Contributions to the preliminary assessment of a Water Pumped Storage System in Terceira Island (Azores)

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Abstract: - The need to provide Spinning Reserve (SR), together with the need to respect some operational constraints, points to high power state combinations of the thermal power plants, therefore reducing the penetration of renewables in the power mix and eventually leading to wind curtailment. Water Pumped Storage Systems (WPSS) are a way to overcome this issue, by storing the surplus energy not needed in the valley periods, to use it later in peak periods. This situation is dealt with in this paper, through the proposal of an energy balance technical model, taking into account the constraints and operational limits of the thermal power plant, together with an economic model based on NPV and IRR. This model is applied to assess the Terceira Island case-study. Despite the fact that this is a simplified model, not using any optimization techniques, it was possible to conclude that WPSS provide both thermal based electricity and wind curtailment reduction, therefore facilitating the integration of renewable energy in the power system and enhancing the environmental aspects of electricity production. Moreover, it was found that there are turbine / pump sizing combinations that can turn the project into an economically viable one. Also, it was demonstrated that further economic feasibility could be achieved if SR requirements could be lowered. This aspect should be considered by Terceira system operator.

Key-Words: - Water pumped storage systems (WPSS), Wind Energy, Integration of renewables, Economical assessment, Spinning Reserve, Wind curtailment.

1 Introduction

The boost in wind power lead to a high penetration level of renewables in the existing electrical systems. For instance, in the European Union (EU-28), from 2000 to 2013, wind energy has seen its contribution in installed power increase from 2% of the total mix, to 13% [1]. In terms of generated electricity, it has increased from 44 TWh (1.3% of total mix) in 2003, to 206 TWh (6.2% of total mix) in 2012. Portugal also witnessed a remarkable development in wind power: the percentage of demand supplied by wind powered generators rose from 1.1% in 2003 to 23.25% in 2013 [2].

Due to its intermittency and difficulty to forecast its availability, wind energy is sometimes regarded as the cause of several problems related to power systems operation. Frequency regulation during load following situations and voltage regulation are identified in the literature as two of the main issues [3].

For small isolated power systems the impact of wind power in the electrical system is even higher, mainly due to the absence of interconnections and to technical constraints associated with the conventional production system [4], [5]. It should be recalled that, in isolated power systems, the conventional production system is thermal based, typically composed by electrical generators driven by internal combustion engines. These generation units have technical operational minimums that must be strictly respected, this acting as a serious constraint to the operation of the power system. Another issue is the need of having Spinning Reserve (SR) able to rapidly react to the fluctuations in both wind power and demand. The need to have SR may force the set of thermal units to operate at a higher combined power output, therefore limiting the wind power usage. Also, the fact that there are no interconnections, that would help in supporting wind power intermittency, limits the penetration of wind energy in isolated grids [6]. These issues may become a cause of the under usage of the wind potential in these systems.

The literature reports several measures to cope with the aforementioned issues: energy storage, like pump storage hydro and flywheels, energy export, wind curtailment and conventional thermal power plants cycling. As pointed out by some authors [3], [7], the latest has non-negligible consequences in the life time expectancy of the power plants, as so, it should be avoided. Wind curtailment has a negative impact, as far as environmental aspects are concerned, and energy export is not possible in isolated power systems. Flywheels are essentially used to store energy for short periods of time, in the range of seconds, and therefore are not suitable for long storage periods. Their applications are more to cope with Fault-Ride-Trough issues [8]. Flywheels are installed in Azores in Flores and Graciosa islands.

Water Pumped Storage Systems (WPSS) have been studied by several authors as a way to support the integration of wind based electricity production in islands. Generally, the implementation of WPSS increases the penetration of renewables [8]–[11] and it can also avoid the need for peak units, typically thermal based. By adequate dimensioning of WPSS, it is also possible to have an economically feasible system; also a reduction in the costs of electricity production is to be expected [12].

Study [13] is concerned with the economic viability of using WPSS to help the integration of wind based energy on a practical case at the island of Lesbos, Greece. It shows that it is possible to use this type of energy storage to absorb the excess wind energy, that otherwise would be lost. The study builds on an energy balance model to determine the highest possible wind penetration in the electrical system load. This model also determines the WPSS optimum configuration based on an economic analysis of the Net Present Value (NPV) and payback time.

Another study [14] considers also the utilization of WPSS to increase wind based energy penetration for the island of Crete, Greece. An economic optimization model based on evolutionary algorithms is used to determine the WPSS system configuration that leads to the best NPV and Internal Rate of Return (IRR). In this study, the possibility of importing energy from the electrical network, in order to keep a sufficient level of water in the upper reservoir for turbine operations, when the excess wind energy is not enough to pump, is also considered.

In [15], the use of WPSS in an isolated system with high levels of thermal base electricity production is considered in order to maximize wind energy production and minimize the energy production cost. The method uses an iterative process to choose the optimum pump and turbine sizes for two islands. It does not consider a predefined production schedule, instead, the energy is stored when there is a rejection of wind and the lower operating cost thermal units are not being used at their nominal power. The study concludes that it is possible to reduce up to 10% of fossil fuel consumption and reduce also the wind curtailment. It also suggests the possibility of using pumped storage systems directly supplied by wind energy.

An energy balance analysis for a WPSS in an isolated island electrical network is done in [16], showing the possibility of using WPSS to reduce wind curtailment. The method first determines the existing and future wind curtailment, and then determines the pump storage system that takes best advantage of surplus wind energy. In order to determine the optimum WPSS sizing it is suggested the application of the methodology together with a complete cost-benefit analysis.

In this paper, the case of Terceira Island (Azores archipelago) is assessed. Terceira has a small isolated electrical network with 35 MW peak load. Current wind penetration is 12.5% of total installed power, but it is foreseen to grow up to 14% by 2020. The increase of penetration of renewables in Terceira is part of the electrical system operator (EDA) plans. The idea is to make the most use possible of the endogenous resources, with the objective of reducing the dependency on fossil fuels, therefore mitigating the pollutant emission levels and decreasing the electricity production costs, which are substantially high in the islands. However, it is expected that operational constraints of the existing thermal units, together with the need to provide spinning reserve, will lead to the necessity of making wind curtailment, therefore not using the full potential of this clean energy source.

The study presented in this paper investigates the possibility of storing the excess energy in a WPSS. This type of plant uses the surplus electricity, usually available in low demand periods, to pump water to an upper reservoir and, typically during peak periods, this stored potential energy is used to produce electricity by running it through a turbine-generator unit. The main objective of this assessment is to develop a proper methodology to determine the optimal rated power of the pump and turbine systems that leads to the best economical option, subject to operational restrictions of existing thermal based electricity generation system. Several scenarios of pump and turbine rated power configurations are investigated and the results in terms of thermal based energy savings versus investment costs for each scenario are economically evaluated and compared to the base case, where no storage is considered. The used economic indexes are NPV and IRR. From all the scenarios assessed, the one presenting the best result is used for further sensitivity analysis. This includes varying SR values, because it is expected that with lower spinning reserve requirements, the thermal based energy savings become higher, therefore leading to increased NPV and IRR, and also lowering the need for wind curtailment. The model is based on an energy balance, therefore the losses of the electrical network are not considered.

The main contribution of this paper is to offer an integrated view of analyzing the technical and economic viability of using a WPSS to reduce the wind curtailment and the production of fossil fuel thermal based electricity. The paper covers a wide range of aspects to be taken into account, from the energy balance study up to the economic viability of the project.

This paper is divided in the following sections. In Section 2, a description of the Terceira power generation system and the data considered for the study is provided. Section 3 describes the used methodology, with a description of the energy balance model, its constraints and limits, pump and turbine sizing, the evaluated scenarios and also a description of the economic evaluation model. In Section 4, the results are presented and discussed. Finally, Section 5 outlines the main conclusions of the work.

2 Characterization of Terceira Power Generation System

Terceira power generation system, as planned for 2020, comprises the following power plants: (i) Belo Jardim thermal power plant (CTBJ), based on internal combustion engines driving electrical generators. The total thermal based installed power is 47.6 MW. These units are using diesel and fuel-oil as fuel and their unit power is divided as: 4 units of 5900 kW each; 2 units of 12,000 kW each; (ii) Serra do Cume wind park (PESC), 10 existing units plus 4 additional units, of 900 kW each. For the purpose of the study, the 4 additional units were considered as having a production equal to the average of the existing units. The total installed wind power is 12.6 MW; (iii) three small-hydro power plants, adding to 1432 kW; (iv) A geothermal power plant, rated at continuous operation of 3000 kW; (v) A waste to energy power plant, rated at continuous operation of 1700 kW.

This power generation system is bound to feed a 35 MW peak load. Geothermal and waste to energy power plants are run in a constant rated power operating mode, as so they do not participate in the voltage and frequency control. The system operator choice is to assign this task to the thermal power plants. As far as the available data is considered, it consists of the electricity demand; hydro and wind based electricity production records, as well as wind speed, in periods of 30 minutes.

3 Methodology

The used methodology aims at determining, for each period of 30 minutes, the excess of electric energy available after the demand is supplied by the existing power plants, using as much as possible the electricity produced by wind energy conversion systems. This surplus energy is stored, subject to operational restrictions and limits of the electricity production and water storage systems. The stored energy in a WPSS is dispatched for each period, in order to minimize the thermal based electricity. The savings obtained by minimizing the thermal based electricity production, as compared to a base case where there is no storage, are then matched to the investment costs needed to build the necessary plant to pump and turbine. An economical model, based on NPV and IRR indexes is used for this purpose, as explained below. This is done for several scenarios of pump and turbine sizing in two steps. In step 1, single units are considered, i.e., one turbine unit and one pumping unit; in step 2, multiple units for the best scenario found in step one are considered.

3.1 Excess energy calculation

The model calculates the excess energy production and storage needs, based on electricity production from thermal fuel units and the other renewable energy sources (wind and hydro) and also considering the available energy stored from the previous period that can be used to satisfy the load, given the turbine constraints.

The excess energy production, Eee_i, for each period i is calculated by:

$$Eee_i = (Ectbj_i + Eh_i + Epesc_i + Egth_i + Ewte_i - Eload_i)\eta_{pump} \quad (1)$$

In equation (1), $Eload_i$, is the total demand for period i; $Ectbj_i$, is the thermal power production for period i, given the operating constraints; Eh_i, is the hydro power production for period i, historical values; $Epesc_i$, is the wind power production for period i, historical values; $Egth_i$, is the total geothermal power production for period i, assumed equal to continuous rating; $Ewte_i$, is the total waste to energy power production for period i, assumed equal to continuous rating; Eee_i, is the excess energy available to be stored during period i, given the constraints of the pumps and the reservoir capacity; η_{pump}, is the pumping efficiency.

3.2 Constraints and limits

The constraints considered were: (i) Load satisfaction; (ii) Spinning Reserve needs; (iii) Technical operational minimum and maximum load of the thermal units; (iv) Feasible states of operation of the thermal power plant; (v) Upper and lower reservoirs maximum capacity; (vi) Minimum number of consecutive periods with same thermal units generation configuration. The ramp constraints of the thermal units were not included in the model because they are smaller than the 30 min period used for analysis.

The limits are: Pump efficiency and its minimum load; Turbine efficiency and its minimum load.

3.2.1 Load satisfaction

As in any electrical power system, load must be fulfilled and storage also contributes to it. This is translated by:

$$Ectbj_i + Eh_i + Epesc_i + Egth_i + Ewte_i + Eee_{i-1}\eta_{turbine} = Eload_i \quad (2)$$

Eee_{i-1}, is the total excess energy stored up to the end of period i-1, available to be turbined, given the turbines constraints and $\eta_{turbine}$ is the turbine efficiency.

3.2.2 Spinning Reserve needs

SR is provided by the thermal units plus the turbine units, subject to its limits, and stored energy. It is established by the power system operator in the following terms:

$$\begin{array}{l} Ws_{pesc} > 15 \text{ m/s};\ SR = 50\% Pr_{pesc} \\ Ws_{pesc} \leq 15 \text{ m/s};\ SR = 100\% Pg_{pesc} \end{array} \quad (3)$$

In equations (3), it is: Ws_{PESC}, is the average wind speed at PESC wind farm; SR, is the spinning reserve; Pr_{PESC}, is the total rated power output at PESC wind farm, 12,600 kW; Pg_{PESC}, is the total net power output at PESC wind farm.

This SR strategy was defined by the system operator and is being currently followed. As so, it was adopted in this paper.

3.2.3 Technical operational minimum and maximum load of thermal units

Due to technical operational constraints of the thermal units, they cannot be operated below 50% of the load. Also, due to network safety constraints, the system operator has determined a minimum of two thermal units operating and that the minimum should be no less than 6 MW.

3.2.4 Feasible states of operation of the thermal units

Considering the developed model and its constraints, it was necessary to determine the feasible combination of operating thermal units, in order to verify which would be the units operating at each period and the corresponding minimum and maximum power output. This is required, because it has implications in the excess energy that can be stored.

The feasible combinations were determined by simple enumeration, considering that a minimum of two units had to be operating. The maximum power for each combination is the added unit power of all units, and the minimum power is the added minimum technical operational limits of each unit, which is 50% of its rated power. It should be noted that for the units with 5.9 MW rated power, the minimum power was set to 3 MW, in order to satisfy the operators' demand of 6 MW minimum. The identified states are represented in Table 1.

The state chosen, and therefore the dispatched thermal units, is the one that first satisfies the load, given the limits and constraints of the system.

Table 1: Possible combination of the thermal units, given the technical minimum operating constraint

	Combination/Unit Power (MW)						Total Power (MW)	
State	12	12	5.9	5.9	5.9	5.9	Min.	Max.
1			x	x			6	11.8
2			x	x	x		9	17.7
3	x		x				9	17.9
4			x	x	x	x	12	23.6
5	x		x	x			12	23.8
6	x	x					12	24.0
7	x		x	x	x		15	29.7
8	x	x	x				15	29.9
9	x		x	x	x	x	18	35.6
10	x	x	x	x			18	35.8
11	x	x	x	x	x		21	41.7
12	x	x	x	x	x	x	24	47.6

3.2.5 Upper and lower reservoirs maximum capacity

The upper and lower reservoir maximum capacity was obtained by calculating, for the base scenario and for each period of 24 hours, the maximum excess energy available for storage; the maximum value reached was then defined as the maximum capacity, converted to reservoir capacity in m^3, as explained below, and applied to all the studied scenarios.

The calculation of this energy is done by subtracting the sum of all the energy production sources historical values and the energy production of the thermal power plant to the total load, given its operational constraints. Finally, the resulting value was affected by pump efficiency. The obtained value was 50,803 kWh.

The maximum storage capacity of the reservoirs is obtained by solving the potential energy equation shown in equation (4), to the equivalent volume of water:

$$Eee_{max} = \frac{V\rho g h \eta_{pump}}{3.6 \times 10^6} \quad (4)$$

where: Eee_{max}, is the maximum excess energy available to be stored from all the daily cycles, in kWh; V is the water volume, in m^3; ρ is the water density, in kg/m^3; g is the acceleration of gravity, in m/s^2; h is the net head, in m; η_{pump}. is the pumping efficiency, considered to be 80%.

Solving equation (4) to V and combining the water volumetric weight ($\gamma = \rho g = 9.81$ kN/m^3) and the pumping efficiency in one single factor (7.85), we obtain the pumped volume as:

$$V = \frac{3.6 \times 10^3 Eee_{max}}{7.85h} \tag{5}$$

3.2.6 Minimum number of consecutive periods with the same generator configuration

In order to avoid a high number of state changes with the consequent shutdown and startup costs of thermal units, it was established a minimum of 4 consecutive periods, resulting in 2 hours minimum continuous operation for the same configuration of units. For the cases in which the load satisfaction constraint is not fulfilled, a transition to a higher power state is allowed, regardless of previous number of operating periods.

3.2.7 Pump and turbine operating limits

The stored energy calculation considered the pump and turbine efficiencies. For small units (1-5 MW), based on existing references [11] and assuming a conservative approach, typical efficiencies of 80% for both the pump and turbine were considered.

The considered minimum operating loads are 70% of nominal rated power for pumps and 15% for turbines (Pelton units). Pelton turbine units were chosen because the net head is 300 meters and because this type of units has a low minimum operating limit, therefore giving them high operational flexibility, but still with high efficiency values [17].

3.3 Pump and turbine sizing

Using the methodology pointed out in the previous paragraph, pump and turbine power for each period of one hour was calculated throughout the whole year. This has enabled the building of histograms showing the frequency of occurrence in 100 kW steps. It was assumed that all the available energy to pump, or turbine, was always fully pumped or turbined. These histograms were used as a tool to aid in the building of the scenarios to be studied, based on pump and turbine sizing.

As mentioned before, the developed methodology consists of two steps: a first step with one unit for turbine and one unit for pump and a second step considering multiple units for the best scenario found in step one. As so, the analyzed scenarios for step one consist in combining rated power values for the turbines and pumps, from 100 kW to 6000 kW, in steps of 100 kW for each type of unit. As so, a total of 3600 scenarios were analyzed, from scenario #1 (one 100 kW turbine and one 100 kW turbine) to scenario #3600 (one 6000 kW pump and one 6000 kW turbine).

3.4 Economic model

The basis for the economic assessment is a discounted difference between incomes and outcomes. The incomes are the avoided production cost of thermal based electricity, which has two components: the average production variable cost and the startup cost. The outcomes are the WPSS investment and O&M expenses. For this, a NPV model was used, as described in equation (6), in order to find out the scenario with the best economic evaluation. Of course, the avoided costs are calculated with respect to the base case in which no WPSS exists.

$$NPV = \sum_{i=1}^{n} \frac{CF_i}{(1+k)^i} - I_0 \tag{6}$$

The meaning and values of the variables in equation (6) are provided below.

CF_i is the cash flow for year i, given by:

$$CF_i = ACT_i + AST_i - COM_i \tag{7}$$

ACT_i are the avoided average variable costs of not using the thermal units to produce electricity

AST_i are the thermal unit avoided startup costs. The reference values of thermal units average variable production costs were obtained from the Portuguese Energy Services Regulatory Authority (ERSE), as an average value of 0.138 €/kWh, for 2012. The startup costs were obtained directly from the Terceira island system operator (EDA) and are 105.25 € for the 5.9 MW groups and 398.45 € for the 12 MW groups. Startup costs occur whenever there is a transition from one state to a different one, and a different configuration of operating units takes place.

COM_i are the operation and maintenance costs of the WPSS. According to several authors [18], [19], these are frequently assumed as a percentage of the initial investment costs. In this case it was assumed an annual expenditure equal to 1.5% of total investment costs I0.

k, is the yearly rate of return, which is assumed to be the system operator rate of return stated in their Account & Reports 2012, with the value of 4.76%.

N, is the total number of years for the project lifetime, which was considered as 30.

NPV, is the Net Present Value.

I_0, are the WPSS investment costs, obtained by estimates of the civil works, electromechanical and engineering costs plus the cost of the reservoir. These estimates are based on the cost functions determined in [20] and cost breakdown explained in [18], as explained below. The cost of the reservoirs is much dependent on the particular site; for this study's purpose, it was used a reference value of 2 €/m^3 of storage volume [15].

The costs are determined by the following structure [18]: (i) Civil costs (power house + penstock): 60% of total investment, of which 47% is the penstock, for high head power plants; (ii) Electromechanical costs: 33%, of which 19% is turbine + generator; (iii) Engineering costs: 7%.

Electromechanical equipment costs (about 19% of total overall costs) were determined using the cost function for Pelton units [20]:

$$Em_{cost1} = aP^{b-1}H^c \\ a = 17.693, b = 0.635275, c = -0.281735 \tag{8}$$

In equation (8), it is: Em_{cost}, is the cost of the electromechanical equipment (turbine plus generator and regulator), in €/kW; P, is the rated power, in kW; H, is the net head in meters (300 m).

The costs for the pump units, including the electrical drive, were estimated as equal to the turbine/generator groups.

The original cost function (8) does not consider multiple units. Still, solutions with multiple units are to be assessed in step two of the methodology proposed in this paper. It was found that [21] establishes cost formulas dependent on the number of units for low heads, therefore not directly applicable to this study. A dedicated study performed on this particular subject found a correlation between high head Pelton unit costs and the low head costs proposed in [22]. Based on the correlation found, the study enabled the definition of some multiplying factors that allowed to extent the single unit Pelton cost function in (8) to multiple units as follows:

$$Em_{cost2} = a_2P^{b-1}H^c, a_2 = 27.070 \\ Em_{cost3} = a_3P^{b-1}H^c, a_3 = 35.209 \\ Em_{cost4} = a_4P^{b-1}H^c, a_4 = 42.109 \tag{9}$$

Equations (8) and (9) express the well-known relationship between per unit power investment cost and rated power / net head: the per unit power investment cost decreases when rated power and net head increase.

Civil costs have a significant impact on the overall costs, as far as high head applications are concerned. As so, civil, engineering and electromechanical (other than equipment) costs were considered equal for single or multiple units. An exception was made regarding the reservoir costs, because there are relevant differences in its size, as explained further in this paper.

4 Results and Discussion

In this Section, the methodology outlined in the previous section is applied to the Terceira island case. First of all, the thermal based electrical energy and costs savings, resulting from the operation of the WPSS, are dealt with. Then, an economic analysis of the different solutions tested is carried on (step 1) and the best solution is deeply assessed by introducing multiple units solutions (step 2). Lastly, a sensitivity analysis on the impact of different spinning reserve strategies is performed.

4.1 Thermal based electricity and wind curtailment savings – Step 1

Each scenario defined in Section 3.3 was analyzed, as far as thermal based energy production and wind curtailment savings are concerned. The savings were computed with respect to the base case, which does not consider storage. The obtained results for the thermal based energy savings are depicted in Figure 1, Figure 2 depicting the results for wind curtailment savings.

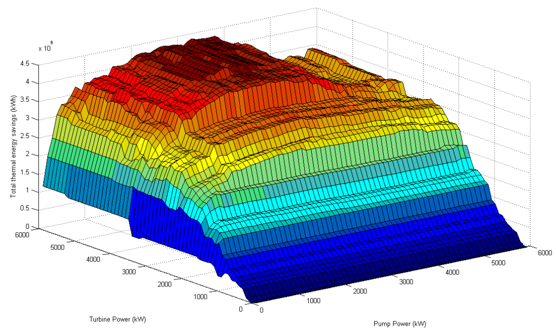

Figure 1: Thermal based electricity savings with respect to the base case (no WPSS) as a function of turbine power and pump power – Step 1

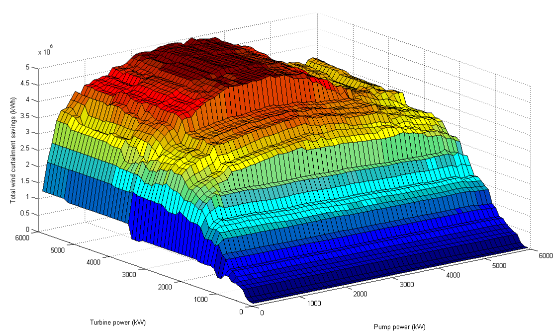

Figure 2: Wind curtailment savings with respect to the base case (no WPSS) as a function of turbine power and pump power – Step 1

The following conclusions may be drawn from Figure 1 and Figure 2: (i) Scenarios with larger or smaller pump power, present lower energy savings as compared to the mid-sized power units. Larger pump power units have higher operating minimum, therefore bringing a limit to the minimum excess energy that can be stored, which means that in periods with low excess energy available, this energy cannot be used for storage leading therefore to wind curtailment. Smaller pump units are also able to pump less, leading to lower energy storage and also higher wind curtailment; (ii) Larger turbine units allow the possibility of using more stored energy due to the fact that the turbines have a low minimum rated load (15% of nominal load), which means that this type of units is able to operate in a wider range power limits contributing to higher usage of available excess of wind energy; (iii) The combination of mid-size pump and large size turbines, contribute to higher savings, both in thermal based energy and wind curtailment.

In order to evaluate the full benefits of one scenario against the other, Figure 1 and Figure 2 clearly show that the investment costs also need to be taken into account, because larger sizes of turbines and pumps also mean higher investment costs, which must be balanced with higher savings.

4.2 Economic analysis – Single units – Step 1

The results of the NPV, based on the model described in Section III.D, are shown in Figure 3.

Comparing the thermal energy savings and wind curtailment savings with the NPV values, it is clear that the combination pump and turbine that lead to best results is not the same: as far as the savings are concerned (Figure 1 and Figure 2), the best results are obtained with large turbine and mid-range pump, but in what concerns the NPV (Figure 3), the best results are obtained with lower to mid-size pump and mid-size turbine. The main reason explaining this outcome is the higher investment costs related to larger units, which are not balanced by the achieved savings.

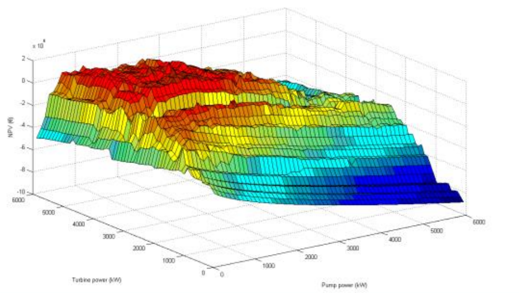

Figure 3: NPV as a function of turbine power and pump power – Step 1

From the analysis of all 3600 scenarios, the 10 ones with higher NPV (10 best) were selected and the investment, the O&M costs and the total avoided thermal based costs are represented in Table 2.

Table 2: Cost assessment – Step 1

Scenario Ref.	Pump Power (kW)	Turbine power (kW)	I0 (k€)	COM (k€/y)	ACT (k€/y)	AST (k€/y)	Total (k€/y)
best #1	1900	4000	6091	91	565	38	603
best #2	2100	4400	6478	97	589	37	626
best #3	1700	4500	6194	93	566	29	595
best #4	1800	3700	5829	87	561	-2	559
best #5	1700	3700	5750	86	561	-10	551
best #6	2100	3900	6205	93	579	6	585
best #7	1900	3900	6033	90	551	6	557
best #8	2000	3700	5999	90	570	-2	568
best #9	1900	3600	5889	88	267	301	567
best #10	1700	3800	5809	87	247	305	552

I0 - Investment costs (k€); COM - O&M costs (k€/y); ACT - Avoided variable costs (k€/y)
AST - Avoided startup costs (k€/y); Total avoided costs (k€/y)

The NPV and IRR results for the above mentioned 10 best scenarios are represented in Figure 4.

The best balance between the investment costs and total avoided costs, the later representing the savings on the project, leads to best #1 being the best scenario. The second best scenario, best #2, has close results, however the relatively higher investment costs are not compensated by the total avoided costs.

From Figure 4, one can conclude that the scenario with best economical results is scenario best#1, being the one with higher NPV and IRR. Nevertheless, it should be noted there are other scenarios presenting a positive NPV. These outcomes of the present work demonstrate that it is possible to achieve an economic profitability by installing a WPSS at Terceira power system.

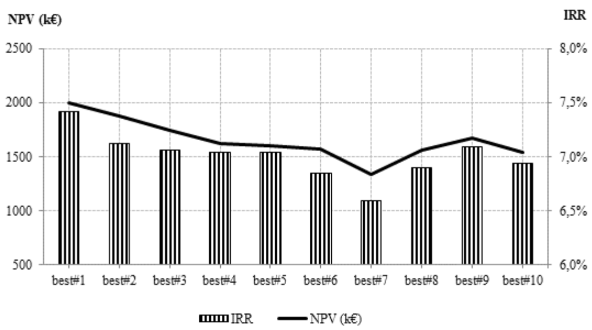

Figure 4: Economic evaluation indexes NPV and IRR – Step 1

4.3 Economic analysis – Multiple units – Step 2

As mentioned before, a further refinement was done in step two, considering only the best scenario found in step one. This refinement consists in splitting the total power in several units, therefore creating a second set of scenarios. A total of 16 combinations of one to four turbines and one to four pumps was assessed. Details on the considered scenarios can be found in Table 3, where the cost assessment, including investment, O&M costs and total thermal based avoided costs, is also shown. The thermal based energy and wind curtailment savings results are represented in Figure 5.

Table 3: Scenarios considered and cost assessment – Step 2

Scenario Ref.	Pump Power (kW)	Pump Number	Turbine Power (kW)	Turbine Number	I0 (k€)	COM (k€/y)	AST (k€/y)	Total (k€/y)
best #1_1	1900	1	4000	1	6091	91	39	603
best #1_2	1900	1	2000	2	6446	97	4	571
best #1_3	1900	1	1333	3	6763	101	-9	543
best #1_4	1900	1	1000	4	7029	105	-7	548
best #1_5	950	2	4000	1	6382	96	-24	595
best #1_6	950	2	2000	2	6736	101	3	613
best #1_7	950	2	1333	3	7065	106	12	628
best #1_8	950	2	1000	4	7332	110	12	626
best #1_9	633	3	4000	1	6596	99	-18	610
best #1_10	633	3	2000	2	6950	104	16	645
best #1_11	633	3	1333	3	7265	109	16	645
best #1_12	633	3	1000	4	7531	113	12	639
best #1_13	475	4	4000	1	6771	102	-12	620
best #1_14	475	4	2000	2	7125	107	15	647
best #1_15	475	4	1333	3	7439	112	17	649
best #1_16	475	4	1000	4	7706	116	17	649

I0 - Investment costs (k€); COM - O&M costs (k€/y);
AST - Avoided startup costs (k€/y); Total avoided costs (k€/y)

The increase in the number of pumps from one unit to multiple units has a high impact on the thermal and wind curtailment energy savings. This is clear from the first 4 scenarios, with only one pump, to the second set of scenarios, where there are two pumps. This is caused by the additional flexibility, to store available energy, introduced by multiple pump units. The variation of the number of turbines has only a slight effect in the savings. This is due to the fact that the type of turbine considered has already a low operation minimum (15% of nominal load) and additional units have little effect on the savings. This leads to the conclusion that the impact on the savings is caused by the variation in the number of pumps, for the same given total installed power.

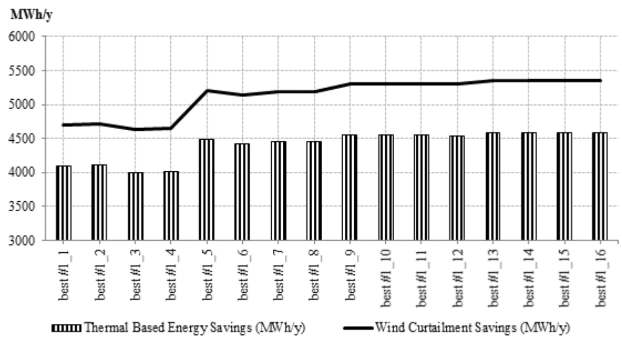

Figure 5: Thermal based electricity and wind curtailment savings – Step 2

Nevertheless, the increased number of units does not lead to the best economical results as can be seen in Table 3 and Figure 6, where the economic assessment, including the NPV and IRR, for Step 2, is depicted.

Figure 6 allows the conclusion that the economic profitability of the project is damaged by splitting the power into multiple smaller units. In fact, there is a negative impact in the final economic result because the extra investment costs are not compensated by the savings in thermal based electricity. This makes the option of using one pump and one turbine (scenario best#1_1) more attractive from an economical point of view.

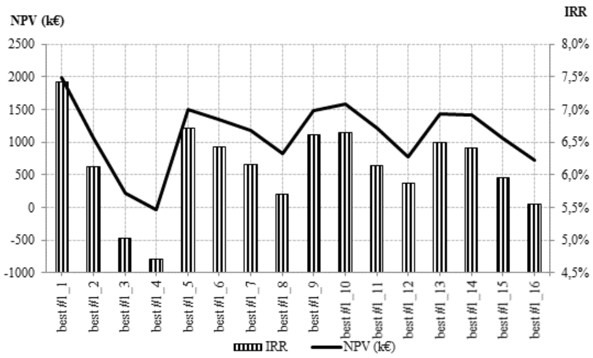

Figure 6: Economic evaluation indexes NPV and IRR – Step 2

4.4 Sensitivity analysis of the spinning reserve impact

The scenario with better economic performance is Scenario best #1_1 (one 1900 kW pump and one 4000 kW Pelton turbine). This was the chosen scenario for further studies of sensitivity on the spinning reserve values. The currently followed base case and two additional spinning reserve management scenarios are described in Table 4. A conservative scenario and an aggressive scenario were considered for further sensitivity assessment.

Table 4: Scenarios for SR sensitivity analysis

Scenario	SR for Ws_{pesc}>15m/s	SR for Ws_{pesc}<=15m/s
Base	50% of Pr_{pesc}	100% of Pg_{pesc}
40/80 (conservative)	40% of Pr_{pesc}	80% of Pg_{pesc}
25/50 (aggressive)	25% of Pr_{pesc}	50% of Pg_{pesc}

We recall that: Pr_{PESC}, is the total rated power output at PESC wind farm, 12,600 kW; Pg_{PESC}, is the total net power output at PESC wind farm.

The results for the thermal based electrical energy and wind curtailment savings are in Table 5. At this respect, it can be concluded that significant gains can be obtained with the relaxation of SR requirements.

The cost assessment and the economic evaluation indexes (NPV and IRR) are represented in Table 6. Once again, it can be observed that the economic viability of the project is expressively enhanced if SR needs are decreased. For instance, in the aggressive scenario, an IRR of almost 13% could be attained.

Table 5: Thermal based electricity and wind curtailment savings – SR sensitivity analysis

Scenario	TBE savings (MWh/y)	WC savings (MWh/y)
Base	3394	3945
Conservative	4514 (+33%)	5019 (+27%)
Aggressive	5497 (+62%)	5739 (+45%)

TBE - Thermal based electricity; WC - Wind curtailment

Table 6: Cost assessment and economic evaluation indexes (NPV and IRR) – SR sensitivity analysis

Scenario	I0 (k€)	COM (k€/y)	AST (k€/y)	Total (k€/y)	NPV (k€)	IRR (%)
Base	6091	91	39	603	1996	7.4
Conservative	6037	91	-84	538	1043	6.2
Aggressive	5936	89	35	794	5208	11.4

I0 - Investment costs (k€); COM - O&M costs (k€/y);

AST - Avoided startup costs (k€/y); Total avoided costs (k€/y)

Based on the achieved results, it is possible to conclude that the SR requirements reduction has the effect of reducing both the thermal based electricity production and the wind curtailment. Furthermore, SR reduction also reduces the need for storage, as shown in the investment costs difference between the conservative case and the aggressive case. In fact, the thermal units have to provide lower SR requirements; as so, they are allowed to operate in a state with lower power production, resulting in a lower excess energy and thus, lower reservoir needs, with direct impact on the investment costs. The reservoir needs for the conservative 40/80 are approximately 35,000 m^3 and for the aggressive case are only about 9,000 m^3.

As far as the conservative case is concerned, it is a fact that larger thermal energy savings and lower investment costs than the base case are achieved. However, startup costs tend to increase, due to more frequent starts and stops of the thermal units. This means that any optimization of spinning reserve policy has to take into consideration this type of costs, as there is no guarantee that a reduction in the SR margins leads straight forward to an operational cost reduction.

5. Conclusions

Water Pumped Storage Systems (WPSS) are a known way to facilitate the integration of renewable energy in a power system. In this paper, a contribution to the technical and economic assessment of the Terceira Island (Azores, Portugal) case has been given. For this purpose, an energy balance technical model, taking into account the constraints and operational limits of the thermal power plant, together with an economic model based on NPV and IRR, were presented and applied to Terceira Island case-study.

It was demonstrated that WPSS allow for a sensible reduction both in wind curtailment and thermal based electricity production, therefore enabling non-negligible environmental benefits to be achieved. As far as the economic assessment is concerned, the situation is not so brilliant, because WPSS investment costs are heavy. Nevertheless, the obtained results showed that the solution using a 4000 kW rated power turbine plus a 1900 kW rated power pump could be economically viable.

This study used a scenario based approach considering several possible combinations of pumps and turbines sizing, leading to a probable optimum solution. However, the combinations chosen do not represent all the possible solutions and do not use any optimization model other than running an energy balance under established constraints, based on the thermal power plant operational limits. Therefore, the results can only provide an indication of a possible optimum solution.

One of the main restrictions affecting the operation of the thermal power plant is the need to provide spinning reserve. It was shown that its influence is notorious. With lower values of spinning reserve to be provided, the thermal production is lower, resulting eventually in lower costs, lower wind curtailment and less storage needs. However a careful evaluation has to be conducted in order to avoid an increase in costs due to higher frequent startup of the thermal units. Nevertheless, we recommend that the possible reduction in SR margin should be evaluated by the Terceira system operator.

The model presented in this paper is to be further developed, by using optimization techniques, so that more reliable results could be obtained.

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