer, it is a commercial technology in comparison to the early stage of other TES, and it has a low cost. However, it deals with corrosive molten salts which have to be preserved at specific temperatures (not allowed to freeze) and usually are integrated into concentrating solar power plants. In general, TES main advantage is the low self-discharge rate and that appears as a highly economically valuable system however with a decreased cycle efficiency [19,24]. TES are used in an extensive range of applications including in electricity generation and load shifting for heat engines cycles or support the peak energy demands. TES also can significantly improve environmental issues as it can replace heat and cold production from fossil fuels [25]. Also, based on the current global power capacity of TES, the main use case is installed for energy time shift and renewable capacity firming which signifies the importance of this technology to the integration of greener sources [26].

2.3. Electrical storage

Another option for energy storage is by using electrical storage devices of SMES, supercapacitors, capacitors, and hybrid supercapacitors.

2.3.1. Superconducting magnetic energy storage (SMES)

With this technology, the general working principle is that at the charging phase the electrical energy is stored in the magnetic form using a coil and a refrigeration mechanism that maintains the coil to a certain temperature to minimize the application's losses. At the discharging phase, the SMES releases the stored energy with a power converters topology [27]. The technology is quite mature and offers a robust solution with high power density. It is optimal for short-term storage and is expected to gain a crucial role in the enhanced utility of variable renewable energy. The pros of SMES are having high efficiency, power density, and low degradation. In contrary the cons of these ESDs types are high cost [28], high self-discharge rate, the environmental impact resulted from magnetics effect and high sensitivity to temperature. The SMES device power capacity ranges from 0.1 to 10 kW, and the energy ranges up to 100 MWh. Furthermore, the SMES power density ranges to 4000 W/L, specific power of 500–2000 (W/kg), and its service life goes beyond 20 years [19].

2.3.2. Capacitors and supercapacitors

2.3.2.1. Capacitors. Capacitors are made of two (at least) electrical conductors from metal foils which are separated with a thin insulator usually made of plastic or ceramic or glass. During the charging process, in the dielectric material energy is stored via the medium of an electrostatic field [29]. Usually, capacitors are used to store a few quantities of energy and for high specific power applications or voltage power correction and smoothing, while their charging time is lower compared to the electrochemical cells. There is a wide range of capacitors with various capacitances and nominal voltages. In recent years, capacitors are mainly useful for frequency converters, tractions systems and drives, while technological improvements might include more efficient heat dissipation and increment of power levels. The pros of capacitors are fast charging time and high power. However, because of self-discharge losses, the provision of low energy, low capacity and high energy dissipations resulted are considered as cons of this type of ESDs [30]. Capacitors, in general, have a power range of 200 kW to some MW, energy of 0.007 kWh to some kWh, the discharge time of some seconds, life duration of 40 years, the efficiency of 60–70%, energy density of 0.07 Wh/kg, specific energy of 0.05–5 Wh/kg, and specific power of 3000–10^7 W/kg [19,31–33].

2.3.2.2. Supercapacitors. Supercapacitors are referred to as electrical or electrochemical double layer capacitors (EDLC) and ultracapacitors, are energy storage systems comprised of two carbon electrodes, a porous membrane acting as a separator, and an electrolyte. Supercapacitors can be shaped into either cylindrical or prismatic enclosures, which change the properties of the cell including energy, power, volume, weight, respectively [19]. Also can have both aqueous and non-aqueous electrolytes, and can be combined into various topologies to meet the application's demands. Due to their structure, supercapacitors comprises the characteristic of electrochemical cells and capacitors [10,19]. Supercapacitors have a power range of some MW, energy of few kWh, the discharge time of some minutes, cycle life of 10^6 cycles, life duration of 10 years at room temperature, efficiency of 95–98%, energy density of 4–7 Wh/kg, specific energy of 2.5–15 Wh/kg, specific power of 500–10^4 W/kg, and self-discharge of 20–40% [31–33].

Because of the high self-discharge rate and the cost, the supercapacitors are not used typically for large-scale applications, but for short-term storage and support instead. Also, supercapacitors have been used for start/stop support of automotive applications due to its superior cycling lifetime capabilities. Similarly, to the capacitors, EDLCs are used in UPS to back-up short-term failures and peak demands, or short-term safety of electronic devices and voltage smoothing of renewable energy sources. The features of longer lifecycle, robust nature and high efficiency are pros, whereas, up to 40% self-discharge rate [33] and high cost [34] are cons of supercapacitor storage devices. Increasing demands for large supercapacitors nowadays are continuing to drop the overall cost of the technology. Also, development on the electrodes with new highly porous materials are enhancing the capacitance of the cells. Lastly, new electrolytes that enable higher voltage operation are expected to improve the technical features with the increase of the specific energy as well. With the review paper, the available storage technologies are separated in the literature according to the type of the stored energy and their working principles, and the summary of the present and future advances of ESDs already installed in the grid are shown in Table 2.

Future advances are identified with (*)

In Table 2, front the meter (FTM) refers to applications connected to generation or transmission of the power, whereas, behind the meter before the meter (BTM) refers to residential, commercial, and industrial (distribution) infrastructures. Many ESDs are currently available and installed for grid support while constant research is taking place to improve them but also discover new possibilities. The technologies that are currently under development for each category are highlighted with (*). Previous studies demonstrated that, for a given energy and power amount, the volume of storage technology is reverse proportional to the energy, and power capabilities. More precisely, the electrical storage devices (SMES, capacitors and supercapacitors) can feed with a certain easiness the power demands without consuming a lot of space. Secondary electrochemical devices (Li-ion, NaS, etc) are described as a good compromise between energy and power, whereas flow electrochemical batteries (VRFB,PSB, and Zn Br) demand more space to meet the demands [19,35–37]. The cycle efficiencies of most of the technologies have more than 60% capabilities, especially electrical and electrochemical devices are up to 95%, and TES stays between 30 and 60% [38]. In addition, the energy cost is predicted by Ref. [39], and compares several battery technologies (Na–S, Li-ion, Pb-Acid, Redox) based on various economical aspects. Similar cost analysis can also be found in Refs. [37,40]. The cost analysis is recent, and costs are expected to drop further due to the high demand for electric energy storage (EES) and the continuous efforts of R&D that can drastically improve their proficiencies. Also, in these studies, the cost calculations of operation and maintenance (O&M), and technical characteristics such as system efficiencies (RTE), cycle life at a certain depth of discharge, response time, lifetime expectancy, and system maturity as manufacturing maturity (MRL) and technology maturity (TRL) levels [39,40] are assessed. The main outcomes show that for an Energy/Power ratio of 4 h the Li-ion serves the best option, both in the current status and in the future. Li-ion might be limited in cycle life, in comparison to Redox batteries or Na–S, however future advances indicate that this challenge will be also surpassed.

The reviews summarized in section 2 have incorporated immense information's on technical and economic and other aspects of ESDs and are considered in the review, and the respective gaps found are intended to be filled in the critical review by using updated data and reliable methods mentioned in **section 1.1**. Moreover, future advances and emerging ESDs technologies and are indicated in the review.

3. Comparison result of the energy storage devices

The key performance characteristics of the electrochemical, electric, thermal, and partially mechanical energy storage are included in section 3, in figures and matrices, and highlight the fact that a single only technology cannot fit the power system application requirements at present. Usually, these requirements define the comparison merits, which are performed for the various cases in previous sections. To begin with, the size of the ESDs in terms of volumetric energy and power is also drawn in the graphical comparative analysis.

3.1. Graphical result analysis and selection of ESDs

ESDs are related and investigated mainly from techno-economic and environmental viewpoints. To properly assess the potential applications of these ESDs in grid-scale applications, all required technical, economic, and environmental criteria are used together with recent and reliable data and hence graphical analysis and comparisons are presented. The following Tables and graphs are presented based on the average value of the collected data from the recent peer-reviewed journals, websites, and datasheets. Accordingly, the comparison between different ESDs and their respective metrices is presented. Each graph is formulated based on the average value of data found from the corresponding Tables. To evaluate the performance of the technical aspect of selected ESDs, the most efficient technical characteristics including specific energy, specific power, energy and power density, round trip efficiency, response time, discharge duration, lifetime, technology maturity level, and daily self-discharge are selected based on the data shown from Tables 3–6. In addition, Figs. 3–5 below shows the technical characteristics of different ESDs and are based on the average value of parameters in Table 3.

From Fig. 3. It is shown that, SCES provides the highest specific power compared to other ESDs. Besides, NaS, Li-ion, PCM and TCS have a higher specific energy. Besides, PSB and thermal storage devices have the least specific power and also SCES and SMES have the least specific energy.

It is seen that SCES, SMES, $NaNiCl_2$ and Li-ion batteries have above 85% of very high round trip efficiency. On the other hand, STES and Ni-MH have a lower cycle efficiency range. In addition, of their service lifetime analysis, compared to selected ESDs, TCS has the largest average service life of about 35 years, while electrochemical ESDs (batteries) have a lower service life of 7.67–14 years.

Fig. 5 shows the self-discharge per day of ESDs, where, NaNiCl2, Ni-MH, and SCES show the highest discharge rate. Whereas PSB, VRFB, and in relation to other ESDs types, the Li-ion technology have a small daily self-discharge ratio. Amongst the electrochemical ESDs, NaNiCl2 and NaS have acquired a high self-discharge rate per day.

From Fig. 6, it is shown that using the power and energy density comparison of different storage technologies it is possible to identify the size of ESDs. The volume of ESDs is found to be decreasing with the increasing energy and power densities and hence smaller size can be attained (The top right corner). On the other hand, a larger volume of ESDs is shown at the lowermost left corner. Fig. 6 shows that all thermal ESDs and electrochemical ESDs including (Ni-MH, Na–S, Li-ion & $NaNiCl_2$) have higher energy density compared to others. On the contrary, the power density of SCES, SMES, and FES is higher than other ESDs types. In addition, CAES and PHS have the least energy density and also, CAES, PHS, VRFB, PSB, and Zn Br provide the least power density. Therefore, it is apparent that, relative to other storage devices, Li-ion battery possess both features of higher energy and power density and hence possess reduced volume and smaller size. Therefore, this potential leads Li-ion batteries to be utilized widely in different transportable devices, transportation, and stationary grid-scale application sectors.

As shown from the bubble chart of Fig. 7. the discharge time and power ratings of various ESDs are compared and found that Mechanical energy storage devices (CAES and PHS) have longer discharge time and higher power range than others. On the other hand, SCES, FES, and SMES have very short discharge time and low power range.

Fig. 8 shows a comparison between the technology maturity level and environmental impact of different ESDs. To measure the maturity level of ESDs, a range of scales (1–9) is used as the initial data is collected on qualitative criteria. Accordingly, Pb-Acid, Ni-MH, PHS, and Ni–Cd batteries are fully commercialized and most matured ESDs. On the other hand, TCS, PSB, and Zn Br are under the category of developing/proven

Table 3
The core technical features of different energy storage devices (ESDs).

Type of ESDs	Specific Energy (Wh/kg)	Specific Power (W/kg)	Round trip Efficiency (%)	Service Life (Years)	Daily Self Discharge Rate (%)
NaS	150-240 [38,41], 100-175 [42]	150-230 [38, 41,43]	75-90 [38, 43], 77 [44], 75–87 [42], 70 [45], 70–90 [41], 89 [46], 80 [47]	10-15 [38, 48], 10-20 [42], 5-15 [41], 15 [46, 47]	20 [38], None [42], 0.05–20 [41]
$NaNiCl_2$	120 [43], 100-120 [38,41], 119 [49]	150 [38,43], 150-200 [38, 41], 169 [49]	85-90 [41], 92.5 [50]	10-14 [38, 41], >8 [51]	15 [38,41], 11.887 [49]
Pb-Acid	30-50 [41–43, 52], 25-32 [53,54], 20-35 [45,55], 15-40 [56], 20 [57]	75-300 [38, 41], 180-200 [42], 25 [45], 74-415 [56]	65-80 [43], 70-90 [38], 85 [47], 72–76 [53], 70-80 [42, 45], 70-82 [41]	5-15 [38,42]	0.1–0.3 [38, 42,43], Low [45], 0–0.6 general battery [58], 0.033–0.3 [41]
Li-ion	200 [43], 75–200 [38,41], 90-170 [53], 80–200 [42], 100–200 [45], 207 [59], 90–200 [56]	150-315 [38, 41], 80-200 [60], 185-370 [42], 300 [57]	95 [43], 80-90 [51], 78-88 [42], 85 [61], 85-98 [41]	5-15 [38, 41], 14-16 [42], 6-20 [56]	0.1–0.3 [38, 41], Medium [45], 0.17–0.33 [62], 0.036–0.0833 [63]
Ni–Cd	50-75 [38,41, 43], 30-80 [42], 40-60 [45,62]	150-300 [38, 41], 100-160 [42], 140-180 [45], 150 [62], 50-150 [56]	72 [42], 60-76 [53], 60-70 [41], 70-90 [62]	10-20 [38], 13-20 [42], 10 [56], 5-20 [41]	0.2–0.6 [38], 0–0.6 general battery [58], 0.2–0.3 [42], 0.33 [62], 0.067–0.6 [41]
Ni-MH	60-80 [45], 43–70 [56], 30.13 [64], 70 [65], 89 [66], 90 [57]	200 [65], 220 [45], 177 [66], 600 [57]	50-80 [45], 66 [51,62]	5-15 [56], >3 [66]	0–0.6 general battery [58], 0.83 [67], 0.3 [66]
VRFB	10-20 [51], 20-29 [53], 20 [42], 25 [45], 23-35 [68]	166 [42], 80-150 [45]	80 [45, 61], 70-85 [62], 78.3 [69], 60-85 [41]	10-20 [42, 51], 5-15 [41]	Small [38], very low [42], 0.2 [41]
PSB	20-29 [53], 10-15 [70]	1.31 [71]	72-83 [53], 60-75 [42], 75 [61]	15 [42, 72], 10-15 [41]	Small [38], 0 [41]
Zn Br	20-29 [53], 34.4–54 [51], 34.4	90-110 [74]	70 [51], 75 [43], 72-83 [53], 65-85 [42],	8-10 [42], 5-10 [41]	Small [38], 0.24 [41]

(continued on next page)

Table 3 (*continued*)

Type of ESDs	Specific Energy (Wh/kg)	Specific Power (W/kg)	Round trip Efficiency (%)	Service Life (Years)	Daily Self Discharge Rate (%)
	[73], 30-50 [41]		68-73 [74], 60-75 [41]		
SCES	2.5–15 [41], 0.5–1.5 [38], 11 [75], 4 [76], 15–22 [53], 0.8–10 [67], 5–15 [77], 08-20 [62], 5–10 [60]	10000 [43], 500–5000 [38,41], 2000–5000 [42], 800-2000 [77], 3500-10000 [60]	95 [43, 45], 95-99 [53], 65-90 [42], 90-98 [41]	20 [38, 41], 8-17 [42]	5-40 [43], 20-40 [38,41]
SMES	10-75 [42], 1-12 [78], 3 [78]	500-2000 [38,41]	95 [77], 80-95 [42], 90-98 [41]	20 [42], 20-30 [41,76]	10-15 [38,41]
STES	80-120 [38], 10-50 [79], 80-250 [24]	10-30 [24]	50-90 [80], 60 [77], 50-90 [79], 30-60 [24]	10-20 [38], 10-30 [24]	0.5 [38], 0.05–1 [24]
PCM	150-250 [38], 80-250 [24]	10-30 [38]	75-90 [80], 50-90 [79], 40-90 [47]	20-40 [38], 30 [47]	0.5–1 [38]
TCS	250 [79], 80-250 [24]	10-30 [24]	75-100 [80], 75-100 [79], 40-90 [47], 30-60 [24]	10-30 [24], 30 [47]	0.05–1 [24]

ESDs. Besides, the environmental impacts of all selected ESDs are presented using the data collected expressed on a qualitative basis. Therefore, a rating scale from 1 to 7 has been used to quantify this criterion. Accordingly, from the result it is found that Pb-Acid, NaS, Ni Cd, Ni-MH, PHS, have a significant adverse impacts on the environment, on the contrary, STES, SCES and FES have very low impacts on the environment.

As shown from Table 6, the estimated capital, and O&M cost of ESDs are summarized and their average values are presented graphically in Fig. 9. From the result, compared to another type of ESDs, Pb-Acid, PCM, TCS and $NaNiCl_2$ have the lower capital cost per kWh. Whereas SMES, STES, FES has a higher capital cost per kWh. In addition, specific to electrochemical ESDs, Li-ion and NaS batteries have a higher capital cost per kWh. Furthermore, NaS and Pb-Acid batteries have higher O&M costs. However, Li-ion batteries have the least O&M costs.

4. Discussion

4.1. Key findings of the graphical analysis of ESDs

The key findings of the graphical analysis of ESDs presented in **section 3.1** are summarized using different performance metrices. In the review, the study on ESDs and their application potentials in grid-scale applications level were assessed. The pros and cons, and application potentials of different ESDs for grid integrations have been studied. Besides, the distinct application classifications of ESDs according to their selection principles of techno-economic features, and environmental effects of ESDs were evaluated. Therefore, to evaluate the potentials and suitability of ESDs in grid integrated applications, all nominated criteria of ESDs are assessed and graphically analyzed. The selected criteria are typically categorized under technical, economical, and environmental perspectives. The technical criteria consider the power range, the specific power & energy, round trip efficiency, energy and power density, discharge time, lifetime, response time, maturity level, and others. The economic criteria consider both capital and operating and maintenance costs result as shown in Table 6 and Fig. 9. Furthermore, the environmental impact of ESDs is evaluated a rating scale of (1–7) as the data collected is of qualitative type. The result of the environmental impact is also shown in Fig. 8.

The main findings of comparative analysis results of ESDs are summarized as follows:

- It is known that the weight of energy storage devices is among the key assessment factor, playing a crucial role in the selection of ESDs for different application areas. So, ESDs having higher specific energy and power (both characteristics), are taken as appropriate for light weight applications. So, from the analysis result, relative to other ESDs Li-ion batteries possess an average of comparable specific energy and specific power than other ESDs (Fig. 3) and are preferred as the best solution in light weight applications.
- In terms of power and energy density, electrochemical storage systems particularly Li-ion battery possess both features of an average of higher power density and energy density in comparison to other ESDs. Hence, Li-ion batteries have the advantages of reduced volume and smaller size. Therefore, this potential favors Li-ion batteries to be utilized in different transportable devices, and stationary application sectors. Besides, it can be used in the mitigation of power fluctuation applications.
- Among ESDs, it is found that PHS, CAES, PSB, Zn Br, TCS, VRFB, and Li-ion are found to be promising in applications requiring a large power range and longer discharge time. Among the electrochemical ESDs, the Li-ion battery is the best candidate for grid integrations of RESs applications. In addition, SCES, SMES and FES can be used in power quality enhancement applications which require short discharge time.
- In comparison to other ESDs types, the PSB, VRFB, and Li-ion batteries are found to have a very small daily self-discharge ratio. On the other hand, the NaNiCl2, Ni-MH, and SCES have higher self-discharge. ESDs with very small daily self-discharge rates are found to be more appropriate for a prolonged duration of storage applications. On the contrary, $NaNiCl_2$, Ni-MH and SCES with high self-discharge rate is more appropriate for short-time duration applications which include the power quality and regulation applications.
- From Fig. 4, it is observed that, TCS storage systems have the largest average service life of 35 years, and are therefore suitable in bulk energy applications, while electrochemical ESDs (batteries) have a lower service life of 7.67–14 years. Accordingly, the electrochemical ESDs are suitable for ancillary services and renewable energy grid integrations.
- As shown from Fig. 9, the capital expenditure per kWh of PCM, TCS, CAES, PHS, NaNiCl2, and PB-Acid are in a very small range. Nevertheless, SMES, FES, STES and FES possess a higher capital expenditure per kWh. For application areas requiring high power output, TCS, $NaNiCl_2$, PCM, SMES, FES, SCES are preferred since these ESDs provide lower capital cost per kW. Besides, Fig. 9, shows the O & M cost comparative analysis of ESDs, and provided that all thermal ESDs, FES and Li-ion batteries have the least $/kW/year, whereas, NaS and VRFB resulted in higher O&M cost ($/kW/year).
- From Fig. 8, it is seen that Pb-Acid, NaS, Ni–Cd, Ni-MH, PHS, have a significant negative adverse effects on the environment. On the

Table 4
Power range, density, discharge and response time characteristics of different energy storage devices (ESDs).

Type of ESDs	Energy Density (kWh/m3)	Power Density (kW/m3)	Power (MW)	Discharge Time (ms to hr)	Response Time (ms to hr)
NaS	150–250 [81,82], 150-250 [38,41], 180-280 [53], 150-280 [7,19]	150–250 [81,82] 3.5–50 [42], 150–300 [54]	0.05–34 [54], 0.05–8 [38], <10 [83,84]	≤6 h [47], 1–24 h [54,85]	1–2min [81], sec-min [54]
$NaNiCl_2$	150–180 [38,41,82], 100–190 [42], 181 [49]	220–300 [41,82], 54–500 [38], 257 [49]	0–3 [82], 0–0.3 [38]	sec–hr [82], seconds [19,38]	< sec [86]
Pb-Acid	50–80 [38,81], 25–100 [53], 50–90 [19]	10–400 [38,81], 10–700 [54]	0–40 [54], 0–20 [38,81]	≤4 h [47], sec-hr [38,54]	milli sec [47], 5-10 milli sec [54]
Li-ion	200–500 [38,82], 200-500 [53], 170–300 [42], 150 -400 [19]	50–800 [30], 1000–5000 [38], >5000 [41]	0–100 [54], 0-3 [53], 27-40 [19]	min–hr [54,82], ≤1 h [47]	20 milli sec-sec [54]
Ni–Cd	60–150 [38,54], 30-150 [56], 15 -140 [62]	150–300 [54], 100 - 450 [19]	0–40 [38,54], 45 [42]	sec-hrs [81], sec-hrs [19]	20 ms-sec [54]
Ni-MH	189.9 [87], 83-170 [56], 294 [66], 170 - 320 [19]	588 [66], 7.8–580 [87]	0.01–3 [53], 0.04–0.8 [19]	–	–
VRFB	16–33 [81], 20–70 [86], 10–70 [43]	0.5–2 [86], 1–34 [43]	0.3–3 [81], 0.05–0.5 [19]	≤8hr [47], sec-10 h [81]	≤10 min [47], Sec [81]
PSB	20-30 [53], 16-60 [41], 10 - 60 [38]	4.16 [68], 1.35 [51], 2–3.5 [51]	8-12 [53], 1-15 [19,38], 0.1–15 [42]	–	–
Zn Br	20-30 [53], 25-30 [63], 30-60 [41]	4-6 [63], 2.58 [73]	0.1–6 [53], 0.1–15 [42], 1 [74], 0.003–0.5 [19]	–	–
SCES	2.5–15 [82], 1–35 [57]	1000–5000 [82] 4000–5000 [19]	0–0.3 [38,81], 0.02–10 [19]	1 min [47], ms–hr [54]	≤10 millisec [47], 8 ms [54]
SMES	0.2–2.5 [82], 0.2–13.8 [42]	1000–4000 [82], 300–4000 [19]	10 [47], 0.1–10 [19,38,81]	1 min [47], ms–8 sec [54], <1 min [19]	≤10millisec [47], <100 ms [54]
STES	80-120 [38]	–	0.001–10 [80]	≤10 min [47]	days-months [80], Short to long term [80]
PCM	150-250 [38], 80-250 [21,22], 120-500 [88]	–	0.001–1 [80]	Hours -days [80]	≤10 min [47]
TCS	250 [79], 80-250 [21,22]	–	0.01–1 [80]	Hours -days [23]	≤10 min [47]
CAES	3–6 [81,82], 0.4–20 [19,38]	0.5–2 [81] 0.5–10 [7,19]	5–300 [81,82], 5–1000 [54]	≤20 h [47], 1-24+ [54,82]	≤15 min [47,54], 1–2 min [81]
PHS	0.5–1.5 [81,82], 0.05–1 [38], 1–2 [19]	0.5–1.5 [89], 1 [19,61]	10–5000 [54,81,82], 100–5000 [19]	6–24 h [47], 1-24+ [38,82]	sec – min [47], sec-min [54], 1–2 min [81]
FES	20–80 [19,82], 20–80 [19,82]	1000–2000 [19,82], 800–2000 [38]	0–0.25 [81,82], 0.1–20 [54]	≤1 h [47], millisec–15 min [82,85]	≤10 millisec [47], <4 ms-sec [54]

contrary, STES, SCES and FES are found to have insignificant environmental impact.

In general, from the summary of key findings and the graphical result of each ESDs, it is found that the results found are almost coherent and even more promising as compared to the results of previous studies presented in section 2. In addition, relative to other energy storage technologies, electrochemical ESDs in particular, Li-ion battery technologies are found to be the best fitting for RESs integration to the grid system.

4.2. Proposed solution of hybrid approach of energy storage devices (HESDs)

From the result analysis presented in section 3.1 and the respective discussion part of section 4.1, the characteristics, and potentials of each ESDs are already identified. However, from the analysis, it is identified that the use of a single storage device for a typical application cannot be fully a viable and permanent solution to mitigate all resulting constraints. Therefore, to resolve these challenges, the use of hybrid ESDs is of current and important solution to be deployed. Hence, multiple technologies are merged together in order to obtain their advantages, and eliminate each other disadvantages [10]. Hybrid energy storage systems electronically combined (at least two energy storage systems) with complementary characteristics and to derive higher power and energy results, such as a combined electrical-electrochemical system. However, the complexity of HES is respectively increased as more control and conditioning circuit is required, usually achieved by power electronics units [45].

4.2.1. Integration of ESDs in the grid

The electrochemical devices can theoretically serve all roles, however, there are various factors as analyzed earlier (cost, scalability, etc.) that discourage this option, whereas other storage technologies could serve a much better solution. For example, electricity quality and power stability can be achieved with electrical devices, whereas local energy optimization could be handled with either lead acid, sodium-based, and Li-ion based batteries. Bulk power management requires large power capabilities and low discharge time, rendering TES as a favorable choice. The integration of renewables in the grid can be supported by energy

Table 5
Technology maturity and Environmental impact characteristics of ESDs.

Type of ESDs	Technological Maturity	Environmental Impact	**Storage Period (Short – Long term)**
NaS	Commercialized/proven [47,54,81,90]	High [81]	Long term [37]
$NaNiCl_2$	Proven/Commercializing [82]	Medium/low [91]	Mid-long term [37]
Pb-Acid	Mature [90], Fully Commercialized [85]	High [81]	Short-mid-term [37]
Li-ion	Demonstration [47,90], Proven/Commercializing [81]	Medium/Low [81]	Short-mid-term [37]
Ni–Cd	Commercialized [81,90]	High [81]	Short-long term [37]
VRFB	Early commercialized [90], Proven/Commercializing [91]	Medium/Low [81]	Long term [37]
PSB	Developing [90]	Medium [47]	Long term [37]
Zn Br	Demonstration [90]	Medium [47]	Long term [37]
SCES	Demonstration [90], Commercial [47,91]	Very low [81]	Short term [37]
SMES	Early Commercialized [90], Commercializing [54]	Low [81]	Short term [37]
STES	Mature [47], Commercialized [90]	Very low [80]	days-months [80], Short to long term [37]
PCM	Mature [47], Commercialized [90]	Low [80]	Hours-months [80], Short to long term [37]
TCS	Mature [47], Commercialized [90]	Low [80]	hours-days [80], Short to long term [37]
CAES	Commercializing [91]	Medium/Low [54,81]	Mid-long term [92,93]
PHS	Commercialized [19,85], Matured [47]	High/Medium [54,81]	Mid-long term [92,93]
FES	Matured [47], Mature/Commercializing [19,85]	Very low [54,81]	Seconds, short-term [92,93]

storage in various aspects, such as voltage control and the off-peak storage, and the rapid support of the demands. For these various roles, the corresponding sizing, operation, and lifetime requirements that the ESDs must comply with are shown in Table 7.

Electrochemical storage, e.g. Li-ion cells can offer a wide range in energy and power capabilities. An application with nickel-manganese-based chemistry can meet the sizing and theoretically the duration of certain WT and PV applications, whereas a lithium-titanate-oxide (LTO) based chemistry can offer improvements in the cycle lifetime however, with an increased cost due to its lower capacity levels. On the other hand, electric devices can meet the rapid power requirements for the PV integration offering a remarkable lifetime and cycling capabilities as well. Thermal storage and flow batteries can be used for off-peak WT integration for high discharge capabilities and superior lifetime-scalability, however with decreased efficiency and response time. Other technologies like lead-acid and nickel-cadmium can be a good candidate for black start services. Methods that encourage the decentralization of the storage systems and hence the self-production/consumption are taking place. Based on economic plans and benefits, PV systems designed for self-consumption are already built. This can help the low-voltage distribution network, which is currently reaching its performance limits because of the growing quantity of PV systems. The energy storage for household levels has an important role in the penetration of renewables [35]. Several projects have been constructed or being under development to support green energy and its easier integration to the grid. A 51 MW facility of WT is supported by a 34 MW NaS storage to smooth the total power and regulate the peak output

Table 6
Capital, and operating & maintenance cost comparison of ESDs.

Type of ESDs	Energy Cost ($/kWh)	Power Cost ($/kW)	**Operating and Maintenance (O &M) cost ($/kW/year)**
NaS	300–500 [38,54], 326–543 [94]	380–3256 [94], 1000–3000 [54]	80 [19], 7-15 [40]
$NaNiCl_2$	100–345 [91], 100–200 [82]	150–300 [82]	–
Pb-Acid	120–150 [54], 54–337 [94], 200–400 [54,95]	300–600 [54], 326–651 [94], 200–300 [81]	50 [19], 7-15 [40]
Li-ion	600–2500 [89], 300–1300 [81]	1303–4342 [94], 1200–4000 [81], 900–4000 [54]	10 (for large scale application(>1 MW)) [96], 6-12 [40]
Ni–Cd	800–1500 [19], 400–2400 [54]	500–1500 [54]	20 [19]
VRFB	190–1085 [94], 150–1000 [81]	651–1628 [94], 600–1500 [81]	70 [19], 7-12 [40]
PSB	150-2000 [53], 110-130 [58], 450 [42], 120–1000 [41] 494.35–1373.2 [42],	800-2900 [53], 1100-4500 [58, 97], 1000-1200 [62], 330-2500 [41]	7-16 [40]
Zn Br	150-1000 [41], 150-2000 [53], 500 [42], 200-400 [41]	800-2900 [53], 1100-4500 [58, 97], 640-1500 [42], 175-2500 [41]	6 (for large scale application(>1 MW)) [96], 7-16 [40]
SCES	300–2000 [54]	271–480 [94], 100–450 [54]	6 [19]
SMES	1085–10854 [94]	217–326 [94], 200–489 [54]	18.5 [19]
STES	0.14–13.65 [79], 0.040–0.150 hydrothermal [42], 0.12–11.78 [80]	3650 hydrothermal [42], 7900 ocean thermal [42]	5 [19]
PCM	13.65–68.26 [79], 88.73 calcium chloride [79], 11.78–58.92 [80]	200-300 cryogenic [38]	5 [19]
TCS	10.92–136.56 [79], 9.43–117.84 [80]	–	5 [19]
CAES	217–271 [94], 2–120 [54]	400–800 [82], 1411–1628 [94]	16.7 [98], 18.9 [40]
PHS	217–271 [94], 5–100 [81,89]	2500–4300 [19], 500–2000 [85], 2171–4342 [94]	15.9 [98], 6.2–43.3 [40]
FES	1085–5427 [94], 1000–5000 [82], 1000–14,000 [54], 500–1000 [81]	271–380 [94], 250–350 [81, 82]	5.6 [98], 5.8 [40]

[35].

Also, large-scale renewable sources penetration sets new requirements and grid codes on the low voltage ride-through capability, frequency and voltage regulations, and active/reactive power control, along with other control functions which can be handled by the energy storage integration [101–103]. So far, for projects related to large-scale PVs integration, the Li-ion technology is the most popular solution utilized for energy storage, with a maximum installed energy storage rating at 100 MWh, used for capacity firming and time-shift [101,104]. In the case of WT, energy storage could be used for various applications of wind power plants, grid personnel's and consumers, as a viable solution to enhance the stability and consistency in future power systems [37]. According to green energy park infrastructure and power ratings, Li-ion technology and supercapacitors are seen as a good candidate, implemented as a hybrid solution.

Additional key findings important to identify the application's suitability and characteristics of ESDs are stated below [100]: s.

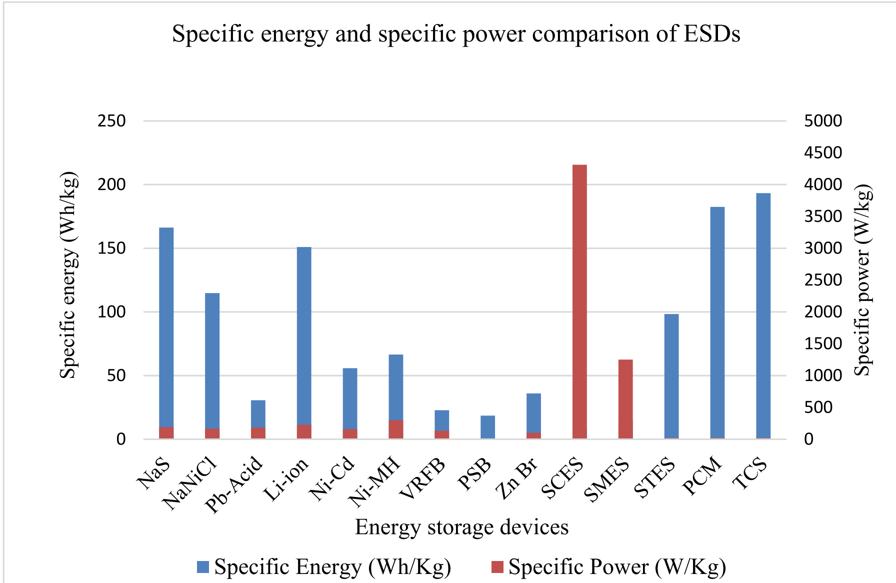


Fig. 3. Specific energy and Specific power Comparison of ESDs based on average value of data collected in Table 3.

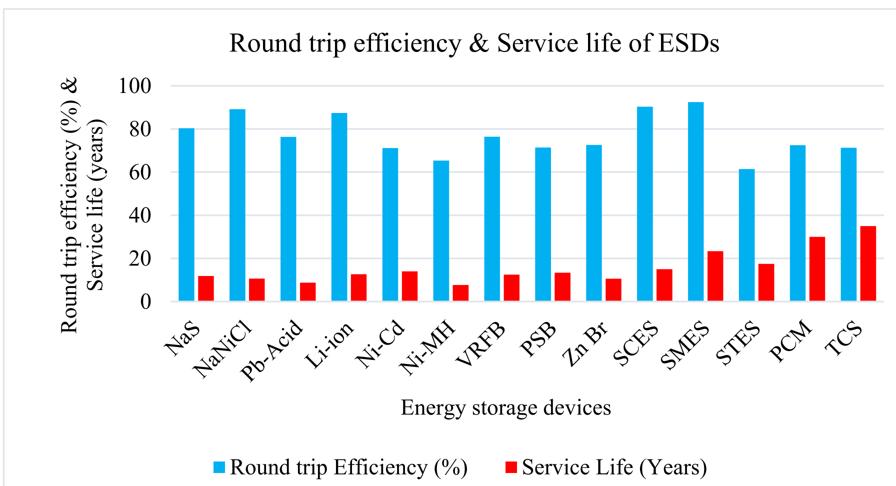


Fig. 4. Round trip efficiency and service life of ESDs based on average value of data collected in Table 3.

- Identify the purpose of the storage
- Estimate power and energy requirements
- Estimate discharge duration and frequency
- Size and site of the application (extra cost on thermal management etc)
- Interconnection with other systems
- Communication and control interfaces
- Data monitor and reporting

Hybrid solutions can also support the integration of renewables by targeting each in different requirements, such as electrochemical solutions for intra-day energy time shift and inter-week energy shift by thermal and other solutions [105]. It can be observed that based on a study [106] and the comprehensive review performed, all storage technologies are capable of supporting green energy generation, in a horizon of the next 10–20 years, as shown in Table 8. Based on the current maturity and future perspectives, electrochemical could be suitable for all levels in the network, whereas other options would mostly be suited to certain of them. The study focused on various characteristics of each technology including energy/power densities, responses, efficiency, lifetime, cost, environmental issues, safety, etc.

In the comprehensive review, a scenario with multiple storages for a certain application is proposed as a solution to enhance the storage application's capabilities, as for instance, thermal storage is promising for seasonal storage for which electrical and electrochemical are not so favorable and this conclusion is similar with the result concluded in Ref. [5]. The last remarks include the several projects related to energy storage which are carried out around the globe, with various applications of ESDs, and can be found in Refs. [107–113]. Also, planning on the construction, safe operation, and maintenance issues must be considered to avoid undesirable faults [114].

4.3. Future advances

The efforts to decarbonize the electricity grid, the rapid increase in energy demands, and the utility of intermittent renewable energy led to currently being carried out a lot of research in all the energy storage technologies. Particularly in battery storage technologies, recent investigations focus on fitting the higher demand of energy density with the future advanced technologies such as Lithium Sulphur (LiS), Lithium

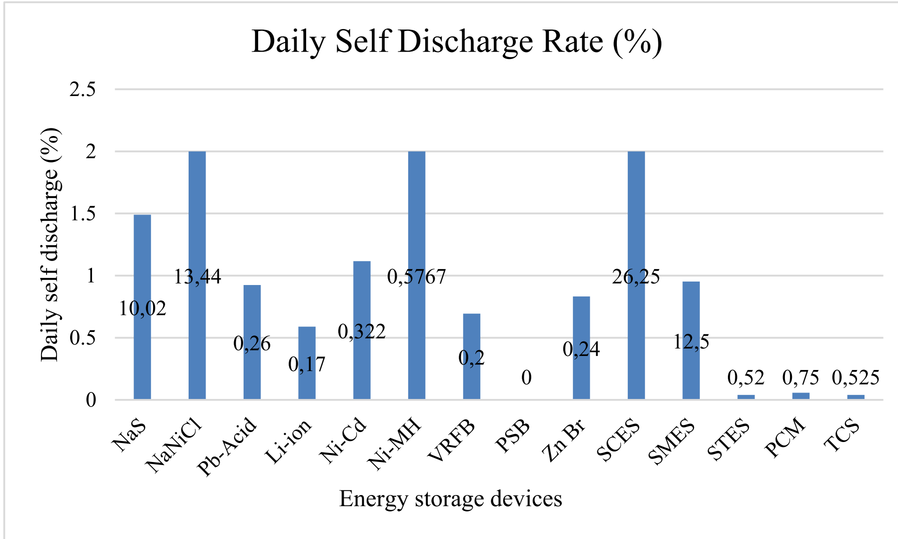


Fig. 5. Daily self-discharge of ESDs based on average value of data collected from Table 3.

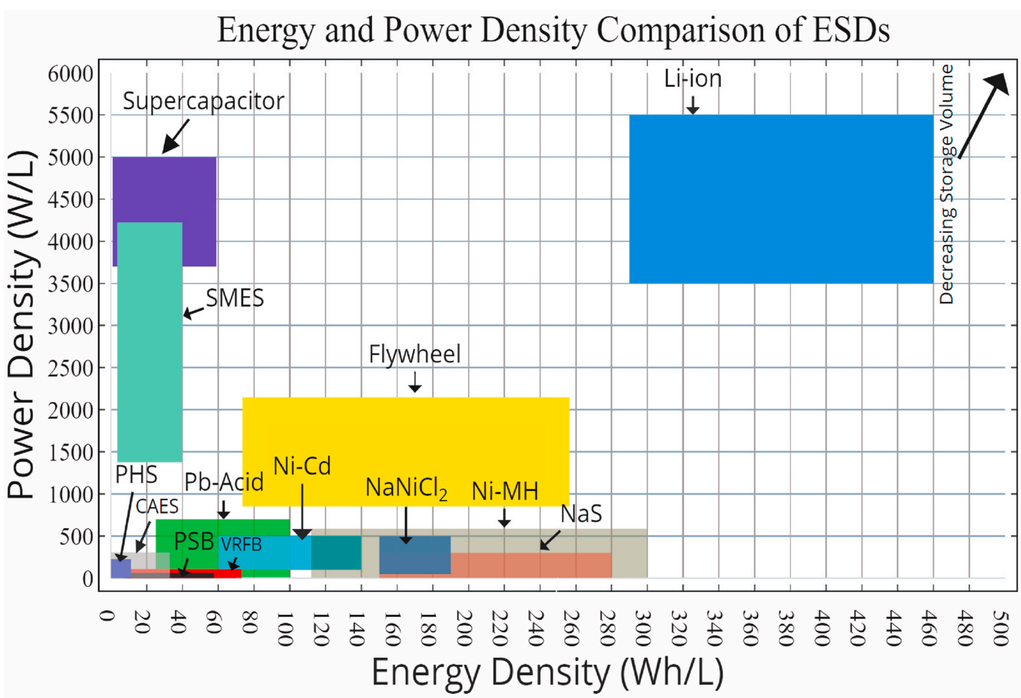


Fig. 6. Ragone chart for the average power and energy density comparison of ESDs based on average value of data collected in Table 4.

oxide (LiO_2), future Li-ion, Metal-Air, Lithium-Air (Li-Air), solid-state batteries, etc. [115]. With respect to Li-ion cells, challenges with energy densities, power capabilities, lifetime, and thermal operation are discovered with new chemistries and materials. Future advanced Li-ion cells are anticipated to enhanced temperature margin and be safer and more consistent throughout their lifespan with lower cost and improved fast charging capabilities [116]. Furthermore, a wide range of materials and interconnections are being researched, beyond Li-ion chemistries, such as lithium-Sulphur, the various option on Metal-Air batteries that all show significant improvements on the specific energy and capacities. Also, solid-state batteries are expected to flourish by replacing the unstable liquid electrolytes with a solid one and ameliorate the cycling performance of the cells. Silicon and Tin batteries are also investigated providing much better theoretical capacities than the current chemistries, while also Metal-ion batteries such as Zinc-ion and Sodium-ion can deal with the economic, availability and recyclability concerns of lithium, which would rise problems if Li-ions are used in large scale stationary applications. Flow batteries offer numerous benefits for energy storage such as scalability, low self-discharge, good power densities as well as high service life and fast response. The most important is that flow batteries decouple the energy and power capabilities in comparison to the other technologies that have them inherently connected. A lot of research is taking place for both redox and hybrid flow batteries by investigating new materials for electrodes, separators and electrolytes to raise the low volumetric energy which is the main limiting factor at the moment [117]. Batteries based on organic radicals serve the most eco-friendliness solution to energy storage, as seen from material abundance, the efficiency of synthesis and recycling

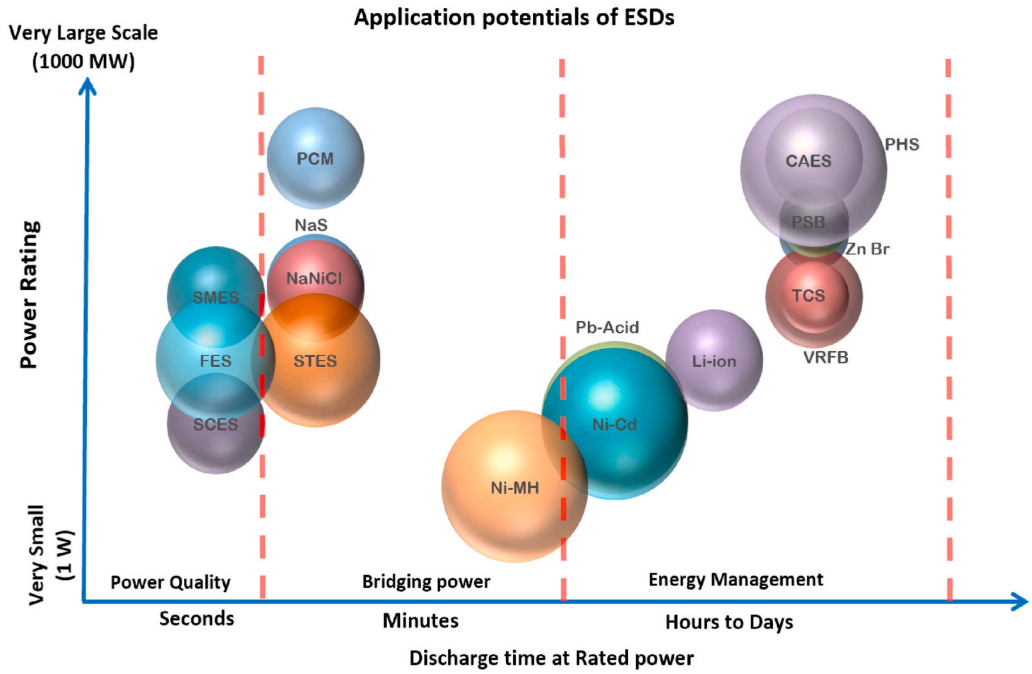


Fig. 7. Discharge time and power rating comparison of ESDs based on average value of data collected in Table 4.

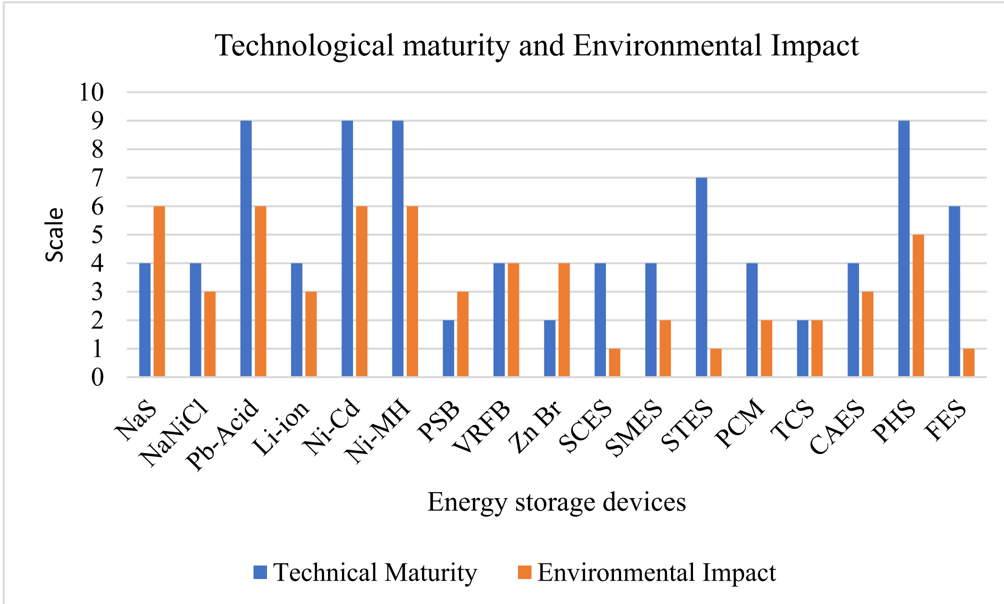
processes, life-cycle analysis and scalability [118]. In the aforementioned technology, the charging and discharging rates are superior as compared to li-ion, and also it is safer during operation as thermal runaways are prevented. On the other hand, resulted in decreased gravimetric and volumetric energy capabilities than the future batteries (e.g. Metal-Air) and operated in lower voltage which would require a higher amount of ORBs to meet the application demands [119]. Concerning the high temperature operation of the Sodium-Sulphur (NaS) can raise safety issues and might trigger obstacles on increasing the usage of NaS with the respectively increased power consumption rates and self-discharge rates that it brings [120]. Studies are taking place to drop the temperature operation window at room temperature which can potentially further increase the capacity of such batteries [121,122].

In the field of electrical storage, hybrid supercapacitors have emerged as the hybrid solution of ESDs that combines the Li-ion cell's storage capability and the power capabilities of EDLCs. This device is known as Li-ion capacitors (LiCs) and incorporates the advantages of both technologies [123]. It consists of a li-ion anode material (carbon-based [124] or titanium-based [125]) and an EDLC cathode and provides a longer lifetime, high power compared to Li-ion, high nominal voltage and energy density compared to EDLC, but lower than Li-ion [125]. Currently, LiCs are used for similar applications as capacitors and supercapacitors. Various types of hybrid supercapacitors under R&D in order to increase the energy densities [126].

Lastly, high temperature TES that include concrete storage, PCMs, standard temperature ionic liquids, and molten salt is currently in use and under constant development, as it plays a decisive role in the RESs integration [127]. PCMs can change their phase from liquid to solid and exchange the latent heat during this transition. During accumulation, the PCM changes from solid to liquid whereas the heat transfer is achieved through a heat transfer fluid. The advantage of this technology is that a latent heat storage gives the possibility of gathering a large quantity of energy in a limited volume efficiently. Another type of TES that is currently at the early R&D phase is thermochemical heat storage (TCS). It is a form of storage by which heat is deposited during an endothermal reaction and released during an exothermal step of a reversible chemical reaction. The heat that is released is used as an energy source [82]. This technology has higher specific energy compared to sensitive or latent heat TES and better efficiency, nevertheless, it comes with a higher cost and complexity. Molten salts are expected to continue to dominate the market of TES for large-scale applications. For the sensible heat TES, most R&D is placed on activities to find new materials and topologies to increase the specific energy, as well as to find efficient thermal insulations [128]. TES systems can be integrated into various application fields. District heat applications, i.e buffer and seasonal storage are already utilized around the globe whereas improvements on several technical and economic issues are currently in progress. For non-residential buildings, the low-temperature latent heat with PCM storage can be used for buffer storage, where developments on the materials are carried out to further optimize the process, with several real and early-stage concepts. For industrial applications, both sensible, latent and thermochemical solutions are under concern, as these ESDs can be used for buffer storage and backup systems [23]. Research is taking place on improving their stability and storage performance with extra focus being placed on the latent PCM TES as several applications are in development: cold storage integration in office buildings, PCM storage with the chilled water system, a PCM-air heat exchanger for peak and demand shifting in buildings are some cases, but also other TES are under research such as plate-based latent heat thermal energy storage system and latent heat storage for low-temperature heat including solar cooling and domestic hot water [23,129]. A new technology called Electric Thermal Energy Storage (ETES) is recently presented which is environmentally friendly and scalable to GWh energy ranges. ETES is planned to be used for grid stability and complement renewable power generation and is commissioned in Hamburg-Altenwerder, Germany in 2019 by Siemens Gamesa Renewable Energy (SGRE) [130].

5. Conclusions

Energy storage is a crucial element of the future electricity network, for meeting the 70% target of the generation produced by renewable energy sources (RESs). It can provide flexibility between supply and demand and it can support fast and efficient integration of the RESs. Consequently, it is expected that the capacity of energy storage will be increased and for this, a broad range of electric and thermal power technologies are built and are under development, to meet all possible operational and economical characteristics. From this comprehensive



Technical Maturity	Scale Conversion		Environmental impact	Scale Conversion
Very Mature	Fully Commercialized	9	Very High	7
Very Mature	Commercialized	8	High	6
Mature	Commercialized	7	High / Medium	5
Mature	Commercializing	6	Medium	4
Mature	Limited Development	5	Medium / Low	3
Proven	Commercializing	4	Low	2
Proven	Limited Development	3	Very Low	1
Proven	Developing	2		
Research	Developing	1		

Fig. 8. Technology maturity and environmental impact comparison of ESDs based on average value of data collected in Table 5.

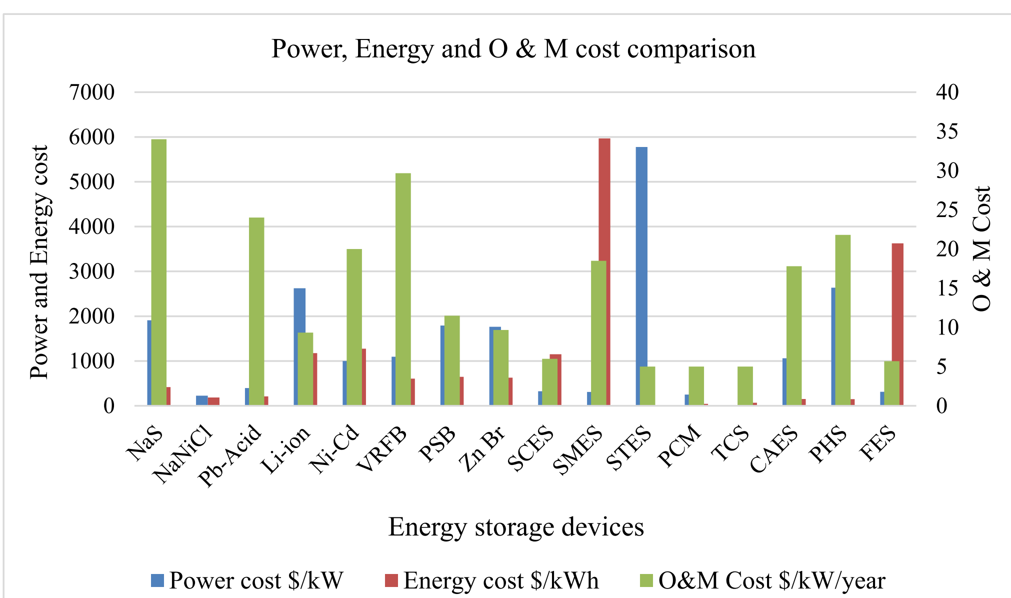


Fig. 9. Power, energy, and O&M cost of ESDs based on average value of data collected in Table 6.

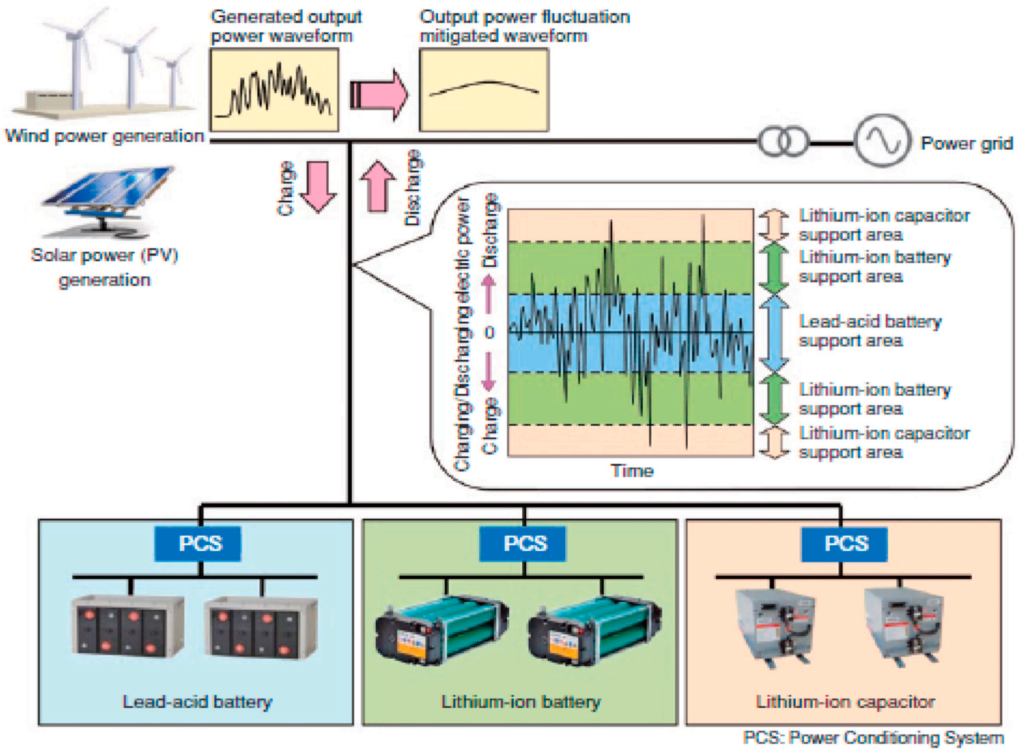


Fig. 10. A hybrid concept of electrical and electrochemical devices [99].

Table 7
General requirements of energy storage for RESs integration to grid [6,100].

Application	Description	Size	Duration	Cycles	Target lifetime	Storage Technology requirements	Candidate ESDs
Renewable energy integration	ramp and voltage support	1–10 MW distributed 10–400 MW centralized	15min	5000cyc to 10000cyc per year	20 years	• Medium-high power •Medium discharge	•Thermal
	off-peak storage	100–400 MW	5 h–10 h	300cyc to 500cyc per year	20 years	•High power •Very Slow discharge	•Thermal •Redox flow batteries •Sodium-Sulphur
	time-shift, voltage sag, rapid demand support	1–2 MW	15min to 4 h	>4000 cycle per year	15 years	•Medium power •Slow discharge	•Redox flow •Li-ion •NaS
	Black starts	5–50 MW	15min-1h	N/A	N/A	•Medium-high power •Slow discharge	•Li-ion •Lead Acid •Hybrid-supercapacitors
	Power oscillation damping	10–100 MW	5sec-2h	N/A	N/A	•Medium-high power •Slow -fast discharge	•SMES •Li-ion
	Wind power gradient reduction	1–50 MW	Sec-min	N/A	N/A	•Medium-high power •Fast discharge	•Thermal •Electrical •Li-ion
	Peak shaving	1–500 MW	1 h–6h	N/A	N/A	•Medium-high power •Slow discharge	•Thermal
	Frequency regulation/ stability Of weak grids	1–50 MW	Sec-min	N/A	N/A	•Medium-high power •Fast discharge	•Flow, Sodium-based, Li-ion, Lead Acid

review, the maturity of each storage technologies, the present status as well as future directions are discussed, with the main focus on the electrical, electrochemical and thermal storage technologies. The main findings of the review on ESDs are summarized as follows.

- The source availability, access, and eco-friendliness of electrochemical energy storage systems should be considered for the life cycle analysis and environmental impact assessment. It is estimated that making 1 kWh of li-ion battery consumes around 400 kWh of energy and produces 75 kg of CO_2, whereas a coal-fired plant emits 1kg/1 kWh instead. This instantly requests at least 400 cycles of the Li-ion system to pay back the energy it consumed, and a long lifetime/service life, to have a positive impact on the environment [102]. From electrochemical ESDs, Li-ion batteries are found to have higher power and energy density, higher round trip efficiency, low environmental impact, light weight etc., and therefore, taken as a promising option for grid-scale stationary application area, especially in RESs grid integration.
- Availability of lithium and cobalt make vulnerable the current technology of Li-ion cells to cost and scalability. Toxic elements such

Table 8
Summary of state-of-the-art repartition of ESDs (Technologies Vs. Applications) based on graphical results of section 3.1 and Table 7 (storage technology requirements).

		Energy Storage Devices														
		Electrochemical									Electrical		Mechanical			Thermal
Application areas		NaS	$NaNiCl_2$	Pb-Acid	Li-ion	Ni-Cd	Ni-MH	VRFB	PSB	Zn Br	SCES	SMES	CAES	PHS	FES	All Thermal
Renewable energy integrations	Time shifting	🟡	🔴	🟡	🟢	🟡	🟡	🟢	🟢	🟢	🔴	🔴	🟢	🟢	🔴	🟢
	Firming capacity	🔴	🔴	🟡	🟢	🟡	🟡	🟢	🟢	🟢	🔴	🔴	🟢	🟢	🟡	🟢
Bulk Energy	Peak Shaving	🔴	🔴	🔴	🟡	🔴	🔴	🟡	🟡	🟡	🔴	🔴	🟡	🟢	🔴	🟢
	Arbitrage of energy	🔴	🔴	🔴	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟡	🟢	🔴	🟢
Ancillary Services	Voltage Support	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟡	🔴	🔴	🔴	🔴	🔴	🟡
	Load balancing	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🟡	🟡	🔴	🔴	🟡	🟡	🔴	🟢
	Spinning reserve	🔴	🔴	🟢	🔴	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🟡
	Black Start	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡
	Frequency balancing	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🟡	🟡	🟡	🔴
Energy Management	Enhancing Power quality	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟡	🟢	🟢	🔴	🔴	🔴	🔴
	Power reliability	🟢	🟢	🟢	🟢	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🔴	🔴
		🟢	Suitable application				🟡	Possible application				🔴	Un suitable application			

as lead, cadmium and mercury are found in many electrodes which raise health and environmental concerns. Recycling, second life and new concepts like V2G/G2V and network storage are important to that extent, since it can help overcome these limitations [131].

- Li-ion batteries are preferred so far for storage solutions for low and medium-range applications. This is due to the drop in cost, but also their good performance compared to other batteries (response times, energy/power ratio, and maturity). Second-life batteries, a.k.a. reconditioned EV batteries, are going to have a crucial role in the residential and distributed storage system. In addition to the capital cost for Li-ion storage, the narrow electrical and thermal operation window requires an extra cost for the control and insurance of safe and reliable operation. Regarding the economic aspect, nowadays few researchers offered the economic viability of Li-ion batteries integrated with grid-connected RESs systems [132].
- Thermal energy storage from renewable sources can help reduce the CO_2 emissions both in residential, non-residential, and industrial sectors by saving large amounts of energy. However, TES faces with cost and stability barriers, especially new technologies like TCS and PCMs. Like other energy storage technologies, a specific design to fit the boundaries and requirements of a certain application has to be made.
- In electrical, electrochemical, and thermal energy storage, research is placed on the improvement of the properties and capabilities of the materials. Electrode optimization, stable and more powerful electrolytes and novel membranes and separators, to enhance the performance of the electric and electrochemical cells are taking place. Most promising solutions include the Li–S, the M-Air, and the solid-state cells as well as new flow batteries and hybrid capacitors. In TES, storage mediums for various temperature ranges, containers, and thermal insulation issues, as well as system design and integration into the processes are being investigated.
- In addition, each technology offers its unique set of benefits in terms of cycle efficiency, service lifetime, capital and O&M cost, self-discharge time, and of course gravimetric and volumetric energy and power values, and hence it can be a cost-effective solution after mapping its performance and cost to the desired applications'.
- Future advances in storage might include increased capacity to promote the integration of greener energy, with higher cycle lifetime and efficiency, and for higher discharge time capabilities.

- Most importantly, hybrid solution that combines more than one technology to meet the demands is also investigated, which can give significant and unique benefits to achieve various applications compared to a single energy storage approach (e.g. battery-supercapacitor, battery-SMES, etc).

With proper identification of the application's requirement and based on the techno-economic, and environmental impact investigations of energy storage devices, it is found that the use of the hybrid solution is proposed as a viable solution for the RESs application sectors.

Finally, to support the increased penetration of renewables, it is important to plan the installation of the ESDs along with the green energy source, set the characteristics and functionalities of the ESDs, and make sure that it can comply with the standards requirements and the services that it should also provide (beyond the standards). Following these workflows and procedures are found as crucial to select the most appropriate type of ESDs for the respective application sector.

Authorship contribution statement

Abraham Alem Kebede: Formal analysis, Methodology, Resources, Writing. **Theodoros Kalogiannis:** Investigation, data curing, Writing – review & editing. **Joeri Van Mierlo:** Visualizations and guidance. **Maitane Berecibar:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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