Chapter

Energy Storage Systems and Their Role in Smart Grids

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Abstract

Energy storage systems play an essential role in today's production, transmission, and distribution networks. In this chapter, the different types of storage, their advantages and disadvantages will be presented. Then the main roles that energy storage systems will play in the context of smart grids will be described. Some information will be given on interactions between energy storage systems and renewables. The emphasis will be on the problems that these storage systems will have to deal with and the possible means that can be used for this purpose. Also the battery management system will be presented as a general concept. The different types of regulation that take place in smart electrical systems (also called smart grids) and the role of energy storage systems will also be discussed. In the end, we will also present one of the biggest weaknesses of storage systems, among others, the degradation of batteries with their use.

Keywords: electric vehicles (EV), energy storage systems (ESS),
battery energy storage systems (BESS), wind farms (WF), vehicle-to-grid (V2G),
photovoltaic (PV)

1. Introduction

Electrical energy in an alternating current (AC) system cannot be stored electrically. However, there are several methods of its storage by converting AC energy into electromagnetic energy storage systems such as superconducting magnetic energy storage (SMES), electrochemical such as various types of batteries (accumulators), kinetically (flywheels), or even as potential energy (hydropower plants) or as compressed air [compressed air energy storage (CAES)]. The energy storage devices currently available on the market are: battery energy storage systems (BESS), energy capacitor systems (ECS), flywheel energy storage systems (FESS). ESSs in an alternating current (AC) grid cannot store electrical energy directly. **Figure 1** depicts the most important storage technologies for the power grid. Among the devices listed above, the BESS is the most commonly used, but it has drawbacks, such as limited lifetime, current and voltage restrictions, and environmental hazards [1]. As a result of the intensive development of renewable energy sources (RES), the development of electromobility, the need to improve the functioning of the existing power grids, the importance of electricity storage has increased in recent years.

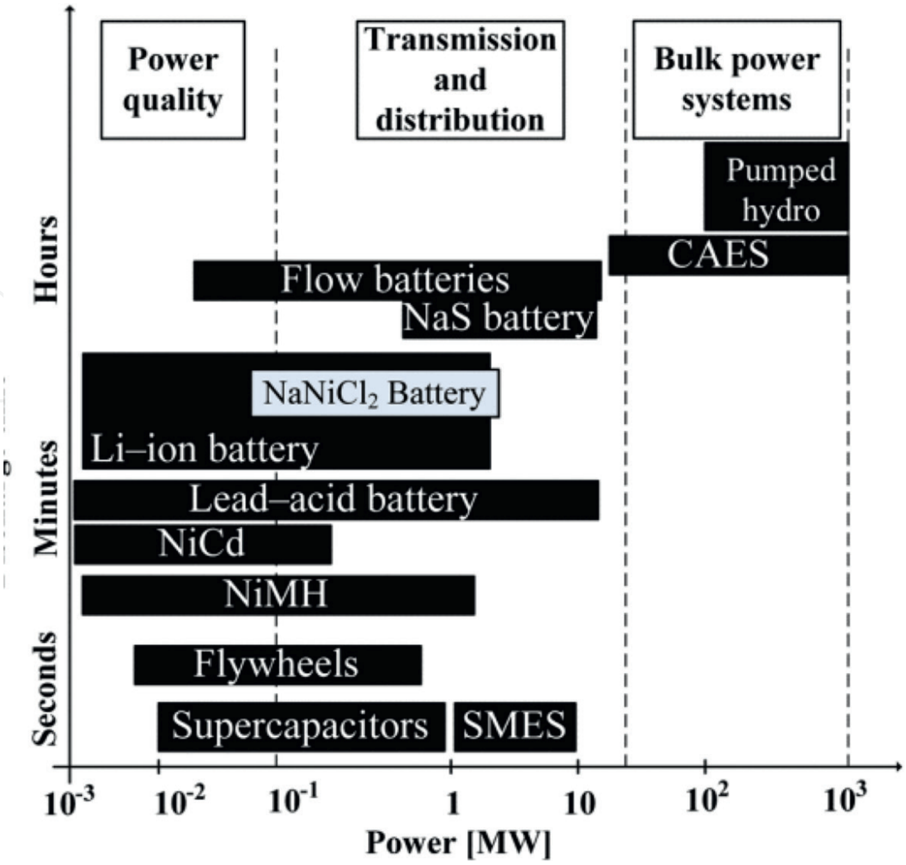

Figure 1.
Storage technologies for the power grid [2].

The superconducting energy storage systems are in the process of moving from their prototype stages to practical applications, which recently also receive special attention for utility applications. The latest technological developments are at such an advanced stage that practically we are now just addressing the performance analyses and the aspect of construction and operating costs. Several articles, among others [3], focus on the performance benefits of adding energy storage to power electronic compensators for utility applications.

Energy storage technologies do not in themselves represent sources of energy. However, they offer significant additional benefits to improve stability, transmission enhancement, power oscillation damping, dynamic voltage stability, tie line control, short-term spinning reserve, load leveling, under-frequency load shedding reduction, circuit break reclosing, subsynchronous resonance damping, power quality improvement, and reliability of supply.

Energy storage systems play a significant role in both distributed power systems and utility power systems. There are many benefits of energy storage systems, including improving the cost-effectivity of the power system and voltage profile. These two features are the most important specifications for storage systems.

Because of the recent development of power electronics, superconductivity, and computer science, the SMES system has received a great attention in the power systems applications. The SMES is notably used in distributed energy storage, spinning reserve, load following, automatic generation control, power quality improvement, reactive power flow control voltage control, and transient stability enhancement [4].

The BESSs have limited lifetime and voltage and current limitations. The FESSs involve other rotating machinery, which is not a preferable, and standby loss is high. Also, the charging method of ECS and its control scheme is not easy.

The fastest-growing power generation technology remains grid-connected solar photovoltaic (PV) power. There was a 70% increase in existing capacity to 13 GW in 2008, while for wind farms, the growth in existing capacity was 29% in 2008 to reach 121 GW, more than double the 48 GW that existed in 2004 [5, 6]. However, like all other renewable energy sources, the main disadvantage of solar and wind energy is their instability. These energy sources depend on natural and meteorological conditions [7]. Great technical challenges related to grid interconnection, power quality, reliability, protection, generation dispatch, and control are to be overcome with higher penetration of intermittent renewable resources [8].

In addition to pumped storage power plants used for years in power systems, other technologies are currently being tested and introduced to enable the storage of electric energy in the form of various energy media.

Electricity storage technologies can be broadly divided into two main categories under the angle of the energy storage form:

- *direct*—it is related to the process of energy storing itself, i.e., how much energy can be stored in a given device. This is a feature of the storage device itself.

- *indirect*—converting energy from electrical to another form (e.g., from electricity to mechanical) determines this. It is also related to the rate at which energy can be transferred to or from the storage device. This conversion mainly depends on the peak power rating of the power conversion unit, but also the response speed of the storage device itself may affect the process.

Type	Energy efficiency (%)	Energy density (Wh/kg)	Power density (W/kg)	Cycle life (cycles)	Self-discharge
Pb-acid	70–80	20–35	25	200–2000	Low
Ni-Cd	60–90	40–60	140–180	500–2000	Low
Ni-MH	50–80	60–80	220	<3000	High
Li-ion	70–85	100–200	360	500–2000	Med
Li-polymer	70	200	250–1000	>1200	Med
NaS	70	120	120	2000	—
VRB	80	25	80–150	>16,000	Negligible
EDLC	95	<50	4000	>50,000	Very high
Pumped hydro	65–80	0.3	—	>20 years	Negligible
CAES	40–50	10–30	—	>20 years	—
Flywheel (steel)	95	5–30	1000	>20,000	Very high
Flywheel (composite)	95	>50	5000	>20,000	Very high

Table 1.
Characteristic parameters of different energy storage technologies.

A detailed overview of various energy storage technologies is presented later in this chapter.

There are several parameters justifying the choice of ESS for an application. One can enumerate the rated power and energy of the application, its response time, its weight, its volume, and its operating temperature. The characteristic parameters of the various energy storage technologies are presented in **Table 1**. These values have been extracted from [9, 10].

2. Different types of energy storage

2.1 Batteries

2.1.1 Lead acid

Lead-acid batteries, commercialized in 1859, are the oldest technology among all batteries that enable the storage of electricity with the use of electrochemical phenomena. Due to its simple structure, the ability to generate high currents, resistance to overcharging, and low price, this technology has become the most common option in DC systems in practically all sectors of the economy. Batteries are used, among others, in automotive starting, lighting and ignition (SLI) and uninterruptible power supplies (UPS), small electric vehicles (e.g., forklifts), or for storing electricity generated in small and medium-sized RES power plants, in the energy and telecommunications sectors.

Due to the maturity of this technology, many new solutions have been developed over the years to optimize the operation of lead-acid batteries, including maintenance-free batteries with liquid electrolyte, with regulated valve (VRLA), with liquid electrolyte absorbed in a separator made of glass mat (AGM), or with gel electrolyte. Despite the design measures that streamline the operation and define new application areas from the point of view of the basic technical parameters, this technology is a technology “leaving” the market. Recent research leads to the conclusion that it is possible to increase power and energy density by replacing lead with lighter materials such as carbon.

2.1.2 Li-ion

Lithium-ion batteries have been used commercially since 1991, primarily to power small electronic devices. In recent years, largely due to the intensive development of electromobility and photovoltaic power plants, the importance of energy storage based on Li-ion cells has increased. Currently, lithium-ion batteries are used both in domestic storage tanks with a capacity of several kilowatt hours and system storage tanks with a capacity of up to several dozen megawatt hours.

Lithium-ion energy storage is characterized by a high voltage of a single battery (usually 3.6 or 3.7 V) and a high energy density. The “power” and “capacity” scaling of the battery tank (as in the case of other battery technologies) consists in combining lithium-ion batteries into series-parallel systems, forming the so-called battery strings.

This type of battery has several advantages; we can list among others the high energy/weight ratios, the absence of memory effect, and the low self-discharge. These batteries find their uses primarily in portable equipment such as laptops, cameras, cell phones, and portable tools. Thanks to its high energy density, Li-ion is also one of the most promising technologies to be used in the power supply of hybrid and rechargeable electric vehicles. However, the start-up costs of the technology remain a fairly significant barrier to its large-scale use.

2.1.3 NiCd/NiMH

The technology of energy storage in nickel-cadmium batteries is known from the beginning of the twentieth century and for many years was the only alternative to lead-acid batteries. Nickel-cadmium batteries are characterized by a short charging time and resistance to ambient temperature fluctuations (from −40°C to +60°C). NiCd batteries were the chemistry of choice for a wide range of high-performance applications between 1970 and 1990. NiCd cells allowed for significant development of portable devices such as radios, camera flashlights, and power tools. The operation of nickel-cadmium batteries is similar to the previously described lithium-ion batteries. In 2006, the Parliament of the European Union approved directives that significantly limit the use of nickel-cadmium batteries. A significant disadvantage of this technology is the occurrence of the so-called memory effect, which causes a decrease in the capacity of the cells during operation. NiCd batteries have also the following disadvantages compared with NiMH batteries: first of all, their life cycle is more expensive. Secondly, in the 1990s, along with the development of lithium-ion and nickel-metal hydride batteries, their role decreased significantly also due to the difficult process of disposal of used batteries, which requires a complex recycling procedure because the batteries contain toxic compounds. This toxicity of Cd, in addition to the lower energy density, and finally the flat discharge curve and negative temperature coefficient could cause thermal runaway during voltage-controlled charging.

For these reasons, nickel metal hydride batteries (NiMH) have gained prominence over NiCd batteries in the recent past. Nickel oxyhydroxide is used by NiMH batteries for the positive electrode and metallic cadmium for the negative electrode. Research on nickel-metal hydride cells began as early as 1967, but initial problems with metal hydride instability led to a greater focus on developing nickel-hydrogen (NiH) technologies. New metal alloys developed in the 1980s allowed for the optimization of NiMH cells and are now widely used as an alternative to disposable alkaline batteries and nickel-cadmium cells, which are characterized by a much lower energy density (about 40% compared with NiMH cells). NiHM batteries have been the chemistry of choice for EV and hybrid EV (HEV) applications due to their relatively high power density, proven safety, good abuse tolerance, and very long life at a partial state of charge.

In the 1990s and 2000s, NiMH was the most popular and mature chemical technology for battery production. Batteries for EVs and hybrid EVs (HEVs) were produced on the basis of NiMH in the 1990s and 2000s. NiMH batteries had relatively high power density, proven safety, good tolerance to abuse, and a very long life at a partial state of charge. The weak point of these batteries was the relatively high self-discharge rate, up to 20% of energy is lost during the first 24 hours after charging, and then 10% during each subsequent month, although the introduction of novel separators has mitigated this problem.

NiMH batteries can also be used in uninterruptible power supply systems (UPS) and in storage tanks cooperating with RES installations. An additional advantage is the possibility of effective recycling and the lack of highly toxic compounds inside the cells, which makes the technology relatively environmentally friendly.

When overcharged, NiMH batteries use excess energy to separate and recombine water. There is then no need to maintain them. However, they should not be charged at such a rate of charge, or cell rupture may occur due to the accumulation of hydrogen. On the other hand, if the battery is overdischarged, the cell may polarize in the opposite direction, which could affect its capacity.

2.1.4 NaS

In sodium-sulfur solid beta alumina, the cathode is made of molten sulfur, the anode is molten sodium, and the electrolyte is a nonporous, solid beta alumina ceramic material (**Figure 2**). As energy is drawn from the energy storage, sodium ions penetrate the solid electrolyte layer toward the cathode, causing the current to flow through the powered circuit. The process is reversed during charging. The battery cells are used to operate in high temperatures (from 300 to 350°C). In 2011–2015, at the University of Kyoto, work was carried out on solutions enabling the operation of sodium sulfur batteries at a much lower temperature of about 100°C, for use in electric vehicles and installations supplying residential buildings.

Due to the possibility of quick entry into operation, high energy density, high efficiency, and long service life, the main area of application of sulfur-sodium batteries is energy storage with very high power and capacity used to optimize the operation of power grids and RES power plants.

2.1.5 FBs

Flow batteries (FBs) production technology is very promising. FBs are produced in such a way that the total energy stored is decoupled from the nominal power. The size of the reactor and the volume of the auxiliary tank are the main elements on which the nominal power and the stored capacity of the battery depend. Thanks to these characteristics, the FB is able to supply large amounts of power and energy required by electric utilities.

One of the most popular FB technologies is the iron-chromium flow batteries (ICBs). This technology was developed in the 1980s by NASA research teams and the Japanese company Mitsui. Thanks to high efficiency of energy exchange (over 80%), easy scaling, and high reliability, ICB cells are a suitable solution for multi-megawatt system energy storage and smaller uninterruptible power supply systems.

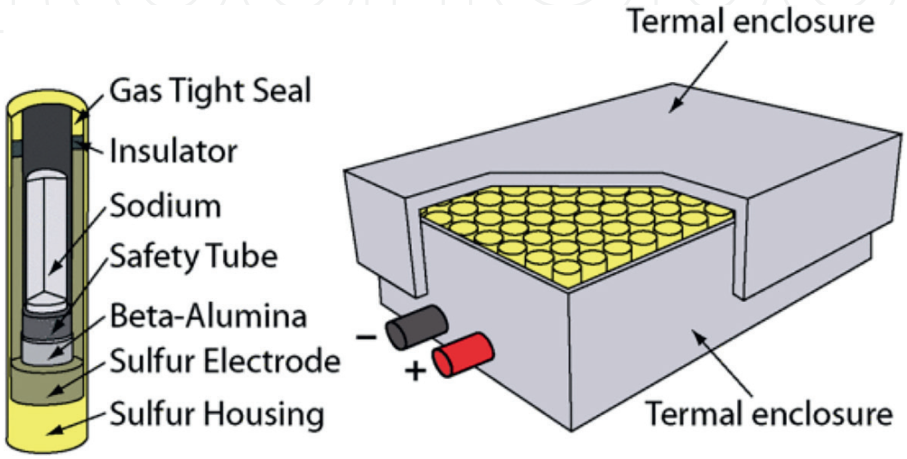

Figure 2.
NaS battery cell and package [11].

ICBs achieve the highest efficiency at relatively high ambient temperatures (in the range from 40°C to 60°C), thanks to which they can be successfully used in regions of hot climatic zones (unlike most electrochemical tanks that require continuous cooling). An additional advantage is the use of common, inexpensive materials—chromium and iron, which are low-toxic, hence safe and environmentally friendly technology.

Energy storage based on ICB cells with a capacity of up to several megawatt hours can be used to secure electricity supplies (e.g., on continental islands or in military bases) and to optimize the operation of RES power plants.

The main disadvantage of ICB cells is the relatively low voltage of a single cell (1.18 V), which results in low energy density and large size of energy reservoirs based on this technology. An additional challenge is posed by the parasitic chemical reactions of chromium with hydrogen, which shorten the life of the cells and cause instability of the liquid electrolyte. It is possible to reduce these phenomena at the expense of lowering the efficiency.

The FB diagram is shown in **Figure 3**. Flow reactants and membrane area define the nominal power, while the total stored energy depends on the capacity of the electrolyte reservoir. It must be remembered that in a conventional battery, the cell itself stores the electrolyte, so there is a strong connection between the power and the nominal energy. A reversible electrochemical reaction takes place in the cell (flow reactor) and produces (or consumes) direct electric current. FB technology is currently used in several large and small-scale demonstration and commercial products.

2.1.6 EDLCs

Supercapacitors, also known as ultracapacitors or electrochemical double-layer capacitors (EDLCs), are characterized by high power density—which translates into short charge and discharge times, high efficiency, and durability. In the case of a supercapacitor, the possibility of quick charging and discharging with high efficiency

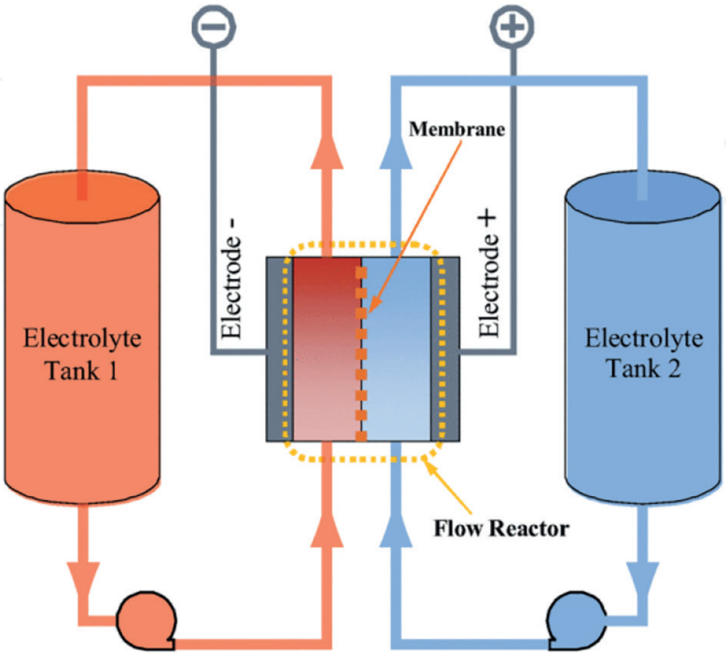

Figure 3.
FB cell.

results from the direct storage of electric energy, because the energy carrier in them is an electric field. Supercapacitors can be used in active filters, improving the quality of electricity, in distribution networks as a tool for energy balancing, and in electric vehicles and trains, popularized, e.g., through Formula 1 racing with KER (kinetic energy recovery systems) systems. There is no faradic process in EDLC, therefore no ionic or electronic transfer results in a chemical reaction. A simple charge separation causes energy to be stored in the electrochemical capacitor.

2.2 Fuel cells

Water and electricity can be produced using FC using electrochemical conversion taking place in special devices that use hydrogen and oxygen. Thanks to the use of FCs, a "hydrogen economy," which is an increasingly popular concept according to which hydrogen is produced by a chemical process, can be ensured. For example, the electrolysis of water, having for objective, among others, the obtaining of hydrogen, which can be used as fuel [12]. Special devices can be used, which combine the function of the FC and the electrolyzer in a single device called regenerative FCs or unitized regenerative FCs. These devices operate as follows: Electricity is produced from hydrogen stored in the form of gaseous fuel, which will later be used for this purpose. FCs are generally optimized to perform only one function, while theoretically they can function as regenerative FCs. By combining the two functions, the size of the system can be reduced for applications requiring both energy storage (hydrogen production) and energy production (electricity production).

2.2.1 Alkaline fuel cells

Alkaline fuel cells (so-called Bacon cells, from the inventor's name—F.T. Bacon) use a liquid alkaline electrolyte (most often potassium hydroxide KOH, which, depending on the type of construction, circulates inside the cell or is contained in an asbestos membrane between the electrodes). An additional advantage of alkaline fuel cells is their resistance to harsh conditions—ambient temperatures below 0°C, high humidity or salt content in the air. AFC cells are currently used primarily as energy sources in uninterruptible power supply systems (UPS), in the own needs of telecommunications and as batteries for electric busses. The disadvantage of AFCs is their low tolerance to carbon monoxide, which reacts undesirably with the electrolyte, making these cells impractical for years.

2.2.2 Phosphoric acid fuel cell

Phosphoric acid fuel cells (PAFCs), developed in the 1960s, were the first commercially produced technology of this type. Since then, PAFC cells have been significantly improved in terms of operational stability, efficiency, and reduction of production costs. In PAFC cells, the electrolyte is gel orthophosphoric acid, placed in a porous layer made of Teflon silicon carbide. The electrodes, on the other hand, are made of porous graphite with an admixture of platinum.

Phosphoric acid fuel cells operate at relatively high temperatures (from 150 to 200°C), which makes them highly resistant to carbon monoxide contamination. Hot water, which is a product of reactions taking place inside the cells, can be used in cogeneration systems for electricity and heat (achieving a high process efficiency of 80%). An additional advantage is their lifetime reaching 40,000 h.

The disadvantage of the PAFC technology is the high corrosivity of the electrolyte, which entails the need to use expensive acid-resistant materials and a relatively low efficiency (30–40%). PAFC cells are used primarily in RES power plants and uninterruptible power systems (e.g., UPS) with installed powers from 50 to 400 kW.

2.2.3 Direct methanol fuel cell

Fuel cells fed directly with methanol are a relatively new solution in the field of electricity storage. The technology was developed by NASA in the 1990s of the last century. DMFC cells use the advantages of methanol as a fuel: high energy density (250–800 Wh/kg), relatively low production costs, and easy transport and storage. This technology is relatively easy to use, because the methanol supplied to the cells can be stored in appropriate tanks located near the bunkers or in replaceable cartridges attached to DMFC cells.

The main area of application of fuel cells directly fed with methanol is loads with relatively low powers, e.g., portable electronic devices or power banks. In recent years, there has been an intensive development of DMFC cells adapted to power small crane vehicles used in large warehouses. Thanks to this, it is possible to shorten the charging time to a few minutes and avoid the costs associated with the installation of battery charging systems for used vehicles.

There are a few other technologies of fuel cell, i.e., Molten Carbonate Fuel Cell, Proton Exchange Membrane Fuel Cell, Solid Oxide Fuel Cell, but their detailed description will be omitted.

2.3 Solar energy and ESS

The annual amount of solar energy received by the earth represents the equivalent of 120,000 TW. Less number of these available solar resources are in a condition to fully replace all nuclear energy and fossil fuels as an energy source [13, 14]. The main obstacles to the further development of solar generation are, among others: the high cost of manufacturing solar cells, dependence on weather conditions, and ultimately, storage and grid connection problem.

Utilities and system operators face some pretty serious challenges due to the integration of significant amounts of solar photovoltaic (PV) generation into the electrical grid. Grid-connected solar photovoltaic units generate and then deliver power to power grids at the distribution level. Installed systems are often designed for one-way power flow from the substation to the customer. The main technical challenges are as follows: transient and steady-state issues due to the widespread adoption of solar generation by customers on the distribution system, voltage variations, sudden weather-induced changes in output, and legacy protection devices designed with power flow in mind [15].

In the case of solar-based electricity generation, weather events such as thunderstorms can have a detrimental effect on solar production—it can range from maximum production to negligible levels in the shortest amount of time. These large-scale weather-related generation fluctuations can be highly correlated within a given geographic area, meaning that the array of solar PV panels on feeder lines downstream of the same substation has the potential to reduce its production considerably in the face of an average meteorological event taking place, for example, on the same day. These disturbances can cause power fluctuations, which can also negatively affect the electrical network in the form of voltage sags if prompt action is not taken to counteract the change in generation. A frequency disturbance can also occur in small electrical systems, resulting from sudden changes in PV generation.

The use of battery energy storage systems (BESS) can provide power quickly in such scenarios to minimize customer interruptions [16] regardless of their location, whether in the center of the substation or distributed along a supply line. Grid-scale BESSs can mitigate the above challenges while improving system reliability and renewable resource economics. This can of course be achieved provided that adequate control schemes are installed.

Regarding the deployment of BESS technologies on the electrical power distribution system, there are two main schools of thought. Centralized storage at the MW level at the distribution station is recommended by a group of scientists. On the other hand, there is a group of people who argue that smaller energy storage systems should be distributed across distribution feeders, networked, and remotely controlled at the substation level.

Each approach has its advantages and disadvantages. Centralized storage has the following advantages in particular—easy access to electrical and Supervisory Control and Data Acquisition (SCADA) equipment of the substation, simplified control schemes, economies of scale on the one hand, and on the other hand because there is already utility-owned land available behind the substation fence. One of the solutions to the problems of deployment of BESS is appropriate sizing and location of the BESS. The ideal sizing and location will depend on the type of site. In the case of large photovoltaic solar installations, preferably a battery system of comparable size connected to the grid is installed in the same substation.

2.3.1 Ramp rate control

One of the main problems with renewable energies is the lack of inertia components. In the case of photovoltaic solar production installations, the inertial components are completely absent. Additionally, the generated power can change very quickly when the sun is obscured by cloud cover. In the case of small electrical systems with high penetration of photovoltaic production, the consequences of this situation could be serious problems of energy supply, since traditional thermal units will have problems compensating for the lack of energy, and hence, maintaining the power balance in the face of rapid changes would be compromised.

As it has been written before, the BESS is used to compensate for the lack of energy in renewable energy installations. In this case where the BESS is coupled to solar power, the BESS must counteract rapid changes in output power to ensure that the installation provides ramp rates deemed acceptable by the system operator. Allowable ramp rates are among the common features of new solar and wind power purchase agreements between utilities and independent power producers. They are usually expressed by the utility in kilowatts per minute (kW/min).

The patent presented in [17] defines the Ramp Rate Control algorithm used in the Xtreme Power - Dynamic Power Resource (XP-DPR) system [18]. This algorithm continuously monitors the actual power output of the solar array and commands the unit to charge or discharge so that the total system power output is within limits set by utility requirements. The operation of an XP-DPR BESS smoothing the volatile power output of a 1 MW solar farm is depicted **Figure 4** [18].

A BESS can be used to discharge when the energy from the solar installation begins to drop in the afternoon. This can be done by charging from the grid at night or from a certain percentage of solar generation during the day. Thanks to this operation,

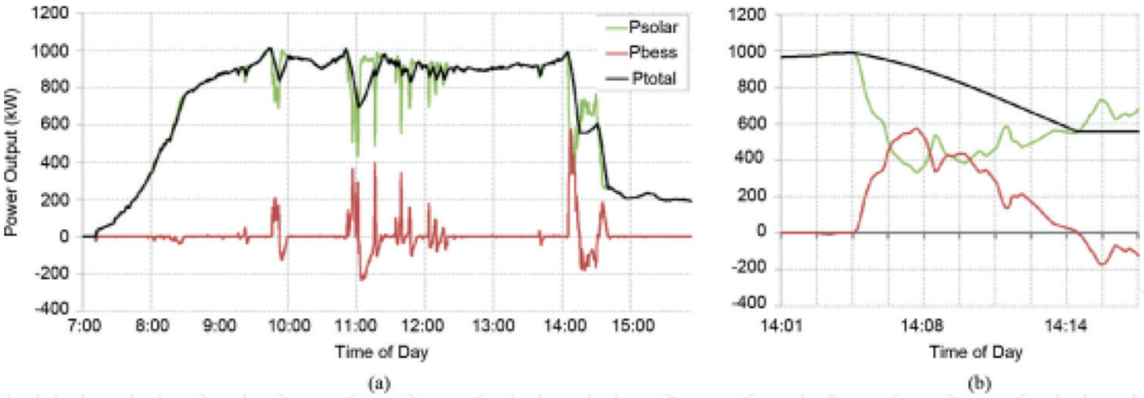

Figure 4.
Ramp rate control to 50 kW/min for a 1 MW photovoltaic installation and a 1.5 MW/1 MWh BESS. (a) Full day. (b) Detail of largest event [18].

the reduction of solar energy at a time when energy is expensive is compensated. This operation is illustrated in **Figure 5** [18].

An excessive part of the electricity produced during the day can be stored in the ESS. On the other hand, during the night, it can be released to complete the energy consumption of a household. Using this method, the total amount of electricity drawn from the power grid can be reduced. Unfortunately, discharging and recharging batteries impact their operational life.

A controller is needed to regulate the charging and discharging process of a battery to protect against overcharging and overdischarging [17]. Despite the use of this controller, some of the energy generated by the PV could still be lost due to the limited energy storage capacity. Apart from this, an inverter must be used to transform the direct current (DC) generated at the PV level into alternating current (AC) to be able to transmit it to the grid. Otherwise, the electrical energy obtained from PV could not be used by household appliances.

In the case of smart grids, it is possible to perform this combination as one of the tasks performed by the main fusion box. Customers choose and register their electricity tariffs in real time, where the price of electricity varies over time [19]. They can also recharge their battery, thereby storing energy in real time from the electricity drawn from the electricity grid, with the aim of reusing it later. The customer can choose the tariff that suits him in order to optimize his bill—for example, by

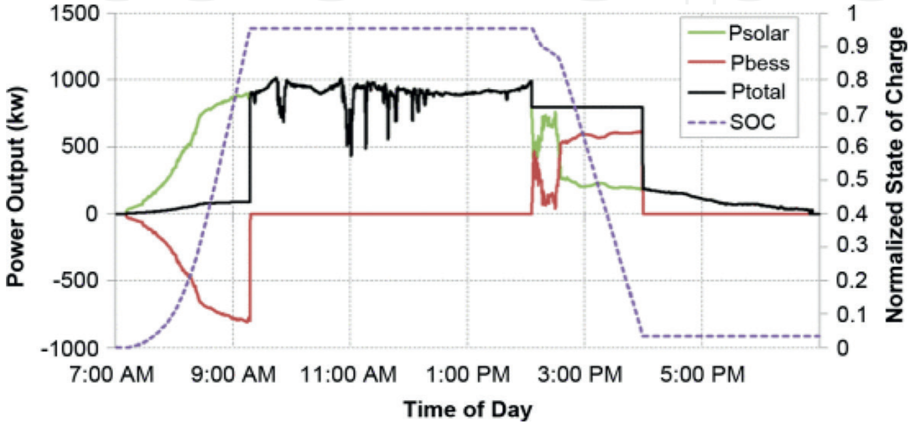

Figure 5.
Full-day output of the solar time-shift application [18].

recharging the battery from the electricity grid when the electricity price is low while discharging it during the period of high electricity prices.

2.3.2 PV and DSM

The scientific literature relevant to energy management in PV-equipped homes mainly focuses on demand-side management (DSM), so how to react to shape the household electrical load during periods of high PV production and to minimize network energy consumption [20].

The local consumption is normally managed in such a way that the ESS battery charge is activated as soon as the PV output power is greater than the electrical load of the house, **Figure 6**. However, this strategy is not able to combat overvoltages that may occur during peak PV production hours (12:00 p.m. to 2:00 p.m.) as the ESS battery is fully charged during the morning hours of sunny days, well before the maximum PV generation period [20].

Figure 6 presents a choice of strategy to be able to move the battery charging period from the "conventional" range to the "proposed" range. This can be achieved by an optimization based on 1-day solar irradiance predictions, described, for example, in [22].

A host of electrical configuration hardware including smart meters, smart sockets, to realize load transfer of different appliances, and main controller to realize load management (i.e., load shift) [23, 24] is used for power management of energy storage systems (ESS) in houses equipped with PV.

2.4 Hydrogen energy storage

The conversion of hydrogen to heat or electricity is fairly easy to accomplish using the popular equation "hydrogen plus air produces electricity and drinking water." Other than that, hydrogen, as the most common chemical element on the planet, is considered an eternal source of energy [14].

In 2004, two institutions, the U.S. National Research Council [25] and the American Physical Society [26], published two comprehensive studies analyzing the technical options concerning the use of hydrogen, including the problem of the cost

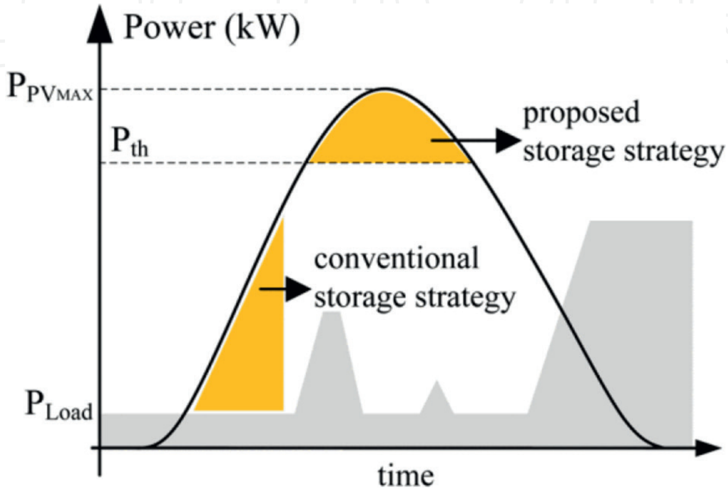

Figure 6.
Conventional storage strategy and proposed strategy compared [21].

of hydrogen obtained from various sources. The only thing missing from these studies is the key question of the overall energy balance of a hydrogen economy.

In fact, there is a whole plethora of processes to be set in motion to obtain hydrogen. We need energy to produce, compress, liquefy, transport, transfer, and store hydrogen. We also lose energy without hope of recovery for its reconversion into electricity with fuel cells [27]. The analysis on the actual energy content in accordance with the law of conservation of energy was analyzed on the basis of the heat of formation or HHV (Higher Heating Value).

2.4.1 How is the hydrogen produced

2.4.1.1 Hydrogen from electrolysis

One of the best-known methods for producing hydrogen is the transformation of water (or rather the dissociation of its molecules) by electrolysis. However, this process is very energy intensive. We envision that in a sustainable energy future, priority will be given to the direct route, i.e., the transformation of renewable electricity into a chemical energy vector. According to [12], the standard water formation potential is 1.48 V, which would correspond to the heat of formation or higher calorific value HHV of hydrogen. The authors [12] also claim that for advanced solid or alkaline polymer electrolyzers, about 0.1 V is lost through biasing, while 0.2 Ω cm^2 is typical for area-specific resistance.

2.4.1.2 Hydrogen generation (PEM electrolyzer) system

The production of hydrogen can be carried out in an efficient manner using the electrolysis of water using polymer electrolyte membrane (PEM) cells. This means of obtaining hydrogen is quite simple to implement. PEM electrolyzers are compact and the current capacity is higher.

The following four auxiliaries are used in the dynamic model of a PEM electrolyzer [28]: the anode, the cathode, the membrane, and the voltage auxiliary (**Figure** 7).

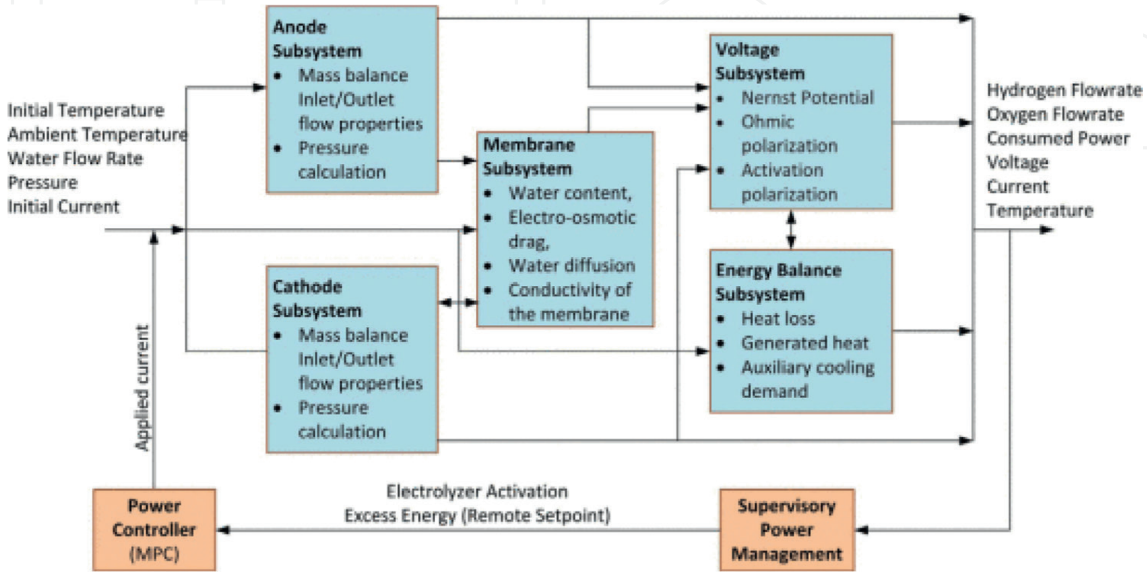

Figure 7.
Electrolyzer modeling block diagram [28].

The flow rates of oxygen and water and their partial pressures are calculated at the auxiliary anode calculated. The calculation of the partial pressures of hydrogen and water as well as their flow rates is carried out by the cathodic system. Water content, electro-osmotic drag, water diffusion, and membrane conductivity are calculated by the membrane auxiliary. The voltage auxiliary calculates the voltage of the electrolyzer by incorporating the Nernst equation, the ohmic bias, and the activation bias.

2.4.1.3 Hydrogen consumption (fuel cell) system

The PEM fuel cell is the inverse equivalent of a PEM electrolyzer. It is modeled similarly to the PEM electrolyzer described in the previous section. A chemical reaction with oxygen is carried out in order to obtain the chemical energy of the hydrogen fuel, which will then be converted into electricity.

Water and heat are the by-products of this reaction. The authors [29] developed the dynamic fuel cell model shown here. This model is made up of four main auxiliaries: the anode, the cathode, the membrane, and the voltage (**Figure 8**).

2.4.1.4 Hydrogen from biomass

It is also possible to produce hydrogen from biomass. However, it seems that this option does not really have a future because, first of all, the process is quite complex: Biomass must be converted into biomethane by aerobic fermentation or gasification before it can produce hydrogen. And secondly, we know, however, that natural-gas-grade biomethane (more than 96% CH4) is already a perfect fuel for transport and stationary applications. Why turn it into hydrogen? There is already a biomethane supply system from waste water digesters in many European countries, the finished

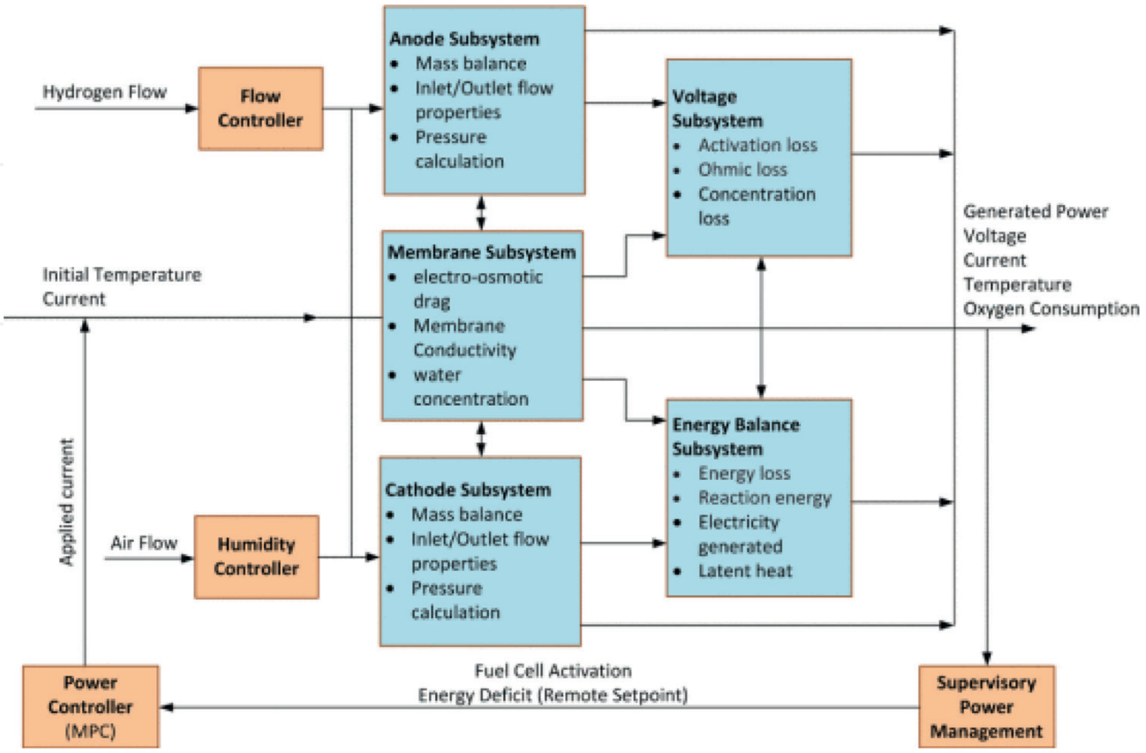

Figure 8.
Full cell modeling block diagram [29].

product of which is already being sold at petrol (fueling) stations to an increasing number of satisfied drivers.

The high energy losses may be tolerated for some niche markets, but it is unlikely that hydrogen will ever become an important energy carrier in a sustainable energy economy built on renewable sources and efficiency.

Moreover, the delivered hydrogen must be converted to a motion for all transport applications. IC engines convert hydrogen within 45% efficiency directly into mechanical motion, while equally efficient fuel cells systems produce DC electricity for traction motors. Further losses may occur in transmissions, etc. All in all, hardly 50% of the hydrogen energy contained in a vehicle tank is converted to motion of a car. The overall efficiency between electricity from renewable sources and wheel motion is only 20–25%.

2.4.2 Hydrogen transformation: fuel-cell-powered vehicles

The most efficient way to use a fuel, in particular hydrogen, in a vehicle is to convert the fuel's energy directly into electricity in a fuel cell. The hybrid design consists of realizing a corresponding illustrated drive train in which the charge of the fuel cell can be leveled using a small battery or an ultracapacitor, much like in a hybrid vehicle with a maintenance electric motor dump. The energy in the battery in question is much smaller than the energy stored in hydrogen. For example, if we store 3 kg of hydrogen, it would be equivalent to three gallons of gasoline or about 100 kWh. This would correspond to more energy than that in the battery of a passenger car.

2.4.2.1 Hydrogen production in micro fuel cell applications

The successful commercialization of miniature fuel cells presents a huge constraint as an alternative to conventional rechargeable batteries for supplying electricity to portable electronic devices such as laptops and mobile phones.

Unfortunately, serious difficulties and significant risks are linked to the storage and handling of hydrogen, whether in the form of compressed gas or liquid, which is used as fuel [30]. Furthermore, compared with storage in the form of liquid hydrocarbons such as methanol, the stored density of hydrogen in compressed or liquid form is significantly lower. This hydrogen can later be reformed to generate the gas when needed. Other methods of hydrogen storage such as in the form of metal hydrides [31, 32] have been discussed extensively in the literature.

There are, however, a number of disadvantages of using hydrides to store hydrogen. These include loss of hydrogen storage capacity after repeated use (limited service life of the alloy), higher weight per unit amount of hydrogen stored (hydrides have the weight of the added metal to the total weight of the storage tank), and the difficulty in extracting all the stored hydrogen due to hysteresis.

2.4.3 Microgrid and hydrogen-based ESS

Most of the projects launched related to wind/solar hydrogen power plant systems [34, 35] and whose results are presented in various scientific articles show the need to introduce greater optimization of the operation of the electrical energy production facility. Although autonomous operation is achieved, several articles report technical problems during operation and serious shortcomings such as electrolyzer breakdowns, high inefficiency in the hydrogen loop, loss of fuel cell performance, breakdowns of pump, etc. It was therefore concluded that the technical problems related to the design and operation of power plants are not yet fully resolved and that an in-depth study is recommended to achieve more reliable operation.

It is also necessary to take into account the fairly complex management of energy production in microgrids (MGs). Energy management in MG is a big challenge to face due to the need to integrate generation, storage systems, and different types of loads, while controlling while the demand is satisfied [36].

In general, two timescales are taken into consideration for MG energy management, as shown in [37]:

- MS energy is analyzed in the long term: this analysis includes generation and load forecasts, maintenance intervals, disconnection of controllable loads and provision of reserve power capacity.

- The authors conducted a short-term energy management of the MG: this analysis takes into account the distribution of energy in real time between the sources and the internal loads.

The process of management of energy production in microgrids is shown in **Figure 9**. The ON-OFF switching thresholds for the electrolyzer and the fuel cell are indicated there. In addition, a protection system against overcharging (high state of charge (SOC)) or undercharging (low SOC) is incorporated into the battery bank.

2.4.4 Control of a grid-connected hybrid system integrating RE, hydrogen, and batteries

There are two uncontrollable but equally essential parameters for the production of RES. These are solar irradiance and wind speed. Therefore, a supporting power source is needed to increase the degree of controllability and operability of the HRES. In almost all solutions for the production and control of renewable energy sources, DC/DC power converters are used to connect them to a central DC bus. In order to coordinate energy use in microgrids, different optimization methods can be used. The use of the supervisory control system based on ANFIS is presented and demonstrated in [38] in order to manage the power of the microgrid.

An example of a grid-connected hybrid system is shown in **Figure 10**. The system is composed of WT and PV panels (renewable and primary energy sources) and a hydrogen subsystem and a battery (SSE).

A three-phase inverter is used to connect the whole system to the grid. Primary renewable sources are generated whenever there is wind or solar radiation. As far as

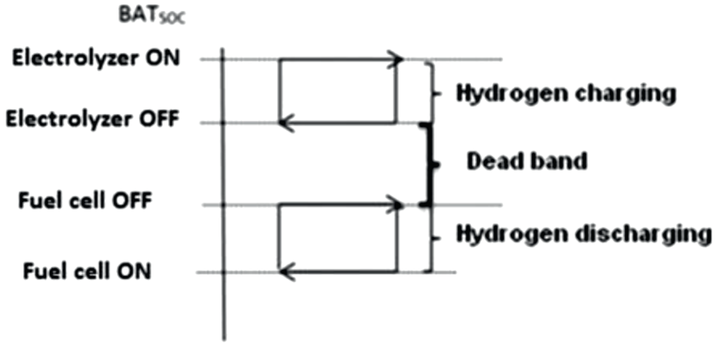

Figure 9.
Scheme of energy management control strategy [33].

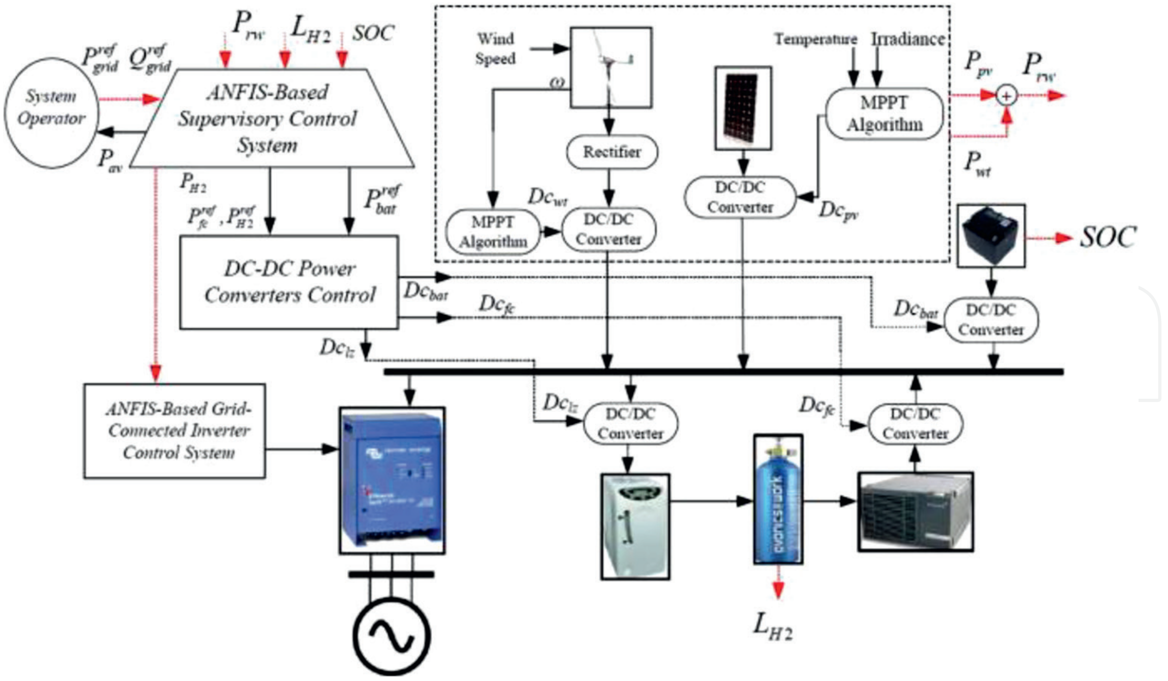

Figure 10.
Grid-connected hybrid system under study [38].

possible, renewable energy is stored in the battery and/or in the form of hydrogen using the electrolyzer. This stored energy will be retrieved at the appropriate time to support renewable generation when needed.

The supervisory control system shown in **Figure 11** is used to determine the power generated by/stored in the hydrogen and the battery. The energy management is carried out taking into account the power requested by the grid, the available power, the level of the hydrogen tank, and the SOC of the battery.

2.5 CAES

In a compressed air energy storage facility (CAES), the surplus energy is used to compress the air for later use. The compressed air is then stored in a cavern as

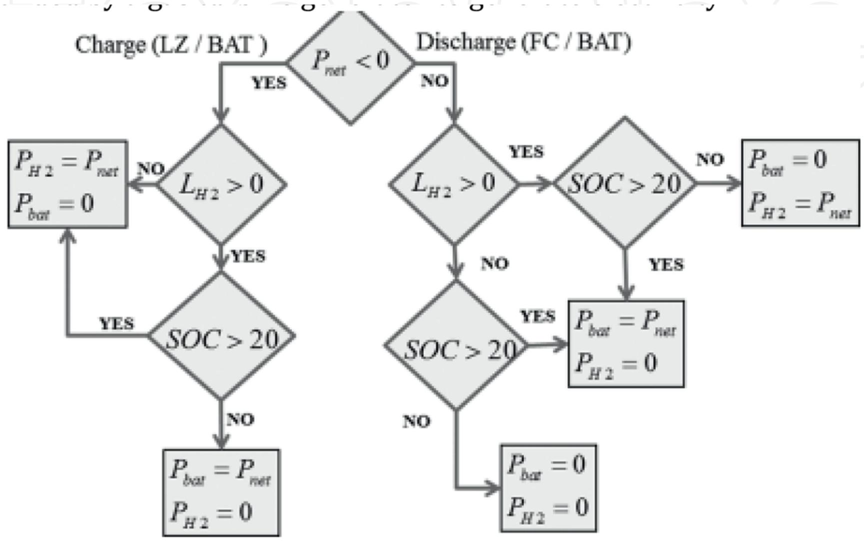

Figure 11.
Scheme of the supervisory control system based on states [38].

potential energy. During the energy demand period, it is expanded back in the turbine. As the energy demand increases, the compressed air is heated and expanded by a gas turbine generator to generate electricity.

CAES replaces the compression ratio of air in the turbine, eliminating the use of fuel gas to compress air. Compression and expansion of air are respectively exothermic and endothermic processes, which in fact makes the design of the system quite complicated. With this in mind, three types of systems are considered to manage heat exchange:

1. Isothermal storage—the air is compressed slowly, allowing the temperature to equalize with the environment [39]. In systems where power density is not critical, such a system is more than enough.

2. Adiabatic systems—in such systems, the heat released is stored during compression and then fed back into the system when air is released. The design of the system is complicated because it requires a heat storage device.

3. Diabatic storage systems—external power sources are used to heat or cool air to maintain a constant system temperature. Most commercially implemented systems are of this type due to the high power density and great flexibility of the system, but at the expense of cost and efficiency.

Many applications are planned for CAES. Among other things, we can cite the use of CAES as a support for the electrical network for load leveling applications [40–42]. In this type of application, energy is stored during periods of low demand and then converted back into electricity when the demand for electricity is high. Natural caverns are used as air reservoirs in commercial systems.

2.6 Flywheel

Flywheel ESS (FESS) is a system for storing energy in a rotating mass, [43].

Flywheel systems are capable of delivering very high peak power. In fact, given recent advances in power electronics and engineering materials, only the power converter is able to limit the input/output peak power. The number of charge-discharge cycles of the FESS is practically infinite. Their power and energy density are very high. Thanks to these characteristics, FESSs are generally used in transmission and power quality applications that require a large number of charge-discharge cycles [44, 45]. This solution is used in particular in synchronous generators to stabilize the output voltage. Lately this technology has become increasingly attractive for a number of other applications such as transmission and improving power quality. FESSs also allow for relatively simple state monitoring, as "state of charge" is a function of easily measurable parameters such as flywheel inertia and speed [46].

The flywheel's maximum rotational speed is the key factor that determines the technology used to build each component. The FESS is classified as low- or high-throughput FESS depending on this speed. The boundary between the two systems is around 10,000 rpm. Not only the material, geometry, and length of the flywheel, but also the type of electric machine and the type of bearing are determined by the rotational speed of the flywheel [40, 47]. High-speed systems are more complex due to technological requirements. However, since the total energy stored in the flywheel depends on the square of the rotational speed, high-speed flywheels provide a higher energy density. Other design considerations such as system performance, security, and reliability are also taken into account [41, 42, 48].

3. Battery management systems

Energy storage systems should intervene in situations where the variation in demand must be taken into consideration. Applications that could benefit from energy storage within the power grid have a wide range of requirements.

There are isolated regions where seasonal energy storage is needed. Megawatt-hours of capacity is stored for months at a time [49]. On the other hand, the stabilization of transport and distribution networks requires that energy can only be stored for a few minutes before being returned to the network or locally. At these precise moments, we are obliged to have energy capacities on the watt-hour scale [50]. Many different forms of energy storage have been developed to operate on all of these time and energy scales. It is also necessary to have an effective management system to maintain safe operation and optimal performance due to the high demands placed on these energy storage systems.

In order to overcome all the different requirements, not only regarding the reaction time of the BESS, a battery management system (BMS) is used to monitor and maintain safe and optimal operation of each battery pack. Additionally, a Supervisory Control System (SSC) must be installed to monitor the entire system.

During their normal operating period, the batteries are permanently in a charge/discharge cycle, therefore in a permanent state of nonequilibrium. Moreover, the situation worsens for the case of storage systems based on intercalation (e.g., Li chemistry), making it difficult to properly monitor battery status and maintain safe operation.

Batteries in a BESS will degrade during cycling, even during normal operation. In extreme load periods, this degradation can even accelerate, especially with the increase in temperature (both ambient and operating). The main role of the basic BMS is to control the batteries only to meet the power demand.

It is possible to reduce the causes of battery degradation and improve system performance by using BMS based on smarter models. There are predictive and adaptive models of BMS, which are particularly useful for large battery packs used in applications such as electric vehicles and grid integration [51–53].

Figure 12 depicts a general BESS-BMS structure for implementing a particular solution used to solve the complex problem of BESS control [54]. The BMS can accurately estimate many internal variables that allow it to gain an in-depth understanding of the battery's state of charge (SOC) and state of health (SOH). This task is carried out using physics-based models.

The tasks for which the BMS is responsible are: operational safety (thermal management, operation between safety current and voltage limits, shutdown on fault detection, etc.), state estimation (determination of the SOC), the estimation of the parameters (determination of the SOH), the remaining time (tr) (according to the load profile applied), and other miscellaneous functions.

For BESSs with Li-ion batteries and other closed-cell systems, the BMS must also perform inter-cell load balancing. For RFBs (redox flow batteries), the BMS must control electrolyte flow based on power demand. Many battery packs with individual BMS will be combined to create a large capacity BESS in large systems. Battery information is transmitted from the BMS to the SSC, which is the interface between the network and the BMS.

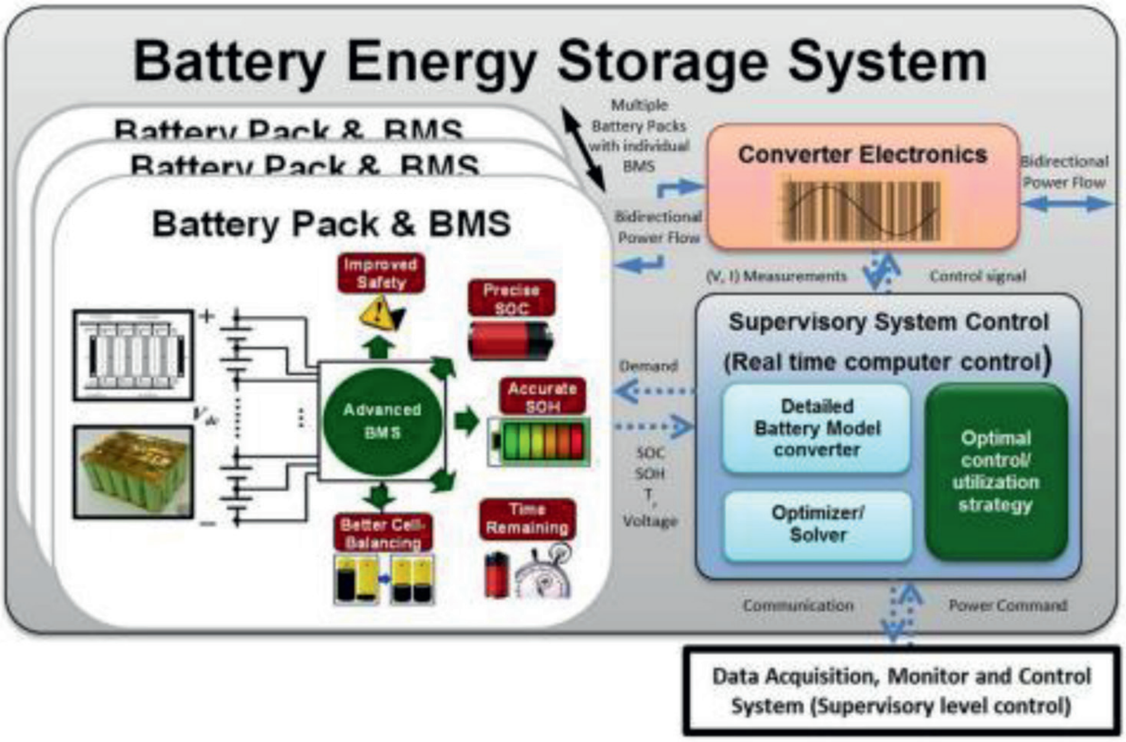

Figure 12.
Schematic for the implementation of a battery pack and BMS into a BESS [54].

The intervention of the BSSs proceeds in the following way—when the grid needs energy from the batteries to supply the load, the SSC chooses the optimal protocol to release the load from a pack (or battery packs) by taking into account both the current state of the batteries and the demand of the network. In order to meet the final power demand, this SSC protocol will call for power to individual packs.

There are times when the required battery power profiles will be more flexible and the BESS may have more control over the charging pattern. For example, the discharge power is severely limited in a peak-shaving application, while the charge power can be chosen according to the needs of the BESS. Here, the best load profiles can be determined by running routines on individual BMSs. The determined load profiles are then transmitted to the SSCs, which then take over the control of the input power of the network.

3.1 BMS architecture

To implement advanced BMS in a grid-scale application requires advanced architecture and a mix of power electronics to connect the battery and BMS within the larger grid. In addition, detailed modeling is extremely useful to predict SOC and SOH as accurately as possible. To manage in real time the nonlinearity, the constraints and the objectives of the model have to be considered. The BMS must be very efficient thanks to the implementation of appropriate algorithms. The implementation of BMS must be done in such a way that an architecture including monitoring and control is realized at several levels [55].

A typical grid storage (GSS) solution consists of a direct current (DC) system, a power conversion system (PCS), a BMS, an SSC, and a grid connection. The DC system is composed of individual cells, which are first assembled into modules, then

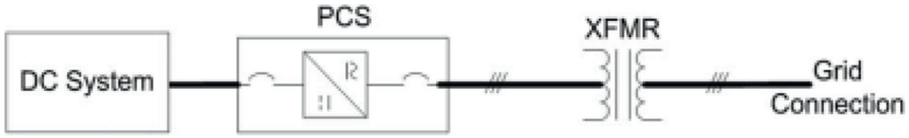

Figure 13.
Simplified illustration of GSS architecture, with a battery-based DC system, a power conversion system (PCS), and a grid connection [54].

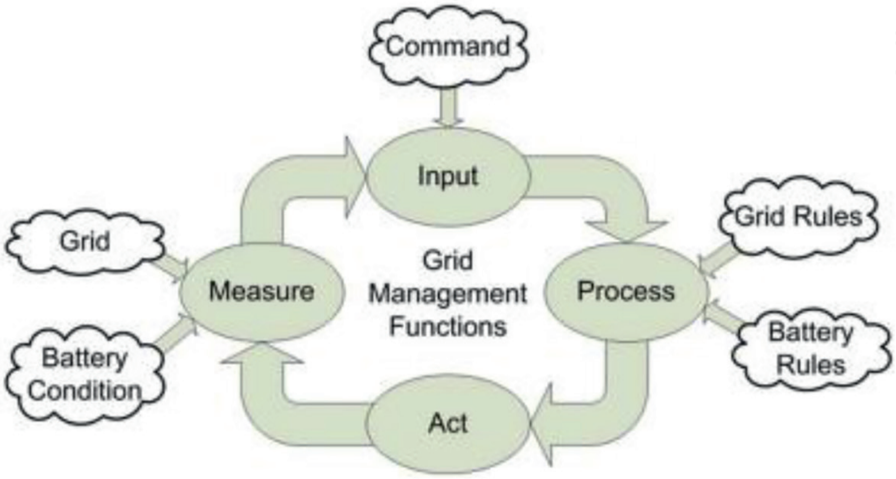

Figure 14.
Conceptual illustration of BMS control cycle [54].

assembled into systems of sufficient capacity to support GSS application requirements. The cells are connected in different electrical configurations in series and in parallel to power a high-voltage bus, which interfaces with the PCS. The PCS is a four-quadrant DC/AC converter connecting the DC system to the grid via a transformer. An illustration of this architecture is shown in **Figure 13**.

Several independent GSSs composed of DC subsystems, PCS, and transformer combinations, called power blocks, can be used in the composition of the system (**Figure 14**). The power supplies can be composed of effectively identical elements, they can also comprise hybrid battery units of different sizes or types. A dedicated BMS manages and controls the operation of the individual power blocks. The SSC on the other hand manages and coordinates the operation of all the power blocks, it also manages the total power of the system and the allocation of this power between the power blocks.

4. Energy storage systems and power grid regulation

As indicated before, high penetration of intermittent renewable resources can introduce technical challenges including grid interconnection, power quality, reliability, protection, generation dispatch, and control. Therefore, the industry will need to confront the challenges associated with higher levels of penetration.

Several articles include a simple diagram for charging and discharging the Battery Energy Storage System (BESS) in order to upgrade the intermittency of renewable energy production. To some extent, this involves storing excess energy when solar/wind power generation exceeds a threshold and offloading it to the grid when load demand is high [56, 57].

4.1 Using ESS for dispatching wind generation

In general, wind energy is considered difficult to control and therefore until now considered non-dispatchable. In conventional grid capacity calculation processes, wind energy is in most cases excluded. One of the suggested ways to overcome this drawback is the use of energy storage systems (see, e.g., [58]). An energy storage system (ESS) can play different roles in the power system—either it can be used to manage energy itself, or it can also be used for energy quality improvement [59].

The combination of energy storage and wind generation improves the availability of wind energy, which can be installed in the grid without worrying about the voltage stability of the system. This allows also to increase the capacity of the existing network infrastructure. Other additional benefits are lower system losses and improved power factor.

For example, the output power of a wind farm can generally be "smoothed" using the ESS, in order to improve the quality of the energy obtained, on the other hand insists on the energy management aspect, which for them is the main objective. In [60], the authors first presented an "*optimization design to determine the most appropriate capacity of the BESS, based on long-term wind speed statistics and maximizing service lifetime/ BESS unit cost*." This is on contrast with what is proposed in [61] where a method for determining the power output schedule of the wind farm, using short-term wind power forecasts, was developed.

Researchers have been taking advantage of the flexible charging/discharging ability of battery energy storage system (BESS) in the design of scheduling schemes for wind farms. In [61], a control strategy for optimal use of the BESS for smoothing out the intermittent power from the wind farm is developed. The simulations the authors have carried out showed that using an actual wind farm data and a realistic BESS model, the desired dispatch set points reasonably close while keeping SOC of BESS within desired limits. The main disadvantage of this method is that it does not allow longer-term power dispatch commitment usually required from generators.

The role assumed by the ESS in wind power trading is another active topic of research (see, e.g., [62]). In some countries, renewable energy plant owners benefit from priority grid supply, where the grid operator has to take control of the energy and pay a fixed return for the energy produced. The article [62] shows how a well-designed ESS can bring additional economic benefits in a project related to energy production. Indeed, if the production of wind energy can be planned in a similar way to the management of energy production from a conventional power plant, the place of wind energy in the power industry will definitely improve significantly, because then one can think about the possibility of dispatching this energy in the power system.

The controllability of power from a wind power generating station by means of BESS is proposed in [63]. This is achieved thanks to two BESSs, one of which is charged using wind power, while the other sends its power into the network. Using statistical wind speed data, the charging characteristics of the BESS are studied and a method to determine the expected charging time of the BESS to reach the stipulated battery state of charge is developed.

A review of design and control of PV and/or wind and/or diesel hybrid systems with energy storage in batteries is presented in [64]. One of the storage technologies to be considered in the future is hybrid hydrogen systems. A particular problem for the installation of this kind of system is the cost of the technologies. Assuming that these costs will decrease over time and investments, the model developed was simulated with prospective costs for the year 2010. The authors of [65] came to the conclusion that the storage system will emerge as the optimal solution, and therefore it is possible to work on a sample of exploitation schemes of a network dominated by renewable energies.

4.2 Use of optimization in designing ESS

As it was written before, one of the main challenges of power generation from wind turbines is the high variability of the wind, which causes the power generation to be intermittent. It is therefore urgent to work on a control system to load/unload the BESS via a converter so that the production of the wind farm can be stabilized and therefore distributed on an hourly basis while taking into account, among others, the SOC and deep discharge limits of the BESS.

This type of problem, whose constraints are more or less difficult to fulfill, can be formulated as an optimal control problem. It is necessary to construct an objective function whose goal is to minimize the deviations between the wind power and the time distribution set points using the BESS. The constraints in question are mainly the constraints on the SOC and the discharge current of the battery, the value margins of which must be fulfilled at all times.

Optimal control, as its name suggests, considers the problem to be solved in such a way as to find a control law for a given system such that a certain criterion of optimality is reached. A control problem includes a cost functional, which is a function of the state and control variables. An optimal control is a set of differential equations describing the trajectories that control variables must follow in order to minimize the cost functional.

Optimal control problems are of different types that can be classified according to (i) the performance index (PI), (ii) the type of time domain (continuous and discrete), (iii) the presence of different types of constraints, and (iv) variables free to be chosen. The optimal control problem can be formulated by considering the following [66]:

1. a mathematical model of the system to be controlled;

2. a specification of the PI;

3. a specification of all boundary conditions on states, and constraints to be satisfied by states and controls.

In [67], an adaptive artificial neural network (ANN)-controlled SMES is presented for enhancing the transient stability of fixed-speed wind farms connected to a multimachine power system. The control scheme of SMES depends on a sinusoidal pulse width modulation (PWM), voltage source converter (VSC), and DC-DC converter using insulated gate bipolar transistors (IGBTs). An adaptive ANN controller is introduced as the control methodology of DC-DC converter. The effectiveness of the proposed adaptive ANN-controlled SMES is then compared with that of an optimally tuned proportional-integral (PI)-controlled SMES by the response surface methodology and genetic algorithm (RSM-GA) considering both of symmetrical and unsymmetrical faults.

The authors [68] presented a new convex optimization and control method to enhance the value of the lithium-ion-based energy storage system. A novel quadratic objective convex optimization problem, aimed at obtaining an optimal schedule for the BESS, has been elaborated on the basis of technical and economic variables. The objectives of the optimization process, according to authors [68] are: (i) obtaining significantly reduced substation transformer losses, (ii) savings on the cost of energy delivered from the grid, (iii) reducing the life cycle cost of the battery storage system, and finally, (iv) taking into account the variability of the distributed generation resources.

A new method for assessing the role of both WF and ESS is shown in [69]. The main contributions of [69] consist of proposing integrated day-ahead bidding and real-time operation strategies for wind-storage systems (abbreviated WF-ESS) as a price taker. Both the WF and ESS are considered as active actors in the energy market, and their failure to comply with the terms of the contract may result in appropriate penalties. The cooperative strategy is that ESS sets charging or discharging reserve capacities at each time interval up to which the ESS can compensate for potential imbalances from the WF. Coordinating the roles of ESS and WF is to fix the charge or discharge reserve capacity at each time interval to compensate for potential imbalances in WF power production.

4.3 Simulations in wind-storage system studies

Wind systems must be analyzed in a complex way to properly model the phenomena that take place there. Offline electromagnetic transient programs are used, among other things. As a general rule, detailed models take too long when studying slow phenomena, such as the impacts of wind fluctuations on the voltage and frequency of the system, so we tend to build more simplified models, which do not have much impact on the veracity of the results obtained, but on the other hand allow rapid simulations of slow phenomena. However, there may be situations where the loss of detail of specific components in a model can lead to inaccuracy in the simulation, which in turn has significant effects on system design and control testing.

The best way to carry out studies of the ESS system integrated into the wind farm is to do real-time simulations for the following reasons [70]:

1. The wind direction is stochastic. Repetitive simulations of a large number of wind profiles using a large database are sometimes necessary.

2. The nonlinearity present in the characteristics of the equipment as well as the performances of storage of the battery very dependent on the preceding operating conditions makes that the created models are very complex.

3. The WTG and ESS interfaces are modeled considering the detailed Insulated Gate Bipolar Transistor (IGBT) switching bridges. It is also necessary to reproduce as accurately as possible the currents to determine the nominal power and the losses of the SSE when studying the sizing compromises of the total and individual storage elements (the supercapacitor and the battery) under economic, loss and efficiency, and operational constraints.

4. Hardware-in-the-Loop (HIL) tests shall be conducted to verify the prototype ESS controller under various normal and fault conditions.

4.4 ESS and V2G

According to the latest trend resulting from advances in analyzing the impact of human behavior from the perspective of environmental friendliness, electric vehicles can to a certain extent be considered environmentally friendly and can significantly reduce fuel consumption of gasoline. It is predicted that they will dominate the future of the automotive industry.

One of the hottest technologies right now is vehicle-to-grid (V2G) technology that allows electric vehicles to act as distributed energy storages that transfer energy back to the main grid when needed. V2G power flow is achieved by local aggregator through communication between grid and consumers/prosumers. Complete information on power exchange is sent directly from the smart meter to the data centers. The main advantages of V2G include: (a) active support of the network, (b) support of reactive power, (c) control power factor, and (d) support for the integration of RES [71–73]. This effectively achieves load flattening, peak shaving, and frequency regulation throughout a day [74]. Moreover, EVs can even be used to transport energy from remote renewable sources to loads in urgent need of power supply [75]. These services can be obtained by charging the EV during periods of inactivity and add extra EV energy in the electricity grid in peak hours. Apart from supporting the provision of effective power, bidirectional V2G has capability of providing reactive power to ensure the voltage regulation.

On the other hand, there is in inverse operation called G2V, during which the power flows from the generator to the vehicle (G2V) to charge the battery and power flow in opposite to provide peak shaving or concept of "spinning reserve." The power flow can be in any of two modes of operation, namely: (a) unidirectional and (b) bidirectional.

4.5 ESS and ancillary services

V2G electric power capacity can be substantial with attractive ancillary services revenue opportunities. The batteries can act as a source of stored energy to provide a number of grid services. The most promising market for these vehicles is probably that of the ancillary services [76]. Possible services for V2G are: supply of peak power, supply of primary, secondary and tertiary control (for frequency regulation and balancing), load leveling, and voltage regulation. It is unlikely that each vehicle will be contracted separately because the maximum power output of each vehicle is too low. But a fleet manager or aggregator could conclude a contract for a fleet of PHEVs. The advantage of dealing with an aggregator or fleet manager is that a single party represents a more significant amount of power, that is, the accumulated power of the vehicles in the fleet. Moreover, the availability profile of a larger group of vehicles is much smoother. A single vehicle owner could conclude a contract with the aggregator without being concerned about the interface with the electricity markets.

4.5.1 Frequency regulation

The network frequency is one of the most important parameters for evaluating the quality of energy. Frequency regulation is the measure of adjusting the frequency of the system to the nominal value by providing small injections of power (positive or negative) into the network. Many organisms, also called transmission network actors, are responsible for frequency regulation. Examples include Regional Transmission Operators (RTOs) as well as Independent System Operators (ISOs) who simply refer to this service as "regulation."

The theory of frequency control is presented in detail in many books and papers [77–81]. The balance between production and demand between control areas is measured in terms of area control error (ACE). Each control zone generates automatic generation control (AGC) signals based on its ACE values, and the regulation resources respond to the AGC signals to perform the regulation. A complex telemetry system performs this operation in real time and is controlled by the grid operator.

As it was indicated previously, the frequency of the network one of the parameters makes it possible to evaluate the quality of energy. So it is essential to keep the frequency at appropriate levels, i.e., between 49.99 and 50.01 Hz according to the ENTSO-E, the former UCTE [82]. The second equally important parameter is the voltage. Network management consists, among other things, of providing power reserves to maintain frequency and voltage, thus facilitating effective management of imbalances or congestion.

The frequency regulation is carried out at several levels of control: primary, secondary, and tertiary control. Primary Frequency Control (PFC) kicks in during the first few seconds when the system frequency exceeds (or drops under) a pre-established dead band and quickly rebalances the generated and consumed power. In the case of the European power system, the primary reserves regulate the frequency and stabilize the European network to avoid breakdowns. Frequency control is automatically and continuously activated. Primary control can only be activated if primary reserves are available.

Primary regulation is the most demanding in terms of response time and therefore is also the most expensive. This is because PFC has traditionally been provided by thermal generators, which are designed to deliver bulk energy, but not to provide fast-acting reserves. One of the alternative or complementary solutions to the participation of thermal generators in the PFC is the active participation of the loads, which is also considered as a fast and profitable alternative. Nevertheless, a reduction in the load can limit the supply of PFC on the load side because in this case it would prove that the intervention of the load would no longer be very useful.

To complement the generation-side PFC, load-side PFC has been considered as a fast-responding and cost-effective alternative [83–89]. Nonetheless, the provision of load-side PFC is constrained by end-use disutility caused by load curtailment.

In order to balance the network, the secondary reserves are allocated the day before and are adjusted automatically and continuously. The set point is calculated upward and downward on a defined time base (i.e.,15 min) [85]. Most of the research on secondary control of frequency is focused on microgrid stand-alone operation [36, 87]. In this case, we can imagine the intervention of the ESS in the following way: if the frequency is lower than 50 Hz, the batteries could discharge (regulation up), and if the frequency is higher than 50 Hz, the batteries could charge (regulation down). These operations are described in detail in the articles [90, 91]. The frequency can be restored through the use of reserves by leveling out the imbalances between the rated and measured power injections and to restore the frequency.

With regard to tertiary reserves, there are two types: tertiary production reserves and tertiary withdrawal reserves. In both cases, the reserves are used only when major imbalances or major congestions appear. Tertiary reserves are not activated automatically as in the case of primary and secondary reserves, but manually. In practice, the tertiary reserves only intervene very rarely, about a few times a year. Their intervention time is estimated at about 15 min.

So far there is no clear position as to what type or types of ancillary services would be economically profitable for EVs. Scientific opinions differ on the subject. One can quote, for example, the position of the authors [71] who affirm that the secondary and tertiary controls are supposed to be competitive, and the primary control is supposed to be highly competitive. Other authors [92], however, state that the primary control should have the highest value for V2G. Still others say [73] peak power control might be the most economical solution, giving as an example the control system used in Japan. According to an analysis presented in [93], it would seem that the power to be delivered by the tertiary reserves would be too high and the duration too long for the vehicles. So in short, as a compromise, we could say that the possibility of using the primary and secondary controls from the point of view of interaction with the ESS is the most probable.

4.5.2 Voltage regulation

The appearance of an imbalance in the production of electricity can also endanger the voltage, as well as the frequency. In particular, when distributed power generators, such as photovoltaics (PV), increase significantly, a significant increase in voltage may occur due to the reversal of current to the distribution system. In this case, we can highlight the intervention of electric vehicles in the same distribution system in order to absorb the excess electricity, thus minimizing the reverse flow, which will contribute to a balanced electrical condition and a steady voltage.

In a low-voltage grid, the cables are common and contrary to the situation in the transmission networks or the medium-voltage networks, the resistance R is large compared with the reactance X. The adjustment of the active power flow in the grid will influence the magnitude of the voltage. Voltage regulation maintains the voltage within the limits defined by the mandatory standard EN50160 [94]. This voltage control can be integrated into the electric vehicle charger. With regard to the participation of electric vehicles in the regulation of the voltage, it can be carried out in the following way: the load of the vehicles stops when the voltage on the level of the connection to the network becomes too weak. In a later step, the discharge of an active power unit can also be taken into account to increase the grid voltage.

4.5.3 Load leveling and peak power

The electricity load profile generally consists of peak and off-peak loads. Usually electricity suppliers offer different types of tariffs in order to encourage consumers to use the most favorable price ranges during off-peak hours. For load leveling, demand is shifted from peak hours to off-peak hours. Therefore, dispatching is necessary. As in the case of other loads, controllable and aggregate electric vehicles can be discharged during off-peak hours (such as at night and early in the morning), therefore the total load during off-peak hours can be increased, and the gap with the peak hours can be optimized. As the difference between peak and off-peak loads is high, the operation of gensets becomes more difficult, as well as their investment and running costs. Energy stored during off-peak hours is typically released during peak hours to relieve congestion in the grid infrastructure. In this case, peak power delivery and load leveling are the same.

Providing peak power in this way would not be very easy for EVs since the power duration would be relatively long and their storage capacity limited, even in the event that aggregators come into play. On the other hand, from a battery wear point of view, providing peak power is generally not cost-effective as the cost of battery wear would be quite high [95].

Load leveling is more convenient for EVs. The vehicle in this case does not necessarily need to unload during peak hours. Total electricity consumption is simply shifted to off-peak hours of low electricity consumption, which would help minimize power losses and increase grid efficiency. In all these scenarios, the implementation of smart meters or real-time pricing and coordinated pricing is essential, as this would control the incoming and outgoing flows of energy from EVs [96, 97].

4.6 Aggregation of energy storage services through V2G

V2G is defined as the provision of energy and ancillary services, such as regulation or spinning reserves, from an EV to the grid. This can be accomplished by discharging energy through bidirectional power flow or through charge rate modulation with unidirectional power flow [71, 72, 98].

For the vehicle-to-grid concept, three elements are required.

1. First, a power connection to the grid must be available.

2. Second, a control connection is essential for communication with the grid operator.

3. Third, there must be an on-board precision metering for knowing the battery content [99].

The vehicle-to-grid (V2G) estimation methods available in the literature mainly focus on determining the achievable power capacity for a group of EVs [71, 90]. However, these methods are applicable only for determining the V2G capacity and not suitable for real-time V2G capacity estimation and scheduling. Apart from the capacity estimation, other methods have been proposed for aggregating EVs and supplying V2G power to the grid. The aggregation process is also governed by the amount of power and energy that the EVs can supply during any given interval. However, none of the methods available in literature consider dynamic EV scheduling for estimating V2G capacity [90].

In cases where EVs participate in the V2G system, the management, i.e., dispatching, of PHEVs is crucial. Reliable communication must be established between the vehicles and the electrical network, because throughout the duration of the process, data exchange will take place to send the request and carry it out at the level of the EVs. There are three main ways to achieve this communication. First of all, the signal can be sent to each vehicle separately, or via a central controller supervising the EVs, this can, for example, be centralized in a car park. A third possibility is also possible—one can realize the communication using a third-party aggregator, which would be responsible for the separately located vehicles.

Since the energy market system was created, a new player called fleet manager or aggregator has taken place. Its role in the new reality where electric cars are taking an increasingly important place in energy control is to help manage contract systems for a fleet of PHEVs. With vehicle-to-grid (V2G) technology, PEVs parked in a certain area can act as a PEV aggregator when connected to the grid through smart equipment. Such a PEV aggregator can represent a well-defined reactive load and provide additional generation capacity for the provision of ancillary services for power grids [100, 101].

The primary role of the aggregator, a business entity as discussed in [102, 103], is to purchase energy to satisfy transportation needs of its fleet of EVs at the minimum cost. The aggregator is a unit that acts as a mediator between the system operator and individual customers, thanks to which it is possible to coordinate the power exchange between owners of electric vehicles (EV) and the power system. The primary goal of the aggregator is to maximize profits from energy trading and regulatory reserve on wholesale markets. At the same time, the aggregator can also seek to increase their revenue by performing energy arbitrage [102, 104, 105] and/or providing ancillary services [101, 106]. The aggregator itself does not have EV batteries, as they are owned by individual customers who have EVs, therefore they should receive reimbursement of the costs of battery degradation due to their additional use beyond transport needs. The V2G capacities of many electric vehicles are combined by aggregators, then submitted to the appropriate markets [90, 102, 106, 107]. The aggregator in question can be a unit of the public service to which the electric vehicles are connected or a third-party company.

Apart from the fact that an aggregator or a fleet manager is the only interlocutor representing a greater volume of "power," therefore the cumulative power of the vehicles in the fleet is greater, there is also greater flexibility in the supply of power to manage because the greater the number of cars in the fleet, the more fluid the availability of a larger group of vehicles. A single vehicle owner can therefore enter into a contract with the aggregator on more flexible terms without worrying about the interface with the electricity markets.

4.7 Considering the battery degradation

Using the batteries as storage devices for grid purposes reduces their lifetime [105]. Therefore, EV owners must be compensated for the lost utility of their batteries due to degradation when providing services, and this payment will reduce aggregator's revenues. In order for the services from EVs to be economically viable, the revenues must outweigh the cost compensation for the degradation of EV batteries.

Unfortunately, the current state of battery production technology as well as the stage at which scientific research in the field of batteries means that for the moment the use of BESS has a number of drawbacks. The main disadvantages of their use are (i) the large investments, (ii) the associated operating costs due to the degradation of their performance over time (SOH, health status problems). Depending on how BESS is managed, their degradation is increased or mitigated, forcing vehicle owners to replace them after a certain period of time. In this context, the sizing and optimal operation of the BESS are two crucial factors to ensure the extension of their life span necessary to achieve the economic viability of the system.

It has been presented before that aggregators participate in the energy market for a defined commercial purpose, that is, to make the maximum profit. For this purpose, in order to define the annual net benefit (ANP) of the system during the lifetime of a battery, for example, it is necessary to make an estimate of the lifetime of the battery. However, this life span is highly dependent on various operating conditions, and therefore, it is not easy to predict how long a battery will last.

In normal times, the cost of operating the system with a battery system includes two elements: (i) the cost of purchasing electricity (ii) the investment cost of the battery and the inverter. These parameters can be determined in an analytical way presented by example in [108]. However, there are other battery working conditions that are considered "abnormal." We can cite, among other things, the degradation of the batteries during periods when the load demand is exceptionally greater than on other days. Battery storage could increase its profitability by providing fast regulation service under a performance-based regulation mechanism, which better exploits a battery's fast ramping capability. However, battery life might be decreased by frequent charge-discharge cycling, especially when providing fast regulation service. According to [109], it is profitable for battery storage to extend its service life by limiting its operational strategy to some degree. This is also presented analytically among others in [110]. These evaluation methods make it possible to calculate in a close way the loss of capacity of the battery taking into account the discharge rate of the demand during the lifetime of the battery.

Other algorithms were presented for different objectives in order to assure the necessary lifetime extension of ESS so that the economic viability of the system is reached. We can enumerate among others day-ahead forecast errors reduction for wind power, battery energy dispatch, peak shaving, and overvoltage prevention of LV grids, respectively [108, 111].

Authors [112, 113] have presented battery degradation costs associated with additional cycling. The main contributions of the formulation used in [112, 113] are: to simultaneously optimize bidding of V2G, it is necessary to take into consideration: energy, regulation up, regulation down, spinning reserves. They formulated the problem as a linear program, which can be quickly and efficiently solved for large groups of EVs.

Another aspect of the battery degradation is how to compensate the customer's loss. Authors [114] present their point of view concerning this matter. They proposed a bidding strategy for the aggregator to maximize its profits from participating in competitive energy and different regulating reserves markets, while compensating EV owners for degradation. According to [114], an optimal strategy for both energy and reserve markets considering their trade-offs and effect on EV battery degradation has to be taken into account. Also the realistic approach to participating in the voluntary reserve markets with price-quantity offers that are justified is of high priority. And finally assessing the expected profit the EV aggregator can collect by participating in the energy and regulation market is also important.

5. Conclusion

Recent advances in electric energy storage technologies provide an opportunity of using energy storage to address intermittency of renewables. Combining energy storage with renewables improves availability, increases the amount of wind generation that may be installed on the grid without risking the system's voltage stability, increases throughput of existing grid infrastructure, and yields various ancillary benefits.

The solar energy source is the fastest-growing energy source. In small electrical systems, sudden changes in PV generation result in a frequency disturbance; hence, in order to minimize customer interruptions, the use of battery energy storage systems (BESSs) can be of great help.

Hydrogen, as the most common chemical element on the planet, is considered an eternal source of energy. One of the best-known methods for producing hydrogen is the transformation of water. The production of hydrogen can be carried out in an efficient manner using the electrolysis of water using polymer electrolyte membrane (PEM) cells. The inverse equivalent of a PEM electrolyzer is the PEM full cell. It is also possible to produce hydrogen from biomass. However, it seems that this option does not really have a future because the process is quite complex.

All the different requirements regarding among others the reaction time of the BESS can be overcome using a battery management system (BMS), which is aimed at monitoring and maintaining safe and optimal operation of each battery pack is necessary. In addition, a System Supervisory Control (SSC) must be installed to monitor the entire system. It is possible to reduce the causes of battery degradation and improve system performance by using BMS based on smarter models. The BMS can accurately estimate many internal variables that allow it to gain an in-depth understanding of the battery's state of charge (SOC) and state of health (SOH). This task is carried out using physics-based models.

An energy storage system (ESS) can be categorized in terms of the role it plays in a power system: either it is for energy management or for power quality enhancement. Because of the recent development of power electronics, superconductivity, and computer science, the SMES system has received a great attention in the power systems applications. It has been utilized in distributed energy storage, spinning reserve, load following, automatic generation control, power quality improvement, reactive power flow control, voltage control, and transient stability enhancement. As the levels of penetration of renewable energy rise, the technical impact of renewable energy on grid operation led to the application of energy storage for renewables.

Electrical vehicles are among the most popular ESSs, selling energy could be beneficial for EV. Their batteries can act as a source of stored energy to provide a number of grid services. V2G is defined as the provision of energy and ancillary services, such as regulation or spinning reserves, from an EV to the grid. Possible services for V2G are: supply of peak power, supply of primary, secondary, and tertiary control (for frequency regulation and balancing), load leveling, and voltage regulation. In order to make EVs efficiently participate in the regulation process, it is important to know when, statistically, vehicles are available for charging or discharging. The connection to the electric power grid offers opportunities for EVs for charging the vehicle but also for discharging and thus injecting energy into the grid. In order to participate in energy markets, the V2G capabilities of many EVs are combined by aggregators and then bid into the appropriate markets. However, using the batteries as storage devices for grid purposes reduces their lifetime. Therefore, EV owners must be compensated for the lost utility of their batteries due to degradation when providing services, and this payment will reduce aggregator's revenues.

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