sustainability

Review

A Review of the Energy Storage Systems of Non-Interconnected European Islands

Maria Fotopoulou [1], Panagiotis Pediaditis [2], Niki Skopetou [1], Dimitrios Rakopoulos [1,*], Sotirios Christopoulos [3] and Avraam Kartalidis [1]

1 Chemical Process and Energy Resources Institute (CPERI), Centre for Research and Technology Hellas (CERTH), 52 Egialias Str., GR-15125 Athens, Greece; fotopoulou@certh.gr (M.F.); kartalidis@certh.gr (A.K.)
2 Department of Wind and Energy Systems, Technical University of Denmark (DTU), Frederiksborgvej 399, 4000 Roskilde, Denmark; panp@dtu.dk
3 Hellenic Electricity Distribution Network Operator (HEDNO), Kallirrois 5 Str., GR-11743 Athens, Greece; s.christopoulos@deddie.gr
* Correspondence: rakopoulos@certh.gr

Abstract: The ongoing energy transition has caused a paradigm shift in the architecture of power systems, increasing their sustainability with the installation of renewable energy sources (RES). In most cases, the efficient utilization of renewable energy requires the employment of energy storage systems (ESSs), such as batteries and hydro-pumped storage systems. The need for ESS becomes more apparent when it comes to non-interconnected power systems, where the incorporation of stochastic renewables, such as photovoltaics (PV) systems, may more frequently reduce certain power quality indicators or lead to curtailments. The purpose of this review paper is to present the predominant core technologies related to ESSs, along with their technical and life cycle analysis and the range of ancillary services that they can provide to non-interconnected power systems. Also, it aims to provide a detailed description of existing installations, or combinations of installations, in non-interconnected European islands. Therefore, it provides an overview and maps the current status of storage solutions that enhance the sustainable environmentally friendly operation of autonomous systems.

Keywords: energy storage systems; non-interconnected islands; ancillary services; sustainability; hydro-pumped storage; batteries; renewable energy sources

Citation: Fotopoulou, M.; Pediaditis, P.; Skopetou, N.; Rakopoulos, D.; Christopoulos, S.; Kartalidis, A. A Review of the Energy Storage Systems of Non-Interconnected European Islands. *Sustainability* **2024**, *16*, 1572. https://doi.org/10.3390/su16041572

Academic Editors: Oscar Barambones, Patxi Alkorta and José Antonio Cortajarena

Received: 17 December 2023
Revised: 23 January 2024
Accepted: 31 January 2024
Published: 13 February 2024

1. Introduction

The need for sustainable development affects all energy sectors, including the power systems. For example, the European Union aims to have at least 42.5% renewable energy sources (RES) in its overall energy mix by 2030 [1] and the United States plan to eliminate fossil fuels as a form of energy generation by 2035 [2]. Consequently, it becomes evident that research and development is focused on the deployment of RES, which shall gradually replace a large proportion of fossil fuel-based conventional generators. The most widely adopted RES are photovoltaic (PV) systems and wind farms (WFs), due to the solar or wind potential of certain regions, respectively [3]. Nevertheless, these solutions have inherent stochasticity, which may inhibit their market penetration. For example, their intermittent production renders them unable to serve the load at all times, unlike conventional generators, and can also cause unexpected congestion to the power system, which might even lead to curtailments of renewable production. Moreover, the large scale implementation of RES often challenges the power quality and stability of the power system, including issues related to the frequency, harmonics, voltage regulation, etc. Additionally, they cannot directly replace the fossil fuel-based production because they do not have black start capabilities (i.e., they usually operate in grid following, instead of grid forming mode) in case a blackout occurs [4,5].

All of these challenges are magnified when the power system is weak, as in the case of non-interconnected islands [6], the control of which is proven to be challenging, especially for a diverse energy mix [7]. This term covers the islands that operate either completely autonomously or interconnected with other islands, as long as there is no connection to the power system of the mainland. Of course, over the past few decades, many islands were connected to the mainland for the purpose of local network enhancement and operating cost minimization [8]. However, there are islands that are so remote that the connection to the mainland would not be an efficient solution, either in terms of cost or energy. In such cases, the predominant solution is the installation of energy storage systems (ESSs), which may mitigate the mismatch between RES production and demand and also provide services to the power system aiming to moderate certain of the aforementioned technical issues [9].

Electrochemical batteries are the most well-known ESSs; yet, depending on the scale and the needs of the island other solutions might apply, such as hydro-pumped storage systems, flywheels, fuel cells, or even combinations of storage technologies [10,11]. For example, Rious and Perez [12] review certain ESSs, primarily batteries, flywheels and supercapacitors, in terms of energy density, efficiency, lifetime, etc., and derive suggestions for the ESSs that could be installed on various islands in order to enhance the operation of their power systems. Also, Habib et al. [13] compare the utilization of lead-acid batteries, lithium-ion batteries, flywheels and supercapacitors for contingencies in microgrids. Papadakis et al. [14] analyze the benefits of hydro-pumped storage systems in particular, review possible architectures and present installations in various countries such as China, Switzerland and Iran, in general, without focusing on non-interconnected islands. Sanchez et al. [15] review the batteries that have been installed on the islands of Galapagos, Fernando de Noronha, and Principe. Groppi et al. [16] review the ESSs and demand side management solutions applied in various smart energy islands. Finally, in a more specialized approach, Navalpotro et al. [17] review various sustainable materials for non-interconnected battery applications in depth while Nitta et al. [18] review the state of the art of lithium-ion batteries in particular, focusing on the chemical specifications.

The aim of this paper is to review the current ESS technologies, focusing on the ones installed in non-interconnected European islands, thus mapping the contemporary status and providing an overview of the trends in storage systems. Therefore, it expands the purpose of [12–18]. To this end, it presents the theoretical analysis, design, operation, advantages and disadvantages of all main ESS technologies, including their technical and life cycle properties, and also highlights the ancillary services that they can provide, especially to a non-interconnected island's system, such as black start and voltage regulation. Having examined the background of all main solutions, the main contribution of this research is the detailed presentation and discussion of the major ESSs that have been installed in European non-interconnected islands, including nominal values and system descriptions, as well as certain major plans and projects for future installations.

2. ESS Technologies

The main ESS technologies can be classified as: (i) electrochemical, including batteries, vehicle-to-grid (V2G), supercapacitors and fuel cells, (ii) mechanical, including hydro-pumped storage systems, flywheels and compressed air, and (iii) thermal, also presented in Figure 1 [19].

2.1. Electrochemical ESSs

Batteries constitute a popular choice in a variety of applications, from gadgets, e.g., smartphones and laptops, up to islands. When it comes to large scale applications, the batteries can be lead-acid, lithium-ion, nickel-cadmium or sodium-sulfur [12,20]. The main properties of each battery type are presented in Table 1.

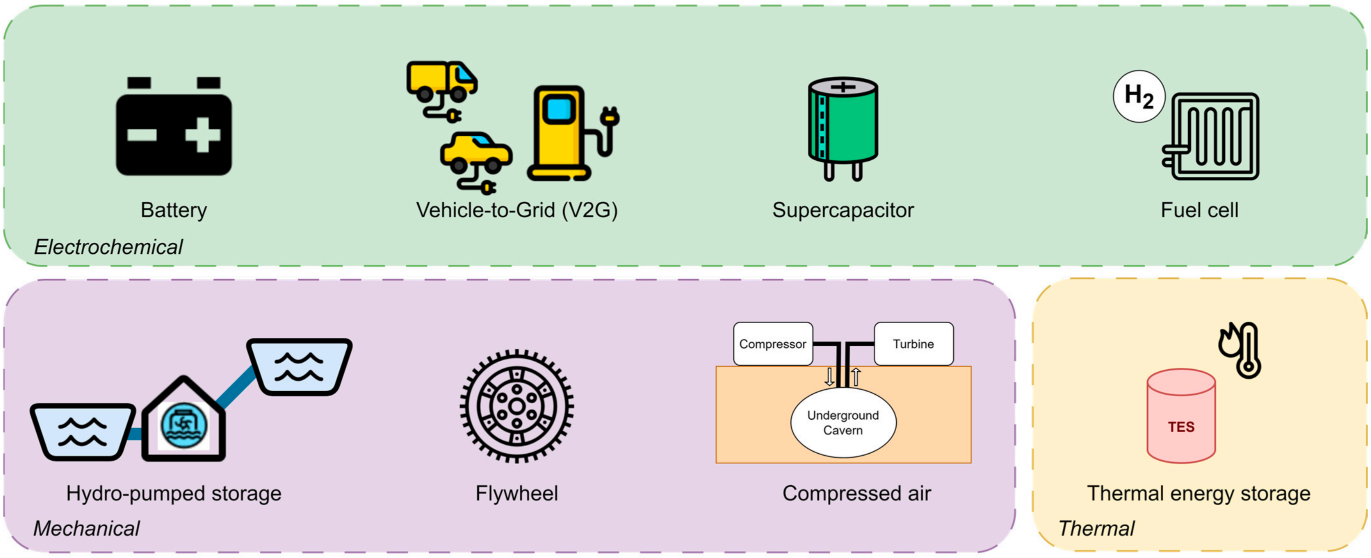

Figure 1. ESS technologies.

Lead-acid batteries are the most mature technology, the first of them being developed in 1860, with large installations (of several MW) since the middle of the 20th century. Their technological maturity is also reflected in their low cost. Nevertheless, lead-acid batteries have low energy density, i.e., 30–50 Wh/kg, relatively low round-trip efficiency, around 80%, and a shorter lifespan than their counterparts. In terms of sustainability, even though all batteries are considered to have a negative impact on the environment, the environmental and health impact of lead-acid batteries is still relatively higher than most of their counterparts because of the lead [21]. On the other hand, lithium-ion batteries were developed about a century later, in 1970, and may have a higher cost but they also have the highest energy and power density, up to 300 Wh/kg and 300 W/kg, respectively. Moreover, they have the highest roundtrip efficiency, exceeding 90%, as well as the highest lifespan, e.g., 5000 cycles. Other choices are the nickel-cadmium and sodium-sulfur batteries, the first of which were developed close to the lead-acid batteries, in 1899, while the latter were developed close to the lithium-ion batteries, in 1966, and therefore, share many of the respective properties. For example, nickel-cadmium batteries have slightly more advanced technical properties than lead-acid batteries, especially in terms of energy density, i.e., 45–80 Wh/kg, and lifespan, about 2000 cycles, and they also have a negative environmental and health impact owing to the presence of cadmium. Sodium-sulfur batteries have similar technical properties with lithium-ion batteries (but not as advanced) and are not as vastly implemented. Finally, a worth mentioning type of batteries is the flow battery, which is a cross between a conventional battery and a fuel cell. Vanadium redox flow batteries are one of the most mature flow battery technologies. Their energy density is considered to be lower than 30 Wh/kg and their round-trip efficiency is lower than 80%. On the other hand, their lifespan may reach up to 20,000 cycles. However, since they have not been extensively tested commercially, their performance has yet to be established [22].

The batteries of electric vehicles (EVs) are considered to be a modern, yet supplementary in most cases, type of storage [23]. More specifically, contemporary research related to the flexibility of distribution networks and microgrids proposes to schedule the charging of EVs according to the needs of the system operator and, in some cases, to use the collective capacity of EVs in a certain charging station as a storage system. This is also known as V2G mode and presupposes that the energy discharged from the EVs will be compensated, both in terms of energy and cost. Relevant research can be found in [24,25]. However, it is evident that such a method includes inherent uncertainties, since the time of arrival, time of departure and state of charge (SoC) of the EVs cannot be fixed. Furthermore, such an initiative would require infrastructures, social awareness, and an aggregator to act as a mediator between the system operator and the EV owners.

Similar to the batteries, supercapacitors constitute a type of electrochemical ESS [26,27]. More specifically, they comprise two electrodes divided by a membrane separator soaked into an electrolyte. Their design allows them to respond extremely fast to the load, with a high power density, up to 10,000–100,000 W/kg, but low energy density, meaning that they are mostly suitable for pulse rather than continuous energy delivery, which renders them a usual supplement to batteries. Another advantage is their lifespan, which is equal to 100,000–1,000,000 cycles. Finally, supercapacitors can be classified as double layer capacitors, pseudocapacitors and hybrid and their application fields include microgrids, traction and ships.

The list of main electrochemical ESSs is completed with the fuel cells [28–30]. A fuel cell converts the chemical energy of a fuel, usually hydrogen, and an oxidizing agent, usually oxygen, into electricity through redox reactions and can produce electricity seamlessly for as long as fuel and oxygen are supplied. If the fuel can be produced on demand (e.g., from an electrolyzer) and can be stored, then the combined fuel cell system can be considered an energy storage system. Even though the first fuel cells were invented in 1838, they are not widely adopted by the market. Their main drawback is considered to be their efficiency, which is lower than 50%.

Table 1. Comparison between battery types [12,20,22].

Battery Type	Energy Density (Wh/kg)	Power Density (W/kg)	Round-Trip Efficiency (%)	Response (Compared to Other Batteries)	Cost	Maturity	Environmental Impact	Lifespan (Cycles)	Lifespan (Years)
Lead-acid	30–50	150	Around 80%	Slow	Low	High, since 1860	High	1000–1500	5–15
Lithium-ion	Up to 300	Up to 300	>90%	Fast	High	Medium, since 1970	Medium	5000	Up to 20
Nickel-cadmium	45–80	150	Around 80%	Medium	Medium	High, since 1899	High	2000	10–20
Sodium-sulfur	150	150	80–90%	Medium-Fast	High	Medium, since 1966	Medium	1500–4500	10–15

2.2. Mechanical ESSs

Regarding mechanical ESSs, the most widely adopted technology is the hydro-pumped storage [31,32]. The main concept includes two water reservoirs, either natural or man-made, located at different heights. In order for the system to be discharged, water is released from the upper reservoir, flowing towards the lower reservoir, through a hydroturbine. In most cases, the hydropower plants comprise Pelton, Kaplan or Francis turbines. On the other hand, in order for the system to be charged, water flows from the lower reservoir to the upper reservoir with the use of pumps, usually powered by RES such as WFs. Hydro-pumped storage systems constitute a mature technology, as the first one was built in 1907 in Switzerland and several others were built in the second half of the 20th century. Their main advantages are their nominal power, which ranges from several MW up to GW and their lifespan, e.g., up to 100 years. However, their energy density is low, up to 1.5 Wh/kg and their response time is very slow, ranging from seconds up to minutes. These technical properties render hydro-pumped storage suitable for large scale, robust, main storage system solutions, able to support the operation of a power system that feeds thousands of people, yet, for rapid phenomena they could be combined with other kinds of ESSs.

Another mechanical ESS with faster response time, suitable for short-term energy storage, is the flywheel [33,34]. A flywheel comprises a large wheel, usually made from steel, on an axle fitted with frictionless bearings. As a result of its rotation, the flywheel stores kinetic energy and the faster it rotates, the more energy it stores. This design has a fast response time (almost as fast as a supercapacitor), high power density, e.g., 100–2000 W/kg, low overall cost and no negative environmental impact. Installations of flywheels in power networks usually range from 10 kW up to 250 kW. Regarding the drawbacks, they have a high self-discharge rate and low energy density, i.e., 5–80 Wh/kg. Nevertheless, over the past years flywheels made of advanced, composite materials, leading to increased energy density, have been developed.

Compressed air energy storage (CAES) constitutes an alternative mechanical ESS [21,22]. The main architecture includes a compressor, an underground cavern, and a turbine. When in charging mode, the surplus energy from the power system is utilized in order to compress the air into the underground cavern. On the other hand, when the system needs to be discharged, the compressed air is heated and expanded through the turbine. Typically, the pressure of the cavern is maintained between 40 and 80 bar. In many cases, the cavern is an old underground salt reservoir or a depleted gas field, in order to avoid the extra cost from the construction of a man-made cavern. The existing installations have a wide range of 1–300 MW. The technical properties of CAES are close to the properties of hydro-pumped storage systems. For example, they are both related to large scale applications and have slow response time (up to minutes), which is a typical trade-off for large ESSs. Furthermore, CAES systems have energy density higher than that of hydro-pumped storage systems and close to the one of lead-acid batteries, e.g., 30–60 Wh/kg. On the other hand, they have a low round-trip efficiency, up to 70%, and a shorter lifetime, up to 40 years.

2.3. Thermal ESSs

Finally, there are the thermal energy storage (TES) systems [35], which constitute a mature, well established technology, with applications from building level up to district heating, often associated with solar power plants, and a strong participation in flexibility markets, e.g., demand response strategies in energy communities. Also, in many cases, they are coupled with the power system but their stored energy is used for heating, e.g., domestic hot water and space heating. Overall, TES systems have minimum environmental impact but a significant drawback is their low round-trip efficiency, usually around 50%.

TES can be classified as low temperature and high temperature. In more detail, examples of low temperature TES systems are the aquiferous low temperature storage and the cryogenic energy storage [36]. In the case of aquiferous low temperature storage, water is cooled/iced during off-peak hours and used later, during peak time, to meet the cooling needs of the consumers. The amount of stored energy depends on the temperature difference between the water stored in the tank and the return water from the heat exchanger. This solution is considered to be particularly suitable for the peak shaving of commercial and industrial cooling loads. On the other hand, cryogenic energy storage employs the expansion ratio of low temperature liquids, usually liquid air or liquid nitrogen, to store energy. Particularly, liquid air is attracting attention due to the high expansion ratio from the liquid state to the gaseous state. The technology is primarily used for the large-scale storage of electrical energy.

Examples of sensible high temperature TES systems include water tanks, which is one of the least expensive, most commonly used options, molten salt or even hot rocks and concrete [37]. The capacity of a sensible heat storage system depends upon the specific heat and mass of the storage medium and a common drawback is the space requirements. Furthermore, regarding latent high temperature TES, the most popular option is phase change materials (PCM). PCMs are materials selected to have a phase change (usually solid to liquid) and can be divided into organic, inorganic and eutectic. Their latent heat in a phase change is considered to offer the potential for higher energy storage density than that of non phase change high temperature materials.

2.4. Comparison between ESS Technologies

The comparison of the technical and life cycle properties between all ESS technologies is presented in Tables 2 and 3, respectively. The large-scale ESSs are the hydro-pumped storage systems, followed by CAES systems, batteries and TES. In most of these cases, the response time is slow, up to minutes, which might be considered as a drawback. Yet, it should be highlighted that the batteries, even though they cannot be as large as the hydro-pumped storage systems, have a relatively fast response time and their energy density is considerably high, up to 300 Wh/kg. On the other hand, the highest power density, up to 10,000–100,000 W/kg, as well as fastest response time out of all ESS technologies is that of the supercapacitor. However, supercapacitors have substantially low energy density, lower than 15 Wh/kg, and the installed power would be more suitable for small-scale applications, as it usually does not exceed a few hundred kW. The flywheel is also characterized by very fast response time, high power density and an advantageous life cycle analysis but, like the supercapacitor, has low energy density and even though it could cover the needs of a small-scale application, it would be insufficient on its own for larger scale applications, e.g., an island. It becomes apparent that there is no single, holistically optimal ESS and it is up to the system operator to decide upon the ESS (or combination of ESSs) to be deployed, considering the needs of the electrical system, such as size, demand, available resources, etc.

Table 2. Technical characteristics of ESS technologies [12,13,19,20,22,26,35].

ESS Type	Energy Density (Wh/kg)	Power Density (W/kg)	Nominal Power	Round-Trip Efficiency (%)	Response
Electrochemical energy storage					
Battery, [12,20]	30–300	150–300	Up to several MW	80–90%	Medium-Fast
V2G (1 EV), [23]	200–300	200–300	<10 kW, e.g., 7 kW for [23]	>90%	Medium-Fast
Supercapacitor, [13,26]	<15	Up to 10,000–100,000	10–300 kW	>90%	Very fast
Fuel cell, [28]	100–1000	10–1000	Up to several MW, even 50 or 80 MW	30–50%	Slow
Mechanical energy storage					
Hydro-pumped storage, [31]	0.5–1.5	N/A	MW–GW	70–87%	Slow, from seconds to minutes
Flywheel, [33]	5–80	100–2000	10–250 kW	90%	Very fast
Compressed air, [21,22]	30–60	N/A	1–300 MW	65–70%	Slow, from seconds to minutes
Thermal energy storage					
Low temperature TES, [35,36]	100–200	N/A	Up to several MW	30–50%	Slow
High temperature TES, [35,36]	80–200	N/A	Up to several MW	Up to 80%, depending	Slow

Table 3. Life cycle analysis of ESS technologies [12,13,19,20,22,26,35].

ESS Type	Cost (per kW)	Environmental Impact	Lifespan (Cycles)	Lifespan (Years)
Electrochemical energy storage				
Battery, [12,20]	Medium-High	Medium-High, especially for lead/cadmium	1000–5000	Up to 20
V2G (1 EV), [23]	High	Medium	>1000	Depending on EV use
Supercapacitor, [13,26]	Low	Low	100,000–1,000,000	Up to 30
Fuel cell, [28]	High	Low	1000–10,000	Up to 15
Mechanical energy storage				
Hydro-pumped storage, [31]	High	Medium, if the reservoirs are man-made	Practically unlimited	Might last up to 100
Flywheel, [33]	Low	None	>20,000	Up to 20
Compressed air, [21,22]	Medium-High	Medium	10,000	20–40
Thermal energy storage				
Low temperature TES, [35,36]	Low-Medium, depending on the application/technology	None-Low	N/A	Up to 40
High temperature TES, [35,36]	Low-Medium, depending on the application/technology	None-Low	N/A	Up to 15

2.5. Integration of ESSs in the Power Network

The main scheme describing the integration of ESS technologies in power systems is presented in Figure 2 [38]. The ESS is usually connected to the distribution network through a bidirectional converter, based on power electronics, and it can be charged or discharged according to the system's needs. Usually, it is more efficient to have a direct current (DC) connection in order to reduce the conversion losses.

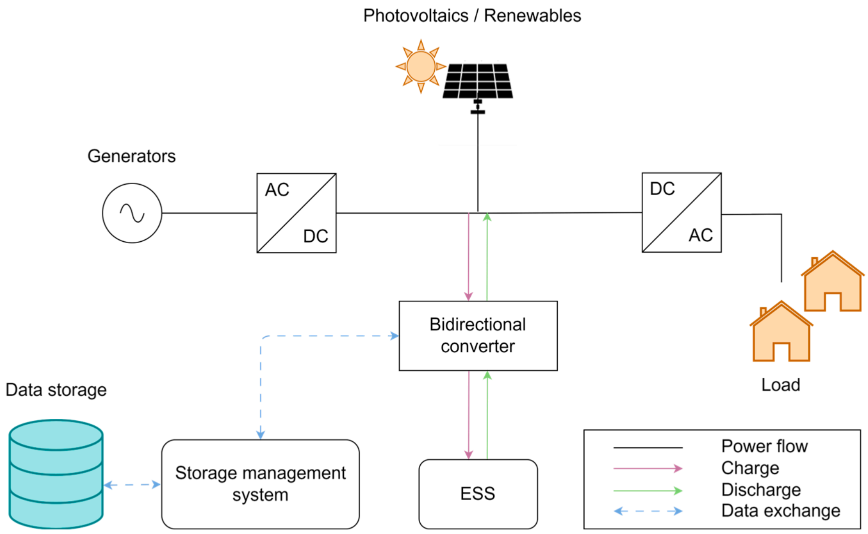

Figure 2. ESS integration in the power network.

The state of charge, SOC, at each time-step, t, is calculated using (1), where P_t^{ch} is the power charged to the ESS at time-step t, P_t^{dch} is the power discharged from the system at time-step t, Δt is the duration of the time-step, η is the efficiency of the ESS and E_{nom} is its nominal energy. Of course, an ESS cannot be charged and discharged simultaneously. Therefore, ESS-related models include binary variables, i.e., u_t^{dch} and u_t^{ch}, which indicate if the ESS is being charged or discharged, respectively. The power balance of the system is presented in (2) where the ESS is added to the formula as either a source or a load, multiplied with the respective binary variables. The energy mix is completed with the production of the generators, P_t^g, and the RES production, P_t^{RES}, while L_t is the load at time-step t. As a consequence, mixed integer linear programming (MILP) or mixed integer non-linear programming (MINLP) optimization problems are formulated. Optimized power flow analysis using the aforementioned formulas as a basis can be found in [25,39,40] where the ESS are lithium-ion batteries, EVs and supercapacitors, respectively.

$$SOC_{t+1} = SOC_t + \frac{P_t^{ch}\Delta t}{E_{nom}}\eta - \frac{P_t^{dch}\Delta t}{E_{nom}\eta} \tag{1}$$

$$P_t^g + P_t^{RES} + P_t^{dch}u_t^{dch} - P_t^{ch}u_t^{ch} = L_t \tag{2}$$

3. Ancillary Services of ESS in Non-Interconnected European Islands

ESSs can provide important ancillary services to power systems, leveraging their unique capabilities to enhance grid stability, reliability, and efficiency. The increased importance of ancillary services provided by ESSs is evident through several research projects which focus on their utilization. For example, there are two Horizon 2020 projects, IANOS and TIGON, where: (i) storage systems, such as flywheels, are deployed in order to provide fast frequency response and (ii) lithium-ion and lead-acid batteries are utilized for black start after emergencies that cause blackouts, respectively [41,42].

The advantages of ESSs become, arguably, more useful in non-interconnected systems such as geographical islands [43]. Although non-interconnected systems are small scale power systems, common issues tend to be more critical due to their diminished shock and risk diffusion capabilities [44]. Therefore, ESS-based ancillary services are valued higher in non-interconnected islands, rendering their installations more lucrative.

A common taxonomy of ancillary services is frequency and non-frequency related [45] or at system and local level [46]. In the context of this analysis the ancillary services are sorted as: (i) frequency-related services which are relevant for the entire system of the non-interconnected island, (ii) non-frequency related services which deal with problems restricted to single nodes (local level) and (iii) other services that may or may not be related to frequency and/or system level problems.

3.1. Frequency-Related Services at System Level

ESSs can respond rapidly to changes in grid frequency by injecting or absorbing power in accordance with the demand [47]. Specifically, when an over-frequency occurs, these systems swiftly absorb surplus power, whereas during under-frequency periods, they promptly deliver power to the grid (P(f) droop control) [48]. In scenarios where small islanded power systems rely heavily on inverter-interfaced generation devices, the absence of substantial rotational inertia renders them more susceptible to higher frequency deviations compared to interconnected networks [49]. Consequently, ESSs play a crucial role in maintaining system frequency within acceptable thresholds and resolving unbalances between power supply and demand. The following sub-sections list each frequency related ancillary service and discuss how ESSs can participate in those services when located in a weak non-interconnected system.

3.1.1. Virtual/Synthetic Inertia

The rapid increase of RES that are coupled via inverters to the power system leads to the decrease of rotational inertia which can have adverse effects on system stability and reliability [50]. In case of frequency fluctuations and disturbances, low inertia systems exhibit higher rates of change of frequency (RoCoF) and larger deviations (zenith or nadir) from the nominal frequency which, in turn, can trigger cascading failures. This phenomenon is stronger in non-interconnected islands, which typically already have lower inertia compared to large continental systems and the RES are usually not dispersed over a large area and thus are subject to the same weather conditions and variations.

In order to address this issue, ESSs have emerged as a promising solution to provide virtual/synthetic inertia, emulating the inertial behavior of synchronous generators. This requirement translates into ESSs reacting to the RoCoF (i.e., a $P - df/dt$ droops). Several algorithms and virtual inertia control strategies have been developed, allowing inertia contributions from ESSs, and other distributed energy resources (DERs), that are shown to be more cost effective than keeping dated synchronous generators online [51]. In non-interconnected systems of islands, due to very low mechanical inertia, the contribution of ESSs with virtual inertia response can be even more crucial, however, the more precarious conditions create stricter requirements in terms of response time and tuning accuracy. In recent literature, it is shown that inertia response can be considered in the unit commitment problem of islands and ESSs can significantly increase the dynamic security of the system [52].

3.1.2. Fast Frequency Response (FFR)

FFR is a relatively newer category of services that lies between virtual inertia and FCR [53]. It has applications (in different forms) in Ireland [54], the UK [55] and the Nordics [56], which are systems with lower inertia compared to the continental system of mainland Europe. The main control trigger of FFR is changes in frequency (ΔF) instead of the RoCoF (df/dt) and the response time is short, usually a few seconds or even less than a second. The goal of FFR is to assist the system in reducing both the RoCoF and the nadir of the frequency deviation by reducing the size of the contingency (ΔP) before the acute transient phase is completed [57]. Most ESS technologies are very well suited for servicing FFR requests due to their response time which can match that of FFR products [58].

3.1.3. Frequency Containment Reserve (FCR)

FCR is one of the main frequency related services available to transmission system operators (TSOs) for balancing the power system [47]. There are minor differences between countries and systems regarding the requirement for servicing FCR, however, typically, full activation time is 30 s after the frequency deviation is detected. In the Nordics, there is a differentiation between FCR-N, which is triggered by small deviations of 0.1 Hz and aims to keep the frequency within the standard frequency range, and FCR-D, which takes effect below 49.5 Hz and above 50.5 Hz and its goal is to limit the frequency deviation during larger disturbances.

Regardless of the specifics, the value of batteries for provisioning FCR has been evaluated in the literature [59–61]. Storage systems can provide the required power to maintain system frequency until they are relieved by the FRR, eliminating the need for a large percentage of the conventional plants that serve this role. However, if not managed correctly, batteries can suffer significant degradation [62,63].

3.1.4. Frequency Restoration Reserve (FRR)

FRR are divided into two main categories: automatic frequency restoration reserves (aFRR) and manual frequency restoration reserves (mFRR). The aFRR is activated automatically and is designed to restore the system frequency to its setpoint value after the initial action of the FCR. The mFRR, on the other hand, requires manual activation and is used to restore the balance between generation and consumption after the activation of aFRR.

In terms of activation times:

- aFRR are activated after FCR, usually within minutes (e.g., 30 s to 5 min)
- mFRR follow aFRR and can be activated within a range of several minutes (e.g., 5–15 min) after the disturbance.

The utilization of storage systems for FRR (and FCR in some cases) presents a certain range of obstacles. The most important one is the large energy volume required by FRR products which a storage system might not be able to serve [64]. Certain types of energy storage systems, like flywheels, are physically excluded from this type of service due to their lack of significant energy storage potential. However, even batteries can fail a FRR request if their SoC is not sufficient. Special consideration in the management of a battery has to be taken into account in order for FRR services to be provisioned. Moreover, considering how dynamic SoC and, by extension, battery availability can be, their inclusion to FRR dimensioning presents extra control and tuning issues for system operators. Dynamic allocation of FRR responsibility to batteries has been proven to be a good solution in non-interconnected systems [65]. The properties of frequency-related services are presented in Table 4.

Table 4. Properties of frequency-related services [47,48].

Frequency Service	Full Activation Time	Activation Bandwidth	Control Input Signal	Duration
Inertia	0 s	-	df/dt	-
FFR	0.5–2 s	±0.1–0.5 Hz	Δf	5 s
FCR-N	30 s	±0.1 Hz	Δf	-
FCR-D	Up to 30 s	±0.5 Hz	Δf	30 s–5 min
aFRR	30 s–5 min	±0.5 Hz	Δf	15 min+
mFRR	5–15 min	manual	-	15 min+

3.2. Non-Frequency-Related Services at Local Level

Similarly to frequency related services, ESSs can be a valuable resource for providing non-frequency related services [66]. Depending on the energy volume they can store, this contribution can range from very short-term services, e.g., short-circuit current, to longer ones, such as network congestion mitigation. Although most of the non-frequency related services are local in nature and, on paper, should not be treated differently in non-interconnected systems, in reality, many islands have underdeveloped infrastructure, compared to the mainland, which renders ESS solutions an attractive alternative to costly infrastructure upgrades. For this reason, it is important to study ESS potential for local ancillary services, as well.

3.2.1. Voltage Regulation

The problem of voltage quality is the one that occupies most of distribution system operators (DSOs) around the world. In medium, but especially low voltage networks, slow voltage problems, i.e., under- and over-voltage instances, are becoming increasingly more common [67]. The former is an old problem which becomes aggravated by the introduction of new loads such as EVs and heat pumps while the latter is a newer problem caused by DERs, such as rooftop PVs. To mitigate such problems, DSOs have a list of options at their disposal. First is grid reinforcement, which reduces electrical impedance, thus mitigating voltage limit violations. Another option is on-load tap changers (OLTC) for the regulation of the voltage at the substation level, thus allowing for larger drops or rises without limit violations. A third, more elaborate, option is the direct or implicit control of DERs. All three options have certain drawbacks: investments can be rather costly, OLTCs have limited capabilities which, if not automated and in the absence of network observability, can do more harm than good, and, finally, control of DERs by DSOs is either prohibited if direct, or needs elaborate mechanisms of tariffs and/or markets if implicit. To this end, many studies suggest the employment of distributed ESSs for addressing the problem of voltage regulation [68].

ESSs can contribute to voltage regulation directly, as utility scale storage owned by the system operator, or implicitly via local flexibility markets, similarly to other DERs [69]. This contribution can materialize through active or reactive power provision, or both. Many ESSs have reactive power provision capabilities via their power electronics interface, e.g., battery storage. The effectiveness of each combination of active and reactive power support can depend on the voltage level which, in turn, is characterized by certain resistance/reactance ratios [68]. To all the above, little distinction can be made between interconnected and non-interconnected systems as under/over-voltage problems are usually purely local.

3.2.2. Network Congestion Mitigation

Network congestions, when not grouped with slow voltage problems, refer to violations of substation transformer maximum current limits or distribution line thermal limits (also correlated to current). These types of problems are also usually confined to the location of the affected equipment. They occur in occasions with high demand–low generation or vice versa and are due to network capacity stretched to its limits or very rapid changes in consumption patterns. Overloading of infrastructure such as transformers and lines can cause equipment failure much sooner than their expected lifespan. Their mitigation measures are similar to that of under/over-voltage problems described before, with the exception of OLTCs. Often, the two problems of voltage and line congestion are grouped together as physical constraints in methods that try to optimize resource management in transmission and distribution networks. The usage of ESSs to solve congestion problems is similar to slow voltage problems with storage being ideal for reducing peaks in consumption and shifting demand towards consuming excess generation. ESSs can store excess energy during times of low demand (night-time) or low-cost generation and discharge it during periods of high demand (day-time) or high electricity prices, usually following a predetermined charge/discharge daily cycle. Load shifting and flattened demand peaks reduce strain on the grid and optimize electricity costs. Storage systems can also be incorporated on the end-user/customer side, offering an innovative approach to mitigating peak demand charges during brief periods of high-power demand [70,71].

3.2.3. Short-Circuit Current

Short-circuit capacity is an attribute that characterizes a distribution network and it is part of its design. It describes the maximum allowed fault current given the networks switchgear, fuses, architecture, and other equipment. This design can be meaningfully affected when DERs are installed in the network, especially when they have power injection capabilities, such as PVs and battery storage [72]. A common case is that of a generating DER that contributes to a fault current, limiting the contribution from the feeder, hence, preventing the proper protection system response. Despite the shortcoming, DERs, and especially ESSs can contribute to the increase of short-circuit levels of distribution network, thus increasing its DER hosting capacity, providing a valuable service to DSOs [73].

3.3. Other Services

The final category includes non-frequency related services that are, usually, not purely local in their scope. These are islanding and black-start services that are characterized by increased complexity, considering that both require a priori configuration by the system operator in order to achieve the desired results. Moreover, both services, in the absence of dispatchable thermal units, are reliant on ESSs for their operation.

3.3.1. Islanding and Uninterrupted Power Supply

One of the consequences of the growing penetration of RES, that becomes critical in smaller and non-interconnected power systems, is the grid forming capability. As conventional dispatchable generators are replaced, it is difficult for intermittent RES to assume grid forming responsibility. In such cases, the role of ESSs, especially those with significant energy storage capabilities, can be crucial as batteries can provide grid forming services to the system operator [74]. The benefit is the safe decommissioning of conventional thermal generators. Furthermore, in cases of fault or disturbances that usually result in interruption of supply, ESSs can exploit their grid forming capabilities to keep part of the network operational in islanding conditions. The resulting microgrids that are formed can keep serving priority loads for a period of time, enhancing system resilience and reducing the frequency and duration of interruptions for customers [51,75].

3.3.2. Black Start

Certain energy storage systems, such as advanced batteries, can provide black start capability. They can initiate the restoration of the power system in the event of a complete or partial blackout, providing the initial power supply needed to bring other generation resources online, in grid forming mode. This is an important ancillary service from the microgrid to the main grid operator because in this way the main grid faces a lower load during its reactivation. Moreover, the consumers of the microgrid can have a lower customer average interruption duration index (CAIDI), which is an important reliability key performance indicator (KPI) and the microgrid's RES remain disconnected for a lower time interval, therefore less RES production is unexploited. In case the energy management system (EMS) is designed to charge the ESS with surplus RES production, it is possible to have a completely sustainable black start, which would not usually happen in large systems that rely on fossil fuel-based generators for this purpose. Sequential and parallel restoration strategies can be found in [76,77].

4. ESSs Installed in Non-Interconnected European Islands

Having analyzed the theoretical aspects of ESSs as well as the services which they may provide, the purpose of this Section is to present and discuss the actual ESS solutions that have been implemented on European islands that are not connected to the power system of the mainland. Of course, the identified islands may be connected with other remote islands, as long as the overall system is not connected to the mainland in any way. The authors acknowledge that these are not the only non-interconnected islands with a storage system but they are the most outstanding in terms of ESS size, technologies or combination of technologies. Furthermore, in the context of this Section, the ESS implementation needs to be complete and operating, therefore, projects under licensing, ongoing projects, etc., are not included.

4.1. ESSs of Non-Interconnected Greek Islands

An interesting case of ESSs is the hydro-pumped storage system located in Ikaria, Greece [78]. This island is currently not connected to any other islands or the mainland. It is mostly known for tourism and therefore the load is considerably higher, more than doubled, during summer, e.g., up to 8 MW. The location of the island has great PV and WF potential. For this purpose, the power system of Ikaria includes conventional generators, installed at 15 kV, but also WFs and PV systems with installed power equal to 1 MW and 0.4 MW, respectively. Taking advantage of the altitude differences of the island, the selected ESS was a hydro-pumped storage system, constructed in 2019, connected to the distribution network with a 33 km double line at 20 kV, as presented in Figure 3. This system comprises a 2.7 MW WF, two hydropower plants with Pelton turbines, 1.05 MW, and 3.1 MW, respectively, and a 3 MW pumping station. Unlike conventional hydro-pumped storage systems, it has three tanks instead of two. More specifically, it comprises: (i) a dam with 900,000 m^3 capacity, principally used for irrigation and water supply while excess water is exploited for energy generation, (ii) an upper reservoir with 80,000 m^3 capacity, located at 167 m below the dam, where the 1.05 MW hydropower plant is installed, and (iii) a lower reservoir with 80,000 m^3 capacity, located 505 m below the upper reservoir, where the 3.1 MW hydropower plant is installed. This ESS as well as the overall power system of the island has been modified and upgraded throughout the years and has also served as a pilot in projects, such as SINNOGENES, an ongoing Horizon Europe project which aims to enhance the flexibility of networks including ESSs [79].

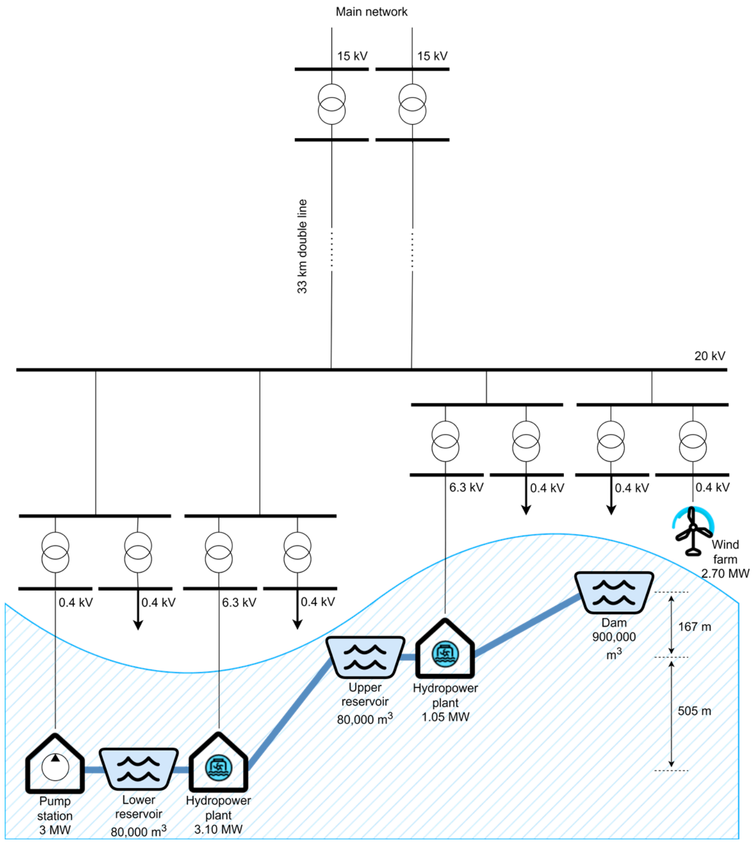

Figure 3. The hydro-pumped storage system of Ikaria, Greece.

Other non-interconnected Greek islands that ought to be mentioned are Agios Efstratios, Tilos and Kythnos, where the selected ESSs were various kinds of batteries, supporting the operation of PV systems and WFs [80–83]. More specifically, Agios Efstratios, which is an island well-known for its "green" energy transition, has a 1.25 MW/2.5 MWh lithium-ion battery connected at 15 kV. Tilos has a 0.8 MW/2.8 MWh sodium nickel chloride battery connected at 20 kV, actively providing frequency-related ancillary services and voltage regulation ancillary services to the operator, while black start has also been successfully performed in the context of research activities. Kythnos has a 0.5 MW/0.4 MWh battery connected at 15 kV. Remarkably, Kythnos not only constitutes a non-interconnected island with sustainable energy resources and storage but is also the island where the first microgrid of Europe was installed, in 2001 [83]. More specifically, the Gaidouromantra microgrid comprises mostly PV systems and vacation houses and uses a lead-acid battery as storage, connected at 0.4 kV.

4.2. ESSs of Non-Interconnected Portuguese Islands

Innovative storage solutions can be found in the autonomous regions of Portugal: Azores and Madeira. These islands are located in the Atlantic Ocean and, therefore, cannot be connected to the mainland. Furthermore, they are worldwide known tourist destinations during summer and need to provide electricity for hundreds of thousands of people. Consequently, they have increased needs, which renders them ideal pilots for various sustainability-related projects, hence the various schemes of ESSs that they have adopted in order to cover the demand. For example, Terceira, located in the Azores archipelago, has a 15 MW/10.5 MWh battery to cover its load [84]. Apart from that, on a lower scale, Terceira has a 100 kW/3 kWh flywheel connected at 15 kV, supporting the operation of the dairy factory of Pronicol, which is one of the largest electricity consumers in Terceira, and V2G, considering the market penetration of EVs. The V2G system comprises thirteen chargers, 22 kW each, and operates at 0.4 kV. It should be noted that the flywheel and the V2G are part of the IANOS Horizon 2020 project, which aims at the decarbonization of the islands [41].

On the other hand, the island of Madeira, located in the Madeira archipelago, has a combination of hydro-pumped storage, battery and V2G [85–88]. More specifically, the main hydro-pumped storage system, also known as Calheta III [85], is considered to cover about 10% of Madeira's electricity demand. It includes one dam with a capacity of 1,000,000 m^3, at 1345 m height, as well as a buffer reservoir with a capacity of 70,000 m^3, at 654 m height. Therefore, the hydro-pumped storage system utilizes a height difference of almost 700 m. The hydroelectric plant comprises two Pelton turbines, 15 MW each, while the pumping station comprises three pumps, 5 MW each. Aside from that, the island has its own battery with nominal values equal to 15 MW/16.4 MWh, large enough to perform black start on part of the 60 kV network and restore its service in the event of an outage. Finally, Madeira is gradually adopting the V2G concept with the installation of four chargers, 10 kW each, two 50 kW quick chargers and one fully SiC 50 kW fast charger, as part of INSULAE, a Horizon 2020 project [89]. It should also be highlighted that Porto Santo, another island of the Madeira archipelago, incorporates a scheme of ESSs [90,91]. Porto Santo is a smaller island, with about 5158 permanent residents. Therefore, the scale of the storage solution is expected to be different. More specifically, it utilizes a 4 MW/3 MWh battery as well as two fuel cells, 5 kW each. The ESSs of Terceira, Madeira and Porto Santo are presented in Figure 4.

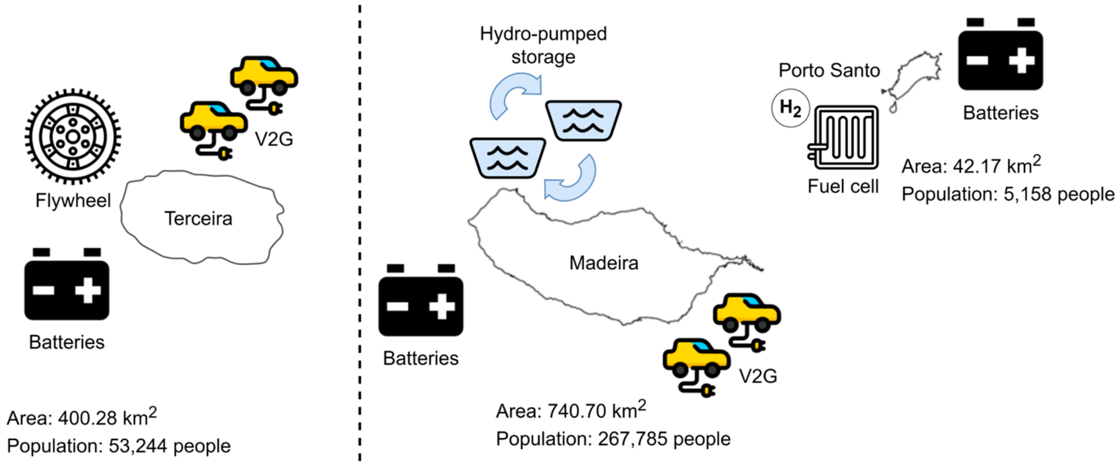

Figure 4. Combinations of ESSs in autonomous regions of Portugal: Terceira, Azores (**left**), Madeira and Porto Santo, Madeira (**right**).

4.3. ESSs of Non-Interconnected Danish, Italian, Spanish, Scottish and Other Islands

The Faroe Islands, Denmark, implement ESSs mostly to fully exploit the energy produced in their WFs. For example, Suduroy has a 6.25 MW/7.5 MWh battery to provide backup power to the 6.3 MW Pokeri WF [92]. Additionally, Streymoy has a 2.3 MW lithium-ion battery to overcome short term variations of the Husahagi WF production, which has installed power equal to 12 MW [93]. The battery provides ramp control to smooth the sharp increases and decreases of power, as well as frequency response and voltage control services.

Notable cases are also the non-interconnected islands of Italy, Favignana and Ustica, where lithium-ion batteries have been installed in the low voltage distribution network. More specifically, in Favignana, the battery installations can be divided in two categories [94]. The first is the 2.4 kW/9 kWh batteries, which are distributed in four single-phase, solar-based microgrids and the second is the 20 kW/23.4 kWh batteries, three of which are installed in the three-phase, low voltage distribution network. Similarly, the island of Ustica has a 64 kW/59.5 kWh lithium-ion battery installed in low voltage [95].

El Hierro, which is part of the Canary Islands, is another example of non-interconnected islands with increased sustainability-related requirements as not only it does belong to the Canary Islands but it is also the most remote (far left) of them. For the purpose of energy storage, and taking into consideration the island's altitude differences, El Hierro has a hydro-pumped storage system supported by a WF [96,97]. In more detail, the 11.5 MW WF comprises five wind turbines, 2.3 MW each, while the 11.3 MW hydropower plant comprises four Pelton turbines, about 2.8 MW each. The pumping station includes two variable-speed pumps, 1.5 MW each, as well as 6 fix-speed pumps, 0.5 MW each, amounting to a total of 6 MW. The overall system operates at 20 kV. Following El Hierro's example, Gran Canaria, which is a larger Canary Island, will adopt a similar hydro-pumped storage solution in the near future.

Last, but not least, there is the case of Eigg, Scotland, which has less than 100 permanent residents. Despite its size, this island has a rich RES energy mix, including hydropower plants, PV systems and WFs, and incorporates an interesting scheme of ESSs too [98]. In particular, Eigg has a lead-acid battery, 60 kW/212 kWh, and also flywheels and supercapacitors, which is a rare combination and unique when it comes to non-interconnected European islands.

Also, there are mentionable cases of non-interconnected islands that are located overseas but are classified as European, more specifically in the French overseas region in the Caribbean [99]. For example, in the French island Marie-Galante in the administrative area of Guadeloupe, there is the Petite Place WF, that consists of nine small wind generators of 275 kW each and assisted by a lithium-ion battery of 0.5 MW. The storage is used to compensate energy production forecast error and provides voltage support. Moreover, a battery system was installed in Guadeloupe by the France National Solar Energy Institute, at the Sainte Rose WF to increase the margin for renewable installations. The total storage is 4 MW/2.32 MWh and an energy management system was installed to monitor and maximize the system's operation.

4.4. Comparison between Existing ESS Installations in European Islands

The identified islands, their storage systems, the nominal values and the voltage levels are presented in Table 5. Taking the aforementioned islands into account, it can be concluded that in such applications the most popular ESS solution is the battery, especially the lithium-ion battery. Another very popular solution is the hydro-pumped storage, in some cases combined with WFs. Other sorts of ESSs may be flywheels, V2G, fuel cells, and supercapacitors, especially in combination with each other and a battery. Regarding the nominal values, there are several cases where the nominal power is in the order of MW, even higher than 10 MW, as in the case of Terceira and Madeira islands, and these values refer to batteries and hydro-pumped storage systems. Moreover, taking all cases into account, the voltage levels are usually close to 20 kV, with certain exceptions. Of course, this does not apply to V2G storage, as it is usually designed to operate at 0.4 kV.

Table 5. ESS installations in non-interconnected European islands.

Island	Storage System	Nominal Values	Voltage
Ikaria, Greece, [78]	Hydro-pumped storage	- 2.7 MW WF - Two hydropower plants 1.05 and 3.1 MW, respectively - 3 MW pumping station	20 kV
Agios Efstratios, Greece, [80]	Lithium-ion Battery	1.25 MW/2.5 MWh	15 kV
Tilos, Greece [81,82]	Sodium Nickel Chloride Batteries	0.8 MW/2.8 MWh	20 kV
Kythnos, Greece, [83] *Gaidouromantra MG*	Battery *Lead-acid (FLA) Battery*	0.5 MW/0.4 MWh *1000 Ah*	15 kV *0.4 kV*
Terceira, Azores, Portugal, [84]	Battery, Flywheel and V2G	Battery: 15 MW/10.5 MWh Flywheel: 100 kW/3 kWh V2G: Thirteen chargers, 22 kW each	15 kV for the battery and the flywheel, 0.4 kV for V2G
Madeira, Madeira, Portugal [85–88]	Hydro-pumped storage, Battery and V2G	Hydro-pumped storage: - 30 MW hydropower plant - 15 MW pumping station Battery: 15 MW/16.4 MWh V2G: - Four chargers, 10 kW each - Two 50 kW quick chargers and - One fully SiC 50 kW fast charger	60 kV for battery and hydro-pumped storage, 0.4 kV for V2G
Porto Santo, Madeira, Portugal, [90,91]	Battery and fuel cell	Battery: 4 MW/3 MWh Two fuel cells, 5 kW each	6.6 kV
Suduroy, Faroe Islands, Denmark, [92]	Battery	6.25 MW/7.5 MWh	20 kV
Streymoy, Faroe Islands, Denmark, [93]	Lithium-ion battery	2.3 MW	20 kV
Favignana, Italy, [94]	Lithium-ion batteries	Four 2.4 kW/9 kWh batteries and Three 20 kW/23.4 kWh batteries	0.4 kV
Ustica, Italy, [95]	Lithium-ion battery	64 kW/59.5 kWh	0.4 kV
El Hierro, Canary Islands, Spain, [96,97]	Hydro-pumped storage	- 11.5 MW WF - 11.3 MW hydropower plant - 6 MW pumping station	20 kV
Eigg, Scotland, [98]	Lead-acid battery, supercapacitors and flywheels	60 kW/212 kWh	3.3 kV
Marie-Galante, Caribbean, [99]	Lithium-ion battery	0.5 MW/0.5 MWh	20 kV
Guadeloupe, Caribbean, [99]	Lithium-ion battery	4 MW/2.32 MWh	20 kV

5. Future Trends and Challenges

The value and necessity of ESSs in modern power systems can be highlighted by the market analysis of the annual installed power capacity in Europe, with projections up until 2030, conducted by the European Association for Storage of Energy, also presented in Figure 5 [100].

According to the analysis, by 2030 there will be almost 12 GW of ESSs in Europe. Furthermore, the countries with the highest ESS share are expected to be Great Britain, Germany, Greece, Italy and Spain. Out of the aforementioned countries, Greece has a plethora of non-interconnected islands and a high proportion of the ESSs shall be installed there. In this context, several studies have been conducted and certain projects for the installation of ESSs on Greek non-interconnected islands have started, as presented in Table 6. The majority of the planned ESSs are electrochemical batteries, which is consistent with the small size of Greek non-interconnected islands. For example, Astypalaia is in the process of installation of a 5 MW/10 MWh battery [101]. On the island of Othonoi and Ereikoussa, studies conducted in the context of the NESOI Horizon 2020 project showcase how diesel-based power stations can be replaced by hybrid power stations combining WF, PV and battery systems [102,103]. Also, in the case of Chios, not only the installation of batteries and PV systems but also the partial replacement of fossil diesel with renewable diesel is studied [104]. On the other hand, there is the island of Sifnos, where a hydro-pumped storage system is to be installed. According to [105], this includes: (i) four Enercon E-82/E4 wind turbines with a nominal power of 3 MW each and a rotor diameter of 82 m, giving a total WF power of 12 MW, (ii) a hydropower plant with four Pelton turbines with nominal power of 2.185 MW each, providing a total plant capacity of 8.74 MW and (iii) a pump station with twelve centrifugal pumps with nominal mechanical power of 0.857 MW each, providing a total station nominal power of 10.28 MW.

Table 6. Future trends of Greek non-interconnected islands [101,103–105].

Island	Status	Storage System	Plan
Astypalaia, [101]	Ongoing	Battery	- Installation of a 5 MW/10 MWh battery - Installation of 3.5 MW PVs
Sifnos, [105]	Ongoing	Hydro-pumped storage	- 12 MW WF - 8.74 MW hydropower plant - 10.28 MW pumping station
Othonoi, [103]	Study	Battery	Diesel-based power stations will be replaced by hybrid power stations combining: - WF - PVs - Battery
Ereikoussa, [103]	Study	Battery	Diesel-based power stations will be replaced by hybrid power stations combining: - WF - PVs - Battery
Chios, [104]	Study	Battery	- Installation of battery within the existing thermal power plant - Installation of new PVs - Partial replacement of fossil diesel with renewable diesel.
Psara, [104]	Study	Battery	- Installation of a battery at the site of its abolished thermal power plant - Installation of new PVs
Oinousses, [104]	Study	Battery	- Installation of a battery - Installation of new PVs

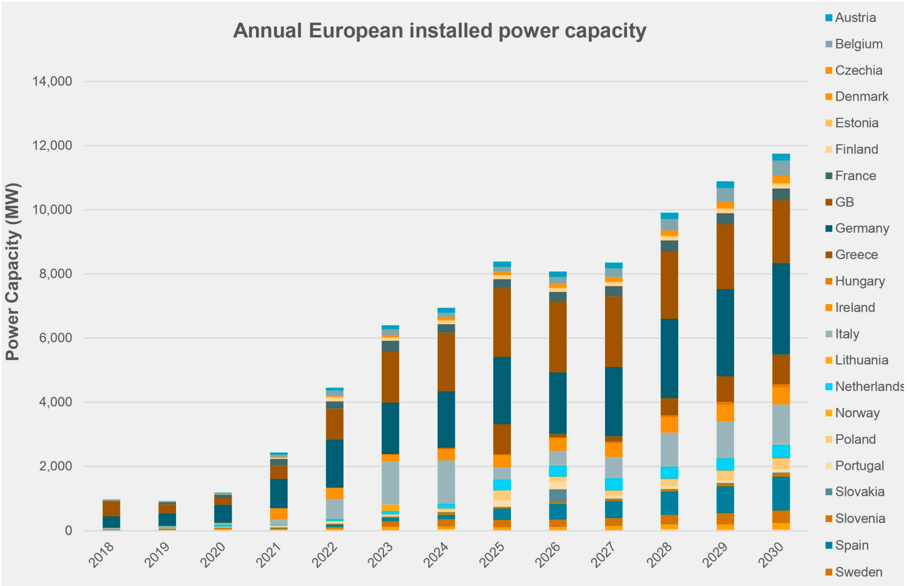

Figure 5. Analysis of the annual European installed capacity, derived from the European Association for Storage of Energy [100].

Although the future of ESSs in non-interconnected islands seems promising, there are certain challenges that should be taken into consideration. A major challenge is the right selection of the ESS technology to be implemented [106]. For example, there may be cases where the high demand of an island would be better served with a hydro-pumped storage system but the low altitude and other geographical limitations render the construction of such a system non-effective. Therefore, the solution for this challenge should be the installation of another kind of ESS, e.g., batteries. Also, there are environmental challenges to be addressed, the predominant of which being the harmful impact of lead, cadmium and/or other chemicals presented in batteries [107]. From a technical point of view, an open research topic/challenge is the optimal combination of ESSs so that the effect of their combined properties, e.g., energy density, power density, efficiency, is maximized, also known as hybrid energy storage systems (HESS) [108]. For this purpose, certain researchers suggest solutions such as the combination of lithium-ion batteries with supercapacitors or fuel cells. For example, Pang et al. [109] have developed a method for the optimal sizing of HESS the purpose of which is to smoothen the fluctuations of wind power. In this case, the HESS comprises batteries and supercapacitors, whereas Chong et al. [110] review the effectiveness of HESS comprising batteries and fuel cells in microgrids with PV systems and WFs [111]. Another open research topic, gaining more interest from the research community, is the implementation of V2G storage where the vehicles incorporate fuel cells instead of lithium-ion batteries, which changes the efficiency and the response time of the system. Regarding safety concerns, it should be highlighted that even the most widely implemented ESSs entail certain risks. Particularly, large-scale lithium-ion batteries (and other kinds of batteries) have caused explosions and fires, leading to damaged equipment or even the loss of human lives [112]. Therefore, adequate safety mechanisms for ESSs remain an open topic. Finally, an important challenge is the social acceptance of certain ESSs (or ESS-related) solutions. For example, there have been cases where part of the local community was against the construction of hydropower plants or the installation of WFs in their region for various reasons ranging from space, agricultural, touristic and archaeological limitations/concerns up to the protection of rare natural habitats [113]. Of course, these concerns should be taken into consideration during the decision making processes so that the technical solutions are harmonized with the needs of the local society.

6. Conclusions

This paper provides a review of the capabilities of ESSs focusing on existing applications on non-interconnected European islands. Its purpose is to highlight the importance of storage systems, which facilitate the ascending merge of RES in the energy mix. The main electrochemical, mechanical, and thermal technologies are presented and compared to each other considering criteria such as energy density, efficiency, nominal power, environmental impact and lifespan, highlighting the extended capabilities of batteries and hydro-pumped storage systems, especially for large-sized networks. The ancillary services, mostly related to frequency and voltage regulation, are presented in detail, showcasing the value of controllable storage systems which are the sustainable counterpart of fossil fuel generators in the modern power system. Finally, the real life installations of ESSs in non-interconnected European islands are analyzed, with special focus on the nominal power and voltage. Interesting and more complex systems, such as the hydro-pumped storage system of Ikaria, Greece, and the storage systems of certain Portuguese islands, such as Terceira, which combines a battery, V2G and a flywheel, are explained in detail. The purpose is to provide an overview of the existing storage installations and assist towards paving the path for the adoption of ESSs by more power systems in the future.

Author Contributions: Conceptualization, M.F. and S.C.; investigation and resources, M.F., P.P., S.C. and A.K.; writing—original draft preparation, M.F., P.P., N.S. and A.K.; writing—review and editing, M.F., P.P., A.K. and D.R.; funding acquisition, D.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Union's Horizon Europe innovation action, SINNOGENES (STORAGE INNOVATIONS FOR GREEN ENERGY SYSTEMS), under grant agreement No 101096992, https://cordis.europa.eu/project/id/101096992 (accessed on 22 November 2023).

Conflicts of Interest: Author Sotirios Christopoulos was employed by the company Hellenic Electricity Distribution Network Operator. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. European Commission Renewable Energy Targets. Available online: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-targets_en (accessed on 29 November 2023).
2. NPR Energy Experts Share How the U.S. Can Reach Biden's Renewable Energy Goals. Available online: https://www.npr.org/2023/02/02/1148370220/biden-renewable-energy-goals (accessed on 29 November 2023).
3. Bansal, A.K. Sizing and Forecasting Techniques in Photovoltaic-Wind Based Hybrid Renewable Energy System: A Review. *J. Clean. Prod.* **2022**, *369*, 133376. [CrossRef]
4. van der Meer, D.W.; Widén, J.; Munkhammar, J. Review on Probabilistic Forecasting of Photovoltaic Power Production and Electricity Consumption. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1484–1512. [CrossRef]
5. Kharrazi, A.; Sreeram, V.; Mishra, Y. Assessment Techniques of the Impact of Grid-Tied Rooftop Photovoltaic Generation on the Power Quality of Low Voltage Distribution Network—A Review. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109643. [CrossRef]
6. Katiraei, F.; Iravani, R.; Hatziargyriou, N.; Dimeas, A. Microgrids Management. *IEEE Power Energy Mag.* **2008**, *6*, 54–65. [CrossRef]
7. Kontis, E.O.; Kryonidis, G.C.; Nousdilis, A.I.; Malamaki, K.-N.D.; Papagiannis, G.K. Power Flow Analysis of Islanded AC Microgrids. In Proceedings of the 2019 IEEE Milan PowerTech, Milan, Italy, 23–27 June 2019; IEEE: Milan, Italy, 2019; pp. 1–6.
8. Deligianni, P.M.; Tsekouras, G.J.; Tsirekis, C.D.; Kontargyri, V.T.; Kanellos, F.D.; Kontaxis, P.A. Techno-Economic Optimization Analysis of an Autonomous Photovoltaic Power System for a Shoreline Electrode Station of HVDC Link: Case Study of an Electrode Station on the Small Island of Stachtoroi for the Attica–Crete Interconnection. *Energies* **2020**, *13*, 5550. [CrossRef]
9. Jing, Z.; Zhu, J.; Hu, R. Sizing Optimization for Island Microgrid with Pumped Storage System Considering Demand Response. *J. Mod. Power Syst. Clean Energy* **2018**, *6*, 791–801. [CrossRef]
10. Krichen, M.; Basheer, Y.; Qaisar, S.M.; Waqar, A. A Survey on Energy Storage: Techniques and Challenges. *Energies* **2023**, *16*, 2271. [CrossRef]
11. Li, X.; Palazzolo, A. A Review of Flywheel Energy Storage Systems: State of the Art and Opportunities. *J. Energy Storage* **2022**, *46*, 103576. [CrossRef]
12. Rious, V.; Perez, Y. Review of Supporting Scheme for Island Powersystem Storage. *Renew. Sustain. Energy Rev.* **2014**, *29*, 754–765. [CrossRef]

13. Habib, H.F.; Lashway, C.R.; Mohammed, O.A. A Review of Communication Failure Impacts on Adaptive Microgrid Protection Schemes and the Use of Energy Storage as a Contingency. *IEEE Trans. Ind. Applicat.* **2018**, *54*, 1194–1207. [CrossRef]
14. Nikolaos, P.C.; Marios, F.; Dimitris, K. A Review of Pumped Hydro Storage Systems. *Energies* **2023**, *16*, 4516. [CrossRef]
15. Sánchez, A.S.; Junior, E.P.; Gontijo, B.M.; de Jong, P.; dos Reis Nogueira, I.B. Replacing Fossil Fuels with Renewable Energy in Islands of High Ecological Value: The Cases of Galápagos, Fernando de Noronha, and Príncipe. *Renew. Sustain. Energy Rev.* **2023**, *183*, 113527. [CrossRef]
16. Groppi, D.; Pfeifer, A.; Garcia, D.A.; Krajačić, G.; Duić, N. A Review on Energy Storage and Demand Side Management Solutions in Smart Energy Islands. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110183. [CrossRef]
17. Navalpotro, P.; Castillo-Martínez, E.; Carretero-González, J. Sustainable Materials for Off-Grid Battery Applications: Advances, Challenges and Prospects. *Sustain. Energy Fuels* **2021**, *5*, 310–331. [CrossRef]
18. Nitta, N.; Wu, F.; Lee, J.T.; Yushin, G. Li-Ion Battery Materials: Present and Future. *Mater. Today* **2015**, *18*, 252–264. [CrossRef]
19. Mitali, J.; Dhinakaran, S.; Mohamad, A.A. Energy Storage Systems: A Review. *Energy Storage Sav.* **2022**, *1*, 166–216. [CrossRef]
20. Breeze, P. Power System Energy Storage Technologies. In *Power Generation Technologies*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 219–249. ISBN 978-0-08-102631-1.
21. Hunt, J.D.; Zakeri, B.; Nascimento, A.; Gazoli, J.R.; Bindemann, F.T.; Wada, Y.; van Ruijven, B.; Riahi, K. Compressed Air Seesaw Energy Storage: A Solution for Long-Term Electricity Storage. *J. Energy Storage* **2023**, *60*, 106638. [CrossRef]
22. Nadeem, F.; Hussain, S.M.S.; Tiwari, P.K.; Goswami, A.K.; Ustun, T.S. Comparative Review of Energy Storage Systems, Their Roles, and Impacts on Future Power Systems. *IEEE Access* **2019**, *7*, 4555–4585. [CrossRef]
23. Electric Vehicle Database Nissan Leaf 24 kWh. Available online: https://ev-database.org/car/1019/Nissan-Leaf-24-kWh (accessed on 29 November 2023).
24. Fotopoulou, M.; Rakopoulos, D.; Blanas, O. Day Ahead Optimal Dispatch Schedule in a Smart Grid Containing Distributed Energy Resources and Electric Vehicles. *Sensors* **2021**, *21*, 7295. [CrossRef] [PubMed]
25. Mohiti, M.; Monsef, H.; Lesani, H. A Decentralized Robust Model for Coordinated Operation of Smart Distribution Network and Electric Vehicle Aggregators. *Int. J. Electr. Power Energy Syst.* **2019**, *104*, 853–867. [CrossRef]
26. Keçili, R.; Arli, G.; Hussain, C.M. Future of Analytical Chemistry with Graphene. In *Comprehensive Analytical Chemistry*; Elsevier: Amsterdam, The Netherlands, 2020; Volume 91, pp. 355–389. ISBN 978-0-323-85371-2.
27. Sisakyan, N.; Chilingaryan, G.; Manukyan, A.; Mukasyan, A.S. Combustion Synthesis of Materials for Application in Supercapacitors: A Review. *Nanomaterials* **2023**, *13*, 3030. [CrossRef] [PubMed]
28. Barbir, F. Fuel Cell Electrochemistry. In *PEM Fuel Cells*; Elsevier: Amsterdam, The Netherlands, 2005; pp. 33–72. ISBN 978-0-12-078142-3.
29. Lei, T.; Yang, Z.; Lin, Z.; Zhang, X. State of Art on Energy Management Strategy for Hybrid-Powered Unmanned Aerial Vehicle. *Chin. J. Aeronaut.* **2019**, *32*, 1488–1503. [CrossRef]
30. Franzoni, D.; Santi, E.; Monti, A.; Ponci, F.; Patterson, D.; Barry, N. An Active Filter for Fuel Cell Applications. In Proceedings of the IEEE 36th Conference on Power Electronics Specialists, Dresden, Germany, 16 June 2005; pp. 1607–1613.
31. Rehman, S.; Al-Hadhrami, L.M.; Alam, M.M. Pumped Hydro Energy Storage System: A Technological Review. *Renew. Sustain. Energy Rev.* **2015**, *44*, 586–598. [CrossRef]
32. Ali, S.; Stewart, R.A.; Sahin, O. Drivers and Barriers to the Deployment of Pumped Hydro Energy Storage Applications: Systematic Literature Review. *Clean. Eng. Technol.* **2021**, *5*, 100281. [CrossRef]
33. Arani, A.A.K.; Karami, H.; Gharehpetian, G.B.; Hejazi, M.S.A. Review of Flywheel Energy Storage Systems Structures and Applications in Power Systems and Microgrids. *Renew. Sustain. Energy Rev.* **2017**, *69*, 9–18. [CrossRef]
34. Xu, K.; Guo, Y.; Lei, G.; Zhu, J. A Review of Flywheel Energy Storage System Technologies. *Energies* **2023**, *16*, 6462. [CrossRef]
35. Chen, H.; Cong, T.N.; Yang, W.; Tan, C.; Li, Y.; Ding, Y. Progress in Electrical Energy Storage System: A Critical Review. *Prog. Nat. Sci.* **2009**, *19*, 291–312. [CrossRef]
36. Luo, X.; Wang, J.; Dooner, M.; Clarke, J. Overview of Current Development in Electrical Energy Storage Technologies and the Application Potential in Power System Operation. *Appl. Energy* **2015**, *137*, 511–536. [CrossRef]
37. McLarnon, F.R.; Cairns, E.J. Energy Storage. *Annu. Rev. Energy.* **1989**, *14*, 241–271. [CrossRef]
38. Azaroual, M.; Ouassaid, M.; Maaroufi, M. Model Predictive Control-Based Energy Management Strategy for Grid-Connected Residential Photovoltaic–Wind–Battery System. In *Renewable Energy Systems*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 89–109. ISBN 978-0-12-820004-9.
39. Nguyen, S.; Peng, W.; Sokolowski, P.; Alahakoon, D.; Yu, X. Optimizing Rooftop Photovoltaic Distributed Generation with Battery Storage for Peer-to-Peer Energy Trading. *Appl. Energy* **2018**, *228*, 2567–2580. [CrossRef]
40. Liu, C.; Li, Q.; Wang, K. State-of-Charge Estimation and Remaining Useful Life Prediction of Supercapacitors. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111408. [CrossRef]
41. Horizon 2020 IntegrAted SolutioNs for the DecarbOnization and Smartification of Islands. Available online: https://cordis.europa.eu/project/id/957810 (accessed on 20 June 2023).
42. Horizon 2020 Towards Intelligent DC-Based Hybrid Grids Optimizing the Network Performance. Available online: https://cordis.europa.eu/project/id/957769 (accessed on 20 June 2023).
43. Karakitsios, I.; Lagos, D.; Dimeas, A.; Hatziargyriou, N. How Can EVs Support High RES Penetration in Islands. *Energies* **2023**, *16*, 558. [CrossRef]

44. Psarros, G.N.; Papathanassiou, S.A. Comparative Assessment of Priority Listing and Mixed Integer Linear Programming Unit Commitment Methods for Non-Interconnected Island Systems. *Energies* **2019**, *12*, 657. [CrossRef]
45. Directive (EU) 2019/944 of the European Parliament and of the Council 2019. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32019L0944 (accessed on 16 December 2023).
46. Rancilio, G.; Rossi, A.; Falabretti, D.; Galliani, A.; Merlo, M. Ancillary Services Markets in Europe: Evolution and Regulatory Trade-Offs. *Renew. Sustain. Energy Rev.* **2022**, *154*, 111850. [CrossRef]
47. Bevrani, H.; Golpîra, H.; Messina, A.R.; Hatziargyriou, N.; Milano, F.; Ise, T. Power System Frequency Control: An Updated Review of Current Solutions and New Challenges. *Electr. Power Syst. Res.* **2021**, *194*, 107114. [CrossRef]
48. Kontis, E.O.; Nozal, A.R.D.; Mauricio, J.M.; Demoulias, C.S. Provision of Primary Frequency Response as Ancillary Service From Active Distribution Networks to the Transmission System. *IEEE Trans. Smart Grid* **2021**, *12*, 4971–4982. [CrossRef]
49. Milano, F.; Dorfler, F.; Hug, G.; Hill, D.J.; Verbic, G. Foundations and Challenges of Low-Inertia Systems (Invited Paper). In Proceedings of the 2018 Power Systems Computation Conference (PSCC), Dublin, Ireland, 11–15 June 2018; pp. 1–25.
50. Tan, B.; Zhao, J.; Netto, M.; Krishnan, V.; Terzija, V.; Zhang, Y. Power System Inertia Estimation: Review of Methods and the Impacts of Converter-Interfaced Generations. *Int. J. Electr. Power Energy Syst.* **2022**, *134*, 107362. [CrossRef]
51. Vasilakis, A.; Zafeiratou, I.; Lagos, D.T.; Hatziargyriou, N.D. The Evolution of Research in Microgrids Control. *IEEE Open J. Power Energy* **2020**, *7*, 331–343. [CrossRef]
52. Lagos, D.T.; Hatziargyriou, N.D. Data-Driven Frequency Dynamic Unit Commitment for Island Systems With High RES Penetration. *IEEE Trans. Power Syst.* **2021**, *36*, 4699–4711. [CrossRef]
53. Fernández-Muñoz, D.; Pérez-Díaz, J.I.; Guisández, I.; Chazarra, M.; Fernández-Espina, Á. Fast Frequency Control Ancillary Services: An International Review. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109662. [CrossRef]
54. Misaghian, M.S.; O'Dwyer, C.; Flynn, D. Fast Frequency Response Provision from Commercial Demand Response, from Scheduling to Stability in Power Systems. *IET Renew. Power Gener.* **2022**, *16*, 1908–1924. [CrossRef]
55. Dallmer-Zerbe, K.; Spahic, E.; Kuhn, G.; Morgenstern, R.; Beck, G. Fast Frequency Response in UK Grid—Challenges and Solution. In Proceedings of the 13th IET International Conference on AC and DC Power Transmission (ACDC 2017), Manchester, UK, 14–16 February 2017; pp. 1–6.
56. Marinelli, M.; Sevdari, K.; Calearo, L.; Thingvad, A.; Ziras, C. Frequency Stability with Converter-Connected Resources Delivering Fast Frequency Control. *Electr. Power Syst. Res.* **2021**, *200*, 107473. [CrossRef]
57. *Fast Frequency Response Concepts and Bulk Power System Reliability Needs*; NREL: Washington, DC, USA, 2020. Available online: https://www.nrel.gov/grid/ieee-standard-1547/bulk-power-reliability-needs.html (accessed on 28 August 2023).
58. Meng, L.; Zafar, J.; Khadem, S.K.; Collinson, A.; Murchie, K.C.; Coffele, F.; Burt, G.M. Fast Frequency Response From Energy Storage Systems—A Review of Grid Standards, Projects and Technical Issues. *IEEE Trans. Smart Grid* **2020**, *11*, 1566–1581. [CrossRef]
59. Astero, P.; Evens, C. Optimum Operation of Battery Storage System in Frequency Containment Reserves Markets. *IEEE Trans. Smart Grid* **2020**, *11*, 4906–4915. [CrossRef]
60. Jomaux, J.; Latiers, A.; De Jaeger, E. Cost-Based Dimensioning of Battery Energy Storage and Energy Management System for Frequency Containment Reserves Provision. In Proceedings of the 2015 IEEE Power & Energy Society General Meeting, Denver, CO, USA, 26–30 July 2015; pp. 1–5.
61. Sandelic, M.; Stroe, D.-I.; Iov, F. Battery Storage-Based Frequency Containment Reserves in Large Wind Penetrated Scenarios: A Practical Approach to Sizing. *Energies* **2018**, *11*, 3065. [CrossRef]
62. Fleer, J.; Stenzel, P. Impact Analysis of Different Operation Strategies for Battery Energy Storage Systems Providing Primary Control Reserve. *J. Energy Storage* **2016**, *8*, 320–338. [CrossRef]
63. Jacqué, K.; Koltermann, L.; Figgener, J.; Zurmühlen, S.; Sauer, D.U. The Influence of Frequency Containment Reserve on the Operational Data and the State of Health of the Hybrid Stationary Large-Scale Storage System. *Energies* **2022**, *15*, 1342. [CrossRef]
64. Cheng, Y.; Tabrizi, M.; Sahni, M.; Povedano, A.; Nichols, D. Dynamic Available AGC Based Approach for Enhancing Utility Scale Energy Storage Performance. *IEEE Trans. Smart Grid* **2014**, *5*, 1070–1078. [CrossRef]
65. Papakonstantinou, A.G.; Papathanassiou, S.A. Battery Energy Storage Participation in Automatic Generation Control of Island Systems, Coordinated with State of Charge Regulation. *Appl. Sci.* **2022**, *12*, 596. [CrossRef]
66. Oureilidis, K.; Malamaki, K.-N.; Gallos, K.; Tsitsimelis, A.; Dikaiakos, C.; Gkavanoudis, S.; Cvetkovic, M.; Mauricio, J.M.; Maza Ortega, J.M.; Ramos, J.L.M.; et al. Ancillary Services Market Design in Distribution Networks: Review and Identification of Barriers. *Energies* **2020**, *13*, 917. [CrossRef]
67. Papathanassiou, S.A. A Technical Evaluation Framework for the Connection of DG to the Distribution Network. *Electr. Power Syst. Res.* **2007**, *77*, 24–34. [CrossRef]
68. Giannitrapani, A.; Paoletti, S.; Vicino, A.; Zarrilli, D. Optimal Allocation of Energy Storage Systems for Voltage Control in LV Distribution Networks. *IEEE Trans. Smart Grid* **2017**, *8*, 2859–2870. [CrossRef]
69. Yi, J.H.; Cherkaoui, R.; Paolone, M. Optimal Allocation of ESSs in Active Distribution Networks to Achieve Their Dispatchability. *IEEE Trans. Power Syst.* **2021**, *36*, 2068–2081. [CrossRef]
70. Oudalov, A.; Chartouni, D.; Linhofer, G.; Ohler, C. Value Analysis of Battery Energy Storage Applications in Power Systems. In Proceedings of the 2006 IEEE PES Power Systems Conference and Exposition, Atlanta, GA, USA, 29 October–1 November 2006. [CrossRef]

71. Kucevic, D.; Semmelmann, L.; Collath, N.; Jossen, A.; Hesse, H. Peak Shaving with Battery Energy Storage Systems in Distribution Grids: A Novel Approach to Reduce Local and Global Peak Loads. *Electricity* **2021**, *2*, 573–589. [CrossRef]
72. Boutsika, T.N.; Papathanassiou, S.A. Short-Circuit Calculations in Networks with Distributed Generation. *Electr. Power Syst. Res.* **2008**, *78*, 1181–1191. [CrossRef]
73. Memon, A.A.; Kauhaniemi, K. Protection of the Future Harbor Area AC Microgrids Containing Renewable Energy Sources and Batteries. *IEEE Access* **2023**, *11*, 57448–57469. [CrossRef]
74. Kleftakis, V.; Lagos, D.; Papadimitriou, C.; Hatziargyriou, N.D. Seamless Transition Between Interconnected and Islanded Operation of DC Microgrids. *IEEE Trans. Smart Grid* **2019**, *10*, 248–256. [CrossRef]
75. Moreno, R.; Trakas, D.N.; Jamieson, M.; Panteli, M.; Mancarella, P.; Strbac, G.; Marnay, C.; Hatziargyriou, N. Microgrids Against Wildfires: Distributed Energy Resources Enhance System Resilience. *IEEE Power Energy Mag.* **2022**, *20*, 78–89. [CrossRef]
76. Xu, Z.; Yang, P.; Zheng, Q.; Zeng, Z. Study on Black Start Strategy of Microgrid with PV and Multiple Energy Storage Systems. In Proceedings of the 2015 18th International Conference on Electrical Machines and Systems (ICEMS), Pattaya, Thailand, 25–28 October 2015; pp. 402–408.
77. Chen, B.; Chen, C.; Wang, J.; Butler-Purry, K.L. Sequential Service Restoration for Unbalanced Distribution Systems and Microgrids. *IEEE Trans. Power Syst.* **2018**, *33*, 1507–1520. [CrossRef]
78. Papaefthymiou, S.V.; Karamanou, E.G.; Papathanassiou, S.A.; Papadopoulos, M.P. A Wind-Hydro-Pumped Storage Station Leading to High RES Penetration in the Autonomous Island System of Ikaria. *IEEE Trans. Sustain. Energy* **2010**, *1*, 163–172. [CrossRef]
79. Cordis Storage Innovations for Green Energy Systems. Available online: https://cordis.europa.eu/project/id/101096992 (accessed on 28 August 2023).
80. Al Katsaprakakis, D.; Proka, A.; Zafirakis, D.; Damasiotis, M.; Kotsampopoulos, P.; Hatziargyriou, N.; Dakanali, E.; Arnaoutakis, G.; Xevgenos, D. Greek Islands' Energy Transition: From Lighthouse Projects to the Emergence of Energy Communities. *Energies* **2022**, *15*, 5996. [CrossRef]
81. Kaldellis, J.K.; Zafirakis, D. Prospects and Challenges for Clean Energy in European Islands.The TILOS Paradigm. *Renew. Energy* **2020**, *145*, 2489–2502. [CrossRef]
82. Kaldellis, J.K. Supporting the Clean Electrification for Remote Islands: The Case of the Greek Tilos Island. *Energies* **2021**, *14*, 1336. [CrossRef]
83. Hatziargyriou, N.; Dimeas, A.; Vasilakis, N.; Lagos, D.; Kontou, A. The Kythnos Microgrid: A 20-Year History. *IEEE Electrific. Mag.* **2020**, *8*, 46–54. [CrossRef]
84. EDP Battery Energy Storage System. Available online: https://www.edp.com/en/battery-energy-storage-system (accessed on 25 April 2023).
85. Energetus. Available online: http://www.energetus.pt/central-hidroeletrica-reversivel-da-calheta-iii-2/ (accessed on 9 August 2023).
86. Siemens Siemens and Fluence Support the Energy Transition on the Island of Madeira and Increase the Resilience of Its Electricity Grid. Available online: https://press.siemens.com/pt/pt/comunicadodeimprensa/siemens-e-fluence-apoiam-transicao-energetica-da-ilha-da-madeira-e-aumentam (accessed on 9 August 2023).
87. Muñoz-Cruzado, J.; Laporta Puyal, E.; Muñoz Gómez, A.M. *50 kW Modular V2G SiC Charger Station in Energy Island Microgrids: A Real Use-Case in Madeira Island*; VDE VERLAG GMBH: Berlin, Germany, 2022.
88. Lighthouse Island 3: Madeira. Available online: http://insulae-h2020.eu/pilots/lighthouse-island-3-madeira/ (accessed on 25 May 2023).
89. CORDIS Maximizing the Impact of Innovative Energy Approaches in the EU Islands. Available online: https://cordis.europa.eu/project/id/824433 (accessed on 28 August 2023).
90. HITACHI ABB POWER GRIDS Grid Edge Solutions 2020. Available online: https://go.hitachienergy.com/grid-edge-solutions (accessed on 9 August 2023).
91. Martins, R.; Krajacic, G.; Alves, L.; Duic, N.; Azevedo, J.T.; Da Graca Carvalho, M. Energy Storage in Islands Modelling Porto Santo Hydrogen System. *Chem. Eng. Trans.* **2009**, *18*, 367–372. [CrossRef]
92. Energy Storage News Hitachi Energy Faroe Islands BESS Project Doubles Wind Farm's Utilisation. Available online: https://www.energy-storage.news/hitachi-energy-faroe-islands-bess-project-doubles-wind-farms-utilisation/ (accessed on 8 August 2023).
93. European Association for Storage of Energy Saft Li-Ion Energy Storage Optimizes Wind Power for the Faroe Islands. Available online: https://ease-storage.eu/news/saft-li-ion-energy-storage-enables-sev-to-optimize-wind-power-for-the-faroe-islands/ (accessed on 8 August 2023).
94. SAFT Saft Powers the Transition of Small Italian Islands to Renewable Energy. Available online: https://www.saft.com/media-resources/press-releases/saft-powers-transition-small-italian-islands-renewable-energy (accessed on 8 August 2023).
95. Power Electronics News Renewable Energy from Italy's Small Islands with Efficient Batteries. Available online: https://www.powerelectronicsnews.com/renewable-energy-from-italys-small-islands-with-efficient-batteries/ (accessed on 8 August 2023).
96. Frydrychowicz-Jastrzębska, G. El Hierro Renewable Energy Hybrid System: A Tough Compromise. *Energies* **2018**, *11*, 2812. [CrossRef]
97. Sarasúa, J.I.; Martínez-Lucas, G.; Pérez-Díaz, J.I.; Fernández-Muñoz, D. Alternative Operating Modes to Reduce the Load Shedding in the Power System of El Hierro Island. *Int. J. Electr. Power Energy Syst.* **2021**, *128*, 106755. [CrossRef]

98. Hernández, Y.; Monagas, C.; Romero Manrique De Lara, D.; Corral, S. Are Microgrids an Opportunity to Trigger Changes in Small Insular Territories toward More Community-Based Lifestyles? *J. Clean. Prod.* **2023**, *411*, 137206. [CrossRef]
99. López-Rodríguez, R.; Aguilera-González, A.; Vechiu, I.; Bacha, S. Day-Ahead MPC Energy Management System for an Island Wind/Storage Hybrid Power Plant. *Energies* **2021**, *14*, 1066. [CrossRef]
100. European Association for Storage of Energy EMMES 7.0—March 2023. Available online: https://ease-storage.eu/publication/emmes-7-0-march-2023/ (accessed on 29 November 2023).
101. Tsagas, I. Greece's Astypalaia Island to Build 3.5 MW of Solar, 10 MWh Battery System 2023. Available online: https://www.pv-magazine.com/2023/04/06/greeces-astypalaia-island-to-build-3-5-mw-of-solar-10-mwh-battery-system/ (accessed on 16 December 2023).
102. CORDIS New Energy Solutions Optimized for Islands. Available online: https://cordis.europa.eu/project/id/864266 (accessed on 29 November 2023).
103. NESOI Just Clean Energy Transition of Diapontia Islands. Available online: https://nesoi.eu/system/files/private/nesoi/Briefs/nesoi_z181_jedi_brief.pdf (accessed on 16 December 2023).
104. Nesoi Dgres-Aegean—Decarbonization of Generation and Resilience of Security of Power Supply in an Autonomous North-Aegean Archipelago. Available online: https://nesoi.eu/content/dgres-aegean-decarbonization-generation-and-resilience-security-power-supply-autonomous (accessed on 29 November 2023).
105. Katsaprakakis, D.A.; Dakanali, E.; Dimopoulos, A.; Gyllis, Y. Energy Transition on Sifnos: An Approach to Economic and Social Transition and Development. *Appl. Sci.* **2022**, *12*, 2680. [CrossRef]
106. Bhola, P.; Chronis, A.-G.; Kotsampopoulos, P.; Hatziargyriou, N. Business Model Selection for Community Energy Storage: A Multi Criteria Decision Making Approach. *Energies* **2023**, *16*, 6753. [CrossRef]
107. Toro, L.; Moscardini, E.; Baldassari, L.; Forte, F.; Falcone, I.; Coletta, J.; Toro, L. A Systematic Review of Battery Recycling Technologies: Advances, Challenges, and Future Prospects. *Energies* **2023**, *16*, 6571. [CrossRef]
108. Camara, M.B.; Dakyo, B. Coordinated Control of the Hybrid Electric Ship Power-Based Batteries/Supercapacitors/Variable Speed Diesel Generator. *Energies* **2023**, *16*, 6666. [CrossRef]
109. Pang, M.; Shi, Y.; Wang, W.; Yuan, X. A Method for Optimal Sizing Hybrid Energy Storage System for Smoothing Fluctuations of Wind Power. In Proceedings of the 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Xi'an, China, 25–28 October 2016; pp. 2390–2393.
110. Chong, L.W.; Wong, Y.W.; Rajkumar, R.K.; Rajkumar, R.K.; Isa, D. Hybrid Energy Storage Systems and Control Strategies for Stand-Alone Renewable Energy Power Systems. *Renew. Sustain. Energy Rev.* **2016**, *66*, 174–189. [CrossRef]
111. Thirumal, V.; Mahato, N.; Yoo, K.; Kim, J. High Performance Li-Ion Battery-Type Hybrid Supercapacitor Devices Using Antimony Based Composite Anode and Ketjen Black Carbon Cathode. *J. Energy Storage* **2023**, *61*, 106756. [CrossRef]
112. Moa, E.H.Y.; Go, Y.I. Large-Scale Energy Storage System: Safety and Risk Assessment. *Sustain. Energy Res.* **2023**, *10*, 13. [CrossRef]
113. Klok, C.W.; Kirkels, A.F.; Alkemade, F. Impacts, Procedural Processes, and Local Context: Rethinking the Social Acceptance of Wind Energy Projects in the Netherlands. *Energy Res. Soc. Sci.* **2023**, *99*, 103044. [CrossRef]