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The role of energy storage systems for a secure energy supply: A comprehensive review of system needs and technology solutions

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ABSTRACT

The way to produce and use energy is undergoing deep changes with the fast-pace introduction of renewables and the electrification of transportation and heating systems. As a consequence, the electrical grid sees much higher power variability than in the past, challenging its frequency and voltage regulation. Energy storage systems will be fundamental for ensuring the energy supply and the voltage power quality to customers. This survey paper offers an overview on potential energy storage solutions for addressing grid challenges following a "system-component-system" approach. Starting from system challenges, the energy storage technologies and their power electronics integration in the grid are described at component level considering the last scientific trends, including the hybrid energy storage concept. The impact of the energy storage technologies on the power systems are then described by exemplary large-scale projects and realistic laboratory assessment with Power Hardware In the Loop techniques, returning at system level. Finally, this work addresses some of the most important challenges for a sustainable and safe integration of energy storage systems, such as the circular economy and the safety aspects.

1. Introduction

Globally the renewable capacity is increasing at levels never seen before. The International Energy Agency (IEA) estimated that by 2023, it increased by almost 50% of nearly 510 GW [1]. European Union (EU) renewed recently its climate targets, aiming for a 40% renewables-based generation by 2030 [2]. In the United States, photovoltaics are growing exponentially, with more than 30 GW per year in 2023 and 2024 [3]. This trend will hit the threshold of 7.3 TW of worldwide installed renewables by 2028 [1].

At the same time, a fast-pace trend for the electrification of loads has been observed in several countries. Electric Vehicles (EV) are substituting internal combustion engines, due to recent improvements in efficiency and mileage range. In just few years, from 2017 to 2022, the sales of EVs increased from 1 million to a 10 million figure [4]. Similar growth has been observed in heat pumps, which can substitute gas-fired boilers for heating and cooling purpose. While globally the heating electrification reaches a double-digit growth, some countries, like Germany, have seen a 100% sales growth in 2023 [5].

However, the electrification path introduces a strong change in how the energy is produced and consumed, shifting the operations from being dispatchable and predictable, to intermittent and strongly user-dependent (e.g., timing in charging of electric vehicles). As a consequence, to guarantee a safe and stable energy supply, faster and larger energy availability in the system is needed.

This survey paper aims at providing an overview of the role of energy storage systems (ESS) to ensure the energy supply in future energy grids. On the opposite of existing reviews on the field that

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target either the technology or the system level aspects, this work follows a $system - component - system$ approach, where the interaction between the system needs and the energy storage technology solutions is described. This paper starts with a description of the current challenges for the electrical grid to achieve a green transition ($system$), with a particular focus on those challenges that energy storage systems can contribute to solve. Focusing on these challenges, the current market-available energy storage solutions are introduced ($components$), explaining their working principles, types, applications and market potential. Their integration into the power grid using power electronics is explained, introducing novelties in power converter topologies and architectures, and describing the integration of more energy storage units in hybrid form. Going back to $system$ level, this paper describes the services that energy storage systems can provide to the electrical grid, dividing them into long-term (>10 h), medium-term (>1 h), and short-term (<1 h) services. Four exemplary large-scale projects are introduced to highlight this system-component level interaction: the "Netzbooster" project, where hybrid energy storage systems increase the supply reliability of the grid; the "Unifi" project, that explore the use of grid-forming control techniques with energy storage systems; the "Genome" project, targeting a comprehensive physics characterization of battery energy storage systems of different technologies; and the SuperHeart project, as example of novel power electronics solutions for an optimal integration of energy storage systems. As many different energy storage technologies are proposed, their testing in realistic grid conditions is challenging. For this reason this paper describes the Power Hardware In the Loop concept and provides the reader of three large-scale labs where energy storage systems are tested at full-rate and in realistic testing conditions: the Energy Lab at the Karlsruhe Institute of Technology, the Flatirons Campus at the National Renewable Energy Laboratory, and the Sandia Energy Storage and power electronics program lab at the Sandia National Lab. Finally, this survey paper concludes the topic by briefly providing the challenges and research open points that should be addressed for the widespread integration of energy storage systems in the electrical grid.

2. Grid challenges

This section provides a short overview of the challenges, which highlight the need for the safe and secure operation of the system (see Fig. 1).

2.1. Secure energy supply

Challenge: Several countries have pledged to be independent in the next 10 to 30 years from fossil fuel-based generation, pointing in the direction of greener energy production. Germany, for example, have opted to phase-out nuclear power plants, aiming at relying mostly on renewable energy sources and at the same time becoming independent from Russian energy imports [6]. In any of these scenarios, a cheap energy supply must be always guaranteed in the short and long term [7]. In the short term, the fast variation of solar irradiation or wind speed can create issues at local level, while in the large scale the effects compensate themselves statically. In the long term, instead is the provision of energy at large scale particularly challenging, when wind- and solar-based energy production is coincidentally low (named "Dunkelflaute" in German), with events concentrating mostly during winter months [8]. These events typically last 12–24 h, but may reach duration up to several days, and in rare cases (few times at year) the power production from wind and solar sources sees a decrease down to 10–30% of its rated power [9].

Emerging economies are also particularly concerned about securing energy supplies. For example, Indonesia has a growing economy and thus energy consumption, while internal fossil-fuel reserves are depleting [10]. The government targeted a growing integration of renewables from 4% in 2011 to 17% in 2025, relying less on internal oil production.

Requirements: Energy shall be available in the short and long term to compensate any mismatch between energy production and consumption. Ideally, during over-production the energy shall be stored, to be re-used during over-consumption conditions. Proposed solutions shall be implemented at very large-scale. For this reasons they must be cheap, easy to manufacture, flexible in sizing and up-scaling once in the field.

2.2. Lines and transformers congestion

Challenge: The electrification of loads is a fundamental step to improve the energy usage. Electrical loads are known to have better efficiency and higher flexibility with respect to fuel-based technologies. However, this means that devices such as heaters, vehicles, and stoves, once mainly fuel-based, are now fed by the electrical grid. This represents a challenge for the design and operation of electrical lines, as the absorption rate of these loads is in the range of kW (heat pumps and induction plates) or tens of kW (electric vehicles), implying a higher capacity usage of distribution lines and transformers. Congestion issues at the distribution grid level have been observed in the intensive integration of these technologies. Let us examine the two examples of heat pumps and electric vehicles charging.

2.2.0.1 Heat pumps: are an efficient way to air-condition households and office areas instead of recurring to gas-boilers. Germany is actively pursuing the substitution of old heating systems with heat-pump-based systems [11]. However, to achieve the same thermal power as gas-based heating sources, heat pumps require several kW of additional electric power per household. In future scenarios, where heat pumps will be a standard solution for households, current congestion issues may occur on a regular basis at transformer and line levels, if no controlled approach is proposed [12,13].

2.2.0.2. Electric vehicles: have on-board batteries in the range of 30–80 kWh that require a charging rate that varies from 3–10 kW for slow charging in private or common parking areas, to 50–300 kW for fast charging on motorways. In the case of slow charging, power is limited; however, typical customers tend to charge vehicles simultaneously (e.g., during office hours, overnight, etc.). If more vehicles charge in parallel, private and public distribution transformers and lines can be easily overloaded [14,15].

Requirements: The grid infrastructure should be upgraded in terms of the hardware and control capabilities. One potential solution is to build new lines and transformers, maybe in a meshed configuration. On the other hand, this implies large investments and high customer disruption during construction work. In some cases, for example in historical cities, this upgrade is difficult or impossible. As an alternative, energy is produced and consumed locally to minimize the power transfer in the mains.

2.3. Renewables forecast error

Challenge: By definition, renewable energy production is intermittent and non-dispatchable, resulting in uncertainties in the power generation scheduling. If no reduction of the power output for upwards and downwards power control capability is considered, the only control leverage left is an accurate forecasting of the produced energy. This is not an easy task and novel methods show great improvements in the forecast accuracy to several days. In addition to national-level forecasts, such as those discussed in recent works [16–18], plant-specific forecasts have been studied to provide automatized and accurate prediction of the produced energy. Automated forecasting models reduce the need for extensive manual intervention, making them suitable for real-world applications and enabling forecast solutions to keep pace with the expansion of photovoltaic (PV) power generation capacity. Accurate forecasting of renewable energy plants largely depends on weather influences, as shown in [19,20]. There are approaches that

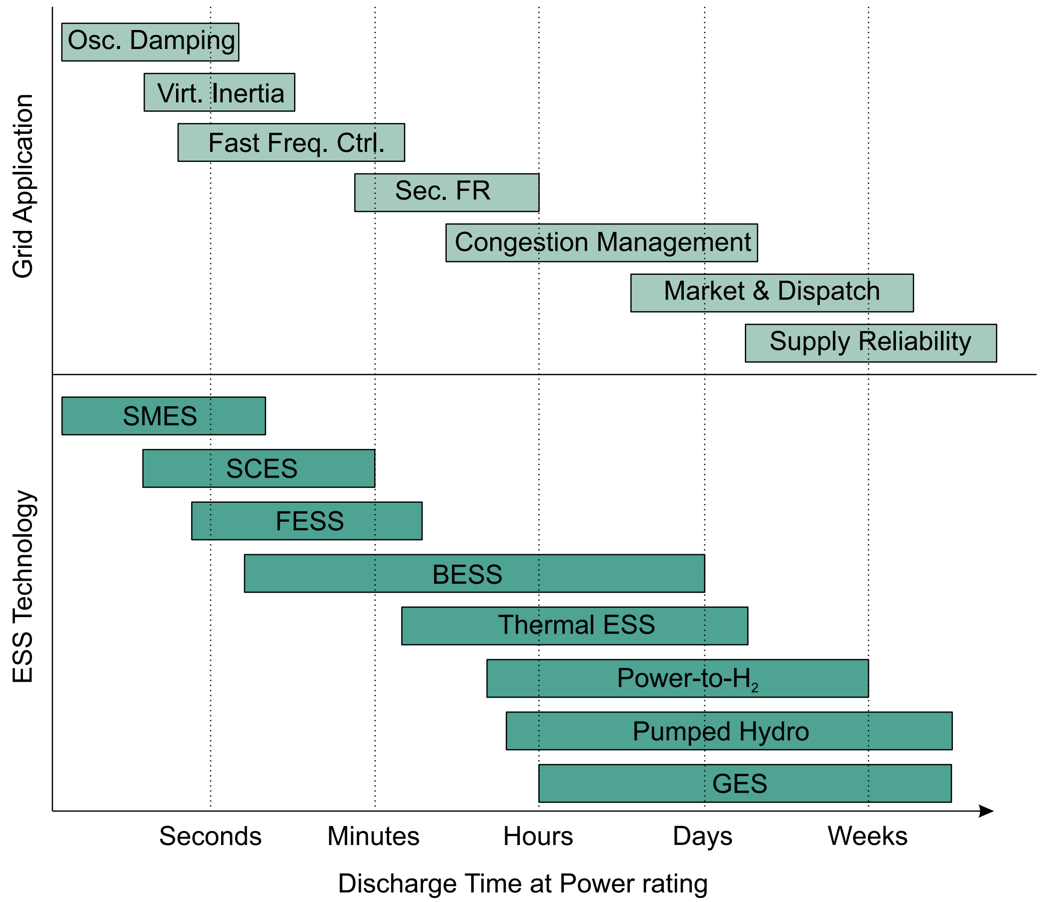

Fig. 1. Time horizon for power system phenomena and typical discharge times for energy storage systems.

enable PV-related forecasting without exogenous weather forecasts [21, 22]. However, PV-related forecasting offers still some unresolved challenges [23], such as (i) missing information about the PV mounting configuration (i.e., tilt and azimuth angles), and (ii) limited availability of historical data to train the PV model (cold-start problem).

It shall be noted that any forecasting error may affect the system operations (e.g., in the frequency or voltage control), and may imply the request for ancillary services or the use of the electricity market [24], increasing the economy efficiency loss [25]. These works connected the resulting higher costs for the system in case of wrong prediction of renewables power output. Similar impact can be seen in the gas market. Errors in the wind power forecast needs to be compensated by dispatchable gas-based generation, involving higher costs for dispatching flexible gas supply in short term [26].

Requirements: Flexible power availability shall be guaranteed anytime, either under consumption or generation form. Demand response or generation re-dispatching approaches can be employed for this purpose by means of market signals, requiring however a more complex communication infrastructure. Accurate forecasts of renewable energy sources and loads are valuable for most energy storage applications, particularly in energy arbitrage, market applications, and the sizing of storage devices [27]. These challenges necessitate the development of robust and accurate forecasting models and methodologies to ensure the effective utilization of energy storage systems in conjunction with renewable energy sources.

2.4. Low inertia grids

Challenge: As renewable energy sources substitute conventional plants, power electronics converters interface with the grid instead of rotating machines. Due to the stored kinetic energy in their rotors, synchronous machines offer the feature to reject power disturbances occurring in the grid, avoiding large deviation of the system frequency [28]. Power electronics systems, however, do not offer intrinsically this feature. These systems work usually at constant power, targeting at maximizing the energy extraction from the renewable source [29]. Typical examples are the Maximum Power Point Trackers (MPPT) of wind and solar plants, where the front-end converter regulates the DC-AC power flow in order to extract the highest amount of energy from the natural source [30]. As a consequence, the front-end converter controllers are programmed to be robust against disturbances coming from the grid side. As an example, in the German connection rules, any converter-based energy source shall not vary its power injection within the frequency range of 49–50.2 Hz and to decrease it gradually with a 40% gradient from 50.2 Hz to 51.5 Hz [31]. During an under-frequency event, these converters will continue to inject the same power as in normal condition, without offering the disturbance rejection capability that rotating machines can offer.

The system stability is impacted strongly by the lack of stability. As mentioned in several academic [28,32,33] and utility works [34], the available kinetic energy at European level is decreasing, anticipating larger frequency disturbances in the future. This will bring inevitably higher costs for the system, due to larger participation of interruptible loads and more frequent use of frequency containment reserve market.

Requirements: Fast power response strategies shall be included in the emergency management response of system operators. Interruptible loads and warm reserve can represent a solution, despite costly and not able to intervene within few seconds. Increasing the rotating mass of the system by means of synchronous compensator (plus a flywheel mass), may help in the short period, but it does not solve the challenge in future power electronics-based grids.

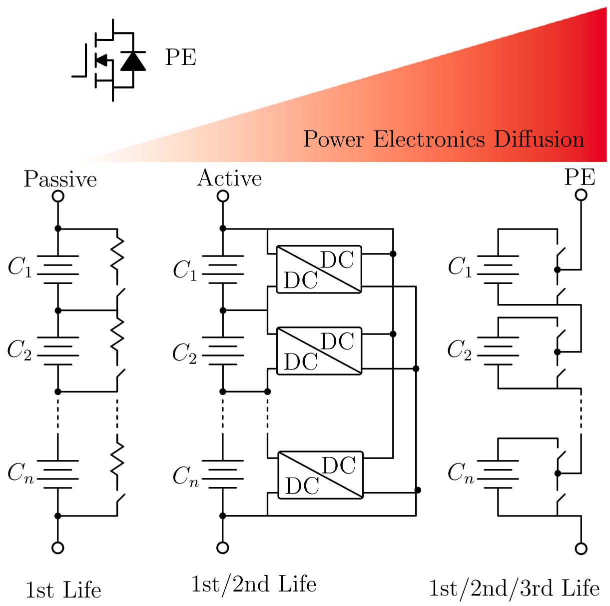

Fig. 2. Evolution of BMS towards fully PE-based technology.

3. Energy storage technologies for stationary applications: state of the art

This section provides an overview on the currently available energy storage technologies for stationary applications. For each introduced energy storage system, the physical principle and technological types are explained. Potential grid applications and the market prospective have been depicted for each technology (see Fig. 1 and Table 1).

3.1. Battery Energy Storage Systems (BESS)

Physical principle: Batteries, such as Li-ion battery are composed of cathode (positive electrode) and anode (negative electrode) which are isolated electronically by a separator. All the components inside the battery cell are wet by electrolyte to ease the ion transport from cathode to anode and vice versa. An introduction to lithium-ion battery operation principles and materials can be found in [35,36].

Types: Batteries are constructed according to different electrochemical principles. The following types of batteries are commonly used in grid applications: Li-ion, Na-ion, NaS, NiCd, NiMH, and lead–acid batteries. Batteries can be built from small cells such as Li-ion, NiCd, Na-ion, and NiMH. Some others such as lead–acid, NaS, emerging solid-state batteries are usually built in bulk parts. In the first category, any voltage and current can be achieved by serial and parallel connection of cells. However, cell balancing technologies should be used. Balancing technologies for batteries are extensively reviewed in [37]. Passive balancing is widely used because of its low cost and ease of implementation, but it is inefficient, especially for aged batteries. Active balancing can restore efficiency, but is still vulnerable to safety issues such as thermal runaway propagation. Fully power electronics-based Battery Management Systems (BMS) can insert or bypass cells and therefore it embeds high modularity and safety which can be used over the battery 1st, 2nd and 3rd life. Fig. 2 shows the evolution of battery management systems from passive and active balancing to fully PE-based.

Grid Applications: BESS ranges between 1 kWh to 20 kWh in residential applications for mainly costs saving purposes. Industrial & commercial BESS works for grid support with sizes between 20 kWh to few MWh, and BESSs for power management range larger than few MWh and reach to GWh. Battery sizing are depicted and compared to other electrochemical energy storage systems in Fig. 3. Battery energy storage systems can provide voltage support, spinning and non-spinning reserve, frequency regulation, energy arbitrage, black start, firming capacity, and power peak-shaping/-shifting, and power oscillation control [38].

Market Perspective:

The total annual demand in GWh for Li-ion batteries including residential, industrial & commercial, and utility-scale BESSs, is expected to grow from 35.7 GWh in 2022 to approximately 283.8 GWh by 2028. 90% of this demand will be for utility-scale BESS with battery capacity of 258 GWh. Residential BESS and industrial & commercial BESS will each account for 5.5%. The total annual market for all types of Li-ion battery BESS is anticipated to grow from approximately 8.2 billion USD in 2022 to approximately 40 billion USD in 2028 [39,40]. The battery cell market spans 70% of the total battery market [39]. The most expensive component of the cell is the cathode, with cobalt contents such as NMC, NCA, etc. Nonetheless, replacing the cobalt contents with non-toxic materials is a priority and the advancement in batteries such as LFP, the cost of cells should decline in the near future. The following trend can be identified in BESS applications:

- Reducing cell material costs
- Cell chemistry Li-ion (High energy density such as NMC, and Cobalt free such as LFP), Na-ion, NaS, flow batteries, and Solid-State Batteries (SSB) [41].
- Use of large cell formats to improve energy density and reduced BMS effort
- Second life batteries of EVs will increase in BESS applications
- Increasing the battery pack voltage (now 48–1000 V DC) to 1500 V. In PV and EVs applications, the trend is towards 1500 V. This will result in lighter cables, lower losses and faster charging speed for batteries [42].
- BMS architecture: The trend is from centralized towards modular BMS. Distributed BMS is still under research and development [43].
- Safety enhancement: Fuses are the fastest and cheapest choice for pack protection. This could be in future replaced by solid-state breakers which do not need replacement [44].
- Eco-compatible batteries with circular economy driven design [45].

3.2. Flow batteries

Physical principle: A flow battery, also known as a redox flow battery (RFB), operates on the principle of redox reactions, where oxidation and reduction processes occur in a fluid electrolyte. The main components of a flow battery include two tanks of electrolyte solutions, one for the catholyte (positive side) and one for the anolyte (negative side), and a cell stack where the electrochemical reactions take place. Flow batteries store energy in liquid electrolytes, which are pumped from external reservoirs into the cell stack during charging and discharging cycles.

Types: Vanadium is currently employed in the majority of flow batteries. However, there are several emerging flow battery technologies that do not include vanadium: (*i*) Zinc-Bromine Flow Batteries, known for their high energy density and their suitability for a variety of applications [46]; (*ii*) Iron Flow Batteries, based on iron salts in different oxidation states. They are cost-effective due to the abundance of iron [47]; (*iii*) Organic Flow Batteries, more environmentally friendly and they can be engineered to have diverse properties [48]; (*iv*) Sodium-based Flow Batteries, aiming to capitalize on sodium's cost-effectiveness and abundance [49].

Grid Applications: Redox flow batteries are suitable as stationary energy storage mainly for industrial applications (backup power, load management), at distribution grid level (MW and MWh range, grid

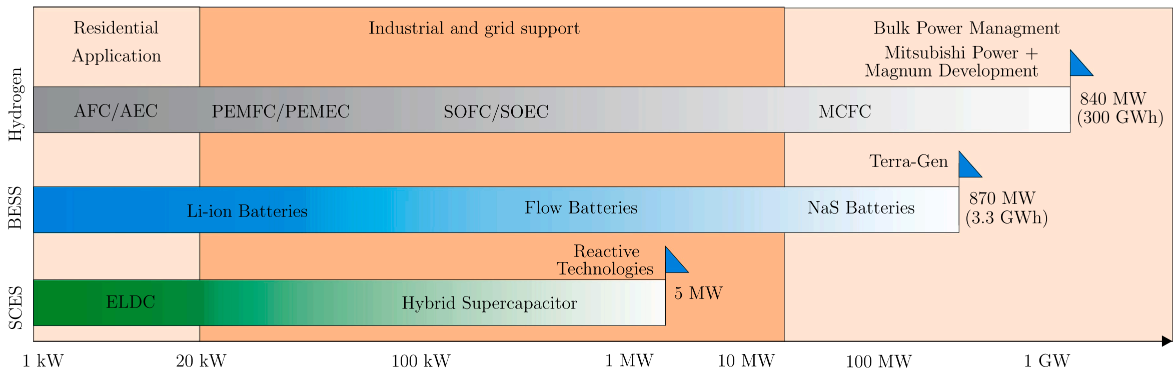

Fig. 3. Power horizon of electrochemical energy storage systems. Flags show the world's largest projects which are reported.

management), and for off-grid applications and minigrids (kW and kWh range, long-term storage) [40].

Market Perspective: RFBs shows promising market potential in energy storage solutions. Various research projects have focused on enhancing RFB technology through electrode screening, characterization, optimization, and control system development [50–55].

3.3. Supercapacitors

Physical principle: Supercapacitor energy storage systems (SCES), also known as ultracapacitors or electrochemical (or electrostatic) double layer capacitors (EDLC), have much higher energy density of the conventional electrolytic capacitors. Both electrodes are usually created from aluminum foils coated with carbon-based compounds. The separator only needs to provide electronic isolation and it is moisturized in an electrolyte. The energy is stored by creating double layers at the interface between the electrolyte and the electrodes.

Types: There are different variants of SCES, such as pure supercapacitor and hybrid supercapacitor. The latter category is divided into battery-supercapacitor, able to reach energy density beyond 10 times of a pure supercapacitor, and pseudocapacitor, with not fully electrostatic capacitance [56,57]. An optimal design of the SCES stack, in particular choosing the optimal discharge ratio [58] and of the power converter to boost the voltage [59], could lead to a significant improvement of the volume in the order of 50% in comparison to not-optimized solutions.

Grid Applications: SCES can be used either to provide short term energy support (e.g., in case of power quality issues such as faults) or in combination with more energy-dense storage technologies. For example, SCES respond quickly to high peak power demands with high cycling, wider operating temperature ranges, and extended system capacity life, and thus batteries may benefit from their combination. Large SCESs are widely used for pitch control in wind turbines to prevent destruction of the turbine, while on the opposite are not widely used in PVs [60].

Market Perspective:

The global market for supercapacitors was approaching one billion USD in 2021. Taking into account the investment of 0.5 billion USD by large manufacturers, the market could reach more than 3.5 billion USD in 2041, with an upside forecast up to 6.5 billion USD in 2041. The share of grid applications will cover almost 15% of the market [61]. Currently, the target is to substitute the battery with supercapacitor in several applications. However, some challenges such as low energy density and high self-discharge should be solved [62]. These requires large SCES with integrated power electronics to ensure safe and optimal operation. Balancing technologies for supercapacitors, including power electronics-based solutions, are extensively reviewed in [63]. The power electronics diffusion in supercapacitors can still improve in reliability [64].

3.4. Flywheels

Physical Principle: A flywheel energy storage system (FESS) preserves kinetic energy by rotating a cylindrical mass. The stored energy is linearly dependent from the mass and quadratic from the rotating speed.

Types: There are many types of FESS based on its structure [65]. Materials employed in the construction of flywheel disks are usually steel or composite materials. Siemens is currently retrofitting existing synchronous machines with large flywheel masses in order to make them working as FESS [66]. It can easily provide rotating inertia, but, as a drawback, it requires a bulky installation. Other companies, such as Stornetic [67], are developing light-weight, high-speed flywheels, able to achieve higher energy density by means of high-speed rotation (>45 000 rpm). The bearings type can differentiate in (i) Permanent (Passive) magnetic bearing (PMB), (ii) Active magnetic bearing (AMB), (iii) Superconducting magnetic bearing (SMB), and (iv) Bearing-less machine (BM).

Grid Applications: While BESSs excel at storing significant energy, they are hindered by limited ramp rates due to internal chemical processes. On the other hand, Supercapacitors boast high power delivery capabilities but have lower energy storage capacity. Positioned between these extremes [68], FESSs offer faster ramp rates than BESS and greater energy storage than SCES. Additionally, FESS enjoys an extended lifespan compared to BESS, making it ideal for mitigating microgrid frequency variations [68,69].

Commonly explored applications of encompass power quality enhancement, frequency regulation, voltage sag management, integration of renewable energy generation, uninterruptible power supplies, and transportation [70,71]. The utilization of FESS primarily occurs in the context of smoothing output power from renewable resources such as wind turbines and PV systems [72–75] or hybrid systems with high-energy density storage solutions like Li-ion batteries [76].

Market Perspective: Despite ongoing advancements in materials and engineering, FESSs face competition from lithium-ion batteries in terms of costs. FESSs have higher upfront costs than electrochemical batteries, with some systems costing nearly ten times more than Li-ion batteries of similar energy capacity. However, they offer competitive cost per (kWh*cycles), considering increased charge/discharge cycles. Unlike batteries or supercapacitors, FESSs involve moving parts, leading to greater uncertainty in failure modes. This issue is particularly notable in composite flywheels due to their higher operational speeds and less predictable mechanical properties [77].

3.5. Hydrogen

Hydrogen can be produced from water electrolysis or fossil resources and can be burned by fuel cells to produce electricity. Based on [78], H_2 production from fossil resources can be divided to black, gray, and blue H_2. H_2 production from water electrolysis can also be

Table 1
Characteristics of some energy storage systems.

Technology	BESS [84,85]				FESS [86,87]	SCES [88]	Hydrogen (fuel cell) [89–91]	SMES [92,93]	PHES [94,95]	TES [96]	GES [97]
	Lead–acid	VRB	Li-ion	NaS							
Specific energy (Wh/Kg)	25–50	10–30	75–200	150–240	5–150	0.2–10	30–45	0.5–5	0.5–1.5	150–250	150–250
Specific power (W/Kg)	75–300	80–150	500–2000	150–230	180–1800	7000–18 000	500	500–2000	0.01–0.12	10–30	10–30
Round-trip efficiency (%)	75–85	75–90	85–97	75–90	85–95	80–95	33–42	95–98	70–87	75–90	80–90
Lifetime cycles (100% depth of discharge)	200–1000	<13 000	1000–10 000	2500–4000	$<10^6$	$<10^6$	20 000	$<10^6$	20 000–50 000	N.A.[b]	N.A.
Lifetime cycles (year)	5–15	5–10	5–15	5–15	15–20	10–30	15–20	20–40	40–80	5–15	20–40
Self-discharge	Low	Very low	Medium	Medium	High	High	Very low	Medium	Very low	Very low	Very low
Discharge time (ms-h)	s-h	s-10 h	m-h	s-h	ms-15 m	≤1 min	s-24 h	≤1 min	h-24 h+	h-24 h+	1–8 h
Average capital cost (USD/kW)[a]	2140	2512	2512	2254	867	229	3243	322	1413	70–3000[c]	250
Average capital cost (USD/kWh)	437	54	546	343	4791	765	540	5350	58	11–73	16

[a] The capital costs are calculated based on each technology's typical discharge time. The average value is the median of the whole price range adopted from the method in [89].
[b] N.A.: not applicable.
[c] The cost of TES depends on the type of storage (Sensible heat, latent heat, …).

divided to green, pink, and yellow H_2. Nowadays, the H_2 is mainly produced from fossil fuels which is not environmental-sustainable.

Physical Principle: The hydrogen storage concept is based on producing, storing and transmitting H_2 to the user end via hydrogen pipelines, instead of relying on electrical cables. H_2 can be either reconverted in energy by means of fuel cells processes, or burned in gas-turbines adapted for hydrogen use.

Types: Water electrolyzers can be classified based on their electrolyte materials. There are three types of water electrolzers [79]: Alkaline Electrolysis Cell (AEC), Proton Exchange Membrane Electrolyzer Cell (PEMEC) with solid polymer electrolyte, and Solid Oxide Electrolysis Cell (SOEC). Fuel cells can be classified as: Alkaline Fuel Cells (AFC), Phosphoric Acid Fuel Cells (PAFC), Molten Carbonate Fuel Cells (MCFC), Proton Exchange Membrane Fuel Cells (PEMFC), and Solid Oxide Fuel Cells (SOFC). SOFC is the same SOEC in the regenerative mode which achieves electrolysis of water.

Grid Applications: Hydrogen storage systems can provide a variety of ancillary services including frequency and voltage control, black start capability, and load congestion management [80–82]. There are still several open points on the dynamic capability of hydrogen-based resources to provide fast dynamic services, such as primary frequency control. A more extensive modeling and experimental validation of hydrogen-based energy storage systems are required to assess they impact on the grid.

Market Perspective: Currently, AEC electrolyzers dominate the market with 75% of global production capacity and PEMECs capacity is estimated at 25% of the total production. The share of SOECs for H_2 production is very low, but potentially growing [81]. By 2050, 60%–80% of hydrogen production is expected by green H_2 which can be approximated 4500 GW. This capacity mainly includes industry sectors such as steel, transportation and power generation/storage. A strong correlation between the development of renewable energy capacity and green H_2 can be considered [83].

3.6. Superconducting Magnetic Energy Storage (SMES)

Physic Principle: Superconducting Magnetic Energy Storage (SMES) systems function by storing energy within a magnetic field generated by a Direct Current (DC) passing through a superconducting coil, that cooled below a critical temperature, enables almost lossless current flow. Niobium-titanium is also commonly used for this purpose, with a critical temperature of 9.2 K [98,99].

Types: There are two types of superconducting materials used in SMES systems [100,101], (*i*) Low-temperature superconductor magnet (LTS), that use low temperatures (30 Kelvin) superconducting materials; and (*ii*) High-temperature superconductor magnet (HTS), that use higher temperature (77 Kelvin) superconducting materials.

Grid Applications: SMES, due to their high costs and limited superconductor supply-chain, had limited applications in grids, mostly limited to power quality applications. Current studies involves SMES technology as short-term energy storage for power systems due to their high efficiencies, reaching up to 95%, especially in large-scale installations [102–104].

Market Perspective: Despite some successful SMES testing and demonstration in international agencies and governmental bodies [105–108], the significant costs for SMES systems has hindered their widespread adoption in the market. However, developing HTS (working temperature above 77 K) and second-generation superconducting wires presents a promising way achieving high magnetic flux density (e.g., 20 tesla) while reducing costs. Enlarging of the supply chain in superconducting coils and auxiliary components can bring further manufacturing costs reductions [93,109]. Currently, the SMES cost varies widely depending on the materials used, ranging from $700 to $10,000 per kWh-h, while power costs can vary from $130 to $515 per kW [110,111].

3.7. Thermal Energy Storage (TES)

Physic Principle: Thermal energy storage (TES) systems can preserve either heat or cold for future use, adaptable to varying conditions like temperature, location, or energy demand [112]. A typical TES setup comprises a storage medium housed in a reservoir or tank and a chiller or built-up refrigeration system, piping, pump(s), and controls [98].

Types: These systems are typically divided into three primary types [113]: (*i*) Sensible heat storage (liquids or solids), (*ii*) Latent heat storage or phase change (solid–solid, solid–liquid, liquid-gas), (*iii*) Sorption and chemical energy storage (thermochemical storage). And depending on the operational temperature range, TES can be categorized into two groups [114,115], such as Low-temperature TES or high-temperature TES, encompassing latent (fusion) heat TES, sensible heat TES, and concrete thermal storage.

Grid Applications: A TES system responds more slowly to grid changes than other ESSs, due to its inherent thermal capacity, which influences thermal transients. TES systems are designed to decrease power demand during peak periods and they are typically found in centralized systems. For example, the city of Kiel in North Germany, has equipped the local gas-thermal plant with a TES system to minimize the thermal power peak request during winter periods [116]. Additionally, cold TES represents a distributed form of TES utilizing refrigeration and air conditioning technologies managed via a virtual power plant to facilitate load shifting. Cold TES has received considerable attention for peak load shifting in applications such as commercial buildings and semiarid cities [117,118]. An exemplary application for TES are thermal solar plants with molten salt storage technology, typically a mixture of sodium nitrate and potassium nitrate, that can be heated to temperatures exceeding 500 °C (932° F), storing energy in large insulated tanks [119]. The main advantage of this application lies in its scalability depending on the available storage tank. However, the complexity of thermal systems, especially those operating at high temperatures with corrosive salts, requires rigorous maintenance regimes, and these plants require a significant amount of land and are usually located in regions with high solar irradiance.

Market Perspective: The TES system can store substantial energy with minimal associated risks, featuring a daily self-discharge loss of approximately 0.05%–1%. The reservoir offers commendable energy density and specific energy, ranging from 80 to 500 Wh/L and 80 to 250 Wh/kg, respectively [120]. Moreover, the system demonstrates economic viability with relatively low capital costs ranging from 3 to 60 $/kWh [121,122]. However, TES systems typically exhibit low cycle efficiency, typically around 30%–60% [123]. Despite this drawback, TES has found widespread application across various domains, including load shifting and electricity generation for heat engine cycles. Some the biggest developed TES are the 280 MW in the Solana Solar Generating Plant project in the USA and 160 MW in NOOR I CSP Solar Plant project in Morocco [95].

3.8. Pumped Hydro Energy Storage (PHES)

Physic Principle: Pumped hydroelectric energy storage operates by storing energy in potential form, pumping water from a lower- to a higher elevation reservoir. During off-peak times, when electricity is cheaper, the pumps are powered to lift the water from the lower reservoir to the upper one. Then, when power demand is high, the stored water is released through hydro turbines, generating electric power.

Grid Application: Pumped storage is widely regarded as the top choice for boosting renewable energy integration, offering peak shaving and dispatching capabilities. With its efficiency being between 70 to 80%, they have an installed capacity between a few hundred kW to thousands of MWs [124,125].

Some of the advantages of PHEs are [126–128]: long lifespan, fast response time, large storage capacity, low operating costs, high efficiency. The main drawback lies in the large space required by the reservoir, that needs to be located near a constant water source.

Market Perspective: Presently, the most economically viable technology for substantial energy storage is Pumped Hydro Storage Plants (PHSP). Nonetheless, significant investment requirements and the necessity of suitable geology and topography are crucial considerations. Additionally, merely having abundant water availability does not assure the suitability of a location for plant construction [129,130].

3.9. Gravity Energy Storage (GES)

Physic Principle: Gravity energy storage technology (GES) operates similarly to PHES by utilizing the vertical displacement of a heavy solid object within a gravitational field to store energy [131]. For instance, during periods of excess power in the grid, energy is absorbed to elevate the weight via electromechanical mechanisms, thereby storing gravitational potential energy. Conversely, when there is a deficit in power within the system, the weight is lowered to return stored energy to the grid [132].

Types: The types of GES are as follows [132]: (*i*) Tower Gravity Energy Storage (TGES), (*ii*) Mountain Gravity Energy Storage (MGES), (*iii*) Advanced Rail Energy Storage (ARES), (*iv*) Shaft Gravity Energy Storage (SGES).

Grid Applications: GES presents an opportunity for cost-effective, long-term energy storage solutions with extended operational lifespans and low generation capacity. This addresses the current need for energy storage technologies capable of providing capacities ranging from 1 to 20 MW and accommodating storage cycles lasting from 7 days to three years. Furthermore, scaling up the technology is feasible, enabling its application in grid storage scenarios to deliver ancillary services [133,134].

Market Perspective: Gravity energy storage is a storage concept currently in the development phase. At present, only demonstration projects are available, and there are no large-scale installations of this system. Developers claim an efficiency of approximately 80% for the system [135,136].

4. Power electronics integration for ESS

The primary functions of a Power Electronics Interface for ESS is to adapt the voltage (e.g., from AC to DC), to offer continuity of service [137] and optimal energy management.

A coordinated design of the battery pack, of the interface-converter and a customized charging strategy could lead to higher efficiency [138]. Several architectures and topologies have been suggested for years [139–141]. Energy storage systems can be either integrated in the electric grid directly with a dedicated converter, or through another device for example a STATCOM [142], a charging station [143] or even a Smart Transformer [144], as shown conceptually in Fig. 4. The advantages of inserting the storage in another device is associated to the cost saving by sharing the power electronics stages and by offering services by means of ESS active power capability. Two respective examples are represented by a STATCOM with storage which can better control the voltage [142], and a Smart Transformer, which can control reactive power and/or voltage in more effective [144]. In the following, several examples of power electronics integration of ESS are described.

4.1. Full power electronics solutions

4.1.1. Transformer-based solutions

Energy storage units are usually installed in low-voltage packs, in order to reduce insulation costs and facilitate the maintenance of operators. However, reaching a certain power level, a connection to higher voltage networks (e.g., medium voltage) may be required. A standard solution is the interposition of a transformer between a low voltage converter and the higher voltage grid as in Fig. 4a: it offers not only the voltage transformation, but, thanks to the galvanic insulation, it guarantees protection against lighting and over-voltages.

4.1.2. Transformerless solutions

With the increase of the power rating, installing line frequency transformers can be bulky, lossy and costly [139]. Power electronics,

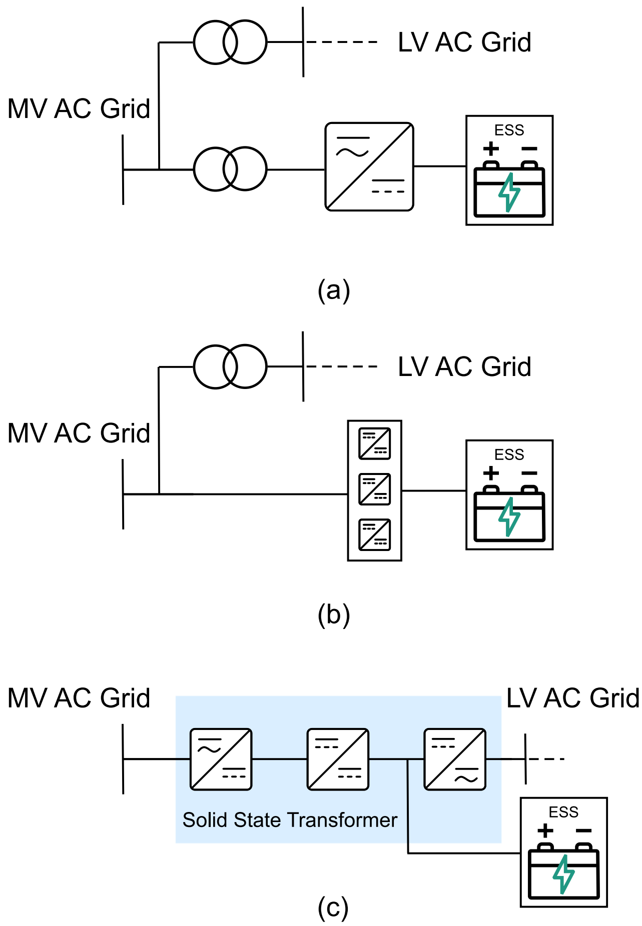

Fig. 4. Integration of ESS into grid: (a) transformer-based direct connection with a dedicated converter, (b) transformerless direct connection with a dedicated converter and (c) multi-stage solution with the ESS integrated into another converter, e.g., Solid State Transformer.

by means of a series connection of switches, enables higher voltage ratings, and thus a direct connection of the converter to higher voltage networks (e.g., medium or high voltage as shown in Fig. 4b). These solutions, called also multi-level converters, switch the semiconductor modules in coordinated way in order to have a sinusoidal output. Despite a higher complexity of these solutions, the lack of a transformer, the reduction of the output filter, and the need for lower switching frequencies for each semiconductor device can reach high efficiency. Among the current solutions, Cascaded Half-Bridge (CHB) converters and Modular Multi-level Converters (MMC) are the most used ones [145]. The MMC is basically created by the combination of two CHBs and can make use of Half-bridge cells. Some works consider the possibility to integrate ESS in each cell [146,147], allowing a better management of the single submodules of an ESS. However safety constraints restricts practical implementation of this solution.

4.1.3. Multi-stage solutions

In the conventional approach, which involves a single power conversion stage, the energy storage system is connected directly to the DC link of the converter (Fig. 4c). Increasing its working voltage requires larger serially-connected cell strings, leading to reductions in system-level reliability. Multi-stage power conversion structures offer a solution to these scalability and reliability limitations. One form of multi-stage approach uses power electronics to decouple the storage system voltage from the inverter's DC link voltage. The simplest form is a bidirectional DC-DC converter placed between the battery system and the DC link. The DC link may serve as a common point of connection for multiple DC-DC converters, each interconnecting an individually controllable sub-assembly of storage resources [148]. In this configuration, these storage sub-assemblies (e.g. individual storage modules) are fully decoupled, eliminating the impact of non-uniformity on performance. Designing DC-DC converters with high voltage conversion ratio, bidirectional power flow, and high efficiency over a wide range of load conditions is a challenging problem. Alternatively, the DC-DC converters of individual sub-assemblies may connect in a series configuration. This requires isolated DC-DC converters and is a more challenging system to control, but it is capable of achieving very high DC link voltages, even when converters with only modest individual voltage gain are employed [148]. With DC link voltage of 10 kV or greater, multi-level inverter topologies may be used to connect directly into medium voltage AC systems without a line-frequency transformer. This system shares many of the benefits of the parallel multi-stage approach, but is able to reach higher power capacities, and it can directly leverage mature multi-level inverter technologies with decades of proven performance in motor drive applications.

4.1.4. Solid State Transformers (SST)

SST is a power electronics-based transformer that provides more than the simple voltage transformation and galvanic insulation of classical transformers. Due to several power electronics stages, the SST is able to provide grid services and enhanced control capabilities [149, 150] (see Fig. 5). The availability of DC links, either at medium- or low-voltage level, offers a natural connection point for energy storage systems [151], avoiding an additional DC/AC conversion stage with consequent increase of energy efficiency [152]. Recent literature have integrated ESSs for increasing the power flexibility of the SST-fed grid. Voltage control [144], increased hosting capacity for renewables [153] and electric vehicle charging stations [154] are just few applications for integrating ESSs by means of Solid State Transformer. Although there is no commercial product available yet, the major power electronics manufacturers have on-going projects and demonstrators to have a product ready in the next few years.

4.2. Partial Power Processing (PPP) solutions

PPP offers the possibility to integrate energy storage sources and to regulate the power flow between two or more ports to allow maximum power point or maximum efficiency tracking with devices rated below the nominal voltage and current. Classical examples can be found in electric vehicle charging stations, if the available charging capacity is beyond the capacity at Power of Common Coupling (PCC); between a photovoltaic system and the grid, to achieve Maximum Power Point Tracking (MPPT) while keeping the power inflow smooth; in smart homes where multiple devices must be connected and optimally coordinated. The PPP envisions that the ESS can be integrated and controlled not necessarily using a power processing unit rated for the full voltage and/or for the full current of the connected system [155]. By adopting the PPP concept, the losses and costs of the power conversion unit are consequently reduced, although it may cause a negative impact on the ESS safety [156]. The PPP unit can connect ESS between two ports such as that the rated current is flowing through the PPP unit with reduced voltage. Alternatively, an isolated PPP unit can offer more input/output combinations leading to control part of the processed power under reduced voltage level [157]. The PPP concept is shown in Fig. 6. This leads to interesting advantage in terms of reducing costs and increasing of efficiency in PV-plants [158] and in electric vehicle charging stations [143].

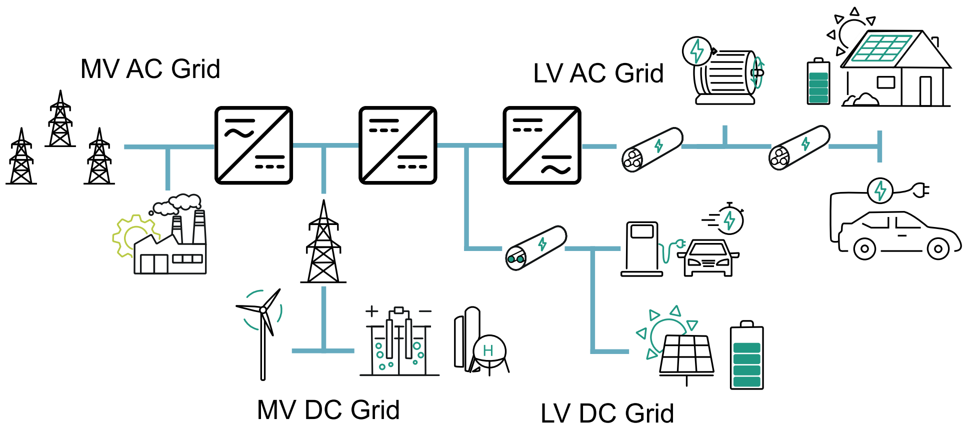

Fig. 5. Solid State Transformer enables the connection of more energy resources and storage technologies at MV and LV levels, both for AC and DC systems.

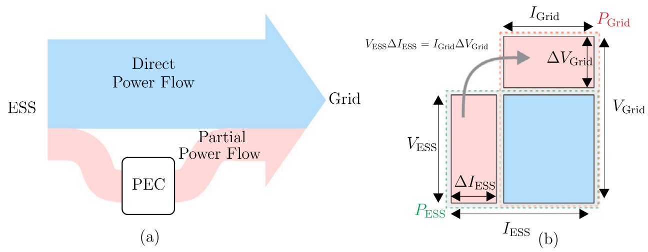

Fig. 6. Partial power processing: (a) principle and (b) use of part of the power flow, leaving the main part uncontrolled and allowing voltage or current to be controlled.

4.3. High efficiency wide-bandgap semiconductor devices

Wide-Bandgap (WBG) semiconductor materials, such as Silicon-Carbide (SiC) and Gallium-Nitrade (GaN), have revolutionized in the last years the semiconductor industry, enabling faster and more efficient switching characteristics in power electronics converters [159]. These materials are characterized by a three times higher Bandgap energy than Silicon devices. This feature allows at building devices with higher blocking voltage, thermal conductivity (for SiC) and switching frequency, while lowering the leakage current [160]. Making a converter switching faster allows to have cleaner output voltage waveforms and to reduce the converter footprint, due to required smaller output filters and smaller magnetics. This is of particular advantage for higher voltage and higher power converters. Currently, several challenges are addressed in academia and industry: higher-voltage devices are developed, for example SiC devices at kV level, targeting to replace high power IGBT and finally thyristors [160]. The reliability of the switches is currently being brought to IGBT standards, in particular for GaN devices [161]. The manufacturing capability is being built-up, decreasing at the same moment the devices costs and delivery times [162].

5. Hybrid energy storage systems

Every ESS described in the previous sections has its own limitation, constraining its applicability in the field. An optimal application requires high energy and power capabilities. Therefore, there is a need to develop systems that combine two or more ESSs to create a Hybrid Energy Storage System (HESS) [97,163]. Combining multiple energy storage systems into a hybrid setup reduces initial costs by covering average power demands, boosts overall system efficiency, and extends storage capacity while optimizing operation to minimize stress on components and enhance longevity.

HESS requires careful design to handle charging, discharging, and energy distribution among storage components efficiently, ensuring smooth operation and optimizing overall performance. Several connection architectures have been proposed in literature for hybrid energy storage systems [164,165], varying for their AC or DC current system, or for series and multi-level connection. Fig. 7 illustrates four commonly examples of HESS topologies consisting of two energy storage, such as BESS and SCES.

- **AC connection** The AC connection represents the most standard approach to connect energy storage systems, that, as independent units, are connected separately to the AC grid. The connection occurs only at control level, and it is based on power and energy management strategies. Despite the need for several conversion stages (usually a DC/DC for power control and a DC/AC for grid connection), this solution offers currently higher modularity because each system can be bought off-shelf in the market, without any tailored solution requirement.
- **DC connection** The majority of energy storage systems are based on DC systems (e.g., batteries, supercapacitors, fuel cells). For this reason, connecting in parallel at DC level more storage technologies allows to save an AC/DC conversion stage, and thus improve the system efficiency and reduce costs. The DC connection can be realized in different way [166,167]: (*i*) by passive connection, where the storage elements are connected to the DC without any converter in between; (*ii*) semi-active connection, where one of the resource is actively controlled by a power converter, and the others are passively connected; (*iii*) active connection, where all the resources are power-electronics connected. While the active connection offers higher power controllability, the semi-active and passive connection allow at saving in components and a faster access to the energy stored (e.g., with capacitors directly connected to the DC link).
- **Multi-Port Converter connection** An alternative to the connection of different energy storage systems (e.g., BESS and SCES) through an AC or a DC connection is the use of a single power converter either non-isolated [168], mostly for on-board applications, or isolated [169,170] for stationary applications where isolation is needed for safety and protections.
- **Modular Multi-Level connection** An interesting approach proposed in the last year is to use multi-level converters to connect different storage technologies at the sub-module level. This approach has been already proposed for integrating battery energy storage systems [171,172], and it has been proposed for hybrid energy storage systems as well [173,174]. This solution offers higher power/energy modularity, and at the same time it can increase the performance of the DC/AC converter. As a drawback, the safety may not be guaranteed in all cases due to the lack of

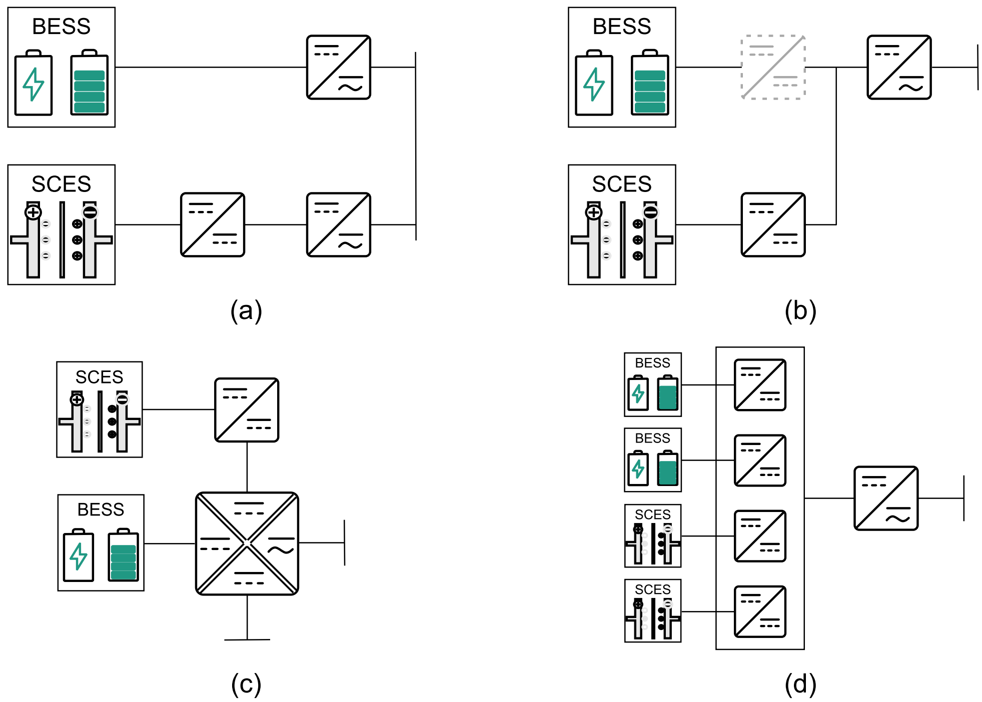

Fig. 7. HESS connections with Battery Energy Storage System (BESS) and Supercapacitor Energy Storage (SCES) (a) Parallel AC connection, (b) Parallel DC connection, (c) Multi-Port Converter connection, (d) Modular Multi-Level connection. In gray are stages that may be included in the topology.

an intermediate power electronics stage. To protect against short circuits at ESS level, additional protection systems (e.g., breakers) may be required.

Various control strategies have been developed and applied in HESS setups, tailored to diverse applications such as renewable energy integration, grid stability, and electric vehicle propulsion [175,176]. Fig. 8 shows an example of power management for HESS. In this figure, the overall power management system receives the contingency on the frequency and voltage (Δf and ΔV) and dispatches reference values for active and reactive power (P and Q) to the respective devices and DC/AC converters. Subsequently, the management system of each device communicates control signals to regulate its operations effectively.

The configuration and storage capacity of each power source impacts directly the hybrid energy storage system performance and longevity [177]. This highlight the need for precise capacity sizing and optimization in hybrid energy storage system research, with clear focus on intelligent control approaches and state-of-charge management strategies [178]. The control strategies for HESS are divided into two basic classes, such as "Rule-based" and "Optimization-based" [179]. The first one allows to establish a direct link between input and output variables. In the second category, the output is determined by an optimization algorithm, that can either be global (e.g., all the system variables are known [180]) or local with partial knowledge of the system status.

5.1. Potential and applications

HESS are commonly integrated in applications where both power and energy features are required. Examples of these applications in the power sector involves:

- Ensuring grid stability, by providing at the same time fast and lasting energy provision.
- Optimizing the life-time of energy-dense energy storage systems using power-dense storage technologies.
- Offering market services, such as peak demand response and peak load shaving/shifting.

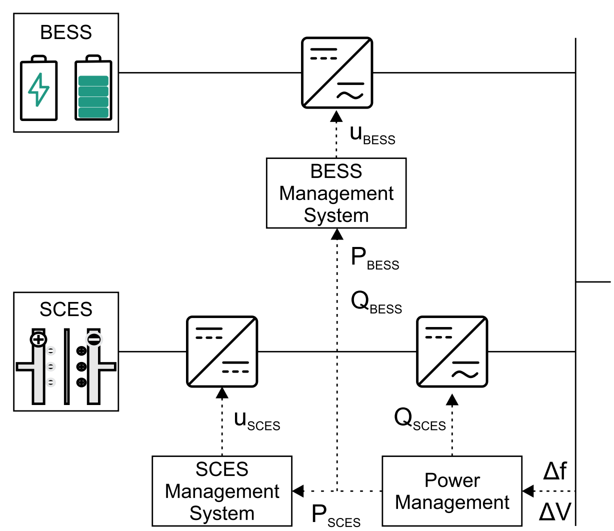

Fig. 8. Example of HESS management system architecture.

Several instances demonstrate real-world applications of HESS, with notable examples below showcasing its various uses [163]:

- HESS with power to heat and battery with a capacity of 20 MW and Li-ion and NaS battery with a capacity of 11.5 MW, both in Germany for frequency regulation
- HESS with lead–acid batteries and lithium-ion capacitors with 1.5 MW capacity in Japan for renewable energy integration
- HESS with supercapacitor and battery with a capacity of 1.2 MW in the USA for peak demand response and load shifting

Although HESSs present a promising solution by combining multiple energy storage technologies to enhance performance and address specific challenges, they encounter several complexities. The challenges of HESS include integration issues, compatibility concerns among diverse technologies, higher upfront costs, and the need for sophisticated control and optimization methods. Sizing and scaling hybrid systems, ensuring safety and reliability, and assessing their lifetime environmental impact are additional challenges [181,182].

6. Services offered for a secure supply in longer time windows (>10 h)

One of the major concern is to supply power during periods where both solar and wind power are not available. Long-term storage (i.e., with a discharge time at nominal power more than 10 h) plays a vital role.

Long Duration Energy Storage (LDES) solutions can be divided in two categories [183].

Inter-day LDES: Used to shift power by 10–36 h. For example, to shift excess generation a night or the next day to serve peak demands. Technologies used include mature non-Li systems like mechanical storage technologies and flow batteries.

Multi-day/week LDES Used to shift power over long time periods 50+ h. For example, to serve as resilience applications, buffer load during multiple days of low wind and solar, and to reduce transmission over-build to support variable renewables.

The $/kWh value of LDES is a function of discharge duration. In a study from Abertus et al. [184], it was estimated that in the US, the value of a 10+ application is $70–$80/kWh, the value of a 50+ h application <$20/kWh, and 50+ h application <$20/kWh. As a comparison, Li-ion in the same reference was placed at $200–$300/kWh. For this reason, Multi-day LDES technology choices are limited to systems based on low-cost materials and long lifespan. Of the technologies listed in Section 3, hydrogen and gravity based systems are being considered.

Advanced Clean Energy Storage (ACES) Project, Utah, USA: This project is focused on creating a green hydrogen storage facility. It uses electrolysis powered by renewable energy sources to convert water into hydrogen, which is then stored underground. The stored hydrogen can be used to generate electricity over long periods, particularly when renewable energy generation is low [185].

Hydrogen Storage in Mainz, Germany: The Energiepark Mainz uses wind energy to produce hydrogen through electrolysis. This hydrogen is then stored and can be used in various applications, including re-conversion to electricity, fuel for hydrogen vehicles, or as a gas for industrial processes [186].

Port of Leith, UK: Located in the UK, this project utilizes a gravity-based storage system where weights are raised in a deep shaft to store energy and dropped to generate electricity. The technology provides a solution for durations from a few hours to several days [187].

When hydrogen and gravity systems are deployed at large scale, additional technical considerations become important.

Hydrogen: Storing hydrogen over the long term presents several challenges: (i) Hydrogen can lead to the degradation of metals through embrittlement; (ii) it has a high propensity for leakage due to its small molecule size, which can escape from containment systems; (iii) when stored as a liquid, hydrogen must be kept at extremely low temperatures (around −252.8 °C) [188,189]. As an alternative, Ammonia is being considered as a medium for hydrogen storage [190]. This is due to its high hydrogen volumetric density, low storage pressure, stability, and available distribution network. Several demonstration projects are being built around the world [191].

Gravity systems: Gravity systems also have some drawbacks: (i) They require significant infrastructure and space and large upfront investment; (ii) their design and maintenance involve complex engineering, especially in creating and controlling the mechanisms that lift and lower weights; (iii) currently, there are only a few commercial deployments of gravity-based energy storage [132].

An alternative approach is based on distributed energy storage resources that can be made available for aggregate LDES services. One of the early attempts to aggregate resources for LDES was from Green Mountain Power, a utility in Vermont, that offered residential customers Tesla Powerwall batteries as part of a grid stability and backup power program [192]. In Europe, Sonnen is testing a community battery systems to allow solar energy generated by residential photovoltaic (PV) systems to be stored collectively [193].

7. Services offered for a secure supply in medium time windows (>1 h)

This section deals with steady state problems that ESS can help solve with a time horizon of a few hours, such as renewables power intermittency. To solve this problem, for a given set of energy storage systems, their charging and discharging have to be scheduled to ensure availability when required. Thus, we identify three building blocks of secure supply for longer time windows: the concept of Dispatchable Feeder, optimal dispatch, and peak-shaving services.

7.1. ESS control for smoothing renewables power: Dispatchable feeder

The use of probabilistic forecasts, as demonstrated in [194], is highly beneficial for quantifying the uncertainty associated with future power demand and generation, especially those that rely heavily on renewable energy sources. In [195], challenges in wind power forecasting are identified, such as biases in weather and wind power forecasts, and the need to account for spatial and temporal dependencies. The study provides insights into the impact of post-processing strategies on probabilistic wind power forecasts, highlighting the benefits of post-processing the final wind power ensemble.

A potential solution to forecasting error is represented by the Dispatchable Feeder (DF) concept [196]. As depicted in Fig. 9, the DF consists of a residential building connected to a low-voltage grid with a battery, rooftop PV and residential load. In [197–200] it has been shown, that a DF can compute and follow a dispatch schedule, that respects the limits of the system. The forecasts that are used for the schedule computation should be tailored to the optimization problem, in order to achieve high quality solutions [198,199]. In [197], the problem was solved with probabilistic forecasts to respect security levels. An experimental proof of concept has been described in [201] and is currently put into action at the Energy Lab at Karlsruhe Institute of Technology [202].

Solving for secure schedules for larger parts of power grids cannot be addressed by small scale schedules like the DF. There are multiple frameworks that consider the combination of an electric grid with RES, conventional generation and storage under forecast uncertainty. In [203], the authors develop a framework with linearized power flow formulation, which considers Gaussian uncertainty with chance constraints. The probabilistic terms are replaced by equivalent analytical terms, such that the problem is recast into a second order cone program, which is comparatively cheap to solve. In a subsequent publication [204], the method is applied to a model of the Turkish grid.

The coordination of storage and resources among multiple operators with deterministic forecasts is investigated in [205], with a distributed optimization algorithm, that can preserve data privacy among the operators.

7.2. Optimal scheduling of ESS

The capacity of all storage systems is limited, and the available energy depends on their respective state of charge. In order to be able to securely supply energy at times when it is needed in an economically efficient way, careful scheduling of charging and discharging is needed. To be able to compute such schedules, one has to integrate forecasts of load and RES production on the one hand, and the physical parameters of the system on the other hand into an optimization problem. Such problems have to be solved on different levels of the system: at one

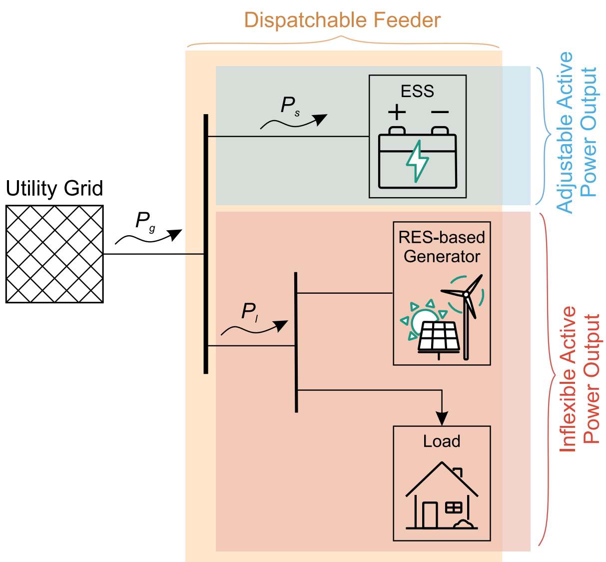

Fig. 9. Schematic diagram of a generic dispatchable feeder. *Source:* Adapted from [197].

extreme, regarding congestion and load management, the entire grid has to be considered over longer time horizons by operators. On the other end of the spectrum, small-scale units, such as residential houses with PV and battery storage, can optimize their own dispatch schedule. In all cases, the main problem is the uncertainty of the forecasts, which has to be considered to compute reliable schedules. The computation of reliable schedules across the entire system and the coordination among the different levels is a challenging and open question. The general scheduling problem is an optimization problem of the form:

$$\min \sum_{t=0}^{T} cost(\text{energy}, \text{forecast}) \tag{1a}$$

$$s.t. \quad \text{physical constraints} \tag{1b}$$

$$\text{Security constraints} \tag{1c}$$

It is solved for the minimal cost of charging and discharging of the storage (1a) over a discretized time horizon $t \in [0, T]$ based on the available forecasts, while respecting the physical constraints such as line limits, capacity limits, and power limits (1b). In some applications, the cost function can also include other factors such as frequency or voltage deviations. In general, security constraints (1c) must be included to account for uncertainty or contingencies. Depending on the assumptions and simplifications, the difficulty of the problem can range from common optimization problems [203] that can be solved with standard solvers, to intractable mixed-integer non-linear programs [206]. The difficulty of the optimization problem generally rises with the following properties:

- System size, number of modeled components
- Inclusion of probabilistic forecasts
- Level of detail of physical models (first principles non-linear models of ESS, power lines, etc.)
- Time horizon and resolution of schedule

7.3. Peak shaving

The correct operation of the power systems relies on the balance between power production and power consumption. However, the electricity demand from loads present strong variability during the day and this needs to be compensated with a variation of the electricity supply by the operators. Covering the demand peaks is especially critical and this leads to benefits in what is referred as peak load shaving or also as load leveling consisting in solutions to flatten the peaks and valleys in the loading profile. Energy storage systems can play a significant role in peak shaving by accumulating energy during off-peak hours and discharging it during the on-peak hours [207]. The conventional approach to cope for peak loading is to add production capacity but normally this involves less efficient and more expensive generators. Moreover, the generation capacity and the lines need to be sized for the peaks despite these occur only few hours per day. In general, peak shaving from energy storage can results in several benefits for the power system operators since this can avoid more expensive and, in several cases, also more polluting generation and also could delay capacity upgrades for the lines. This can lead to a more robust and stable power system and also to less CO2 emissions. Operators of the storage units can find an economic advantage benefiting from the difference in electricity price during peak hours and off-peak hours. Battery energy storage systems are considered the most suitable technology for providing peak shaving since the charge and discharge cycles are in the order of several minute to a few hours [208]. The storage units can be centralized with large capacities installed in key location of the power system but particularly attractive from a technical perspective is also the installation of decentralized storage systems closer to the demand side in residential and industrial areas [209,210].

8. Services offered for a secure supply in shorter time windows (<1 h)

This section highlights services can be offered to the grid by ESSs that require charge or discharge over a relatively short time window typically ranging from a few seconds to several minutes. Examples of these services include the frequency support with eventually virtual inertia provision and active damping of power oscillations (Fig. 10). Moreover, ESS may facilitate the implementation of grid forming functionalities in power electronic converters by providing the energy needed for supporting the grid when necessary. Thus, this section provides also a brief introduction to grid forming features especially highlighting the role of ESSs.

8.1. Grid forming control of power electronic converters

The operation of the power systems in the last decades has largely relied on the characteristics and features inherently offered by synchronous generators. The displacement of power production from conventional power plants to converter interfaced renewable energy sources raised growing concerns of the system operators on the general behavior of future power systems and on their stability [211]. Thus, power electronics converters are expected to participate more in the correct operation of the power systems by offering additional services similarly to synchronous generators. These considerations have been the main rationale for the development of several control approaches for power electronics converters that are presently categorized as grid forming.

The most conventional control schemes for grid connected converters, referred as grid following, present essentially a behavior equivalent to a current source. The synchronization to the grid is normally ensured with dedicated functions that estimate the grid voltage phase and frequency (e.g. Phased Locked Loop). This also implies that the operation of a grid following converter generally requires an external grid that regulates the frequency. A large number of control schemes has been presented in the technical literature based on alternative mechanisms for maintaining the synchronization to an external grid and consequently claiming “grid forming” features but without a generally accepted definition of grid forming. The efforts to introduce grid forming requirements in the future grid codes is promoting a gradual convergence in the definition of functional specifications for grid forming unit. For example, in [212] it is indicated that grid

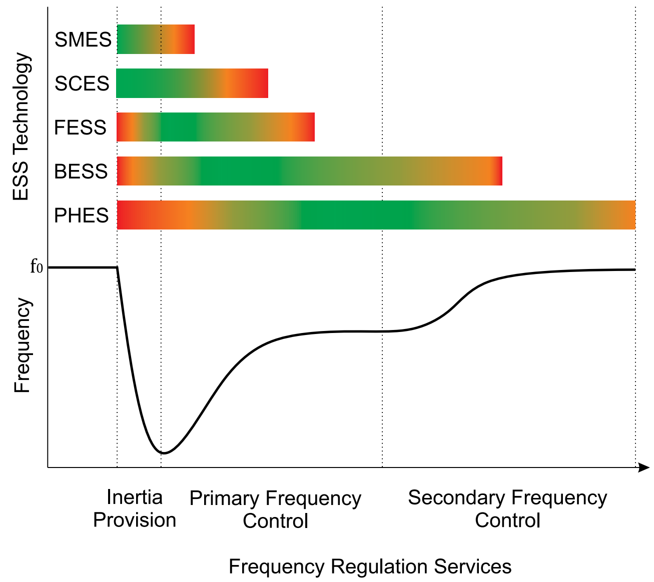

Fig. 10. Energy Storage Technologies contribution during frequency disturbances. Color meaning: green, suitable for service provision; orange, suitable but with technological limitation; red, unsuitable due to technical or economical reasons.

forming converters should equivalently behave as a voltage source behind an impedance and that should offer five mandatory functions: self-synchronization, phase jump active power, inertial active power, inherent reactive power, and positive damping power.

The provision of virtual inertia and frequency support to the grid from a grid forming converter requires a net flow of active power. The energy necessary in these conditions exceeds what is normally stored in the dc bus capacitors by a few orders of magnitude. Thus, the grid forming converter should rely on an external unit controlling the dc voltage and providing energy or should integrate an ESS.

8.2. Inertia provision and fast frequency support

In a first approximation the small signal frequency dynamics of power systems can be modeled with a swing equation in per unit [213] aggregating all rotating masses inertia as:

$$\frac{d\Delta\omega}{dt} = \frac{1}{2H}(T_m - T_e - K_d\Delta\omega) \tag{2}$$

where ω is the angular velocity associated to the system frequency, T_m and T_e the equivalent mechanical and electromagnetic torque, K_d a damping coefficient and H the inertia time constant. The inertia time constant depends largely by the power generation with higher values when large synchronous machines are connected, and lower values for high share of converter interfaced renewables. In largely interconnected systems, the inertia time constant is in the range of a few seconds. In case of a power unbalance between production and consumption the system, the frequency exhibits a rapid transient and it is critical to limit the rate of change of frequency (i.e. ROCOF) and the maximum deviation (i.e. frequency nadir) in order to avoid triggering system protections and eventually automatic disconnection of loads or generation units.

Power electronic converters can provide fast frequency support by promptly increasing the active power injected in the grid when the frequency is decreasing and viceversa. If the power injection is proportional to the frequency derivative the power electronic converter will provide the equivalent of an inertia and the multiplicative coefficient is normally indicated as virtual inertia or synthetic inertia. It should be noted that virtual inertia can be provided by both grid forming and grid following schemes. Indeed, the frequency derivative can be estimated (e.g. by a PLL) and an extra term for active current or active power added to the references in most conventional grid following control schemes. The concept of virtual synchronous machines is a widely adopted approach for grid forming control explicitly aiming at reproducing with a power electronic converter the behavior of a synchronous machine. Several implementations are presently available but in general a common denominator is calculation of the reference phase for the output voltage with a swing equation model [214,215]. This formulation inherently provides virtual inertia and allows to easily configure the inertia time constant and the damping and frequency droop coefficients.

In general, fast frequency reserve activation should occur in around a second and last for several seconds (e.g. 5–30 s) [216]. Faster reactions time are beneficial for the power system in limiting ROCOF and frequency nadir. Similar considerations in terms or reaction time and duration of the intervention are applicable also for the inertia provision. More sustained frequency support as for example with a frequency droop can extend the energy provision for several minutes until the corrective actions of the secondary controllers in the power system re-establish the nominal frequency.

8.3. Damping of frequency oscillations

Power system stabilizers (PSSs) of large synchronous generators play a key role in ensuring the damping of natural frequency oscillations in the power system. These oscillations are often associated to large areas of the power systems swinging against each other (e.g. inter-area oscillations) and are characterized by a frequency range between 0.1 and 1 Hz. Power electronic converters can implement controls aiming at damping oscillations by active on active and reactive power and these are normally denoted as power oscillation damping (POD) controllers. Several implementations are available in literature [217,218] but in general the principle is to inject power in counterphase with the grid oscillation with the aim of attenuating the amplitude and act as a dissipative element of the oscillation energy. The controllers can be tuned to address a predefined range of oscillation frequencies or rely on an online identification. It should be noted that virtual synchronous machine control schemes also contain typically damping terms in their inner inertia model and that can contribute to the damping of oscillations.

The energy required for effectively contributing in the damping of power oscillations may exceed what is available in the bus capacitance of the converters and the presence of a ESS can be very beneficial. Due to the inherently oscillatory nature of these phenomena and their frequency, oscillation damping would require charge–discharge cycles of several seconds.

9. Large projects on energy storage integration

This section provides four examples of large projects covering several systems and component aspects on ESS integration: the hybrid energy storage concept with hydrogen and batteries (Netzbooster project), the grid-forming control (Unifi project), the acceleration for market-introduction of novel energy storage technologies (Rapid Operational Validation Initiative), and novel power electronics solutions for connecting ESS to data center (Super-Heart project).

9.1. “Netzbooster” project: how to avoid line congestion and ensure grid stability

Partners: TransnetBW GmbH, Karlsruhe Institute of Technology (KIT), Ulm University of Applied Sciences (THU), Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW)

Goal: Grid boosters employ a battery energy storage system to virtually upgrade the power transmission network, allowing power lines to exceed the $(n-1)$ criteria while ensuring the security of the

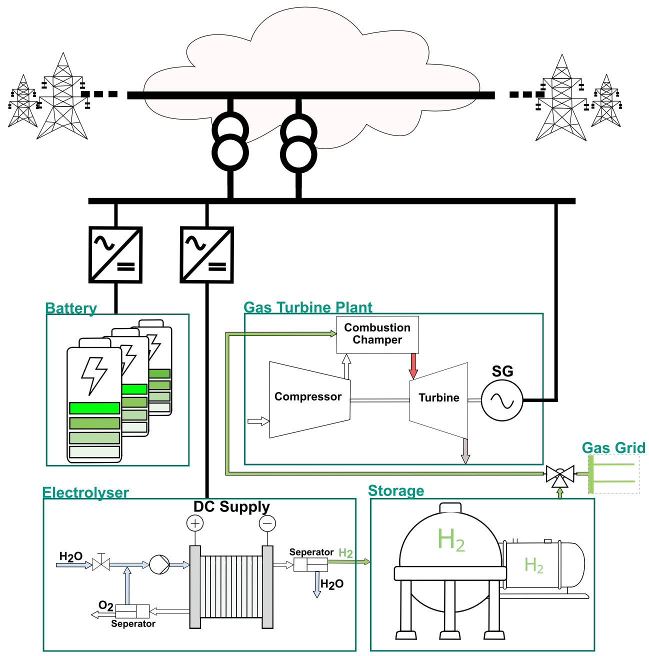

Fig. 11. The main elements of H2REB project.

power supply [219,220]. However, a notable drawback to this method is the high costs associated with batteries. An extension to the approach involves a hybrid energy storage-based grid booster, which combines the fast dynamics of a BESS with a slower but more economical ESS (e.g., hydrogen) [221].

The BWPlus HydrogREenBoost (H2REB) project aims to extend the TransnetBW's grid booster project in Kupferzell as a part of the Federal Network Agency's grid development plan integrating an electrolyzer and a gas turbine in addition to the battery system [221] (see Fig. 11).

The Institute of Automation and Applied Informatics (IAI) at the Karlsruhe Institute of Technology is developing comprehensive technical and economic simulation models for the entire H2REB system. These models will be instrumental in examining the control design of individual components, analyzing the overall system dynamics, and evaluating their economic viability.

Results: Large-scale electrolyzers can participate in the ancillary services market through dynamic operation, thereby generating additional income and thus operating more economically [222]. Some projects have already demonstrated that Proton Exchange Membrane (PEM)-Electrolyzer and Alkaline Electrolysis (AEL) systems can participate wholly or at least partially in various ancillary service markets, including manual (mFRR) and automatic Frequency Restoration Reserve (aFRR), and even Frequency Containment Reserve (FCR) [222–225]. Anion Exchange Membrane (AEM) systems should also be capable to meet the requirements for grid services [226,227].

This could become a crucial aspect of grid stability, particularly with the disappearance of rotating masses. PEM technology, in particular, can achieve dynamics of 10% per second [228]. Beyond power increased utilization of the network and hydrogen production, H2REB can theoretically provide various additional services, including frequency regulation, black startup, active filtering, sectors coupling, flexible load management, and acting as a Static Synchronous Compensator (STATCOM) [229,230].

A pure battery ESS can support the grid only for a limited time, being the needed large quantity of energy costly [231]. Hydrogen can inexpensively store energy for long periods. Comparable projects have already demonstrated that gas turbines can generate power using mixtures ranging from 0 to 100% hydrogen/natural gas [232,233]. Hybrid boosters, thanks to their design, are capable of black start and can thus cover an additional application [234,235].

Within the scope of the H2REB, the economic viability as well as control and regulation concepts will be described during the execution of the project. Thus, the H2REB system can be operated in a grid-friendly manner and has multiple applications due to its high power flexibility and high energy density.

9.2. Unifi: enabling grid forming concept

Partners 37 partners coming from academia, national labs, utilities and manufacturing industry mostly from North America.

Goal In 2021, the U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO) established a $25 million program aimed to establish a Consortium the Universal Interoperability for Grid Forming Inverters (UNIFI) [236]. The goal of the UNIFI Consortium is to lead the energy industry towards using the full potential of grid-forming converter technologies and create self-sustained collaborative community long-term engagement and innovation. UNIFI is advancing and promotes grid-forming technologies by further maturing it and tackling challenges related to power electronic devices, system level considerations, technology commercialization and standardization, development of guidelines and good engineering practices, education and workforce development. To achieve these objectives, the UNIFI consortium focuses on three main areas:

- R&D activities related to interoperability modeling and simulations, developing controls for grid services, hardware testing at laboratory scales.
- Demonstration and Commercialization using an at least 20-MW field project, standardization efforts, and stimulation of domestic production.
- Outreach and training of the next generation of engineers

Results One example of impactful UNIFI outcome is development of Specifications for grid-forming-based inverter-based resources (IBR) to provide uniform technical requirements for the interconnection, integration and interoperability of GFM IBRs of any capacity in power systems at any scale.

9.3. Rapid operational validation initiative

Partners Pacific Northwest, Argonne, Idaho, Oack Ridge, Sandia National Labs, and the National Renewable Energy Laboratory

Goal The Rapid Operational Validation Initiative (ROVI) is a strategic effort launched by the Department of Energy's Office of Electricity. Its primary goal is to significantly decrease the time required for emerging energy storage technologies to transition from the laboratory to market readiness. ROVI focuses on creating innovative tools and methods that accelerate the testing and validation processes essential for ensuring the commercial success of new technologies. ROVI leverages advanced data science methods, including artificial intelligence and machine learning, to utilize extensive datasets on energy storage performance across various scales. This approach enables the generation of lifetime performance predictions for new technologies with minimal real-time testing.

A critical part of ROVI is the creation of a data collection and analysis framework. This framework identifies the fundamental data needs for different Long Duration Energy Storage (LDES) technologies and develops protocols for collecting and storing data in a standardized format. The initiative also allows for the collection of real-world data from energy storage systems, which can then be used to refine and validate these technologies [237].

Overall, ROVI represents a significant advancement in streamlining the path from innovation to implementation for energy storage technologies, facilitating a more rapid adoption and integration of these critical systems into the energy market. Several of the principle

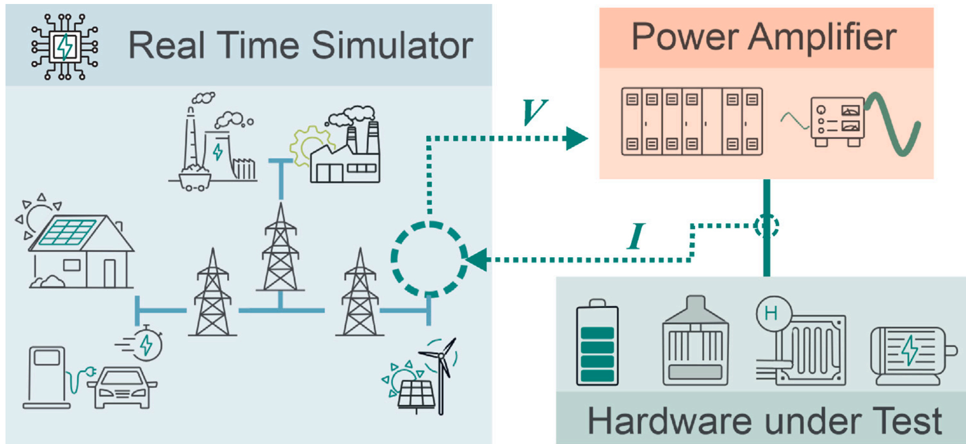

Fig. 12. Power hardware in the loop concept.

adopted by ROVI were also detailed in a perspective paper by Logan et al. [238]. The authors highlighted how an obstacle in advancing battery development through data science is the lack of access to substantial, high-quality data due to the fragmented nature of the existing ecosystem. The authors suggests a framework for addressing these through the establishment of a strong network of public data hubs that adopt standardized practices and offer flexible data-sharing options. One example of such data hubs is Battery Archive that is based on open source software developed at Sandia and contains public Li-ion cycling and abuse testing datasets available for visualization and downloading.

Results Introducing data archives and open-source tools. Coordinate accelerated testing, modeling, and system monitoring and optimization.

9.4. Super-heart: multi-source integration of energy storage for data centers

Partners Trinity College Dublin, Kiel University, Fraunhofer ISIT

Goal A power failure in a data centre for a fraction of second can be devastating, disrupting business and losing data. The aim of the Super-HEART is to develop a power supply that can reliably use several sustainable energy sources, such as hydrogen and solar energy, at the same time. In the project research groups from the fields of power electronics and materials sciences at Kiel University and Trinity College Dublin are cooperating. Supercapacitors, despite their very high power density, they are suffering from power energy density. In Super-Heart, MXenes (Titanium Carbide) and graphene will be structured and optimized at nano-, and micro-scale to enhance the energy density and also safety of the supercapacitors. The modular transformer and the supercapacitors for short-term energy storage are technological break-throughs themselves. By combining and developing them an increase of 20% in performance in terms of stored energy, reliability of power supply and reduction in operating costs is expected.

Results Within Super-HEART, micro- and nano-structured supercapacitor electrodes based on MXenes (Titanium Carbide) dispersions are produced and up-scaled to enable their utilization in high power applications. To up-scale the fabrication process of graphene-based network structures are used. MXenes and graphene have shown promising advantages in batteries and supercaps [239] as well as water electrolyzers [240]. In the final demonstrator, a multiwinding-based four-port DC transformer will realized to interface supercapacitor-, battery-, and hydrogen-based energy storage systems to ensure the reliability of the connected data center while the number conversion stages are reduced and the power density and efficiency are increased [241].

10. Validation of energy storage solutions

As highlighted in the previous sections, energy storage systems can offer a range of services, varying from day-ahead dispatch to inertia provision. Testing such a variety of services in real grid conditions has been always challenging. Laboratory testing can offer only standard conditions to test these services, and only in “stiff” conditions, i.e., without feedback from the system. On the other side, field tests provide high fidelity results, but they are costly, inflexible, and limited in the testing possibilities.

Power Hardware In the Loop (PHIL) testing can play a key role to accelerate the introduction to market of new energy storage solutions and to validate their services. The PHIL concept consists on connecting the real hardware prototype with a real-time simulated grid by means of power amplifiers (see Fig. 12). The PHIL concept has been described in details in many previous publications, depicting the advantages and drawbacks [242–246]. This section instead focuses on providing some demonstrator examples for testing commercial-level energy storage systems and for validating their services provision performances.

10.1. Testing techniques for energy storage systems

Energy storage systems are complex systems with tens to hundreds of components and controllers, that is not simple to account for during power systems studies. In addition, their services can spread from the milliseconds to hours to months range, making it difficult to find one-for-all testing solution. In the following, four common techniques have been considered to classify the services mentioned in this paper with a specific testing technique.

- **Simulations** consists in formulating hypothesis on the required model complexity for studying a certain power system phenomenon. These hypothesis are then translated in simplification steps for the model, in order to retain a certain degree of accuracy, while reducing the computational burden that the model requires to be computed [247,248]. From one side, simulations offer a great flexibility in testing, thanks the capability to change the testing conditions digitally. On the other side, only the slower dynamics of models can be emulated properly. Faster dynamics, such as the semiconductor switching, require detailed time-dependent modeling approaches, that involve large computational burden.
For this reason, simulation approaches are used for energy storage systems mostly at the planning level (see Table 2): resilience, transmission upgrade, seasonal capacity and forecasting studies require only static models, with only the power/energy limits of energy storage systems to be covered. If dynamic studies shall

Table 2
Testing techniques for energy storage systems services provision: Advantages and disadvantages.

	Simulation	Lab testing	PHIL	Field testing
Resilience studies	++	- -	- -	- -
Transmission planning	++	- -	- -	- -
Seasonal capacity studies	++	- -	- -	- -
Forecasting of RES	++	-	o	+
ESS Scheduling	+	-	+	+
Peak Shaving	+	-	+	+
Grid-forming control	o	+	++	o
Inertia provision	-	+	++	o
Frequency oscillations damping	-	-	++	o

be considered, simulations provide good accuracy at slower dynamics, while its flexibility meets limitations at faster dynamics. Studies on fast frequency support and inertia provisions can be always be performed in simulation, but they need always an experimental validation to confirm the conclusions: communication delays, ramp-rate saturation, non-linear dependency of the storage state-of-charge, measurement uncertainties are some of the variables that cannot be easily modeled in simulation, and only an experimental validation can provide accurate results.

- **Laboratory Testing** involve the development of an hardware prototype and the emulation of grid conditions by means of controllable voltage or current sources in the lab. On the opposite of simulations, laboratory testing do not require any initial hypothesis on the technology under test and thus they can provide high testing fidelity. As an exception to this rule, a scale-down prototype (i.e., not at rated power) may be tested, if the power capabilities of the lab do not meet the ESS rated power.
Despite the high fidelity feature, laboratory testing suffers in flexibility. Based on a combination of conventional power sources with passive circuits (e.g., for low voltage ride through or DC fault testing), these testing setups can reproduce only discrete grid conditions and they do require a large set of hardware (e.g., different line impedances) to perform parameter variation analysis. They are thus indicated mostly for type and factory tests, with limited capability on grid integration of ESS.
- **Power Hardware In the Loop** concept adds flexibility to the laboratory testing. The hardware under test is interfaced by means of a power amplifier with a digital real time simulation, where realistic grid conditions have been simulated. In the last years, the PHIL concept proved to offer testing flexibility in a large variety of cases for ESS [249]: fast frequency response [250,251], inertia provision [252,253], power and energy management [254,255], automotive [256,257]. Additionally, the PHIL concept permits testing, that are otherwise dangerous to be performed in field, such as short circuit ones for validating protection strategies.
The advantages of such testing setup are clear: the energy storage systems can be tested under realistic conditions, taking into account the grid complexity. This is particularly important when dynamic studies are involved. Grid forming control, inertia and fast frequency regulation provision, oscillation damping are services that require a feedback from the system, and thus they need for a closed-loop analysis, while they need to consider the system non-linearities, and thus they need for real hardware. Longer testing for peak shaving and ESS scheduling purposes are possible and realistic, but they suffer a clear limitation: working with a real time simulation environment, the PHIL system needs to be operational the whole duration of the testing, also if this lasts hours. There is no practical way to accelerate the testing, and this may involve high energy costs if the hardware under test is rated at full power.
- **Field Testing** enables a final experimental validation of new energy storage technologies before the introduction in the market. This approach enables high testing fidelity, because the technology is directly implemented where it should operate as business as usual. This allows at storing large and comprehensive amount of operational data, such as the state-of-health of the storage unit, the frequency in providing a certain service (e.g., frequency support), external variables that can affect the storage lifetime (e.g., temperature, humidity), and random events impact on the system, such as grid faults. On the other side, field testing has a clear drawback: the testing conditions cannot be changed. It follows that for studying a particular power system phenomenon (e.g., fault ride through), the field testing needs to be performed for a certain amount of time for gathering a sufficient amount of data. This requires time, manpower, and it is costly. In addition, certain testing either cannot be performed (e.g., converter fault testing), or it may cause large disruption to nearby customers.

10.2. Large scale PHIL facilities for energy storage testing

10.2.1. KIT energy lab

To achieve a successful energy transformation in Europe, the use of multiple energy sources and storage systems is required. However, this requires multi-disciplinary and multi-sector studies, that consider a multi-modal energy grid, where the electrical, thermal, gas and cyber layers are intertwined and optimized. Therefore, the Energy Lab was created at the Karlsruhe Institute of Technology, where institutes and experts in different energy areas can formulate comprehensive answers to the energy transformation challenge.

A major focus of the Energy Lab is energy storage, which includes a variety of technologies such as batteries, flywheels, supercapacitors, and thermal and hydrogen-based storage systems. As depicted in Fig. 13, these resources are connected with our Smart Energy System Simulation and Control Center (SEnSSiCC).

The SEnSSiCC lab energy storage potential consists of:

- A 1 MVA PHIL system, composed of five-200 kVA Compiso power amplifiers from the company Egston Power, that allow parallel or series connection, to perform power testing up to 1.5 kVdc in series mode, or up to 4.5 kA if connected in parallel mode.
- A 120 kW, 7.2 kWh high-speed Stornetic Flywheel, with high power dynamic capability.
- A 400 kW, 1.0 kWh supercapacitor energy storage system [258] that aims at improving the power quality in the electrical grid, both in steady state (e.g., harmonic compensation) and during transients (e.g., fault-ride through).
- A 100 kW, 200 kWh battery energy storage system, that is based on distributed MMC architecture. A battery module is connected directly to the half-bridge cell of the MMC, working both for control and energy storage purposes.
- A 50 kW electrolyzer, 10 kW fuel cell that composes the $H2-in-the-loop$ hydrogen energy storage lab, that, connected with the PHIL setup, allows testing the hydrogen technologies performance in realistic grid conditions, such as under fast power or frequency variations.
- A 1.2 MW fuel cell, 1.8 MW, 1.17 MWh battery hybrid energy storage system for mobility applications, where the potential in using hydrogen in hybrid cargo trains is explored and experimentally validated with a full-scale power setup. This setup is currently being built with the support of Siemens Mobility and it will be operative in 2025.

These resources are connected through a common distributed AC connection, and they communicate status information (e.g., state-of-charge, frequency measurement) to the central data server, that is

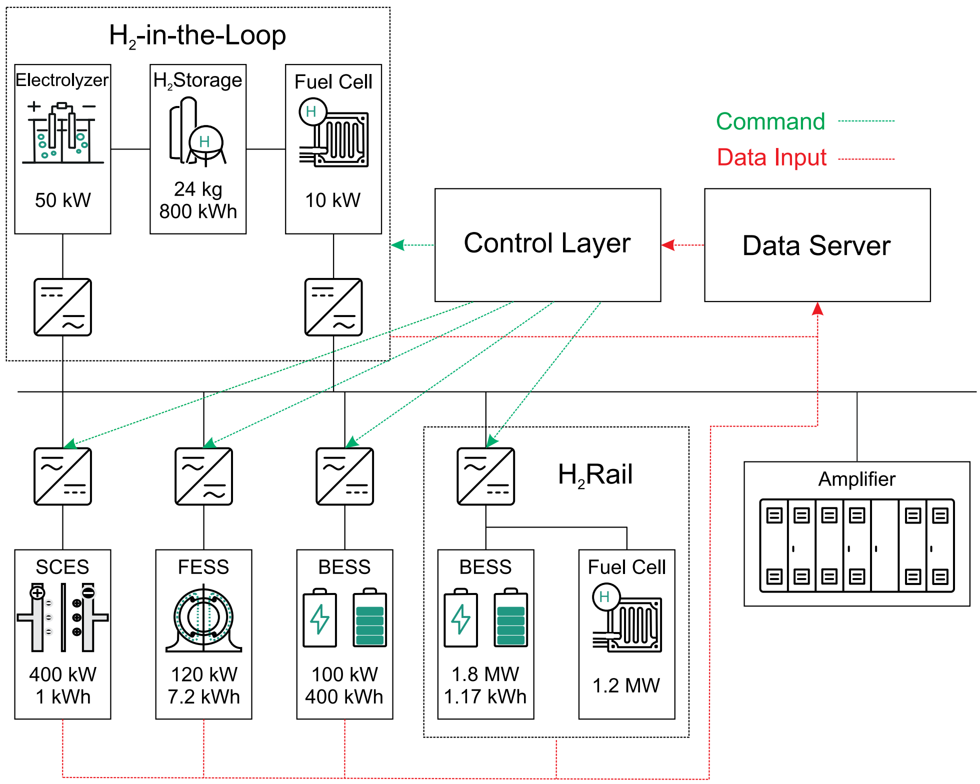

Fig. 13. Power Hardware In the Loop testing lab for energy storage systems in Energy Lab 2.0 at the Karlsruhe Institute of Technology.

connected to a control layer. Depending on the applications, the control layer is realized on a microcontroller or integrated in the digital real-time simulator.

The tests that the 1 MVA PHIL setup can perform to validate energy storage systems are as follows:

- **Inertia and Fast frequency regulation provision** The flywheel has proved to provide frequency and inertia support during frequency disturbances [252,259], and as well acting as virtual synchronous machine [250]. The PHIL testing helped not only to validate the proposed algorithms but also to compare them with the current state of the art. In [259], the proposed algorithm has been compared with already proposed solutions, showing its advantages and limitations.
- **Hybrid Energy Storage Testing** The large set of energy storage systems allows to combine them in hybrid form. The Flywheel is currently being tested with the battery and supercapacitor system, and novel power management algorithms are being proposed for efficiently sharing the power set-points.
- **Data-driven models** As explained in recent works [247,260], simulation models are valid only for specific scenarios. For this reason, the PHIL has been employed in [261] to develop a data-driven model of the Flywheel, and to validate it in realistic grid conditions. The results showed a minimal mismatch with respect to the real hardware for any fast-frequency regulation scenarios.

10.2.2. NREL flatirons campus

During recent years, the U.S. DOE and NREL developed the Advanced Research on Integrated Systems (ARIES) platform that enables energy systems research and validation at scale. ARIES is designed to match the complexity of the future energy systems and facilitate the development and deployment of groundbreaking technologies. The ARIES research platform can validate the multiple applications of energy storage using real hardware—from wind turbines to utility-scale batteries—and with real-time controls. Two main test apparatuses used

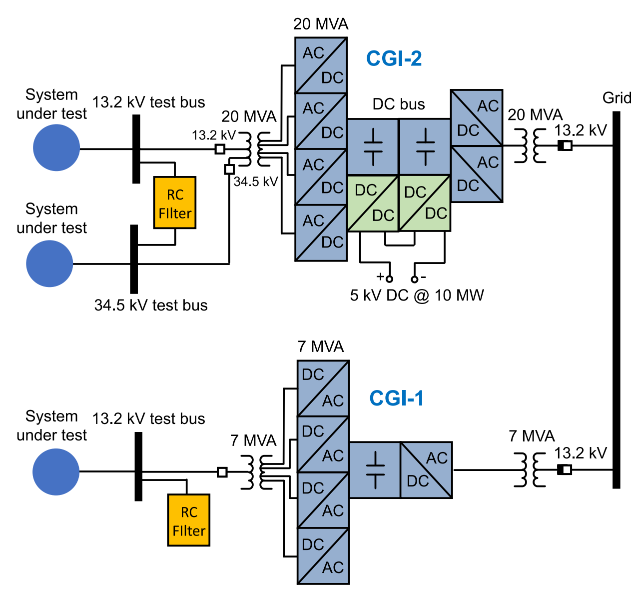

Fig. 14. Diagram of NREL CGI-1 and CGI-2.

for PHIL testing of all types of Inverter-Baser Resources (IBRs) including inverter-coupled energy storage systems, are the NREL multi-MW Controllable Grid Interfaces (CGI). Main characteristics and simplified diagrams of both CGI-1 and CGI-2 are shown in Fig. 14 respectively. The CGI-1 has been in operation since 2013, and CGI-2 has been commissioned during 2023.

Both CGI-1 and CGI-2 are four-quadrant power electronic grid simulators (built by ABB) with independent voltage control in each phase and very low voltage harmonic distortions. Each CGI can operate either as a voltage source (both ideal and behind virtual impedance) or

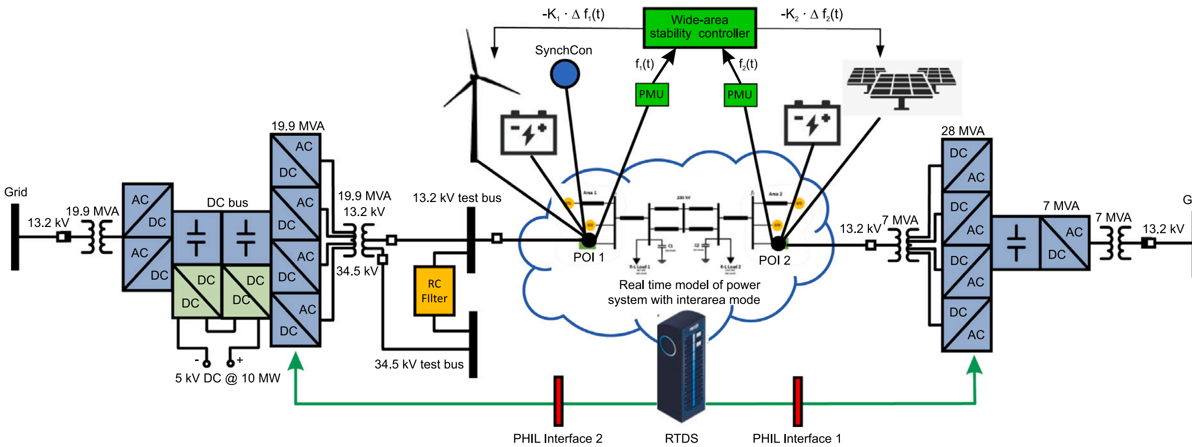

Fig. 15. Conceptual diagram of two-area PHIL experiment.

current source. Emulation of any types of voltage faults (balanced and unbalanced), over-voltage conditions, frequency variations (for both 50 Hz and 60 Hz systems) are possible. Both CGI were built with short-term over-current capability so they can absorb different levels of short circuit current produced by test articles during fault testing. Because of their fast bandwidth both CGIs have capability and have been enhanced with NREL-developed control to perform frequency scans of any device under test and produce impedance characteristics of inverters for up-to 3 kHz range. CGI capabilities coupled with the existing multi-MW and multi-technology devices deployed at NREL's Flatirons campus allow unique testing and validation environment based on the combination of fully controlled grid conditions and resource variability. Large number of MW-scale PV systems, battery energy storage systems, utility-scale wind turbines and controlled loads can be tested individually or in combination for various purposes, such as model validation, development and testing of new controls, tuning up controls, at-scale testing of systems including real site assets and virtual assets emulated in PHIL. One example of two points of interconnection (POI) experiment for understanding the impacts of variable generation and energy storage on power system stability is shown in Fig. 15. Many research projects funded by the U.S. DOE or in collaboration with U.S. and international energy industry have been conducted using different configurations for the existing and virtual assets. Many research projects, especially in the area of GFM controls for battery storage, PV and wind inverters, have been conducted in a similar manner. Recently, the NREL test platform has been enhanced by the DOE Solar program-funded Power Electronic Grid Interface (PEGI) platform including advanced 3 MW PV-battery inverter, 2.5 MVA synchronous machine and medium voltage impedance network. Synchronous machine is an important component of fundamental stability research revealing the nature of dynamic and control interactions and instability phenomena that my exist in the grid with the mix of conventional and inverter-based resources. Medium voltage impedance introduces capability of real hardware emulation of weak point of common couplings for any device under test. Very low Short Circuit Ratio (SCR) levels, all the way down to SCR = 1, are possible to achieve with this system. In addition, several research projects including long-duration energy storage and power-to-X experiments are on-going at the site. This includes 1.25 MW PEM electrolyzer and 1 MW PEM fuel cell systems both coupled with 600 kg hydrogen storage.

10.2.3. Sandia energy storage and power electronics program

Sandia National Laboratories, in collaboration with the Pacific Northwest National Laboratory (PNNL), manages the Energy Storage program for the U.S. Department of Energy's Office of Electricity [262]. This program focuses on the advancement of emerging energy storage technologies and their integration with power electronics to facilitate direct connections of batteries to medium voltage grids ranging from 4 kV to 38 kV. Sandia operates various specialized labs to foster the development, assessment, and demonstration of batteries, power electronics, sub-systems, and entire systems. Notably, the Sandia Medium Voltage Lab, which can handle up to 15 kV and 750 kW, is instrumental in testing control systems for modular power converters developed as part of the Grid Modernization Consortium. Additionally, the Energy Storage Test Pad (ESTP) is designed to link energy storage containers with grid assets up to 1 MVA. Within the ESTP, Sandia has conducted evaluations on pioneering commercial energy storage solutions, including one of the first commercial Vanadium Redox Batteries (250 kW/1 MW). Sandia also oversees the Energy Storage Safety Lab, equipped for destructive testing of cells and battery systems up to 25 kWh. This lab is dedicated to developing strategies for the early detection of thermal runaway and enhancing the overall safety of energy storage systems. These efforts are crucial in promoting safer and more efficient energy storage solutions. In partnership with the Office of Energy Efficiency and Renewable Energy (EERE), Sandia National Laboratories has constructed and operated a Concentrated Solar Power (CSP) plant at the National Solar Thermal Test Facility (NSTTF) [263]. The facility is anchored by a 200-foot solar tower, which is surrounded by 212 computer-controlled heliostats. These heliostats focus sunlight onto the tower, delivering a total thermal capacity of 6 megawatts and achieving a peak solar flux of 300 watts per square centimeter. This setup enables intensive solar energy studies and the development of solar thermal energy applications.

11. Challenges for a broader integration of BESS in the electrical grid

Energy storage systems technologies grew enormously in the last 20 years, in particular in the electrochemical sector: power and energy densities increased, manufacturing became faster and cheaper, operation reliability can be easily ensured by current technologies.

However, there are still several challenges that must be addressed before to rely only on energy storage instead of fuel-based solutions. In this work, two challenges have been highlighted, that represents a bottleneck for energy storage systems, in particular for a widespread integration of batteries: the circular economy and the safety issue.

11.1. Circular economy

The rapid market growth of Li-ion batteries brings concerns on the raw material availability and the environmental impact of their production. In the past 10 years, a 10-fold increase of this kind of batteries took place in the market [264].

The European union recently approved a circular economy regulation [265], with the scope to protect the human and environmental safety from production and dismissal of batteries, and at the same time creating additional job markets for re-purposing exhaust battery cells [266]. The current literature is proposing a Digital Battery Passport [267] for enhancing the circular economy opportunities for batteries, that it can be extended to any energy storage systems in the market.

Positive examples already exists. Lead–acid batteries have a well-established, economically viable recycling system with over 90% of the material being recyclable. In contrast, the recycling rate for Li-ion batteries is currently much lower, and the economic incentives are not as strong due to higher processing costs and the lower value of recovered materials. This is because of several factors. Li-ion batteries come in a variety of chemistries (e.g., lithium cobalt oxide, lithium iron phosphate), each requiring different recycling processes [268,269]. This variability adds complexity and cost to the recycling process. Lead–acid batteries, on the other hand, are more uniform and easier to recycle. Efficient recycling of Li-ion batteries is hindered by the lack of infrastructure for collection, sorting, and transportation, which are more mature for lead–acid batteries. Finally, handling and transporting spent Li-ion batteries is more hazardous due to risks of fire and explosion. This requires more stringent safety and regulatory measures compared to lead–acid batteries.

The ongoing development in Li-ion battery recycling aims to improve the efficiency of these processes and overcome the current limitations. As the technology matures and scales, it is expected that recycling Li-ion batteries could become more economically viable and environmentally sustainable, drawing closer to the well-established practices seen in lead–acid battery recycling.

11.2. Safety of energy storage systems

Stationary energy storage systems are sting being perfected. Safety incidents have taken place. As Li-ion cells go into thermal runway, they have the potential of damaging an entire installation or neighboring facilities. Accidents have taken place in several facilities around the world over the years. A few examples are listed below.

- **Arizona, USA**: A 2-MW battery storage system in Surprise, Arizona caught fire and exploded, resulting in injuries to firefighters and temporary shutdown of nearby plants [270].
- **Liverpool, UK**: A lithium-ion battery energy storage system used for frequency regulation experienced an incident during operations [271].
- **Belgium, Drogenbos**: A frequency regulation research park in Belgium faced a lithium-ion battery-related safety incident [271].
- **Jeolla Province Incident**: An ESS facility experienced a battery overcharge, where the state of charge reached 95%, 5 percentage points above the safe threshold [272].
- **Neermoor, Germany Incident**: A thermal runaway ignited in a large BESS container, destroying it entirely. The container was physically isolated to prevent the fire from spreading.

These incidents highlight the complex challenges and safety concerns associated with lithium-ion battery technology, especially in high-capacity applications like energy storage systems. For a more comprehensive list and details on specific incidents, you might consider checking databases that track such events, like the EPRI Storage Wiki's BESS Failure Event Database [271]. Efforts are being made to understand and mitigate these risks, particularly through research and improved safety standards. Efforts involve several strategies at the material, cell, and system levels [273].

- **Material Level**: Advances in materials science have led to the development of more stable electrode and electrolyte materials that are less likely to degrade and initiate thermal runaway under stress.
- **Cell Level**: Design improvements include the integration of thermal barriers and flame retardants within the battery cells. These enhancements can slow down or prevent the spread of thermal runaway between cells within a battery pack.
- **System Level**: Incorporation of sophisticated thermal management systems is crucial. These systems actively control the temperature of the battery pack through cooling mechanisms. Additionally, state-of-charge management restricts the charge level to a safe range to reduce stress on the batteries.
- **Advanced Monitoring and Controls**: Implementing sensors and battery management systems (BMS) that can detect early signs of failure, such as unusual temperature spikes or voltage anomalies, is another key approach. These systems can initiate preventive measures, such as disconnecting affected cells or modules to prevent the escalation of the situation.

Each of these strategies plays a role in a comprehensive approach to reducing the risks associated with thermal runaway in lithium-ion batteries, aiming to enhance the overall safety of these energy storage systems.

To ensure the safety of installation, Energy storage safety tests have been introduced in Europe, the US, and internationally. Globally, various standards apply depending on the region and specific application of the battery system. The International Electrotechnical Commission (IEC) standards like IEC 63056 and IEC 62485-5 are widely recognized. These standards address safety requirements for secondary lithium cells and batteries used in ESS, ensuring they meet rigorous safety criteria before being marketed [274].

In the European Union, the safety of stationary battery systems is evaluated through a series of specified tests which are outlined in EU regulations. For instance, the IEC 62619 standard is pivotal in Europe for testing stationary lithium-ion batteries [274]. It covers a range of safety tests at the cell level, including assessments for short circuits, overcharging, thermal abuse, and drop and impact scenarios. It also includes functional safety tests at the battery level, such as voltage and current control to prevent overcharging and overheating.

Moreover, the UL 9540 A standard is used for evaluating thermal runaway fire propagation in battery energy storage systems, which is a critical aspect of safety testing given the potential fire risks associated with battery systems [275].

12. Conclusions

This invited paper aimed at providing an overview on the current challenges, potential and services for energy storage systems. The major energy storage technologies have been considered, varying from discharging times from few seconds to weeks, and their integration in the power systems by means of power electronics has been discussed. This work introduced several examples of large industrial and national-lab related projects, and testing capability, such as the Power Hardware In the Loop based ones. The closing chapter of this contribution is related to the open points that still need to be addressed: circular economy, to achieve a sustainable usage of energy storage components, and safety measures, in particular for batteries, to ensure safe and secure deployment in the grid.

CRediT authorship contribution statement

Giovanni De Carne: Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization. **S. Masoome Maroufi:** Writing – original draft, Visualization, Investigation. **Hamzeh Beiranvand:** Writing – original draft, Visualization, Investigation. **Valerio De Angelis:** Writing – original draft, Investigation. **Salvatore D'Arco:** Writing – original draft, Investigation, Conceptualization. **Vahan Gevorgian:** Writing – original draft, Investigation, Conceptualization. **Simon Waczowicz:** Writing – original draft, Investigation. **Barry Mather:** Supervision, Investigation. **Marco Liserre:** Investigation, Conceptualization. **Veit Hagenmeyer:** Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Giovanni De Carne reports financial support was provided by Helmholtz Association of German Research Centres. Veit Hagenmeyer reports financial support was provided by Helmholtz Association of German Research Centres. Masoome Seyede Maroufi reports financial support was provided by Helmholtz Association of German Research Centres. Simon Waczowicz reports financial support was provided by Helmholtz Association of German Research Centres. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

[1] International Energy Agency, Renewables 2023, 2024, [Online]. Available: https://www.iea.org/reports/renewables-2023.
[2] European Union, Renewable energy targets, 2022, [Online]. Available: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-targets_en#related-links.
[3] U.S. Energy Information Administration, Short-term energy outlook, 2024, [Online]. Available: https://www.eia.gov/outlooks/steo/report/BTL/2023/02-genmix/article.php#:~:text=Renewables'%20output%20tends%20to%20follow%20capacity%20additions&text=Power%20generators%20are%20reporting%20plans,(31%20GW)%20in%202024.
[4] International Energy Agency, Trends in electric light-duty vehicles, 2023, [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2023/trends-in-electric-light-duty-vehicles.
[5] International Energy Agency, Heat pumps, 2023, [Online]. Available: https://www.iea.org/energy-system/buildings/heat-pumps.
[6] F. Atzler, J. Türck, R. Türck, J. Krahl, The energy situation in the federal Republic of Germany: Analysis of the current situation and perspectives for a non-fossil energy supply, Energies 16 (12) (2023) [Online]. Available: https://www.mdpi.com/1996-1073/16/12/4569.
[7] F. Ausfelder, C. Beilmann, M. Bertau, S. Bräuninger, A. Heinzel, R. Hoer, W. Koch, F. Mahlendorf, A. Metzelthin, M. Peuckert, L. Plass, K. Räuchle, M. Reuter, G. Schaub, S. Schiebahn, E. Schwab, F. Schüth, D. Stolten, G. Teßmer, K. Wagemann, K.-F. Ziegahn, Energy storage as part of a secure energy supply, ChemBioEng Rev. 4 (3) (2017) 144–210, [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/cben.201700004.
[8] F. Mockert, C.M. Grams, T. Brown, F. Neumann, Meteorological conditions during Dunkelflauten in Germany: Characteristics, the role of weather regimes and impacts on demand, 2022, arXiv:2212.04870.
[9] B. Li, S. Basu, S.J. Watson, H.W.J. Russchenberg, A brief climatology of dunkelflaute events over and surrounding the north and Baltic Sea Areas, Energies 14 (20) (2021) [Online]. Available: https://www.mdpi.com/1996-1073/14/20/6508.
[10] S. Mujiyanto, G. Tiess, Secure energy supply in 2025: Indonesia's need for an energy policy strategy, Energy Policy 61 (2013) 31–41, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421513004746.
[11] Federal Ministry for Economic Affairs and Energy (BMWi), Energy efficiency strategy for buildings: Methods for achieving a virtually climate-neutral building stock, 2015, [Online]. Available: https://www.bmwk.de/Redaktion/EN/Publikationen/energy-efficiency-strategy-buildings.pdf?__blob=publicationFile&v=3.
[12] S. Zhan, T. Gu, W. van den Akker, W. Brus, A. van der Molen, J. Morren, Towards congestion management in distribution networks: a Dutch case study on increasing heat pump hosting capacity, in: IET Conference Proceedings, Institution of Engineering and Technology, 2022, pp. 364–369, (5), [Online]. Available: https://digital-library.theiet.org/content/conferences/10.1049/icp.2023.0128.
[13] D.B. Nguyen, J.M.A. Scherpen, F. Bliek, Distributed optimal control of smart electricity grids with congestion management, IEEE Trans. Autom. Sci. Eng. 14 (2) (2017) 494–504.
[14] R. Mehta, D. Srinivasan, A.M. Khambadkone, J. Yang, A. Trivedi, Smart charging strategies for optimal integration of plug-in electric vehicles within existing distribution system infrastructure, IEEE Trans. Smart Grid 9 (1) (2018) 299–312.
[15] S. Deb, A.K. Goswami, P. Harsh, J.P. Sahoo, R.L. Chetri, R. Roy, A.S. Shekhawat, Charging coordination of plug-in electric vehicle for congestion management in distribution system integrated with renewable energy sources, IEEE Trans. Ind. Appl. 56 (5) (2020) 5452–5462.
[16] R. Basmadjian, A. Shaafieyoun, ARIMA-based forecasts for the share of renewable energy sources: The case study of Germany, in: 2022 3rd International Conference on Smart Grid and Renewable Energy, SGRE, IEEE, Doha, Qatar, 2022, pp. 1–6, [Online]. Available: https://ieeexplore.ieee.org/document/9774082/.
[17] R. Basmadjian, A. Shaafieyoun, S. Julka, Day-ahead forecasting of the percentage of renewables based on time-series statistical methods, Energies 14 (21) (2021) 7443, [Online]. Available: https://www.mdpi.com/1996-1073/14/21/7443.
[18] M. López, C. Sans, S. Valero, C. Senabre, Empirical comparison of neural network and auto-regressive models in short-term load forecasting, Energies 11 (8) (2018) 2080, [Online]. Available: http://www.mdpi.com/1996-1073/11/8/2080.
[19] M. Abdel-Basset, H. Hawash, R.K. Chakrabortty, M. Ryan, PV-Net: An innovative deep learning approach for efficient forecasting of short-term photovoltaic energy production, J. Clean. Prod. 303 (2021) 127037, [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0959652621012567.
[20] J. Bottieau, Z. De Grève, T. Piraux, A. Dubois, F. Vallée, J.-F. Toubeau, A cross-learning approach for cold-start forecasting of residential photovoltaic generation, Electr. Power Syst. Res. 212 (2022) 108415, [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0378779622005648.
[21] J.Á. González Ordiano, S. Waczowicz, M. Reischl, R. Mikut, V. Hagenmeyer, Photovoltaic power forecasting using simple data-driven models without weather data, Comput. Sci. - Res. Dev. 32 (1–2) (2017) 237–246, [Online]. Available: http://link.springer.com/10.1007/s00450-016-0316-5.
[22] Y. Li, Y. Su, L. Shu, An ARMAX model for forecasting the power output of a grid connected photovoltaic system, Renew. Energy 66 (2014) 78–89, [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0960148113006551.
[23] S. Meisenbacher, B. Heidrich, T. Martin, R. Mikut, V. Hagenmeyer, AutoPV: Automated photovoltaic forecasts with limited information using an ensemble of pre-trained models, in: Proceedings of the 14th ACM International Conference on Future Energy Systems, ACM, Orlando FL USA, 2023, pp. 386–414.
[24] S. Goodarzi, H.N. Perera, D. Bunn, The impact of renewable energy forecast errors on imbalance volumes and electricity spot prices, Energy Policy 134 (2019) 110827, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421519304057.
[25] C. Croonenbroeck, S. Hüttel, Quantifying the economic efficiency impact of inaccurate renewable energy price forecasts, Energy 134 (2017) 767–774, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S036054421731071X.
[26] N. Keyaerts, E. Delarue, Y. Rombauts, W. D'haeseleer, Impact of unpredictable renewables on gas-balancing design in Europe, Appl. Energy 119 (2014) 266–277, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261914000300.
[27] V. Sharma, A. Cortes, U. Cali, Use of forecasting in energy storage applications: A review, IEEE Access 9 (2021) 114690–114704, [Online]. Available: https://ieeexplore.ieee.org/document/9509501/.
[28] F. Milano, F. Dörfler, G. Hug, D.J. Hill, G. Verbič, Foundations and challenges of low-inertia systems (invited paper), in: 2018 Power Systems Computation Conference, PSCC, 2018, pp. 1–25.
[29] J. Fang, H. Li, Y. Tang, F. Blaabjerg, On the inertia of future more-electronics power systems, IEEE J. Emerg. Sel. Top. Power Electron. 7 (4) (2019) 2130–2146.
[30] R.A. Mastromauro, M. Liserre, A. Dell'Aquila, Control issues in single-stage photovoltaic systems: MPPT, current and voltage control, IEEE Trans. Ind. Inform. 8 (2) (2012) 241–254.
[31] VDE, VDE-AR-N 4105 anwendungsregel:2018-11, erzeugungsanlagen am niederspannungsnet, 2018.

[32] A. Ulbig, T.S. Borsche, G. Andersson, Impact of low rotational inertia on power system stability and operation, IFAC Proc. Vol. 47 (3) (2014) 7290–7297, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1474667016427618, 19th IFAC World Congress.

[33] P. Tielens, D. Van Hertem, The relevance of inertia in power systems, Renew. Sustain. Energy Rev. 55 (2016) 999–1009, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S136403211501268X.

[34] ENTSOE, The inertia challenge in Europe – Present and long-term perspective. Insight report, 2021, [Online]. Available: https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/TYNDP2020/FINAL/entso-e_TYNDP2020_Insight_Report_Inertia_2108.pdf.

[35] C. Liu, G. Cao, Fundamentals of rechargeable batteries and electrochemical potentials of electrode materials, in: Nanomaterials for Energy Conversion and Storage, World Scientific, 2018, pp. 397–451.

[36] B.C. Melot, J.-M. Tarascon, Design and preparation of materials for advanced electrochemical storage, Acc. Chem. Res. 46 (5) (2013) 1226–1238.

[37] Z. Zhao, H. Hu, Z. He, H.H.-C. Iu, P. Davari, F. Blaabjerg, Power electronics-based safety enhancement technologies for lithium-ion batteries: An overview from battery management perspective, IEEE Trans. Power Electron. 38 (7) (2023) 8922–8955.

[38] Z. Zhou, S. Pugliese, M. Langwasser, M. Liserre, Sub-synchronous damping by battery storage system in grid forming control, IEEE Trans. Power Electron. (Early Access) (2024).

[39] S. Agarwal, Market and technology report: Battery pack for energy storage system, 2023.

[40] S. Wolf, M. Lüken, Future battery market, in: S. Passerini, L. Barelli, M. Baumann, J. Peters, M. Weil (Eds.), Emerging Battery Technologies To Boost the Clean Energy Transition: Cost, Sustainability, and Performance Analysis, Springer International Publishing, Cham, 2024, pp. 103–118.

[41] E. Commission, Roadmap on advanced materials for batteries, 2021.

[42] A. Poorfakhraei, M. Narimani, A. Emadi, A review of multilevel inverter topologies in electric vehicles: Current status and future trends, IEEE Open J. Power Electron. 2 (2021) 155–170.

[43] S. Steinhorst, Z. Shao, S. Chakraborty, M. Kauer, S. Li, M. Lukasiewycz, S. Narayanaswamy, M.U. Rafique, Q. Wang, Distributed reconfigurable battery system management architectures, in: 2016 21st Asia and South Pacific Design Automation Conference, ASP-DAC, 2016, pp. 429–434.

[44] T. Pereira, H. Beiranvand, M. Liserre, Advanced solid-state-based protection scheme for high-voltage li-ion battery energy storage system, in: PCIM Europe 2023; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, VDE, 2023, pp. 1–10.

[45] J. Neumann, M. Petranikova, M. Meeus, J.D. Gamarra, R. Younesi, M. Winter, S. Nowak, Recycling of lithium-ion batteries—current state of the art, circular economy, and next generation recycling, Adv. Energy Mater. 12 (17) (2022) 2102917.

[46] M. Wu, T. Zhao, H. Jiang, Y. Zeng, Y. Ren, High-performance zinc bromine flow battery via improved design of electrolyte and electrode, J. Power Sources 355 (2017) 62–68, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378775317305530.

[47] H. Zhang, C. Sun, Cost-effective iron-based aqueous redox flow batteries for large-scale energy storage application: A review, J. Power Sources 493 (2021) 229445, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378775320317286.

[48] P. Leung, A. Shah, L. Sanz, C. Flox, J. Morante, Q. Xu, M. Mohamed, C. Ponce de León, F. Walsh, Recent developments in organic redox flow batteries: A critical review, J. Power Sources 360 (2017) 243–283, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378775317306985.

[49] The emerging chemistry of sodium ion batteries for electrochemical energy storage, Angew. Int. Ed. 54 (2015) 3431–3448, [Online]. Available: https://doi.org/10.1002/anie.201410376.

[50] M. Skyllas-Kazacos, H. Sylvania, R. Miron, All-vanadium redox battery. US patent, 4786567, 1988.

[51] M. Skyllas-Kazacos, M. Rychcik, R.G. Robins, A. Fane, M. Green, New all-vanadium redox flow cell, J. Electrochem. Soc. 133 (5) (1986) 1057.

[52] M. Rychcik, M. Skyllas-Kazacos, Evaluation of electrode materials for vanadium redox cell, J. Power Sources 19 (1) (1987) 45–54.

[53] B. Sun, M. Skyllas-Kazacos, Modification of graphite electrode materials for vanadium redox flow battery application—I. Thermal treatment, Electrochim. Acta 37 (7) (1992) 1253–1260.

[54] F. Rahman, M. Skyllas-Kazacos, Solubility of vanadyl sulfate in concentrated sulfuric acid solutions, J. Power Sources 72 (2) (1998) 105–110.

[55] M. Kazacos, M.S. Kazacos, High energy density vanadium electrolyte solutions, methods of preparation thereof and all-vanadium redox cells and batteries containing high energy vanadium electrolyte solutions, 2002, US Patent 6, 468, 688.

[56] B.K. Kim, S. Sy, A. Yu, J. Zhang, Electrochemical supercapacitors for energy storage and conversion, in: Handbook of Clean Energy Systems, 2015, pp. 1–25.

[57] W. Zuo, R. Li, C. Zhou, Y. Li, J. Xia, J. Liu, Battery-supercapacitor hybrid devices: recent progress and future prospects, Adv. Sci. 4 (7) (2017) 1600539.

[58] A. Sengupta, T. Pereira, M. Liserre, Optimal design of supercapacitor stacks for size-critical applications, in: 2024 IEEE Applied Power Electronics Conference and Exposition, APEC, 2024, pp. 977–983.

[59] A. Sengupta, T. Pereira, M. Liserre, Design optimization of dual active bridge converter for supercapacitor application, IEEE Trans. Power Electron. (2024) 1–14.

[60] C. Abbey, G. Joos, Supercapacitor energy storage for wind energy applications, IEEE Trans. Ind. Appl. 43 (3) (2007) 769–776.

[61] P. Harrop, Supercapacitor markets, technology roadmap, opportunities 2021–2041, 2021.

[62] M. Xia, J. Nie, Z. Zhang, X. Lu, Z.L. Wang, Suppressing self-discharge of supercapacitors via electrorheological effect of liquid crystals, Nano Energy 47 (2018) 43–50.

[63] F. Naseri, S. Karimi, E. Farjah, E. Schaltz, Supercapacitor management system: A comprehensive review of modeling, estimation, balancing, and protection techniques, Renew. Sustain. Energy Rev. 155 (2022) 111913.

[64] F. Jiang, Z. Meng, H. Li, H. Liao, Y. Jiao, M. Han, J. Peng, Z. Huang, Consensus-based cell balancing of reconfigurable supercapacitors, IEEE Trans. Ind. Appl. 56 (4) (2020) 4146–4154.

[65] A.G. Olabi, T. Wilberforce, M.A. Abdelkareem, M. Ramadan, Critical review of flywheel energy storage system, Energies 14 (8) (2021) [Online]. Available: https://www.mdpi.com/1996-1073/14/8/2159.

[66] [Online]. Available: https://www.siemens-energy.com/global/en/home/stories/killingholme-rotating-grid-stabilizer-conversion.html.

[67] [Online]. Available: https://www.stornetic.com/.

[68] M.S. Mahdavi, G.B. Gharehpetian, H.A. Moghaddam, Enhanced frequency control method for microgrid-connected flywheel energy storage system, IEEE Syst. J. 15 (3) (2021) 4503–4513.

[69] H. García-Pereira, M. Blanco, G. Martínez-Lucas, J.I. Pérez-Díaz, J.-I. Sarasúa, Comparison and influence of flywheels energy storage system control schemes in the frequency regulation of isolated power systems, IEEE Access 10 (2022) 37892–37911.

[70] F. Goris, E.L. Severson, A review of flywheel energy storage systems for grid application, in: IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, 2018, pp. 1633–1639.

[71] M.E. Amiryar, K.R. Pullen, A review of flywheel energy storage system technologies and their applications, Appl. Sci. 7 (3) (2017) [Online]. Available: https://www.mdpi.com/2076-3417/7/3/286.

[72] H.H. Abdeltawab, Y.A.-R.I. Mohamed, Robust energy management of a hybrid wind and flywheel energy storage system considering flywheel power losses minimization and grid-code constraints, IEEE Trans. Ind. Electron. 63 (7) (2016) 4242–4254.

[73] N.S. Gayathri, N. Senroy, I.N. Kar, Smoothing of wind power using flywheel energy storage system, IET Renew. Power Gener. 11 (3) (2017) 289–298.

[74] G. Wang, M. Ciobotaru, V.G. Agelidis, Power smoothing of large solar PV plant using hybrid energy storage, IEEE Trans. Sustain. Energy 5 (3) (2014) 834–842.

[75] A. Awad, I. Tumar, M. Hussein, W. Ghanem, et al., PV output power smoothing using flywheel storage system, in: 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I&CPS Europe, IEEE, 2017, pp. 1–6.

[76] P. Mouratidis, B. Schüßler, S. Rinderknecht, Hybrid energy storage system consisting of a flywheel and a lithium-ion battery for the provision of primary control reserve, in: 2019 8th International Conference on Renewable Energy Research and Applications, ICRERA, 2019, pp. 94–99.

[77] X. Li, A. Palazzolo, A review of flywheel energy storage systems: state of the art and opportunities, J. Energy Storage 46 (2022) 103576, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352152X2101255X.

[78] K. Ham, S. Bae, J. Lee, Classification and technical target of water electrolysis hydrogen production, J. Energy Chem. (2024).

[79] B. Rego de Vasconcelos, J.-M. Lavoie, Recent advances in power-to-X technology for the production of fuels and chemicals, Front. Chem. 7 (2019) 454241.

[80] L. Jesus, R. Castro, A.S. Lopes, Hydrogen-based solutions to help the electrical grid management: Application to the Terceira Island case, Int. J. Hydrog. Energy 48 (4) (2023) 1514–1532.

[81] R. Cozzolino, G. Bella, A review of electrolyzer-based systems providing grid ancillary services: current status, market, challenges and future directions, Front. Energy Res. 12 (2024) 1358333.

[82] M. Rasul, M. Hazrat, M. Sattar, M. Jahirul, M. Shearer, The future of hydrogen: Challenges on production, storage and applications, Energy Convers. Manage. 272 (2022) 116326.

[83] A. Wang, J. Jens, D. Mavins, M. Moultak, M. Schimmel, K. van der Leun, D. Peters, M. Buseman, et al., Analysing future demand, supply, and transport of hydrogen, 2021.

[84] X. Hu, C. Zou, C. Zhang, Y. Li, Technological developments in batteries: A survey of principal roles, types, and management needs, IEEE Power Energy Mag. 15 (5) (2017) 20–31.

[85] F. Milano, Á.O. Manjavacas, Converter-Interfaced Energy Storage Systems: Need for Energy Storage; 2. Technical and Economic Aspects; 3. Energy Storage Technologies; Part II. Modelling: 4. Power System Model; 5. Voltage-Sourced Converter Model; 6. Energy Storage System Models; Part Iii. Dynamic Analysis: 7. Comparison of Dynamic Models; 8. Control Techniques; 9. Stability Analysis; Part IV. Appendices, Cambridge University Press, 2019.

[86] I. Hadjipaschalis, A. Poullikkas, V. Efthimiou, Overview of current and future energy storage technologies for electric power applications, Renew. Sustain. Energy Rev. 13 (6) (2009) 1513–1522, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032108001664.

[87] M.E. Amiryar, K.R. Pullen, D. Nankoo, Development of a high-fidelity model for an electrically driven energy storage flywheel suitable for small scale residential applications, Appl. Sci. 8 (3) (2018) [Online]. Available: https://www.mdpi.com/2076-3417/8/3/453.

[88] K. Xu, Y. Guo, G. Lei, J. Zhu, A review of flywheel energy storage system technologies, Energies 16 (18) (2023) [Online]. Available: https://www.mdpi.com/1996-1073/16/18/6462.

[89] B. Zakeri, S. Syri, Electrical energy storage systems: A comparative life cycle cost analysis, Renew. Sustain. Energy Rev. 42 (2015) 569–596, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032114008284.

[90] G. Farivar, W. Manalastas, H. Dehghani Tafti, S. Ceballos, A. Sanchez-Ruiz, E. Lovell, G. Konstantinou, C. Townsend, M. Srinivasan, J. Pou, Grid-connected energy storage systems: State-of-the-art and emerging technologies, Proc. IEEE PP (2022) 1–24.

[91] A. Khaligh, Z. Li, Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles: State of the art, IEEE Trans. Veh. Technol. 59 (6) (2010) 2806–2814.

[92] P. Mukherjee, V. Rao, Design and development of high temperature superconducting magnetic energy storage for power applications - A review, Phys. C 563 (2019) 67–73, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0921453419301066.

[93] B.B. Adetokun, O. Oghorada, S.J. Abubakar, Superconducting magnetic energy storage systems: Prospects and challenges for renewable energy applications, J. Energy Storage 55 (2022) 105663, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352152X22016516.

[94] F.A. Diawuo, E.O. Antwi, R.T. Amanor, Chapter 3 - Characteristic features of pumped hydro energy storage systems, in: A.T. Kabo-Bah, F.A. Diawuo, E.O. Antwi (Eds.), Pumped Hydro Energy Storage for Hybrid Systems, Academic Press, 2023, pp. 43–59, [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128188538000066.

[95] G.G. Farivar, W. Manalastas, H.D. Tafti, S. Ceballos, A. Sanchez-Ruiz, E.C. Lovell, G. Konstantinou, C.D. Townsend, M. Srinivasan, J. Pou, Grid-connected energy storage systems: State-of-the-art and emerging technologies, Proc. IEEE 111 (4) (2023) 397–420.

[96] S. Sabihuddin, A.E. Kiprakis, M. Mueller, A numerical and graphical review of energy storage technologies, Energies 8 (1) (2015) 172–216, [Online]. Available: https://www.mdpi.com/1996-1073/8/1/172.

[97] H. Chen, T.N. Cong, W. Yang, C. Tan, Y. Li, Y. Ding, Progress in electrical energy storage system: A critical review, Prog. Nat. Sci. 19 (3) (2009) 291–312, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S100200710800381X.

[98] X. Luo, J. Wang, M. Dooner, J. Clarke, Overview of current development in electrical energy storage technologies and the application potential in power system operation, Appl. Energy 137 (2015) 511–536, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261914010290.

[99] N. Koshizuka, F. Ishikawa, H. Nasu, M. Murakami, K. Matsunaga, S. Saito, O. Saito, Y. Nakamura, H. Yamamoto, R. Takahata, Y. Itoh, H. Ikezawa, M. Tomita, Progress of superconducting bearing technologies for flywheel energy storage systems, Phys. C 386 (2003) 444–450, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0921453402022062, Proceedings of the topical conference of the International Cryogenic Materials Conference (ICMC 2002). Superconductors for Practical Applications.

[100] A. Morandi, B. Gholizad, M. Fabbri, Design and performance of a 1 MW-5 s high temperature superconductor magnetic energy storage system, Supercond. Sci. Technol. 29 (1) (2015) 015014.

[101] S. Schoenung, W. Meier, R. Fagaly, M. Heiberger, R. Stephens, J. Leuer, R. Guzman, Design, performance, and cost characteristics of high temperature superconducting magnetic energy storage, IEEE Trans. Energy Convers. 8 (1) (1993) 33–39.

[102] S. Suzuki, J. Baba, K. Shutoh, E. Masada, Effective application of superconducting magnetic energy storage (SMES) to load leveling for high speed transportation system, IEEE Trans. Appl. Supercond. 14 (2) (2004) 713–716.

[103] C.-S. Hsu, W.-J. Lee, Superconducting magnetic energy storage for power system applications, IEEE Trans. Ind. Appl. 29 (5) (1993) 990–996.

[104] X. Xue, K.W.E. Cheng, D. Sutanto, Power system applications of superconducting magnetic energy storage systems, in: Fourtieth IAS Annual Meeting. Conference Record of the 2005 Industry Applications Conference, 2005, Vol. 2, IEEE, 2005, pp. 1524–1529.

[105] S. Nagaya, N. Hirano, T. Katagiri, T. Tamada, K. Shikimachi, Y. Iwatani, F. Saito, Y. Ishii, The state of the art of the development of SMES for bridging instantaneous voltage dips in Japan, Cryogenics 52 (12) (2012) 708–712, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0011227512000859, Special Issue: ACASC 2011.

[106] V.J. Lyons, G.A. Gonzalez, M.G. Houts, C.J. Iannello, J.H. Scott, S. Surampudi, Space Power and Energy Storage Roadmap, Tech. Rep., NASA, 2012.

[107] M. Bortolotti, European energy storage technology development roadmap 2017 update, in: EASE and EERA, 2017.

[108] B.G. Marchionini, Y. Yamada, L. Martini, H. Ohsaki, High-temperature superconductivity: a roadmap for electric power sector applications, 2015–2030, IEEE Trans. Appl. Supercond. 27 (4) (2017) 1–7.

[109] U. Bhunia, S. Saha, A. Chakrabarti, Design optimization of superconducting magnetic energy storage coil, Phys. C 500 (2014) 25–32, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0921453414000483.

[110] A. Colmenar-Santos, E.-L. Molina-Ibáñez, E. Rosales-Asensio, J.-J. Blanes-Peiró, Legislative and economic aspects for the inclusion of energy reserve by a superconducting magnetic energy storage: Application to the case of the Spanish electrical system, Renew. Sustain. Energy Rev. 82 (2018) 2455–2470.

[111] S. Nomura, T. Shintomi, S. Akita, T. Nitta, R. Shimada, S. Meguro, Technical and cost evaluation on SMES for electric power compensation, IEEE Trans. Appl. Supercond. 20 (3) (2010) 1373–1378.

[112] L. Cabeza, I. Martorell, L. Miró, A. Fernández, C. Barreneche, 1 - Introduction to thermal energy storage (TES) systems, in: L.F. Cabeza (Ed.), Advances in Thermal Energy Storage Systems, in: Woodhead Publishing Series in Energy, Woodhead Publishing, 2015, pp. 1–28, [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9781782420880500018.

[113] L. Cabeza, 3.07 - Thermal energy storage, in: A. Sayigh (Ed.), Comprehensive Renewable Energy, Elsevier, Oxford, 2012, pp. 211–253, [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780080878720003073.

[114] M.F. Demirbas, Thermal energy storage and phase change materials: an overview, Energy Sources B 1 (1) (2006) 85–95.

[115] A. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, Renew. Sustain. Energy Rev. 13 (2) (2009) 318–345.

[116] [Online]. Available: https://www.stadtwerke-kiel.de/ueber-uns/kuestenkraftwerk/technik.

[117] Y. Sun, S. Wang, F. Xiao, D. Gao, Peak load shifting control using different cold thermal energy storage facilities in commercial buildings: A review, Energy Convers. Manag. 71 (2013) 101–114.

[118] B.L. Ruddell, F. Salamanca, A. Mahalov, Reducing a semiarid city's peak electrical demand using distributed cold thermal energy storage, Appl. Energy 134 (2014) 35–44.

[119] T. Bauer, C. Odenthal, A. Bonk, Molten salt storage for power generation, Chem. Ing. Tech. 93 (2021) 534–546, [Online]. Available: https://onlinelibrary.wiley.com/doi/full/10.1002/cite.202000137.

[120] H. Ibrahim, A. Ilinca, J. Perron, Energy storage systems—Characteristics and comparisons, Renew. Sustain. Energy Rev. 12 (5) (2008) 1221–1250.

[121] M. Aziz, Z. Zain, S. Baki, M. Muslam, Review on performance of thermal energy storage system at S & T complex, UiTM Shah Alam, Selangor, in: 2010 IEEE Control and System Graduate Research Colloquium, ICSGRC 2010, IEEE, 2010, pp. 49–54.

[122] E. Gent, Liquid Air Energy Storage Could Become£ 1bn Industry, The Institution of Engineering and Technology (IET) Engineering and Technology (E&T) Magazine, 2013, Published 9th May.

[123] H. Chen, T.N. Cong, W. Yang, C. Tan, Y. Li, Y. Ding, Progress in electrical energy storage system: A critical review, Prog. Nat. Sci. 19 (3) (2009) 291–312.

[124] A. Blakers, M. Stocks, B. Lu, C. Cheng, A review of pumped hydro energy storage, Prog. Energy 3 (2) (2021) 022003.

[125] M. Gimeno-Gutierrez, R. Lacal-Arantegui, Assessment of the European potential for pumped hydropower energy storage based on two existing reservoirs, Renew. Energy 75 (2015) 856–868, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S096014811400706X.

[126] T. Hino, A. Lejeune, Pumped storage hydropower developments, 2012.

[127] A. Mitteregger, G. Penninger, Austrian pumped storage power stations supply peak demands, World Pumps 2008 (500) (2008) 16–21.

[128] M. Nazari, M. Ardehali, S. Jafari, Pumped-storage unit commitment with considerations for energy demand, economics, and environmental constraints, Energy 35 (10) (2010) 4092–4101.

[129] M.R.N. Vilanova, A.T. Flores, J.A.P. Balestieri, Pumped hydro storage plants: a review, J. Br. Soc. Mech. Sci. Eng. 42 (8) (2020) 415.

[130] M.S. Javed, T. Ma, J. Jurasz, M.Y. Amin, Solar and wind power generation systems with pumped hydro storage: Review and future perspectives, Renew. Energy 148 (2020) 176–192, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0960148119318592.

[131] W. He, M. King, X. Luo, M. Dooner, D. Li, J. Wang, Technologies and economics of electric energy storages in power systems: Review and perspective, Adv. Appl. Energy 4 (2021) 100060, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2666792421000524.

[132] W. Tong, Z. Lu, W. Chen, M. Han, G. Zhao, X. Wang, Z. Deng, Solid gravity energy storage: A review, J. Energy Storage 53 (2022) 105226, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352152X22012257.

[133] J.D. Hunt, B. Zakeri, G. Falchetta, A. Nascimento, Y. Wada, K. Riahi, Mountain gravity energy storage: A new solution for closing the gap between existing short-and long-term storage technologies, Energy 190 (2020) 116419.

[134] S. Haider, H. Shahmoradi-Moghadam, J.O. Schönberger, P. Schegner, Algorithm and optimization model for energy storage using vertically stacked blocks, IEEE Access 8 (2020) 217688–217700.
[135] A. Berrada, K. Loudiyi, I. Zorkani, System design and economic performance of gravity energy storage, J. Clean. Prod. 156 (2017) 317–326, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959652617307515.
[136] M. Aneke, M. Wang, Energy storage technologies and real life applications–A state of the art review, Appl. Energy 179 (2016) 350–377.
[137] S. Hansen, F. Hahn, H. Krueger, F. Hoffmann, M. Andresen, R. Rainer Adelung, M. Liserre, Reliability of silicon battery technology and power electronics based energy conversion, IEEE Power Electron. Mag. 8 (2) (2021) 60–69.
[138] N. Blasuttigh, H. Beiranvand, T. Pereira, S. Castellan, A.M. Pavan, M. Liserre, η_{max}-Charging strategy for lithium-ion batteries: Theory, design, and validation, IEEE Trans. Power Electron. (Early Access) (2024).
[139] G. Wang, G. Konstantinou, C.D. Townsend, J. Pou, S. Vazquez, G.D. Demetriades, V.G. Agelidis, A review of power electronics for grid connection of utility-scale battery energy storage systems, IEEE Trans. Sustain. Energy 7 (4) (2016) 1778–1790.
[140] M.G. Molina, Energy storage and power electronics technologies: A strong combination to empower the transformation to the smart grid, Proc. IEEE 105 (11) (2017) 2191–2219.
[141] B.M. Grainger, G.F. Reed, A.R. Sparacino, P.T. Lewis, Power electronics for grid-scale energy storage, Proc. IEEE 102 (6) (2014) 1000–1013.
[142] T. Engelbrecht, A. Isaacs, S. Kynev, J. Matevosyan, B. Niemann, A.J. Owens, B. Singh, A. Grondona, STATCOM technology evolution for tomorrow's grid: E-STATCOM, STATCOM with supercapacitor-based active power capability, IEEE Power Energy Mag. 21 (2) (2023) 30–39.
[143] F. Hoffmann, J. Person, M. Andresen, M. Liserre, F.D. Freijedo, T. Wijekoon, A multiport partial power processing converter with energy storage integration for EV stationary charging, IEEE J. Emerg. Sel. Top. Power Electron. 10 (6) (2021) 7950–7962.
[144] X. Gao, F. Sossan, K. Christakou, M. Paolone, M. Liserre, Concurrent voltage control and dispatch of active distribution networks by means of smart transformer and storage, IEEE Trans. Ind. Electron. 65 (8) (2018) 6657–6666.
[145] G.G. Farivar, W. Manalastas, H.D. Tafti, S. Ceballos, A. Sanchez-Ruiz, E.C. Lovell, G. Konstantinou, C.D. Townsend, M. Srinivasan, J. Pou, Grid-connected energy storage systems: State-of-the-art and emerging technologies, Proc. IEEE 111 (4) (2023) 397–420.
[146] L. Leister, N. Katzenburg, K. Kuhlmann, L. Stefanski, M. Hiller, Faster than real-time electro-thermal-aging emulation of multiple batteries within a modular multilevel converter, in: 2023 25th European Conference on Power Electronics and Applications, EPE'23 ECCE Europe, 2023, pp. 1–9.
[147] M. Quraan, P. Tricoli, S. D'Arco, L. Piegari, Efficiency assessment of modular multilevel converters for battery electric vehicles, IEEE Trans. Power Electron. 32 (3) (2017) 2041–2051.
[148] J. Mueller, Development of modular hardware architectures for medium voltage energy storage systems, in: 2023 DOE Office of Electricity Energy Storage Program Peer Review, Santa Fe, NM, DOE, 2023.
[149] M. Liserre, G. Buticchi, M. Andresen, G. De Carne, L.F. Costa, Z.-X. Zou, The smart transformer: Impact on the electric grid and technology challenges, IEEE Ind. Electron. Mag. 10 (2) (2016) 46–58.
[150] M. Liserre, M.A. Perez, M. Langwasser, C.A. Rojas, Z. Zhou, Unlocking the hidden capacity of the electrical grid through smart transformer and smart transmission, Proc. IEEE 111 (4) (2023) 421–437.
[151] L. Zheng, R.P. Kandula, D. Divan, Current-source solid-state DC transformer integrating LVDC microgrid, energy storage, and renewable energy into MVDC grid, IEEE Trans. Power Electron. 37 (1) (2022) 1044–1058.
[152] C. Kumar, R. Zhu, G. Buticchi, M. Liserre, Sizing and SOC management of a smart-transformer-based energy storage system, IEEE Trans. Ind. Electron. 65 (8) (2018) 6709–6718.
[153] L. Zheng, A. Marellapudi, V.R. Chowdhury, N. Bilakanti, R.P. Kandula, M. Saeedifard, S. Grijalva, D. Divan, Solid-state transformer and hybrid transformer with integrated energy storage in active distribution grids: Technical and economic comparison, dispatch, and control, IEEE J. Emerg. Sel. Top. Power Electron. 10 (4) (2022) 3771–3787.
[154] D. Das, C. Kumar, M. Liserre, Stabilization of smart transformer based islanded meshed hybrid microgrid during electric vehicle charging transients, IEEE J. Emerg. Sel. Top. Ind. Electron. 4 (4) (2023) 1255–1264.
[155] J. Anzola, I. Aizpuru, A.A. Romero, A.A. Loiti, R. Lopez-Erauskin, J.S. Artal-Sevil, C. Bernal, Review of architectures based on partial power processing for dc-dc applications, IEEE Access 8 (2020) 103405–103418.
[156] H. Beiranvand, F. Hoffmann, F. Hahn, M. Liserre, Impact of partial power processing dual-active bridge converter on li-ion battery storage systems, in: 2021 IEEE Energy Conversion Congress and Exposition, ECCE, 2021, pp. 538–545.
[157] Y.D. Kwon, F.D. Freijedo, T. Wijekoon, M. Liserre, A multi-port partial power converter for smart home applications, IEEE Trans. Power Electron. (Early Access) (2024).
[158] Y.D. Kwon, F.D. Freijedo, T. Wijekoon, M. Liserre, Series resonant converter based full-bridge DC-DC partial power converter for solar PV, IEEE J. Emerg. Sel. Top. Power Electron. (2024).
[159] A.Q. Huang, Power semiconductor devices for smart grid and renewable energy systems, Proc. IEEE 105 (11) (2017) 2019–2047.
[160] B.K. Bose, Power electronics: My life and vision for the future [my view], IEEE Ind. Electron. Mag. 16 (2) (2022) 65–72.
[161] A. Bindra, T. Keim, APEC talks reliability and production of WBG devices: Disclosing the latest developments in components, packaging, transportation electrification, and renewable energy, IEEE Power Electron. Mag. 6 (2) (2019) 48–56.
[162] J.D. Blevins, Development of a world class silicon carbide substrate manufacturing capability, IEEE Trans. Semicond. Manuf. 33 (4) (2020) 539–545.
[163] T.S. Babu, K.R. Vasudevan, V.K. Ramachandaramurthy, S.B. Sani, S. Chemud, R.M. Lajim, A comprehensive review of hybrid energy storage systems: Converter topologies, control strategies and future prospects, IEEE Access 8 (2020) 148702–148721.
[164] S. Hajiaghasi, A. Salemnia, M. Hamzeh, Hybrid energy storage system for microgrids applications: A review, J. Energy Storage 21 (2019) 543–570, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352152X18305188.
[165] T. Sutikno, W. Arsadiando, A. Wangsupphaphol, A. Yudhana, M. Facta, A review of recent advances on hybrid energy storage system for solar photovoltaics power generation, IEEE Access 10 (2022) 42346–42364.
[166] W. Jing, C. Hung Lai, S.H.W. Wong, M.L.D. Wong, Battery-supercapacitor hybrid energy storage system in standalone DC microgrids: areview, IET Renew. Power Gener. 11 (4) (2017) 461–469.
[167] R. Hemmati, H. Saboori, Emergence of hybrid energy storage systems in renewable energy and transport applications – A review, Renew. Sustain. Energy Rev. 65 (2016) 11–23, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032116302374.
[168] S. Athikkal, G. Guru Kumar, K. Sundaramoorthy, A. Sankar, A non-isolated bridge-type DC–DC converter for hybrid energy source integration, IEEE Trans. Ind. Appl. 55 (4) (2019) 4033–4043.
[169] H. Tao, J.L. Duarte, M.A. Hendrix, Multiport converters for hybrid power sources, in: 2008 IEEE Power Electronics Specialists Conference, 2008, pp. 3412–3418.
[170] T. Pereira, F. Hoffmann, R. Zhu, M. Liserre, A comprehensive assessment of multiwinding transformer-based DC–DC converters, IEEE Trans. Power Electron. 36 (9) (2021) 10020–10036.
[171] M. Vasiladiotis, A. Rufer, Analysis and control of modular multilevel converters with integrated battery energy storage, IEEE Trans. Power Electron. 30 (1) (2015) 163–175.
[172] A. Hillers, M. Stojadinovic, J. Biela, Systematic comparison of modular multilevel converter topologies for battery energy storage systems based on split batteries, in: 2015 17th European Conference on Power Electronics and Applications, EPE'15 ECCE-Europe, 2015, pp. 1–9.
[173] W. Jiang, C. Zhu, C. Yang, L. Zhang, S. Xue, W. Chen, The active power control of cascaded multilevel converter based hybrid energy storage system, IEEE Trans. Power Electron. 34 (8) (2019) 8241–8253.
[174] W. Jiang, K. Ren, S. Xue, C. Yang, Z. Xu, Research on the asymmetrical multilevel hybrid energy storage system based on hybrid carrier modulation, IEEE Trans. Ind. Electron. 68 (2) (2021) 1241–1251.
[175] A. Bharatee, P.K. Ray, A. Ghosh, A power management scheme for grid-connected PV integrated with hybrid energy storage system, J. Mod. Power Syst. Clean Energy 10 (4) (2022) 954–963.
[176] M.M.A. Seedahmed, M.A.M. Ramli, A. Abusorrah, M.M. Alqahtani, Control-oriented model of an optimally designed hybrid storage system for a standalone microgrid, IEEE Access 11 (2023) 119161–119186.
[177] Y. Tang, H. Yang, Q. Xun, M. Liserre, An energy management framework with two-stage power allocation strategies for electric-hydrogen energy storage systems, in: 2023 IEEE Energy Conversion Congress and Exposition, ECCE, 2023, pp. 216–221.
[178] Q. Xun, M. Langwasser, F. Gao, M. Liserre, Optimal sizing and energy management of smart-transformer-based energy storage systems for residential communities, in: 2023 IEEE 14th International Symposium on Power Electronics for Distributed Generation Systems, PEDG, 2023, pp. 891–896.
[179] T. Bocklisch, Hybrid energy storage systems for renewable energy applications, Energy Procedia 73 (2015) 103–111, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1876610215013508, 9th International Renewable Energy Storage Conference, IRES 2015.
[180] Q. Li, H. Yang, Q. Xun, M. Liserre, Model predictive control with adaptive compensation for power management in fuel cell hybrid electric vehicles, in: 2023 IEEE Power and Energy Society General Meeting, PESGM, 2023, pp. 1–5.
[181] X. Li, R. Ma, N. Yan, S. Wang, D. Hui, Research on optimal scheduling method of hybrid energy storage system considering health state of echelon-use lithium-ion battery, IEEE Trans. Appl. Supercond. 31 (8) (2021) 1–4.
[182] T. Sutikno, W. Arsadiando, A. Wangsupphaphol, A. Yudhana, M. Facta, A review of recent advances on hybrid energy storage system for solar photovoltaics power generation, IEEE Access 10 (2022) 42346–42364.
[183] DOE Office of Electricity, The pathway to: Long duration energy storage commercial liftoff, 2023, [Online]. Available: https://liftoff.energy.gov/long-duration-energy-storage.

[184] P. Albertus, J.S. Manser, S. Litzelman, Long-duration electricity storage applications, economics, and technologies, Joule 4 (1) (2020) 21–32, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2542435119305392.
[185] Mitsubishi, 2023. [Online]. Available: https://power.mhi.com/regions/amer/references/advanced-clean-energy-storage-project.
[186] 2015. [Online]. Available: https://www.energiepark-mainz.de.
[187] 2021. [Online]. Available: https://www.pv-magazine.com/2021/03/10/uk-start-up-builds-gravity-based-storage-system-at-scottish-port.
[188] T. Trainer, Some problems in storing renewable energy, Energy Policy 110 (2017) 386–393, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421517304925.
[189] [Online]. Available: https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery.
[190] M. Aziz, A. Tri Wijayanta, A. Bayu Dani Nandiyanto, Ammonia as effective hydrogen storage: A review on production, storage and utilization, Energies 13 (12) (2021) 3062.
[191] [Online]. Available: https://www.futurebridge.com/industry/perspectives-energy/green-ammonia-for-energy-storage.
[192] 2022. [Online]. Available: https://greenmountainpower.com/rebates-programs/home-energy-storage/powerwall.
[193] 2023. [Online]. Available: https://www.reuters.com/business/energy/german-solar-battery-firm-sonnen-sees-bigger-role-backing-up-grid-2023-08-16.
[194] K. Phipps, S. Meisenbacher, B. Heidrich, M. Turowski, R. Mikut, V. Hagenmeyer, Loss-customised probabilistic energy time series forecasts using automated hyperparameter optimisation, in: Proceedings of the 14th ACM International Conference on Future Energy Systems, in: e-Energy '23, ACM, Orlando FL USA, 2023, pp. 271–286, [Online]. Available: https://dl.acm.org/doi/10.1145/3575813.3595204.
[195] K. Phipps, S. Lerch, M. Andersson, R. Mikut, V. Hagenmeyer, N. Ludwig, Evaluating ensemble post-processing for wind power forecasts, Wind Energy 25 (8) (2022) 1379–1405, [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1002/we.2736.
[196] F. Sossan, E. Namor, R. Cherkaoui, M. Paolone, Achieving the dispatchability of distribution feeders through prosumers data driven forecasting and model predictive control of electrochemical storage, IEEE Trans. Sustain. Energy 7 (4) (2016) 1762–1777.
[197] R.R. Appino, J.Á.G. Ordiano, R. Mikut, T. Faulwasser, V. Hagenmeyer, On the use of probabilistic forecasts in scheduling of renewable energy sources coupled to storages, Appl. Energy 210 (2018) 1207–1218.
[198] D. Werling, M. Beichter, B. Heidrich, K. Phipps, R. Mikut, V. Hagenmeyer, Automating value-oriented forecast model selection by meta-learning: Application on a dispatchable feeder, in: Energy Informatics Academy Conference, Springer, 2023, pp. 95–116.
[199] D. Werling, M. Beichter, B. Heidrich, K. Phipps, R. Mikut, V. Hagenmeyer, The impact of forecast characteristics on the forecast value for the dispatchable feeder, in: Companion Proceedings of the 14th ACM International Conference on Future Energy Systems, 2023, pp. 59–71.
[200] D. Werling, B. Heidrich, H.K. Çakmak, V. Hagenmeyer, Towards line-restricted dispatchable feeders using probabilistic forecasts for PV-dominated low-voltage distribution grids, in: Proceedings of the Thirteenth ACM International Conference on Future Energy Systems, in: e-Energy '22, Association for Computing Machinery, New York, NY, USA, 2022, pp. 395–400, [Online]. Available: https://doi.org/10.1145/3538637.3538868.
[201] S. Beichter, M. Beichter, D. Werling, J. Galenzowski, V. Weise, C. Hildenbrand, F. Wiegel, R. Mikut, S. Waczowicz, V. Hagenmeyer, Towards a real-world dispatchable feeder, in: 2023 8th IEEE Workshop on the Electronic Grid, EGRID, IEEE, 2023, pp. 1–6.
[202] F. Wiegel, J. Wachter, M. Kyesswa, R. Mikut, S. Waczowicz, V. Hagenmeyer, Smart energy system control laboratory–a fully-automated and user-oriented research infrastructure for controlling and operating smart energy systems, At-Automatisierungstechnik 70 (12) (2022) 1116–1133.
[203] R. Bauer, T. Mühlpfordt, N. Ludwig, V. Hagenmeyer, Analytical uncertainty propagation and storage usage in a high RES Turkish transmission grid scenario, in: Proceedings of the Thirteenth ACM International Conference on Future Energy Systems, in: e-Energy '22, ACM, Virtual Event, 2022, pp. 489–495, [Online]. Available: https://dl.acm.org/doi/10.1145/3538637.3539762.
[204] R. Bauer, T. Mühlpfordt, N. Ludwig, V. Hagenmeyer, Analytical uncertainty propagation for multi-period stochastic optimal power flow, Sustain. Energy Grids Netw. 33 (2023) 100969.
[205] X. Dai, Y. Guo, Y. Jiang, C.N. Jones, G. Hug, V. Hagenmeyer, Real-time coordination of integrated transmission and distribution systems: Flexibility modeling and distributed NMPC scheduling, 2024, arXiv preprint arXiv:2402.00508.
[206] C.E. Murillo-Sánchez, R.D. Zimmerman, C.L. Anderson, R.J. Thomas, Secure planning and operations of systems with stochastic sources, energy storage, and active demand, IEEE Trans. Smart Grid 4 (4) (2013) 2220–2229.
[207] M. Uddin, M.F. Romlie, M.F. Abdullah, S. Abd Halim, A.H. Abu Bakar, T. Chia Kwang, A review on peak load shaving strategies, Renew. Sustain. Energy Rev. 82 (2018) 3323–3332, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032117314272.
[208] K. Divya, J. Østergaard, Battery energy storage technology for power systems—An overview, Electr. Power Syst. Res. 79 (4) (2009) 511–520, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378779608002642.
[209] C. Jankowiak, A. Zacharopoulos, C. Brandoni, P. Keatley, P. MacArtain, N. Hewitt, Assessing the benefits of decentralised residential batteries for load peak shaving, J. Energy Storage 32 (2020) 101779, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352152X20316169.
[210] J. Mair, K. Suomalainen, D.M. Eyers, M.W. Jack, Sizing domestic batteries for load smoothing and peak shaving based on real-world demand data, Energy Build. 247 (2021) 111109, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378778821003935.
[211] ENTSOE, High penetration of power electronic interfaced power sources (HPoPEIPS), 2017.
[212] InterOPERA, Grid-forming functional requirements for HVDC converter stations and DC-connected PPMs in multi-terminal multivendor HVDC systems, 2024.
[213] P. Kundur, Power System Stability and Control, McGraw Hill, 1994.
[214] S. D'Arco, J.A. Suul, Virtual synchronous machines — Classification of implementations and analysis of equivalence to droop controllers for microgrids, in: 2013 IEEE Grenoble Conference, 2013, pp. 1–7.
[215] S. D'Arco, J.A. Suul, O.B. Fosso, A virtual synchronous machine implementation for distributed control of power converters in SmartGrids, Electr. Power Syst. Res. 122 (2015) 180–197, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378779615000024.
[216] ENTSOE, Technical requirements for fast frequency reserve provision in the Nordic Synchronous Area – External document, 2021.
[217] N. Jankovic, J. Roldan-Perez, M. Prodanovic, J.A. Suul, S. D'Arco, L.R. Rodriguez, Power oscillation damping method suitable for network reconfigurations based on converter interfaced generation and combined use of active and reactive powers, Int. J. Electr. Power Energy Syst. 149 (2023) 109010, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0142061523000674.
[218] X. Zhang, C. Lu, S. Liu, X. Wang, A review on wide-area damping control to restrain inter-area low frequency oscillation for large-scale power systems with increasing renewable generation, Renew. Sustain. Energy Rev. 57 (2016) 45–58.
[219] IRENA, Virtual power lines, 2020.
[220] TransnetBW, Storage-as-transmission. [Online]. Available: https://www.transnetbw.de/en/company/portrait/innovations/grid-booster.
[221] TransnetBW, HydrogREenBoost – hydrogen for system stability. [Online]. Available: https://www.transnetbw.de/de/unternehmen/portraet/innovationen/hydrogreenboost.
[222] M. Kopp, D. Coleman, C. Stiller, K. Scheffer, J. Aichinger, B. Scheppat, Energiepark Mainz: Technical and economic analysis of the worldwide largest power-to-gas plant with PEM electrolysis, Int. J. Hydrog. Energy 42 (19) (2017) 13311–13320, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319917300083. Special Issue on The 21st World Hydrogen Energy Conference (WHEC 2016), 13-16 June 2016, Zaragoza, Spain.
[223] E. Union, Periodic reporting for period 3 - QualyGridS (Standardized qualifying tests of electrolysers for grid services), in: Standardized Qualifying Tests of Electrolysers for Grid Services, 2022, [Online]. Available: https://cordis.europa.eu/project/id/735485/reporting.
[224] K. Zach, V. Rudolf Zauner, Deliverable D2.3 specifications of pilot test 3 use case 3, in: H2Future Green Hydrogen, 2017, [Online]. Available: https://www.h2future-project.eu/publications.
[225] NREL, Hydrogen energy storage grid and transportation services, Elyntegration (2015) [Online]. Available: https://elyntegration.eu/wp-content/uploads/2015_NREL_H2grid_transportServices.pdf.
[226] S.r.l. Enapter, AEM Nexus 1000, Tech. Rep., Enapter S.r.l., 2024, [Online]. Available: https://handbook.enapter.com/electrolyser/aem_nexus/downloads/Enapter_Datasheet_AEM-Nexus-1000.pdf.
[227] S.r.l. Enapter, FAQ, Tech. Rep., Enapter S.r.l., 2024, [Online]. Available: https://www.enapter.com/faqs.
[228] S.E.G.G. a. Co. KG, Silyzer 300, Tech. Rep, Siemens Energy Global GmbH a. Co. KG, 2024, [Online]. Available: https://assets.siemens-energy.com/siemens/assets/api/uuid:a193b68f-7ab4-4536-abe2-c23e01d0b526/datasheet-silyzer300.pdf.
[229] IRENA, Innovation landscape brief: Utility-scale batteries, 2019.
[230] J. Lotze, D. Moser, P. Sittaro, D. Sun, G. Savvidis, K. Troitskyi, M. Mogel, N. Kidane, C. John, D. Lehner, Energy System 2050 Towards a decarbonised Europe, TransnetBW GmbH, Stuttgart, 2022.
[231] F. Cebulla, T. Naegler, M. Pohl, Electrical energy storage in highly renewable European energy systems: Capacity requirements, spatial distribution, and storage dispatch, J. Energy Storage 14 (2017) 211–223.
[232] E. Union, Gas turbine runs with 100 % green hydrogen, a world first, in: HYFLEXPOWER, 2024, [Online]. Available: https://cordis.europa.eu/article/id/447634-gas-turbine-runs-with-100-green-hydrogen-a-world-first.
[233] vgbe energy e.V., Factsheet: H2-readiness für gasturbinenanlagen, 2023.
[234] S. Energy, Gasturbinen von siemens energy ermöglichen klimaneutrale energieversorgung der stadt leipzig, 2020, [Online]. Available: https://press.siemens-energy.com/global/de/pressemitteilung/gasturbinen-von-siemens-energy-ermoeglichen-klimaneutrale-energieversorgung-der.

[235] 50Hz, Amprion, TransnetBW, Tennet, Modalitäten für anbieter von systemdienstleistungen zum netzwiederaufbau gemäßart. 4 abs. 2 lit. b) der verordnung (EU)2017/2196 der kommission vom 24. November 2017 zur festlegung eines netzkodex über den notzustand und den netzwiederaufbau des übertragungsnetzes, Übertragungsnetzbetreiber (2018) [Online]. Available: https://www.netztransparenz.de/portals/1/Content/EU-Network-Codes/ER-VErordnung.
[236] UNIFI Consortium, UNIFI specifications for grid-forming inverter-based resources. [Online]. Available: https://sites.google.com/view/unifi-consortium/home?authuser=0.
[237] DOE Office of Electricity, Rapid Operational Validation Initiative (ROVI), 2023, [Online]. Available: https://www.energy.gov/oe/rapid-operational-validation-initiative-rovi.
[238] L. Ward, S. Babinec, E.J. Dufek, D.A. Howey, V. Viswanathan, M. Aykol, D.A. Beck, B. Blaiszik, B.-R. Chen, G. Crabtree, S. Clark, V. De Angelis, P. Dechent, M. Dubarry, E.E. Eggleton, D.P. Finegan, I. Foster, C.B. Gopal, P.K. Herring, V.W. Hu, N.H. Paulson, Y. Preger, D. Uwe-Sauer, K. Smith, S.W. Snyder, S. Sripad, T.R. Tanim, L. Teo, Principles of the battery data genome, Joule 6 (10) (2022) 2253–2271, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2542435122004093.
[239] M. Pandey, K. Deshmukh, A. Raman, A. Asok, S. Appukuttan, G. Suman, Prospects of MXene and graphene for energy storage and conversion, Renew. Sustain. Energy Rev. 189 (2024) 114030.
[240] A. Boretti, S. Castelletto, Mxenes in polymer electrolyte membrane hydrogen fuel and electrolyzer cells, Ceram. Int. 48 (23) (2022) 34190–34198.
[241] A. Sengupta, T. Pereira, M. Liserre, Design of the dual active bridge converter to minimize RMS current in supercapacitor interface applications, in: 2023 IEEE Energy Conversion Congress and Exposition, ECCE, 2023, pp. 2348–2354.
[242] W. Ren, M. Steurer, T.L. Baldwin, Improve the stability and the accuracy of power hardware-in-the-loop simulation by selecting appropriate interface algorithms, IEEE Trans. Ind. Appl. 44 (4) (2008) 1286–1294.
[243] G.F. Lauss, M.O. Faruque, K. Schoder, C. Dufour, A. Viehweider, J. Langston, Characteristics and design of power hardware-in-the-loop simulations for electrical power systems, IEEE Trans. Ind. Electron. 63 (1) (2016) 406–417.
[244] C.S. Edrington, M. Steurer, J. Langston, T. El-Mezyani, K. Schoder, Role of power hardware in the loop in modeling and simulation for experimentation in power and energy systems, Proc. IEEE 103 (12) (2015) 2401–2409.
[245] F. Huerta, J.K. Gruber, M. Prodanovic, P. Matatagui, Power-hardware-in-the-loop test beds: evaluation tools for grid integration of distributed energy resources, IEEE Ind. Appl. Mag. 22 (2) (2016) 18–26.
[246] A. Benigni, T. Strasser, G. De Carne, M. Liserre, M. Cupelli, A. Monti, Real-time simulation-based testing of modern energy systems: A review and discussion, IEEE Ind. Electron. Mag. 14 (2) (2020) 28–39.
[247] G. De Carne, G. Lauss, M.H. Syed, A. Monti, A. Benigni, S. Karrari, P. Kotsampopoulos, M.O. Faruque, On modeling depths of power electronic circuits for real-time simulation – A comparative analysis for power systems, IEEE Open Access J. Power Energy 9 (2022) 76–87.
[248] C. Eckel, D. Babazadeh, C. Becker, Classification of converter-driven stability and suitable modelling and analysis methods, IEEE Access (2024) 1.
[249] P. Kotsampopoulos, D. Lagos, N. Hatziargyriou, M.O. Faruque, G. Lauss, O. Nzimako, P. Forsyth, M. Steurer, F. Ponci, A. Monti, V. Dinavahi, K. Strunz, A benchmark system for hardware-in-the-loop testing of distributed energy resources, IEEE Power Energy Technol. Syst. J. 5 (3) (2018) 94–103.
[250] F. Reißner, G. De Carne, Virtual synchronous machine integration on a commercial flywheel for frequency grid support, IEEE Trans. Power Electron. (2024) 1–4.
[251] Y.-J. Kim, J. Wang, Power hardware-in-the-loop simulation study on frequency regulation through direct load control of thermal and electrical energy storage resources, IEEE Trans. Smart Grid 9 (4) (2018) 2786–2796.
[252] S. Karrari, G. De Carne, M. Noe, Adaptive droop control strategy for flywheel energy storage systems: A power hardware-in-the-loop validation, Electr. Power Syst. Res. 212 (2022) 108300.
[253] S. Bruno, G. Giannoccaro, C. Iurlaro, M. La Scala, C. Rodio, Power hardware-in-the-loop test of a low-cost synthetic inertia controller for battery energy storage system, Energies 15 (9) (2022) [Online]. Available: https://www.mdpi.com/1996-1073/15/9/3016.
[254] R. Todd, H.J. Uppal, T. Feehally, A.J. Forsyth, A.M. Pavan, A power hardware-in-the-loop simulation facility for testing grid-connected storage systems, in: 2019 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference, ISGT, 2019, pp. 1–5.
[255] C. Seitl, C. Messner, H. Popp, J. Kathan, Emulation of a high voltage home storage battery system using a power hardware-in-the-loop approach, in: IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society, 2016, pp. 6705–6710.
[256] L. Vu-Ngoc, B.-H. Nguyen, T. Vo-Duy, M.C. Ta, J.P.F. Trovão, Power hardware-in-the-loop simulation of hybrid energy storage system considering supercapacitor voltage limitation, in: 2022 IEEE Vehicle Power and Propulsion Conference, VPPC, 2022, pp. 1–6.
[257] T. Alharbi, M. Restrepo, M. Kazerani, K. Bhattacharya, Control and hardware-in-the-loop simulation of community energy storage systems based on repurposed electric vehicle batteries, IEEE Access 11 (2023) 146238–146249.
[258] M. Hetzel, D.D. Ocampo, G. De Carne, M. Hiller, Supercapacitor modeling and parameter identification of a 400 kW grid-connected supercapacitor energy storage system using the inherent impedance spectroscopy capability of its DC/DC converter, in: 2023 IEEE Energy Conversion Congress and Exposition, ECCE, 2023, pp. 459–465.
[259] S. Karrari, H.R. Baghaee, G. De Carne, M. Noe, J. Geisbuesch, Adaptive inertia emulation control for high-speed flywheel energy storage systems, IET Gener. Transm. Distrib. 14 (22) 5047–5059.
[260] G. De Carne, M. Langwasser, M. Ndreko, R. Bachmann, R.W. De Doncker, R. Dimitrovski, B.J. Mortimer, A. Neufeld, F. Rojas, M. Liserre, Which deepness class is suited for modeling power electronics?: A guide for choosing the right model for grid-integration studies, IEEE Ind. Electron. Mag. 13 (2) (2019) 41–55.
[261] S. Karrari, G. De Carne, M. Noe, Model validation of a high-speed flywheel energy storage system using power hardware-in-the-loop testing, J. Energy Storage 43 (2021) 103177, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352152X2100877X.
[262] 2024. [Online]. Available: https://energy.sandia.gov/programs/energy-storage.
[263] 2021. [Online]. Available: https://energy.sandia.gov/wp-content/uploads/dlm_uploads/2012/04/NSTTF_factsheet_2021.pdf.
[264] S. Passerini, L. Barelli, M. Baumann, J. Peters, M. Weil, Emerging Battery Technologies to Boost the Clean Energy Transition, Springer, 2024.
[265] European Commission, Proposal for a regulation of the European parliament and of the council concerning batteries and waste batteries, repealing directive 2006/66/EC and amending regulation (EU) No 2019/1020, 2020, [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020PC0798.
[266] H.E. Melin, M.A. Rajaeifar, A.Y. Ku, A. Kendall, G. Harper, O. Heidrich, Global implications of the EU battery regulation, Science 373 (6553) (2021) 384–387, [Online]. Available: https://www.science.org/doi/abs/10.1126/science.abh1416.
[267] K. Berger, J.-P. Schöggl, R.J. Baumgartner, Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases, J. Clean. Prod. 353 (2022) 131492, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959652622011131.
[268] T. Georgi-Maschler, B. Friedrich, R. Weyhe, H. Heegn, M. Rutz, Development of a recycling process for Li-ion batteries, J. Power Sources 207 (2012) 173–182, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378775312002984.
[269] K. Yanamandra, D. Pinisetty, A. Daoud, N. Gupta, Recycling of Li-ion and lead acid batteries: A review, J. Indian Inst. Sci. 102 (2022) 281–295, [Online]. Available: https://doi.org/10.1007/s41745-021-00269-7.
[270] 2021. [Online]. Available: https://www.aps.com/-/media/APS/APSCOM-PDFs/About/Our-Company/Newsroom/McMickenFinalTechnicalReport.pdf?la=en&sc_lang=en&hash=5447FA391CD988DD24226FA485F81F23.
[271] 2024. [Online]. Available: https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database.
[272] 2021. [Online]. Available: https://batteriesnews.com/korea-measures-energy-storage-systems-safety-batteries-fire/.
[273] A. Pfrang, A. Kriston, V. Ruiz, N. Lebedeva, F. di Persio, Chapter eight - safety of rechargeable energy storage systems with a focus on li-ion technology, in: L.M. Rodriguez-Martinez, N. Omar (Eds.), Emerging Nanotechnologies in Rechargeable Energy Storage Systems, in: Micro and Nano Technologies, Elsevier, Boston, 2017, pp. 253–290, [Online]. Available: https://www.sciencedirect.com/science/article/pii/B978032342977100008X.
[274] 2024. [Online]. Available: https://www.tuvsud.com/en-us/industries/mobility-and-automotive/automotive-and-oem/automotive-testing-solutions/battery-testing/testing-of-stationary-energy-storage-systems.
[275] UL 9540A test method, 2024, [Online]. Available: https://www.ul.com/services/ul-9540a-test-method.