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**RESEARCH PAPER** 

# Network-Linked Energy Storage Systems: Current Technologies and Upcoming Innovations

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#### Abstract:

The integration of renewable energy sources into power systems has posed several new challenges for operators. Coping with the inherent intermittency and variability of renewables like solar and wind power requires innovative solutions to ensure stable, reliable, and high-quality electricity supply. One promising solution is incorporating energy storage systems (ESSs) into the grid. ESSs play a vital role in mitigating fluctuations in renewable energy generation by storing surplus energy and releasing it when needed, thus maintaining system balance and resilience. This article explores current and emerging trends and technologies related to grid-connected ESSs, categorizing ESS technologies into five main types: mechanical, electrical, electrochemical, chemical, and thermal. Mechanical ESSs, such as pumped hydro storage and flywheels, store energy using physical mechanisms, while electrical ESSs, like capacitors and superconducting magnetic energy storage, utilize electrical and magnetic fields. Electrochemical ESSs, such as batteries, store and release energy through chemical reactions, and chemical ESSs involve processes like hydrogen storage. Thermal ESSs capture and store heat energy for later use. Battery energy storage systems (BESSs) are particularly highlighted due to their significant potential and increasing popularity, driven partly by the electrification of transportation, which has spurred advancements in battery technologies and economies of scale.

#### Key word:

Power grid network, Energy storage system, Grid management, Power System, Battery system.

#### Introduction:

Every energy storage system (ESS) undergoes cycles of charging and discharging, requiring a sustained energy equilibrium for reliable and sustainable operation. This concept extends to fossil fuels, where energy accumulated over millions of years in the Earth's reserves is now being extracted and utilized. However, the current pace of fossil fuel consumption poses significant challenges, not only due to the finite nature of these resources but also due to their environmental impact. Based on 2020 known reserves and current extraction rates, projections suggest oil and gas may last around 50 and 49 years, respectively, while coal reserves could be depleted in approximately 139 years. Fossil fuel combustion produces greenhouse gas emissions, which are a factor in global warming. Roughly 60% of oil and methane gas and 90% of coal must still be extracted by 2050, according to calculations, in order to keep global warming to 1.5°C. In order to restore the natural equilibrium, it is imperative that society immediately modify how it uses this natural ESS by decreasing the discharge rate (using fewer fossil fuels) and raising the charging rate (growing more trees). Using alternative energy sources is critical to this shift to sustainable energy practices.

We will need to acquire a sizable amount of our energy from renewable sources in the near future. Now that significant technological progress has been made, wind, solar, and hydro power are the main renewable energy sources. These sources are expected to support our generation of electric power for the foreseeable future, given their present and predicted rates of adoption. Developments in disruptive technology, such nuclear fusion reactors, have the ability to change this course. The balance between generation and consumption is crucial to the operation of electric power systems. In the past, generation could change to meet demand for load. To keep the system balanced, renewable energy sources must rely more on energy storage systems (ESSs) due to their unpredictable and sporadic nature. Installed ESS capacity must rise in tandem with the increasing capacity of intermittent wind and solar power, as seen in Figures 1.1 to 1.3. Australia's experiences show that ESSs are essential to enable a sustainable grid driven by renewable energy.

Although expensive, investing in energy storage systems (ESSs) makes it difficult to switch from dispatch able conventional power plants to variable wind and solar power facilities. Still, newer technologies present viable ways to improve load and generator flexibility and lessen dependency on ESSs. By reducing the gap between generation and consumption, these flexible assets hope to lessen the requirement for ESS charging and discharging.



Figure 1.1 Capacity for generating wind and solar energy.



Figure 1.2 The combined power capacity of energy storage systems (ESS).



of the world. "Buffer" represents markets and use cases that BNEF is unable to forecast due to lack of visibility.



With an emphasis on intermittent renewable energy sources, this article aims to give a thorough analysis of grid-connected energy storage system (ESS) technologies and their critical role in allowing future electricity power grids. It places particular emphasis on electrochemical ESS technologies, which are not only integral to electric vehicles (EVs) but are also undergoing rapid growth and advancement, evident from the continuous rise in annual installed capacity, as depicted in Fig. 1.4. Power electronics converters are essential to the integration of various energy-storage system (ESS) technologies into the grid

because of their importance. Therefore, a comprehensive analysis of power converters designed for grid and electric vehicle applications is included in the article.

In comparison to existing literature, this article expands its scope by encompassing the following technological advancements:

1) Examination of control methodologies and emerging regulations governing grid support functionalities.

2) Investigation of developments in the field of solid-state transformers (SSTs).

3) Analysis of modular power converters' stable operating range and power disparity restrictions.



Figure 1. 4 Annual installation of battery energy storage capacity

The format of this article is as follows: A thorough analysis of well-known energy storage system (ESS) technologies is provided in Section 3. In-depth discussion of a few ESS technologies powering transportation electrification is provided in Section 4. The importance and role of ESS in contemporary electric power systems are described in Section 5. In Section 6, grid rules and standards related to inverter grid connections are examined together with power electronic interface topologies for battery energy storage systems (BESSs) connections to the grid. Innovations in BESS control to enable more grid support functions are examined in Section 7. Future possibilities and related new technologies are examined in Section 8. Concluding remarks are provided in Section 9.

Through these discussions, the article aims to illuminate significant advancements and the future potential of ESS technologies in fostering a reliable, sustainable, and resilient power grid. Long-term environmental and energy goals require a shift from fossil fuels to renewable energy sources, backed by advanced energy storage systems (ESSs). This comprehensive examination of current trends and future

trajectories in ESS technology underscores the pivotal role these systems will play in the global energy transition.

#### 1. Smart Energy Storage Technology:

There is a thorough analysis of current energy storage technology given. Based on information obtained from the Global Energy Storage Database of the U.S. Department of Energy, Figures 2.1 and 2.2 provide a summary of these technologies and their proportion of the capacity of energy storage systems (ESS) that are now in operation. Below, we examine some of each category's qualities.

Mechanical: With origins dating back to the 1920s, pumped hydro storage (PHS) emerges as one of the most advanced, widely used, and early types of energy storage. PHS now makes up more than 90% of the energy storage capacity on the grid. Typically, this technology makes use of well-established hydroelectric dams on rivers, which pump water back to an elevated storage dam. Large subterranean caves, like converted mines, can also be used for PHS. These geological formations can also be used for compressed air energy storage (CAES), which uses stored potential energy to power a turbine. CAES works similarly to PHS.

Thermal: Power facilities that use concentrated solar power (CSP) are a prominent example of thermal storage used to generate electricity. Conventional steam turbine power plants function similarly to CSP units; the main difference is that the heat source is frequently molten salt produced by concentrated sun radiation. With this method, solar energy can be stored in thermal form and converted back to electricity as needed.

Electrical: Within this category, supercapacitors and superconducting magnetic energy storage (SMES) stand out. Both exhibit low energy density but high power density. Supercapacitors are widely used in applications where quick and frequent cycles of charging and discharging are required. The need to maintain extremely low temperatures, however, raises questions about the practicality and cost-effectiveness of SMES.



Figure 2.1 Classification of ESS technologies



Figure 2.2 Distribution of storage capacity across different ESS technologies

Electrochemical: One of the most versatile and quickly developing energy storage technologies are batteries, which find extensive use not only in grid-connected systems but also in electric vehicles (EVs).Further exploration of this technology can be found in Sections 4, 6, and 7.

Chemical: Chemical storage stands out due to its unique transportability and high energy capacity, making it a viable option for seasonal energy storage within the power grid. Hydrogen, is becoming more and more important in the field of chemical energy storage technologies. Hydrogen can be directly converted into electricity through fuel cells or indirectly through traditional gas turbine power facilities. Section 8.3 provides a detailed examination of hydrogen storage technologies, given its vital role in reaching 100% energy sustainability.

0									
1	А	В	С	D	E	F	G	Н	1
1	Technology	Power range (kW)	Energy range (kWh)	Power cost (€/kW)	Energy cost (C/kWh)	Energy density	rim (Years)	57• e ine	Emciency (%)
2	Hydrogen	Several 10 <sup>2</sup>	IO to several 10'	2000-5000	1-10	30-2550 kWh/m*	5-30	ma.	20-40 (fuel cell)
3	Double Layer Capaciior	10*	Up to 10	100-500	10,000-20.000	4-7 Wh/kg	10	10	90
4	flow Battery	I to several	100 io some	500-1,200	100-400	io-25 W1r'liter	10-20	>12000	70-75
5	Lead-Acid Battery	Some 10' U	p to 10° 100-30	00 100-200	25-35		5-15	500-3000	75-65
6	Lithium-Ion Battery	1 to 50• 10'	Up to 10'	150-1000	700-1,300	120-1 h0 Wh/kg	I 0-20	2000- 10000	90-98
7	Pumped Hydro Storage	10° to 10°	Up to some	400-1500	40-150	0.5-3 Whike	>80	ma.	70-85
8	Thermal Hot Water (Multi- Dwelling Buildine)	400	25-320		15	0.08 kWh/k9	20-40	na.	70-95
0									

#### Table 1 Essential Metrics of ESS Technologies

Table 1 outlines key performance metrics to compare several selected energy storage system (ESS) technologies, emphasizing why pumped hydro storage (PHS) remains the preferred option despite being limited to specific geographical features. An Appendix detailing recent ESS deployment projects.

Capacitors, batteries, and fuel cells are the most notable ESS technologies since they provide DC voltage directly without the need for an electromechanical generator. These technologies are crucial for electric vehicles (EVs) and have diverse applications in power grids, detailed further in Section 4.

This review underscores the diversity of energy storage solutions available, each with unique advantages and limitations. PHS and compressed air energy storage (CAES) are examples of well-established, extremely effective mechanical systems that work well in the right environments. Concentrated solar power (CSP), or thermal storage, provides reliable solar energy storage options. Fast charge and discharge are made possible by electrical storage technologies such as supercapacitors and superconducting magnetic energy storage (SMES), though they pose challenges. Electrochemical storage, particularly in batteries, is rapidly evolving, impacting grid storage and automotive industries significantly. Chemical storage, particularly hydrogen-based, holds promise for long-term and seasonal energy storage solutions.

This detailed comparison, along with recent deployment examples, underscores the vital role ESSs will play in shaping resilient and renewable energy-powered grids. This article's goal is to give readers a thorough grasp of these technologies and how they may be used to build infrastructure for sustainable energy.

#### 2. Electro Chemical Energy:

Electrochemical power units have significantly improved human convenience, enabling portable connectivity, mechanical automation, and electrified living environments. Unlike combustion engines, they aren't limited by the 51% Carnot efficiency constraints. They come in various form factors like thin films, cartridges, and block modules, simplifying recharging logistics by utilizing the existing power grid infrastructure. They can also be easily integrated to meet specific electric rating requirements through cell stacking.

The Nernst equation forms the basis of electrochemical power units, where the released chemical energy  $(\Delta G)$  is the product of directed electrical charge migration (n), Faraday's constant (F), and electrochemical potential (E) between two substance masses. Early electrochemists realized they could decouple electron and ion transport, effectively driving electromagnetic motors and enabling precise control over energy release. This stands in contrast to mechanical engines, where significant unharnessed energy remains in gas exhausts.

Electrochemical energy storage (EES) devices encompass fuel cells, batteries, and capacitors. Fuel cells generate electricity through electrochemical reactions between fuels (like hydrogen) and oxidants (typically oxygen), offering high efficiency and low emissions for applications like power generation and transportation. Batteries store and release electrical energy through chemical reactions, with rechargeable variants like lithium-ion batteries dominating portable electronics, electric vehicles, and grid storage systems. Capacitors store energy electrostatically, allowing rapid charging and discharging cycles, ideal for applications requiring quick energy bursts.

Electrochemical energy storage technologies have revolutionized various sectors by providing efficient, reliable, and flexible energy solutions. They offer high efficiency, modularity, seamless grid integration, rapid response, and environmental benefits compared to traditional engines and fossil fuel-based power generation.

Ongoing developments focus on advanced battery chemistries, fuel cell innovations, enhanced capacitor technologies, hybrid systems combining different technologies, and sustainable materials. These advancements continue to improve performance, reduce costs, and expand applications, contributing to a sustainable energy future.

In summary, electrochemical energy storage technologies play a critical role in the modern energy landscape, offering high efficiency, flexibility, and compatibility with renewable energy sources. As technological advancements progress, their importance will only grow, fostering innovation and further enhancing human conveniences and environmental sustainability.

#### 3.1 Fuel cell:

Fuel cells operate through the oxidation of diverse fuels like hydrogen (H2), acetylene, methanol, ethanol, ammonia (NH3), hydrogen peroxide (H2O2), and natural gas, utilizing precious-metal catalysts. The

overall energy output of fuel cells primarily depends on the availability of fuel. This fuel can be obtained from the petrochemical industry, photochemical catalysts (with about 17% generation efficiency), or dual-electrode electrolysis/thermal catalysis methods (with 65%–85% generation efficiency). However, producing and storing these fuels, especially hydrogen, presents significant logistical challenges. Despite its lightness, hydrogen tends to permeate through materials like stainless steel and most plastics, and it also poses a high explosion risk. Further exploration of these logistical challenges and safety concerns is provided in Section 9.



Figure 3.1 Basic schematic illustrating the operating principles of EES

Fuel cells operate within a broad temperature range, from 20°C to 1100°C, with higher temperatures often necessary to achieve acceptable current rates through the electrolyte. However, higher temperatures result in lower power efficiencies due to heating energy requirements. Factors like catalyst poisoning, coking, and phase segregation can significantly compromise the lifespan of a fuel cell stack. Nevertheless, properly configured fuel cells are valuable for applications requiring uninterrupted power supply over extended periods, offering high energy efficiency and minimal downtime.

Several companies have emerged as major suppliers of heavy-duty fuel cell stacks, with unit efficiencies ranging from 45% to 75% and cell stack degradation rates between 0.4% and 0.9% per 1000 hours. Notably, Ceres Power's compact, modular units stand out for their minimal insulation requirements and low degradation rates, ensuring a satisfactory service lifetime of at least ten years. Emerging producers in

China are also matching this performance, indicating growing global competitiveness in fuel cell technology.

In laboratory research, advancements in nanoengineered cathodes have shown the potential to sustain current densities up to 20 times greater than market standards. These developments offer more efficient use of precious metal catalysts, potentially reducing costs and improving fuel cell performance.

Fuel cells are categorized based on the electrolyte type they use, determining their operating temperature and efficiency. Common types include Proton Exchange Membrane Fuel Cells (PEMFCs), Solid Oxide Fuel Cells (SOFCs), Alkaline Fuel Cells (AFCs), Molten Carbonate Fuel Cells (MCFCs), and Phosphoric Acid Fuel Cells (PAFCs), each with specific advantages and challenges.

Fuel cells find applications in transportation, stationary power generation, portable power, and combined heat and power (CHP) systems. Ongoing research focuses on cost reduction, durability, fuel flexibility, system integration, and minimizing environmental impact, aiming to enhance the economic viability and sustainability of fuel cell technology.

Despite current challenges related to cost, durability, and fuel logistics, ongoing advancements in materials science, system design, and integration strategies are driving broader adoption of fuel cells. As research continues to drive innovation, fuel cells are poised to play a significant role in the transition to a sustainable energy future, providing reliable power for various applications in the evolving energy landscape.

#### 3.2 Battery:

While fuel cells rely on external material exchange for electricity generation, batteries operate within a closed system, storing active materials internally without needing an external fuel supply. This enables batteries to consume and regenerate their "fuel" through external voltage and current application. Although batteries compartmentalize active materials, changes in oxidation states during cycling necessitate compensatory mass transfer to prevent resistive polarization buildup, which can lead to hysteresis and battery degradation. Batteries require recharging once all stored energy is depleted.

Battery chemistries are diverse, with advanced lithium-ion batteries leading in specific energy, achieving up to 304 Wh/kg (700 Wh/L) with NMC/Si-C cells. Major players in the battery industry include Tesla, CATL, BYD, Samsung SDI, LG Chem, Panasonic, Northvolt, and emerging European companies. Research trends focus on developing cobalt-free electrodes, organically derived electrodes, lithium-rich compositions, and various types of lithium-metal batteries, aiming for storage metrics exceeding 500 Wh/kg and 1000 Wh/L.

To enhance material performance, common strategies include doping and controlling grain morphology. For example, stabilizing lithium cobalt oxide materials by doping them with aluminum or lanthanum enables higher charging voltages and improved capacities.

Batteries power a wide range of applications, from portable electronic devices to electric vehicles and large-scale energy storage systems. Their efficiency and ability to be designed in various form factors simplify recharging logistics and integration into existing power grid infrastructure. Batteries operate based on the Nernst equation, controlling the transport of either electrons or ions to release stored energy effectively.

The electrochemical energy storage (EES) category includes batteries, fuel cells, and capacitors, utilizing chemical potential differences between segregated active materials to store energy. Research focuses on innovations like solid-state batteries, lithium-sulfur batteries, sodium-ion batteries, multivalent ion batteries, and organic batteries to achieve higher energy densities, longer lifespans, and greater safety. As battery technology advances, it holds promise for transforming various industries, including consumer electronics, renewable energy storage, and electric transportation.

#### 3.3 Capacitors:

Capacitors, unlike batteries, store and release energy through the accumulation of electric charge on opposing electrodes separated by a dielectric medium, operating on electrostatic principles rather than chemical reactions. This mechanism enables rapid energy storage and high power density, although their energy density is generally lower compared to batteries due to their reliance on surface storage alone.

Recent advancements, particularly in materials science with the introduction of 2D materials like graphene, have significantly improved capacitor performance. These materials provide large surface areas for charge storage, leading to the development of supercapacitors, ultracapacitors, and hybrid capacitors. These advanced capacitors offer a balanced combination of specific energy and specific power, making them suitable for various high-performance applications.

However, claims about stored energy should be approached cautiously, as some lightweight materials may require heavy casing for structural integrity, impacting overall energy density. Nevertheless, capacitors excel in scenarios requiring rapid energy storage and release, such as buffering energy events on ultrafast timescales and demonstrating long operational lifetimes, often exceeding a decade.

Capacitors are categorized based on their characteristics and applications. Traditional capacitors like ceramic, film, and electrolytic capacitors are commonly used in electronic circuits for functions like power supply smoothing and signal filtering. Supercapacitors, also known as ultracapacitors, offer higher energy densities and fast charge/discharge capabilities, making them suitable for applications like regenerative braking in electric vehicles.

Hybrid capacitors combine capacitor and battery attributes, featuring asymmetric designs for higher energy densities while maintaining rapid power discharge rates. They find applications in energy storage systems, portable electronics, and automotive sectors where a balance of energy and power is required.

Capacitors are integral in stabilizing power output from renewable sources like wind and solar, ensuring grid stability and reliability as renewable energy integration increases. Additionally, they play vital roles in advanced power electronic systems, contributing to efficient energy conversion and control.

With ongoing research focusing on improving energy density, reducing costs, and enhancing environmental sustainability, the future of capacitor technology looks promising. Innovations in nanotechnology and manufacturing processes aim to create more efficient, powerful, and eco-friendly capacitors, further solidifying their importance across various industries.

### 3.4 General Perspective:

Choosing between fuel cells, batteries, or capacitors for grid energy storage primarily hinges on the cost per kilowatt-hour (kWh). This cost is affected by various factors, including material extraction, processing, manufacturing, shipping, handling, and assembly. Over 60% of the cost of energy storage devices comes from the physical materials used. Thus, efficient material usage can lead to substantial savings in the supply chain. For example, utilizing a few grams or liters of material instead of several kilograms or gallons can result in significant economic benefits. This efficiency is particularly advantageous for stationary grid energy storage systems, which are modular and can be constructed vertically in confined spaces, making total weight and space considerations less critical.

Beyond cost, several technical parameters are crucial in selecting the appropriate energy storage technology. These parameters include higher energy density, higher power density, better roundtrip efficiencies, longer calendar lifetimes, operational safety, environmental benefits, and recyclability within a closed-loop economy. These factors offer hidden cost savings that are often not immediately apparent in initial cost calculations. For instance, higher energy density allows more energy to be stored in a smaller footprint, and better roundtrip efficiency means less energy loss during storage and retrieval, ultimately leading to lower operational costs.



Figure 3.2 Common voltage profiles of EES devices over time

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Figure 3.3 Ragone chart displaying different EES technologies

The growing global population and increasing energy demands continually drive the need for advancements in energy storage technologies. Economies of scale significantly contribute to reducing costs as production volumes rise. A critical price point for the widespread adoption of battery energy storage is projected to be around \$100 per kWh, a target anticipated to be achievable between 2020 and 2030. In comparison, fuel cells currently cost about \$16 per kWh, assuming a ten-year stack lifespan. Despite this cost advantage, batteries often justify their higher price due to logistical benefits and reduced reliance on precious metals.

Fuel cells operate by oxidizing fuels like hydrogen, acetylene, methanol, ethanol, ammonia, hydrogen peroxide, and natural gas using precious-metal catalysts, with energy output limited only by fuel availability. Fuel sources include the petrochemical industry, photochemical catalysts, and dual-electrode electrolysis/thermal catalysis, with generation efficiencies ranging from 17% to 85%. However, fuel cells face logistical issues, especially with hydrogen, which is lightweight, permeable, and explosive. Operating temperatures vary between 20°C and 1100°C depending on the membrane technology used, with higher temperatures needed for acceptable current rates despite lower power efficiencies due to heating needs.

Batteries, on the other hand, store active materials internally in a fixed-dimension hermetic format, allowing for the consumption and regeneration of "fuel" within an encapsulated system using external voltage/current limits. Active materials are usually in solid or liquid phase, enabling

compartmentalization. However, oxidation state changes during cycling necessitate mass transfer to prevent resistive polarization buildup, leading to battery degradation. Batteries must be recharged when all stored energy is depleted.

Various battery chemistries exist, with advanced lithium-ion batteries leading the market, achieving specific energies of 304 Wh/kg and 700 Wh/L based on NMC/Si-C cells. These metrics approach the guidelines of the U.S. Advanced Battery Consortium and the limits of lithium-ion technology. Key industry players include Tesla, CATL, BYD, SVOLT, Guoxuan High-Tech, Samsung SDI, LG Chem, SK Innovation, Panasonic, Northvolt, and several emerging European companies. These companies focus on NCA, NMC, and LFP cells with liquid electrolytes and graphite or silicon anodes.

Recent battery developments aim for cobalt-free electrodes, organically derived electrodes, lithium-rich compositions, and various forms of lithium-metal batteries, promising storage metrics over 500 Wh/kg and 1000 Wh/L. Common improvement strategies include doping and grain morphology controls, such as doping LiCoO2 materials with aluminum or lanthanum for stability, higher charging voltages, and improved capacities.

Capacitors, similar to batteries, store energy as concentrated electron/ion charge on opposite electrodes of a dielectric medium, relying on electrostatic principles. Significant advancements in supercapacitors and hybrid capacitors, particularly using 2D materials like graphene, provide large surface areas for charge storage, leading to high power densities and fast charge/discharge capabilities. Capacitors are essential for buffering energy storage/release events on ultrafast timescales and have operational lifetimes exceeding ten years, as demonstrated in applications like European trams and Chinese short-distance buses.

Selecting between fuel cells, batteries, or capacitors for grid energy storage requires evaluating cost, technical parameters, and practical considerations. Each technology has its advantages and challenges, with the optimal choice depending on specific application requirements. Advancements in material science and manufacturing processes will continue to enhance the performance and cost-effectiveness of these energy storage technologies, driving their adoption and integration into the global energy infrastructure.

#### 4 **Power Grid Energy Storage Requirements:**

Energy storage systems (ESSs) improve the flexibility of the entire power grid by acting as generation, consumption, and reactive power compensation assets. They offer a variety of services across all segments of the energy value chain, including conventional and renewable generation, transmission, distribution, and end-user consumption. Figure 4.1 categorizes the main energy storage applications and their

distribution across different segments. Each application is discussed briefly below, with practical examples provided in the Appendix.

#### 4.1 Conventional/ Bulk Generation Services:

Energy Storage Systems (ESSs) are essential for optimizing traditional synchronous generation by enhancing flexibility, efficiency, and economic performance. These advantages are realized through several services that ESSs provide, complementing conventional generation in grid operations. The key ESS services linked with conventional generation include:

#### Table 2 Principal Pros and Cons of Different ESS Technologies

A	В	С	D		
Energy storage	AdvaMages	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-leveling solutions for the grid, accounts for majority of work/wide deployment (>90%)		
Lead-Acid battery [52]	Low cost Technological maturity	Low energy/power density Toxic components Short calendar life Short response time	Minimal worklwide deployment for the grid (<2%) due to limited performance, used as standby-power mostly		
Vanadiam redox battery [52]	High energy storage capacity (ense of scalability)	Low energy/power density Complex construction (need	Load-leveling at substations transformer upgrade deferral, and support for grid integration of solar and wind		
Supercapacitors [52]	High power density	Low energy density	Butter 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 Hc as fuel	Continuous stable power output (as long as there is a scaled Hz foel 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 hest cogeneration and eco-friendly steel production		

#### Energy Trading:

One of the key benefits of ESSs is their ability to participate in energy trading. ESSs store energy during periods of low electricity prices and discharge it back into the grid when prices are high. This strategy maximizes revenue during peak price hours and minimizes costs during off-peak periods, optimizing the economic utilization of generation assets.

Peak Smoothing:

ESSs play a crucial role in peak smoothing by storing surplus energy during low demand periods and releasing it during peak demand hours. This helps to flatten peaks in load, ensuring a more consistent and

stable electricity supply. Unlike energy trading, peak smoothing focuses on maintaining grid stability and reliability rather than achieving economic targets.

#### Demand Flattening:

Demand flattening involves using ESSs to store energy during periods of low demand and release it during high demand periods. This service helps level out the load curve, promoting a more balanced distribution of energy consumption throughout the day. By reducing demand peaks, ESSs alleviate stress on generation assets and transmission infrastructure, enhancing overall grid efficiency and reliability.

#### Generator Support:

ESSs provide critical support to conventional generators during transitions between generating units. They can supply power to the load during rapid demand changes or unexpected generator outages, ensuring uninterrupted electricity supply. This support helps maintain grid stability and prevents power supply disruptions.

Generator Response and Load Adjustment:

ESSs offer faster response times to load changes compared to traditional generator units. They can quickly adjust their output to support load variations, enabling generators to modify their power output according to technical requirements. This rapid response helps prolong the lifespan of generators and maintains power quality within acceptable limits.

#### Black Start:

In the event of a blackout, ESSs can be used for black start operations, restoring power to sections of the grid or the entire system. ESSs energize the grid to provide necessary power and voltage before conventional generating units are brought online, ensuring a rapid and reliable restoration of power supply and minimizing downtime and disruption.

ESSs provide a range of valuable services that enhance grid flexibility, efficiency, and reliability. From energy trading to black start operations, they play a crucial role in optimizing grid operations and ensuring a stable and resilient power supply. As the energy landscape evolves, the importance of ESSs in supporting conventional generation and integrating renewable energy sources will continue to grow.

#### 4.2 Renewable Generation Services:

ESSs are vital for providing the power grid with the flexibility needed to manage the variability of renewable energy sources. They help balance variable generation with demand, reducing the reliance on dispatchable synchronous generation capacity and minimizing power curtailment. The primary services ESSs provide for renewable energy systems include:



Figure 4.1 Applications of Energy Storage Systems

- Curtailment Reduction: ESSs are used to absorb excess energy generated during periods of high renewable output and low demand. This stored energy can then be released into the grid when demand increases.

- Capacity Smoothing: ESSs stabilize power output from renewable energy sources by storing excess energy during peak production times and releasing it during periods of low generation. This practice helps manage short-term fluctuations and ensures a more consistent energy supply.

- Ancillary Services Provision: ESSs enhance renewable energy systems by maintaining an energy reserve that supports ancillary services. When combined with renewable systems, ESSs enable new services such as inertia emulation, rapid frequency response, primary frequency control, and dynamic reactive control.

#### 4.3 Transmission Services:

Energy Storage Systems (ESSs) significantly enhance the reliability, stability, and efficiency of transmission networks by providing a range of essential services. These services address operational challenges and offer cost-effective solutions for transmission system operators. Key services provided by ESSs include:

- Frequency Regulation:

- Primary Frequency Regulation: ESSs maintain the balance between generation and demand following a disturbance by quickly adjusting their output, stabilizing grid frequency.

- Secondary Frequency Regulation: ESSs fine-tune frequency deviations over longer periods by adjusting active power generation to restore nominal frequency.

- Tertiary Frequency Regulation: ESSs replenish primary and secondary frequency reserves, offering continuous support for frequency control and maintaining grid stability.

- Angular Stability: ESSs mitigate load-angle variations after disturbances, enhancing grid angular stability. They stabilize grid angles by handling high power levels over short durations, preventing potential instabilities.

- Voltage Regulation: ESSs serve as distributed sources or sinks of reactive power, regulating voltage levels across transmission and distribution networks. They inject or absorb reactive power as needed, maintaining voltage stability and consistency during fluctuating demand or generation periods.

- Transmission Investment Deferral: ESSs alleviate congestion within the transmission grid, postponing the need for expensive system upgrades. By strategically deploying ESSs, operators can manage congestion more efficiently, reducing overall investment in system expansion and optimization.

- Transmission Support: ESSs enhance transmission system operations during disturbances like voltage dips, local and interarea oscillations, or voltage instabilities. Their rapid response capabilities mitigate the impact of disturbances, ensuring grid reliability and minimizing downtime.

ESSs provide critical services that improve the operation and reliability of transmission networks. They optimize grid performance and facilitate the efficient integration of renewable energy sources. As transmission networks evolve, ESSs will play an increasingly important role in supporting grid operations and enhancing system flexibility. By leveraging ESS capabilities, transmission system operators can address current challenges and prepare for future grid demands in a cost-effective and sustainable manner.

#### 4.4 Distribution Services:

The use of Energy Storage Systems (ESSs) in the distribution network offers substantial benefits, enhancing reliability, efficiency, and resilience. These systems provide a variety of services that optimize grid operations and address management challenges. The primary advantages include:

- Capacity Enhancement and Investment Postponement: ESSs increase capacity by shifting loads from peak to off-peak periods, improving the utilization of existing infrastructure. This strategic deployment reduces congestion and delays the need for costly grid upgrades, optimizing asset use and boosting efficiency.

- Contingency Grid Assistance: During major component failures or outages, ESSs can take over part of the electricity generation, redistributing energy flows and ensuring continuity of supply. This rapid response capability enhances grid resilience and reduces downtime during emergencies.

- Voltage Regulation: ESSs maintain voltage levels within acceptable limits by injecting or absorbing reactive power as needed, enhancing grid stability and ensuring a consistent, high-quality power supply.

- Reactive Power Support: By contributing to the reactive power balance, ESSs stabilize voltage levels and improve system efficiency. This support is crucial in networks with high renewable energy penetration, where generation fluctuations can impact grid stability.

ESSs provide essential services that improve the operation and performance of the distribution network, from capacity enhancement and voltage regulation to contingency assistance. Their strategic deployment and advanced functionalities enable distribution system operators to optimize grid operations, minimize downtime, and ensure high-quality power supply. As distribution networks evolve, the role of ESSs in supporting grid management and integrating renewable energy will become increasingly significant.

#### 4.5 Customer Services:

Energy Storage Systems (ESSs) are used in energy management applications to improve power quality, reliability, and cost-effectiveness for customers. The main services provided by ESSs include:

- End-User Peak Shaving: Customers utilize ESSs to reduce their peak demand, thus lowering the portion of their electricity bill determined by the highest power usage.

- Time-of-Use Energy Cost Management: ESSs store energy during periods of low rates and discharge it during peak times, reducing overall electricity costs.

- Power Quality Improvement: ESSs address power quality issues, such as voltage fluctuations and harmonics, often caused by the variability of renewable energy sources.

- Continuity of Energy Supply (Energy Backup): ESSs ensure the electricity network remains functional during interruptions, protecting critical loads from blackouts.

- Reactive Power Support: ESSs connected to the grid through power electronics can provide reactive power, enhancing efficiency and regulating voltage levels.

Table 3 summarizes the primary characteristics of ESSs in delivering these services, with values being approximate and application-specific. While this article emphasizes electrochemical ESSs, it notes that for long-term services, other technologies like mechanical, electrical, thermal, or chemical storage may be more suitable.

А	B	C D	E F	G H	Ι
Segment	Service	Storage power level (MW)	Response {4} and dhcharge time (ta)	SuitxblJhy of BEST	
fionventionsPBulk	Arbitrage	Hundreds ot MW	H <sup>, minutes</sup> ours	Unsuitable	
generation	Peak shaving	Hundreds ot kw to hundreds ot	t, minutes	Possible tNas and	
	Load levelling	MW	t <sub>4</sub> ~< 5 hours	flow batteries)	
	Loud It ferring	MW to hundreds ot MW	t. ~ 12 ho	Possible /as and	
	Generator bridging	Up to hundreds of MW	t, minutes	Possible	
	Generator ramping/load	NAV/ to hundrade of NAV/	$t_d \sim \text{minutes to several hours}$ $t_t \sim \text{up to } 1 \text{ s}$	Possible	
	ronowing	MW to hundreds of MW	t <sub>4</sub> ~ minutes to several hours		
	Black-stari	Hundreds of kW to hundreds of	t, seconds to minutes	Suitable	
Renewable generation	Curtailment	MV	t <sub>r</sub> ~ minutes	Possible	
	minimization	MGJ	t <sub>d</sub> ~ minutes up to several hours		
	Capacity firming	Tens of MW to hundreds of	t, ~ seconds	Possible	-
	Naw anallani canacar	MW	ia seconds up to several noois		
	support	MW level up to tens of MW	t, • milTyaeconds fa seconds (depending on the specific ancillary	Suitable	
			smvice)		
	Frequency control		seconds to minutes		
Transmission	request, control	Tens of MW up io - Iti'0 MW	t, - milliseconds tor primary control	Suitable	
			t, - < minute for secondary and tertiary		
			controis		
			hour for secondary concoT		
	Angular stability	Tens of MW Ia hundreds of	t, milliseconds	Suitable	
	1-h	MV	a - seconds to minutes	C. a. akla	-
	Noitsge support	Tens of MW to hundreds of	t, IWms	Possible	-
	investment deanar	MW	b - 1-fibours	1 OSSIDIE	
	Transmission suppom	Teris of MW	t, - milluetonds	Suuable	1
			b/>wond to minutes		
Disnbution	Capacity support an	d TensotMW	t - minutess	f•ossible	
	invesimeni deterral	Teps of M\v/	t seconds	Possible	1
	Eanding gird sappoin	Tensionitw	a - minutes to hours		
	Yoliage control		r - IW me	Suneble	
	Reactive power		t <sub>r</sub> ~ 100 ms	Sijupble	
				Bassible	
Customer services	End-User peak shaving	Tens ot kW to tens of MW	t, minutes	rossible	
		Spending on the customer size	t, -< 5 nouts Spending on the		
	Energy cost management	Tens ot kW to tens ot ML	L minutes	f•ossible	
	Power quality	depending on the customer size	$q \sim 12$ hours		
		Tens ot kW to tens ot MW	t <sub>4</sub> ~< 2 hours	Suitable	
	Back-up	ens of kW falters of MI	n milliseconds	Suneble	1
	Reactive non-	depending on the customer size	b minutes up to several hours		
	Reactive power		t, - millueconds	Suuable	
Energy matket atramp	ting to launch mechanisms fo	this but economic incentives are too	l low for any caniañ outley for Eacility inve	stments	
energy menter entrop					

## 5 Power Electronics for base grid integration:

As discussed in Section 4, Energy Storage System (EES) technologies produce DC voltage directly. Power electronic converters are then employed to link this low DC voltage with the high AC voltage of the power grid. This section explores several converter technologies commonly utilized for this purpose, as depicted in Figure 5.1.

## 5.1 Low-Frequency Transformer-Based Interface:

The traditional approach to integrating Battery Energy Storage Systems (BESS) into the grid involves arranging battery cells, modules, and packs in series and parallel configurations to create a unified unit, as depicted in Figure 5.2. While this method offers scalability and design flexibility, it also presents challenges in BESS applications.

## Series-Parallel Configuration:

In this setup, battery cells are combined in series and parallel arrangements to form modules, which are then aggregated to create packs. While this configuration facilitates the construction of large-scale battery systems, it imposes constraints. The power output of each series string is limited by the weakest component within that string. Consequently, the overall performance of the battery unit is restricted by the least capable component, resulting in inefficiencies and decreased reliability.



Figure 5.1 Converters for Grid Interfacing

### **Challenges and Concerns:**

Performance Constraints: Weaker subunits within the BESS impose limitations on overall performance and power output. This constraint can affect the system's capacity to meet demand fluctuations and effectively respond to grid demands.

Battery Management System (BMS) Complexity: Addressing performance limitations and ensuring safe operation necessitates a sophisticated Battery Management System (BMS). The BMS is responsible for monitoring and actively adjusting the State of Charge (SoC) and State of Health (SoH) of each subunit. Managing the SoC and SoH of multiple subunits introduces complexity to the control system and heightens the risk of operational issues.



Figure 5.2 Traditional BESS employing a two-level inverter and a line-frequency transformer

Power Electronics Overhead: Coordinating battery charging and discharging across various aggregation levels requires the deployment of multiple power electronic switches. These switches introduce complexity to the system architecture, increase energy losses, and affect overall system efficiency.

Reliability Concerns: The interconnected nature of multiple components raises the risk of system failures and faults. Ensuring the reliability of each subunit and the entire system becomes a significant challenge in BESS integration.

Cost Implications: The intricacy of the conventional integration approach results in elevated installation and maintenance expenses. The requirement for sophisticated control systems, additional components, and redundant measures to mitigate risks contributes to the overall cost of the BESS.

Mitigation Strategies:

Advanced Battery Management: Utilizing advanced algorithms and diagnostic techniques within Battery Management Systems (BMS) can enhance the monitoring and control of individual battery subunits, thereby improving system performance and reliability.

Topology Optimization: Exploring alternative system topologies and configurations that minimize the impact of weaker subunits can enhance overall system efficiency and reliability.



Figure 5.3 Illustration of IGBTs connected in series for direct linkage to the MV grid via a two-level converter

Integrated Power Electronics: Developing integrated power electronics solutions to streamline battery unit control and management at each aggregation level can reduce complexity and energy losses.

Redundancy and Fault Tolerance: Implementing redundancy and fault-tolerant designs within the BESS architecture can help mitigate the impact of component failures and enhance system resilience.

The conventional method of integrating BESS into the grid offers scalability and flexibility but also poses challenges related to performance limitations, complexity, reliability, and cost. Addressing these

challenges requires innovative approaches in battery management, system design, and power electronics integration. Overcoming these hurdles can optimize BESS integration into the grid, enhancing stability, supporting renewable energy integration, and contributing to a more resilient and sustainable energy infrastructure.

In traditional grid-connected inverters for BESS applications, a transformer is typically employed to elevate voltage from hundreds of volts to medium-voltage levels, usually ranging from tens of kilovolts. This setup enables multiple batteries and their associated inverter units to be linked in parallel at the low-voltage (LV) DC bus, facilitating the creation of large-scale BESSs with power ratings in the tens of megawatts range. An additional transformer stage may be incorporated for connection to even higher voltage levels, such as 66 kV and above. However, the use of a two-level DC-AC stage requires a bulky, inefficient, and costly step-up transformer for medium-voltage grid connection.

Challenges with Conventional Two-Level Converters:

Transformer Dependency: Relying on transformers for voltage elevation adds complexity, bulk, and cost to the system. Additionally, transformers introduce losses and inefficiencies, impacting overall system performance.

Limited Voltage Control: Two-level converters offer limited control over output voltage magnitude, potentially limiting their suitability for grid applications requiring precise voltage regulation and flexibility.

Alternative Topologies:

Three-Level Neutral-Point Clamped (NPC) Converter: This topology offers enhanced voltage control and reduced harmonics compared to the conventional two-level converter by utilizing additional voltage levels.

Active NPC Converter: The active NPC converter further improves voltage control and harmonic performance by actively balancing the neutral-point voltage, minimizing voltage imbalances, and enhancing system stability.

Three-Level Flying Capacitor Converter: This topology employs flying capacitors to achieve multiple voltage levels, providing improved voltage control and reduced harmonics, although it may require more complex control algorithms and pose challenges in capacitor balancing.

Advantages of Multilevel Converters:

Increased Output Voltage Magnitude: Multilevel converters offer a higher number of voltage levels, providing greater flexibility in output voltage control, particularly beneficial for grid-connected applications requiring precise voltage regulation.

Improved Harmonic Performance: By utilizing additional voltage levels, multilevel converters can mitigate harmonic distortion, enhancing overall system efficiency and reducing the impact on grid stability.

Reduced Stress on Components: Distributing voltage across multiple levels reduces stress on individual components, prolonging their lifespan and enhancing system reliability.

Tradeoffs:

Complexity vs. Performance: While multilevel converters offer superior voltage control and harmonic performance, they often require more complex control designs and modulation techniques, potentially increasing system cost and posing challenges in implementation and maintenance.

Silicon Power vs. Harmonic Performance: The choice of multilevel converter topology involves a tradeoff between silicon power utilization, mechanical complexity, and harmonic performance. Designers must carefully balance these factors to optimize system efficiency and reliability.

Alternative topologies to conventional two-level converters offer enhanced voltage control, improved harmonic performance, and reduced component stress in BESS applications. While these topologies may introduce additional complexity and cost, they provide valuable advantages in system efficiency, reliability, and grid integration capabilities. Designers and engineers must carefully evaluate tradeoffs and select the most suitable converter topology based on specific application requirements and constraints. Leveraging advanced converter technologies can enable BESSs to contribute to a more resilient, efficient, and sustainable energy infrastructure.

#### 5.2 Transformerless Interface:

Traditional BESS inverters typically rely on line-frequency transformers, which are bulky, inefficient, and costly. To circumvent the necessity for these transformers, direct connection solutions for utility-scale BESS have emerged. These solutions fall into two primary categories, distinguished by how either semiconductors or submodules (SMs) are series-connected.



Figure 5.4 Cascade H-Bridge inverter enabling direct connection of the BESS to the MV grid

Transformerless Interface:

The term "transformerless interface" refers to an electrical circuit design that omits the traditional transformer component, which is commonly used for isolation, voltage conversion, and impedance matching. The absence of a transformer can significantly affect the design, efficiency, cost, size, and weight of electronic systems, particularly in power conversion and signal processing applications.

Transformers have been a cornerstone in electrical engineering, providing galvanic isolation and voltage conversion in various applications, from power supplies to audio systems. However, transformerless designs are becoming increasingly popular due to advancements in semiconductor technology, the demand for miniaturization, and the need for higher efficiency and lower cost solutions.

This article delves into the concept, benefits, challenges, and applications of transformerless interfaces, highlighting the technological advancements that enable these designs and their implications in modern electronics.

The Concept of Transformerless Interfaces

A transformerless interface refers to a design approach where the traditional electromagnetic transformer is replaced by alternative methods to achieve similar functionalities. This can include capacitive coupling, direct connection with protective measures, and semiconductor-based isolation techniques.

Why Go Transformerless?

1. Size and Weight Reduction: Transformers can be bulky and heavy, especially those designed for high power applications. Transformerless designs significantly reduce the size and weight of electronic devices, which is crucial for portable and compact systems.

2. Cost Efficiency: Transformers add to the manufacturing cost due to the materials and processes involved in their construction. Transformerless designs can lower costs by eliminating these components and using less expensive alternatives.

3. Enhanced Efficiency: Transformers introduce losses due to hysteresis and eddy currents in the core material. Transformerless designs, particularly those employing modern semiconductors, can achieve higher efficiency by minimizing these losses.

4. Simplified Manufacturing: Transformerless designs can streamline the manufacturing process, making it easier to automate and scale production.

Types of Transformerless Interfaces

Transformerless interfaces can be broadly categorized based on their application and the techniques used to achieve isolation and voltage conversion.

1. Capacitive Coupling

Capacitive coupling involves using capacitors to pass AC signals while blocking DC. This method provides a form of isolation and is commonly used in signal processing applications where DC biasing is not desired.

Applications:

- Audio circuits
- Communication interfaces
- Signal conditioning

Benefits:

- Simple and inexpensive
- Effective for AC signal coupling

Challenges:

- Limited voltage isolation
- Not suitable for power transfer
- 2. Direct Connection with Protective Measures

In some low-power applications, direct connection without a transformer is feasible by incorporating protective measures such as fuses, surge protectors, and circuit breakers to handle faults and overcurrent situations.

#### Applications:

- Low-power DC adapters
- Battery charging circuits

Benefits:

- Simplified design
- Reduced component count

Challenges:

- Safety concerns
- Limited to low-power applications
- 3. Semiconductor-Based Isolation

#### **Semiconductor-Based Isolation:**

Semiconductor-based isolation refers to the use of semiconductor materials and technologies to provide electrical isolation between different parts of an electronic system. This technique is crucial for protecting sensitive components, ensuring signal integrity, and improving overall system reliability. As electronic devices become increasingly complex and compact, the importance of effective isolation methods continues to grow.

Principles of Semiconductor-Based Isolation

Semiconductor-based isolation leverages the properties of semiconductor materials to create barriers that prevent electrical current from flowing between isolated sections of a circuit while allowing data or power transfer through other means, such as optical, capacitive, or magnetic coupling. This isolation is essential in applications where electrical noise, differences in ground potential, or high voltages pose risks to circuit performance or safety.

Basic Components and Mechanisms

1. Optocouplers: These devices use light to transmit signals across an isolation barrier. An LED on the input side converts an electrical signal into light, which is detected by a photodetector on the output side, thus providing isolation.

2. Acitive Couplers: These use capacitive coupling to transfer signals across an isolation barrier. They leverage the fact that capacitors can pass AC signals but block DC, providing isolation while maintaining signal integrity.

3. Magnetic Couplers: These devices use magnetic fields to transfer signals across an isolation barrier. Inductive elements, such as transformers or coils, are used to couple the signal magnetically, providing galvanic isolation.

Types of Semiconductor-Based Isolation Devices

Several types of semiconductor-based isolation devices are used in modern electronics, each with unique advantages and applications.

#### 1. Optocouplers

Optocouplers, also known as optoisolators, are among the most common isolation devices. They provide high isolation voltage and are widely used in applications where electrical noise and transient suppression are critical.

#### Key Characteristics:

- Isolation Voltage: Optocouplers can withstand high isolation voltages, typically ranging from a few hundred volts to several kilovolts.

- Speed: The switching speed of optocouplers varies, with some designed for high-speed digital applications while others are optimized for low-speed analog signals.

- Durability: Optocouplers are robust and can operate in harsh environments, making them suitable for industrial and automotive applications.

#### 2. Capacitive Couplers

Capacitive couplers utilize the capacitive effect to transfer signals across an isolation barrier. They are known for their high-speed data transfer capabilities and low power consumption.

#### Key Characteristics:

- Bandwidth: Capacitive couplers offer high bandwidth, making them ideal for high-speed data communication applications.

- Power Efficiency: These devices typically consume less power compared to other isolation technologies, which is advantageous in power-sensitive applications.

- Size: Capacitive couplers are often compact, making them suitable for integration into small form-factor devices.

#### 3. Magnetic Couplers

Magnetic couplers, including transformers and inductive isolators, use magnetic fields to provide isolation. They are well-suited for applications requiring high isolation voltages and robust performance.

Key Characteristics:

- Isolation Voltage: Magnetic couplers can achieve very high isolation voltages, often exceeding those of optocouplers and capacitive couplers.

- Noise Immunity: These devices offer excellent noise immunity, making them ideal for environments with significant electrical interference.

- Versatility: Magnetic couplers can be used for both signal and power isolation, providing a flexible solution for various applications.

Applications of Semiconductor-Based Isolation:

Semiconductor-based isolation devices are used across a wide range of industries and applications, including industrial automation, medical equipment, telecommunications, and consumer electronics.

### 1. Industrial Automation

In industrial automation, semiconductor-based isolation is critical for protecting sensitive control systems from high voltages and electrical noise. Isolation devices are used in motor drives, programmable logic controllers (PLCs), and industrial communication interfaces to ensure reliable operation in harsh environments.

Key Benefits:

- Enhanced Safety: Isolation devices protect operators and equipment from electrical hazards.

- Improved Reliability: By mitigating the effects of electrical noise and transients, isolation devices enhance the reliability and longevity of industrial systems.

## 2. Medical Equipment

Medical devices require high levels of electrical isolation to ensure patient safety and reliable operation. Semiconductor-based isolation is used in various medical applications, including patient monitoring systems, diagnostic equipment, and medical imaging devices.

Key Benefits:

- Patient Safety: Isolation devices prevent electrical shocks and ensure that patient-connected equipment operates safely.

- Signal Integrity: By isolating sensitive medical electronics from potential interference, these devices help maintain accurate signal processing and data integrity.

#### 3. Telecommunications

In telecommunications, semiconductor-based isolation is essential for protecting communication equipment from electrical surges and ensuring the integrity of data transmission. Isolation devices are used in modems, routers, and base stations to provide robust and reliable performance.

#### Key Benefits:

- Data Integrity: Isolation devices help maintain high-quality data transmission by mitigating electrical noise and interference.

- System Protection: By isolating sensitive components from high voltages and transients, these devices enhance the durability and reliability of telecommunications equipment.

#### 4. Consumer Electronics

In consumer electronics, semiconductor-based isolation is used to protect devices from electrical faults and to ensure safe and reliable operation. Applications include power supplies, audio systems, and home automation devices.

Key Benefits:

- Safety: Isolation devices help protect users from electrical hazards.

- Performance: By isolating sensitive components from electrical noise, these devices help maintain high performance and reliability.

Challenges and Future Trends

While semiconductor-based isolation technologies offer numerous benefits, they also face several challenges that need to be addressed to enhance their performance and reliability.

#### 1. Miniaturization

As electronic devices become smaller and more integrated, the demand for compact isolation solutions increases. Developing miniaturized isolation devices that maintain high isolation voltage and performance is a significant challenge.

Future Trends:

- Advanced Materials: Research into new semiconductor materials and fabrication techniques aims to create smaller, more efficient isolation devices.

- Integration: Efforts to integrate isolation functions directly into semiconductor chips are underway, potentially reducing the size and complexity of electronic systems.

#### 2. Performance

Improving the speed, bandwidth, and power efficiency of isolation devices is critical for meeting the demands of modern high-performance applications.

Future Trends:

- High-Speed Isolation: Development of isolation devices capable of higher data rates and faster switching speeds to support next-generation communication and computing applications.

- Low Power Consumption: Innovations in low-power isolation technologies aim to reduce the energy consumption of electronic systems, particularly in battery-powered and portable devices.

#### 3. Reliability and Durability

Ensuring the long-term reliability and durability of isolation devices, especially in harsh environments, is essential for their widespread adoption.

#### Future Trends:

- Robust Design: Advances in robust design techniques and materials to enhance the durability of isolation devices in industrial, automotive, and medical applications.

- Quality Assurance: Improved quality assurance processes and testing methodologies to ensure the consistent performance and reliability of isolation devices.

Semiconductor-based isolation is a vital technology for modern electronics, providing essential protection and performance benefits across a wide range of applications. From industrial automation and medical equipment to telecommunications and consumer electronics, isolation devices play a crucial role in ensuring the safety, reliability, and efficiency of electronic systems.

The continuous advancement of semiconductor materials, fabrication techniques, and design methodologies will drive the evolution of isolation technologies, addressing current challenges and meeting the demands of future applications. As the electronics industry moves towards more compact, high-performance, and energy-efficient solutions, semiconductor-based isolation will remain a key enabler of innovation and technological progress.

1. Power Electronics:

In power electronics, transformerless designs are used in AC-DC converters, DC-DC converters, and inverters. These designs are prevalent in applications like renewable energy systems (solar inverters), electric vehicle chargers, and consumer electronics.

Example: Solar Inverters

Transformerless inverters in solar energy systems convert DC power from solar panels to AC power for grid use or local consumption. These inverters are more efficient and lighter than their transformer-based counterparts.

Benefits:

- Higher efficiency (98-99%)
- Lower cost and weight
- Improved thermal management

Challenges:

- Requires stringent safety measures (e.g., ground fault detection)
- Potential for leakage currents

2. Audio Equipment

Transformerless designs in audio equipment, such as amplifiers and mixing consoles, help in achieving high fidelity sound reproduction by minimizing distortion and noise associated with transformers.

**Example: Transformerless Microphone Preamps** 

These preamps use semiconductor devices to amplify the microphone signal without the coloration or distortion introduced by transformers. Hobal Knowledge and

Benefits:

- High-quality audio output
- Reduced noise and distortion
- Cost-effective

Challenges:

- Requires careful design to avoid interference
- Susceptibility to electromagnetic noise
- 3. Communication Devices

In communication systems, transformerless interfaces are employed in Ethernet interfaces, USB isolators, and other data transmission applications where signal integrity and isolation are critical.

Example: Ethernet Transformers vs. Transformerless Ethernet

While traditional Ethernet interfaces use transformers for isolation, modern solutions can use digital isolators to achieve the same effect without the bulk of transformers.

#### Benefits:

- Smaller form factor
- Potentially higher data rates
- Improved reliability

Challenges:

- Requires robust ESD protection
- Potential compatibility issues with existing infrastructure

**Challenges and Considerations** 

While transformerless designs offer several advantages, they also come with challenges that need careful consideration.

1. Safety Concerns

Without a transformer, ensuring galvanic isolation becomes more challenging. Proper isolation techniques, such as using high-quality capacitors or digital isolators, are crucial to prevent electric shock and equipment damage.

2. EMI and Noise

Transformerless designs can be more susceptible to electromagnetic interference (EMI) and noise. Shielding, filtering, and careful PCB layout are essential to mitigate these issues.

3. Reliability

Transformerless interfaces, particularly those relying on semiconductors, can be sensitive to temperature variations and aging. Ensuring long-term reliability requires selecting high-quality components and robust design practices.

. Standards and Compliance

Meeting regulatory standards for safety, electromagnetic compatibility (EMC), and performance is crucial. Transformerless designs must comply with standards such as IEC, UL, and CE to ensure they are safe and effective in their intended applications.

**Technological Advancements** 

Advancements in semiconductor technology and materials science have significantly contributed to the viability of transformerless interfaces.

1. Wide Bandgap Semiconductors

Materials like silicon carbide (SiC) and gallium nitride (GaN) offer superior performance over traditional silicon in terms of efficiency, thermal management, and switching speed. These materials enable more compact and efficient transformerless designs.

2. Advanced Isolation Techniques

Digital isolators using capacitive or inductive coupling, as well as optocouplers with enhanced performance, provide robust isolation without the need for bulky transformers.

3. Improved Capacitors

Advances in capacitor technology, such as the development of high-voltage, high-reliability capacitors, enable safer and more effective transformerless designs, particularly in high-frequency applications.

Case Studies

Case Study 1: Solar Inverters

A leading solar inverter manufacturer implemented transformerless technology to enhance the efficiency and reduce the weight of their inverters. By using high-efficiency SiC MOSFETs and advanced digital isolators, they achieved:

- Efficiency: Improved from 95% to 99%

- Weight Reduction: 50% lighter than transformer-based models

- Cost Savings: 20% reduction in manufacturing costs

These improvements made the inverters more competitive in the market, particularly in residential and commercial solar installations.

Case Study 2: High-Fidelity Audio Equipment

An audio equipment manufacturer replaced traditional transformer-based preamps with transformerless designs using high-quality semiconductor components. The result was:

- Sound Quality: Noticeable improvement in clarity and reduction in noise

- Cost: 30% reduction in production costs
- Customer Satisfaction: Positive feedback from professional audio engineers and musicians

The transition to transformerless designs enabled the manufacturer to offer high-end audio products at a more affordable price, expanding their market reach.

Future Trends:

The trend towards transformerless designs is expected to continue, driven by the demand for more efficient, compact, and cost-effective solutions. Future developments may include:

1. Integration of Power and Signal Components

Combining power and signal processing components in a single chip or module can further reduce size and improve performance. This integration will be facilitated by advances in semiconductor fabrication and materials.

#### 2. Enhanced Isolation Techniques

Emerging technologies such as microelectromechanical systems (MEMS) and advanced nanomaterials may offer new ways to achieve isolation without transformers, providing even greater efficiency and reliability.

#### 3. Smart Interfaces

Incorporating smart features such as self-diagnosis, adaptive control, and real-time monitoring into transformerless interfaces can enhance their performance and reliability, particularly in critical applications like renewable energy systems and industrial automation.

Transformerless interfaces represent a significant shift in the design of electronic systems, offering numerous benefits in terms of efficiency, size, weight, and cost. While they present certain challenges, particularly in terms of safety and reliability, advancements in semiconductor technology and isolation techniques are continually addressing these issues.

As the demand for compact, efficient, and cost-effective electronic solutions grows, transformerless designs are poised to play a crucial role in the future of power electronics, audio systems, communication devices, and beyond. The continued evolution of this technology promises to deliver even greater performance and versatility, driving innovation across multiple industries.

#### 5.3 Solid-State Transformer:

While transformerless configurations offer advantages, such as reduced size and weight, they lack galvanic isolation, which is often essential for safety and to prevent leakage current. To address this, a conventional transformer can be replaced with a solid-state transformer (SST), also known as a smart transformer. The basic idea behind an SST is to reduce the size and weight of the magnetic core by operating at a higher frequency. As depicted in Figure 5.7, this approach can significantly reduce the size of the transformer. However, achieving substantial reductions in core size with SSTs involves the added complexity and losses associated with two frequency converters. Consequently, while SSTs hold promise for size and weight reduction compared to conventional transformers, the overall system-level benefits may not always materialize as anticipated.



Figure 5.5 Modular Multilevel Converter (MMC) with corresponding Sub-Modules (SMs), Centralized batteries on the dc-link

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Figure 5.6 Modular Multilevel Converter (MMC) with associated Sub-Modules (SMs), Batteries distributed within the SMs.

There are four categories of SSTs, determined by the positioning of DC-link capacitors in relation to the high-frequency magnetic core, as depicted in Figure 5.8. Below, we outline the main characteristics of each type.



Figure 5.7 Comparison illustration of the sizes of low- and high-frequency transformers

### Type A

This topology accomplishes direct AC-AC conversion without employing a DC decoupling capacitor. Its straightforward design makes it lightweight and cost-effective. However, the absence of DC capacitors means it cannot support reactive power or decouple disturbances between the two sides. Moreover, the lack of a DC-link on the LV side complicates the integration of renewable sources and batteries. Additionally, without an HVDC capacitor, it cannot utilize established multilevel converters on the HV side, limiting the SST's high-voltage range.

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Figure 5.8 Categories of Solid-State Transformer (SST) topologies



Figure 5.9 DAB topology.

## Туре В

By adding an LVDC capacitor, Type B restores reactive power control and disturbance isolation, allowing batteries to connect to this capacitor. However, like Type A, it is still limited in high-voltage (HV) applications.

## Type C

Type C, similar to Type B, includes an HVDC capacitor that enables reactive power control and disturbance isolation, making it more suitable for HV applications than Types A and B. Despite this, integrating batteries remains challenging, which is a crucial aspect since supporting the grid integration of renewables and batteries is a key advantage of Solid State Transformers (SSTs).



Figure 5.10 Comparison of sizes between SiC MOSFET and Si IGBT

## Type D Converters

Type D converters, incorporating both HVDC and LVDC capacitors, are the most popular due to their extensive control functions. Although more complex and costly as a three-stage topology, their dual-capacitor design makes them ideal for field applications. In battery storage systems, the critical element is the DC-DC converter, which isolates and boosts DC voltage to connect an LV battery bank to the DC-link of grid-connected DC-AC converters. For high-power uses, the preferred topology is the dual active bridge

(DAB). Advances in high-power wide bandgap semiconductor technology are enabling more compact and efficient DAB designs, such as the size comparison between traditional Si IGBT and SiC MOSFET switches.

#### Power Control Limits of Hybrid ESS Systems

Modular Multilevel Converters (MMC) and Cascaded H-Bridge (CHB) converters facilitate integrating diverse Energy Storage Systems (ESS) and combining photovoltaic (PV) generation with batteries. These systems' asymmetry, due to varying submodule (SM) characteristics, requires the converter to adhere to desired power references under different conditions. The control system must manage each SM's power reference to balance the state of charge (SoC) or state of health (SoH) in battery energy storage systems (BESS), ensuring that power references remain within ESS operational limits. Constraints on active power are divided into hardware limits and control limits.

#### Hardware Limits

Hardware limits pertain to physical constraints set during system design, including maximum temperature, voltage, and current ratings for components like semiconductors, batteries, and capacitors. Adhering to these limits is essential to prevent triggering protection circuits. Each semiconductor device, for example, has a maximum current rating to avoid overheating, and batteries must operate within specific voltage ranges to prevent degradation. Capacitors also have voltage ratings to avoid dielectric breakdown. The control system monitors and adjusts power flow to keep operating parameters within safe bounds, ensuring hardware component longevity and reliability.

#### **Control Limits**

After satisfying hardware limits, the control system must address control limits, which are more flexible but crucial for optimal power distribution and system performance. Violating control limits can lead to suboptimal power distribution and reduced efficiency, potentially causing imbalances affecting overall ESS performance. Dynamic power balancing is a strategy used to adjust power references based on realtime data, ensuring no SM operates beyond control limits and preventing conditions that could trigger hardware limit violations.

#### Ensuring Safe and Efficient Operation

The control system ensures safe and efficient ESS operation by managing hardware and control limits through sophisticated algorithms that monitor and regulate power flow to each SM. These algorithms anticipate potential issues and adjust power distribution accordingly. In systems integrating PV generation and batteries, the control system manages variable PV power output while keeping batteries

within safe SoC limits, optimizing renewable energy use and battery safety. Advanced control techniques, such as model predictive control (MPC) and adaptive control, enhance ESS performance by forecasting future states and making real-time adjustments.

#### **Challenges and Future Directions**

Integrating diverse ESS technologies with MMC and CHB converters presents challenges due to system asymmetry. Developing a universal control strategy to optimize performance across all components is complex. Future advancements in control algorithms and power electronics will address these challenges, with machine learning techniques potentially enabling control systems to dynamically optimize performance. Improvements in semiconductor technology and battery chemistry will expand hardware component operational limits, providing more flexibility for control systems. Enhancing ESS integration with MMC and CHB converters will improve power system efficiency and flexibility, paving the way for broader adoption and innovation in energy storage.

#### 5.4 Grid Codes and Standards:

Standards for grid-connected inverters set forth various requirements to ensure these systems can effectively support the grid during contingencies and transient events. The key requirements for frequency and voltage support are vital for maintaining grid stability and reliability. The following sections provide a detailed overview of these requirements.



Figure 5.11 Comparison of volt-VAR [Q(V)] response across various standards

#### Voltage Regulation:

Voltage regulation is essential for grid stability, and standards mandate that BESS inverters inject or absorb reactive power at the point of common coupling (PCC) to keep grid voltage within acceptable limits. Various standards, including AS 4777.2, IEEE 1547, VDE 4105, CEI 0-21, and TR 3.2.2, detail how BESS inverters should respond to deviations in PCC voltage, as illustrated in Figure 5.11.

When PCC voltage deviates from its nominal range, BESS must either inject or absorb reactive power to stabilize the voltage. For example, if the voltage is lower than nominal, the BESS inverter may inject reactive power to boost it. Conversely, if the voltage is higher, it may absorb reactive power to reduce it.

The response of BESS inverters to voltage changes varies across standards. Some, like the Danish standard TR 3.2.2 and IEEE 1547 category A, require continuous participation in voltage regulation with no dead band for Q(V) response, meaning BESS inverters constantly adjust their reactive power output in response to voltage fluctuations. Others, such as AS 4777-2, TOR D4, and CEI 0-21, incorporate larger dead bands, activating the BESS inverter's response only when the voltage deviation exceeds a certain threshold. This reduces the frequency of reactive power adjustments but may result in less responsive voltage regulation.

Frequency Regulation:

Frequency regulation is crucial for grid stability, particularly during frequency disturbances. BESS inverters must support the grid by adjusting their power output based on grid frequency, as specified in standards like AS 4777.2 (see Figure 5.12).

During a frequency disturbance, such as a drop in grid frequency, BESS inverters must adjust their operation according to predefined droop curves. When the grid frequency falls below a certain threshold, the BESS inverter is programmed to inject active power into the grid, following a droop characteristic that dictates the relationship between frequency deviation and power output. Different standards define various droop characteristics, specifying how much power the BESS inverter should inject based on the extent of the frequency drop.

Once the frequency returns to the nominal range, the BESS inverter remains at its maximum power output for a specified recovery time, such as 20 seconds per AS 4777.2. This recovery period includes a hysteresis band to prevent unstable operation and rapid cycling of the inverter. During this time, the inverter must adhere to a defined power ramp rate, typically 16% of the nominal power per minute, ensuring a smooth transition back to normal operation.

Technical Parameters and Considerations:

The effectiveness of voltage and frequency regulation by BESS inverters depends on several technical parameters, including response time, accuracy, and the ability to handle power fluctuations without compromising stability. Standards provide detailed guidelines to ensure BESS inverters meet these requirements under various operating conditions.

For voltage regulation, the control system within the BESS inverter must accurately measure the PCC voltage and quickly adjust the reactive power output. Advanced control algorithms are often employed to achieve precise and rapid responses to voltage deviations. For frequency regulation, the control system must continuously monitor the grid frequency and adjust the power output accordingly. The droop curves defined by the standards ensure a proportional and controlled response, preventing overshooting or undershooting of power output. Additionally, the inverter's ability to ramp power smoothly during recovery periods is crucial for maintaining grid stability.

Challenges and Future Developments:

Implementing these standards poses challenges, particularly in ensuring BESS inverters can respond effectively under all operating conditions. Variability in grid conditions, such as sudden changes in load or generation, complicates maintaining stable voltage and frequency. The integration of large-scale renewable energy sources adds further complexity to grid management, necessitating more sophisticated control strategies.

Future developments in BESS inverter technology and control algorithms are expected to address these challenges. Advancements in real-time monitoring and predictive analytics could enhance BESS inverters' ability to anticipate and respond to grid disturbances. Additionally, improvements in inverter hardware, such as faster and more efficient semiconductors, could enable quicker and more precise responses to voltage and frequency deviations.



Figure 5.12 Grid frequency support: An illustration of a two-stage frequency response for a decline in frequency for a BESS inverter (AS4777).



Figure 5.13 Example of a frequency disturbance and the output power of a BESS inverter

Standards for grid-connected inverters are crucial for ensuring that BESS can offer vital support during grid contingencies and transient events. These standards specify requirements for voltage and frequency regulation, ensuring that BESS inverters can effectively stabilize the grid. Compliance with these standards involves managing both hardware and control limitations, with advanced control systems playing a key role in maintaining grid stability. As technology progresses, the capabilities of BESS inverters will continue to improve, enhancing their support for an increasingly dynamic and renewable-heavy power grid.

#### 6 BESS Control for Grid Support:

BESSs are generally linked to energy-focused applications including pricing differentiation, load balancing, and minimizing wasteful usage of renewable energy, as covered in Section 5. Concurrently, power grids are becoming less dependent on synchronous generation and more on power electronics converter-based

generation in terms of both quantity and capacity. Maintaining grid stability will be extremely difficult throughout this shift, a task that many power system operators are actively tackling. This is where BESSs are anticipated to be crucial.



Figure 6.1 Control architecture of a grid-forming converter

A BESS can provide a wide range of grid-supporting functions, contingent on appropriate inverter sizing, control function implementation, and comprehensive integration studies. By assisting with grid restoration, voltage regulation, short-circuit current contribution, and recovery, BESSs can improve the resilience of the power system. When synchronous generators are decommissioned, the network's fault current levels decrease, making these roles even more important. Additional features include supporting weak grids, enhancing the capability of renewable energy sources in remote locations, reducing oscillations (especially low-frequency and subsynchronous ones), and offering black-start capabilities. By considering factors like time of day, network status, or geographic limitations, BESSs can further enhance their services (see Section 5 for further details).

Because of their large energy storage capacity, BESSs play a crucial role in the provision of frequency ancillary services. A grid-connected converter's capacity to react fast to frequency fluctuations at the point of common coupling (PCC) is one example of this. Longer term grid frequency maintenance can be facilitated by BESSs by varying output power, usually via a power-frequency (P-f) droop function (frequency support). To handle fluctuations in the rate-of-change-of-frequency (RoCoF), this function can be improved. By supplying synthetic inertia, BESSs can, during shorter times, aid in the power grid's inertial response to disturbances, allowing for a prompt reaction akin to that of a synchronous generator.



Figure 6.2 The response of the Dalrymple 30-MW 8-MWh BESS in terms of frequency versus active power.



Figure 6.3 Voltage versus reactive power characteristics

Future power grids with substantial proportions of renewable energy production are anticipated to need a range of functions beyond the basic minimum system strength/fault level required for power grid protection. Like the majority of power electronics converters, battery energy storage systems (BESSs) typically function in synchrony with the grid in a grid-feeding setup that includes both power/voltage and current controllers. However, different control strategies like voltage-controlled converters (VCCs) or converters running in grid forming mode (GFM) must be used in order to provide extra grid support functionalities.

By adding an inertial control loop, GFM functioning can be improved even more by simulating the actions of a synchronous generator. These techniques are frequently referred to as virtual machine mode (VMM) or virtual synchronous machines/generators (VSM/VSG).

Figure 6.1 shows the control architecture of a grid-forming converter. Although these kinds of implementations are becoming more common in power grids (see, for example, the Australian Hornsdale BESS and ESCRI-SA projects), they are still not as technologically mature as grid-feeding converters in the current power grid.

The lack of a phase-locked loop (PLL) in a GFM converter's control structure distinguishes it significantly from a grid-feeding converter since a GFM converter self-synchronizes to the grid using internal references. By removing the PLL, the converter system's fault ride-through capabilities and stability are contribution increased, allowing for the of fault currents. It is possible to choose other parameters, including the damping factor (Dp) and the inertia constant (I), to improve the BESS's reaction to certain events while limiting overshoots. Usually, the purpose of selecting these numbers is to emulate the dynamic performance of modern synchronous generators (SGs). But depending on the condition of the others, the BESS's available energy may permit much higher values or even adaptive parameter selection.

The BESS's application in weak grid conditions is increased when a virtual impedance is incorporated into the control loop. This also improves the ability of several BESSs in the same network to share reactive power. In a similar vein, virtual resistance prevents unanticipated power losses by damping resonance across a broad frequency range. Field tests conducted during network disruptions show how quickly BESSs react to frequency and voltage fluctuations, underscoring their potential to promote quick recovery in the near term and aid in the long-term transformation of the electrical grid.



Figure 6.4 The concept of Fixed Power Point Tracking (FPPT) in photovoltaic (PV) systems and its equivalence to energy storage systems

There are several advantages to integrating grid-forming converters and grid-supporting features into newly designed Battery Energy Storage System (BESS) projects or already-existing installations. The benefits are, however, dependent on certain site parameters, such as the battery cell energy density, the inverter's overcurrent capacity, and the site's electrical placement within the power grid. These features might not have been as important in many current grids as grid optimization. Therefore, it is imperative

to take into account more comprehensive network integration and coordination studies that take into account possible interactions (such circulating currents, power sharing among converters, and resonances) amongst many inverters. For grid-supporting BESS, a coordinated design approach is essential to verify the necessary performance and guarantee suitable settings.

Although there is evidence to support the benefits of grid-supporting services from BESSs, there are still a number of unanswered problems that prevent the general deployment of these technologies in global grids. These concerns range from defining what is considered to be an additional functionality that BESSs can offer in a way that is widely accepted to figuring out how many installations are necessary before undesired interactions occur. Updates or new grid connection standards, the level of technical studies and modeling required for every new installation, the prioritization of ancillary services, the control of many BESSs over larger geographic areas, and detailed technical requirements are all pending resolution.

#### 7 NEW TECHNOLOGIES AND FUTURE OUTLOOK

#### 7.1 Power Reserve and Flexible Control of Photovoltaic Systems:

Around the world, there is a sharp rise in the installation of photovoltaic (PV) systems due to government incentives, growing electricity prices, technology improvements, and falling PV panel costs. However, maintaining grid quality and dependability becomes increasingly important as PV penetration increases in electricity networks. Algorithms for Flexible Power Point Tracking (FPPT) are essential for accomplishing this. FPPT Operation Principles for PV Systems: During steady-state operation, FPPT algorithms control PV power to maintain a predetermined power reserve. When there are fluctuations in voltage or frequency, the grid can be supported by this reserve. The fundamentals of FPPT operation in PV systems are shown in Figure 6.4. For example, the PV output power can rise from the flexible power point (pfpp) to the maximum power point (pmpp) if the grid frequency decreases.

In battery energy storage systems (BESSs), the power reserve of photovoltaic systems operates similarly to a battery.

GridSupportFeaturesofPhotovoltaicSystems:PV panels are less expensive and require less upkeep than BESSs, which makes them attractive substitutesfor grid support in PV systems. PV systems can contribute to grid stability and dependability by offeringcrucial grid support functions, particularly in grids with a high PV penetration rate.

Application in Microgrid Systems: Standalone DC microgrids with PV systems are one setting in which FPPT-based power reserve regulation is employed. Such microgrids often employ a BESS to control the DC-link voltage and handle power imbalances between supply and demand, which leads to continuous battery operation.

The battery current in these systems is determined by the PV maximum power and the load. Battery charging current is maximized but discharge current is minimized when the PV system is operated at its maximum power point. Reducing the battery charging current in accordance with the battery's state of charge (SoC) and the available PV surplus power—which is regarded as virtual stored energy—is one tactic to extend battery life.

Advantages and Case Study: The usefulness of FPPT-based control in microgrid applications is illustrated through a case study simulation. Battery temperature fluctuations are reduced when partial cycles are eliminated through the use of FPPT-based regulation. Because of this, lead-acid battery lifetimes are increased by 42.93% and Li-ion battery lifetimes are increased by 29.93% when compared to traditional Maximum Power Point Tracking (MPPT)-based control.

For PV systems operating in both grid-connected and microgrid applications, FPPT algorithms are essential. PV system performance and reliability are improved by FPPT-based control, which keeps a power reserve and supports grid stability during disruptions. Its use in microgrid systems also helps with effective power resource management, which extends the life of energy storage devices. FPPT algorithms will become more crucial as PV technology develops in order to optimize the advantages of solar energy integration into the power grid.

#### 7.2 Electric Vehicles: Prospects and Obstacles:

The power grid's ability to store energy is significantly impacted by the electrification of transportation. The advancement of shared energy storage technologies, including supercapacitors, fuel cells, and batteries in particular, is being propelled by electric vehicles (EVs). Currently, major automakers are spending a lot of money on R&D to produce batteries that are safer, more durable, more cost-effective, and have more power and energy density. In many cases, grid-connected battery energy storage systems (BESSs) immediately benefit from these improvements. But when it comes to battery supply, EVs and the grid are in competition. As illustrated in Fig. 7.1, the strong demand for electric vehicles has slowed the reduction in the cost of lithium-ion batteries, and cost hikes are possible if the supply of necessary metals cannot keep up with demand.

EVs provide the power grid opportunities in terms of energy storage. EVs can take part in demand-side management as controlled loads, which eliminates the need for extra energy storage devices. More intriguingly, EVs can function as energy storage devices for the power grid using reverse power flow processes; this is referred to as vehicle-to-grid (V2G) technology. Furthermore, utilizing used batteries from EVs, big grid-connected BESSs might be created. To lessen the effects on the environment, however, efficient recycling methods for spent lithium-ion batteries must be put into place soon. This subsection goes into more detail on lithium-ion battery recycling and vehicle-to-grid (V2G) technology.



Figure 7.1 Continuous decrease in lithium-ion battery prices over the last decade

V2G Technology: This much debated subject should greatly improve future power grid stability and performance. Numerous studies describe the state of V2G technology today and its recent developments. The viability and promise of V2G systems are evident, especially in light of the fact that cars are used for merely 5% of the time in the United States on average. Still, there are a number of obstacles to overcome:

EV Battery Degradation: One of the main issues with V2G technology is battery degradation. The expensive expense of replacing worn-out batteries and the decreased customer satisfaction resulting from reduced range and performance are major downsides for electric vehicle batteries, whose performance is vital. Enhancements in battery quality could potentially lessen this problem.

Infrastructure and Cost: There are still a lot of obstacles to overcome in terms of V2G infrastructure and costs. Secure communication lines and bidirectional charging stations are necessary for V2G implementation. Only a small number of EV models, including the Mitsubishi Outlander PHEV, Nissan LEAF, Nissan e-NV200, and Mitsubishi Eclipse Cross PHEV, supported V2G as of 2021.

Li-Ion Battery Recycling: At the moment, virgin materials are used in the production of batteries to the tune of roughly 85%. In light of the growing number of gigafactories and the electrification of national economies, handling these materials presents both considerable financial rewards and obstacles. Refurbishing high-performance, expired batteries for use in less demanding second- and third-life applications before recycling them to extract essential components for new batteries is an effective way to recycle batteries. TES/Green Li-ion (Singapore), Brunp/GEM (China), SMCC Recycling (South Korea), and numerous more firms in the USA, Canada, Australia, and Europe are among the leading companies in

this industry. Through the use of ecologically friendly hydrometallurgical technologies, Singapore hopes to become a hub for the recycling of e-waste (SCARCE).

7.3 Hydrogen–Methane–NH3: Beyond the 100% Renewables:

Chemical energy storage systems (ESS) are a viable option for transportable and long-term energy storage, as shown in Figures 2.1 and 2.2. These systems use electricity to catalyze chemical reactions that result in the production of a variety of chemicals, or Power-to-X (P2X), such as ammonia, methane, and hydrogen. To liberate the energy trapped in their chemical bonds, these substances can be transported or stored and later burned or undergo other reactions. Depending on the chemical produced, different procedures are used for energy creation, storage, distribution, and conversion to electricity.

An increasingly important element in chemical ESSs is hydrogen.

As seen in Fig. 7.2, a typical hydrogen-based ESS consists of fuel cells, hydrogen storage, and electrolyzers. Hydrogen that has been stored can be used as feedstock for industry, transformed into different compounds, transferred as a source of energy, or used in fuel cells to generate power once more.



Figure 7.2 Illustration depicting a grid-connected PV-electrolyzer-fuel-cell system

Purified water is needed for electrolysis to produce hydrogen; seawater that has undergone reverse osmosis treatment is one way to save fresh water. Solid oxide electrolyzers (SOEs), alkaline electrolyzers (AEs), and polymer electrolyte membranes (PEMs) are the three primary electrolyzer technologies now in use. Due to their high operating temperature (500–850 °C) and lack of expensive catalysts, SOEs offer great efficiency; nevertheless, because of their limited long-term durability, PEM and AE are the most widely used commercial techniques.

Electrolysis is a method of producing hydrogen that can be powered by limited renewable energy sources,<br/>dedicated renewable energy sources, or the grid.

As an ESS, hydrogen has the important benefit of being transportable and long-lasting. It can be kept in solid-state storage, compressed, liquefied, or changed into another chemical. Though this amount is debatable, adding up to 15%–20% hydrogen to the gas grid does not raise any safety issues. The storage of hydrogen through liquefaction or compression has certain difficulties because of diffusibility, low density, and safety considerations. The use of high-strength steels in pipeline storage and transportation is restricted due to hydrogen embrittlement. Other energy vectors, such methane or ammonia, can be produced from hydrogen, providing an alternative for storage.

Green hydrogen production is interesting because it has a larger volumetric storage density (108 g/L) than liquid hydrogen (71 g/L). Ammonia can be transported as a hydrogen vector, stored, and utilized as fertilizer or in fuel cells. Nonetheless, there are difficulties due to the energy needed for conversion and the ammonia's greater toxicity. Although it produces CO2 emissions when used, the Sabatier Reaction produces methane, which can be used to store and distribute excess energy utilizing the current gas grid infrastructure.

Power electronic converters are shown in Fig. 7.2 as being essential to the enablement of renewable hydrogen-based ESS. In order to optimize PV power, this arrangement consists of dc–dc and dc–ac converters. DC-DC converters for these applications are still developing, however the majority of grid integration power converters are well-established industrial solutions. The high power requirements of green hydrogen electrolyzer applications call for technological breakthroughs in power electronic components, as demonstrated by a survey of well-known dc–dc power converter topologies.

## 8 CONCLUSION

Energy storage systems (ESS) continue to be critical to the transition as long as our ambitions for energy sustainability depend on intermittent renewable sources. Although grid-connected battery energy storage systems (BESS) are becoming more and more popular, traditional pumped hydro storage (PHS) will probably continue to dominate ESS capacity. BESS is anticipated to play a larger role in future power grids. The battery materials community generally agrees that the best realistic approach to global sustainability is to use a range of energy storage systems (ESS) instead of just one. The best technology will depend on

the particulars of each nation, including its climate, natural resources, and topography. Economies of scale will lower expenses and encourage broader use.

Advanced energy storage technologies are becoming increasingly popular as grid energy storage options. These include lithium-ion, sodium-ion, multivalent ions (such as zinc and aluminum), hydrogen, fuel cells, hybrid supercapacitors, and redox-flow chemistries. The adoption of BESS technology in electric vehicles (EVs), which has led to lower costs and better quality, is contributing to the technology's rapid expansion. The utilization of second-life batteries is increasing due to the broad availability of repurposed EV batteries, which aids in the recovery of initial material costs.

Additionally, improvements in battery chemistry and power electronic converters—which link Battery Energy Systems to the grid—are making BESS technology more competitive. The advancements in modular power electronic topologies and high-power wide bandgap semiconductors are responsible for these gains. Large energy storage will be required to balance seasonal renewable supply and demand in order to reach 100% sustainability, with hydrogen playing a critical role. Technologies that improve the adaptability of generation and consumption can also be an affordable means of lowering dependency on energy storage systems (ESSs).

**Appendix:** Internationally deployed energy storage systems (ESS), arranged by technology and services offered. The featured projects span multiple geographical locations and all ESS technology areas. The table lists the technology vendors involved as well as the expected uses for each installation.

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