Grid-Connected Energy Storage Systems: State-of-the-Art and Emerging Technologies

This article discusses pros and cons of available energy storage, describes applications where energy storage systems are needed and the grid services they can provide, and demonstrates different power electronic solutions.

By Glen G. Farivar, *Senior Member IEEE*, William Manalastas, Jr., Hossein Dehghani Tafti, *Senior Member IEEE*, Salvador Ceballos, Alain Sanchez-Ruiz, *Senior Member IEEE*, Emma C. Lovell, Georgios Konstantinou, *Senior Member IEEE*, Christopher D. Townsend, *Member IEEE*, Madhavi Srinivasan, and Josep Pou, *Fellow IEEE*

ABSTRACT | High penetration of renewable energy resources in the power system results in various new challenges for power system operators. One of the promising solutions to sustain the quality and reliability of the power system is the integration of energy storage systems (ESSs). This article investigates the current and emerging trends and technologies for grid-connected ESSs. Different technologies of ESSs categorized as mechanical, electrical, electrochemical, chemical, and thermal are briefly explained. Especially, a detailed review of battery ESSs (BESSs) is provided as they are attracting much attention owing, in part, to the ongoing electrification of transportation. Then, the services that grid-connected ESSs provide to the grid are discussed. Grid connection of the BESSs requires power electronic converters. Therefore, a survey of popular power converter topologies, including transformer-based, transformerless with distributed or common dc-link, and hybrid systems, along with some discussions for implementing advanced grid support functionalities in the BESS control, is presented. Furthermore, the requirements of new standards and grid codes for grid-connected BESSs are reviewed for several countries around the globe. Finally, emerging technologies, including flexible power control of photovoltaic systems, hydrogen, and second-life batteries from electric vehicles, are discussed in this article.

KEYWORDS | Battery energy storage system (BESS); energy storage system (ESS); grid codes; hydrogen; power electronic converter; renewable energy.

I. INTRODUCTION

Every energy storage system (ESS) runs through a cycle of charge and discharge with a long-term energy balance required between charge and discharge for the stable and sustainable operation of the system. Energy stored in the

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Glen G. Farivar is with the Energy Research Institute, Nanyang Technological University, Singapore 639798 (e-mail: gfarivar@ntu.edu.sg).

William Manalastas, **Jr**., and **Madhavi Srinivasan** are with the School of Materials Science and Engineering, Nanyang Technological University, Singapore 639798 (e-mail: wmanalastas@ntu.edu.sg; madhavi@ntu.edu.sg).

Hossein Dehghani Tafti and **Christopher D. Townsend** are with the Department of Electrical, Electronic, and Computer Engineering, The University of Western Australia, Crawley, WA 6009, Australia (e-mail: hossein002@e.ntu.edu.sg; townsend@ieee.org).

Salvador Ceballos is with Tecnalia, Basque Research and Technology Alliance (BRTA), 48160 Derio, Spain (e-mail: salvador.ceballos@tecnalia.com).

Alain Sanchez-Ruiz is with Ingeteam R&D Europe, 48170 Zamudio, Spain, and also with the Department of Electronic Technology, University of the Basque Country (UPV/EHU), 01006 Vitoria-Gasteiz, Spain (e-mail: alain.sanchez@ehu.eus).

Emma C. Lovell is with the School of Chemical Engineering, University of New South Wales, Sydney, NSW 2052, Australia (e-mail: e.lovell@unsw.edu.au).

Georgios Konstantinou is with the School of Electrical Engineering and Telecommunications, University of New South Wales, Sydney, NSW 2052, Australia (e-mail: g.konstantinou@unsw.edu.au).

Josep Pou is with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798 (e-mail: josep.pou@ieee.org).

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earth as fossil fuels over the course of millions of years is no exception to this. The issue with the current rate of utilization is not just the inevitable depletion of this valuable resource (with current production rates based on 2020 known resources, oil and gas are estimated to last 50 and 49 years, respectively, while coal will run out after 139 years [1]) but also its side effect of emitting greenhouse gases. In fact, considering the latter, it is estimated that, by 2050, nearly 60% of oil and methane gas and 90% of coal must remain unextracted to have a 50% probability of limiting global warming to 1.5 °C [2]. Accordingly, there is a need to urgently modify the way society uses this natural ESS by drastically reducing the discharge rate (burn fewer fossil fuels) and increasing the charging rate (plant more trees) to restore the natural balance. Achieving this of course relies on utilizing other energy sources.

Inevitably, in the near future, almost all of our energy consumption will be generated from sustainable sources. Currently, wind, solar, and hydro are the predominant renewable sources that have reached technological maturity and with the current projection of deployment rates; presumably, they will be the backbone of our electric power generation for the foreseeable future [3]. Of course, any breakthrough in promising disruptive technologies, such as nuclear fusion reactors, can alter this presumption [4]–[6].

Electric power grids operate on a delicately maintained balance between generation and consumption. Conventionally, generation was flexible to follow the load demand. However, given the intermittent and uncontrolled nature of renewable power generation, power grids will have to increasingly rely on ESSs to preserve balanced operation. This is why, as seen in Fig. 1, in line with an increasing amount of intermittent wind and solar generation capacity [1], installed ESS capacity has to increase as well [7]. ESSs' role as an enabler for having a sustainable grid based on renewables is demonstrated based on Australia's experience in [8].

Having to invest in often-expensive ESSs is indeed an undesirable consequence of replacing dispatchable conventional power plants with intermittent wind and solar plants. However, there are promising emerging technologies that add flexibility to both generators and loads to effectively reduce reliance on ESSs [9], [10]. Such flexible assets essentially try to reduce the mismatch between generation and consumption and, as a result, reduce ESS charge and discharge.

This article aims to provide an overview of grid-connected ESS technologies and the role they play in enabling electricity power grids of the future when dominated by intermittent renewable sources. Special attention is given to electrochemical ESS technologies that are also used in electric vehicles (EVs), and as a result, they are experiencing rapid growth and development activities, which is evident from an ever-increasing yearly installed capacity, as shown in Fig. 2 [11]. Power electronics converters are the enablers for grid integration of such ESS technologies. A comprehensive review of power converters for grid and EV applications is provided in [12] and [13]. Compared to these references, this article expands the review by including the following technology advancements:

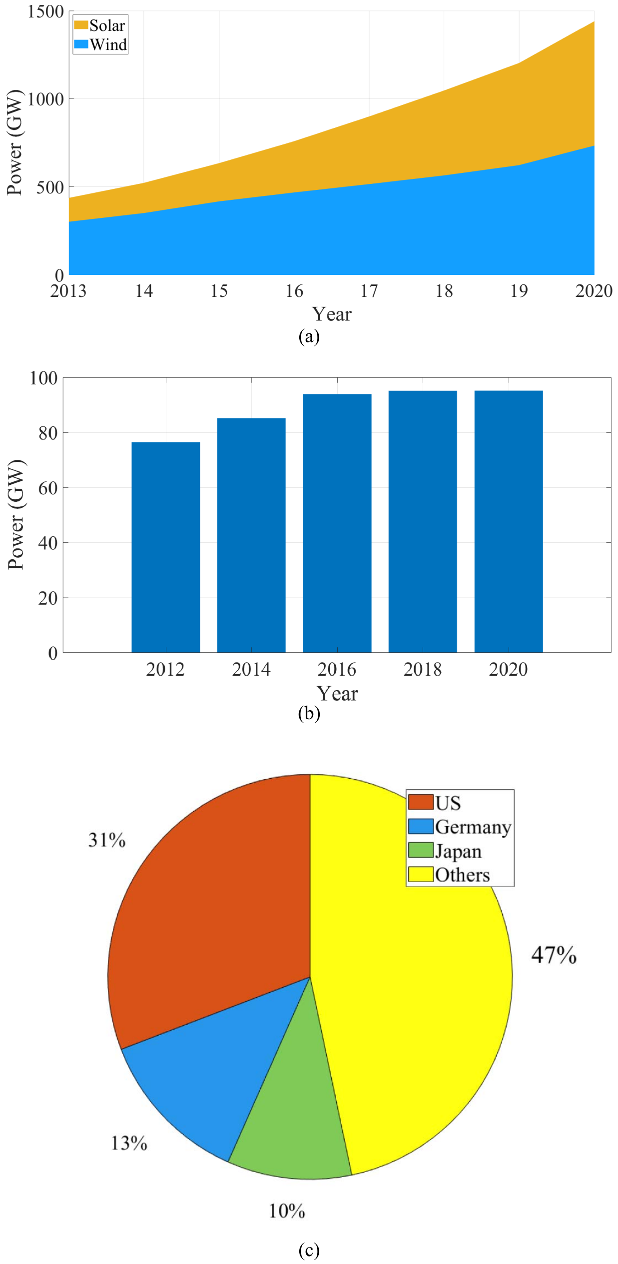


Fig. 1. ***(a) Wind and solar generation capacity (data sourced from [1]). (b) Cumulative ESS power capacity (data sourced from [7]). (c) Worldwide distribution of the aggregate operational ESS power capacity (data sourced from [7]).***

1) control and emerging regulations for grid support functionalities;
2) advancements in solid-state-transformer (SST) technology;

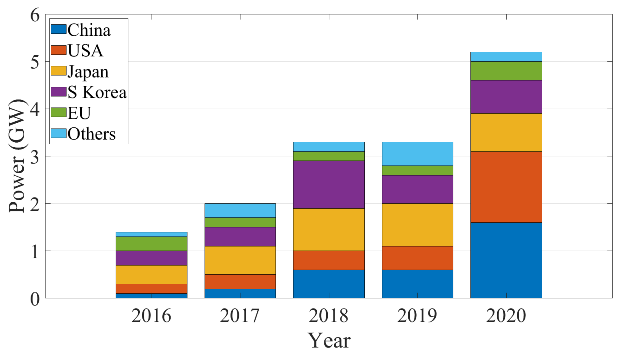


Fig. 2. ***Yearly installed battery energy storage capacity (data sourced from [11]).***

3) power disparity limits and stable operating range of modular power converters.

The organization of this article is given as follows. For the sake of completeness, in Section II, prominent ESS technologies are reviewed. Section III is devoted to further expanding the review on selected ESS technologies that are empowering the electrification of transportation. In Section IV, the significance and role of ESS in modern electric power grids are established. Power electronic interface topologies for grid connection of battery ESSs (BESSs) and grid codes and standards related to grid connection of inverters are reviewed in Section V. Section VI looks at advancements in controlling BESSs to enable additional grid support functionalities. Section VII discusses some upward trending related technologies and prospects. Finally, some concluding remarks are provided in Section VIII.

II. ENERGY STORAGE TECHNOLOGIES

A comprehensive review of available energy storage technologies is reported in [14]–[17]. Fig. 3 shows an overview of the energy storage technologies [18] and their share of current operational ESS capacity based on the data from the U.S. Department of Energy, Global Energy Storage Database [7]. Some features of each category are discussed in the following.

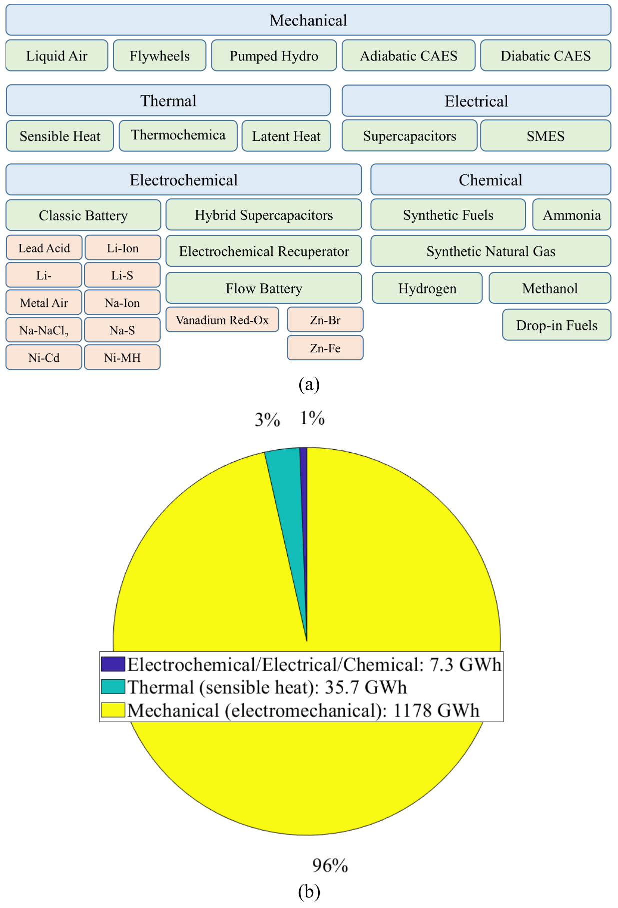
Mechanical: In this category, pumped hydro storage (PHS) is one of the oldest, most popular, and most mature forms of storing energy dating back to the 1920s and currently accounts for over 90% of grid energy storage capacity [19]. Pumped storage is normally associated with established hydroelectric dams on rivers, where water is pumped back to an elevated storage dam. However, it is also possible to use large underground caverns for PHS purposes [20]. Such geological caverns or old mines are suitable for use in compressed air energy storage (CAES) as well [21]. CAES operates on a similar principle to PHS, i.e., driving a turbine through stored potential energy.

Thermal: A notable example of thermal storage for producing electricity is the concentrated solar power plant (CSP). CSP operates in a similar way to a conventional steam turbine power plant; however, the heat source is often molten salt produced by concentrating solar radiation [22].

Electrical: Supercapacitors and superconducting magnetic energy storage are the two prominent electrical energy storage technologies. Both feature low energy density and high power density. While the former has found many applications requiring fast and frequent charge and discharge [23], the cost-effectiveness of the latter in practice is still debatable as it requires maintaining extremely low temperatures [24].

Electrochemical: Batteries are one of the most diverse and rapidly growing forms of energy storage technology. Their significance is not just relevant to grid-connected systems but also to the automotive industry [25]. More discussion about this technology is provided in Sections III, V, and VI.

Chemical: Chemical storage compared to the previously discussed technologies is unique in the sense that it can be transported and, owing to its high-energy capacity, can provide a seasonal energy storage option for the power



(a)

(b)

Fig. 3. ***(a) Category of ESS technologies (details available in [18]). (b) Storage capacity distribution among the ESS technologies (data sourced from [7]).***

Table 1 Key Performance Indicators of ESS Technologies (Data Sourced From [18])

Technology	Power range (kW)	Energy range (kWh)	Power cost (€/kW)	Energy cost (€/kWh)	Energy density	Life (Years)	Cycle life	Efficiency (%)
Hydrogen	Several 10^6	10 to several 10^6	2000-5000	1-10	30-2550 kWh/m^3	5-30	n.a.	20-40 (fuel cell)
Double Layer Capacitor	10^3	Up to 10	100-500	10,000-20,000	4-7 Wh/kg	10	10^6	90
Flow Battery	1 to several 10^3	100 to some 10^3	500-1,300	100-400	10-25 Wh/liter	10-20	>12000	70-75
Lead-Acid Battery	Some 10^3	Up to 10^4	100-500	100-200	25-35 Wh/kg	5-15	500-3000	75-85
Lithium-Ion Battery	1 to 50×10^3	Up to 10^4	150-1000	700-1,300	120-180 Wh/kg	15-20	2000-10000	90-98
Pumped Hydro Storage	10^3 to 3×10^6	Up to some 10^8	400-1500	40-150	0.5-3 Wh/kg	>80	n.a.	70-85
Thermal Hot Water (Multi-Dwelling Building)	400	25-320		15	0.08 kWh/kg	20-40	n.a.	70-95

grid [26]. In particular, hydrogen is emerging as a target in chemical energy storage technology. The reverse process of generating electricity occurs either indirectly through conventional gas turbine power plants or directly through fuel cells [27]. Given the significance of this technology for reaching 100% energy sustainability, it is comprehensively reviewed in Section VII-C.

In order to compare the main features of some selected ESS technologies, Table 1 summarizes their key performance indicators. From the provided data, it is not hard to see why PHS is the dominant and preferred ESS option. However, it can only be applied where a suitable geographical setting is available nearby. Some examples of the recent ESS deployment projects are provided in the Appendix.

Among the ESS technologies, capacitors, batteries, and fuel cells are closely related as they directly produce a dc voltage (without the need for any electromechanical generator), and in addition, for power grid applications, they are applied to power EVs. A more comprehensive review of these technologies is provided in Section III.

III. ELECTROCHEMICAL ENERGY STORAGE

Electrochemical power packs have fostered human comforts of portable connectivity, mechanical automation, and an electrified living environment. Such devices are capable of ultrahigh efficiencies. They do not suffer from the 51% Carnot efficiency thresholds of combustion engines. They can be used in a versatile range of form factors, ranging from thin films to cartridges to block modules. They simplify recharging logistics by taking advantage of a large preexisting power grid architecture. In addition, they can be readily integrated as per electric rating requirements via cell stacking.

The technological principle is ultimately based on the Nernst equation: $\Delta G = nFE$. Here, the released chemical energy (ΔG) is the product of the directed migration of electrical charge (n), Faraday's constant (F), and the electrochemical potential (E) between two substance masses. The genius of the early electrochemists was the realization that electron transport and ion transport occurring in mundane combustion, for instance, could theoretically be decoupled, thus effectively driving electromagnetic motors. Not only that, by limiting the transport of either electrons or ions, one could effectively switch OFF the release of stored energy. This has, thus, created a bridge between space and time for supplying electric energy when and where it is needed at very low penalties of entropic energy loss. This is in stark contrast to mechanical engines based on pressure–temperature differentials, wherein gas exhausts still carry substantial unharnessed energy.

The terminological category for electrochemical power packs is electrochemical-energy storage (EES) devices. They exploit the chemical potential differences existing between segregated active materials, which represents stored energy. Active materials when brought together in direct intimate contact may result in an explosive burst of heat energy from electron-ion diffusion intermixing. What EES devices do is decouple the ion transport using an internal electrolyte, from the electron transport, which is redirected through an external load to perform useful work. EES devices can be classified into fuel cells, batteries, and capacitors, as shown in Fig. 4.

Remark: In this section and hereafter in this article, for ease of reference and to underscore the close association of these technologies, the definition of EES is expanded to include capacitors (electrical) and fuel cells (chemical) ESS technologies.

A. Fuel Cells

Fuel cells oxidize "fuels" (e.g., H_2, acetylene, methanol, ethanol, NH_3, H_2O_2, and natural gas) using precious-metal catalysts, and their total energy output is only limited by how much fuel can be supplied [28]–[30]. This fuel derives mostly from the petrochemical industry, photochemical catalysts ($\sim$17% generation efficiency), or dual-electrode electrolysis/thermal catalysis (65%–85% generation efficiency). Generated fuels pose logistical challenges, and in particular, H_2, although lightweight, permeates through stainless steel and most plastic piping, and is explosive (more discussions are provided in Section VIII). Fuel cells typically operate between 20 °C and 1100 °C depending

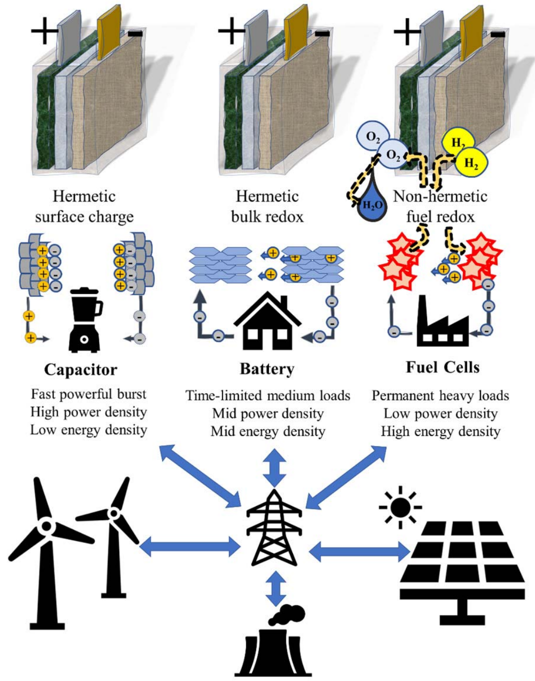


Fig. 4. ***General diagram for EES working principles: batteries, capacitors, and fuel cells. Batteries depend on shuttle-like chemical redox reactions. Capacitors are based on field-induced charge separation. Fuel cells provide power by oxidizing external fuels through their catalyst electrodes.***

on the membrane technology, where elevated temperatures are usually required to achieve acceptable current rates through the electrolyte despite lower power efficiencies (due to the need for heating) [31], [32]. The lifetime of a fuel-cell stack can further be seriously limited by poisoning/coking/phase segregation issues of the catalyst core in an uncontrolled setting. Properly set up, however, fuel cells are extremely valuable for energy-voracious installations requiring uninterrupted power supply for prolonged periods with virtually zero intermittent downtime. The largest commercial suppliers for heavy-duty stacks as of the year 2020 include Bloom Energy, Kyocera, SOLIDpower, and FuelCell Energy with unit demonstrations exhibiting 45%–75% electrical efficiencies and cell stack degradation rates of 0.4%–0.9% per 1000 h (3.5%–7.9% per year) [33]. Ceres Power stands out for compact, modular units (5 kW) requiring minimal high-temperature insulation, exhibiting $<0.2\%$ degradation/1000 h ($\sim 1.7\%$ per year), guaranteeing a satisfactory service lifetime of at least ten years, operating at ~ 0.9 V/cell and >250 mA/cm^2 near 600 °C [34]–[37], which is a feat echoed by fast-rising producers in China as well [38]. On the lab scale, nanoengineered cathodes have been able to sustainably achieve 20x the market current rates (4.7 A/cm^2 at 0.7 V, 650 °C), a most promising feat for more effective utilization of precious metal catalysts [39].

B. Batteries

Whereas fuel cells rely on an external material exchange, batteries operate on a fixed-dimension hermetic format, which stores internally all the active materials. The device allows for both consumption and regeneration of the "fuel" in an encapsulated device, simply by using external connectors with applied voltage/current limits. Herein, the active materials are often in a solid or liquid phase, which facilitates material compartmentalization, but this is not perfect. A key point is that the oxidation states in the electrodes vary through cycling, and compensatory mass transfer must occur to prevent a resistive polarization buildup. Hysteresis in the mass transfer is often the culprit for battery degradation. Furthermore, batteries must inevitably go through a charging step when all the stored energy is spent, unlike fuel cells.

Battery chemistries are widely diverse and can make use of most elements across the periodic table [40], [41]. Of these, advanced lithium-ion batteries lead with 304-Wh/kg (700-Wh/L) specific energies based on state-of-the-art NMC/Si-C cells, which are quite close to the performance guidelines set by the U.S. Advanced Battery Consortium (350 Wh/kg and 750 Wh/L) and also the physicochemical limits (400 Wh/kg and 800 Wh/L) of Li-ion battery technology [42]–[44]. Battery-related behemoths today include the American Tesla, the Chinese CATL/BYD/SVOLT/Guoxuan High-Tech, the Korean Samsung SDI/LG Chem/SK Innovation, the Japanese Panasonic, the Swedish Northvolt, and a consortium of other emerging European players, who have committed investments on NCA (or NMC or LFP)/liquid electrolyte/graphite (or Si) cell technologies mostly. Other than these, the now-defunct Aquion is specialized in affordable grid-deployed aqueous-electrolyte sodium batteries but was eventually overtaken by Li-ion battery advances through economies-of-scale pricing and sheer policy support. Moving away from Na-S, Ni-Cd, lead-acid, and redox-flow batteries [45], the developing trends focus on developing Co-free electrodes through fluorination, organically derived electrodes, Li-rich compositions, liquid-electrolyte Li-metal batteries, solid-electrolyte Li-metal batteries, anionic shuttle batteries, and multivalent-ion aqueous batteries, the best of which promises greater than 500-Wh/kg and 1000-Wh/L storage metrics [42]. Doping and grain morphology controls are common thematic strategies for improving material performances, for instance, in the case of $LiCoO_2$ materials, which, although possessing a theoretical capacity of 274 mAh/g, traditionally, attained only 165 mAh/g in commercial samples due to significant structural instability when charging above 4.35 V (versus Li+) but for which 190-mAh/g levels have, finally, been unlocked via Al/La doping stabilization to enable charging until 4.50 V (versus Li+) [46].

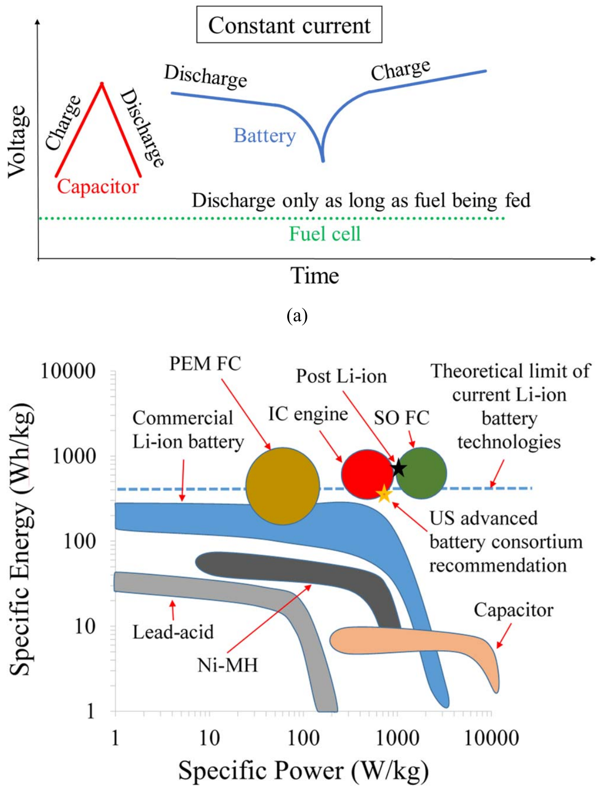
C. Capacitors

Capacitors operate similar to batteries, except for the absence of redox reactions. Here, energy is stored as concentrated electron/ion charge on opposite electrodes of a dielectric medium. Because capacitors rely on surface storage, their relaxation time is very fast, and their power density is consequently very high. However, they lose out on energy density to batteries, which can utilize both the surface material and the subsurface bulk. Recent trends in 2-D-material active materials (one-atom-thick sheets or few-layer sheets) blur the barrier between batteries and capacitors (supercapacitors, ultracapacitors, and hybrid capacitors), achieving a favorable balance of specific energy and specific power performances [47], [48]. However, one must be lucid in interpreting claims in reported stored energies, as very light, fluffy, and poorly packing materials may actually necessitate a higher amount of heavy casing material [49]. Nonetheless, capacitors are critical for buffering energy storage/release events on ultrafast timescales (<1 min) and possess exceptionally very high operation lifetimes (>10 years), as actively exemplified in European trams and Chinese short-distance buses.

D. General Perspective

The chief consideration in choosing fuel cells, batteries, or capacitors for grid storage relies primarily on one consideration: cost per kWh. Material mining, processing, production, shipping, handling, and assembly all represent heavy economic overheads, wherein >60% of the device cost derives from the physical material components [50], [51]. Needing only a few grams (liters) instead of a few kilograms (gallons) of material represents significant supply-chain savings. Therefore, there is always an advantage to efficient material usage even though the total weight and space footprints are nonissues with grid EES as they are immobile modular installations and can be built vertically in limited patches of land. Furthermore, technology-choice parameters of higher energy density, higher power density, better roundtrip efficiencies, longer calendar lifetimes, operational safety, environmental benefits, and recyclability in a closed-loop economy have hidden cost savings normally unaccounted for in apparent cost calculations. These technical parameters are summarized in Fig. 5 and Table 2 [52], [53].

On an additional note, with burgeoning population growth and energy needs throughout the globe, there is no shortage of a perennial economic driver for improved EES technologies. Coupled with economies-of-scale, the critical price point for massive adoption of EES technologies is expected to be at the 100 $/kWh point for batteries (optimistically setting within this decade, 2020–2030), which is still much more expensive than the 16 $/kWh promised by fuel cells (assuming a ten-year stack lifetime). This added price premium for batteries over fuel cells is still tolerable given the logistical advantages and reduced reliance on precious metals [54]–[56].



(a)

(b)

Fig. 5. ***(a) Typical voltage profiles of EES devices with respect to time (galvanostatic conditions: when holding electric current constant). (b) Ragone plot of various EES technologies (adapted from [32] and [42]–[44]).***

IV. POWER GRID ENERGY STORAGE REQUIREMENTS

ESSs add flexibility to the entire power grid by being able to function as the generation, consumption, and/or reactive power compensation assets. They deliver a wide range of services that cover all the segments of the energy value stream ranging from conventional and renewable generation, transmission, and distribution up to the final customer [16], [57]–[59].

Fig. 6 shows a classification of the main energy storage applications and how they are distributed per segment [57], [58]. Each application is briefly discussed in the following, and some practical examples are given in the Appendix.

A. Conventional/Bulk Generation Services

ESSs provide services that contribute to optimize the operation of conventional synchronous generation in terms of flexibility, efficiency, and economic return. The main ESS services associated with conventional generation are given as follows.

Table 2 Key Advantages/Disadvantages for Various ESS Technologies

Energy storage system	Advantages	Disadvantages	Application
Conventional Li-ion battery [52]	High energy density High power density Short response time (minutes to hours)	High cost Aging	Peak-shaving/load-levelling solutions for the grid, accounts for majority of worldwide deployment (>90%)
Lead-Acid battery [52]	Low cost Technological maturity	Low energy/power density Toxic components Short calendar life Short response time	Minimal worldwide deployment for the grid (<2%) due to limited performance, used as standby-power mostly
Vanadium redox battery [52]	High energy storage capacity (ease of scalability)	Low energy/power density Complex construction (need pumps)	Load-levelling at substations. transformer upgrade deferral, and support for grid integration of solar and wind
Supercapacitors [52]	High power density	Low energy density	Buffer spike pulses (60s) in transmission or distribution lines to improve power factor and overall system efficiency
PEM fuel cells	Room-temperature operation possible	Can only use H_2 as fuel	Continuous stable power output (as long as there is a scaled H_2 fuel tank)
Solid oxide fuel cell [53]	Can use various hydrocarbons as fuels	High-temperature operation necessary (>350°C)	Can operate both as fuel cell and electrolyzer, can be deployed with heat cogeneration and eco-friendly steel production

Energy Arbitrage: The practice of using ESSs to store the energy when the price is low and to sell it at peak times when the price is high. It contributes to optimize economically the use of generation assets [60]–[62].

Peak Shaving: The practice of using ESSs to store energy when the demand is low and discharge it to remove the peaks of the load. The principle of peak shaving is similar to that of energy arbitrage, but peak shaving does not follow any economic target [63], [64].

Load Leveling: Load leveling makes use of ESSs to store energy when the demand is low and to inject it back into the grid when the electrical load is high. The main difference between load leveling and peak shaving relies on that the former focuses on flattening the load rather than just removing the peaks [65], [66].

Generator Bridging: It is the practice of using ESSs to supply the load while transitioning between generators [57], [58], [67].

Generator Ramping and Load Following: Usually, ESSs offer more rapid response times to load changes compared to generator units. This service makes use of ESSs to provide support in following load changes and take over fast load variations allowing the generators to ramp up/down their power according to their technical recommendations. It contributes to enhance the life cycle of the generators and the power quality [68], [69].

Black-Start: It is the practice of using ESSs to restore a part of the power grid after a black out. When referring to isolated grids, it is the practice of energizing the grid providing the required power and voltage before the generating units come into operation [70]–[72].

B. Renewable Generation Services

ESSs are required to provide the power grid with the required flexibility to cope with the inherent variability of renewable energy systems. They contribute to balancing variable generation with the load, thus decreasing the need for dispatchable synchronous generation capacity and the rates of power curtailment. The main ESS services associated with renewable energy systems are given as follows.

Curtailment Minimization: The practice of using ESSs to absorb the energy that cannot be injected into the grid

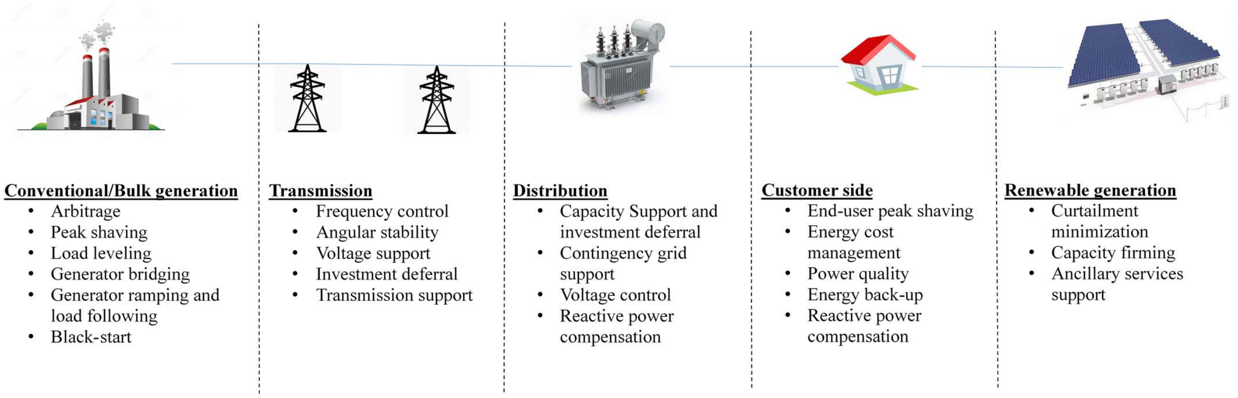


Fig. 6. ***ESS applications.***

during periods of time with excess renewable generation, due to the availability of primary resources, and low demand. Storage energy is delivered to the grid when needed [73], [74].

Capacity Firming: The practice of using ESSs to smooth the power injected into the electrical grid by renewable energy systems during a given period. This service makes use of ESSs to store energy during hours of peak production regardless of the load. The stored energy is injected back into the grid to supplement the variable energy generation when the generation decreases. Capacity firming is also used to smooth short-time energy fluctuations due to fast changes in the primary resource [75], [76].

Ancillary Services Support: The use of ESSs to help variable renewable generation systems to contribute to the provision of ancillary services by keeping an extra energy reserve. In this way, renewable generation systems combined with ESSs can contribute to the provision of new ancillary services, such as inertia emulation, fast frequency response, primary frequency control, or dynamic reactive control, among others [77]–[79].

C. Transmission Services

ESSs are capable of performing as transmission assets as well. The main services that ESSs provide to the transmission system are given as follows.

Primary/Secondary/Tertiary Frequency Control: ESSs can contribute to correct frequency deviations by means of [80]–[82] the following:

1) maintaining a balance between generation and demand within a synchronous area after a disturbance (primary frequency control);
2) adjusting the active power generation to restore the nominal frequency following a disturbance (secondary control);
3) restoring the primary and secondary frequency control reserves (tertiary control).

Angular Stability: It refers to the practice of using ESSs to contribute to the reduction of load-angle variations following a disturbance by means of processing high power levels in short periods. This contributes to improve the angular stability of the grid [82], [83].

Voltage Support: ESSs can also be used as distributed reactive power sources or sinks, thus contributing to regulate voltage levels through the nodes of the transmission and distribution networks [82], [83].

Transmission Investment Deferral: It refers to the use of ESSs to solve congestion issues within the transmission grid, thereby deferring the need to implement transmission system upgrades [84], [85].

Transmission Support: It refers to the ability of ESSs to improve the operation of the transmission system during disturbances, such as voltage sags, local and interarea subsynchronous oscillations, or voltage instabilities, among others [86], [87].

D. Distribution Services

The distribution grid also benefits from the use of ESSs mainly due to the following services.

Capacity Support and Investment Deferral: Capacity support refers to the practice of using ESSs to shift load from peak to base period, thus contributing to increase the utilization factor of infrastructure and reduce the congestion through the distribution network. Consequently, the need to implement distribution grid upgrades is deferred [84], [85].

Contingency Grid Support: It refers to the practice of using ESSs to take over part of the electricity generation, thus redistributing the energy fluxes, following the loss of a major component of the grid. It contributes to reduce the impact of the loss of a component in the distribution grid [88], [89].

Voltage Control: The practice of using ESSs to regulate the voltage profile within admissible limits through the distribution network, thus improving the quality of supply. Due to the nature of distribution grids, the voltage profile can be regulated by controlling both the reactive and active power injections [90], [91].

Reactive Power Compensation: It refers to the use of ESSs to contribute to the reactive power balance of the grid [92].

E. Customer Services

ESSs are also used in energy management applications mainly intended to improve the quality and reliability of the power supplied to the customer and reduce customer costs. The main customer services that ESSs provide are given as follows.

End-User Peak Shaving: It refers to the practice of using ESSs by customers to smooth their own peak demand, thus contributing to reduce the part of the cost that is fixed according to the highest power demand [93].

Time-of-Use Energy Cost Management: The practice of using ESSs to reduce the electricity bill by storing energy when electricity rates are low and discharging it at peak times [94].

Power Quality: Fluctuations of the generated power, mainly attributed to the variability of renewable primary resources, cause power quality issues mainly leading to voltage variations and harmonics. ESSs can be used to attenuate these power fluctuations, thus contributing to improve power quality and mitigate disturbances to customer loads [95].

Continuity of Energy Supply (Energy Backup): It refers to the use of ESSs to replace the function of the electricity network after an interruption, therefore preventing critical loads from being affected by blackouts [96], [97].

Reactive Power Compensation: It refers to the capacity of ESSs connected to the grid by means of power electronics to provide reactive power to compensate for customer loads, thus contributing to improve efficiency and regulate voltage levels [98].

Table 3 ESS Characteristics to Provide Different Services to the Grid

Segment	Service	Storage power level (MW)	Response (t_r) and discharge time (t_d)	Suitability of BESS
Conventional/Bulk generation	Arbitrage	Hundreds of MW	t_r minutes t_d ~ < 15 hours	Unsuitable*
	Peak shaving	Hundreds of kW to hundreds of MW	t_r minutes t_d ~< 5 hours	Possible (Nas and flow batteries)
	Load levelling	MW to hundreds of MW	t_r minutes t_d ~ 12 hours	Possible (Nas and flow batteries)
	Generator bridging	Up to hundreds of MW	t_r minutes t_d ~ minutes to several hours	Possible
	Generator ramping/load following	MW to hundreds of MW	t_r ~ up to 1 s t_d ~ minutes to several hours	Possible
	Black-start	Hundreds of kW to hundreds of MW	t_r ~ seconds to minutes t_d ~ seconds up to few hours	Suitable
Renewable generation	Curtailment minimization	Tens of MW to hundreds of MW	t_r ~ minutes t_d ~ minutes up to several hours	Possible
	Capacity firming	Tens of MW to hundreds of MW	t_r ~ seconds t_d ~ seconds up to several hours	Possible
	New ancillary services support	MW level up to tens of MW	t_r ~ milliseconds to seconds (depending on the specific ancillary service) t_d ~ seconds to minutes	Suitable
Transmission	Frequency control	Tens of MW up to ~ 100 MW	t_r ~ milliseconds for primary control t_r ~ < minute for secondary and tertiary controls t_d ~ < 15 minutes for primary control t_d ~ < 1 hour for secondary control t_d ~ > 1 hour for tertiary control	Suitable
	Angular stability	Tens of MW to hundreds of MW	t_r ~ milliseconds t_d ~ seconds to minutes	Suitable
	Voltage support	-	t_r ~ 100 ms	Suitable
	Investment deferral	Tens of MW to hundreds of MW	t_r ~ minutes t_d ~ 1-6 hours	Possible
	Transmission support	Tens of MW	t_r ~ milliseconds t_d ~ second to minutes	Suitable
Distribution	Capacity support and investment deferral	Tens of MW	t_r ~ minutes t_d ~ 1-6 hours	Possible
	Contingency grid support	Tens of MW	t_r ~ seconds t_d ~ minutes to hours	Possible
	Voltage control	-	t_r ~ 100 ms	Suitable
	Reactive power compensation	-	t_r ~ 100 ms	Suitable
Customer services	End-User peak shaving	Tens of kW to tens of MW depending on the customer size	t_r minutes t_d ~< 5 hours depending on the customer load profile	Possible
	Energy cost management	Tens of kW to tens of MW depending on the customer size	t_r minutes t_d ~ < 12 hours	Possible
	Power quality	Tens of kW to tens of MW depending on the customer size	t_r ~ 100 ms t_d ~< 2 hours	Suitable
	Back-up	Tens of kW to tens of MW depending on the customer size	t_r ~< milliseconds t_d minutes up to several hours	Suitable
	Reactive power compensation	-	t_r ~ milliseconds	Suitable

* Energy market attempting to launch mechanisms for this, but economic incentives are too low for any capital outlay for facility investments.

Table 3 shows the main characteristics of the ESSs to supply these services [16], [59]. The values indicated in the table should be understood as approximate since they depend on the specific characteristics of the applications. Since the focus of this article is on electrochemical ESSs, the suitability of batteries to provide these services is indicated. For long-term services for which batteries are not often utilized, it is required to use other energy storage technologies, such as mechanical, electrical, thermal, or chemical.

V. POWER ELECTRONICS FOR BESS GRID INTEGRATION

As discussed in Section III, the EES technologies directly produce dc voltage. Power electronic converters are then used for interfacing this low dc voltage with the high ac voltage of the power grid. In this section, some of the popular converter technologies, as shown in Fig. 7, are discussed.

A. Low-Frequency Transformer-Based Interface

The conventional approach for grid integration of BESS is shown in Fig. 8 [12], [13], [99]. Here, the battery unit is composed of battery cells, modules, and packs. A series and parallel combination of cells makes up a module, and a series and parallel combination of modules makes up a pack. In this approach, the battery is treated as one aggregated unit. However, such series and parallel connection of many battery subunits is the root cause of many problems in BESS applications. This is predominantly due to the power of each series string being limited by the weakest subunit in the string [100]. Therefore,

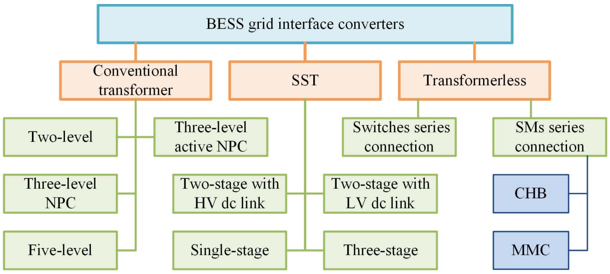


Fig. 7. ***Grid interface converters category.***

to prevent battery fires, improve battery lifetime, and maximize usable battery energy, a battery management system (BMS) is required to monitor and actively modify the state of charge (SoC) and state of health (SoH) of each subunit [101]. Several power electronic switches are, therefore, required to control battery charging and discharging at each level of battery aggregation, which negatively affects efficiency, reliability, and ultimately cost of the system [12].

In the conventional grid-connected inverter for BESS applications, a transformer is used to boost the voltage from hundreds of volts to medium-voltage levels, i.e., tens of kilovolts. Many batteries and their associated inverter units can be connected in parallel at the low-voltage (LV) dc bus to create large-scale BESSs with power ratings of tens of megawatts. Another transformer stage may be added for connection to a higher voltage level, i.e., 66 kV and above. In addition, the use of a two-level dc–ac stage necessitates having a bulky, lossy, and expensive step-up transformer for medium-voltage grid connection.

Alternative topologies to the well-established two-level converter, for BESS applications, include the three-level neutral-point clamped (NPC) converter [102], [103], the active NPC converter, and the three-level flying capacitor converter. A number of five-level converters have also been proposed [104]–[106]. The control design and modulation techniques for these converters are more complicated than the conventional two-level converter [107]–[109]; however, they provide an extra degree of freedom to increase the output voltage magnitude of the converter and improve harmonic performance. There is a tradeoff for different types of multilevel monolithic converters between the increased installed silicon power, the mechanical complexity, and harmonic performance [12].

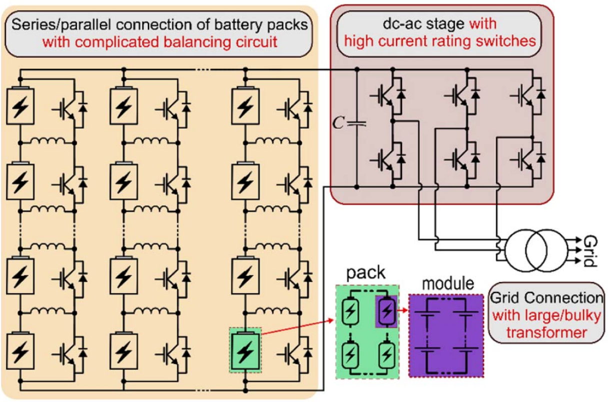


Fig. 8. ***Conventional BESS using a two-level inverter and line-frequency transformer.***

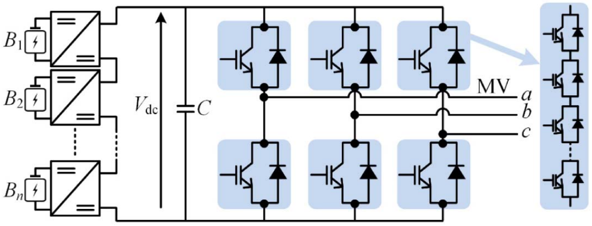


Fig. 9. ***Example of a series connection of IGBTs for direct connection to the MV grid using a two-level converter.***

B. Transformerless Interface

The line-frequency transformer used in the previously described BESS inverters is bulky, lossy, and costly. To avoid the use of a line-frequency transformer, directly connected utility-scale BESS solutions have been developed. These solutions can be classified into two main categories [12]. These are based on the series connection of: 1) semiconductors or 2) submodules (SMs).

1) *Series connection of semiconductors*: For direct connection to the medium-voltage ac grid, many two- or three-level converter topologies can still be utilized. An example using a two-level converter is presented in Fig. 9. Compared to Fig. 8, multiple IGBTs are connected in series, as a single IGBT with a voltage rating of a few kilovolts (e.g., 1.7–6.5 kV) is unable to block the required dc-link voltage. However, some drawbacks of this approach include implications for the converters' physical construction with many series-connected switching devices, and specific design of the gate driver/semiconductors to ensure each device is synchronously turned on/off. The use of this topology also necessitates a low switching frequency to achieve acceptable switching losses, which, in turn, implies a higher cost of output filters.
2) *Series connection of SMs*: Direct connection of BESS to the MV grid without the use of a line-frequency transformer can be achieved through the use of cascaded modular converters based on a basic inverter block (also referred to as a bridge, SM, or cell) [110].

1) Cascaded H-Bridge Converter (CHB): The CHB, as illustrated in Fig. 10, consists of three-phase legs,

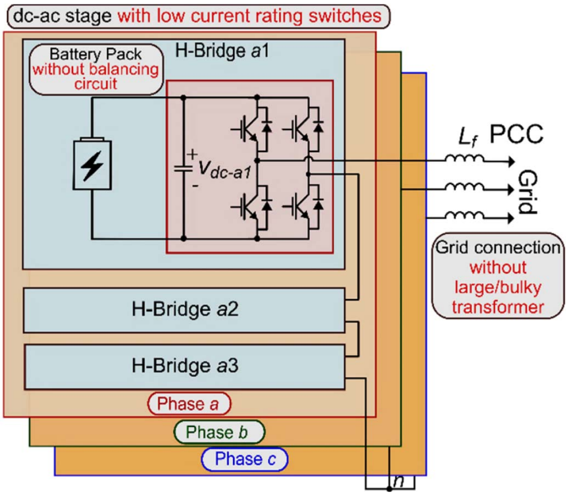


Fig. 10. ***CHB inverter with direct connection of the BESS to the MV grid.***

each having multiple H-bridge cells connected in series [111]–[113]. The utility-scale BESS is normally composed of hundreds of battery modules. Therefore, battery modules can be equally distributed to each cell in the form of shorter battery strings [114]. The use of cascaded topologies enables boosting each LV battery string to MV levels without the use of transformers. Each full bridge can regulate the power flow of the battery modules connected to its dc-link.

2) Modular Multilevel Converter (MMC): The MMC topology with half-bridge SMs (see Fig. 11) provides an alternative cascaded topology for the integration of utility-scale BESS and has attracted research interest over recent years [115]–[117]. The structure of the MMC allows for connection of the energy storage elements either directly to the MV dc-link or in a distributed manner across the SMs that form the converters' arms [116], [118]. In the case of centralized batteries connected to the common dc-link of the MMC, as shown in Fig. 11(a), long battery strings are required negating most of the advantages of the cascaded structure; hence, the distributed approach, as shown in Fig. 11(b), represents a more feasible implementation of the MMC in BESS applications.

When the MMC is considered solely for the purpose of connecting a BESS to the network, the additional complexity/cost of the MMC structure compared to a CHB (six arms instead of three), as well as the less optimal utilization of the converter (double the number of switching devices for the same number of voltage levels), put the MMC at a disadvantage as the topology of choice. However, integration of EES in MMC converters for high-voltage dc (HVdc) transmission, motor drive systems, or other grid support systems enhances the possible functions and the value that the power converter can provide in these applications [118]–[120].

C. Solid-State Transformer

Though transformerless topologies have some advantages, they have the disadvantage of lacking galvanic isolation, which may be required in practice for safety and leakage current reasons. The need to minimize injected dc current to the grid can also necessitate a line-frequency transformer. Alternatively, instead of removing the conventional transformer, it can be replaced by an SST [121], [122]. The idea behind the SST (also known as a smart transformer) is simple, reducing the size and weight of the magnetic core by operating at a higher frequency. Fig. 12 visualizes the size reduction of a 20-kHz transformer compared to a 50-Hz transformer. Of course, achieving such significant core size reduction in SSTs comes with the expense and losses of two frequency converters, and as seen from the figure, the expected size and weight reduction of the SSTs compared to the conventional transformers may not materialize at the system level.

Based on the availability of the dc-link capacitors at either side of the high-frequency magnetic core, there are four categories of SSTs, as shown in Fig. 13 [123], [124]. The most prominent features of each type are discussed next [123].

Type A: This topology achieves a direct ac–ac conversion without using any dc decoupling capacitor. Solutions in the Type A category, owing to their simple configuration, are lightweight and low-cost. On the other hand, due to the lack of dc capacitors, they are unable to provide reactive power support and disturbance decoupling between the two sides. Furthermore, the lack of dc-link at the LV side makes it difficult to integrate renewable sources and batteries. Besides, the lack of an HVdc capacitor prevents the use of established multilevel converters at the HV side

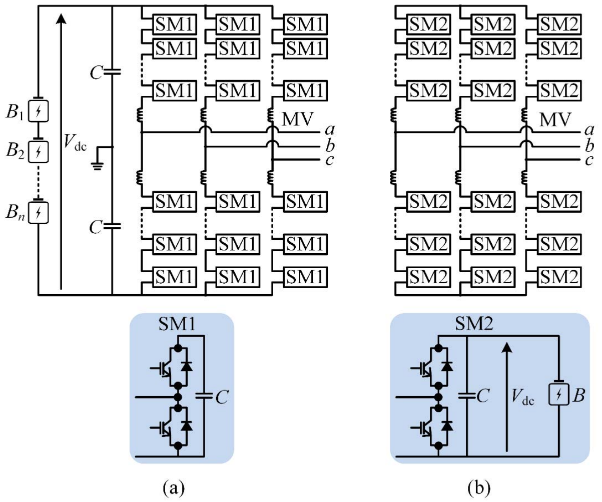


Fig. 11. ***MMC and corresponding SMs. (a) Centralized batteries on the dc-link. (b) Distributed batteries in the SMs.***

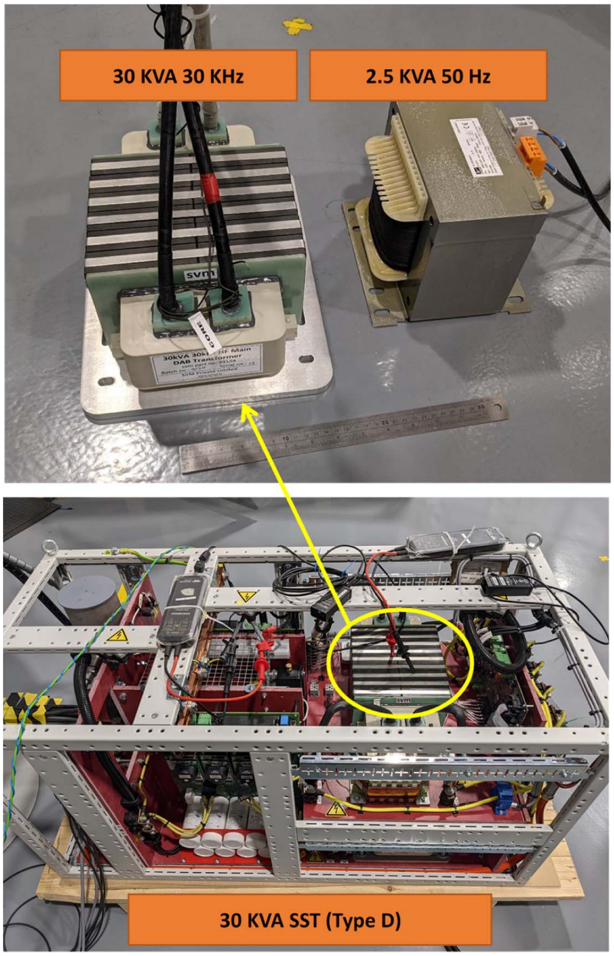


Fig. 12. *Illustration of the size comparison between low- and high-frequency transformers (please note that the systems are experimental prototypes, and the size representation may not be accurate).*

(discussed in Section V-I) and, thus, limits the HV range of the SST.

Type B: Because of the addition of an LVdc capacitor, reactive power control functioning and disturbance isolation are restored, and batteries can readily be connected to this capacitor. However, similar to Type A, HV applications remain a drawback.

Type C: Same as Type B, the presence of an HVdc capacitor enables reactive power control and disturbance isolation. In addition, this topology is more suitable for HV applications compared to Types A and B. However, integration of batteries becomes challenging, which is a significant drawback considering that facilitating grid integration of renewables and batteries is one of the selling arguments of SSTs [125].

Type D: Among all the mentioned variants, Type D with both HVdc and LVdc capacitors is the one with the most control functions and popularity. However, since it is a three-stage topology, it is more complex and has a higher cost than the other solutions. Nevertheless, owing to the advantages of having both LVdc and HVdc capacitors, normally, SSTs for field applications are of this type.

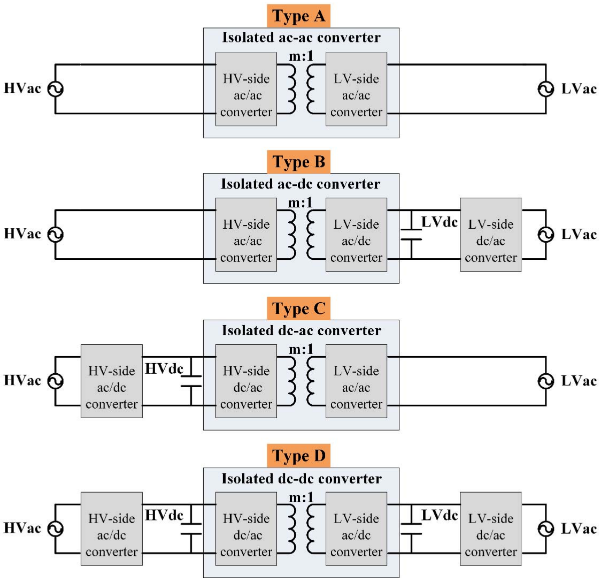


Fig. 13. *SST topology categories.*

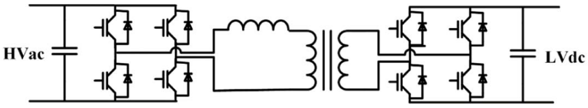


Fig. 14. *DAB topology.*

From the perspective of the battery storage, the part that matters is the dc–dc converter section of the SST. This dc–dc converter provides isolation and dc voltage boosting to connect an LV battery bank to the dc-link of any of the grid-connected dc–ac converters discussed previously. For high-power applications, the popular topology of choice is called dual active bridge (DAB) [126], as shown in Fig. 14. Recent advancements in high-power wide bandgap semiconductor technology offer the opportunity to design more compact and higher efficiency DABs [127], [128]. As an example, Fig. 15 shows the size comparison between a conventional Si IGBT and SiC MOSFET switches [123].

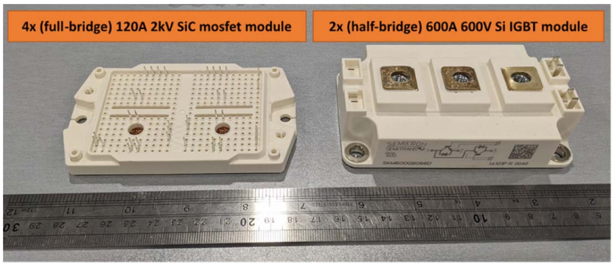


Fig. 15. *Size comparison of SiC MOSFET and Si IGBT.*

D. Power Control Limits of Hybrid ESS Systems

The modular structure of the MMC and CHB converters gives the opportunity of using EESs with different characteristics or even a mixture of photovoltaic (PV) generation and batteries [129], [130]. Such systems are not symmetric, and some operating conditions could yield a significant power disparity among the SMs. Thereafter, the question is how to ensure that the converter can safely follow the desired power references.

The power reference of each SM is determined by the control system to achieve some control objectives (e.g., balancing SoC/SoH in BESS). The control, however, needs to ensure that the generated power references are within the power limits of the ESS. Two types of limitations restrict the active power of the SMs, namely, hardware limits and control limits [110], [117].

Hardware Limits: The hardware limits are related to the physical limitations of individual components. These limits are a natural consequence of the design considerations (they are established during the design phase). Maximum temperature, voltage, and current ratings of the semiconductors, batteries, capacitors, and so on are all examples of hardware limits. These limits are critical, and the control must not disobey them, as they will cause triggering protection circuits. As the hardware limit of one SM only affects the power of that individual SM, it is straightforward to satisfy the hardware limits during the operation.

Control Limits: After satisfying the hardware limits, on the second priority layer, comes the control limits. Violating the control limits not always leads to failure but often results in nonoptimal power distribution. Nevertheless, in some critical cases, violating control limits can lead to triggering a hardware limit, such as overvoltage on a capacitor [110].

E. Grid Codes and Standards

Standards impose several types of requirements on grid-connected inverters for supporting the grid under contingencies and transients. The two main grid support requirements relating to frequency and voltage support are discussed in the following.

Voltage Support: To support the grid voltage at the point of common coupling (PCC), standards impose injection or consumption of reactive power on BESS inverters based on the grid voltage. Fig. 16 shows the volt-VAR $[Q(V)]$) requirement of various standards, including AS 4777.2 [131] TOR R4 [132], IEEE 1547 [133], VDE 4105 [134], CEI 0-21 [135], and TR 3.2.2 [136]. It is clear that, if the PCC voltage is smaller than the nominal range, the BESS is required to inject some amount of reactive power (similar to a capacitor bank) into the grid to help increase the PCC voltage. On the other side, if the voltage is larger than the nominal range, the inverter is required to consume some amount of reactive power (similar to an inductor) to help decrease the voltage at the PCC.

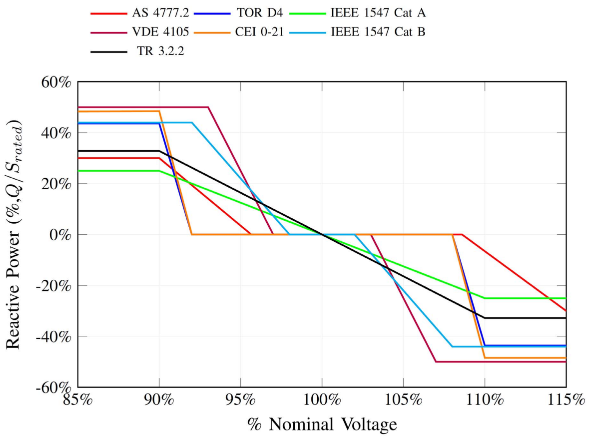


Fig. 16. ***Comparison of volt-VAR [Q(V)] response in different standards.***

As shown in Fig. 16, there is no dead band for *Q(V)* response in Danish standard TR 3.2.2 and category A of IEEE1547, which means that BESS inverters participate in voltage regulation frequently. For standards with large dead bands (i.e., AS 4777-2, TOR D4, and CEI 0-21), the response would rarely be activated even with the function enabled. In VDE4105 and IEEE1547 category B, narrow dead bands (3%) allow easier activation of *Q(V)* response, but VDE4105 has a relatively large reactive power range (up to 50% of S_{rated}), which requires higher reactive power capability from the inverters.

Frequency Support: BESS inverters are required to support the grid frequency under frequency disturbance conditions. Fig. 17(a) shows the requirement of AS 4777.2 standard for an ESS inverter under the frequency decrease. A sample frequency disturbance is also illustrated in Fig. 17(b), while the BESS output power is shown in Fig. 17(c). Before t_1, the grid frequency is at a nominal range, and the BESS is charging with power p_1 (operation point A). After the start of frequency decrease at t_1, the BESS inverter should stop charging, while frequency is decreased to f_{stop} (operation point B). This is the first operation stage of the inverter. In the second operation stage, if the frequency decreases below f_{stop}, the BESS inverter should inject active power to the grid, following the droop curve. In the example shown here, the frequency drops below $f_{P\max}$, in which the output power should increase to the inverter nominal power (operation point C). Various standards define different frequency droop characteristics [137]. When the frequency recovers to the nominal range, for a period of time T_{ss} (20 s, as required by AS 4777.2 [131]), the inverter shall stay at its maximum power, before it returns to the charging mode (as predisturbance condition). This period provides a hysteresis band in the control of the inverter to reduce the risk of unstable operation. During the recovery time, the BESS inverters are required to follow the power ramp

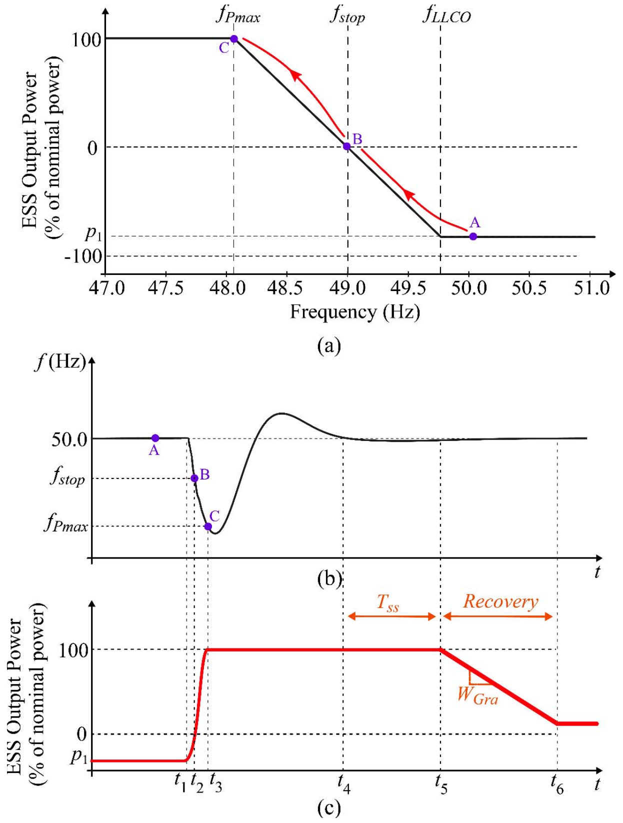


Fig. 17. ***Grid frequency support. (a) Example two-stage frequency response for a decrease in frequency for BESS inverter (AS 4777). (b) Example frequency disturbance. (c) BESS inverter output power.***

rate, defined in the corresponding standard (16% of the nominal power per minute, as specified by AS 4777 [131]).

VI. BESS CONTROL FOR GRID SUPPORT

BESSs, as discussed in Section IV, are typically linked with energy-oriented applications, such as peak shaving, price arbitrage, and minimization of renewable energy curtailment. At the same time, power grids are transitioning away from synchronous generation, and an increasing amount of power electronics converter-based generation, both in numbers and rated capacity, is connected to the electricity network. Maintaining power grid stability with a high proportion of power electronic converters is a challenging task that many power system operators will encounter and endeavor to address in the near future, and BESSs are expected to play a critical role in achieving this goal.

The set of grid-supporting functionalities that a BESS can provide is expansive, considering appropriate inverter sizing, control functions implementation, and detailed integration studies. BESSs can enhance power grid strength, both in terms of voltage management, short-circuit current contribution, and grid recovery, as well as facilitate grid restoration. Such functions are critical, especially following retirements of synchronous generation and the associated reduction in fault current levels across a network. Other functions include damping of oscillations, especially low frequency and subsynchronous oscillations [138], supporting weak grids, increasing the hosting capacity of renewables, particularly in remote locations, and black-start capabilities [139]. BESSs can further optimize the services that they can provide considering geographical constraints, the status of the network, or the time of day (refer to Section IV for more details).

Of particular interest, owing to the amount of available energy stored in the BESSs, is the provision of frequency ancillary services; the ability of a grid-connected converter to provide rapid respond to frequency disturbances in the PCC. On a longer timescale (usually a few seconds to a few minutes), a BESS can contribute to maintaining the grid frequency within predefined limits by regulating the output power, usually through a power–frequency (P–f) droop function (frequency support). This function can be further enhanced to respond to rate-of-change-of-frequency (RoCoF) variations. In shorter timescales, BESSs can contribute to the inertial response of a power grid to disturbances through the provision of synthetic inertia, allowing an immediate response that mimics the behavior of a synchronous generator.

In fact, it is expected that future power grids with high penetration of renewable energy generation will require this set of functionalities [140] in addition to the regular minimum system strength/fault level required for the correct operation of power grid protection functions.

BESSs, and most other power electronics converters, operate fully synchronized to the grid in a grid-feeding configuration, which typically includes a power/voltage and a current controller. In order to provide additional grid supporting functionalities, alternative control methods need to be implemented. Options for BESS include voltage-controlled converters (VCCs) or converters operating in grid forming mode (GFM) [141]. The latter operation can be further expanded by including an inertial control loop [142], effectively emulating the operation of a synchronous generator in a GFM. Such methods are commonly referred to as virtual synchronous machines/generators (VSM/VSG) or the virtual machine mode (VMM).

The control structure of a grid-forming converter is shown in Fig. 18. Such implementations are becoming more common across power grids (e.g., the ESCRI-SA and Hornsdale BESS projects in Australia) but have yet to reach the level of technological maturity that grid feeding converters have in the current power grid.

The most notable difference in the control structure of a GFM compared to a grid-feeding converter is the lack of a phase-locked loop (PLL) as a GFM converter is self-synchronized to the grid through internal references. A PLL may still be used for measurement of the grid frequency (or its deviation from the nominal value) to implement frequency droop control; however, it is no longer a critical element for the operation of the converter.

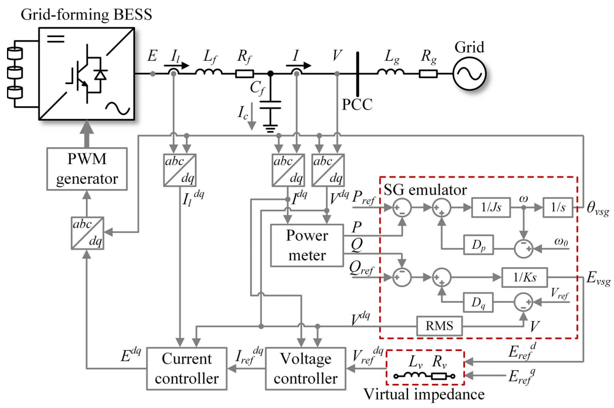


Fig. 18. ***Control structure of a grid-forming converter.***

A PLL might cause subsynchronous resonances by introducing a negative resistance in parallel with the grid input impedance [143]. Removing the PLL also enhances the stability of the converter system and its fault ride-through capabilities enabling contribution to fault currents.

Additional parameters, such as the inertia constant (J) and the damping factor (Dp), can be selected to optimize the response of the BESS to specific events while maintaining overshoots (and the corresponding converter oversizing) within limits. These values are usually selected to replicate the dynamic performance of current SGs. However, the available energy of the BESS can allow for significantly larger values or even adaptive parameter selection [144] depending on the state of the rest of the network. For instance, Tesla's VMM inertia constant can be selected up to 50s [145], ten times greater than the range of a typical SG of coal or gas-fired power station. In a similar manner, the parameters of the reactive power loop (which corresponds to the excitation of the SG) can be selected to adjust the reactive power response, facilitate voltage regulation, or shape the low-frequency impedance of the converter.

The use of a virtual impedance in the control loop of the BESS further expands the application of BESSs in weak grid conditions and can be used to enhance the reactive power sharing capabilities of multiple BESSs in the same network [146]. Moreover, virtual resistance helps to damp a wide frequency range of resonance related to impedance mismatching, inappropriately tuned controller, or improper control setup and, meanwhile, avoids introducing unexpected power losses [147]. Similar to all other VSG parameters, the values of the virtual impedance can be selected in a demand-oriented manner.

As an example of field measurements under network disturbances, Fig. 19 shows the power response of the Dalrymple 30-MW 8-MWh BESS installed in South Australia for a single-line fault in the upstream transmission line [148]. The speed of the response of the BESS in frequency and voltage disturbances demonstrates the value that BESSs are expected to play, supporting rapid recovery in the short term and toward power grid transformation in the long term.

Grid forming converters and grid supporting functionalities can be designed in new BESS projects or enabled in existing BESS installations. However, the benefits are strongly linked to certain site-specific properties, such as the electrical location within the power grid, the energy sizing of battery cells, and the overcurrent capabilities of the inverter. For most existing grids, such capabilities might have been of a lesser priority compared to grid optimization. As such, it is important to consider wider network integration and coordination studies, including the potential for interactions (i.e., circulating currents, power sharing of converters, and resonances) between multiple inverters. A coordinated approach in the design of grid-supporting BESS is necessary to validate the required performance and appropriate settings.

Despite current available evidence for the benefits of grid-supporting functions from BESSs, many open questions need to be answered to assist with the further uptake of such technologies in grids, worldwide. These range from a generally agreed and accepted definition of enhance functionalities that can be provided from BESSs to whether there is a critical number before we start experiencing unwanted interactions. Detailed technical requirements on aspects such as: 1) the control of multiple BESSs across a broader geographical area; 2) priority of ancillary services;

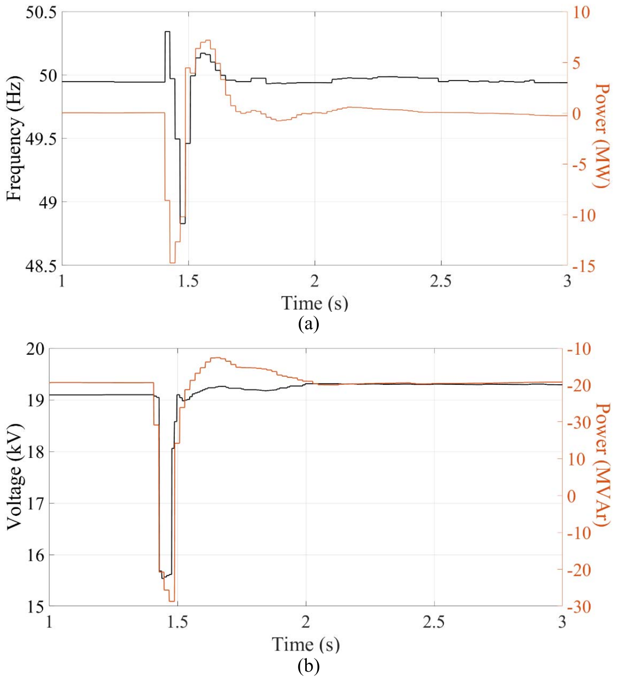


Fig. 19. ***Response of the Dalrymple 30-MW 8-MWh BESS. (a) Frequency versus active power. (b) Voltage versus reactive power.***

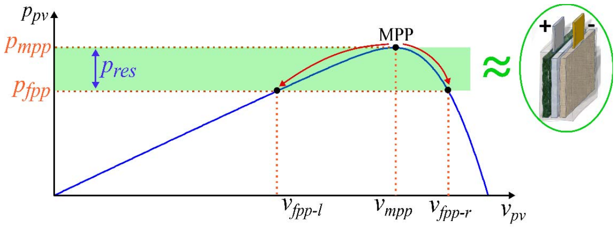


Fig. 20. *Principle of FPPT in PV systems and its equality to energy storage systems.*

3) the required level of technical studies and modeling required for each new installation; and 4) updated or new grid connection standards are waiting to be addressed.

VII. EMERGING TECHNOLOGIES AND PROSPECTS

A. Power Reserve and Flexible Power Control of PV Systems

Installation of PV systems is growing rapidly worldwide because of government support, high electricity costs, improving technology, and a decrease in the PV panel cost. To sustain power grid reliability and power quality in power grids with high penetration of PV systems, flexible power point tracking (FPPT) algorithms are implemented in these systems [9], [149]. Principles of FPPT operation in PV are illustrated in Fig. 20. Under this operation mode, the PV power is regulated in such a way that a predefined amount of power reserve p_{res} is kept in the PV system during the steady-state operation. This amount of power reserve can be utilized to support the grid under frequency or voltage disturbances. For example, if the grid frequency decreases, the PV output power can increase from p_{fpp} to p_{mpp}. Following the discussions in Section VII, this operation mode is similar to the behavior of BESSs. Accordingly, this power reserve in PV systems operates similar to a battery. The decreased cost of PV panels and low maintenance requirements of PV systems make them promising alternatives for BESSs in supporting the grid. Such functionalities of PV systems are demonstrated in [150]–[153].

Power reserve control with FPPT operation has also been implemented in microgrid applications [154], [155]. In stand-alone dc microgrids with a PV system, a BESS is conventionally used for regulating the dc-link voltage and dealing with the power mismatch between the supply and the demand, causing a continuous battery operation. Conventionally, the load and the PV maximum power dictate the battery current. Though operating the PV system at its maximum power point yields minimum battery discharge current, the opposite is true for battery charging current. Therefore, reducing the battery charging current based on its SoC and the amount of available PV surplus power (which can be treated as virtual stored energy) is an opportunity that is pursued in [155] for improving the battery life. The simulation case study shows how the FPPT-based control eliminates partial cycles, reduces the battery temperature fluctuations, and, thus, extends the Li-ion battery lifetime by 29.93% and the lead-acid battery lifetime by 42.93% compared to a conventional MPPT-based control [155].

B. Electric Vehicles: Opportunities and Challenges

Electrification of transportation has some profound implications on electricity power grid energy storage. Undoubtedly, EVs are helping to fast-track development and improvements in shared energy storage technologies, such as supercapacitors, fuel cells, and, most importantly, batteries. Nowadays, large car manufacturers are running an intense campaign of research and development activities to produce safe, longer lasting, cheaper, and higher power and energy density batteries. These technologies are often directly applicable in grid-connected BESSs. On the other hand, EVs are also competing with the grid for battery supply. Due to the large demand for EVs, the downward trend of the lithium-ion battery cost, as shown in Fig. 21, has almost flattened and is now at the risk of reversing course unless the supply of key metals can keep up with demand [156].

At large, from the perspective of energy storage requirements, EVs present opportunities for the power grid. First, being a controlled load, they can participate in demand-side management and reduce the need for ESSs. Even more interestingly, with reverse power flow mechanisms, EVs can play the role of ESSs in the power grid [vehicle-to-grid technology (V2G)] [157], [158]. Second, there is the opportunity to build mass grid-connected BESSs by reusing cheap second-life batteries from EVs [159], [160]. Nonetheless, in a near future, recycling technologies for exhausted Li-ion batteries should be implemented to limit the environmental impact. The rest of this subsection is devoted to further discuss V2G and Li-ion battery recycling technologies.

V2G Technology: This is one of the heavily debated topics that are expected to have a major positive impact on the operation and stability of the future grid. Recent

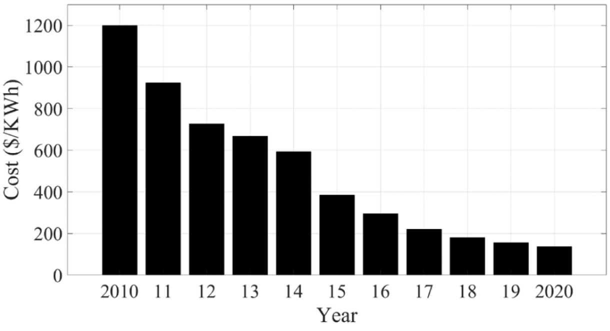


Fig. 21. *Persistent decline of lithium-ion battery prices over the past decade (data sourced from [156]).*

advancements and updated status of this technology are provided in [161]. Considering that, on average, vehicles in the United States, as an example, are only used 5% of the day, the feasibility and potential of implementing the V2G system are undeniable [162]. However, so far, its potential remains untapped mainly due to the following hurdles.

1) EV battery degradation is arguably the main drawback of V2G technology. EVs' battery performance is a key factor to consider when they are compared to conventional vehicles. In addition to the high cost of replacing worn-out batteries, reduced user satisfaction due to the reduction in range and performance of EVs is another downside of implementing the V2G system. This can change in the near future with improvements in battery quality.
2) Infrastructure for implementing V2G and the associated cost of it, for now, remain another hurdle. V2G requires bidirectional charging stations and secure communication channels. Due to the associated costs, as of 2021, only a handful of EV brands support V2G (Nissan e-NV200, Nissan LEAF, Mitsubishi Outlander PHEV, and Mitsubishi Eclipse Cross PHEV [163]).

Li-Ion Battery Recycling: Roughly, 85% of current battery manufacturing relies on virgin materials [164]. With the rise of gigafactories and electrification of national economies, this presents daunting material management challenges. This is a significant problem with a tantalizing economic reward and one that necessitates direct partnerships between manufacturers and recycling companies. For instance, a 400-kg car battery with a capacity of 50 kWh contains roughly 100-kg graphite, 32-kg nickel, 11-kg cobalt, 10-kg manganese, and 6-kg lithium, apart from aluminum, steel, and plastic components [165].

The prevalent view for battery e-waste management is a ladder-utilization system, wherein expired high-performance batteries are refurbished for not-so-demanding second- and third-life applications, before finally going to the recycling pipeline to extract the key elements for making new batteries [166], [167]. In this regard, TES/Green Li-ion (Singapore), Brunp/GEM (China), SMCC Recycling (South Korea), American Battery Technology/ReCell Center/Retriev/Redwood Materials (USA), Li-cycle (Canada), Primobius (Australia), and Recupyl/Akkuser/Duesenfeld/Solvay/Northvolt/BASF/Veolia/Enel Group/Stena Recycling/ReLIB/Reneos/Elemental Holding/Powervault/Umicore (Europe) are leaders in the field [168], [169]. Singapore, in particular, is eyeing itself as an e-waste recycling hub using benign hydrometallurgical processes to achieve this purpose (SCARCE) [170], [171].

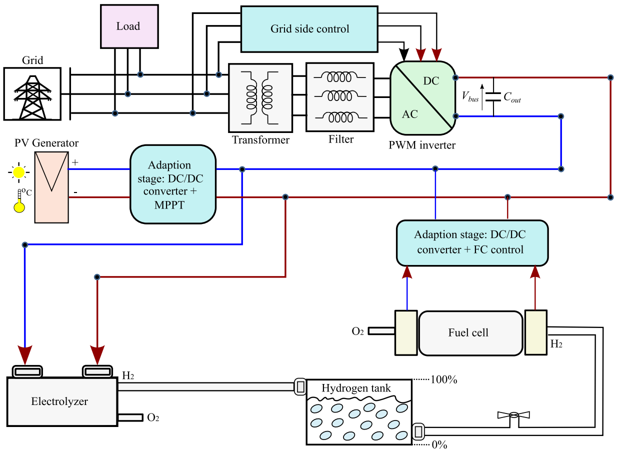


Fig. 22. ***Diagram outlining a grid-connected PV-electrolyzer-fuel-cell system [174].***

C. Hydrogen–Methane–NH_3: Beyond the 100% Renewables

As outlined in Fig. 3, chemical ESSs are a strong candidate for long-term, and transportable, energy storage. For chemical ESS, electricity is used to drive chemical reactions in order to produce a range of chemicals, often referred to as Power-to-X (P2X). "X" can be considered as inclusive of a range of chemicals, such as hydrogen, ammonia, and synthetic natural gas (methane). The synthesized chemicals can then be stored and/or transported and then either combusted or reacted to release the energy stored within the chemical bonds. Depending on the chemical being produced (X), the approaches to electricity conversion, storage, distribution, and energy generation vary considerably.

Hydrogen is rapidly emerging as one of the key vectors in chemical ESSs. A hydrogen-based ESS typically consists of electrolyzers, hydrogen storage, and fuel cells (see Fig. 22). The hydrogen stored, then, can be utilized as an industrial feedstock, converted into other "X"s, distributed as an energy vector, or directly converted back to electricity using fuel cells (refer to Section III-A).

The production of hydrogen via electrolysis requires a purified water source with reverse-osmosis (RO)-treated seawater being also considered as a pathway to mitigate the requirements for use of fresh water, which can be a scarce resource [172]. To date, there are three key electrolyzer technologies being considered, polymer electrolyte membranes (PEMs), alkaline electrolyzers (AEs)m, and solid oxide electrolyzers (SOEs). SOEs operate at high temperatures (500 °C–850 °C), which results in high efficiencies, and no need for expensive catalysts; however, this high temperature hinders long-term durability [173]. Hence, to date, PEM and AE approaches are the most common commercially. Electrolyzer-driven hydrogen production can be grid-connected, connected directly to dedicated renewables (behind the meter/off-grid), or powered by curtailed renewables [174].

The use of hydrogen as an ESS technology has the key benefit of being both a long-term and transportable/exportable storage vector of renewable power.

Table 4 Examples of Deployed ESS Technologies

Technology	Project	Country	Power (MW)	Services	Technology provider
Mechanical	Bath County Pumped Storage	USA	3000	Arbitrage	Dominion Generation
	Huizhou Pumped Storage Power Station	China	2448	Arbitrage Frequency control Spinning reserve	Alstom
	Tumut Hydroelectric Power Station 3	Australia	1500	Arbitrage	Toshiba
	Palmiet Pumped Storage Scheme	South Africa	400	Arbitrage Frequency control Spinning reserve Voltage Control Black-start	Voith
Thermal	Solana Solar Generating Plant	USA	280	Capacity firming	Abengoa Solar
	NOOR I (Ouarzazate) CSP Solar Plant	Morocco	160	Capacity firming	ACWA Power, Aries, TSK (Developer)
	Ashalim CSP Plant	Israel	121	Capacity firming	Abengoa Solar
	Andasol 2 CSP Solar Power Plant	Spain	50	Capacity firming	ACS/Cobra group (Developer)
Electrochemical	Dalian VFB	China	200	Arbitrage Capacity firming Black-start Contingency grid support	UET/Rongke Power
	Hornsdale Power Reserve Battery	Australia	100	Capacity firming Frequency control	Tesla
	Notrees Battery Storage Project-Duke Energy	USA	36	Arbitrage Capacity firming Fequency control	Xtreme Power
	Magdeberg SK Innovation BESS	Germany	30	Capacity firming	SK Innovation
	Annobon Island Microgrid	Equatorial Guinea	5	Customer services/Microgrid applications	GE Energy Storage
Electrical	Ferrolinera WESS: Ultracapacitors - Win Inertia	Spain	0.3	Capacity firming Energy back-up Transport sector	Maxwell Technologies
	SEPTA Wayside Energy Storage System - Griscom Ultracapacitors	USA	0.07	Voltage support Transport sector	Maxwell Technologies
	UCSD - Maxwell Technologies Ultracapacitor Bank	USA	0.028	Capacity firming Frequency control Voltage support Ramping support	Maxwell Technologies
Chemical	Hydrogenics Power-to-Gas	Canada	2	Frequency control	Hydrogenics
	Ingrid Hydrogen Demonstration Project	Italy	1.2	Capacity firming Transport sector	Hydrogenics, McPhy
	EnBW Stuttgart Hydrogen Testing Facility	Germany	0.4	Capacity firming Transport sector	Linde AG, Hydrogenics

Typically, hydrogen can be stored through four approaches: 1) compression; 2) liquefaction; 3) transformation; and 4) solid-state storage [175]. Hydrogen can also be fed to gas grid up to 15%–20% without any safety concerns (although this number is subject to contention) [176]. The storage of hydrogen via compression or liquefaction (1, 2) is not without its difficulties. Safety concerns, along with hydrogen's low density and diffusibility, result in significant challenges. Embrittlement, caused by hydrogen diffusion, limits the use of high-strength steels for hydrogen storage and transportation via pipeline [177]. The transformation of hydrogen (3) covers its conversion to other energy vectors, such as methane (synthetic natural gas) and ammonia.

The production of ammonia (through green hydrogen fed Haber Bosch, $N_2 + 3H_2 \rightarrow 2NH_3$), is gaining increasing interest as ammonia has a higher volumetric storage density compared to liquid hydrogen (108 g/L versus 71 g/L, respectively) [178]. Ammonia can then be stored, used as a fertilizer, in fuel cells or exploited as a hydrogen vector for transport. The energy inputs associated with the conversion of ammonia and the regeneration of hydrogen from ammonia along with its relative toxicity present some hindrances. The production of methane (via the Sabatier Reaction, $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$), often referred to as power-to-gas (P2G), allows excess energy to be stored and distributed in the form of methane. This allows integration with the gas grid, utilizing existing infrastructure, however, results in the distributed emission of CO_2 upon use [179].

In Fig. 22, it is important to note the role of power electronic converters in enabling this renewable hydrogen-based ESS. As can be seen, there are two types of power converters in this configuration, the dc–ac grid-connecting one, and the dc–dc stage for optimizing PV power. Most of the power converters for grid integration (discussed in Section V) are considered mature and established industrial solutions, whereas the dc–dc part for such applications is still evolving [180]. A comprehensive review of prominent dc–dc power converter topologies is provided in [180]. In short, a high-power requirement of the green hydrogen electrolyzer applications will demand technology improvement for power electronic components [181], [182].

VIII. CONCLUSION

As long as our best-laid plan to achieve energy sustainability rests with intermittent renewable generation, ESS technologies remain an inevitable component to enable the transition. Though the conventional well-established PHS technology is likely to maintain the lion's share of installed ESS capacity for the foreseeable future, the use of grid-connected BESSs is accelerating and is expected to play a bolder role in future grids. The prevalent view in the battery materials community is that an arsenal of ESS technologies, and not just one technology but a multipronged approach, is viewed as the most practical approach for the global sustainability drive. Each country will have endemic special conditions, which may favor one technology over another (geography, natural resources, climate, and so on). Economies of scale will push prices down, facilitating wider adoption. Future energy storage technologies based on advanced Li-ion, Na-ion, multivalent-ion (Zn, Al), hybrid supercapacitors, hydrogen, fuel cells, and redox-flow chemistries are gaining overwhelming traction as grid energy storage solutions. BESS technology, in part owing to its application in EVs, is growing rapidly as evidenced by declining prices, while quality improves, and the foreseeable ubiquity of dumped EV batteries is seeing a massive drive in the rise of second-life battery utilities to recover initial battery material costs. Along with improvements in battery chemistry, power electronic converters that are used for interfacing BESSs to the grid are experiencing a major turn in their evolution thanks to advancements in both high-power wide bandgap semiconductors and modular power electronic architectures, further improving the competitiveness of BESSs. Reaching 100% sustainability will require storing a massive amount of energy to cater to seasonal renewable generation and demand, for which hydrogen will play a major role. Finally, using technologies that add flexibility to vary generation and consumption to some extent can be a cost-effective way of reducing reliance on ESSs. ■

APPENDIX

Table 4 shows some examples of deployed ESSs around the globe categorized based on the technology and services that they provide [183].

The projects are selected to include examples from all ESS technology categories and diverse geographic locations. Furthermore, the intended purposes of each installation and their technology providers are included in Table 4.

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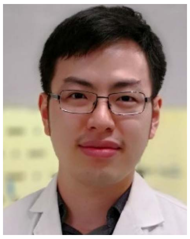
ABOUT THE AUTHORS

Glen G. Farivar (Senior Member, IEEE) received the B.Sc. degree in electrical engineering from the Noshirvani Institute of Technology, Babol, Iran, in 2008, the M.Sc. degree in power electronics from the University of Tehran, Tehran, Iran, in 2011, and the Ph.D. degree in electrical engineering from the University of New South Wales, Sydney, NSW, Australia, in 2016.

He is currently a Senior Research Fellow with the Energy Research Institute, Nanyang Technological University (ERI@N), Singapore. He is also a Co-Director of the Power Electronics and Applications Research Laboratory, ERI@N, and a Co-Founder of SciLeap, Perth, WA, Australia, which aims to promote research integrity, accessibility, and openness. His research interests include renewable energy systems, high-power converters, energy storage, flexible ac transmission systems (FACTS), and electric vehicles.

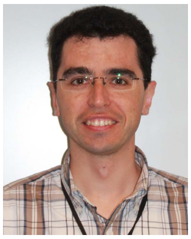


William Manalastas, Jr., was mentored by the ALISTORE European Electrochemistry Network, Dr. Frederic Aguesse at CIC energiGUNE, Álava, Spain, and Prof. John Kilner at Imperial College London, London, U.K. He is a battery scientist/engineer active in the areas of advanced lithium-ion/lithium-metal batteries and aqueous multivalent-ion batteries. He is currently a Research Fellow with the Energy Storage Laboratory, Nanyang Technological University, Singapore, in the group of Prof. Madhavi Srinivasan.

Dr. Manalastas, Jr., was a recipient of a JASSO Grant, an Erasmus Mundus Scholarship, and a CIC Energigune PhD Fellowship.

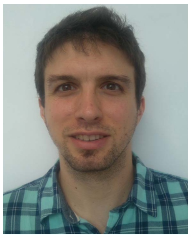
Hossein Dehghani Tafti (Senior Member, IEEE) received the B.Sc. and M.Sc. degrees in electrical engineering and power system engineering from the Amirkabir University of Technology, Tehran, Iran, in 2009 and 2011, respectively, and the Ph.D. degree in electrical engineering from Nanyang Technological University, Singapore, in 2018.

From January 2018 to April 2020, he was a Research Fellow with Nanyang Technological University, where he was working on the control of photovoltaic systems for grid support. From May 2020 to May 2021, he was a Senior Research Associate with the University of New South Wales, Sydney, NSW, Australia, where he worked on modeling and testing commercial photovoltaic inverters. He is currently a Research Fellow with the Department of Electrical, Electronic and Computer Engineering, The University of Western Australia, Perth, WA, Australia. His research interest includes the grid integration of renewable energy sources, in particular, photovoltaics, energy storage, and the design and control of multilevel power converters.



Salvador Ceballos received the M.S. degree in physics from the University of Cantabria, Santander, Spain, in 2001, and the M.S. and Ph.D. degrees in electronic engineering from the University of the Basque Country, Bilbao, Spain, in 2002 and 2008, respectively.

Since 2002, he has been with Tecnalia, Basque Research and Technology Alliance (BRTA), Derio, Spain, where he is currently a Principal Researcher with the Energy, Climate and Urban Transition Unit. His research interests include multilevel converters for high- and medium-voltage applications, fault-tolerant power electronic topologies, renewable energy systems, and power systems with high penetration of power converters.



Alain Sanchez-Ruiz (Senior Member, IEEE) received the B.Sc. degree in electronics engineering, the M.Sc. degree in automatics and industrial electronics, and the Ph.D. degree in electrical engineering from the University of Mondragon, Mondragon, Spain, in 2006, 2009, and 2014, respectively.

He joined Ingeteam R&D Europe, Zamudio, Spain, in May 2014, where he is currently an R&D Engineer. From February 2012 to May 2012, he was a Visiting Researcher with The University of Tennessee, Knoxville, TN, USA. Since January 2017, he has been a Lecturer with the University of the Basque Country (UPV/EHU), Bilbao, Spain. His current research interests include modeling, modulation, and control of power converters, multilevel topologies, advanced modulation techniques, high-power motor drives, and grid-tied converters.

Emma C. Lovell received the Ph.D. degree from the University of New South Wales (UNSW), Sydney, NSW, Australia, in 2016, developed catalysts for carbon dioxide conversion (with a research exchange at the University of Bremen, Bremen, Germany). Her Ph.D. work focused on developing nickel-based catalysts for the carbon dioxide (dry) reforming of methane.

She is currently a Lecturer at the School of Chemical Engineering, UNSW. Her research focuses on developing novel catalysts for a range of applications; with a particular focus on energy and environmental catalysis. Her current research focuses on developing catalytic materials for a range of different energy inputs; this includes developing catalysts for the photo-/plasmon-enhanced thermal catalytic carbon dioxide methanation, the plasma-catalytic carbon dioxide methanation, and nitrogen fixation, as well as developing defective electrocatalysis for hydrogen evolution reaction and carbon dioxide reduction reactions.

Dr. Lovell was a recipient of the Women in Engineering Scholarship for the duration of her studies.

Georgios Konstantinou (Senior Member, IEEE) received the B.Eng. degree in electrical and computer engineering from the Aristotle University of Thessaloniki, Thessaloniki, Greece, in 2007, and the Ph.D. degree in electrical engineering from the University of New South Wales (UNSW Sydney), Sydney, NSW, Australia, in 2012.

From 2013 to 2016, he was a Senior Research Associate with UNSW Sydney, where he was part of the Australian Energy Research Institute. Since 2017, he has been with the School of Electrical Engineering and Telecommunications, UNSW Sydney, where he is currently a Senior Lecturer. His main research interests include multilevel converters, power electronics in high-voltage dc (HVdc), renewable energy, and energy storage applications.

Dr. Konstantinou is also an Associate Editor of IEEE TRANSACTIONS ON POWER ELECTRONICS, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, and *IET Power Electronics*.

Christopher D. Townsend (Member, IEEE) received the B.E. and Ph.D. degrees in electrical engineering from the University of Newcastle, Callaghan, NSW, Australia, in 2009 and 2013, respectively.

Subsequently, he spent three years working at ABB Corporate Research, Västerås, Sweden, working on next-generation high-power converter technologies. Since then, he has held various postdoctoral research positions, including at the University of New South Wales, Sydney, NSW, Australia, the University of Newcastle, and Nanyang Technological University, Singapore. In 2019, he joined the Department of Electrical, Electronic and Computer Engineering, The University of Western Australia, Perth, WA, Australia, as a Senior Lecturer. He has authored more than 50 published technical papers and has been involved in several industrial projects and educational programs in the field of power electronics. His research interests include topologies and modulation strategies for multilevel converters applied in power systems, renewable energy integration, and electric vehicle applications.

Dr. Townsend is also a member of the IEEE Power Electronics and Industrial Electronics Societies.

Madhavi Srinivasan graduated from IIT Madras, Chennai, India. She did her Ph.D. dissertation on lithium-ion batteries at the National University of Singapore, Singapore.

Her research focuses on the synthesis, fabrication, and application of nanoscale materials/architectures in improving the performance of electrochemical energy storage devices, such as advanced lithium-ion batteries, supercapacitors, sodium-ion batteries, and multivalent aqueous Zn/Al batteries. Her research is also on the recycling of lithium-ion batteries e-waste by novel hydrometallurgical techniques toward a closed-loop approach.

Dr. Srinivasan has won several prestigious awards, including the 2019 Asia’s Top Sustainability Superwomen, the L’Oreal for Women in Science National Fellowships, the Great Women of Our Time given by *The Singapore Women’s Weekly* magazine, and the NRF Investigatorship Award awarded to top scientists in Singapore by the National Research Foundation (NRF).

Josep Pou (Fellow, IEEE) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the Technical University of Catalonia (UPC)-Barcelona Tech, Barcelona, Spain, in 1989, 1996, and 2002, respectively.

In 1990, he joined the Faculty of UPC as an Assistant Professor, where he became an Associate Professor in 1993. From February 2013 to August 2016, he was a Professor with the University of New South Wales (UNSW), Sydney, NSW, Australia. He is currently a Professor with Nanyang Technological University (NTU), Singapore, where he is also the Cluster Director of Power Electronics of the Energy Research Institute at NTU (ERI@N) and a Co-Director of the Rolls-Royce, NTU Corporate Laboratory. From February 2001 to January 2002 and February 2005 to January 2006, he was a Researcher with the Center for Power Electronics Systems, Virginia Tech, Blacksburg, VA, USA. From January 2012 to January 2013, he was a Visiting Professor with the Australian Energy Research Institute, UNSW. He has authored more than 410 published technical papers and has been involved in several industrial projects and educational programs in the field of power electronics. His research interests include modulation and control of power converters, multilevel converters, renewable energy, energy storage, power quality, high-voltage dc (HVdc) transmission systems, and more-electrical aircraft and vessels.

Dr. Pou received the 2018 IEEE Bimal Bose Award for Industrial Electronics Applications in Energy Systems. He is also an Associate Editor of the IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS. He was the Co-Editor-in-Chief and an Associate Editor of the IEEE TRANSACTIONS ON Industrial Electronics.