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Review

Selection and Dimensioning of Energy Storage Systems for Standalone Communities: A Review

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Abstract: The European Union's energy and climate policies are geared on reducing carbon dioxide emissions and advancing sustainable energy, focusing on a faster propagation of renewable energy sources to decarbonize the energy sector. The management of locally produced energy, which can be implemented by a microgrid capable of either being linked to the main grid or operating independently, is equally crucial. Additionally, it seems that electricity storage is the only practical way to manage energy effectively within a microgrid. Energy storage is hence one of the main technological parameters upon which future energy management has to be based. Especially during crisis periods (such as the COVID-19 pandemic or the ongoing energy crisis), storage is a valuable tool to optimize energy management, particularly from renewables, in order to successfully cover demand fluctuation, hence achieving resilience, while at the same time reducing overall energy costs. The purpose of the paper is to analyze and present, in brief, the state-of-the-art of the energy storage systems that are available on the market and discuss the upcoming technological improvements of the storage systems and, in particular, of batteries. The analysis will focus on the storage systems that can be used within a stand-alone community such as a microgrid, but not limited to it. In the analysis, short- and long-term storage options are discussed, as well as varying storage capacities of the different technologies. The analysis is based on contemporary optimization tools and methods used for standalone communities. Understanding the state-of-the-art of energy storage technology is crucial in order to achieve optimum solutions and will form the base for any further research.

Keywords: energy storage system; batteries; standalone communities; microgrids; mini-grids; energy management; optimization; tools

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1. Introduction

Europe and the rest of the world face an existential danger from climate crisis and its impact on the environment. The European Green Deal has set the outline, in the form of the Fit for 55 package and its accompanying series of legislative measures, aiming to make Europe the first continent to be carbon neutral by 2050, while ensuring on a social level that vulnerable groups are not left behind. All economic sectors will need to be active in order to meet this 2050 goal, by means of actions that include investing in environmentally friendly innovations, encouraging industry to advance, switching to cheaper, more advantageous forms of private and public transportation, decarbonizing the energy sector, ensuring that buildings are more energy efficient, and collaborating with international partners to advance global environmental benchmarks. The aforementioned goals can only be accomplished by converting climatic and ecological difficulties into genuine possibilities via equitable and all-inclusive activities. The ongoing energy crisis, which started in late 2021, has triggered the REPowerEU set of measures, aiming at diversifying gas supplies and expediting the roll-out of renewables, so as to ensure security of supply, while maintaining sustainability as a primary goal [1–3].

Prior to the European Green Deal, the Paris Agreement had already made it plain that governments must reduce emissions globally as quickly as possible to achieve a climate-neutral world by the middle of the century to meet the long-term temperature aim of an increase of no more than 2 °C. To achieve this, it is necessary to unite all countries around the shared goal of launching ambitious initiatives to fight climate change and prepare for its consequences. It was also emphasized that it is only possible to fully grasp the notion of technology development and transfer for enhancing climate change resilience and lowering greenhouse gas emissions (GHG) if technical advancements work in accordance with those scopes. The significance of technology frameworks as a means of directing efforts to reduce environmental pollution is also being emphasized [4,5].

Furthermore, the United Nations' Sustainable Development Goals provide a comprehensive description of the objectives that must be met, in order to improve human well-being and environmental survival, in addition to the aims and goals that have been defined in accordance with GHG reduction and environmental pollution restriction. The appeal calls for action from all nations, including those with low, medium, and high incomes, in order to advance prosperity and preserve the environment. It is understood that addressing practices and technological improvements toward a carbon-neutral environment is of great importance [6,7].

Finally, the ongoing energy crisis, which can end up as the worst event since the oil crisis of 1973, has hit particularly in Europe, as gas prices have reached unprecedented levels, while at the same time, oil prices have followed, albeit to a lesser extent. However, the real threat lies in shortages in the supply of natural gas, which poses a real threat for power generation in the coming winter while leading many energy providers at the edge of bankruptcy and presenting a major risk for most industrial sectors [8].

Still, one must keep in mind that this crisis stems from a combination of events, starting with the COVID-19 pandemic, which has created intense uncertainties both in the energy sector and in the global economy. The economic slowdown led to a collapse in energy demand in 2020, with oil prices being extremely low, while this decline was corrected by the "reopening" of global economic activity [8]. In Europe, energy costs for households have already increased by 20–30% in 2021, to an average of EUR 1450 annually, while in 2022, they are expected to increase by a further 20–40% to EUR 1850, with predictions that they will continue to rise in 2023 [9]. At the same time, industrial consumers will also receive a big blow as the price increases in electricity reached 20% and in natural gas 15% in 2021, and a further increase of 70 and 100%, respectively, is predicted in 2022, while in 2023, it is expected to bring further increases in gas prices [10].

As it is understood, in addition to the need for RES systems to become less cost-intensive, integrating energy storage systems into their operation is equally important because, unlike fossil fuels and particular renewable, the yield from wind and solar energy is directly related to weather conditions, making energy output less predictable and non-dispatchable. Combining algorithms and mathematical programming with technology breakthroughs allows for considerable progress in integrated system layout and dimensioning, along with the previously less appealing environmental advantages of reduced carbon dioxide emissions and energy availability for demand response. Energy storage systems (ESS) present in that sense an answer to these issues, because they allow for excess energy to be stored during times of strong solar radiation and/or prevailing winds and low demand and then release it when the load calls for it. These systems include batteries, the use of which has seen significant growth in recent years, and which are expected to further do so in the years to come, due to their perfect suitability for this use and the drastic decline in their cost.

2. Standalone Communities

The technology of power grids operating outside the core network (mini-grids), is constantly developing, enabling a shift from remote central station units to a more local, distributed generation scheme. According to the International Renewable Energy Agency

(IRENA) [11], these networks can be categorized in several ways. Table 1 shows a categorization according to the applications, users and the individual parts of their systems, while in Table 2, the separation was made based on the size, capabilities and complexity of the system.

Table 1. Categorization of systems based on applications, users and individual segments [12].

	Stand-Alone			**Grids**		
	DC		**AC**	**AC/DC**		**AC**
System	Solar Lighting etc.	DC solar home systems	AC solar home systems	Nano-grid Pico-grid	Microgrid Mini-grid	Full-grid
Applications	Lighting	Lighting and Appliances	Lighting and Appliances	Lighting and Appliances and Emergency Systems	All uses	All uses
User	Residential Community	Residential Community	Community Commercial	Community Commercial	Commercial Industry	
Key Component	Generation Storage Lighting Cell charger	Generation Storage DC special appliances	Generation Storage Lighting Regular AC appliances	Generation single-phase distribution	Generation three-phase distribution and controller	Generation three-phase distribution and transmission

Table 2. Network separation based on system size, capabilities and complexity [12].

	Size (kW)	**Capability**	**Complexity**
Stand-alone systems	0–0.1		
Pico-grid	0–1	Single Controller	
Nano-grid	0–5	Single Voltage Single Price Controllers negotiate with other across gateways to buy or sell power	Both grid and remote systems Preference for DC systems Typically serving single building Single administrator
Microgrid	5–100	Manage local energy supply and demand Provide variety of voltages Provide variety of quality and reliable options Optimize multiple output energy systems	Incorporate generation Varying pricing possible
Mini-grid	0–100,000	Local generation satisfying local demand Transmission limited to 11 kV	Interconnected costumers

With respect to its substance, a microgrid consists of a set of buildings, consumers and/or producers; renewable energy source (RES) systems; and possible thermal and/or electrical storage media. Essentially, it is an active distribution network, as its elements produce and consume in a distribution system. Most often, it operates connected to the central network and is treated by it as a single controlled unit, meeting local energy needs; however, it is often also found in isolation, mainly in applications of remote islands [12]. Its main objectives are to achieve a reliable and efficient supply of electricity, to enhance local autonomy and to improve the operation and stability of the regional electricity grid, while at the same time ensuring a greener and more sustainable way of producing energy, especially in urban and rural areas [13].

More specifically, each microgrid, as well as the central network, has the necessary mechanisms for the production, distribution and regulation of energy provision. Power is supplied locally and is largely produced by RES (mainly solar and wind energy). The main differences it bears compared to the conventional power plants of the core network are the much lower power (<100 kW) production units, the direct supply of the energy produced to the distribution network, provided of course that it is at distribution voltage, and the installation of production close to consumption, reducing the transmission losses [14]. The distribution of energy is carried out by conventional connections between homes, businesses, services, etc. Due to the deferred production and demand, there is often a storage medium for the autonomy of the system, which can be either central (one or more common storage facilities, where the excess energy from the distributed producers will reach), or distributed (many, different storage facilities, each close to each production). For greater reliability, it is customary to connect to the region's core network. However, in the event of a network error, there is a possibility of disconnection from it. Then, for the proper operation of the microgrid and to ensure energy supply to the higher priority loads (e.g., hospitals), the microgrid has a series of controllers, so that its operation is performed in an automated and efficient way, ensuring its members the desired reliability and safety. At the same time, when conditions allow, it can become an important link in the restoration of the core network [15]. Finally, Figure 1 presents the main categorization of a microgrid.

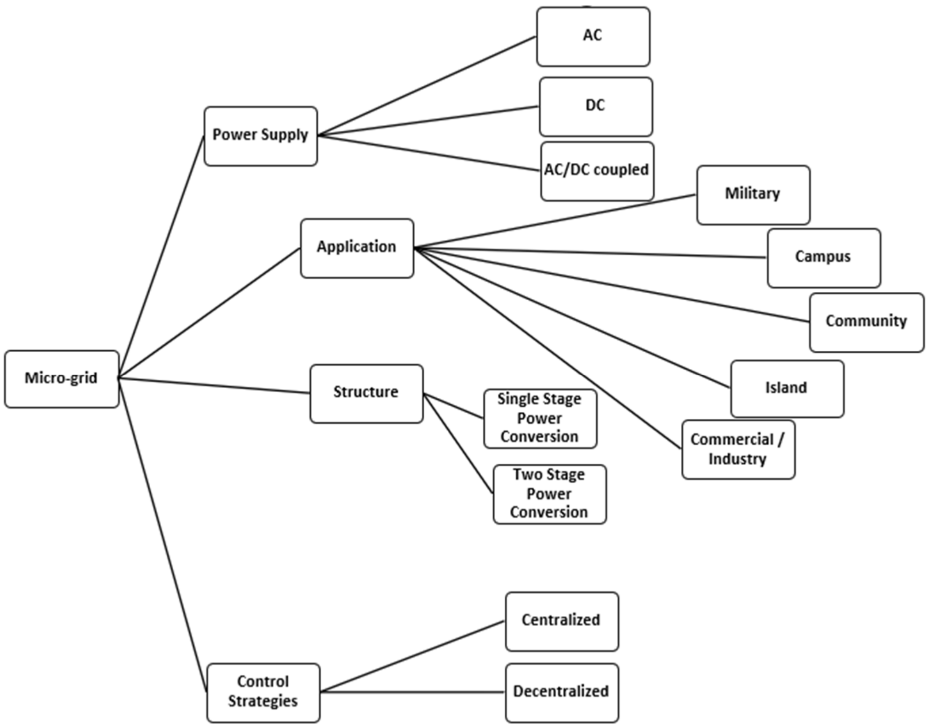

Figure 1. Microgrid categorization [16].

The main characteristics of microgrids, with respect to their function, can be described as follows:

Microgrids are local. As already mentioned, the microgrid is a local energy system, which means that energy is produced close to consumers. This fact distinguishes microgrids from large central networks, in which electricity is generated in the various power plants and driven through transmission and distribution lines to end users. Understandably, the transfer of energy over long distances entails some losses, which can be significantly reduced if production takes place near the service points [17].

Due to the microgrids' local characteristics, they can use local biomass as fuel, such as when steam generators are included into miniature Rankine cycles. This helps to clean up forest lands and gives bushes and shrubs a marketable purpose. Since the fuels utilized will frequently be local, meaning they do not have major transportation expenses incorporated in their pricing, this will aid in the repopulation of rural regions, the reduction in the number and intensity of forest fires, as well as the reduction of electricity prices.

Since the contaminants that these Rankine cycles produce will also be absorbed, they are non-polluting processes.

Microgrids are independent. A microgrid can be disconnected from the main network and operate independently. This autonomous operating capacity allows consumers to be uninterruptedly supplied with electricity even when a storm or some other event causes damage to the central power grid. Although they have this capability, they usually remain connected to the host network, unless they are in a remote area where either there is no network or there is but it is unreliable. Thus, as long as the main network is functioning normally, it and the microgrid are in a kind of symbiotic relationship [17].

Microgrids are "smart". This property of theirs is due to the existence of a controller, which is the central "brain" of the total system, and its role is to manage all the individual elements of the microgrid, such as the various energy sources, batteries, and energy systems of buildings, with a high degree of complexity. The controller regulates the operation of the various energy sources by modulating the use of any of them or a combination of them, in order to achieve the goals, set by the users, which may concern the achievement of lower prices, cleaner energy, greater reliability or anything else. For example, an advanced controller can monitor, in real time, changes in the electricity prices of the core network, which are constantly changing based on supply and demand. If it is economically appropriate, it can choose to buy energy from the grid to serve consumers instead of, for example, using the energy produced by the photovoltaic system's photovoltaics. Thus, the electricity generated for example by photovoltaics could charge the batteries of the microgrid and be utilized later, when the energy of the grid becomes expensive [17].

The advantages that microgrids can bring are therefore easily recognizable:

- They have a smaller environmental impact, compared to conventional grids, due to reduced emissions of gases and particles, as losses are smaller.
- They reduce the distance between production and demand, leading to an improvement in the voltage profile, reduction of losses and costs in transmission and distribution, reduction of investments in transmission and distribution systems and reduction of power congestion in transmission and distribution.
- They improve power quality and reliability by decentralizing production, better matching of energy supply and demand, reducing the impact of large outages on transmission and production and reducing downtime, and improving the time to restart production using the power of small producers.
- They lead to cost savings, through the use of efficient cogeneration of heat and power and the integration of many small producers, in order to increase local production and reduce the cost of distribution and transmission losses.
- They enable profits from participation in the electricity markets, both by enabling power purchases when prices are lower and selling when prices are higher, but also by providing ancillary services, acting as distributed generation units [11].

However, there are also certain disadvantages, which are challenges that have to be overcome, such as:

- The high investment costs of RES systems, although this has dropped drastically lately.
- The possible technical difficulties from the inexperience of controlling a large number of small producers.
- The lack of standards regarding the operation and protection of microgrids.
- Legal and managerial issues; due to lack of legislation and regulations on the operation of microgrids, that have an impact on licensing and connecting.
- Issues of the energy market, such as regulating the price of energy provided by the microgrid during its autonomous operation [11].

Some of these issues may be solved by converting existing networks and developing new smart grids. According to the International Energy Agency (IEA) [18], a smart grid is defined as "the electrical network that uses digital and other advanced technologies to monitor and manage the transfer of energy from all production sources to meet the changing electrical loads of consumers. Smart grids coordinate the needs and capabilities of all generators, network operators, consumers and all those involved in the electricity market to operate all parts of the system as efficiently as possible, minimizing costs and environmental impacts, while maximizing system reliability, flexibility and stability." In Europe, they are given the descriptions: flexible, accessible, reliable and economically attractive [11].

In existing intelligent networks, only localized protection systems and energy control centers are applied. However, to achieve the desired level, processors and sensors should be installed on each device, substation and production unit, which will be accompanied by operating systems that will work together and communicate with each other, forming a large computing platform. The applications and experiences of the microgrid can help in this transformation [11].

3. Methods and Characteristics of Energy Storage Systems

RES systems are increasingly penetrating the production of electricity, and given their stochastic nature and the differentiation between production and consumption, storage technologies offer great potential for better exploitation of the energy derived from them. Thus, during periods of intense sunshine and/or prevailing wind, the additional energy produced by photovoltaics and wind generators can be stored and exploited when generation is not possible. Currently, energy storage systems are used in various applications, such as to reduce the total cost of electricity production, to provide stable power to non-interconnected systems, to use the grid more efficiently, to provide backup energy, to smart microgrids and smart buildings, to electric vehicles, etc. Thus, it is of paramount importance to achieve a truly sustainable transformation, and for this reason, political actors, industry and other relevant stakeholders should continue to work together in order to create a supportive regulatory framework that will allow the storage sector to thrive.

3.1. Storage Methods

Energy storage methods can, according to [19], be classified into two general categories:

- *Based on the duration of storage of the produced energy*;
- *Based on the form of storage of the produced energy*.

As will be discussed in the following sections, there is a wide range of energy storage applications, which can be classified both under technical and economic criteria. In addition, they can be classified depending on whether they are installed centrally or distributed, as they find applications in individual small systems (residences), in larger systems (shopping centers, neighborhoods), in systems of the electricity distribution network or in RES operating facilities.

- *Storage duration*

Short-term storage. It is used to serve the peaks of energy demand for a certain period within the course of a day. Thus, the demand on central power plants, transmission and distribution systems is reduced. For such applications, one can use flywheels, supercapacitors, superconducting materials and liquid storage tanks.

Medium-term storage. It is used when excess energy or seasonal gain can be transferred with a delay of a few days to a few weeks and serve future demand. Such means are batteries, solid thermal beds and hydrogen storage systems.

Long-lasting storage. It is used in systems with a large energy capacity and small or very small losses. The storage period can be from a few months up to an annual basis. The applications that use these systems take advantage of the annual climate variation and achieve minimization of annual energy requirements or serve a multitude of consumers (city, settlement, industrial areas) in exceptional cases. Common systems include the technologies of pumped storage, storage of compressed air, geothermal, underground storage of heat in solid or liquid media [19].

- *Storage form*

Electricity can only be stored after its conversion to another form of energy. The most common forms are presented in Figure 2 and are analyzed below:

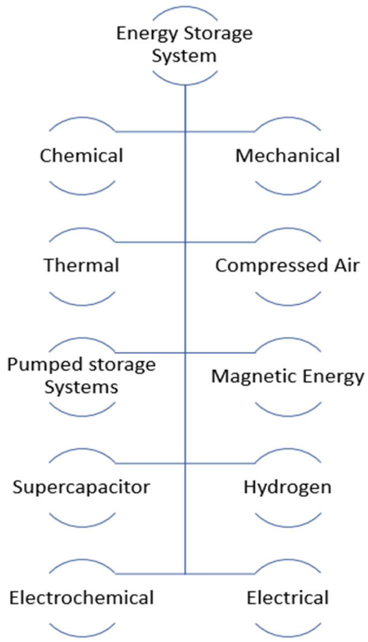

Figure 2. Energy storage systems categories.

Chemical energy. This includes electrochemical energy storage systems such as batteries, photochemical storage through photochemical reactions, thermochemical storage through two-way reactions that can release and store large amounts of energy or systems for dissolving, absorbing and adsorption. Additionally, it includes energy storage in the form of hydrogen, which is stored in liquid, gaseous or solid form and then used as fuel. [20–22]

Mechanical energy. This includes systems that store energy in the form of dynamic energy (elevated bodies, elastic materials), kinetic (rectilinear or rotational motion) and compressed gas energy. Most common technologies are pumped storage, flywheels and compressed air systems. The operational pattern of flywheels has been known for decades [19]; in their present form, their rotational speeds exceed 50,000 RPM and magnetic frictions and chambers under vacuum are used to reduce aerodynamic losses and rotor pressure [18]. Unlike batteries, flywheels systems are not sensitive to temperature, and their performance can reach up to 80–90%. In addition, they have a high energy density (in the range of 5–100 Wh/kg) [23]. Their expected lifespan reaches 15–20 years (for use at high frequencies); however, they require minimal maintenance and monitoring. Flywheels are used in power applications, as they can be discharged within a few seconds if necessary. Thus, they are increasingly preferred for extensive RES applications as well as for meeting energy demand at peak times where immediate supply of a relatively large amount of energy is required. They can therefore balance the sharp and rapid load changes that would quickly wear out batteries due to the limited life cycles of the latter. The main disadvantages of flywheels are the high investment cost, the risk of an accident in case of mechanical failures, and the high self-discharge rates, which reduce energy efficiency when the discharge charge cycle is not continuous, for example, when energy is stored for a period between charging and discharging. Such high discharge rates reinforce the view that the flywheel is not a sufficient device for long-term energy storage, but only to provide reliable backup solutions [20–22].

Thermal energy. This includes energy storage systems in the form of sensible heat in solid or liquid media and latent heat in various materials. Thermal energy storage (TES) systems use materials that can be kept at high or low temperatures in insulated containers. The heat or cold supplied can be used to generate electricity using thermal machines.

Thermal storage systems are categorized into low and high temperatures depending on whether the operating temperature of the storage medium is less than or greater than the room temperature. More specifically, TES systems are divided into industrial cooling (<−18 °C), domestic cooling (0–12 °C), domestic heating (25–50 °C) and industrial heating systems (>175 °C) [18].

Compressed air. Compressed air energy storage (CAES) systems find application in large-scale storage projects. With the exception of the reversible hydroelectric systems, no other method has the ability to store such large amounts of energy for long periods. The power of such an energy storage system can start from 50 MW and exceed 300 MW [24]. They are complex, large scale facilities, since they consist of the power section, the compression section, controls, auxiliary systems and, more importantly, they require an underground airtight reservoir for the storage of the compressed air [20,25–28].

Pumped storage system. Today, the most reliable solution for storing the generated energy on a large scale is provided by pumped storage systems and mainly by reversible hydroelectric systems, whose energy conversion units are reversible, that is, they can function either as turbines (production phase) or as pumps (storage phase). The excess energy that occurs during the hours of low load and high-RES production is used to pump water into the upper reservoir and is therefore stored in the form of dynamic energy. They are usually large-scale facilities of hundreds of MW installed power, although one can also find small scale plants, especially in insular systems. The cost per energy unit stored is in the latter case quite high [18,29–31].

Magnetic Energy. It is used mainly to smooth out fluctuations in the network voltage and boost power at peak hours, but also with the prospect of application to RES is the superconduction magnetic energy storage system (SMES). In a superconducting magnetic energy storage system, energy is stored in the magnetic field generated by the DC flow in a superconducting material coil. The stored energy can be attributed to the AC system when conditions require it. The problem with SMES is the need for cooling to cryogenic temperatures, by using liquid helium or nitrogen, which is costly [32–35]. In addition, their energy density is low, and, in the case of large superconducting magnetic energy storage systems, the resulting magnetic field can also have a significant environmental impact. On the plus side, they feature a very short time delay during charging and discharging. Power is available almost instantaneously, the very high-power supply being available for a short period. They have a long life cycle and are therefore suitable for applications that require stable, complete recycling and continuous operation rates. The energy efficiency of a superconducting magnetic energy storage system can become more than 97% [18].

Supercapacitor. The supercapacitor is an electrochemical capacitor and contains components associated with both a battery and a capacitor. Accordingly, the voltage of an element is limited to a few volts. Depending on the technology of the materials used for the manufacture of electrodes, supercapacitors can be classified into: (a) electrochemical double layer capacitors (ECDL), (b) pseudocapacitors and (c) hybrid capacitors (hybrid capacitors).

ECDL supercapacitors are usually the least expensive in their manufacture and are currently the most widespread types of supercapacitors. Similar to a battery, they are based on electrostatic action [36–39]. However, since no chemical reaction occurs, the effect is easily reversible with minimal degradation to high loading or overcharging, and the typical shelf life is hundreds of thousands of cycles. In addition to the high resistance to large charges, the fact that no chemical reaction takes place means that supercapacitors can be easily charged and discharged in seconds, much faster than batteries. At the same time, neither heat nor hazardous substances are released during charging. Energy efficiency is very high and ranges from 85% to 98%. The limiting factor in terms of service life with lifespans of up to 12 years are reported. Another limiting factor is the high rate of self-discharge, reaching a level of 14% of the nominal energy each month [18].

Additionally, the hybrid capacitors are a combination of pseudo-capacitors and double-layer supercapacitors, with one electrode using an electric double-layer mechanism and the other pseudo-capacitive material. Hybrid supercapacitors can also be manufactured using two suitably adulterated conductive materials or mixed metal oxides. Polymer aluminum and hybrid wet tantalum are some of the examples of hybrid capacitors [40–42].

Hydrogen (H2) is in theory the ideal energy carrier. It is the most abundant element in the universe [43], has the highest energy content per unit weight (120.7 kJ/g), and the product of its use (combustion or electrochemical conversion) is water or water vapor. Furthermore, it can be stored as a gas, liquid or even solid, and can be transported by pipelines and tank vehicles of ships.

Unfortunately, it is rarely found alone in Earth; for that reason, there is need to use energy to produce it, and hence, from the environmental aspect, it makes sense only when electricity from RES is used, leading to the production of "Green Hydrogen". It is also difficult to store, since it is a very light gas and requires high pressures, or very low temperatures, around 22 K, at low pressures around 3 to 4 bar, to achieve liquefaction [44] so as to store it in reasonable quantities. Pressures of 700 bar (ambient temperature) are needed to store H2 as a gas; temperatures of −253 °C (pressures from 3–4 bar) are needed to stores H2 as a liquid; and in insulated tanks, the chemical compound of hydrogen with another material (such as metal hydrides). For these reasons, distribution and storage infrastructure requirements are complex and cost-intensive investments [18,45,46].

A synopsis of the aforementioned storage methods is presented in Table 3, accompanied by their features [16,29–34].

Table 3. Typical features of basic storage methods [47].

	Discharge Time	Cycles of Lifetime	Energy Density (w/lt)	Efficiency
Pumped Hydro	4–16 h	30–60 years	0.2–2	70–85%
Compressed Air	2–30 h	20–40 years	2–6	40–70%
Lithium-Ion Battery	1 min–8 h	1000–10,000	200–400	85–95%
Lead-Acid Battery	1 min–8 h	6–40 years	50–80	80–90%
Flow Battery	hours	12,000–14,000	20–70	60–85%
Hydrogen	mins–week	5–30 years	600	25–45%
Flywheel	sec–min	20,000–100,000	20–80	70–95%

Additionally, Table 4 summarizes the main advantages and disadvantages of the different energy storage systems.

Table 4. Synopsis of available ESS [20,48–89].

Type of Energy Storage System	Advantages	Disadvantages
Flywheel	Environmentally friendly High power density No temperature control equipment More life span	Increased capital investment Big self-discharge Decreased energy density
Thermal	Releases energy during daytime Decreased capital cost Decreased rate of self-discharge Environmentally Friendly	Life span Temperature issues Space issues
Compressed Air	Control of voltage and frequency Temperature response Air quality Peak energy performance System stability	Geographical regions Increased capital cost Water loss evaporation
Electrochemical	Adaptable at voltage and current level Nontoxic Variety of sizes Decreased losses	Decrease life span Increased cost Decreased energy density Difficult maintenance

Regarding the storage of energy produced in a standalone community, in a single residential or commercial building or in a cluster of buildings, the desired characteristics of the storage system are:

- Duration of energy storage, varying from few hours to a few days;
- Storage capacity at an order of magnitude of few to tens of kWs;
- Increased degree of efficiency;
- Immediate return of the stored energy;
- Widely available technologies, with reduced maintenance requirements;
- Technologies that can be used in an urban environment;
- Affordable purchase costs.

Table 5 synoptically presents the technical characteristics of the aforementioned energy storage systems.

Table 5. Technical characteristics of energy storage systems [37,55,90–104].

Energy Storage System	Power [MW]	Specific Energy (Wh/kg)	Energy Efficiency (%)	Rate of Discharge (h)	Time of Response	Cycles of Lifespan	Self Discharge Per Day (%)
Flywheel	0–1.65	5–80	80–90	0–0.01	<1 cycle	104–107	100
Thermal	50–250	80–200	14–18	1–24	–	3–5 years	0.05–1
Compressed Air	5–350	30–60	41–75	1–24	sec–min	>10,000	0
Hydrogen	0–50	400–1000	35–42	<12	<1/4 cycle	>1000	0

As it can be deduced, electrochemical storage, in the form of batteries, seem to be the most suitable option, and it will be discussed in detail in the following section. A standalone battery system is able to provide energy during periods when there is no solar radiation or wind, to cover instant load demand spikes, to keep the voltage constant in the system, and to store the additional energy demand, in order to reduce losses, etc. [21,22,35,105,106]. Furthermore, batteries are particularly suitable for static applications, due to their technological maturity and ease of use. Furthermore, because of the lower life cycles compared to super-capacitors, flywheels, and superconducting magnetic storage systems, they are best applicable for small-scale applications with the particular demand features of buildings or building clusters. [30] They will therefore be discussed in more detail in the next section.

3.2. *Electrochemical Battery Structure and Characteristics*

The electric accumulator is a storage method that converts chemical energy into electricity through an electrochemical reaction inside. It consists of one or more electrical elements, which are properly connected in series and/or in parallel, in order to deliver the desired voltage and capacity of the array [107–111].

Each element consists of two plates of different metals (anode and cathode), which are immersed in a conductive liquid (electrolyte). The anode, the negative electrode, is negatively charged and provides the electrons to the charge. It is selected taking into account good conductivity, stability, ease of manufacture, low cost, and is usually made of metals. On the other hand, the cathode, the positive electrode, is positively charged and accepts the electrons. It is a good oxidizing agent and does not interact chemically with the electrolyte. The materials that are usually chosen for its manufacture are metal oxides. Finally, the electrolyte is usually some solution that contributes to the conductivity of the device, that is, to the transfer of electrons between the electrodes. To prevent its leakage, each element is sealed in an appropriate way, while some have valves to allow the escape of gases generated during operation. The final shape that a battery carries can be cylindrical, flat or prismatic [112–116].

During the electrochemical reactions that occur in the different stages of charging and discharging the battery, the electrodes react with the electrolyte, and electron displacement is carried out. In the discharge state, and if there is a connected external charge, electron transfer occurs from the electrode with the lowest potential (anode) to the electrode with the highest potential (cathode) through the load, due to the existing potential difference. On the contrary, when charging, the ions of the reaction are transferred from the cathode to the anode through the separator. The separator, in which the electrolyte is placed, electrically isolates the electrodes, but allows for the movement of ions [28,117–119].

Table 6 presents the main battery categorization.

Table 6. Basic classification of batteries [32,112,120–123].

Size Categorization	Capacity (kWh)	Application
Small	0.01–0.05 1–12	Portable electrical devices and tools Electrical bikes, scooters, etc.
Medium	25–100 200–1000	Batteries for residential buildings, electrical vehicles EV Batteries for large buildings, PV plants
Large	<10,000 <20,000 <40,000 >100,000	Frequency regulation for power quality Renewable integration Spinning service UPS, peak shaving, energy time-shifting

3.3. Types of Electrochemical Energy Storage Systems

The most used rechargeable batteries, second-order elements, are lead–acid, nickel–cadmium, nickel–metal hydride and lithium-ion. Table 7 shows the characteristics of each one in aggregate, followed by further analysis.

Table 7. Characteristics of basic types of batteries [124].

Specifications	Lead Acid	NiCd	NiNH	Lithium-Ion
Specific Energy	30–50	45–80	60–120	90–250
DoD	200–300	1000	300–500	500–2000
Charge Time	8–16 h	1–2 h	2–4 h	1–4 h
Self Discharge/Month	5%	20%	30%	<5%
Cell Voltage	2V	1.2 V	1.2 V	3.2–3.7 V
Cost	Low	Moderate	Moderate	High
Safety Requirements	Thermally stable	Thermally stable	Thermally stable	Protection circuit mandatory
Internal Resistance	Very Low	Very Low	Low	Moderate-Low
Maintenance Requirement	3–6 months	Full discharge every 90 days for full use	Full discharge every 90 days for full use	Maintenance free
Charge Temperature	−20–50 °C	−20–65 °C	−20–65 °C	−20–60 °C
In use since	1800	1950	1990	1991–1999
Toxicity	Very High	Very High	Low	Low
Peak Load Current Best Result	5 C 0.2 C	20 C 1 C	5 C 0.5 C	>30 C <10 C
Coulombic efficiency	90%	70% slow charge 90% fast charge	70% slow charge 90% fast charge	99%
Overcharge Tolerance	High	Moderate	Low	Low

Lithium-Ion

There are many types of lithium-ion batteries on the market, mostly for use in small-scale storage applications. They are a relatively new technology that is quickly acquiring market share in several industries. Although their initial cost is considerable, it is steadily decreasing, which encourages their spread in the market. Most have an anode made of pure carbon graphite, a lithium salt electrolyte, and a cathode of lithium oxide (LiMO2, $LiCoO_2$, or $LiNiO_2$) ($LiPF_6$). Lithium-ion batteries are more energy-efficient (99–100%) and have a longer life cycle (500–2000 cycles) than other kinds of batteries [87,88]. With the greatest electrochemical potential and the best energy density in battery designs (up to 250 Wh/kg), lithium is the lightest of all the metals [50,51]. Additionally, they do not need maintenance since their self-discharge rate is modest (5%), and they are not affected by the memory phenomenon. As a result, they do not need any planned total discharges to maintain them in top condition. Some of the disadvantages include a safety circuit need, a restricted capacity for stress resistance, and a shorter life cycle at high temperatures. Every array has a circuit that prevents any drops in the peak voltage of individual elements while charging or discharging. To avoid lithium metal plating owing to overload, temperature, maximum charge and discharge currents, and temperature are all controlled [125–127].

One of the most successful Li-ion systems uses nickel, manganese, and cobalt as the cathode (NMC). Similar to Li–manganese, these systems may be adapted to function as power cells or energy cells. For instance, the NMC in an 18,650 cell under moderate load conditions has a capacity of roughly 2800 mAh and is capable of producing 4 to 5 A [128]. A silicon-based anode's capacity may be boosted to 4000 mAh and higher, but doing so comes at the expense of a decreased loading capability and a shorter cycle life. The anode expands and shrinks with charge and discharge, rendering the cell mechanically unstable, which is a drawback of silicon added to graphite [129]. Lithium nickel-cobalt-aluminum oxide (NCA), which is mostly employed in electric cars, serves as the cathode material for lithium-ion batteries. Lithium nickel-cobalt-aluminum oxide (NCA) has a high nickel content, which increases the capacity of batteries and increases the amount of distance that can be covered on a single charge [129]. The practical charge storage capacity of NCA ranges between 180 and 200 mAh/g [130,131]. The two materials, NCA and NMC, have comparable high energy densities and performance, as well as similar structures, electrochemical behavior, and performance. Cobalt and lithium are expected to each weigh 4.5 to 9.5 and 11.6 kg, respectively, in the NCA battery [130,131].

Due to their low cost and usage as storage devices, alkali metal ions such as lithium (Li), sodium (Na), and potassium (K) ions have been extensively exploited for the creation of rechargeable batteries during the past few decades. In each of these, lithium-ion batteries (LIBs), sodium-ion batteries (SIBs), and other high-energy storage devices can potentially be replaced by K-ion batteries (KIBs), which work through electrochemical reactions. Because potassium is abundant in the Earth's crust and because graphite-based anodes function well in KIBs on a commercial level, KIBs are of interest to scientists. One of the main benefits of KIBs over alkali and alkali metals (Li, Na, and Mg) is that K-ions generate smaller solute ions. This is in contrast to Li and Na ions. As a result, dissolved K ions have higher transport numbers and ionic conductivities than Li and Na ions [132,133].

It has been demonstrated that the intercalation of K ions into graphitic carbon materials occurs spontaneously, and that in particular, the cycling test of the intercalated K ions into graphitic carbon has shown that with a reversible capacity of 246 mAh g^{-1}, KIBs perform better than LIBs and SIBs. The graphitic carbon anode changes significantly in volume during K-ion intercalation and de-intercalation, and its kinetics and cycle stability are lower in KIBs than in LIBs with the same anode [134,135].

However, there are critical reports of lithium mining from salt deserts. Lithium extraction inevitably degrades the soil and intensifies water scarcity and biodiversity loss while being harmful to ecosystem functions, contributing to global warming. Lithium salt pans are typically found in arid areas. In these places, access to water is key to the livelihood of local communities as well as to the preservation of the minimum local flora and fauna. About 2.2 million liters of water (500,000 gals gallons) are needed to produce one ton of lithium, resulting in conflicts related to access to water by local communities [136,137].

On the part of experts, it is not yet clear to what extent the increasing drought is related to lithium mining. Unfortunately, the underground water flows in the Atacama Desert of Chile have not been sufficiently studied to have safe conclusions about how mining (of lithium and copper in the region) are factors influencing the microclimate alongside tourism, intensive agriculture and the climate crisis. Certainly, lithium production does not require drinking water; however, the extraction of "salt water" can mobilize or lower the level in groundwater, leading to an influx of fresh water into the salt deserts [136,137].

Lead–Acid

Rechargeable batteries are the most popular kind of battery since they are safe, dependable, and have a low purchase frequency. Lead dioxide (PbO_2) serves as their cathode, while lead (Pb) serves as their anode, and sulfuric acid (H_2SO_4) serves as their electrolyte [19,54]. The low rate of discharge (5%) and the battery's capacity to operate at a variety of temperatures are two benefits of the technology [113,124]. However, they also have some drawbacks, such as a lower energy density (30–50 Wh/kg), higher maintenance needs, a shorter life cycle (200–300 cycles with 80% DOD), lower efficiency (90%), slower charging (8–16 h), and particularly, the use of toxic building materials that make these batteries harder to recycle than other types [138]. Cars, hoisting and lifting equipment, shipping, and uninterruptible power supply (UPS) systems all meet these requirements. Additionally, they have been the most popular PV storage system up to this point [139,140].

Nickel–metal hydride (NiMH)

Alkaline batteries, which include nickel–cadmium and nickel–metal hydride batteries, have characteristics in common. The energy density of the second kind of battery (60–120 Wh/kg) is 30–40% greater than that of the first type [130,141,142]. While the charging time is extended to 2–4 h, the life cycle is reduced to 300–500 cycles. The memory phenomenon, which is a problem with many battery types because it reduces availability and usage, has less of an impact on them. Finally, this style uses primarily recyclable, non-toxic materials [142]. These are different-sized rechargeable disposable batteries that are used to swap out non-rechargeable ones in computers, medical equipment, and other devices. They may also be used in renewable energy applications [141].

Nickel–cadmium (NiCd)

The current battery design features a positive electrode made of nickel hydroxide and a negative electrode made of cadmium hydroxide. The electrolyte is an aqueous solution of potassium hydroxide and lithium hydroxide. They have a lower energy density (45–80 Wh/kg) than lead acid batteries while having a higher energy density. One of their downsides is increased discharge (approximately 20%), which is accompanied by low voltage in each cell. The usage of hazardous components is one more of this battery type's inherent drawbacks [141]. Applications for this battery type include power tools, communication equipment, and medical devices. They are ideal for renewable energy systems, but they are infrequently employed because of their high initial cost, costing up to four times as much as lead acid batteries and twice as much as lithium ion ones [142].

Flow Batteries

The most common sort of battery is an electrochemical cell, which works by moving chemical energy between two chemical components dissolved in liquids on opposite sides of a membrane. While each liquid circulates in its own area, the membrane serves as a conduit for ion exchange, which is followed by the movement of an electric current. The Nernst equation confirms cell voltage, which in practical applications may range from 1.0 to 2.43 volts. A flow battery may be used as a fuel cell or as a rechargeable battery by collecting used fuel and pumping in fresh fuel, with the fuel regeneration being powered by an electric power source [143,144]. Although it has several technical advantages over conventional rechargeable batteries, including the potential for separate liquid tanks and almost limitless battery life, the present implementations are less potent and need more intricate electronics. There have been many kinds of flow cells constructed, including redox, hybrid, and membraneless flow cells. Regular batteries and flow cells vary primarily in that energy is stored in the electrode material in the former while being stored in the latter's electrolyte. Long life cycles, greater safety due to non-flammable materials, adaptable architecture, and quick reaction to energy demands are some of its benefits [145]. Additionally, they create less pollutants. The battery's poor energy density and low charge and discharge rates are further downsides that raise the cost of ownership. The standards for their use in RES systems, standalone systems, electric vehicles, and power conversion technologies are met, however [145].

4. Optimization Methods and Demand Side Management Systems

In order for any energy storage system to be efficient and cost-effective, it has to fit well with the demand profile for which it is used. The most effective way to achieve it, is to apply demand side management (DSM) so as to adapt the consumer's requirement to the energy system's features, without affecting the overall produced output, i.e., by still meeting the consumer's requirements. In that sense, the aim of DSM is to change the end use of electricity, to move the time of energy use from peak hours to off-peak hours and to manage it in situations of unstable production, with the ultimate interest of reducing operating costs on the production side. DSM does not necessarily reduce overall energy consumption, but is expected to reduce the need for investments in networks and/or power plants to cover peak demands and reduce the use of existing units or lead existing units to serve more consumers [146]. DSM measures can be divided into four categories as presented below [147,148]:

1. Information programs. They aim to inform users about the advantages of energy efficiency. Information can be distributed through advertising campaigns, brochures, seminars, etc. Update programs are the basis of the DSM and are present in every DSM measure.
2. Technical support programs. They provide consumers with energy inspections and record the technical difficulties that exist in introducing methods of changing demand.
3. Financial support programs. They aim to reduce the costs for importing energy efficiency measures. The programs contain loans and subsidies for the purchase of energy-efficient equipment.
4. Direct intervention programs. These are programs that "intervene" in the market and promote efficient equipment at no or low cost. Government directives that refer to the determination of the minimum criteria that equipment must meet in order to be considered energy efficient are essentially direct intervention programs.

The combined examination of energy storage systems and demand side management are a prerequisite for the successful implementation of both in a standalone community. Table 8 presents a synopsis of an extensive review of the optimal use of energy storage systems and energy management within small grids.

Table 8. State-of-the-art of the optimization methods and research findings based on energy storage systems in standalone communities.

Optimization Approach	Research Findings	Reference
A comparison of several battery types is made for domestic PV panel applications.	Lithium-ion batteries are the most promising field of research.	[149]
Swarm optimization for fuzzy logic control in energy storage.	Grid-friendly requirements and consumer comfort and reliability.	[150]
Second use of lithium-ion batteries, firstly used in electric cars.	Batteries can effectively be used without being recycled, as a circular economy option in residential applications.	[151,152]
Maximum power point tracking for standalone communities.	Significant improvement of microgrid performance.	[153]

Table 8. *Cont.*

Optimization Approach	Research Findings	Reference
Statistical methods for prediction of energy supply and loads.	Enables the community to operator to anticipate generation and loads and make the necessary preparations.	[154,155]
Region contraction algorithm for energy cost minimization.	Increase of 21.74% of energy efficiency for solar spectrum splitting integrated with energy storage system.	[156]
PV batteries for usage in Greece and Denmark; system design and battery selection are cost-effective.	Batteries will become more affordable for storage in Greece because of a 10% cost decrease and in Denmark due to a 30% cost reduction.	[157]
High temporal and low-term power flow simulation.	Results in low-energy houses but needs further future analysis.	[158]
Optimization of minimizing dependance by the main grid.	Good communication and management system is needed within the community.	[159]
Hydrogen energy storage system and model predictive control for cost minimizing through two-stage energy management system.	Economic benefit.	[160]
Second use of lithium-ion batteries, firstly used in electric cars.	Batteries can effectively be used as a circular economy option in residential applications and recycled at the end of the lifetime.	[152,161]
Short-term speed prediction.	Optimized performance of the hybrid system with energy efficiency increase.	[162]
Coordinated control for ESS and PV-integrated distribution system voltage regulation.	System stability and energy balance.	[163]
Using information that is presently accessible, the effects of producing different kinds of batteries have been assessed in terms of energy, raw materials, and greenhouse gas emissions.	Lithium-ion batteries are the most prevalent source of manufacturing in a number of environmental industries.	[164]
Algorithm for voltage comparison mechanism for microgrids.	Reliable controller, increased ESS performance without DC deviation.	[165]
Pay-back period reduction and technoeconomic analysis for households employing solar panels and battery storage systems.	For non-interconnected homes, the payback time is 51 years, whereas for connected families, it is 30 years.	[166]
Congestion control in electric power networks using optimal ESS planning and scheduling, including generation from RE resources.	System congestion relief.	[167]
Two-stage rolling optimization.	13.3% energy efficiency increase and 14.55% system cost reduction.	[168]
Review of Li-ion battery LCA studies with a focus on the production of batteries.	Estimated average values for environmental effects based on the literature review.	[169]
Bi-level sizing optimization of ESS.	Reduction of 5.8% in cost, 22.3% in primary energy.	[170]
Community size optimization for cost reduction.	The optimum cluster size is 10 or 12. Cost is significantly impacted by pipeline length and load complementarity.	[171]
Proposed renewable based multi-energy system optimization method.	Minimization of emissions and cost.	[172]
LCA is a term used to describe the energy and environmental effects of sodium/nickel chloride batteries, one of the latest battery technologies for energy storage and smart grids.	By increasing efficiency and reducing carbon emissions during the manufacturing process, the battery's life-cycle effect may be reduced.	[173]

Table 8. *Cont.*

Optimization Approach	Research Findings	Reference
Panel surface area for one household's energy management after a month/cost reduction.	Increased panel surface area is not always the most economical option, but battery utilization is always crucial.	[174]
Cost optimization of a microgrid considering selling or purchasing of electricity.	The whole operating expense is decreased by 7.43%.	[175]
The comparison/LCA of equivalent structures for single-family and community-scale deployments.	A household-scale PV system integrated into a microgrid with neighborhood-scale wind turbines and Li-ion batteries is the option that is the most ecologically friendly.	[176]
Grid generation and transmission expansion planning that is linked with on-grid data centers.	When the percentage of data center load in the system is 4% or 26%, respectively, the cost of grid expansion is reduced by 1.37% and 6.78%.	[177]
Best utilization of the two technologies in conjunction with cost reduction for home PV and batteries.	In order for batteries to be viable, their price has to drop by 60–70%.	[178]
A power system's economic dispatch takes into account the geographical request schedule of on-grid data centers.	Reduction in the cost of dispatch is a little over 21%; for renewable, a high penetration rate grew by almost 15%.	[179]
Environmental footprints of sodium-ion, lithium–air, and lithium–sulfur are compared.	LieS batteries and sodium-ion batteries both have comparable carbon and environmental footprints. Additionally, sodium-ion batteries have a far bigger water impact than LieS batteries.	[180]
Management of battery use integrated to an off-grid RES system.	In comparison to the battery-only system, the suggested system's battery life is increased by 19%. The suggested system's power losses, however, are 1.7% more than those of the battery-only system.	[181]
Microgrid PV, battery, and diesel engine for the greatest technology choices and fusion.	During the summer, increasing the battery's initial capacity to 90–100% had positive effects.	[182]
Management of battery use integrated to an on-grid RES system.	In comparison to a battery-only system, the suggested approach smooths out the battery current and increases battery life by 32.18%.	[183]
With several advantages such a light and compact construction, high performance, consistent operation, and extended cycle life, lithium-ion batteries are ideally suited for this application. This research examines both the present and foreseeable pricing difficulties as well as the technical characteristics of lithium-ion battery packs for solar home systems.	The lithium-ion battery is cost-competitive for energy storage despite its relatively high starting cost.	[184]
Maximization of net present value of an ESS on grid community.	Load control needed for net present value maximization.	[185]
Based on different economic aspects and cost reduction, PV and battery systems.	Optimized outcome for the most solar panels and the smallest battery system feasible.	[186]
Minimization of carbon emissions within a microgrid using ESS.	Maximization of energy share is needed.	[181]
Researchers used ReCiPe-2008 to analyze the global warming potential (GWP) and cumulative energy demand (CED) of four stationary battery technologies: lithium-ion, lead–acid, sodium–sulfur, and vanadium redox flows.	For fixed grid operation, greater round-trip efficiency batteries, such as lithium-ion, are advised.	[187]
Boost the damping of oscillations in the power supply using ESS.	Smooth seasonal loads and minimization ESS units.	[188]

Table 8. *Cont.*

Optimization Approach	Research Findings	Reference
To attain net-zero, reduce a building's net grid energy.	According to the findings, the yearly battery dispatch had a normalized root mean square error of 2.0%.	[189]
LCA of a 60 MW lithium–manganese oxide (LMO) LIB-powered 100 MW ground-mounted PV system.	Both the life cycle global warming potential and the energy payback time increase by 7–30%.	[190]
The ideal battery size for a home with heat pumps and solar panels in terms of operational costs.	Given the prices on the market right now, lithium-ion batteries are not cost-effective.	[191]
California's energy industry life cycle environmental impact study.	Lithium-ion battery storage had much less of an impact than natural gas generating in four of the six environmental impact categories examined (climate change, fine particulate matter, photochemical ozone production, and land acidification).	[131]
Evaluates the environmental effects of energy production and ESS using a retrospective consequential LCA.	ESS was operated and deployed with grid optimization, which reduced total marginal operating costs by 28% and GHG emissions by 53%.	[192]
Batteries as a potential solution for Greece's distributed energy issues based on PV panel energy production.	Grid transition issues enhanced distribution and transition processes.	[193]
Residential and communal systems developed as part of this project, which mix diesel, solar, and wind energy with battery storage, and have a life cycle environmental sustainability.	Up to 88% of the life cycle effect of a residential energy system is accounted for by batteries, making them a significant environmental problem.	[176]
Selection of photovoltaic panels for a single residence or a microgrid based on battery consumption and cost reduction.	The only strategy that can be optimized is the use of microgrids.	[194]
Employing the life cycle assessment method, conduct research on the effects of developing, disposing of, and using power storage technologies for grid applications.	The results suggest that the power feedstocks utilized during the consumption stage are related to the performance of the storage systems.	[195]
Battery sizing based on one home's rooftop solar panels and year cost reduction.	The self-producer achieves more effective effects by using batteries.	[196]
Hybrid optimization methods for energy and cost minimization.	7% reduction in energy demand and up to 57% reduction in emissions.	[197]
Hybrid optimization methods for selection of battery types.	Lithium-ion batteries for decreased levelized cost of electricity and net present value.	[198]
Multiple optimization methods for off-grid technoeconomic optimization.	Batteries are essential for a PV–biomass standalone system.	[199]
Novel of clustering technologies and combined optimization methods.	17% reduction in daily operating costs for nickel–cadmium batteries. More attractive lead–acid and sodium–sulfur.	[200]
Aging of lithium-ion batteries under different scenarios.	Lithium-ion phosphate cells degradation rate is less with respect to discharge energy.	[201]
Teaching learning-based optimization for optimal power flow within a grid.	Minimization of operating costs, losses and voltage stability.	[202]

As it is concluded by the most recent research papers on standalone dimensioning and optimization methods, using energy storage systems, two main factors are examined: the reduction of energy and economic costs for energy production and the reduction of greenhouse emissions. The analysis concludes that the current technological improvements on which the existing grids are based can help in meeting the modern needs and possibilities for a rational production and use of energy. Research in the direction of disengagement from fossil fuel-based production units is necessary for the development of models aimed at reducing the environmental and economic impacts they bring. At the same time, optimization in the field of energy management is a process of utmost importance for the best possible design of the systems that already exist and those that are being developed. In this sense, optimizing energy demand is appropriate not only for the operation of standalone communities but also for conventional grids managing electricity. The gathered research indicates that optimization methods can result in significant improvements, as most of the studies result in cost and emission reduction. More specifically, energy costs can be decreased for a standalone community using optimization methods, as the energy demand and production can be managed properly through demand side management, leading to the aforementioned reductions. Additionally, energy savings is a core parameter, as through the optimizations, the systems losses can be minimized, for optimized demand and production. Continuing, energy storage systems are the milestone leading to both emission and cost reduction. Even though their initial cost seems to be increased, the life cycle cost and the life cycle assessments used to the studies indicate that for a standalone community, energy storage systems can effectively be used. For that reason, several studies have focused on their proper dimensioning and better type selection. The studies conclude that lithium-ion batteries continue to be the most efficient type of energy storage systems for standalone communities. However, improvements are constantly being made for losses minimization and degradation of the storage systems. Finally, system stability, load control, energy efficiency and better communication of a standalone system are also some of the main advantages that optimization methods result in.

Additionally, it is also worth examining the most recent review papers that deal with energy storage systems (Table 9), the components and the techniques of energy storage, the management of energy and the integration of them in a standalone community.

Table 9. References of the most recent review papers on ESS.

Review Paper Categorization	Reference
Types of Energy Storage System	[16,20–22,25–27,30–33,36–39,44,203–207]
Optimization and Management Approaches	[28,29,34,35,105–118]
Specific System Components	[23,24,43,119]

Furthermore, the integration of energy storage systems, in this case batteries, as a "bridge" between the renewable energy generation systems and the consumers allows the electricity grid to balance the electricity demand and supply from the renewable energy generation systems, both on the grid level and on the consumers' level. In the Net Zero Emissions by 2050 Scenario, grid-scale storage is crucial for a number of the electrical system's functions, including short-term balancing and operating reserves, ancillary services for grid stability, postponing the investment in new transmission and distribution lines, long-term energy storage, and restarting the grid after a blackout [208]. On the consumer's level, that is "after the meter", peak shaving of the demand and short-term storage of renewable energy produced in the building is a substantial part of the zero energy buildings' strategy. For those reasons, the use of energy storage systems, combined with demand side management, allows for the most efficient use of renewable energy sources and the least possible use of units powered by expensive and polluting fossil fuels. Through their contribution to balancing energy supply and demand, energy storage systems significantly improve the efficiency of renewable sources and enable maximum penetration of renewable energy into the national energy mix.

Compared to the older, established storage options, grid-scale batteries are catching up and are anticipated to account for the bulk of storage expansion globally, despite being presently far smaller than pumped-storage hydropower capacity. Batteries are often used for daily, hourly, and sub-hourly balancing. At the end of 2021, the total installed grid-scale battery storage capacity was close to 16 GW, the majority of which was added over the previous five years. Installed capacities rose significantly in 2021, jumping by 60% over 2020 as more than 6 GW of storage capacity was installed. This is the second year in a row that installations have grown at such a pace. With increases on the gigawatt scale, the United States, China, and Europe took the top three spots in the market. In comparison to 2020, the mix of grid-scale battery technologies remained mostly stable in 2021. The bulk of the newly installed capacity continues to be stored in lithium-ion batteries, which are still the most popular kind [208]. This increase in capacities is expected to have an impact on the costs of batteries, since economies of scale will lead to further reductions of investment cost per energy unit stored. The smaller applications, for buildings and clusters of buildings, will also benefit from this development.

An IRENA survey conducted in 2019 [194] estimated that the prices of batteries will experience a price reduction of 54–61% by 2030. More specifically, for lithium-ion battery storage systems, prices between 245–620 USD/kWh are expected. This decline in combination with the possible reduction of the cost of photovoltaics, the decrease in the sale price of photovoltaic energy in the grid, the increase in the pricing of imported energy from the grid and the possible imposition of taxes (e.g., CO_2 emission tax), is expected to lead to the massive use of this technology in the future. Based on the findings of this paper, the technical and financial data, the state-of-the-art of the energy storage and the optimization methods used, one can conclude that battery storage systems seem to be the most effective option for usage in standalone communities. When combined with demand side management, a reliable, resilient and flexible energy provision system is perfectly feasible.

5. Conclusions

Standalone communities are part of most energy scenarios for a sustainable future. They can be isolated, such as for example insular systems, or integrated in the main grids, such as for example energy communities. In both cases, energy storage is crucial for an effective and efficient operation. As discussed in this paper, there are various storage options and technologies, and they have been categorized and presented within the main characteristics of them, the advantages, the disadvantages and the specific technical characteristics of each of them.

Most recent studies dealing with energy storage optimization methods met in standalone communities, as presented in the paper, adopt optimization methods that use criteria that include life cycle levelized energy costs, environmental impact, capacity sizing and energy management. Additionally, the aspects of circular economy are an upcoming topic that should be emphasized, as they can eventually determine the effectiveness of storage systems in a holistic way.

As it can be concluded by the study, energy requirements are expected to continue to increase, and at the same time, a concentration of loads appear in large urban centers, away from production locations. This has turned the focus toward the building sector, which is proving to be an important consumer of electricity, but also a potential producer. Thus, methods are developed to reduce the required operating energy of each building, and green energy production facilities are formed on or in its surrounding area. The most easily applicable and efficient energy source for these conditions is solar energy, with photovoltaic becoming the first choice in almost all cases. The two emerging problems are the fact that it is not possible to always supply solar-generated electricity and that the introduction of a great number of small producers in the electrical distribution system can cause instabilities in the operation of the core network in the very near future.

The solution to these problems is the adoption of storage systems, on the level of buildings and buildings' clusters, allowing for the storage of excess energy production and the reduction of peak demands to the core network. Batteries are ideally suited for this purpose, given the great development they have undergone in recent years, a development that is estimated to continue in the coming years, both in terms of performance and of cost-effectiveness. In addition, the optimization methods and frameworks met in the studies are an important tool for understanding the processes and performance of the microgrid integrated with energy storage systems. The applications developed support the investigation of various configurations of the microgrid and the adaptation of functions to the needs of the user in a friendly environment. In this way, it is possible to achieve an application-specific analysis based on the efficient design of the microgrid and energy storage systems.

However, for the batteries to be optimally exploited, their optimal design and dimensioning is required. Detailed analysis is necessary and should bring about an economically feasible and materially achievable result. Further challenges lie in adopting the concept of product reuse, which is important for the transition to a zero-emission economy, especially with regard to lithium-ion batteries, the production of which is a highly polluting process. In addition, it is equally important to improve recycling processes with a view to effectively recover more and more materials included in these batteries, the discharge of which into the environment has adverse effects. This is one of the key areas of research work to be carried out at a high pace.

In that sense, one must refer to future improvements and further explore the potential of energy storage systems in microgrids. It would therefore be interesting to explore:

(a) a more integrated approach that may include, among other things, the investigation of the possibility of energy exchange when the energy production is concentrated in the buildings of the microgrid and there is no possibility of utilizing renewable energy;
(b) the economic and technical analysis of the proposed system and the analysis of the costs for the development of the microgrid, the involvement of the users' behavior with the availability of real-time data on the characteristics of energy demand and weather conditions, as well as the utilization of forecasting models based on the data obtained.

Finally, a legislative and regulatory framework should be established that will treat energy storage as an energy source so that it can be valued appropriately and that will also consider the reverse supply chain of batteries. Technological solutions, even the most cost-effective ones, have rarely developed without an ambitious yet realistic regulatory framework.

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Nomenclature

AC	Alternating Current
CAES	Compressed Air Energy Storage
CED	Cumulative Energy Demand
DC	Direct Current
DOD	Depth of Discharge
DSM	Demand Side Management
ECDL	Electrochemical Double-Layer Capacitors
ESS	Energy Storage System
EV	Electric Vehicles

GHG	Greenhouse Gas Emissions
GWP	Global Warming Potential
H2	Hydrogen
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
KIB	K-Ion Batteries
LCA	Life Cycle Assessment
LIB	Lithium-Ion Batteries
LMO	Lithium–Manganese Oxide
NCA	Nickel–Cobalt–Aluminum
NMC	Nickel–Manganese–Cobalt
PV	Photovoltaic
RES	Renewable Energy Systems
RPM	Rounds per Minute
SIB	Sodium Ion Batteries
SMES	Superconduction Magnetic Energy Storage System
TES	Thermal Energy Storage
UPS	Uninterruptible Power Supply

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