Energy storage systems supporting increased penetration of renewables in islanded systems

E.M.G. Rodrigues\textsuperscript{a,b}, R. Godina\textsuperscript{a}, S.F. Santos\textsuperscript{a}, A.W. Bizuayehu\textsuperscript{a}, J. Contreras\textsuperscript{c}, J.P.S. Catalão\textsuperscript{a,d,e}\textsuperscript{*}

\textsuperscript{a} University of Beira Interior, R. Fonte do Lameiro, 6201-001 Covilha, Portugal
\textsuperscript{b} ALSTOM, Future Tech. Execution, Zentralstrasse 40, 5242 Birr, Switzerland
\textsuperscript{c} E.T.S. de Ingenieros Industriales, Univ. Castilla – La Mancha, 13071 Ciudad Real, Spain
\textsuperscript{d} INESC-ID, R. Alves Redol, 9, 1000-029 Lisbon, Portugal
\textsuperscript{e} IST, University of Lisbon, Av. Rovisco Pais, 1, 1049-001 Lisbon, Portugal

Abstract

Nowadays, with the large-scale penetration of distributed and renewable energy resources, Energy Storage (ES) stands out for its ability of adding flexibility, controlling intermittence and providing back-up generation to electrical networks. It represents the critical link between the energy supply and demand chains, being a key element for increasing the role and attractiveness of renewable generation into the power grid, providing also numerous technical and economic benefits to the power system stakeholders. On islanded systems and micro-grids, being updated about the state-of-the-art of ES systems and their benefits becomes even more relevant. Hence, in the present paper a comprehensive study and analysis of ES leading technologies’ main assets, research issues, global market figures, economic benefits and technical applications is provided. Special emphasis is given to ES on islands, as a new contribution to earlier studies, addressing their particular requirements, the most appropriate technologies and existing operating projects throughout the world.

Keywords: Storage technologies; Renewables penetration; Islanded systems.

1. Introduction

In the past, power systems utilities have operated in its simpler form via one-way transportation from large centralised power generation systems, distant from the point of consumption, mostly based on the burning of fossil fuels. Electric power is a commodity that may be wasted if it is not preserved or consumed. In particular, the electricity generated using renewable energy resources is difficult to adjust in response to the demand needs.

Renewable energy production is considered as a key step to create environmentally friendly energy systems and consequently less dependent on fossil fuels. Despite being abundant and relatively easy to get, solar and wind generation are unstable and intermittent by nature. Main constraints when incorporating renewable sources at large scale has to do with the limited time coincidence of the resource with electricity demand, together with the limited flexibility of thermal generators to reduce output. Moreover, the excess energy from these resources can’t be used unless exported in less favourable economic conditions, which tend to yield lower incomes. On the other hand, insufficient power transmission infrastructure can also raise the electricity prices. Thus, renewable generation when not fully explored leads to increased operating costs [1].
With the introduction of distributed and renewable energy resources, Energy Storage (ES) applications (after long disregard) are making a comeback, upon the recognition and technological advancement of its role in adding flexibility, controlling intermittence and providing uninterruptible power supply to the network.

ES systems can drive strong renewable incorporation since the intermittent electricity generated in excess can be captured and released as additional capacity to the grid when it is necessary. Their numerous applications will strengthen power networks and maintain load levels even during critical service hours, avoiding stability problems since it is no longer feasible to consider building over-designed and expensive power plants as an ultimate solution [2].

In addition, higher portion of renewable generation and distributed generation lead to a large-scale integration fundamental problem, which is finding a balance between electricity demand and production. This may give birth to new problems in relation to management and operation of energy transfer, as well as in the effective integration of renewable energy resources into the grid. Such complex impact is not limited to hourly intermittence, but also may lead to disrupt the harmonization in energy conversion, affecting grid frequency and voltage stability [3]. Energy systems security issues that result from intermittent renewable power injection can also be alleviated through energy storage, enabling a better predictable response of these resources, while at the same time provides additional flexibility in the energy system.

As a result, ES systems represent one of the critical links between energy supply and demand chains, standing as a key element for the increasing grid integration of renewable energies, as well as for distributed energy generation spread and stand-alone power systems feasibility. Moreover, in a broader sense, ES will enable the Smart Grid concept to become a reality.

Currently, European policies have more rigorous norms in relation to renewable energy integration into grids. The implementation of such actions comprises the replacement of conventional power production with combined heat and power (CHP) production units, an increase of renewable energy systems (RES) and other distributed sources in the energy supply. Recent studies also illustrate that seeing the electricity sector as part of a complete sustainable energy system rather than a separate part of the energy system is a more cost-effective solution for smart grid applications, which will lead to a smart energy system approach rather than a solely electricity smart grid approach [4].
Even with ES systems back-up to smooth fluctuations in a scenario of high levels of renewable generation, technical and economic issues may prevent their use in large scale as a single solution for the future [5].

Energy system flexibility is a necessary step to create sustainable energy system with high levels of renewable integration through a mix of coordinated strategies and technologies, including flexible conventional generation, energy storage and flexible load management [6].

Recent studies show that the certain type of flexible loads, such as large heat pumps (HP), electric boilers (EB), heat storages with CHP production systems, and electric vehicles (EV) can play a significant role in facilitating the integration of renewable electricity [7].

In recent past, strong European energy policies were established to promote the adoption of more effective energy generation technologies. CHP plants are among these technologies, since they combine heat and energy production simultaneously in one process, which results in improved overall efficiency comparatively to conventional plants. CHP facilities are normally small or medium size scattered over diverse spots such as urban areas or industrial complex. CHP and renewable energy sources belong to the same classification of distributed generation and are seen as important parts for addressing the global warming issue [8].

However, the integration of renewable electricity along CHP production expansion poses challenges to system operators. An excess renewable electricity problem comes from the fact that wind power production and CHP production are time swaps with electricity demand. In order to accelerate increased fluctuating electricity supply, existing CHP plants must be complemented with large scale HP installations along with ES [9]. HP enables system operators to use the excess renewable production for heat production instead of producing electricity for heat production. Solving excess problem can also be complemented by promoting CHP plants to participate in the balance of supply and demand. Average CHP unit is designed with relatively low power rating, which itself creates an impediment to provide balancing services due to restrictive electricity market rules. In order to benefit from the opportunities related to the emergency of power regulation energy services, small sized CHP plants could create a partnership to gain minimum dimension to offer competitive grid services in electricity market [10].

In some countries like Denmark, wind power along CHP plants can already represent half of the electricity demand, becoming a permanent challenge for balancing electricity. On a utility scale, pumped hydroelectric energy storage (PHES) and compressed air energy storage (CAES) are the natural choice for large scale energy storage. From electricity market point of view they offer the highest economic feasibility [11, 12].
Hence, flexible energy systems to face higher shares of fluctuating renewable energy source are now feasible with limited technical and economic implications [13].

A “vehicle-to-grid” (V2G) based EV is a non-conventional emerging energy storage solution that can participate on flexible energy systems by exchanging power to the grid. V2G fleets combined with HP and CHP plants can provide complementary enhanced storage service, especially for matching the time of generation to the time of load, raising electric power system capability to absorb more renewable electricity [14].

Despite the ambitious targets for exploiting high levels of renewable energy, strong reserves prevent energy systems to become fully dependent on renewable sources. Electricity network stability issues as well as substantial investments to store the required quantities of energy are the main reasons [15].

In this regard, parallel research activities are focused on alternative ways to lower fuel fossil consumption, such as zero emission and zero energy buildings concept. This approach permits highly energy-efficient construction designs, which minimize electricity demand as well as heating needs. Consequently, by promoting sustainable practices at domestic scale, energy production needs are less demanding on energy systems [16].

Non-interconnected power systems are a particular case of energy systems, which show specific issues to be faced when it comes to incorporate large renewable production. In particular, on islands’ power systems, there are some additional challenges to face. Under a large-scale renewable penetration scenario, being remotely located and not electrically connected to other grids, ES applications along with efficient management of the distribution networks take an even more important role. Thus, special emphasis must be given to ES on islands, studying their particular requirements and the most appropriate technologies.

In the context of island energy systems, the fundamental question should be how to design energy systems with exceptional capability of utilizing intermittent RES. One of the ways to make a comparison of different systems in terms of capability is using excess electricity diagram. In these diagrams, a curve represents the inability of the system to integrate fluctuating RES-based power against the yearly production specific technology in question. On the other hand, the bright future of intermittent energy resources rests on successfully increasing energy system flexibility; such solution could be achieved introducing storage and the principle of relocation. The Danish Energy Authority emphasized the cost-effectiveness of thermal storages and large HPs to allow more flexible and system-responsive CHP production modes [4].
This recommendation pointed towards an innovation in renewable energy system design, the principle of storage and relocation in 2nd generation renewable energy system, further improvement is also proposed incorporating mobility demand, and introducing ES and quad-generation for added further operational flexibility in 3rd generation renewable energy system [9].

In this context, electricity supply in combined conventional and decentralized grids using renewable energy resources requires affordable and reliable power management mechanisms, including sustainable storage systems, despite of some drawbacks in storage systems applied to electricity, related to the type of technology and operating costs [17, 18]. Several storage technologies have been developed with different response characteristics, and the state-of-the-art of these ES systems, their benefits and their applications have been reviewed and analysed throughout this paper.

2. Description of Energy Storage

2.1. Basic ES principles

ES, as shown in Figure 1, refers to the process of converting electrical energy from a power source or network via an energy conversion module (ECM) into another form or energy storage medium (ESM), such as chemical, mechanical, thermal or magnetic. This intermediate energy is stored for a limited time in order to be converted back into electrical energy when needed. The roundtrip efficiency of the ES system is reduced by both energy transformation processes inherent efficiencies and storage losses.

An ES is characterized by many features related to its electrical capacity, efficiency, charge/discharge behaviour, lifetime, cost and environmental/location issues. Some of these characteristics are intimately related to each other. For instance, in some technologies, particularly lead-acid batteries, the depth-of-discharge is critical and can shorten or enlarge their lifetime. Most relevant features of ESS are discussed and defined for existing technologies later on section 3 on this paper.

The study of ES technology suitability is carried out taking into consideration all features, to the benefits of different power system parties/stakeholders (from utilities to end-users).
2.2. Benefits of using ES

Basically ESs benefits can be classified into two generic categories that make ES interesting. On the one hand, high energy ES would help improving profitability, i.e., it secures economic benefits to the power system stakeholders. On the other hand, high power ES provide reliability, safety and productivity, i.e., it provides technical benefits. Furthermore, this classification is not compulsory whatsoever, being possible to find high profitability on high power applications and vice-versa.

At the same time, these power and energy benefits may be classified according to what they provide to the power system stakeholders, economic savings/revenues or technical enhancements.

2.2.1. Technical Benefits

The most relevant technical benefits of ES are the following:

a) Bulk energy time-shifting, for load leveling and peak shaving, providing electricity price arbitrage. For instance, electric vehicles represent one type of ES that can provide these power management benefits, leading to smart grid and RES integration.

b) ES may play an important role in the integration of renewable energy into the grid.

c) More efficient use and contribution of renewable energy is guaranteed using ES, also fomenting the use of distributed energy supply options in grids.

d) Several base-load generation plants are not designed for operation as part load or to provide variable output. However, storage may provide attractive solution to these drawbacks by setting the optimal operation point, rather than firing standby generators. In addition to that, ES have superior part-load efficiency [19].

e) Efficient storage can be used to provide up to two times its capacity for regulation applications; using full charge (down) and full discharge (up).

f) Storage output can be changed rapidly giving a ramping support and black-start to the grid (from none to full or from full to none within seconds rather than minutes) [19].

g) ES is a practical way to provide transmission congestion relief.

h) Energy storage can be used as a solution for improving grid service reliability.

i) There are always ideal locations for portable ES in a distribution system. On top of that, these systems can be also relocated so that after a certain number of years, when an upgrading of the system is performed, portable ES can be moved and used to perform the same function again.
j) Energy storage can benefit utilities or independent system operators allowing transmission and distribution upgrade deferrals.

k) ES can serve as a stand-by power source for substations on-site and distribution lines, or to add transformers.

l) In the near future, ESS technologies may facilitate other non electrical energy uses, like transportation and heat generation.

2.2.2. Economic Benefits

The most relevant economic benefits of ES are the following:

a) Energy storage can cut costs for customers of electricity.

b) In general, off-peak electricity is cheaper compared to high-peak electricity, and this also benefits the seller of electricity.

c) It plays a key role on stabilizing the electricity market price freeing the power sector from speculations and the volatility imposed by fossil fuels.

d) ES usage also overrides the need for peak generation, avoiding unnecessary additional cost burdens for generators.

e) It will contribute to the economic development and employment opportunities for many countries.

f) It will allow more efficient use of renewable and off-peak generation capacity, encouraging more investment opportunities on these technologies.

g) ES may help to avoid transmission congestion charges, which are very expensive and most of utilities try to avoid them in a deregulated market environment.

h) Reduces the need for transmission and distribution capacity upgrades, thus minimizing unnecessary investments.

i) Increases and improves availability of ancillary services, reducing penalties to generators and the cost of over dimensioning infrastructures.

j) Allows a market-driven electricity dispatch, fostering proactive participation of the customers to secure their benefits and creates a cost sharing scheme in the power system.

k) Storage tends to lower GHG and other emissions, reducing carbon cost. However this cost reduction is specific to the resource and varies greatly between technologies.

l) Compared to an average value for power-related installations under construction today, the cost of the storage components is relatively inexpensive.
More practical illustrations of the benefits of ES applications are, for instance: the Kaheawa wind power project II in Maalea Maui Island, Hawaii, USA, since 2012, serving more than 145,000 persons (approximately 68,000 customers) with tourist and agricultural uses.

The peak demand for the site is nearly 195 MW, supplied using 72 MW of wind, 1.2 MW of PV and 290 MW of fossil fuels, as main sources of energy. The project uses a battery storage system based on advanced lead-acid battery with 10 MW of capacity and a rated discharge of 45 min, designed for applications to support nearly 21 MW.

It represents a significant portion of the wind farm output employed, including electric supply reserve, ramping and renewable capacity firming, among other benefits [20].

The Santa Rita jail smart grid project with a completion date in March 2012, launched by Alameda County and Chevron Energy Solutions, is another illustration of ES integration on onsite wind power, solar thermal, solar photovoltaic’s, fuel cell cogeneration, using advanced ES systems with outstanding performance on the energy management system, increasing reliability and security.

The system comprises 2 MW (12 MWh) Lithium Ferrous Phosphate battery storage with a duration of 2 h at rated power and 1 MW fuel cell, 1.2 MW PV, 200 kW wind, and two 1 MW diesel generators to supply a 3 MW load, reducing the demand on the distribution feeder by 15 %.

Such system integration has improved significantly grid reliability, providing support to the electric distribution grid by providing dispatchable renewable energy, enabling seamless islanding and ensuring secure operation and cost reduction [21].

An additional illustration of the benefits of ES systems application is the Sodium Sulfur Battery (NAS) with a capacity of 1 MW at Catalina Island (Channel Islands of California, Pacific Ocean, USA), in operation since 2011.

This ES system is intended to guarantee grid-connected residential reliability, voltage support and supply support applications, thus improving energy quality at the end user side [20].

3. ES technologies’ main assets and research issues

Main existing ES technologies are studied in this chapter, which covers cost, efficiency, electrical capacity, discharge behavior, lifetime, maturity and applications for each ES technology. Moreover, their main assets along with the research issues are listed in the following epigraphs, in order of relevance.
3.1. Pumped-hydro energy storage (PHES)

Main assets:
- High power rating and energy storage capacity;
- Mature and widespread (over 99% of ES installed capacity);
- Low levelized cost of electricity (LCE);

Research issues:
- Pump-turbine head limits (700 m) at high speed;
- New PHES designs, such as the use of seawater as lower reservoir, tidal barrages, GPMES, Green Power Island concept, etc.

3.2. Compressed air energy storage (CAES)

Main assets:
- High power rating and energy storage capacity, comparable to PHES;
- Has quick response (secs-mins) and the afore mentioned large-scale features, being suitable for numerous power & energy grid applications;

Research issues:
- Relatively reduced round trip efficiency (RTE) related to cooling/heating processes;
- Turbine technology (high pressure turbine);
- Development of efficient thermal energy storage;
- Small-scale and Mini CAES for smaller applications;
- Advanced-adiabatic CAES (AA-CAES) technology.

3.3. Small-scale compressed air energy storage (SS-CAES)

Main assets:
- Installed above ground, avoiding conventional CAES geological requirements;
- No gas turbine required;
- Low pressure requirements for equipment;
Research issues:

- Development of portable units.

3.4. **Thermal Energy Storage (TES)**

Main assets (see Figure 2):

- High energy storage capacity (up to 2 GWh) and power rating (up to 200 MW);
- Scalable;
- Solar thermal being a zero emission and zero cost “fuel”;

Research issues:

- New collector and storage mediums for high temperature solar thermal plants, phase change materials, etc.;
- Reduce heat losses in storage, heat exchangers and pipes;
- High-temperature sensible heat storage with turbine is to be developed.

3.5. **Hydrogen energy storage system (HESS)**

Main assets (see Figure 3):

- Flexible technology as, once H\textsubscript{2} has been collected as a product of the electrolysis, it can be used as fuel for combustion engines or to serve as input along with O\textsubscript{2} for a fuel cell to produce electricity again;
- High energy mass density (100-1,000 Wh/kg);
- Suitable for energy & power applications, and due its scalability, it is defined as bridging;

Research issues:

- Scale-up limits;
- Development of fuel cells;
- Hydrogen storage materials.

3.6. **Chemical energy storage system / Batteries (BESS)**

Main assets:

- Almost instantaneous response (~20ms);
- Low initial capital cost for most mature BESS;
There are numerous BESS technologies, the following ones outstanding as the most relevant:

- Lead-Acid and Advanced Lead-Acid batteries;
- Nickel-Cadmium batteries;
- Nickel-Metal Hydride batteries;
- Lithium-Ion batteries;
- Sodium-Sulfur batteries;
- Sodium Nickel Chloride batteries;

They cover all power systems size needs and all the applications (except for baseload generation capacity)

Modularity, scalability and portability

Research issues:

- Hazardous chemicals (Lead, Cadmium, Sulfurs…) disposal solutions;
- Batteries recycling;
- Development of efficient thermal energy storage devices;
- Most mature BES Lead-Acid high density limitation, being improved at Advanced Lead-Acid batteries. However, others more efficient and lighter chemicals are being researched and tested for large-scale grid applications (i.e. Li-ion with up to 95% RTE and 245-2,000 W/kg).

3.7. Flow batteries energy storage (FBES)

Main assets:

- Higher discharge duration (up to 20 hrs) and energy storage capacity than conventional batteries;

There are various technologies:

- Vanadium Redox, the most mature;
- Zinc-Bromine Redox, in test for commercial units;
- Polysulfide Bromide Regenesys;

Research issues:

- Demonstration for utility applications for Vn Redox FBES;
- Research being carried out for ZnBr Redox FBES for over 100kW applications.
3.8. Flywheel energy storage system (FESS)

Main assets:
- Quick response time (~4ms);
- High RTE (80-95%);
- Low-speed and high-speed technology developed;

Research issues:
- Rotor component improvement;
- Flywheel farm approach;
- High-power applications;
- Longer operation periods;
- Self-discharge limitation.

3.9. Super-capacitors energy storage (SCES)

Main assets:
- Highly efficient technology (RTE ~95%);
- Higher power density (800-2,000 W/kg) and energy density than batteries;
- Quick response;

Research issues:
- Dielectric material development;
- Pseudocapacitors;
- Material prizes must severely come down for the current extremely high cost of SCES to decrease as well.

3.10. Superconducting magnetic energy storage (SMES)

Main assets:
- Quick deployment time (response time plus ramping up to peak discharge power) and charging time;
- High power rating (up to 100 MW);

Research issues:
- Reduced RTE related to cooling at around -270ºC;
- Development of materials.
3.11. Energy storage in substitute natural gas (SNG)

Main assets (see Figure 4) [22], [23]:

- High potential for energy storage and discharge time, even higher than PHES;
- Environmentally friendly SNG (CH$_4$) can be generated from:
  - Electricity coming from renewable energy in off-peak times, by electrolysis (H$_2$ + CO$_2$);
  - “Wet” biomass for anaerobic fermentation (biogas to SNG);
  - “Dry” biomass for thermochemical gasification (biosyngas to SNG);

Research issues:

- Clean coal technology, minimization of CO$_2$ emissions for gasification;
- Turbine technology enhancement (high pressure turbine).

3.12. Electric vehicles (EVs)

Main assets:

- G2V and V2G integrated in large-scale would provide very flexible storage, balancing power demand curve;
- EVs work with many battery technologies and fuel cells (H$_2$ produced by electrolysis, and CH$_4$ produced by H$_2$ electrolysis plus CO$_2$);

Research issues:

- Development of Smart Grids;
- Fuel Cell vehicles;
- Price arbitrage incentive regulations must be adequately considered not to induce massive consumption trends.

3.13. Promising technologies

Several promising cutting-edge technologies, which have not been discussed previously, are currently being developed:

a) Advanced Na-ion batteries, including Na-halide chemistry
b) New types of Na/S cells (e.g., flat, bipolar, low-temperature, high power).
c) Advanced lead acid batteries.
d) Ultra batteries (a hybrid energy storage that combines VRLA battery with an electrochemical capacitor).
e) Metal air batteries.

f) Mini-CAES, a portable version of CAES.

g) Gravity Power Module (GPMES): a start-up based in California has devised a system that relies on two water-filled shafts, one wider than the other, which are connected at both ends (see Figure 5). Water is pumped down through the smaller shaft to raise a piston in the larger shaft containing a high-weight piston; reversing such a process forces the water to flow back through the pump to generate electricity.

h) New flow battery couples, including ion-chrome and zinc-chlorine (ZnCl); but, their suitability for use as utility-scale storage devices is still being studied.

i) Green Power Island concept, in Denmark, which involves building artificial islands with wind turbines and a deep central reservoir.

j) Advanced Rail Energy Storage (ARES) to harness the potential of gravity is under research in Santa Monica, California, this system requires specific topography and delivers more power for the same height to PHES and could achieve more than 85% efficiency. A demonstration system is being built, and should become operational in 2013.

k) CES is a newly developed ES technology (see Figure 6). Off-peak electricity is used to liquefy air or nitrogen, which is then stored in cryogenic tanks. Heat can then be used to superheat the cryogen, boiling the liquid and forming a high pressure gas to drive a turbine to produce electricity. CES is at an early stage of commercialization, with a 500 kW project in the UK [24].

l) Pumped Heat Energy Storage (PHES) approaches taken by a company based in Cambridge, England. PHES is an energy storage system in the form of heat, which uses argon gas to transfer heat between two vast tanks filled with gravel. Incoming energy drives a heat pump, compressing and heating the argon and creating a temperature differential between two tanks, with one at 500°C and the other at -160°C. During periods of high demand, the heat pump runs in reverse as a heat engine, expanding and cooling argon and generating electricity. The system has an overall efficiency of 72-80%, depending on size [25].

3.14. Global markets data and key features of ES technologies

Global markets data can be seen in Figure 7 and Table 1. The state-of-the-art of ES technologies, regarding the key features of the most relevant ones, has been summarized in Tables 2 and 3 [26-31].
4. ES applications

There is a wide range of ES applications for power systems, as summarized in Table 4, starting from few seconds-minutes system support to hours-days full load management of grid operations [32-40].

Regarding the applications, in several cases different sources provide alternative terms/names for the same application. Among other reasons, this can be due to the fact that they refer to different power systems, European UCTE or others in USA, which have their own definitions for their particular power systems parties, elements, responses, reserves, etc. An effort has been made on gathering into one single application (one cell) all the synonyms separating them by “/” in order to clarify the terminology. On top of that, this has allowed us to be able to classify them into groups according to the power systems element or shareholder involved and function.

Three main characteristics / requirements have been defined for each application: power rating, discharge duration and response time. An ES is considered suitable for a certain application if, according to its features, it meets all the corresponding requirements along with other issues such as maturity. Cost-effectiveness has not been taken into account in this table; only technical features have been considered. Related charts from other sources have been studied. Only ES technologies with enough available information regarding their application have been included.

5. ES on Islands

5.1. Islands specific requirements / challenges

Nowadays, the two main factors that rule the deployment of new infrastructure on power systems are environmental sustainability and cost-effectiveness, both factors are taken into account for any investment to be made. In many cases, renewable generation technologies (mainly hydro, wind and solar) have become economically competitive with conventional ones (fossil fuels and nuclear), since they become more mature, their amortization periods decrease and their use become more extended.

According to the International Renewable Energy Agency (IRENA) there are several experiences about island projects around the world. Some of the critical issues to consider for the deployment of ES systems are: the right dimensioning of the ES, the project financial sustainability, system complexity and integration, end-user buy-in (financially and politically), and systematic deployment strategy.
The experience indicates that, there is no single best storage technology solution and storage is not always necessarily appropriate for island energy systems. For instance, storage can add value in transmission systems with capacity constraints or suffering low power quality at the end of the distribution system; in contrast, it may not be adequate for solving chronic supply shortage or poorly performing transmission and distribution systems [31].

Therefore, the main idea of ES applications on island grids is not to support basic diesel generation, since it is a well-known fact that storage definitely improves diesel efficiency; however, the present objective is slightly different due to increased need of renewable integration and grid code fulfilment in isolated grids. In addition, islands have special features that differentiate them from mainland interconnected grids. Accordingly, there are additional challenges they face due to their special grid characteristics.

It is common that a 15% solar plus wind share of the total power supply is established as upper-limit on power systems without ES systems installed in it [41]. Large-scale renewable integration brings numerous benefits and usually islands have plenty of resources to achieve this goal.

In a broad sense, the core issues arising with ES implementation in an island grid have diverse challenges that can be summarized into three main groups.

- High renewable integration challenges into power systems:
  - Instantaneous, daily and seasonal fluctuations of renewable resources are directly translated into notable variations on electrical generation output.
  - Limited predictability or forecasting of these fluctuations on generation.
  - The two previous issues can lead to power quality and reliability decrease due to power imbalances between generation and demand. For instance, erratic wind output can cause a dip or a spike on grid frequency and, if very severe, it could trigger a blackout.
  - Possible waste of an important share of free renewable resources available, i.e. wind curtailment, the same way bypassing the turbine in run-of-river hydropower potential to match demand and supply.
  - Adequacy of storage technology for the integration with other electricity system components, the more system components the greater the complexity of system integration.
• The ability of making smooth control, operation and getting appropriate link of components to optimize their operation. That means to increase the recoverable portion of renewable energy and at the same time smoothen the variable outputs of renewable input.

• The need to understand the technologies as a system, not only focusing on storage but also on the full delivery system. Critically assuming that any system is robust as the robustness of its critical elements.

• Economical and technical challenges in remotely located power systems, such as islands or isolated continental spots:
  ▪ Investment costs are very high and lower capital recovery factors.
  ▪ High fuel transportation costs, i.e. fuel for diesel generators.
  ▪ Importance of testing and evaluating thoroughly beforehand emerging technologies before sending them into the field and focus on robust technical solutions that are tried and tested.
  ▪ Lack of trained personnel available nearby, for maintenance and/or occasional technical assistance.
  ▪ High cost of spare parts, when a technical failure occurs, if damaged pieces are not in stock and need to be acquired.

• Issues present on Stand-Alone Power Systems (SAPS):
  ▪ No electrical interconnections with other power systems results in the unavailability of power exchanges (positive or negative) between grids in order to match generation and demand when needed. Power quality and reliability issues arise from these mismatches, leading to serious concerns (widespread blackout, damaged equipment, etc.)
  ▪ It is critical to make systems financially sustainable since end-user buy-in (financially and politically) is critical.
  ▪ Some isolated power systems are exposed to a high risk where the island’s sole power plant may undergo total shutdown, caused by any natural or manmade disasters (terrorist attack, hurricane, fire, earthquake etc.)
  ▪ Suppliers experience and capability to preview remote area location issues is a very important factor to consider.
  ▪ There should be somehow a systematic revise between the base electrical generation system and the storage technology to be used.
The subjects mentioned previously stand as constraints for wide renewable penetration on the generation mix, the supply of high quality and reliable electricity, as well as for the smart grids concept introduction into island grids. Generally speaking, the smaller and the more remote the island is, the more serious these concerns become.

Hopefully, ES can help to mitigate most of these effects and nowadays there is a wide variety of available ES technologies mature enough, providing the required features for specific applications. ES integration on islands is critical, more than in the rest of interconnected power systems, and each case should be individually studied.

5.2. ES technologies best suited for island grids

A wide range of applications of ES exists depending on their specific characteristics. Generally there are two groups: those best suited for power applications, and those suited for energy applications [19, 37]. In the context of islands, those suited for power applications have a good response time and high power output for relatively short periods of time. Some of these technologies are: FES, Capacitors and BESS.

Meanwhile, in order to offset the purchase or the generation when needed, the basic requirements for energy applications are large storage capacity and discharge times from several minutes to hours. Examples of these systems are PHES, CAES and TES [19].

Currently, more than ever, there is a great interest on large-scale or mega-scale ES systems in order to get economic and technical advantages resulting from linking demand to supply market.

Pumped storage plants are characterized by long construction times and high capital expenditure. In particular, pumped hydro storage requires a variable speed pump that is slightly more expensive than a conventional pump. The modalities of this storage system are: the ones with upper-lower reservoirs, high dam hydro plants with storage capability, underground pumped storage, or open sea reservoirs.

In general terms, PHES is a dominant bulk storage facility worldwide, accounting for more than 99% of bulk storage. However, it has a constraint due to the scarcity of ideal sites for such systems. Several ways of devising these systems are under research.

1. One of these ambitious plans is a Green Power Island concept devised by Gottlieb Paludan, a Danish architecture firm, with researchers at the Technical University of Denmark. This plan involves building artificial islands with wind turbines and a deep central reservoir.
2. Another system is the Gravity Power Module (GPMES): a start-up based in California has devised a system that relies on two water-filled shafts, one wider than the other, which are connected at both ends. Water is pumped down through the smaller shaft to raise a piston in the larger shaft containing a high-weight piston; reversing such a process forces the water to flow back through the pump to generate electricity.

According to the size of the power system of an island, some ES are more suitable than others. In Table 5, applicable grid system size ranges are given for various common technologies.

5.3. Economic ranking of ES technologies for islands by size

In 2009, a techno-economic study was published based on the Aegean Sea islands, in which several ES technologies performances on the grid were analyzed and economic results drawn [42]. Islands are divided into four groups, according to their peak power demand (MW) and average annual electricity consumption (GWh), and average values are taken for defining the power system characteristics. The study is performed for two energy autonomy periods (do=12 hrs and do=24 hrs), as can be seen in Figure 8.

Schematically, the ES systems have been listed in order of their specific energy storage cost (€/kWh) for the different scenarios:

- **Very Small Islands (<1 MW & <2 GWh):**
  - Up to 12 hrs of energy autonomy:
    - NaS battery < Flywheel < Flow battery (Regenesys) < Li-Ion battery < Lead-Acid battery
  - 24 hrs of energy autonomy:
    - NaS battery < Regenesys

- **Small Islands ([1-5 MW] & [2-15 GWh]):**
  - Up to 12 hrs of energy autonomy:
    - PHES < NaS battery < CAES < Regenesys < Lead-Acid battery
  - 24 hrs of energy autonomy:
    - PHES < CAES < Regenesys < NaS battery

- **Medium-size Islands ([5-35 MW] & [15-100 GWh]):**
  - Up to 12 hrs of energy autonomy:
PHES < NaS battery < CAES < Regenesys

- 24 hrs of energy autonomy:
  PHES < CAES < Regenesys < NaS battery

❖ Big Islands ( >35/40 MW & >100 GWh]):
  - Up to 12 hrs of energy autonomy:
    NaS battery (not yet used at this scale) < Lead-Acid (not yet used at this scale) < PHES < Regenesys < CAES
  - 24 hrs of energy autonomy:
    PHES < CAES

These classifications can serve to provide a general notion of the cost-effectiveness of the different ES systems on islands depending on their grid size. This study is currently not 100% applicable as it was made some years ago (2009) and not all of today’s available ES technologies are included. In addition to that, an in-depth study on specific ES applications has not been included, but only general energy management has been considered.

5.4. Existing ES on islands

5.4.1. Case studies

Nowadays, as a matter of fact, interest in ES is growing both in connected and non-interconnected power systems. However, there are not many grids that already include ES components as part of their power system and with information available, but a great number of projects are planned or under construction.

For island systems in particular, fewer experiences can be found. Nonetheless, data from several islands has been gathered and is presented in islands sizes, being classified into the same groups as in the previous section: very small, small, medium-size and big islands. A summary of ES technology applications from different sources and about their implementation in islands context is presented in Table 6. From the information provided in this table, some ES trends could be drawn and it can serve as a reference of the up-to-date ES operating projects on islands.
5.4.2. Lessons learned and practical recommendations

Being updated about previous experiences on the ES field represents a great source of information in order to minimize the possible mistakes made when planning, designing and integrating ES systems. From the case studies chosen for this paper, there are some important lessons that have been drawn and listed:

- Close attention must be paid to system design, especially on system components sizing and software for their general integration. The more components there are the more complexity on their integration.
- One technical innovation introduction at a time, stepwise enhancements.
  - Santa Rita Jail Microgrid: Since 2001 to 2011, renewable energy generation and energy efficiency measures have been deployed step by step. The smart grid project concluded in 2011 with the installation of a 2 MW Lithium Iron Phosphate Battery.
- Proper system monitoring and operation & maintenance (O&M) are essential for providing reliability and long lifecycles. Well monitored, operated and maintained Lead-Acid Batteries can lead over 9 years of lifespan.
  - Apolima Island: Frequent maintenance of Lead-Acid Batteries is worth it in terms of reliability and longevity.
  - Metlakatla Island: Lead-Acid Batteries were replaced after 12 years, and were reported to be still in very good condition.
- Perform test and debugging of equipment components and software before transportation to remote locations. Search for robust technical solutions, if possible working with an experienced, more critically for emerging technologies.
  - King Island: Vanadium Redox Battery was unrepairably damaged due to overcharging.
  - Ramea Island: Hydrogen generators have had some technical issues that are waiting to be repaired. Most likely they are cause by concerns related to the common exhaust of the various generators and to the fuel injectors.
- Household-size ES for independent renewable generation is also an alternative for providing basic services.
  - Kiribati islands: Individual household size Lead – Acid Batteries can clearly provide these basic services.
Equipment transportation and expertise trips to remote locations (islands, isolated or villages, etc.) are complex, take time and usually come at a high cost. Trained personnel, spare parts and technical assistance availability must be considered, emphasizing the importance of the initial test and debugging.

- Bella Coola Island: Frequent need for highly trained operations staff.

Diesel generators oversizing on islands seems as the easiest solution, but it is to be avoided as it contributes to high diesel consumption along with its associated environmental and economic cost. Unreliable diesel supply may lead to a shortage in fuel to energize the regional power system.

- Most of the projects listed: This was one of the main reasons for installing the ES.

Generally speaking, new technologies or pilots are not cost-effective, no global revenues to be expected.

- Bella Coola Island: HES is clearly not cost-effective, H₂ cost needs to come down for enabling this technology to be economically competitive.

No matter if initial investments/costs are publicly subsidized or privately funded, O&M costs should be financially studied/estimated to be sustainably covered by electricity sale revenues.

- Apolima Island: Not realistic trying to amortize investment from the rural community end-users.
- Padre Cocha Island: An economic analysis showed that only 22% of total costs and 59% of operational costs of the whole PV / Diesel / Lead – Acid Batteries was paid off by revenues.

Financial and political consumers’ support/endorsement is essential.

6. El Hierro island sustainable energy system

6.1. Hybrid hydro-wind electricity generation system

A study of the newly implemented electricity production system in El Hierro island from the Canary archipelago, Spain, can now be seen as a model for other insular systems. El Hierro is the smallest island of the Canaries and like the rest of the archipelago it relied significantly on diesel consumption [43]. From the end of 2014 El Hierro will be an energy-isolated territory in the world able to power itself almost entirely from renewable energy sources. For the first time the traditional problem of intermittency of renewable energy sources will be overcome through combining the power generation of a wind farm with a hydraulic storage system. The wind-hydro system operation will supply more than 80% of the energy needs.
Table 7 shows the main elements of the hybrid hydro-wind electricity generation power plant, making a comparison of the performance on the consumption and costs of energy generation with the current production model based exclusively on burning diesel.

In terms of environmental impacts this project will avoid an annual consumption of 6000 tonnes of diesel, which is equal to 40000 barrels of oil that would have to be imported by boat to the island, thus generating a saving of over 1.8 million euros per year. As a consequence, a yearly emission of 100 tonnes of SO$_2$ will be avoided, as well as 400 tonnes of NO$_x$ and 18700 tonnes of CO$_2$.

### 6.2 Investment analysis

The hydro-wind power plant’s economic life is 65 years; however, a part of the wind farm equipment and mechanical and electrical systems of turbines and pumps have to be replaced repeatedly after 20, 25 and 30 years, respectively, in order to ensure the continued operation during the useful life of the construction. This data and other is shown in Table 8.

Therefore, the time horizon of the profitability calculations is considered to be 20 years, which leads to a review of the hydro-wind power plant remuneration after this period of time by considering sequential replacements of the wind farm, of the mechanical pumping equipment, discharge and the rest of the electrical equipment, and by ensuring the recovery of the unamortized portion of the investments in the civil work until the end of its economic life.

It is established that the preliminary analysis of remuneration should ensure the internal rate of return (IRR) and free cash flow after tax of 7% in the first 20 years by considering this period without replenishment (coinciding with the economic life of the wind generation) and taking into account the residual value of the plant during the same 20 years.

The techniques that are usually used to assess investments are the IRR and the Net Present Value (NPV). The discount rate for which the NPV is equal to zero is the IRR. Both methods highlight the significance of the time value of money and are seen as more complete and simpler than other techniques. Based on the IRR, the financial feasibility of the El Hierro’s wind energy and hydro storage power system is studied.

Other authors have assessed investments of renewable energy production with storage solutions in isolated systems.
An example of such studies is the integration of wind and hydrogen technologies in the power system of the Corvo island, Azores [44] and the technical–economic analysis of wind-powered pumped hydro storage systems [45, 46].

IRR is the rate of return – r – that equates the discounted future cash outflows with initial inflow, given by:

\[ \sum_{n=1}^{N} \frac{F_n}{(1 + r)^n} + F_0 = 0 \]

where:

- \( F_0 \) = cash flow at time zero (\( t_0 \)),
- \( F_n \) = cash flow at year n (\( t_n \)),
- \( r \) = IRR,
- \( n \) = number of years.

By replacing the known constants with data values from El Hierro’s wind-hydro pump storage power plant project, the following expression is obtained:

\[ \sum_{n=1}^{20} \frac{F_n}{(1 + 0.07)^n} - 82\,000\,000 = 0 \]

where:

- \( F_0 = -82\,000\,000 \) €
- \( R = 7\% = 0.07 \)
- \( n = 20 \) years

The solution is shown in Table 9, where the discount rate for which the NPV is equal to zero is the IRR, therefore it is achieved the average yearly cash flow.

6.3 Energy balance forecast during the economic life of the hydro-wind power plant

According to [47], in the first 10 years of life of the hybrid installation it is expected an increase of the annual consumption by around 2%. Then, until the end of the useful life of the installation, it will decrease to an annual growth of 1%. With the wind–pumped hydro storage system functioning at full capacity and for forecasting purposes we consider as constant the annual wind power production and a portion of this production is intended to operate the hydro pumping station and the synchronous compensation.
Precise management of reservoirs is crucial to reach maximum efficiency of the operating system, which signifies storing the amount of extra wind energy by pumping. Knowing that the pumping energy will never be performed with power from the diesel source and with the aim of maximizing the renewable penetration in the island the diesel resource should solely be used to meet the demand when the hydro pumped storage power plant system is insufficient. Accordingly, a strong reduction on diesel generation production in the early years is expected.

The energetic mix will vary along the useful life of the hydro pumped storage power plant system. The maximum penetration of renewables will be reached in 2015 (77%). For the first two decades renewable energy sources will contribute with more than 75% of power needs. The incorporation of new renewable generation facilities in the future will be needed to maintain or increase the renewable quota, if the demand keeps increasing around 2% per year.

7. Conclusion

In this paper, the need for increasing the ES worldwide capacity has been substantiated by providing the rationale behind its technical and economic benefits, always along with the inherent environmental interest. The main advantages and research issues for ES systems were analyzed, as well as ES data by technology and by region. In spite of major technological advancement on ES technologies, there are still many challenges related to island applications, especially when the isolated system operation is combined with high renewable energy participation scenarios. No similarity or uniformity on ES application could be verified with total certainty, since it is dependent on the scale and type of application requirements. A range of storage solutions for island applications have been reviewed with different storage technologies. Practical recommendations have been compiled from real case studies and lesson learned were provided regarding all technological, technical and economic aspects. Any solution provided to meet grid requirements should be aligned to the specific island needs and grid requirement, abundance of the natural resources, the scale of economy and the type of storage technology to be deployed.

Finally, it can be stated that the current research issues related to ES are:

- Design improvement of existing storage systems. Even PHES technology, which is the most mature of all, is involved in design enhancement research.
- Influence of flexible energy systems such as heat pump and heat storage systems including CHP plants in the balancing of supply and demand and in the supply of ancillary services on islands.
• Influence of different storage options in large-scale wind integration of insular grid systems. ES makes an excellent partner for wind generation, particularly on islands where wind resources are highly available and ES is more essential for power quality and, above all, power system reliability.

• Improvement of life expectancy models in terms of cycling capacity. Charge/discharge use is critical in BESS.

• Improvement on storage efficiency evaluation models.

• Complete study of interaction and optimization of storage with integrated grid elements and renewable resources.

• Large-scale deployment of bulk storage systems that will require regulator as well as technical progress. MWs grid applications for currently mature technologies for kWs applications.

Finally, a techno-economical overview of a large renewable integration example was presented and discussed.

8. Acknowledgment

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9. References


[33] Beams Department, “Energy storage technologies for wind power integration”, 2010, Université Libre de Bruxelles Faculté des Sciences Appliquées, Service BEAMS groupe Energie.


Figure captions

Figure 1. ES cycle schematic representation

Figure 2. TES simplified diagram
Figure 3. Regenerative hydrogen fuel cell

Figure 4. SNG simplified diagram
Figure 5. Gravity Power Module Energy Storage (GPMES) working principle

Figure 6. CES simplified diagram
Figure 7. Global ES Capacity (MW) by Technology (excluding PHES)

Figure 8: Electricity production comparison for islands by size [42]
### Table 1. Global ES Projects by Region and Installed Capacity

<table>
<thead>
<tr>
<th>EES TECHNOLOGIES</th>
<th>North America</th>
<th>Western Europe</th>
<th>Asia Pacific</th>
<th>RoW</th>
<th>Global</th>
<th>Global (MW)</th>
<th>% Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAES</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>400</td>
<td>33.9%</td>
</tr>
<tr>
<td>NaS BESS</td>
<td>8</td>
<td>3</td>
<td>171</td>
<td>3</td>
<td>182</td>
<td>316</td>
<td>26.8%</td>
</tr>
<tr>
<td>Molten Salt TES</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>150</td>
<td>12.7%</td>
</tr>
<tr>
<td>Flow BESS</td>
<td>11</td>
<td>2</td>
<td>19</td>
<td>1</td>
<td>33</td>
<td>89</td>
<td>7.5%</td>
</tr>
<tr>
<td>Lead Acid BESS</td>
<td>19</td>
<td>1</td>
<td>0</td>
<td>20</td>
<td>20</td>
<td>75</td>
<td>6.4%</td>
</tr>
<tr>
<td>Lithium ion BESS</td>
<td>6</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>14</td>
<td>49</td>
<td>4.2%</td>
</tr>
<tr>
<td>Flywheels FESS</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>40</td>
<td>3.4%</td>
</tr>
<tr>
<td>New PHEs</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>30</td>
<td>2.5%</td>
</tr>
<tr>
<td>NICD BESS</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>26</td>
<td>2.2%</td>
</tr>
<tr>
<td>Thermal TES</td>
<td>68</td>
<td>4</td>
<td>9</td>
<td>1</td>
<td>82</td>
<td>3</td>
<td>0.3%</td>
</tr>
<tr>
<td>Hydrogen HESS</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>0.1%</td>
</tr>
<tr>
<td>Lead / Carbon BESS</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Superconductor</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>TOTAL excluding PHEs</td>
<td>117</td>
<td>17</td>
<td>207</td>
<td>5</td>
<td>345</td>
<td>1,179</td>
<td>100.0%</td>
</tr>
<tr>
<td>PHEs (Data of 2013)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>350</td>
<td>152,000</td>
<td>Excluded</td>
</tr>
</tbody>
</table>
Table 2: ES Technologies Features (part 1) [26-31]

<table>
<thead>
<tr>
<th>ESS TECHNOLOGIES → DEFINING FEATURES</th>
<th>Unit</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.- COST</td>
<td></td>
<td>[$/kW]</td>
<td>300</td>
<td>425 - 1,250</td>
<td>517 &amp; 1,950 - 2,150</td>
<td>300 - 2,200</td>
</tr>
<tr>
<td>INITIAL CAPITAL COST / INVESTMENT PER KW</td>
<td>[$/kW]</td>
<td>2,000 - 72,000</td>
<td>3 - 150</td>
<td>50 &amp; 350 - 430</td>
<td>170 - 8,800</td>
<td>2 - 15</td>
</tr>
<tr>
<td>1.3 BOP (Balance Of Plant): housing, environment control &amp; electrical connection equipment</td>
<td>[$/kWh]</td>
<td>1,500</td>
<td>50</td>
<td>40</td>
<td>9.60</td>
<td>-</td>
</tr>
<tr>
<td>1.4 FIXED RUNNING COST (OPERATION + MAINTENANCE)</td>
<td>[$/kWh]</td>
<td>8 - 26</td>
<td>1.42</td>
<td>3.77</td>
<td>1,000</td>
<td>2 - 15 €/kWh</td>
</tr>
<tr>
<td>1.5 VARIABLE RUNNING COST (OPERATION + MAINTENANCE)</td>
<td>[$/kWh]</td>
<td>0.5 - 2</td>
<td>0.01</td>
<td>0.27</td>
<td>0.4</td>
<td>1</td>
</tr>
<tr>
<td>2.- EFFICIENCY</td>
<td>ROUNDTRIP EFFICIENCY (RTE) [%]</td>
<td>80 - 95</td>
<td>64 - 80</td>
<td>50 - 57</td>
<td>60 - 95</td>
<td>34 - 42</td>
</tr>
<tr>
<td>3.- ELECTRICAL CAPACITY</td>
<td>POWER RATING [MW]</td>
<td>0.001 - 100</td>
<td>20 - 500</td>
<td>3 - 100</td>
<td>0.1 - 20</td>
<td>0.0001 - 50</td>
</tr>
<tr>
<td>ENERGY STORAGE CAPACITY [MWh]</td>
<td>&lt; 0.25</td>
<td>400 - 7,000</td>
<td>250</td>
<td>0.0052 - 5</td>
<td>0.00012 - 200</td>
<td></td>
</tr>
<tr>
<td>POWER DENSITY [kW/kg]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ENERGY MASS DENSITY [kWh/ton]</td>
<td>10 - 75</td>
<td>3.2 - 5.5</td>
<td>15 - 100</td>
<td>100 - 1,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.- STORAGE / DISCHARGE BEHAVIOUR</td>
<td>SELF-DISCHARGE [%]</td>
<td>10 - 15 %</td>
<td>0</td>
<td>-</td>
<td>1 - 3</td>
<td>-</td>
</tr>
<tr>
<td>DEPTH OF DISCHARGE [%]</td>
<td>~ 100</td>
<td>-</td>
<td>-</td>
<td>~ 100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>STORAGE TIME [h]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Days - 1 Week</td>
<td></td>
</tr>
<tr>
<td>RESPONSE TIME [s]</td>
<td>~ 17 ms</td>
<td>Sec - Min</td>
<td>Sec - Min</td>
<td>~ 4 ms</td>
<td>&lt; 1/4 cycle</td>
<td></td>
</tr>
<tr>
<td>DISCHARGE DURATION [h]</td>
<td>1 - 30 min</td>
<td>6 Hrs - Days</td>
<td>1 - 6 hrs</td>
<td>1 Hr</td>
<td>Min - Hrs</td>
<td></td>
</tr>
<tr>
<td>5.- LIFETIME</td>
<td>DISCHARGE CYCLES</td>
<td>10,000 - 100,000</td>
<td>10,000 - 30,000</td>
<td>&gt; 10,000</td>
<td>10,000,000</td>
<td>-</td>
</tr>
<tr>
<td>Lifespan / Longevity [years]</td>
<td>20 - 40</td>
<td>50 - 60</td>
<td>90 - 120</td>
<td>20 - 30</td>
<td>2 - 20</td>
<td></td>
</tr>
<tr>
<td>6.- ENVIRONMENT</td>
<td>ENVIRONMENTAL HOSTILITY, POLLUTION, SAFETY</td>
<td>Magnetic field safety issue</td>
<td>Greenhouse emissions</td>
<td>Gas emissions, pressure vessels</td>
<td>Containment safety</td>
<td>Highly flammable</td>
</tr>
<tr>
<td>GEOLOGICAL REQUIREMENTS</td>
<td>Medium (Underground site)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7.- STATE-OF-THE-ART</td>
<td>MATURITY</td>
<td>Mature</td>
<td>Mature</td>
<td>Demonstration</td>
<td>Commercial in Low-Speed. Pre-commercial in High-Speed</td>
<td></td>
</tr>
<tr>
<td>8.- APPLICATIONS</td>
<td>POWER APPLICATIONS</td>
<td>ENERGY APPLICATIONS</td>
<td>POWER &amp; ENERGY APPLICATIONS</td>
<td>BRIDGING APPLICATIONS</td>
<td>Short-Term</td>
<td>Real Long-Term</td>
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Table 3: ES Technologies Features (part 2) [26-31]
<table>
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<tr>
<th>EES TECHNOLOGIES</th>
<th>UTILITY SYSTEM</th>
<th>APPLICATIONS REQUIREMENTS</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
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<tbody>
<tr>
<td><strong>POWER RATING (MW)</strong></td>
<td>1000</td>
<td>4.5</td>
<td>20</td>
<td>100</td>
<td>50</td>
<td>25</td>
<td>15</td>
<td>10</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>DISCHARGE DURATION (HRS)</strong></td>
<td>4.5</td>
<td>20</td>
<td>100</td>
<td>50</td>
<td>25</td>
<td>15</td>
<td>10</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RESPONSE TIME</strong></td>
<td>1 Min</td>
<td>5 Min</td>
<td>15 Min</td>
<td>30 Min</td>
<td>1 Hrs</td>
<td>3 Hrs</td>
<td>6 Hrs</td>
<td>12 Hrs</td>
<td>24 Hrs</td>
<td>48 Hrs</td>
<td>72 Hrs</td>
<td>96 Hrs</td>
<td></td>
</tr>
<tr>
<td><strong>SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)</strong></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td><strong>COMPRESSED AIR ENERGY STORAGE (CAES)</strong></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td><strong>SOLAR ENERGY STORAGE SYSTEM (SES)</strong></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td><strong>PUMPED HYDRO ENERGY STORAGE (PHES)</strong></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td><strong>FLOW THRU ENERGY STORAGE (FTES)</strong></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td><strong>SUPER-CAPACITOR ENERGY STORAGE (SCE)</strong></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td><strong>CHEMICAL ENERGY STORAGE (CES)</strong></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4. ES Applications [31-40]**

- **Provide System Capacity Resource Adequacy / Electric Supply Capacity / Loadability or investment deferral**
- **Energy Price Arbitrage / Electric Energy Time-Shift / Renewable Energy Time-Shift / Load Leveling and Peak Shaving**
- **Load Management / Provide Spin & Non-Spin Reserve / Electric Supply Reserve Capacity / Conventional Spinning Reserve / Primary Regulation / Deployment time 5-30 minutes**
- **Provide Spin & Non-Spin Reserve / Electric Supply Reserve Capacity / Fast Response Spinning Reserve / Secondary Regulation (Deployment time 2-10 minutes)**
- **Provide Voltage & Pressure Regulation / Area Regulation / Primary Regulation (Deployment time 5-30 seconds)**
- **Provide Black-Start and Ramp / Power system Start-Up**
Table 5: Applicable grid system size for ES [31-40]

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>RESTRICTING FEATURES</th>
<th>ELECTRICAL SYSTEM</th>
<th>REMARKABLE PROTECTION</th>
<th>TECHNOLOGY</th>
<th>FEATURES</th>
<th>APPLICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kahawale Wind Power Plant</td>
<td>Saskatoon, Man.</td>
<td>Mind PV / Fossil &amp; Battery Storage</td>
<td>Advanced Lead-Acid Battery</td>
<td>10-20 MW, 1-2 MW, 2.5-1 MW</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Kahawale Wind Power Plant</td>
<td>Saskatoon, Man.</td>
<td>Mind PV / Fossil &amp; Battery Storage</td>
<td>Advanced Lead-Acid Battery</td>
<td>10-20 MW, 1-2 MW, 2.5-1 MW</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Kawaraka Island</td>
<td>Kiski, MAN</td>
<td>Mind PV / Fossil &amp; Battery Storage</td>
<td>Advanced Lead-Acid Battery</td>
<td>10-20 MW, 1-2 MW, 2.5-1 MW</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sonowill Island</td>
<td>Kiski, MAN</td>
<td>Mind PV / Fossil &amp; Battery Storage</td>
<td>Advanced Lead-Acid Battery</td>
<td>10-20 MW, 1-2 MW, 2.5-1 MW</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6: Existing ES on Islands. Case Studies [31-40]

<table>
<thead>
<tr>
<th>ISLAND</th>
<th>LOCATION</th>
<th>PROJECT</th>
<th>牆</th>
<th>FEATURES</th>
<th>APPLICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>King Island</td>
<td>Tasmania</td>
<td>A109</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Metsats</td>
<td>Australia</td>
<td>A109</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Seta Sita</td>
<td>California</td>
<td>A109</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Jima Island</td>
<td>Austria</td>
<td>A109</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 7. El Hierro energy system comparison: before and after.

<table>
<thead>
<tr>
<th></th>
<th>EL HIERRO’S ENERGY SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2011</td>
</tr>
<tr>
<td><strong>Conventional generation</strong></td>
<td></td>
</tr>
<tr>
<td>Diesel power</td>
<td></td>
</tr>
<tr>
<td>a) Nominal output</td>
<td>13.6</td>
</tr>
<tr>
<td>b) Annual production</td>
<td>44.6 GWh</td>
</tr>
<tr>
<td>c) Annual fuel consumption (220g/kWh)</td>
<td>9812 Ton</td>
</tr>
<tr>
<td>d) Electricity Generation cost (0.242€/kWh)</td>
<td>10.79 M€</td>
</tr>
<tr>
<td><strong>Renewable generation</strong></td>
<td></td>
</tr>
<tr>
<td>Wind power</td>
<td></td>
</tr>
<tr>
<td>a) Nominal output</td>
<td>0</td>
</tr>
<tr>
<td>b) Available annual production</td>
<td>0 GWh</td>
</tr>
<tr>
<td>c) Maximum annual production</td>
<td>0 GWh</td>
</tr>
<tr>
<td>- Generation at demand period</td>
<td>0 GWh</td>
</tr>
<tr>
<td>Consumed by the pumping station</td>
<td>0 GWh</td>
</tr>
<tr>
<td>Destined to synchronous compensation</td>
<td>0 GWh</td>
</tr>
<tr>
<td>d) Electricity generation cost</td>
<td>0 €/kWh</td>
</tr>
<tr>
<td>e) Total cost</td>
<td>0 M€</td>
</tr>
<tr>
<td><strong>Hydro power capacity</strong></td>
<td></td>
</tr>
<tr>
<td>a) Nominal output</td>
<td>0</td>
</tr>
<tr>
<td>b) Annual production</td>
<td>0 GWh</td>
</tr>
<tr>
<td>c) Turbine efficiency</td>
<td>0 %</td>
</tr>
<tr>
<td><strong>Total generation</strong></td>
<td>44.6 GWh</td>
</tr>
<tr>
<td><strong>Annual energy demand (including desalination plant)</strong></td>
<td>44.6 GWh</td>
</tr>
<tr>
<td><strong>Peak demand</strong></td>
<td>7.56 MW</td>
</tr>
</tbody>
</table>
Table 8. Life Cycle and amortization years for the hybrid hydro-wind electricity generation plant

<table>
<thead>
<tr>
<th>EQUIPMENT</th>
<th>NOMINAL CHARACTERISTICS</th>
<th>CYCLE LIFE (YEARS)</th>
<th>AMORTIZATION (YEARS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind farm</td>
<td>5x2.3 MW wind turbine generators</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Hydro plant</td>
<td>4x2.83 MW Pelton turbine-generator groups</td>
<td>65</td>
<td>30</td>
</tr>
<tr>
<td>Pumping plant</td>
<td>2x1.5MW pump sets + 6x500kW pump sets</td>
<td>65</td>
<td>30</td>
</tr>
</tbody>
</table>

Upper reservoir
- Storage capacity: 379,634 m³
- Maximum water level: 12 m³
- Location above sea level: 709.5 m

Lower reservoir
- Storage capacity: 150,000 m³
- Maximum water level: 15 m
- Location above sea level: 56 m

Hydro and Pumping plants civil work: 65

Table 9. Average yearly cash flow at a discount rate of NPV equal to zero.

<table>
<thead>
<tr>
<th>Year</th>
<th>Cash flows (average per year)</th>
<th>Discount factor</th>
<th>Present values</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>- 82 000 000 €</td>
<td>1</td>
<td>- 82 000 000 €</td>
</tr>
<tr>
<td>1</td>
<td>7 740 219.910 €</td>
<td>0.935</td>
<td>7 233 850.384 €</td>
</tr>
<tr>
<td>2</td>
<td>7 740 219.910 €</td>
<td>0.873</td>
<td>6 760 607.836 €</td>
</tr>
<tr>
<td>3</td>
<td>7 740 219.910 €</td>
<td>0.816</td>
<td>6 318 325.080 €</td>
</tr>
<tr>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>18</td>
<td>7 740 219.910 €</td>
<td>0.296</td>
<td>2 290 051.766 €</td>
</tr>
<tr>
<td>19</td>
<td>7 740 219.910 €</td>
<td>0.276</td>
<td>2 140 235.304 €</td>
</tr>
<tr>
<td>20</td>
<td>7 740 219.910 €</td>
<td>0.258</td>
<td>2 000 219.911 €</td>
</tr>
</tbody>
</table>

NPV = IRR