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Electrical Energy Storage Systems Feasibility; the Case of Terceira Island

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Abstract: The Azores Regional Government, through the Sustainable Energy Action Plan for the Azorean Islands, assumed that by the year 2018, 60% of electricity would be generated from renewable energy sources. Nevertheless, by increasing renewable energy sources share in the electricity mix, peak energy that exceeds grid capacity cannot be used unless when considering energy storage systems. Therefore, this article aims at determining, among batteries and Pumped Hydro Systems, the most cost-effective energy storage system to deploy in Terceira Island, along with geothermal, wind, thermal and bio waste energy, while considering demand and supply constraints. It is concluded that a pumped hydro system sited in Serra do Morião-Nasce Água is the best option for storage of the excess generated energy when compared with batteries. However, further studies should analyze environmental constraints. It is demonstrated that by increasing the storage power capacity, a pumped hydro system improves its cost efficiency when compared with batteries. It is also demonstrated that, to ensure quality, economic feasibility, reliability and a reduction of external costs, it is preferable to replace fuel-oil by wind to generate electricity up to a conceivable technical limit, while building a pumped hydro system, or dumping the excess peak energy generated.

Keywords: economics; Pumped Hydro Systems; batteries; energy storage; geothermal; wind; thermal; bio waste energy

1. Introduction

Countries that are not producers of non-renewable energy become economically dependent on others, which can pose a threat to their security. Therefore, the growing international concerns regarding these and other matters on the economic, technological, institutional and environmental spheres have led to an increase in Renewable Energy Sources (RES) share in the energy mix worldwide.

Pollution, climate change, energy supply and security still pose huge challenges, requiring major changes in the energy infrastructures [1] and energy policy.

With the increase in intermittent RES share in the energy mix, such as wind and solar, when supply exceeds demand, energy surplus often occurs and overall efficiency is not achieved in the electricity system. In order to enable a further increase in the share of RES in the energy mix, three options may be considered. The first is to export the excess power, the second is to curtail the excess power and the third is to deploy an Energy Storage System (ESS) in order to accommodate all power generated from RES. Given that islands have isolated grids and cannot export electricity, only the second and the third options can be considered for these regions. It is worth mentioning that the European Union has more than 500 inhabited islands with isolated grids, occupying 6% of the territory [2].

ESS provides three primary functions: energy management, bridging power, power quality and reliability [3]. Several stationary storage options, such as Pumped Hydro Systems (PHS), batteries, capacitors, superconducting magnetic energy storage, flywheels, Hydrogen Pallet Handling Systems

(HPHS), Compressed Air Energy Storage (CAES), Thermal Energy Storage (TES) and Community Energy Storage (CES), can be used in order to allow higher RES penetration [3,4].

Given that Terceira Island has a high potential to generate wind and geothermal energy, that geothermal and bio-waste energy generation projects are approved to be deployed up to the year 2018, and that the oil-based thermal power plant will require renovations in the near future, the time is ripe to analyze the cost-effectiveness of an ESS to deploy in Terceira Island, together with RES generation projects as well as energy investments. Two options to consider could be a PHS or a battery system, given their advantages, in terms of cost effectiveness, when related to other ESS [5].

Several authors have analyzed the introduction of RES in the electricity mix. Some performed a techno-economic comparison of the energy storage systems of electrical networks for autonomous islands [6], others analyzed optimum sizing of photovoltaic energy storage systems for autonomous small islands [7]; others developed an energy balance analysis of wind-based PHS systems of electrical networks for remote islands [8]; others studied the optimization of small electric energy systems management, including RES [9]; others analyzed optimal energy management of micro-grids with RES and demand response [10]; others analyzed and developed optimized hybrid systems [11]; others studied innovations regarding RES introduction in the energy mix [12] and others calculated systems-scale energy efficiency and net energy returns in a bottom-up matrix-based approach [13].

Several authors studied the deployment of RES and ESS in small islands [2,6–8,14–22]. Nevertheless, none of the authors referred to have performed a sensitivity analysis comparing batteries with PHS solutions to store energy for different power capacities and dispatched energy decoupled from the costs of the energy generating systems. Besides, given local specificities, it is important to identify the best options for storing the excess peak energy at specific locations on Terceira.

For electricity storage, a combination of sodium sulfide (NaS) and lithium-ion (Li-ion) batteries is a good option to achieve a system that combines a stable network with quick response, good frequency adjustment and voltage regulation. Li-ion batteries are rechargeable batteries in which lithium ions move from the negative to the positive electrode during discharge and move back when charging [23]. NaS batteries are molten state batteries built from sodium (Na) and sulfur (S), operating between 300 °C and 350 °C and can be used for power quality applications, grid stabilization and integration of RES [23]. In 2010, over three hundred grid applications of NaS batteries could be found worldwide [24].

Therefore, the aim of this article is to determine the best option to adopt in the storage of the excess peak energy in Terceira Island through a technical and cost-effectiveness analysis of three sitting options for a PHS and a battery solution (NaS + Li-ion). Finally, a sensitivity analysis considering power capacity and energy as critical variables is performed.

2. Literature Review

2.1. Electrical Energy Storage Systems

It is generally possible to achieve a share of RES in the energy mix up to 20% without making major adjustments in the structure or operation of the power grid [25]. Nevertheless, when the goal is to increase the share of RES in the energy mix, given their intermittency and unavailability when demand is at its peak, it is relevant to study the integration of RES with ESS even though the capital cost of many grid storage technologies is very high when compared to conventional alternatives, such as gas-fired power plants, which can be constructed quickly and are perceived as a low-risk investment by both regulated utilities and independent power producers [4].

ESS technologies can be divided in stationary and non-stationary. Stationary storage technologies include PHS, compressed air, large-scale batteries, flow batteries, capacitors, superconducting magnetic energy storage, flywheels, thermal storage, HPHS, CAES, TES and CES [3,4], and non-stationary include electric vehicles which can act as a battery [26].

Although commercially available, none of the ESS is ideal in terms of being mature, environmentally friendly and having a long lifespan, low costs, high density and efficiency [25].

Each EES has a suitable application range. CES is suitable for energy management application; flywheels, batteries, capacitors and super-capacitors are better for power quality and short duration UPS, whereas batteries, flow batteries, fuel cells and metal-air cells are more suitable for bridging power [3]. Regarding grid storage, round trip efficiencies range from below 30% to over 90%.

PHSs leverage the existing topographic and hydrological conditions of the land and, if necessary, use artificially built water reservoirs [24], thereby, making it well suited for places where geography contributes to decrease investment costs. PHS uses the excess peak energy which occurs during low demand periods (generally during the night) to pump water from the lower to the upper reservoir, and turbine water from the upper to the lower reservoir to generate electricity when demand exceeds supply.

The first PHSs were built in Switzerland and Italy in 1890. It is relatively simple to project a PHS, and the operating cost per energy unit is estimated to be among the cheapest [23]. However, investment costs are high due to the construction of reservoirs (when necessary) and pipes, among other infrastructures. In terms of negative environmental externalities, disturbances of the local flora and fauna and the daily fluctuations of the water level shall be considered.

Batteries can be classified into two groups. The primary type batteries are non- rechargeable and are, therefore, not suitable for RES integration systems. The secondary type batteries are rechargeable, being necessary to analyze battery capacity, energy density, total battery losses, battery types [24,27] as well as battery costs.

Battery capacity is given in ampere-hours (Ah) and varies with environmental conditions, such as temperature and humidity, and with the current and discharge depth. It decreases over time, with a battery being normally considered to have reached its lifespan when capacity is reduced to 80% of its nominal capacity. Energy density, which is the amount of energy stored per unit of volume or weight, is measured in Watt-hour per kilogram. Total battery losses vary with technology, 20% losses being a common consideration. Nevertheless, this value depends on the battery type.

Table 1 presents the description, advantages and disadvantages of the several battery types.

Table 1. Batteries for integration with Renewable Energy Sources (RES).

Battery Types	Description	Advantages	Disadvantages
Lead-acid	Rechargeable; For starter motors, solar, wind and hydropower ("Deep Cycle").	Great durability; Relatively low cost. Resistant to temperature variations.	Very heavy; High load time.
Lithium	Used in devices which require long lifetimes. Frequency adjustment; Voltage regulation; Integration with RES.	Auto low discharge factor. Low recharge time; High energy density; Ability to tolerate more discharge cycles; High energy efficiency.	High costs; Negative effects of overload on the unloading; Potential overheating.
Sodium Sulfide	Network stabilization; Integration of RES.	High energy density; Long life cycle; Quick response; High efficiency in loading-unloading cycles; Tolerates high numbers of charge/discharge cycles.	May require heating; Potential security issues with the sodium.

Source: adapted from Jung (2010) and Ponte (2012).

Table 2 presents the characteristics of PHS, NaS batteries and Li-ion batteries [3,6–8,28,29]. It is relevant to mention that this is meant to be an indicative source of information, being necessary to consult the referred sources in order to have information about the specific conditions of each study which gave rise to these data.

Table 2. Characteristics of Pumped Hydro Systems (PHS), Sodium-sulfur (NaS) batteries and Li-ion Batteries.

Technology	PHS	NaS Batteries	Li-ion Batteries
Capacity	5 MW–2 GW [b] 100–5000 MW [e]	50 kW–8 MW [e]	0–100 kW [e]
Response time	1–24 h+ [e]	seconds–hours [e]	minutes–hours [e]
Cycles	25,000 [d]	3000 [d]	4000 [d]
Suitable storage duration	4–100 h [b] Hours–months [e]	Seconds–hours [d,e]	minutes–hours [d] inutes–days [e]
Self Discharge per day	very small [e]	~20% [e]	0.1–0.3% [e]
Efficiency (%)	65–80 [a] 55–80 [b] 85 [d]	75–90 [a] 75 [d]	85–98 [a] 85 [d]
Lifetime (years)	30 [a] 50 or more [b] 30–50 [c] 40–60 [e]	5–15 [a] 10–15 [c]	5–15 [a]
Development stage	mature [b]	developed [e]	developed [e]
Energy density	0.5–1.5 Wh/L [e]	150–240 Wh/kg [a]	75–200 Wh/kg [a]
Power density	0.5–1.5 W/L [e]	150–230 W/Kg [a]	150–315 W/Kg [a]

Source: [a] Cho et al. (2015); [b] Maidonis, 2013; [c] Kaldellis et al. (2009) and Kaldellis et al. (2010a); [d] Schoenung (2011); [e] Chen et al. (2009).

Summarizing, PHS is more suitable for high capacities, with faster response times, longer lifespan, and a maximum depth of discharge up to 95% without affecting their service period [6] and more maturity in terms of technological development and knowledge of applications when compared to batteries. Nevertheless, PHS has higher investment costs when it is necessary to build two reservoirs or the distance among reservoirs is high. Besides, the environmental impact on the surroundings due to construction and operation may constitute a drawback.

2.2. Energy Economics

Electricity generating costs continue to vary greatly from region to region, reflecting influences such as the shale gas boom in the United States, changing utilization rates in areas of high renewables penetration, the shortage of local gas production in East Asia, carbon prices in Europe, differing regulations on nuclear power all over the world, and contrasting resources for solar generation [30].

However, it is possible to point out global average values. According to the Bloomberg New Energy Finance (2015), in the first semester of 2015, the global average LCOE for onshore wind was nearly $85/MWh; for offshore wind $176/MWh; for crystalline silicon PV solar $129/MWh; for biomass incineration $134/MWh; for coal-fired generation $66/MWh (in the Americas), $68/MWh (in Asia-Pacific) and $82/MWh (in Europe); and for combined-cycle gas turbine generation $76/MWh (in the Americas), $85/MWh (in Asia-Pacific) and $103/MWh (in Europe, Middle East and Africa). Moreover, the referred study mentions that nuclear, coal and gas have very different LCOE levels from one region of the world to another, but both the Americas and the Europe, Middle East and Africa region had LCOE of nearly $261/MWh (in the first semester of 2015).

The authors of the Bloomberg New Energy Finance (2015) refer that (for the analyzed countries) onshore wind is now fully cost-competitive with both gas-fired and coal-fired generation, once carbon costs are taken into account, in the UK and Germany, and that in China, onshore wind was in the first semester of 2015 cheaper than gas-fired power, at $77/MWh versus $113/MWh, but much more expensive still than coal-generated electricity ($44/MWh), while solar PV power was at $109/MWh [31].

In the United States, coal and gas were still cheaper, at $65/MWh, against onshore wind at $80/MWh and PV at $107/MWh [31].

According to the Annual Energy Outlook projections to year 2040 from the Energy Information Administration (2015), the Brent spot price for crude oil is estimated to increase from $56/bbl (bbl is the abbreviation for barrel) in year 2015 to $76/bbl in year 2018, reaching $141/bbl in the year 2040 ($229/bbl in nominal dollars) [32].

Moreover, according to Fraunhofer Institute for Solar Energy Systems (2013) estimates, presented in Figure 1, it is expected that generating electricity from wind onshore becomes more appealing, in economic terms, than generating electricity from coal or from any other renewable energy, such as PV, Wind offshore or Biogas, in average terms [33]. Generating electricity from wind can be already cheaper than doing it in utility diesel > 10 W, since the last has average LCOE of nearly 0.12 to 0.13 €/kWh [31]. However this may vary significantly according to the oil price, taxes or subsidies given to each type of energy.

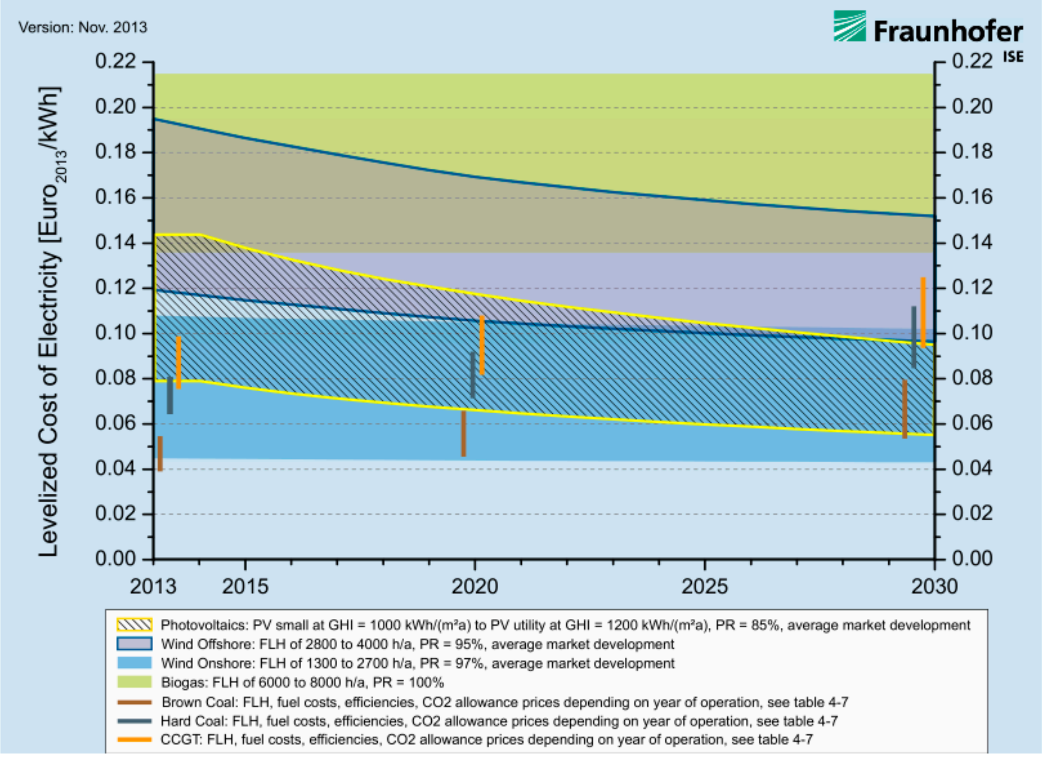

Figure 1. Forecast for the Development of Levelized Cost of Energy (LCOE) of renewable technologies as well as conventional power plants in Germany by 2030. Source: Fraunhofer Institute for Solar Energy Systems (2013).

Therefore, it is imperative to consider the deployment of energy solutions that are less dependent on fossil fuels, while disregarding oil-based thermal power until the allowed technical limits of electrical utilities.

It is also relevant to mention that pricing of electricity from energy sources may not include all external costs [34]. External costs may include environmental impacts, usage lifespan, energy storage, recycling costs, or beyond-insurance accident effects. If external costs such as damage to the environment and to human health are taken into account, the cost of producing electricity from coal or oil is expected to double over its present value, and the cost of electricity production from gas is expected to increase by 30% [35,36]. These estimates do not include the external cost of global warming from these sources.

The Methodological Convention of the Federal Environment Agency of Germany arrived at external costs of electricity from lignite as 10.75 Eurocent/kWh, from hard coal as 8.94 Eurocent/kWh, from natural gas as 4.91 Eurocent/kWh, from photovoltaic as 1.18 Eurocent/kWh, from wind as 0.26 Eurocent/kWh and from hydro as 0.18 Eurocent/kWh [37] and the Federal Environment Agency arrived at external environmental costs of nuclear energy as 10.7–34 Eurocent/kWh [38].

Therefore, while considering the data from the Fraunhofer Institute for Solar Energy Systems (2013) presented in Figure 1 and the data from the Methodological Convention of the Federal Environment Agency [37], one can say that while considering the LCOE and external costs of energy forecasts, it is certain that wind will most probably supplant coal as an energy source to generate electricity in economic, social and environmental terms, even while considering the costs to store electricity.

There are many possibilities to store electricity. However, batteries and PHS, given their mature state of technology development seem to be the most appealing nowadays.

3. Methodology

3.1. Characterization of Terceira Island Electricity Demand and Supply System

Terceira is one of the nine islands that make up the Azores archipelago, which is located in the Atlantic Ocean. The Azorean electrical systems are small and dispersed, with nine small and isolated systems, with fossil fuels currently contributing more than 80 percent of the overall energy consumption of the Azores [39].

The Azores Regional Government, following the 20-20-20 agenda, declared that by the year 2018, 60% of electricity would be generated from renewable sources; 20% of total primary energy would come from renewable sources; and 35% of the total primary energy would be used in the form of electricity towards a reduction of fossil fuel import and greenhouse gas emissions minimization [39].

According to Electricidade dos Açores (EDA) [40], on Terceira, electricity is mainly generated on an oil-based thermal power station, named Central do Belo Jardim (nearly 82.7% of the total generation of electricity), with thermal generators varying from 3 to 12.3 megawatts (MW) each, being most of these old and inefficient. The ones being mostly used have 6.1 MW and 12.3 MW and are more recent (from 2004). Diesel is also used in periods of repairs and start-ups of Central do Belo Jardim. Electricity is also generated on a 12.6 MW wind farm (17.0%) and on three hydroelectric power stations (0.2%). Table 3 presents the electricity generation per energy source in Terceira.

Table 3. Terceira Electricity Generation, 2012.

Power Station	Installed Power (MW)
Thermal PowerStation (fuel-oil + diesel)	61.116
Hydropower station	1.432
Wind Energy	12.6
Total	75.148

Source: adapted from Electricidade dos Açores, 2014 [41].

It is estimated that, by the end of the year 2018, Terceira will have 12.6 MW wind power (in Serra do Cume), 1.7 MW bio-wastes energy recovery and 10 MW geothermal power in Central of Pico Alto, besides oil-based thermal power [42]. The Azores Regional Government decided to increase geothermal power because this is a RES without the intermittency associated with wind or solar energy and because of its high local potential. Figure 2 presents the estimated medium load profile per energy source and the estimated medium electricity supply and demand curves for Terceira by the year 2018.

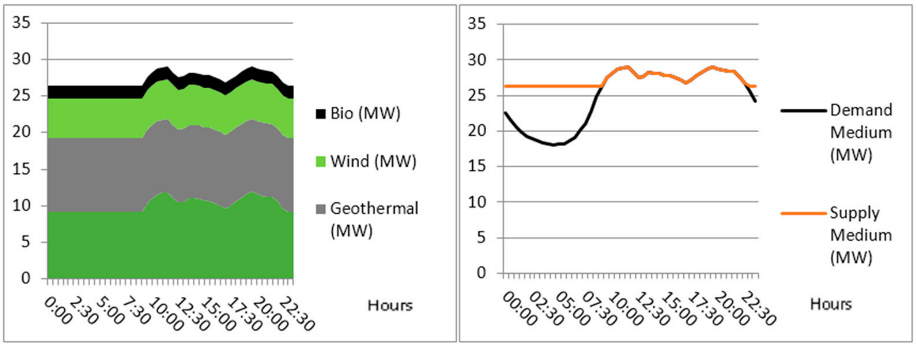

Figure 2. The 2018 estimates for the medium load profile per energy source, and medium electricity supply and demand curves in Terceira Island. Source: adapted from Electricidade dos Açores, 2012.

For the year 2018, wind power figures were estimated from historical data to be nearly 5.45 MW, and hydropower was assumed to be 0 MW, bio-waste power to be 1.7 MW and geothermal power to be 10 MW. Thermal energy is estimated to vary from 9.2 MW to 11.88 MW, in order to ascertain that electricity supply satisfies the demand, while considering the restrictions of the oil-based thermal power station [42].

According to the Standard 65/2011 of 17 August, in the Azores, priority is given to feeding in the grid all the electricity generated from RES. Therefore, to maximize RES penetration, the thermal power groups of the oil-based thermal power station should operate under reduced loads.

Therefore, Figures 2–4 consider the thermal power station to operate with the 6.1 and 12.3 MW thermal power groups [42], given that their auxiliary systems are those representing less weight in the internal consumption of the power plant and that these are able to grant the spinning reserve [42]. According to Electricidade dos Açores (2012), there is a technical limit under which these thermal power groups should not operate, which is approximately 50% of their rated power.

On Terceira, electricity demand is expected to follow the current trend, and to be different for the several months, for weekdays and weekends and for the hours of the day. Following the current trend, one can estimate variations between weekdays and weekends (with higher electricity demand during the day for weekdays when compared with weekends) and between winter and summer, with the months of May and June having lower electricity demands when compared with the remaining months of the year [40,41]. A large variation between the minimum off-peak and the maximum peak electricity demand can be found during the day.

Figure 3 presents the estimated off-peak minimum load profile per energy source and the estimated minimum off-peak electricity supply and demand curves for Terceira by the year 2018.

Figure 4 presents the estimated maximum peak load profile per energy source and the estimated maximum peak electricity supply and demand curves for Terceira (2018).

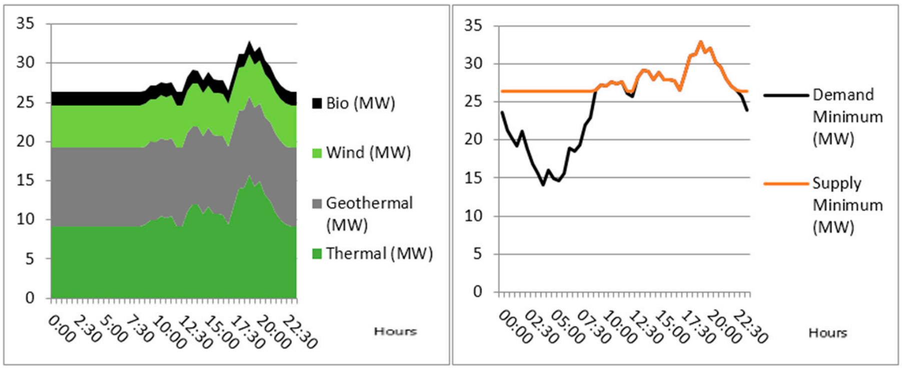

Figure 3. The 2018 estimates for off-peak minimum load profile per energy source, and electricity supply and demand curves in Terceira. Source: adapted from Electricidade dos Açores, 2012.

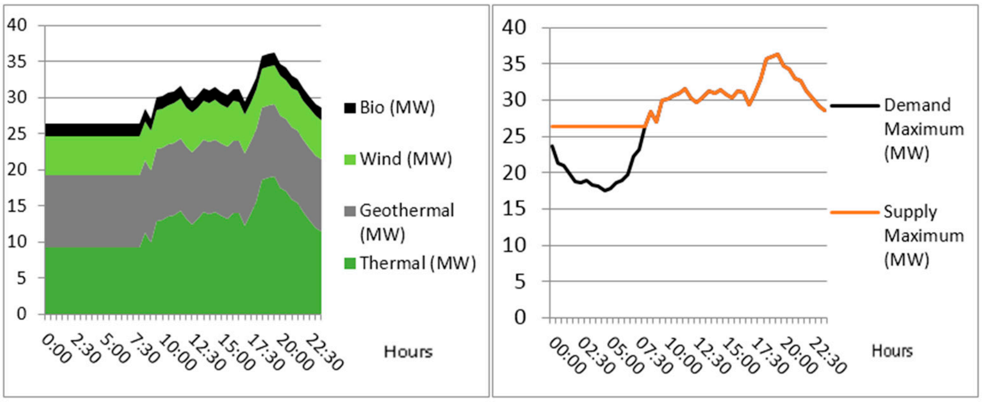

Figure 4. Year 2018 estimates for the maximum peak load profile per energy source, and electricity supply and demand curves in Terceira Island. Source: adapted from Electricidade dos Açores, 2012.

3.2. Technical Feasibility Analysis

First, a technical feasibility analysis is done in order to determine the best site to build the PHS. Power capacity is determined by considering the electricity demand and supply curves of Terceira (Figures 2–4) and the storage capacity of the excess peak energy to feed the grid when demand is higher than supply.

The potential energy, released from the upper reservoir or stored in the battery bank, is derived from Equation (1) [20].

$$E_c = \eta_{day} \times E_{load} = \frac{\eta_t \rho \times V \times g \times h}{3.6 \times 10^6}, \tag{1}$$

where E_c is the energy storage capacity of a battery bank or a water reservoir (Joules); η_{day} is the number of autonomous days powered solely by the battery storage bank; E_{load} is the daily energy consumption; η_t is the overall efficiency of turbine mode, ρ is the density of water (kg/m^3); V is the volume of the water reservoir (m^3); g is the gravitational acceleration (9.81 m/s^2); and h is the total height (m). Therefore, it is possible to derive the volume of the reservoir (V) from Equation (1). The autonomy period here considered is one day.

The water flow rate pumped from the lower reservoir is given by Equation (2), being comparable to the charging rate of the battery [20].

$$q_p(t) = \frac{\eta_p \times P(t)}{\rho \times g \times h} = c_p \times P(t), \tag{2}$$

where P is the charging power from the generator to the pump (W); h is the elevating height (m); g is the acceleration due to gravity (9.8 m/s^2); ρ is the density of water (1000 kg/m^3); η_p is the overall pumping efficiency; and c_p is the water pumping coefficient of the pump unit (m^3/kWh).

When water is drawn from the upper reservoir in order to operate the hydro turbines, the released power from the turbine/generator unit is given by Equation (3) [20].

$$P_t(t) = \eta_t \times \rho \times g \times h \times q_t(t) = c_t \times q_t(t), \tag{3}$$

where η_t stands for the overall efficiency of the turbine unit; $q_t(t)$ represents the water volumetric flow rate input into the turbine (m^3/s); and c_t stands for the turbine generating coefficient (kWh/m^3). The remaining calculations for the battery and PHS systems follow Ma et al. methodology [20].

The PHS shall, preferably, have an elevation difference between the two reservoirs of at least 300 to 400 m and hydraulic circuits of less than 2.5 km. It is then necessary to connect both reservoirs using a hydraulic circuit under pressure and build a central station near the reservoir bottom. If one uses existing reservoirs, a chamber for pumps should be built [43]. It is also necessary to consider the environmental sensitivity of the area, as less prudent or even more intrusive actions may trigger an environmental imbalance. According to Yang and Jackson (2011), pumping may increase the water temperature and stir up sediments at the bottom of the reservoirs or lagoons, thereby deteriorating water quality, trapping and killing fishes [44]. Nevertheless, systems to minimize fish entrapment may be installed. Besides, the water inlet and outlet could be designed to minimize turbulence, and an oxygen injection system could also compensate for the potential oxygen loss due to water temperature increase and pumping. In some cases, the PHS system stabilizes water level and maintains water quality.

The potential impacts of PHS projects are site-specific and must be evaluated on a case-by-case basis [44]. Nevertheless, it is not the scope of the article.

Table 4 presents the pump and turbine requirements for the PHS according to different static waterfalls and flow rates [43].

Table 4. Pump and turbine requirements.

Static Waterfall (m)	Pump		Turbine		Volume for Pumping During 6 h (m^3)	Volume for Pumping During 7 h (m^3)	Volume for Pumping During 8 h (m^3)
	Flow Rate (m^3/s)	Requested Main Power (MW)	Flow Rate (m^3/s)	Power Supplied to Network (MW)			
200	1	2.4	1	1.6	21,600	25,200	28,800
	2	4.8	2	3.2	43,200	50,400	57,600
	3	7.3	3	4.8	64,800	75,600	86,400
	4	9.7	4	6.3	86,400	100,800	115,200
300	1	3.6	1	2.4	21,600	25,200	28,800
	2	7.3	2	4.8	43,200	50,400	57,600
	3	10.9	3	7.1	64,800	75,600	86,400
	4	14.5	4	9.5	86,400	100,800	115,200
400	1	4.8	1	3.2	21,600	25,200	28,800
	2	9.7	2	6.3	43,200	50,400	57,600
	3	14.5	3	9.5	64,800	75,600	86,400
	4	19.4	4	12.7	86,400	100,800	115,200

Source: Electricidade de Portugal, 2008.

This analysis considers the artificial lagoons of Cabrito and Cinco Ribeiras as candidates for the PHS systems. In spite of neither Morião nor Nasce Água having lagoons, they are considered as an option to site the PHS, given the good elevation difference between these two sites and their proximity to the electricity grid. Therefore, a technical analysis is done for Cabrito lagoon, Cinco Ribeiras lagoon and Morião-Nasce Água lagoon.

Cabrito lagoon is located near Serra do Morião. It features a 400 m elevation and can store up about 200,000 m^3 of water. However, despite presenting a very attractive storage volume, no areas with the required elevation difference are found close enough. Through cartographic inspection, a site was identified about 1.2 km away with an elevation of 575 m.

Although having a low static waterfall (around 175 m), this option is analyzed given the possibility of building just one reservoir with a hydraulic circuit of 1.2 km to connect both reservoirs [43].

Additionally, water oxygenation would be an advantage since eutrophication is currently posing a problem. Table 5 presents data regarding this option.

Table 5. Cabrito Lagoon pump and turbine systems characteristics.

Static Waterfall (m)	Pump		Turbine		Volume Required to Pump during 7 h (m^3)	Pipe Diameter (m)
	Flow Rate (m^3/s)	Requested Main Power (MW)	Flow Rate (m^3/s)	Power Supplied to Network (MW)		
175	1	2.1	1	1.4	25,200	0.8
	2	4.2	2	2.8	50,400	1
	3	6.4	3	4.2	75,600	1.1
	4	8.5	4	5.5	100,800	1.3

Source: Electricidade de Portugal, 2008.

Cinco Ribeiras lagoon has a volume of 100,000 m^3 and is sited at an elevation of 520 m [43]. Through cartographic inspection, it is possible to admit a close location for the upper reservoir at an elevation of 710 m, thus obtaining an elevation difference of 190 m and a hydraulic circuit of 1.6 km [43]. Table 6 presents data regarding this option. A volume of 80,000 m^3 was considered for the analysis, corresponding to 80% of the total volume of the reservoir.

Table 6. Cinco Ribeiras Lagoon pump and turbine systems characteristics.

Static Waterfall (m)	Pump		Turbine		Volume Required to Pump during 7 h (m^3)	Pipe Diameter (m)
	Flow Rate (m^3/s)	Requested Main Power (MW)	Flow Rate (m^3/s)	Power Supplied to Network (MW)		
190	1	2.3	1	1.5	25,200	0.8
	2	4.6	2	3	50,400	1
	3	6.9	3	4.5	75,600	1.2
	1	2.3	1	1.5	25,200	0.8

Source: Electricidade de Portugal, 2008.

The option of sitting the PHS in Morião-Nasce Água is considered, despite having no lagoons, since it has a very significant height above the area where a discharge chamber already exists with about 200 m. Electricidade de Portugal (2008) identified a site to deploy the upper reservoir at an elevation of 600 m. There is also an area that meets the conditions for the construction of the lower reservoir, equipped with turbines and pumps, at an elevation of 260 m, taking advantage of an elevation difference of 340 m. It would be necessary to deploy a hydraulic circuit in parallel with the existing duct with nearly 1.3 km, as the existing one would not comply with the requirements of this project. Table 7 presents data regarding this option.

Table 7. Morião-Nasce Água lagoon pump and turbine systems characteristics.

Static Waterfall (m)	Pump		Turbine		Volume Required to Pump during 7 h (m^3)	Pipe Diameter (m)
	Flow Rate (m^3/s)	Requested Main Power (MW)	Flow Rate (m^3/s)	Power Supplied to Network (MW)		
340	1	4.1	1	2.7	25,200	0.7
	2	8.2	2	5.4	50,400	0.9
	3	12.4	3	8.1	75,600	1
	4	16.5	4	10.8	100,800	1.1

Source: Electricidade de Portugal, 2008.

For the PHS, storage is determined considering the pump and turbine requirements (Table 7) as well as the estimated load diagrams for the year 2018 (Figures 2–4) with the input of bio-waste and geothermal energy to replace thermal energy, taking into account all the excess peak energy to be stored. Turbines are considered to be at their rated maximum power in order to meet the storage of energy during the low demand period (Figures 2–4). A seven-hour pumping and a round trip efficiency (electricity dispatched by the storage system divided by the electricity used to pump water) of nearly 65% are considered, as proposed by Kaldellis et al. (2009). Therefore, the system is designed to have 12.4 MW for pumping and 8.1 MW as storage capacity.

For the battery solution, a combination of NaS and Li-ion batteries are considered since NaS batteries have good network stabilization properties while Li-ion batteries are applied in frequency and voltage regulation. Batteries are considered to be stored under cover for protection from the corrosive and salty air of the region.

3.3. Cost Effectiveness Analysis

When the goal is to compare projects which do not have different rents among them, one may perform a cost-effectiveness analysis and compare the Present Costs of the different projects. In the case of electricity generation projects, the COE can also be compared for the different projects.

First, Investment, Operation and Maintenance (O & M) costs and replacement costs are estimated for the best PHS technical solution and for a battery system (NaS + Li-ion). After that, a cost-effectiveness analysis is performed. Finally, a sensitivity analysis is performed with the critical variables: power capacity and energy generation.

Investment costs are estimated based on parametric curves for each type of work, extrapolated from Electricidade de Portugal (2008). For the upper reservoir costs, land movements, foundations and walls are considered.

A height of 3 m is considered for the reservoir, and equipment costs are estimated to account for 10% of the total cost. The pipeline would be built in parallel to the existing one. The cost of excavations and for provisional and final coating is considered. For the 1.3 km hydraulic circuit, diameters of 0.7 m, 0.9 m, and 1 m to 1.1 m are considered. The costs of piping material, fittings, transport of materials, assembling, and earth moving are also accounted. Thus, 70% of the total cost corresponds to equipment (including the hydraulic pipeline) and 30% corresponds to civil construction.

Costs of the PHS equipment include the costs of the power equipment, auxiliary equipment, electrical equipment and automation system. In this case, the equipment costs represent 80% of the total cost. Costs inherent to the project (connection to the grid, maintenance of infrastructures, among others) account for 10% of the project investment. Land costs are considered to be low, as Nasce Água belongs mainly to the regional government, and Serra do Morião is sited at a high altitude level with low temperature and high humidity rates not suitable for many activities. Mitigation costs account for 2% for the total investment costs, and costs of studies, design and supervision account for 8% of the total investment cost.

The Present Cost (PC), given in €, is calculated according to Equation (4) [17].

$$\mathrm{PC} = I + \sum_{\mathrm{i}=0}^{\mathrm{n}} \frac{Ci}{(1+t)^{\mathrm{i}}}, \tag{4}$$

where I refers to Initial Investment (€), Ci refers to total costs in year i (€) and t refers to the discount rate (%). Salvage costs are included (with a negative sign) under the Ci.

A lifespan of 10 years for the batteries and 50 years for the PHS are considered [6,7,28]. A discount rate (t) of 8% is used and investment is considered to be paid 100% by equity.

The analysis uses the assumption of an annual loss of efficiency of 2.5% for the batteries.

A project lifespan of fifty years is considered. It is assumed that the PHS does not need to be replaced during the lifetime of the project and that batteries should be replaced every ten years, losing 2.5% efficiency every year until it reaches 80% of its capacity in the 10th year.

Given that the expected lifespan of the PHS is 50 years, it is assumed that this would be replaced after that period, which is also the lifetime of the project.

The Levelized Cost of Energy Storage (COEs), given in €/kWh, is calculated according to Equation (5) (adapted from Ma et al., 2015).

$$\mathrm{COEs} = \frac{I + \sum_{\mathrm{i}=0}^{\mathrm{n}} Ci}{\mathrm{E}_{\mathrm{load}}}, \tag{5}$$

where I stands for the initial investment, Ci for total costs in year i and $\mathrm{E}_{\mathrm{load}}$ for the energy dispatched by the storage system over the project lifetime.

To calculate the COEs, all the dispatched energy by the storage system is considered and an efficiency of 65% for the PHS and 85% for the battery system are assumed.

Table 8 presents the fixed and variable O & M costs for the PHS and battery solutions [29,45]. Fixed costs vary with the installed power and variable costs vary with the dispatched electricity.

The PHS costs are estimated from a PHS system projected by EDA for Furnas on the island of São Miguel in the Azores, and the costs for the battery system are estimated from a battery storage system (composed of Li-ion and NaS batteries) deployed in 2014 by EDA on the island of Graciosa in the Azores.

However, in average terms, PHS investment costs, which comprise costs of equipment, connections, land expropriation, environmental mitigation studies, projects and monitoring, are known to range from 190 €/kWh to 340 €/kWh. Moreover, PHS efficiency are known to range from 75 to 80%, with losses of nearly 1.5% in pipe friction, 2% for electricity consumption, 6% for generation and 12% for pumping [23].

In addition, regarding batteries, Cho et al. (2015) pointed out power costs of 1000–3000 USD/kW for NaS batteries and 175–4000 USD/kW for Li-ion batteries. NaS batteries Present Costs range from 350 € to 440 € per kWh, while the Li-ion Present Costs range from 700 to 1400 €/kWh [23].

Table 8. Operation and Maintenance costs.

Technology	Fixed Costs (€/kW·Year)	Variable Costs (€/kWh)
PHS	3.8	0.38
Batteries	0.34	0.51

Source: International Electrotechnical Commission, 2011 and Maidonis, 2013.

4. Results and Discussion

4.1. Technical Feasibility Analysis

Table 9 presents the PHS characteristics for the three analyzed sites in Terceira.

Table 9. Main features of the analyzed pumped hydro system for Terceira Island.

Features	Cabrito Lagoon	Cinco Ribeiras Lagoon	Morião-Nasce Água Lagoon
Lagoons to build	1	1	2
Upstream/downstream elevation (m)	575/400	710/520	600/260
Static waterfall (m)	175	190	340
Flow (m^3/s)	3	3	3
Mobilized volume—pump 7 h (m^3)	75.6	75.6	75.6
Pumped power (MW)	6.4	6.9	12.4
Dispatched power (MW)	4.2	4.5	8.1
Pipe extension (km)/Diameter (m)	1.2/1.1	1.6/1.2	1.3/1.0
Weak and Strong points	Reduced elevation difference		Proximity of the existing grid

Source: adapted from Electricidade de Portugal, 2008.

From the technical point of view, the most feasible PHS should guarantee the requested available power during peak periods. Therefore, Serra do Morião-Nasce Água seems to be the best option amongst the studied ones, with a static waterfall suitable to supply the grid with the required electricity while benefiting from grid proximity. The order of magnitude of the volumes is compatible with the pump flow rates ($\leq$4 m^3/s). For higher flow rates (6–8 m^3/s), artificial reservoirs for pumping may be built. Metallic pipelines for extensions not exceeding 1 km should have diameters ranging from 0.6 to 0.8 m and extensions up to 2 km should have diameters ranging from 1.0 to 1.3 m.

4.2. Cost-Effectiveness Analysis

The cost-effectiveness analysis for the PHS in Morião-Nasce Água (scenario 1) and for the battery system composed of NaS and Li-ion batteries (scenario 2) is presented as follows.

4.2.1. Scenario 1—Pumped Hydro System in Morião-Nasce Água

Scenario 1 considers a PHS in Morião-Nasce Água. Table 10 presents for different flow rates (1, 2, 3 and 4 m^3/s) and different power storages (2.7, 5.4, 8.1 and 10.8 MW) the pumping volume, the total volume and the investment costs (million Euros) disaggregated by categories, as well as the annual O & M costs. An equipment overall η of 85%, a pumping overall η of 65% and a pressure fall of 5% are assumed.

Table 10. Investment and operation and maintenance (O & M) costs for the pumped hydro system sited in Morião-Nasce Água.

Equipment Flow Rate (m^3/s)		**1**	**2**	**3**	**4**
Power (MW)		2.7	5.4	8.1	10.8
Volume required for pumping during 7:0 (m^3)		25,200	50,400	75,600	100,800
Total volume (m^3)		20,319	25,674	32,696	38,315
Refurbishment of roads	Construction (M€)	0.1			
	Equipment (M€)	0.01			
	Sub-total (M€)	0.11			
Cost of upper reservoir	Construction (M€)	1.93	2.41	3.04	3.54
	Equipment (M€)	0.1	0.1	0.09	0.08
	Sub-total (M€)	2.03	2.51	3.13	3.62
Pipeline/hydraulic circuit cost	Sub-total (M€)	2.2	3.91	5.9	7.59
Hydroelectric power plant costs	Construction (M€)	0.2	0.38	0.51	0.72
	Equipment (M€)	0.85	1.48	2.24	2.85
	Sub-total (M€)	1.05	1.86	2.75	0.57
Electrical connection, land, expropriations and accesses	Sub-total (M€)	0.51	0.87	1.2	1.5
Environmental mitigation	Sub-total (M€)	0.09	0.21	0.27	0.4
Studies, projects and monitoring	Sub-total (M€)	0.45	0.78	1.08	1.39
Total investment costs (M€)		6.44	10.25	14.44	18.18
Annual O & M costs (M€)		0.038	0.065	0.092	0.119

4.2.2. Scenario 2—Batteries

Scenario 2 considers an 8.1 MW/48.6 MWh Li-ion and NaS battery system with an efficiency of 85% [23] and six hours storage with investment costs of 1.5 M€/MW (for equipment, transport, auxiliary equipment, costs of infrastructure, refurbishment of roads, environmental studies, projects and inspections).

These figures are in line with the costs proposed by Cho et al. (2015). Table 11 presents the investment costs disaggregated by cost categories and annual O & M costs for 2.7, 5.4, 8.1 and 10.8 MW.

Table 11. Investment and operation and maintenance costs for sodium sulfur + Li-ion batteries).

Power (MW)		**2.7**	**5.4**	**8.1**	**10.8**
Refurbishment of roads	Construction (M€)	0.1			
	Equipment (M€)	0.01			
	Sub-total (M€)	0.11			
Cost varying with installed power (batteries including transport + auxiliary equipment + infrastructures)	Sub-total (M€)	4.05	8.1	12.15	16.2
Electrical connection, land, expropriation and accesses	Sub-total (M€)	0.51	0.87	1.2	1.5
Environmental mitigation	Sub-total (M€)	0.09	0.21	0.27	0.4
Studies, projects and monitoring	Sub-total (M€)	0.45	0.78	1.08	1.39
Total investment costs (M€)		5.21	10.07	14.81	19.6
Annual operation and maintenance costs (M€)		0.095	0.189	0.284	0.378

4.2.3. PHS and Battery System Comparison

Table 12 summarizes the costs for an 8.1 MW power capacity storage system. O & M costs for the PHS solution are much lower than the ones for the battery solution. While for the PHS the O & M costs are nearly 0.092 million euro per year, for the battery solution they are nearly 0.2835 million Euros per year.

Table 12. Fixed and Variable Annual operation and maintenance (O & M) Costs (8.1 MW).

	PHS [a]	Batteries
Initial investment costs (M€)	14.44	14.81
Replacement costs (M€) [b]	0.00	12.15
Variable costs (O & M) (M€/year)	0.055	0.041
Fixed costs (O & M) (M€/year)	0.0000044	0.243
Total O & M costs (M€/year)	0.092	0.2835

Notes: [a] Morião-Nasce Água; [b] Every 10 years for the battery option.

Table 13 presents the cost-effectiveness analysis results, while considering the Terceira Island load profile estimated for the year 2018, with the $PC_{B/P}$ ratio resulting from the division of the batteries system's Present Cost and PHS' Present Cost and the $COEs_{B/P}$ ratio resulting from the division of the batteries system's COEs and PHS' COEs.

Table 13. Cost-effectiveness analysis for the 8.1 MW Terceira Island storage systems.

Power Capacity (MW)	Dispatched Electricity (MWh/Year)		Present Costs (M€)		COEs (€/kWh)		$PC_{B/P}$ Ratio	$COE_{B/P}$ Ratio
	PHS	Batteries	PHS	Batteries	PHS	Batteries		
8.1	7039.21	9205.12	15.564	28.273	0.0538	0.1680	1.82	3.12

Notes: only accounts for the costs for the storage system (Batteries 8.1 MW/6 h; PHS 8.1 MW/7 h); PHS sited in Morião-Nasce Água.

According to Table 13, the battery solution Present Cost is almost two times higher than the one for the PHS solution ($PC_{B/P}$ ratio = 1.82), and the battery solution COEs is nearly three times higher than the one for the PHS solution ($COEs_{B/P}$ ratio = 3.12). Therefore, while considering the estimated load profile for the year 2018, the PHS sited in Morião-Nasce Água is, amongst the analyzed options, the best to store energy in Terceira Island for the expected demand (with a storage system of 8.1 MW).

Given that the electricity mix in Terceira is currently composed mostly by fuel oil and commercial diesel (82.7%), being the component of commercial diesel only 10% of these, used for start-ups and stops of the system; but also by wind (17.0%) and hydroelectric power (0.2%), it is relevant to compare the costs to generate electricity from wind plus the costs to store energy with the costs to generate electricity from fuel oil.

Worldwide, in average terms, up to 2020, wind is expected to be in a similar range or even cheaper than fuel oil; with LCOE varying according to countries fuel prices, taxes and subsidies [31].

Moreover, while considering data from the Methodological Convention of the Federal Environment Agency [37] for the external cost estimates, one can say that the PHS energy storage costs of 5.38 Eurocent/kWh are much lower than the average external costs of coal (lignite: 10.75 Eurocent/kWh; hard coal: 8.94 Eurocent/kWh) and nuclear energy (10.7–34 Eurocent/kWh); slightly higher than the ones for natural gas (4.91 Eurocent/kWh); and largely higher than the ones for photovoltaic (1.18 Eurocent/kWh), wind onshore (0.26 Eurocent/kWh), or hydro (0.18 Eurocent/kWh) energy [38].

It is relevant to mention that the calculated costs of energy storage in this paper do not include external costs of the storage system, and therefore further work should be developed in order to assess the magnitude of these, given that these may be significant, according to the site in study. Moreover, it is also relevant to mention that the referred external costs of energy generation do not include the external cost of global warming from these sources. When accounting for these, the considered storage systems would be even more feasible in economic, social and environmental terms, when compared to coal, diesel or fuel oil.

It is also possible to derive that it is preferable to replace fuel oil by wind energy to generate electricity up to a conceivable technical limit, while building a PHS, or even dumping the excess peak energy generated, as it is possible to generate wind energy in some areas of Terceira Island with an unsubsidized levelized cost of energy of nearly 4.00 Eurocent/kWh [46], much lower than the one for fuel oil or diesel (ranging from average values of 0.21 USD/kWh to 0.28 USD/kWh, in 2016) [47]. Given the technical limitations associated with the high penetration of wind energy in the electricity mix, it is preferable to have a solution that includes, along with wind energy generation, a PHS, even though it is a slightly more expensive solution.

Moreover, while considering that the expected energy mix for 2018, in Terceira will comprise 12.6 MW wind power, 1.7 MW bio-wastes energy recovery and 10 MW geothermal power, it is relevant to assess also the average costs for bio-wastes energy recovery and geothermal power.

According to the Fraunhofer Institute for Solar Energy Systems (2013) estimates, and without accounting for external costs, biogas energy costs are expected to range between nearly 13.80 and 21.50 Eurocent/kWh, up to 2030, which are much higher than the costs of a combined wind energy generation and PHS system for Terceira (4.00 Eurocent/kWh plus 5.38 Eurocent/kWh), and therefore, if one accounts only with the energy generation potential, generating energy from biogas does not seem a good option, when other options are on the table. However, when analyzing if one should prosecute with biogas recovery, other considerations must be done, regarding waste management options.

When considering geothermal power, it is known that the investment costs are generally very high, but lifetimes are higher than 20 years and O & M costs are a small percentage of total costs, depending on location and size of the facility, type and number of plants, and use of remote-control; ranging from 0.009 USD/KWh (large flash) to 0.025 USD/KWh (small binary), excluding well replacement drilling costs [48].

OECD/IEA (2010) presents some figures of LCOE for geothermal energy generation, namely 0.072 USD/kWh (for a 30 MW binary development in United States); 0.05–0.07 USD/KWh (New Zealand; high temperature resources; with no subsidies); 0.12 USD/KWh (United States, new Greenfield); and 0.20 USD/KWh (Europe, lower temperature resources). OECD/IEA (2010) also reported estimated Enhanced Geothermal Systems (EGS) production costs using current power plant technology ranging from 0.10 USD/KWh (300 °C resource at 4 km depth) to 0.19 USD/KWh (150 °C resource at 5 km) in the United States, and in Europe of nearly 0.25–0.30 USD/KWh. Moreover, it is expected that in Europe, capital costs decrease by about 5% by 2020 [48].

Therefore, while considering the figures previously presented, it is possible to conclude that geothermal energy generation costs are very volatile according to site specificities and technologies, but these are expected to be far more expensive than generating energy from a wind and PHS combined system, while not accounting for external costs. However, geothermal is a good alternative when compared to fuel oil to grant the baseload power in an electricity grid. Further studies should assess if geothermal is indeed the best way to grant this baseload power, and estimate also the external costs associated to it, at the local scale.

4.3. Sensitivity Analysis Regarding the Power Capacity

It is also relevant to analyze the cost effectiveness of the PHS and the battery systems, with power capacity as critical variable, only accounting with the costs for the storage system. It is considered that the system would operate at the maximum capacity according to the Terceira Island load profile (Table 14).

Table 14. Sensitivity analysis for Terceira Island pumped hydro system (PHS) and battery storage systems.

Power Capacity (MW)	Dispatched Electricity (MWh/Year)		Present Costs (M€)		COE (€/kWh)		$PC_{B/P}$ Ratio	$COE_{B/P}$ Ratio
	PHS [a]	Batteries	PHS [a]	Batteries	PHS [a]	Batteries		
2.7	4484.03	5026.05	6.904	9.704	0.0370	0.1159	1.41	3.13
5.4	8968.05	10,052.10	11.044	19.046	0.0300	0.1150	1.72	3.84
8.1	13,452.08	15,078.15	15.564	28.273	0.0282	0.1146	1.82	4.07
10.8	17,936.10	20,104.20	19.633	37.551	0.0268	0.1144	1.91	4.27

Notes: [a] Morião-Nasce Água.

The PHS sited in Morião-Nasce Água solution is always more cost effective than the battery solution to store energy in Terceira Island for the analyzed power capacities (2.7 to 10.8 MW). The ratio of the battery solution by the PHS solution Present Costs ($PC_{B/P}$ ratio) is nearly 1.41, 1.72, 1.82 and 1.91 for the 2.7 MW, 5.4 MW, 8.1 MW and 10.8 MW, respectively. The ratio for the battery solution COE by the PHS solution COE ($COE_{B/P}$ ratio) is nearly 3.13, 3.84, 4.07 and 4.27 for the 2.7 MW, 5.4 MW, 8.1 MW and 10.8 MW, respectively. Therefore, the higher the power capacity, the higher the cost effectiveness of the PHS solution when compared to the battery solution.

4.4. Sensitivity Analysis Regarding the Dispatched Energy

Moreover, it is relevant to perform a sensitivity analysis, only accounting with the costs for the storage system, while considering the fact that the ESS would not operate at its maximum capacity, with a reduction of the stored energy (as the critical variable). A reduction of 25% and 50% of the stored capacity related to its nominal capacity are considered (Table 15).

Table 15. Sensitivity analysis with a 25% and 50% reduction of the stored energy.

Power Capacity (MW)	25% Reduction of Stored Energy				50% Reduction of Stored Energy			
	Dispatched Electricity (MWh/year)		COE (€/kWh)		Dispatched Electricity (MWh/year)		COE (€/kWh)	
	PHS [a]	Batteries	PHS [a]	Batteries	PHS [a]	Batteries	PHS [a]	Batteries
2.7	3363.02	3372.54	0.0494	0.1263	2242.01	2248.36	0.0741	0.1666
5.4	6726.04	6745.07	0.0399	0.1251	4484.03	4496.71	0.0599	0.1648
8.1	10,089.06	10,117.61	0.0376	0.1246	6726.04	6745.07	0.0563	0.1640
10.8	13,452.08	13,490.14	0.0357	0.1226	8968.05	8993.43	0.0535	0.1637

Notes:[a] Morião-Nasce Água.

Battery lifespan is considered to decrease, until attaining 80% of its original capacity, up to 13 years for the 25% reduction scenario and a maximum of 15 years for the 50% reduction scenario. A reduction of 25% and 50% in the efficiency losses is accounted for, according to each scenario. Battery salvage costs are accounted for in the analysis.

By reducing the energy stored for the same power capacity by 25% and 50%, the PHS solution is always more cost effective than the battery solution, even considering an extension of the battery lifespan, according to each scenario (according to Tables 14 and 15).

5. Conclusions

This study introduces a methodology concerning the sizing of a Pumped Hydro Storage System and a Battery Storage System and then applies it to Terceira Island for the year 2018 according to an estimated scenario for electricity demand and supply, which considers an energy mix composed of geothermal, wind and thermal power and biowastes energy recovery. The methodology includes a technical and a cost-effectiveness analysis, as well as a sensitivity analysis, to determine the most suitable ESS to deploy in Terceira Island.

From the technical effectiveness analysis, it is concluded that for the year 2018, a PHS sited in Serra do Morião-Nasce Água (8.1 MW) would be the best amongst the studied options, with a static waterfall suitable to satisfy demand. Nevertheless, when compared to other sites, it has the disadvantage of requiring the construction of two reservoirs, with higher investment costs.

Regarding the cost-effectiveness analysis, while considering a storage facility with 8.1 MW power capacity for Terceira Island 2018 load profile, the PHS solution sited in Serra do Morião-Nasce Água (Present Cost: 15,564 M€; COE: 0.0538 €/kWh) is more cost-effective than the battery solution (Present Cost: 28,273 M€; COE: 0.1680 €/kWh).

Besides, according to a sensitivity analysis, it is concluded that for the range of 2.7 to 10.8 MW power capacity, the PHS solution (in Morião-Nasce Água) is always more cost effective than the battery solution. The high O & M costs and high replacement costs, as well as the loss of efficiency of the batteries, are the factors that mostly contribute to the low-cost effectiveness of the battery solution for the power capacity range analyzed.

Given that fuel oil and wind energy costs are expected to be, on average, across the same range up to 2020, the option to replace fuel oil by a wind and PHS combined system was considered. It was concluded that the PHS energy storage costs of 5.38 Eurocent/kWh are much lower than the average external costs of fuel oil, but slightly higher than the ones for natural gas, and largely higher than the ones for photovoltaic, wind or hydro energy. When accounting for the external cost of global warming from these sources, the PHS and battery systems would be even more feasible in economic, social and environmental terms, when compared to fuel oil.

It is relevant to mention that the calculated costs of energy storage in this paper do not include external costs of the storage system, and therefore further work should be developed in order to assess the magnitude of these, given that these may be significant, according to the site in study.

It is preferable to replace fuel oil by wind energy to generate electricity up to a conceivable technical limit, while building a PHS, or even dumping the excess peak energy generated, as it is possible to generate wind energy in some areas of Terceira Island with a cost of nearly 4.00 Eurocent/kWh [46].

Moreover, and while considering that the expected energy mix for 2018, in Terceira Island will comprise 12.6 MW wind power, 1.7 MW bio-wastes energy recovery and 10 MW geothermal power, it is relevant to mention that if one accounts only with the energy generation potential, generating energy from biogas does not seem a good option, when other options, such as wind, are on the table. However, when analyzing if one should prosecute with biogas recovery, other considerations must be done, regarding waste management options.

Geothermal energy generation costs are very volatile according to site specificities and technologies, but these are expected to be far more expensive than generating energy from a wind and PHS combined system, while not accounting for external costs. However, geothermal is a good alternative when compared to fuel oil in order to grant the baseload power in an electricity grid. Further studies should assess if geothermal is indeed the best way to grant this baseload power, and estimate also the external costs associated to it, at the local scale.

Given the intermittency of most RES and the PHS feasibility demonstrated here, it becomes vital to deploy PHS whenever feasible in order to reduce dependence on oil-based thermal power stations to produce electricity and avoid dumping excess peak energy when increasing RES in the energy mix, thus decreasing electricity costs and negative externalities of electricity generation.

This methodology is vital in informing local decision makers towards a sustainable approach to reach efficiency in the electricity generation system, optimizing the energy supply and demand chain, besides contributing to achieve high quality of power supply and reliability in isolated grids, such as the one of Terceira Island and, as a result, reducing imports of fuel and decreasing the vulnerability to external markets.

However, huge challenges and opportunities still remain for scholars and engineers in this field. Given the high complexity associated with the studied options, it is important that, in the future, these results are explored at the same time as aspects such as public preferences concerning the impact of these infrastructures on the landscape, environmental or any other restrictions, accounting for the expected increase in the future price of crude oil, internalizing externalities, and considering the exact cost of alternative energy sources, whenever possible, given that these are variable according to local conditions.

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References

1. Jacobson, M.Z.; Delucchi, M.A. Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy* **2011**, *39*, 1154–1169. [CrossRef]
2. Duić, N.; Carvalho, M.G. Increasing renewable energy sources in island energy supply: Case study Porto Santo. *Renew. Sustain. Energy Rev.* **2004**, *8*, 383–399. [CrossRef]
3. Chen, H.; Cong, T.N.; Yang, W.; Tan, C.Y.; Li, Y.; Ding, Y. Progress in electrical energy storage system: A critical review. *Prog. Nat. Sci.* **2009**, *19*, 291–312. [CrossRef]
4. Parfomak, P.W. Energy Storage for Power Grids and Electric Transportation: A Technology Assessment. Available online: http://fas.org/sgp/crs/misc/R42455.pdf (accessed on 30 June 2014).
5. Zakeri, B.; Syri, S. Electrical energy storage systems: A comparative life cycle cost analysis. *Renew. Sustain. Energy Rev.* **2015**, *42*, 569–596. [CrossRef]
6. Kaldellis, J.K.; Zafirakis, D.; Kavadias, K. Techno-economic comparison of energy storage systems for island autonomous electrical networks. *Renew. Sustain. Energy Rev.* **2009**, *13*, 378–392. [CrossRef]
7. Kaldellis, J.K.; Zafirakis, D.; Kondili, E. Optimum sizing of photovoltaic-energy storage systems for autonomous small islands. *Eletr. Power Energy Syst.* **2010**, *32*, 24–36. [CrossRef]
8. Kaldellis, J.K.; Kapsali, M.; Kavadias, K.A. Energy balance analysis of wind-based pumped hydro storage systems in remote island electrical networks. *Appl. Energy* **2010**, *87*, 2427–2437. [CrossRef]
9. Battistelli, C.; Baringo, L.; Conejo, A.J. Optimal energy management of small electric energy systems including V2G facilities and renewable energy sources. *Electr. Power Syst. Res.* **2012**, *92*, 50–59. [CrossRef]
10. Parvizimosaed, M.; Farmani, F.; Anvari-Moghaddam, A. Optimal energy management of a micro-grid with renewable energy resources and demand response. *J. Renew. Sustain. Energy* **2013**, *5*, 053148. [CrossRef]
11. Maheri, A. Multi-objective design optimization of standalone hybrid wind-PV-diesel systems under uncertainties. *Renew. Energy* **2014**, *66*, 650–661. [CrossRef]
12. Joe, T.; John, B.; Keith, P. *Managing Innovation*, 3rd ed.; Wiley: West Sussex, UK, 2005; Available online: https://pt.scribd.com/doc/133224039/Tidd-Managing-Innovation (accessed on 23 June 2017).
13. Brandt, A.R.; Dale, M.; Bamhart, C.J. Calculating systems-scale energy efficiency and net energy returns: A bottom-up matrix-based approach. *Energy* **2013**, *62*, 235–247. [CrossRef]
14. Bueno, C.; Carta, J.A. Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands. *Renew. Sustain. Energy Rev.* **2006**, *10*, 312–340. [CrossRef]
15. Blechinger, B.; Seguin, R.; Calder, C.; Bertheau, P.; Breyer, C. Assessment of the Global Potential for Renewable Energy Storage Systems on Small Islands. *Energy Procedia* **2014**, *46*, 325–331. [CrossRef]
16. Calise, F.; Cipollina, A.; d'Accadia, M.D.; Piacentino, A. A novel renewable polygeneration system for a small Mediterranean volcanic island for the combined production of energy and water: Dynamic simulation and economic assessment. *Appl. Energy* **2014**, *135*, 675–693. [CrossRef]
17. Ma, T.; Yang, H.; Lu, L. A feasibility study of a stand-alone hybrid solar–wind–battery system for a remote island. *Appl. Energy* **2014**, *121*, 149–158. [CrossRef]
18. Ma, T.; Yang, H.; Lu, L. Feasibility study and economic analysis of pumped hydro storage and battery storage for a renewable energy powered island. *Energy Convers. Manag.* **2014**, *79*, 387–397. [CrossRef]
19. Ma, T.; Yang, H.; Peng, J. Pumped storage-based standalone photovoltaic power generation system: Modeling and techno-economic optimization. *Appl. Energy* **2015**, *137*, 649–659. [CrossRef]
20. Ma, T.; Yang, H.; Lu, L.; Peng, J. Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in Hong Kong. *Renew. Energy* **2014**, *69*, 7–15. [CrossRef]
21. Papaefthymiou, S.V.; Papathanassiou, S.A. Optimum sizing of wind-pumped-storage hybrid power stations in island systems. *Renew. Energy* **2014**, *64*, 187–196. [CrossRef]
22. Rodrigues, E.M.G.; Godina, R.; Santos, S.F.; Bizuayehu, A.W.; Contreras, J.; Catalão, J.P.S. Energy storage systems supporting increased penetration of renewables in islanded systems. *Energy* **2014**, *75*, 265–280. [CrossRef]
23. ARUP. *Five Minute Guide to Electricity Storage Technologies*; ARUP: London, UK, 2014. Available online: https://www.arup.com/en/publications/Promotional-Materials/Section/Five-minute-guide-to-electricity-storage (accessed on 30 June 2014).

24. Jung, J. *Armazenamento de Energia em Smart Grids (Storage of Energy in Smart Grids)*; Universidade Federal do Rio Grande do Sul: Porto Alegre, Brazil, 2010. Available online: http://hdl.handle.net/10183/33071 (accessed on 30 June 2015).
25. Leão, R.P.S.; Antunes, F.L.M.; Lourenço, T.G.M.; Andrade, K.R., Jr. A Comprehensive Overview on Wind Power Integration to the Power Grid, IEEE Latin America Transactions. *IEEE Latin Am. Trans.* **2009**, *7*, 620–629. Available online: http://www.ewh.ieee.org/reg/9/etrans/ieee/issues/vol07/vol7issue6Dec.2009/7TLA6_02PastoraSaraivaLeao.pdf (accessed on 30 June 2015). [CrossRef]
26. Xiong, Y.; Jayaweera, D. Performance assessment of smart distribution networks with strategic operation of battery electric vehicles. *J. Renew. Sustain. Energy* **2015**, *7*, 023103. [CrossRef]
27. Ponte, C.C. *Modelação de Sistema de Armazenamento por Bombagem de Água em São Miguel (São Miguel Reversible Pumping System's Modelling)*; Instituto Superior Técnico: Lisboa, Portugal, 2012. Available online: https://fenix.tecnico.ulisboa.pt/downloadFile/395144976206/dissertacao.pdf (accessed on 30 June 2014).
28. Cho, J.; Jeong, S.; Kim, Y. Commercial and research battery technologies for electrical energy storage applications. *Prog. Energy Combust. Sci.* **2015**, *48*, 84–101. [CrossRef]
29. Maidonis, T. Facilitating Energy Storage to Allow High Penetration of Intermittent Renewable Energy. ESHA 2nd Policy Forum 2013, Munich. Available online: http://www.store-project.eu/uploads/docs/presentation-esha-2nd-policy-forum-thomas-maidonis.pdf (accessed on 30 June 2015).
30. Schoenung, S. Energy Storage Systems Cost Update, a Study for the DOE Energy Storage Systems Program. Available online: http://prod.sandia.gov/techlib/access-control.cgi/2011/112730.pdf (accessed on 19 October 2015).
31. Bloomberg New Energy Finance. Wind and Solar Boost Cost-Competitiveness versus Fossil Fuels. 2015. Available online: http://www.bbhub.io/bnef/sites/4/2015/10/BNEF_PR_20151006_Global-Cost-of-Energy.pdf (accessed on 30 July 2015).
32. Energy Information Administration. *Annual Energy Outlook with Projections to 2040*; U.S. Energy Information Administration: Washington, DC, USA, 2015. Available online: http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf (accessed on 30 July 2015).
33. Fraunhofer Institute for Solar Energy Systems. *Levelized Cost of Electricity—Renewable Energy Technologies. Ed November 2013*; Fraunhofer Institute for Solar Energy Systems ISE: Freiburg, Germany, 2013. Available online: https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/Fraunhofer-ISE_LCOE_Renewable_Energy_technologies.pdf (accessed on 30 July 2015).
34. European Commission. *Subsidies and Costs of EU Energy*; Report No. DESNL14583; European Commission, Directorate-General for Energy: Brussels, Belgium, 2014; p. 52. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/ECOFYS%202014%20Subsidies%20and%20costs%20of%20EU%20energy_11_Nov.pdf (accessed on 30 July 2015).
35. European Commission. *New Research Reveals the Real Costs of Electricity in Europe*; European Commission, Research Directorate-General: Brussels, Belgium, 2001. Available online: http://www.ier.uni-stuttgart.de/forschung/projektwebsites/newext/externen.pdf (accessed on 30 July 2015).
36. ExternE-Pol. Externalities of Energy: Extension of Accounting Framework and Policy Applications. Available online: http://www.externe.info/externe_2006/expoltec.pdf (accessed on 30 June 2015).
37. UBA. *Best-Practice-Kostensätze für Luftschadstoffe, Verkehr, Strom- und Wärmeerzeugung*; 44pp REPORT No. Anhang B der Methodenkonvention 2.0 zur Schätzung von Umweltkosten; Umweltbundesamt: Dessau-Roßlau, Germany, 2012. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/uba_methodenkonvention_2.0_-_anhang_b_0.pdf (accessed on 30 July 2015).
38. Meyer, B. Externe Kosten der Atomenergie und Reformvorschläge zum Atomhaftungsrecht. Available online: http://www.foes.de/pdf/2012-09-Externe_Kosten_Atomenergie.pdf (accessed on 30 July 2015).
39. Cota, D. Energias Renováveis nos Açores—Passado, Presente e Futuro. Available online: http://www.portal-energia.com (accessed on 30 July 2015).
40. Eletricidade dos Açores. *Procura e Oferta de Energia Eléctrica, Dezembro de 2014*; EDA: Ponta Delgada, Portugal, 2014. Available online: http://www.eda.pt/Mediateca/Publicacoes/Producao/ProducaoConsumo/POEE%20dezembro_2014.pdf (accessed on 30 July 2015).
41. Eletricidade dos Açores. *Caracterização das Redes de Transporte e Distribuição de Energia Elétrica da Região Autónoma dos Açores*; EDA: Ponta Delgada, Portugal, 2014. Available online: http://www.eda.pt/EDA/DocsDistribuicao/CARE%202014.pdf (accessed on 30 June 2014).

42. Eletricidade dos Açores. *Maximização de Produção de Energia Eléctrica com Origem em Fontes Endógenas da Ilha Terceira—Impacto No Sistema Electroprodutor, Ponta Delgada*; EDA: São Miguel, Portugal, 2012, unpublished work.
43. Eletricidade de Portugal. *Aproveitamentos Hidroeléctricos Reversíveis nas Ilhas de S, Miguel e Terceira, EDP, Ponta Delgada*; EDP: Lisbon, Portugal, 2008, unpublished work.
44. Yang, C.J.; Jackson, R. Opportunities and barriers to pumped-hydro energy storage in the United States. *Renew. Sustain. Energy Rev.* **2011**, *15*, 839–844. [CrossRef]
45. International Electrotechnical Commission. *Electrical Energy Storage*; IEC: Geneva, Switzerland, 2011. Available online: http://www.iec.ch/whitepaper/pdf/iecWP-energystorage-LR-en.pdf (accessed on 30 June 2014).
46. Rodrigues, A.; Silva, V.; Barcelos, E.; Silva, C.; Dentinho, T. Geographical information systems and cost benefit analysis-based approach for wind power feasibility: A case study of Terceira Island. *J. Renew. Sustain. Energy* **2015**, *7*, 053115. [CrossRef]
47. LAZARD. Lazard's Levelized Cost of Energy Analysis. Available online: https://www.lazard.com/media/438038/levelized-cost-of-energy-v100.pdf (accessed on 30 November 2016).
48. OECD/IEA. Renewable Energy Essentials: Geothermal. Organisation for Economic Co-operation and Development and International Energy Agency. Available online: https://www.iea.org/publications/freepublications/publication/Geothermal_Essentials.pdf (accessed on 30 July 2015).