RESEARCH ARTICLE

# Contribution of Pumped-Hydro Storage to Electrical Grids and Improvement Measures

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ABSTRACT: An analysis to the current global and regional situation of electricity production is drawn, with focus on share of installed capacity, impacts to the environment, costs, reserves and forecasts for fossil, nuclear and renewable sources. Although desirable, the increase of the share of renewable energy generation in electrical grids raises security and stability problems, as it introduces added variability in the consumption/supply load curves. Pumped hydro storage is studied, focusing on different available technologies and possible system improvements, in order to make it more efficient, as well as its role in balancing the variability of supply/demand load diagrams which is introduced by renewable energy sources. The case study of the Multiple Purpose Socorridos System in Madeira Island is made, with analysis to its functioning diagram and schedule, its impacts on avoided greenhouse gas emissions, renewable energy penetration and load diagram balancing. The introduction of a new reversible system, the Calheta Hydroelectric Reversible System - Calheta III, is also analyzed. An optimization procedure using MATLAB is done to compare the existing system to the introduction of different system improvements, namely the use of adjustable speed equipment and the use of a separate penstock for pumping and turbining. Performance is measured through generated revenues and, in the end, results are discussed and compared.

**Key-words:** pumped hydro storage, renewable energies, load balancing, electrical grid, adjustable speed, energy efficiency.

## 1. INTRODUCTION

Energy demand in the world has never been greater, and is expected to continue to increase in the foreseeable future, as global population grows and the world evolves. The continuous overuse of fossil fuel in energy generation is linked to the global warming phenomenon and its increasingly serious problematics. Furthermore, the over-reliance in fossil fuels by sovereign states is an economical challenge in most cases, and presents a threat to the security in energy generation, due to the proneness to sensitive geopolitical matters or natural disasters affecting the availability of necessary raw materials. Renewable energy sources (RES) are inexhaustible, with minimum global warming emissions and general environmental impacts, and offer stable energy prices. Production intermittency is the major drawback of RES, as the required conditions for generation may not always be guaranteed, raising problems like power outages or abrupt changes to the electrical grid's frequency, which are the more serious in higher RES penetration grids. These problems are often mitigated with the continuous operation of fossil fuel plants as spinning reserves, beating the original purpose of minimizing fossil fuel usage. This paper studies the importance of pumped hydro storage (PHS) in enabling the safe increase of in the grid RES penetration, and ways to improve PHS systems.

## 2. ELECTRICITY GENERATION OVERVIEW

Approximately 67% of the world's net electricity comes from fossil fuels, while nuclear and renewable sources account for roughly 12% and 21%, respectively. With current policies, fossil fuels are estimated to still have the biggest share of the world's net electricity generation by 2040, at roughly 62%, while renewable and nuclear sources increase to 25% and 13%, respectively. With current policies, fossil fuels are estimated to still have the biggest share of the world's net electricity generation by 2040, at roughly 62%, while renewable and nuclear sources increase to 25% and 13%, respectively. Net generation will grow from 20.2 trillion kilowatt-hours in 2010 to 39 trillion kilowatt-hours in 2040, a 93% increase (EIA, 2013). The overuse of fossil fuels in the generation of electricity presents two main problems: excessive greenhouse gas (GHG) emissions and the finite nature of these resources. Natural gas is the fossil fuel with the least GHG emissions, and currently the second most commonly used in electricity generation. Coal is currently the primary fuel for electricity generation and responsible for roughly 70% of $CO_2$ emissions. Oil is significantly less used in power generation, but also has a high emissions intensity. Most renewable energies have some indirect contribution to GHG emissions, as a result of the construction of the infrastructure and its maintenance. However, these are very low rate emissions: the GHG break-even point for a reference 33-unit of 3.0 MW turbines wind farm, which is how soon it can offset the GHG emitted to build, run and recycle it over a 20-year life cycle, with the GHG avoided in its power generation, can be as little as 7 weeks (IEA, 2012).

On the other hand, it is necessary to find ways to supply the world with energy beyond fossil fuels availability. At current consumption levels, proven reserves-to-production ratio is in the 40 to 45 years range for conventional oil, 55 to 60 years for conventional gas, while hard coal is in the range of 110 to 120 years, but will grow as more reserves become exploitable (IEA, 2013).

Nuclear power is fueled by Uranium, a metal that is ubiquitous on Earth, but economically recoverable concentrations are far less common. The total identified uranium resources have grown, but since the costs of production have also increased, lower cost category resources have been significantly reduced (IAEA, 2011).

Fossil fuels will become increasingly expensive as conventional reserves become less abundant and new technologies are required to allow for extraction. More so, carbon taxing is commonly used by policymakers as a mean to reduce emissions in a cost-effective way, based on the principle that the 'polluter pays', and the use of carbon capturing technology also comes at a cost.

Nuclear power is a capital-intensive technology. In addition to high investment costs, licensing and public acceptance issues have delayed construction periods for power plants in many countries, which resulted in higher than estimated costs and investment risk. Some reports suggest that subsidies play a major role in the economic success of nuclear power, even to the point of arguing that they wouldn't be sustainable without the said subsidies, which usually consists of a shift in construction-cost and operating risks from investors to taxpayers and ratepayers (Koplow, 2011).

Renewable power generation technologies (RPGT) have become increasingly cost-competitive in the last years, and are today, in most cases, the most economic option for off-grid electrification. The overall competitiveness of RPGT greatly depends on the locations' natural resources, but the rapid deployment and high learning rates have a significant positive impact on costs. As an example, solar PV modules costs decrease as much as 22% for every doubling in solar PV installed capacity.

The supply and demand curves on the electrical grid need to be closely matched, and both can be divided into base load, intermediate or middle load and peak load, as depicted in Figure 1.

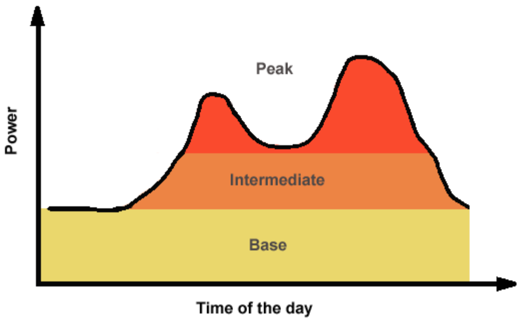


Figure 1 - Daily load curve separated into base, intermediate and peak load (adapted from Cordaro (2008))

Base load power sources consist of power plants with typically long startup times, such as nuclear and coal plants, that generate the minimum level of demand over 24 hours, producing continuous, reliable and efficient power at low cost. Since they are somewhat inefficient at less than full output, base load plants run continuously throughout the year and only stop when there is need for repair or maintenance. The intermediate demand describes the somewhat predictable variation in demand that happens throughout the day, and is supplied by plants that are capable of working within minutes to an hour and have moderate operating costs (typically natural gas combined cycle), and are also commonly called as "load following" or "cycling" plants. Peak load demand describes the sudden increase in consumption that might occur during the day, posing a risk to energy security. In these situations, a highly flexible power plant that can go to full capacity immediately is needed, typically NGCC (natural gas combined cycle) or hydropower, which has the fastest response time, being able to go from full power to zero and vice versa within one minute.

As RES capacity and grid penetration increases, so does the challenge of ensuring that supply matches demand at all times without the use of fossil fuel spinning reserves. Interconnection of adjacent power grids presents a solution, where effective balancing of supply and demand is facilitated through electricity trade with other regions. However, in a geographically close cluster of interconnected systems lying under a single weather system, trading is not an option for fast access to additional electricity. A solution for this is the use of large-scale energy storage systems, as stored electricity is available almost instantaneously.

Figure 2 shows the relationship between the net variation of wind power and the necessary storage in 2010, 2015 and to comply with the EU's Blue Map scenario's projections of high RES in 2050, while attending to energy security.

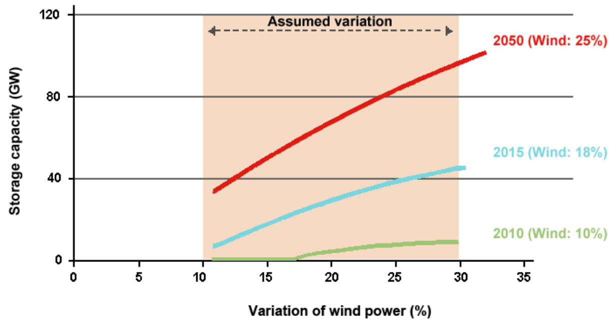


Figure 2 - The relationship of net wind power variation and necessary storage capacities (adapted from (Inage, 2009))

Wind generation net variation ratios between 10% and 30% in 2050 correspond to needed storage capacities ranging from 40 GW to 100 GW, which is equal to an additional capacity of 7 to 67 GW.

## 3. PUMPED STORAGE

In its traditional functioning mode, pumped hydro storage (PHS) stations consist of two reservoirs at different levels, with pump and hydropower stations where energy is either injected or converted with the passage of a water flow. In some cases, large water streams or water bodies, or even the ocean can be used as one of the reservoirs. Revenues are generated by the difference between low demand hours electricity price (usually during the night time, early mornings or during the weekend), when electricity is acquired to pump the water to the higher reservoir where it is stored, and the sell back price of the electricity generated when the water is later turbined in peak demand hours (usually during weekdays on late mornings, afternoons, and/or evenings). PHS allows for a reduced peak generation capacity from thermal plants, since it's possible to accumulate energy off peak and discharge when demand is peaking, and it avoids new transmission and distribution capacity. PHS can also provide capacity and energy for a black-start after a system failure, since it requires very little initial power to start and can provide a large amount of power in a short time scale to help other units restart, while providing a reference frequency for synchronization. Their efficiency is given by

$$\eta = \eta_c \cdot \eta_d = \left[\eta_p \cdot \eta_M \left(\frac{H - \Delta H_p}{H}\right)\right] \cdot \left[\eta_t \cdot \eta_G \left(\frac{H - \Delta H_t}{H}\right)\right] \quad (1)$$

where $\eta_c$ is the charging efficiency, $\eta_d$ is the discharging efficiency, $\eta_p$ is the pumping efficiency, $\eta_t$ is the turbine efficiency, $\eta_M$ is the motor efficiency of generator/motor, $\eta_G$ is the generator efficiency of generator/motor, H is the head, $\Delta H_p$ is the loss head of water way in pumping operation, $\Delta H_t$ is the loss head of water way in turbine operation.

The energy density of the water in the upper reservoir increases as the turbine head increases, as Equation (2) shows, meaning that high-head pumped hydro units have a large amount of energy stored in the upper reservoir. Figure 3 shows the relationship between net head and volume in the upper reservoir to obtain 1 000 MWh of stored energy.

$$E = \frac{\int P dt}{\rho V} = gH \tag{2}$$

where E is the specific energy or energy density of water (J/kg), P is the power (W), ρ is the water density (kg/m³), V is the volume of water (m³), g is the gravitational acceleration (m/s²), H is the pump turbine head (m).

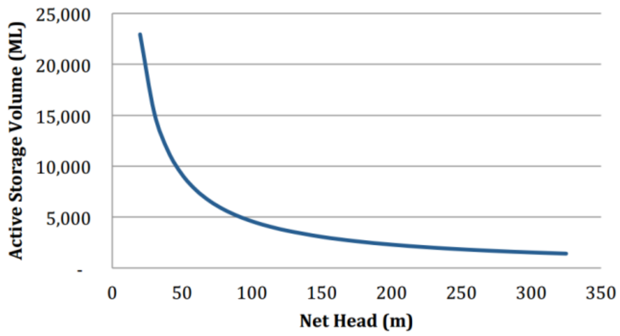


Figure 3 - Relationship between water volume requirements as a function of net head between reservoirs, for 1,000 MWh of stored energy (Hearps et al., 2014)

The installed power of the system also increases proportionally with the head and with the discharge, as Equation (3) shows. Given that the construction costs of a higher net head system are the same as a lower one, it will most likely be preferable to opt for the former with a lower discharge to obtain the same installed power, leading to a lower ratio of €/MW.

$$P = \gamma \, Q \, Hu \, \eta \tag{3}$$

where P is the installed power (kW), γ is the specific weight of fluid (N/m³), Q is the discharge (m³/s), Hu is the head (m), η is the turbine-generator efficiency.

The capacity of the pump is usually smaller than the capacity of the water turbine in reversible pump-turbines, which means that the water pumping process requires more time than the generation process. The addition of water pumping capacity can increase the efficiency of the whole system, by speeding up the pumping process and extending the period where water is available for generation.

Another improvement that can be made to pumped storage systems is the use of adjustable-speed pump turbine units and motor generators, which can operate over a larger range of rotation speeds. For units of up to 50 MW a synchronous generator can be linked to the grid by a static frequency convertor, while in larger units a double fed induction machine with a static frequency feeding the rotor are commonly used, which consists in creating a rotating magnetic field on the rotor, allowing the unit to be operated over a range of rotating speeds around the synchronous speed, while attached to a fixed frequency network.

Traditional synchronous machines are directly connected to the grid and operate at a constant speed and constant input pumping power, which means frequency regulation while in pump mode is not possible. Adjustable speed systems, on the other hand, allow the power consumed in the pumping mode to be varied over a range of outputs, enabling them to perform frequency regulation, since the power absorbed can be varied at fixed head, as Figure 4 shows.

Figure 5 illustrates how adjustable-speed technology is able to store more energy than synchronous-speed, and also that it can offer network balancing during pump mode, and it requires less starts and stops.

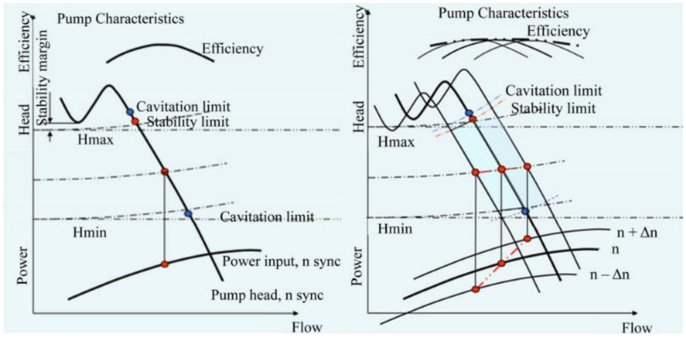


Figure 4- Operating ranges of fixed-speed (left) and adjustable-speed (right) pumps (adapted from Krenn et. al (2013)).

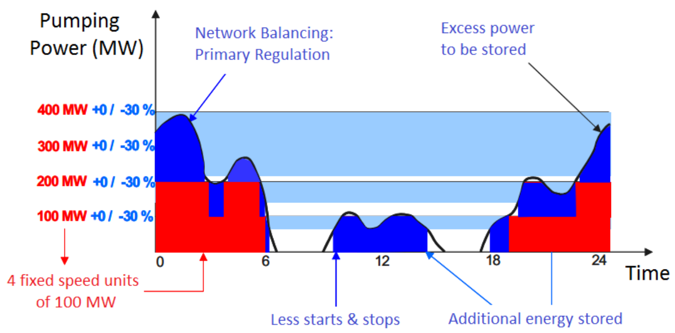


Figure 5 - System reserve and power storage from variable-speed vs single-speed pumped storage (Ciocan et. al, 2012)

Adjustable-speed also allows for the turbine to operate at peak efficiency power over a larger portion of its operating spectrum. Furthermore, the rate of changing the output is faster than synchronous speed systems. The overall more efficient use of the equipment, enabled by adjustable speed, further reduces the need for thermal plant "spinning" units, thus avoiding GHG emissions (Inage, 2009).

The net head in turbine operation is obtained by subtracting the head losses form the static head, while in pump operation the head losses are added to the static head, therefore making the pump mode net head larger. Consequently, a pump-turbine is always too large to operate as a turbine, meaning that the best efficiencies of the turbine characteristics are outside the actual operating range of the machine in a single speed configuration as Figure 6 shows, where the operating range (red area) of fixed and adjustable speed turbine are compared.

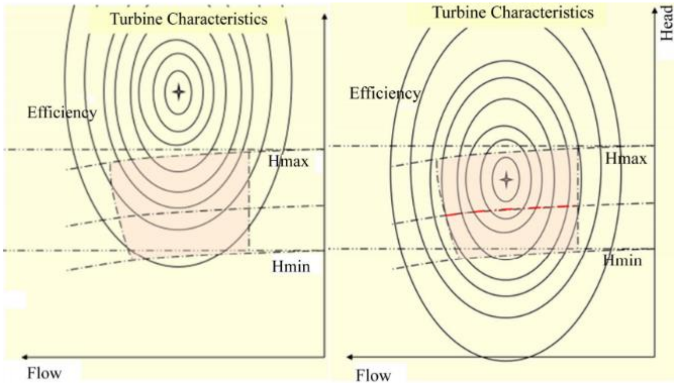


Figure 6 - Operating ranges of fixed-speed (left) and adjustable-speed (right) turbines (adapted from Krenn et. al (2013))

Another option for system improvement is the use of separate parallel circuits for pumping and turbining. While a single penstock is a cheaper solution, a double penstock can offer operational flexibility, since pumping or turbining become independent operations, and allows for a quick response operation of the turbine when needed. This could be advantageous if a wind power unit, or other variable generating unit, is directly connected to the pump, for example, as could happen in an off the grid system

**Mitigation of variability in RES generation**

Frequency regulation (the ability to respond to small, random fluctuations around the normal load) and contingency reserves require units that can rapidly change output. The fast nature of these fluctuations require fast response of regulation reserves, which are often provided by plants that are online and "spinning", commonly known as spinning reserves. The variable input of RES to the grid can be interpreted as a source of demand reduction, so conventional generators provide the "residual load" of normal demand minus the electricity produced by renewable generators.

Figure 7 illustrates how a renewable generation is subtracted from the normal load, showing the "residual" or net load that the system would need to meet with other sources. The reduction implies a reduction in fuel use (and associated emissions) from these sources.

However, the use of variable generation also has negative impacts on the grid. Because it increases ramping rate, and short term variability, there is an increased need for frequency regulation. A reduction in minimum load can force base load generating units to cycle off during periods of high wind output. Finally, the unpredictable nature of a variable source reflects on the resulting net load. At higher penetration of variable RES generation, the ability of conventional generators to reduce output becomes an increasing concern. In Figure 8, variable RES generation shows periods (the first 12 hours of each day) where it reduces demand so much that it begins to displace units that usually work with a constant output, and whose ability to reduce output is somewhat constrained. If the base load generators cannot reduce output then wind energy will need to be curtailed, a largely undesirable practice because it throws to waste a cost-free (in regards to production) and emissions-free energy. A solution to avoid curtailment is provided by energy storing facilities, by absorbing otherwise unusable generation and moving it to times of high net system load (where net load is defined as normal load minus variable generation), as Figure 9 shows. Energy that is stored from the surplus of wind power generation, for example, can be shifted to high demand hours. The additional flexibility that pumped storage adds to the system is also of significant importance: by providing operating reserves, it reduces the need for partially loaded thermal generators which may otherwise restrict the contribution of variable RES generation. Finally, by providing firm capacity and energy derived from variable RES sources, pumped storage can effectively replace base load generation, which reduces the minimum loading limitations.

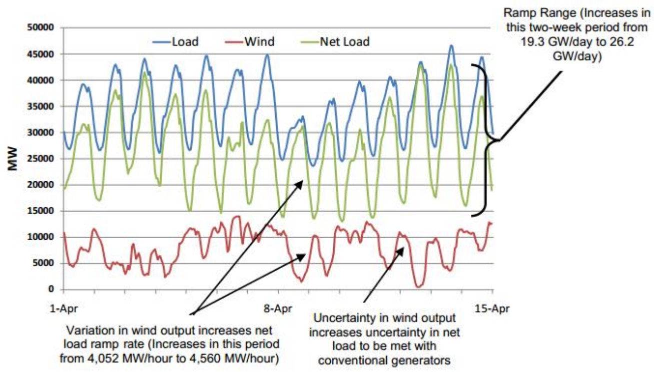


Figure 7 – Impact on net load from increased use of variable generation units (Denholm et. al, 2010)

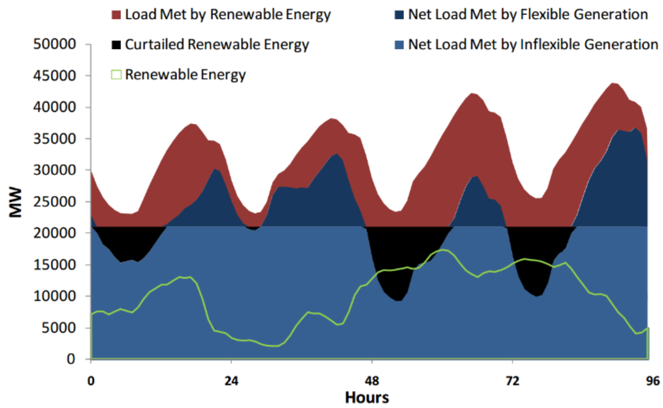


Figure 8 – Variable RES generation curtailment in a high RES penetration grid (adapted from (Denholm et. al, 2010)

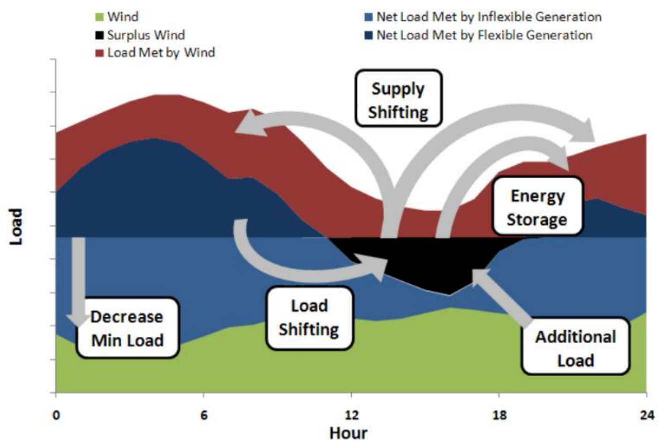


Figure 9 – Storage as an option for increasing the use of variable RES by decreasing curtailment (Denholm et. al, 2010)

## 4. CASE STUDY- MULTIPLE PURPOSE SOCORRIDOS SYSTEM

The Multi-Purpose Socorridos Hydroelectric System, situated in Madeira Island, began operating in 1995 under an initial configuration that featured a 15.5 km long string of hydro tunnels and canals, allowing the transfer of water collected on the higher altitude and more pluvious northern side of the island, to the southern side of the island, a loading chamber in Covão with a maximum capacity of just 7 500 $m^3$, and a hydroelectric station with three 8 MW turbines. Another branch of the system connects to the Stª Quitéria mini hydropower station, which is equipped with a single Pelton turbine with a nominal flow of 1 $m^3/s$

The small capacity loading chamber could only provide guaranteed power during winter, which led to the improvement of the system in the period between 2004 and 2006, with the introduction of four main new features:

- Transformation of the hydroelectric station into a reversible system with the installation of 3 working pumps of 3.75 MW, 0.65 $m^3/s$ flow and a peak of 457 m each, plus a similar one as a backup;
- Addition of a 5 243 m long tunnel between Covão and Campanário with a 32 500 $m^3$ water storage capacity, which supplies irrigation water on both of its ends, and provides storage, in order to ensure a reliable water supply and electricity production;
- Addition of a storage gallery with 40 000 $m^3$ capacity in Socorridos, which accumulates the turbined water and feeds the pumping station;
- Renovation of the Encumeada (2 850 m) and Canal do Norte (2 768 m) tunnels, and installation of gates to regulate water flow, allowing the storage of up to 55 000 $m^3$ of water.

With these changes, the project's objectives were:

- to guarantee that 24 MW of power and 44 MWh are available daily;
- to cut energy losses, which were estimated at 2.54 GWh per year;
- to introduce additional wind power estimated at 25 MW;
- to reduce the use of fossil fuels in power generation;
- to reduce GHG emissions in power generation;
- to improve the management of hydroelectric resources;
- to increase reliability of the water supply system to the populations of Funchal (through the Water Treatment Station at Stª Quitéria) and Câmara de Lobos (through the Water Treatment Station at Covão);
- to deliver 65% of irrigation water to the distribution facilities at Covão and Campanário, minimizing estimated losses by some 1 300 $m^3$/day in the Canal do Norte (southern section) between the Serra de Água power station and Campanário.

The introduction of Loiral and Pedras wind farms alone, made possible by the Socorridos reversible system, allowed for a reduction of 27 600 tonnes of $CO_2$ (carbon dioxide), 116 tonnes of $SO_2$ (sulfur dioxide), 478 tonnes of $NO_x$ (nitric oxide) and 7 tonnes of particles.

Snapshots of the schematic operation of the system in the summer are displayed in Figure 10, corresponding to the turbine mode, and Figure 11, corresponding to the pumping mode.

In reversible systems with big stream flows and small elevations, Francis turbines are commonly used, but due to the large head of this station (the gross head is 456.9 m) Pelton turbines were installed, at a topographic level of 89 m, where the hydropower station sits. The characteristics for the turbines are presented in Table 1.

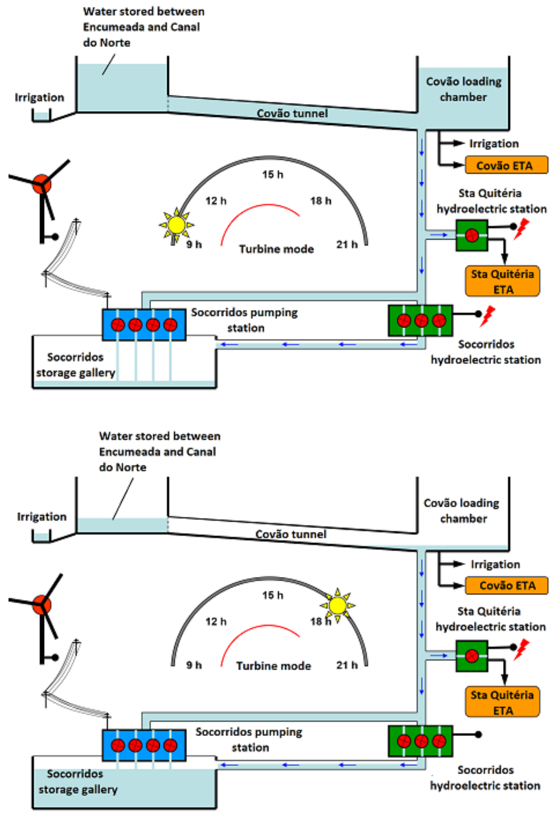


Figure 10- Snapshots of the schematic operation of the system in turbine mode (adapted from (EEM, 2006))

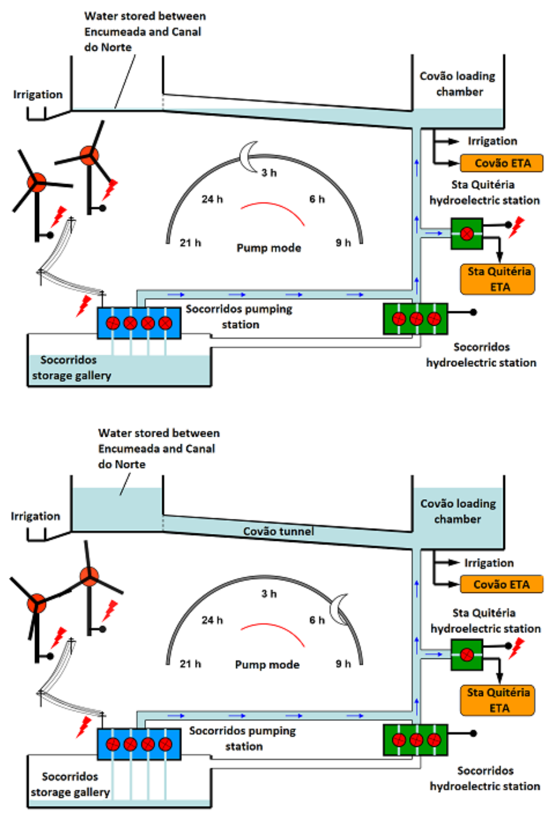


Figure 11- Snapshots of the schematic operation of the system in pump mode (adapted from (EEM, 2006))

Table 1 - Socorridos Hydroelectric Station turbine characteristics

| Turbines | |
|---|---|
| Number of units | 3 |
| Type | Pelton |
| Gross Head (m) | 457 |
| Net Head (m) | 450/433 |
| Number of Paddles per Wheel | 19 |
| Nominal Wheel Diameter (m) | 1.118 |
| Maximum Flow (m$^3$/s) | 2 |
| Nominal Speed (r.p.m.) | 750 |
| Nominal Power (kW) | 8 000 |
| Constructor | Noell |

The use of reversible turbines to pump the water back to Covão was inadequate, considering the range of power and head required and, as so, an autonomous pumping system was installed in parallel, using the same hydraulic infrastructure (penstock and intake/discharge chambers). The pump station is buried, and sits at a topographic of level 85 m, using four pumps with the characteristics listed in Table 2, with one of them serving as a backup. It was designed to pump as much as 40 000 m3 of water stored in Socorridos gallery during electricity low demand hours (from 0 to 6 am).

Table 2 – Socorridos Pump Station pump characteristics

| Pumps | |
|---|---|
| Type | Centrifugal |
| Number of Units | 3+1(backup) |
| Installed power (kW) | 3 750 |
| Head (m) | 457 |
| Maximum Flow (m$^3$/s) | 0.65 |

The Região Autónoma da Madeira (RAM) government committed to a 20% reduction in $CO_2$ emissions by 2020, below 1990 values, and to raise the share of RES in the energy mix up to at least 20% by the same deadline, by signing in to the Pact of Islands. In recent years the evolution has been significantly positive, having already surpassed the 20% RES share mark 11 years ahead of schedule.

The introduction of the new wind turbine parks of Paul da Serra (6.0 MW), Pedras (10.20 MW), Fonte do Juncal (8.1 MW), Loiral (5.1 MW) and Loiral II (6.0 MW), between 2008 and 2011, increased by almost 5 times the installed power for this source, for a total of 45 MW. In 2011, solar panel parks were also installed in Loiral (9.0 MW) which raised the total installed capacity of this source up to 17 MW.

This increase was made possible with the commissioning of the Multiple Purpose Socorridos System reversible functioning mode. In fact, without a hydro power plant to regulate peak demand, the system would be left with only one major thermal power plant serving as base, middle and peak load. Figure 12 and Figure 13 illustrate how the Socorridos System affects the daily load diagram in autumn, showing how wind penetration is maximized due to pumping in low peak demand hours, and thermal generation is substituted for hydro production in peak hours, which is allowed by storage, effectively "smoothing" out the load diagram. As so, less spinning reserves are required.

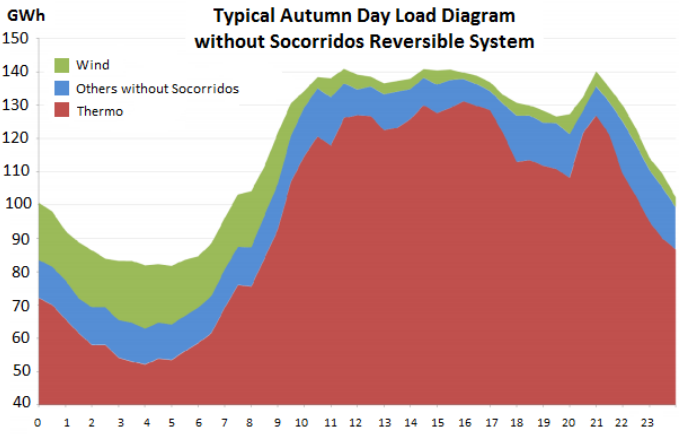


Figure 12– Load diagram in grid without Socorridos Reversible System (adapted from (EEM, 2010))

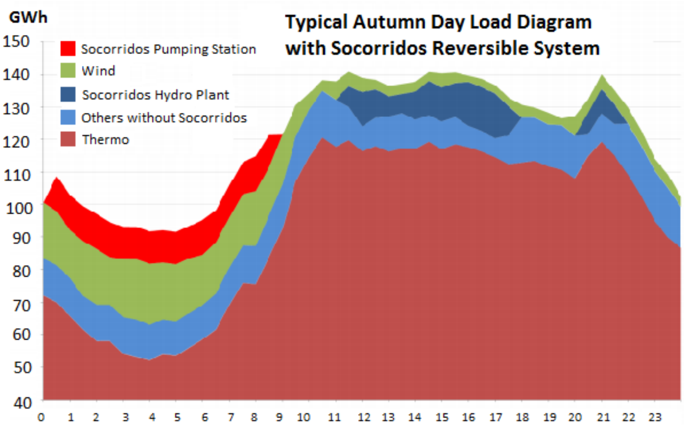


Figure 13 – Load diagram in grid with Socorridos Reversible System (adapted from (EEM, 2010))

The projected share of RES in electricity generation in RAM is expected to grow even higher, to as much as 52% by 2020. Soon more storage capacity will be needed, to ensure grid security to variation in generation. A new reversible project in Calheta (Calheta Hydroelectric Reversible System - Calheta III) is currently under construction. The project's main components are (Calheta Hydroelectric System: Calheta III – New Reversible System, EEM, 2011):

- Pico da Urze Dam
  - 31 meters height
  - 1 000 000 m$^3$ of storage capacity
  - Flooded area of 7 ha
- Calheta Dam
  - 34.5 m height
  - 73 750 m$^3$ total storage volume for the retention of the water turbinated in Calheta III, for subsequent pumping to Pico da Urze's reservoir
  - Flooded area of 6 360 m$^2$
- Calheta III Hydroelectric Power Plant and Calheta Pumping Station
  - 2 generators with 15 MW of power each (2x15 MW)
  - 3 pumps for Calheta Pumping Station, each one with 4.9 MW
  - *

- Penstocks
    - 1500 mm steel tubing
    - 3.460 m length, from Calheta and Paul stations to Pico da Urze's bayou)
- Water Pumping Station of Paul
    - 2x150 kW electric pumps to pump the collected water by Paul I water channel (Levada do Paul I), below the Pico da Urze dam, and also by Paul II water channel (Levada do Paul II), both to Pico da Urze bayou.
- Paul II Water Channel (Levada do Paul) Expansion
    - 10.6 km length between the Juncal stream (Ribeira do Juncal) and the forebay of Paul, by raising the side walls to increase transport capacity
- Paul Old Water Channel (Levada Velha do Paul) Expansion
    - main source of supply to Pico da Urze's bayou
    - 1 600 m length , between the Lajeado stream (Ribeira do Lajeado - where it takes in the water) and the Alecrim stream (where it gives back the intake water)
    - building of a channel in order to increase the carrying capacity
- Lombo Salão Water Channel (Levada do Lombo do Salão) Renewal
    - 1 690 m long, located between Calheta I Hydroelectric Power Plant and Lombo do Salão forebay
    - aims at reducing water flow losses during its path, in order to improve the water delivery to irrigation and adduction to Calheta II Hydroelectric Power Plant (Central de Inverno da Calheta - Calheta II)

This project is expected to generate an added 29 GWh of annual average hydropower production, of which 18 GWh will derive from direct water exploration and the remaining 11 GWh will be a result of the pumped water storage usage, and it will allow for the inclusion of as much as 25 MW of added variable generation, namely wind power (Figueira, Calheta Hydroelectric System - Calheta III – New Reversible System, 2011).

The projected daily load diagram of the RAM's electricity grid with the inclusion of the Calheta reversible system is shown in Figure 14. As expected, the load diagram is further smoothed out in comparison with the one displayed in Figure 13 where only the Socorridos system was considered, with increased RES penetration possibility, of up to 30% of the electricity production share, and reduced need for spinning reserves. This results in the avoidance of 81 400 tonnes of fuel oil importing, which corresponds to a 3.8 M€ savings per year, and to an avoided emission of 253 000 tonnes of $CO_2$.

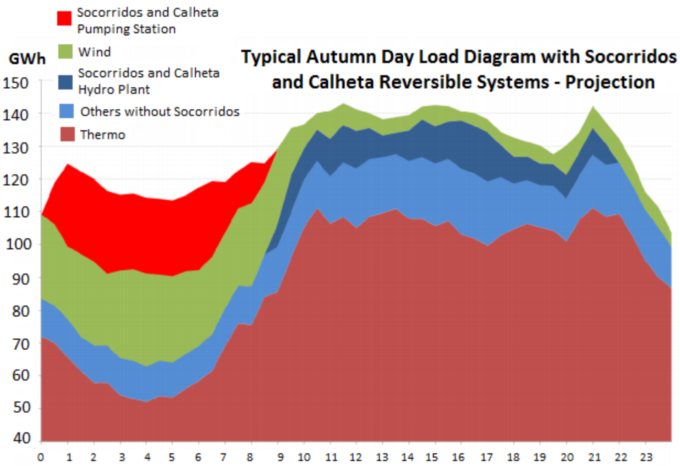


Figure 14 - Load diagram in grid with both Socorridos and Calheta Reversible System (adapted from EEM, 2010)

**Optimization Algorithm**

In order to draw a comparison between different technology solutions in PHS systems, an optimization procedure is developed using MATLAB, with objective functions that represent the Multiple Purpose Socorridos System in its real configuration and with the use of adjustable-speed equipment, and the installation of a double penstock. This is an adaptation of a previously done study to the same system by Ramos and Vieira -Hybrid solution and pump-storage optimization in water supply system efficiency: A case study, Ramos and Vieira, 2008 - where wind energy integration to power the pump station is studied. Performance of each alternative is measured and classified accordingly with its generated revenues, meaning that costs are minimized and benefits are maximized in the optimization procedure, and by accounting RES integration ability and energy surplus which is provided by the electrical grid. Costs of installation, operation and maintenance works of these alterations, as well as of the wind park are out of the scope of this exercise and as so not considered. The objective functions are solved for water level variation, since it is directly correlated to the amount of energy that is either consumed or produced, provided that the system remains unchanged throughout the modelling time period. With this optimization procedure, a schedule for the best possible performance is obtained, being energy tariff and wind energy availability the criteria for the algorithm to either store or generate energy, within the set boundaries. Nonlinear MATLAB algorithm solvers are used, which stop when a local minimum is found. The script is run in a loop a hundred times with randomly generated initial points, and the best solution is automatically picked out and worked in EXCEL.

Some considerations and simplifications are implemented in the system in order to make the modelling simpler, without compromising the proposed comparison:

- The modelling is common to both adjustable and synchronous technologies, meaning the schedule obtained is the same for both. The results are, however, treated independently;
- The top and bottom reservoirs are considered identical, with a rectangular parallelepiped shape, and effective dimensions of 100 x 100 x 4 [$m^3$] amounting for 40 000 $m^3$ of water storage capacity, meaning the maximum level is 4 m, while the minimum is set at 0.5 m for the upper reservoir, and 0,1 m for the lower reservoir;
- Only the dry season is considered, since the pump is never or very rarely used during wet season;

- The electricity tariff is adapted from the 2015 real tariff from EEM (Empresa de Electricidade da Madeira) to "final clients in medium tension", so that the peak to low (and vice versa) period switch occurs on the hour, instead of on the half hour, to make it compatible with the time step increments of the modelled systems. No criteria was used in choosing the tariff since it will affect all alternatives equally, except that it corresponds to the dry season period;
- The equipment is considered to work as a unit in the modelling phase, meaning all 3 turbines and pumps work as a single unit. Later on they are accounted for separately, considering the efficiency of each pump and turbine;
- For the wind integration simulation, it is considered that there is one park with 6 VESTAS V90 wind tower turbines of 3000 kW each in Loiral. The wind speed data is compiled from a monthly record for July in 2014;
- During the day some of the wind energy is considered to be directly consumed and so only a percentage is made available to the system;
- The net head is considered fixed, for all calculations, at 457 m;
- Ten simulations are run with different initial levels for the reservoirs, starting at the minimum level for the upper reservoir and ending at 1 m above that, which are considered to occur with equal probability;
- In order to ensure spinning reserve capacity at peak demand hours, a minimum upper reservoir level is required to be verified at 10 am and 8 pm;
- During peak demand hours, only the turbine station can operate, and during low demand hours only the pump station can operate.

A Microsoft Excel is used as the input for the MATLAB optimization, to allow it to be flexible and adaptable to different situations. The inputs for the modelling are:

- Hourly water consumption in the upper reservoir (m) - $N_{CU}$
- Hourly water inlet in the upper reservoir (m) - $N_{IU}$
- Hourly water consumption in the lower reservoir (m) - $N_{CL}$
- Hourly water inlet in the lower reservoir (m) - $N_{IL}$
- Electricity tariff (€) - c
- Initial water level in the upper reservoir (m) - $N_{INITU}$
- Initial water level in the lower reservoir (m) - $N_{INITL}$
- Maximum water level in the upper reservoir (m) - $N_{MAXU}$
- Maximum water level in the lower reservoir (m) - $N_{MAXL}$
- Minimum water level in the upper reservoir (m) - $N_{MINU}$
- Minimum water level in the lower reservoir (m) - $N_{MINL}$
- Water level rise/decrease for each time step (determined by pump/turbine flows – $dN_h$
- Volume per meter in height in the reservoirs (dependent from their dimensions) ($m^3$/m)- $V_U$
- Net head – $H_U$
- Pumping station efficiency - $\eta_P$
- Maximum water level rise in upper reservoir – $N_{QP}$
- Maximum water level decrease in upper reservoir - $N_{QT}$
- Generating station efficiency – $\eta_T$
- Wind speed curve
- Wind turbine power curve
- Wind energy powered water level variation available on each hour - $dN_{h\_w}$

**Pumped hydro storage with double penstock**

To model the single penstock system Function (i) is used:

$$\sum_{h=1}^{24}\left[\left|\left(dN_{h,W}/dN_h\right)-1\right| \times \frac{C_{P,h}}{\eta_P}\left(\frac{dN_h + |dN_h|}{2}\right) + C_{T,h}\,\eta_T\left(\frac{dN_h - |dN_h|}{2}\right)\right] \quad \text{(i)}$$

where $C_{P,h}$ is the electricity tariff for each hour (€/kWh), $dN_h$ is the water level variation in the upper reservoir (Covão) (m), $dN_{h,W}$ is the water level variation that can be produced by wind energy in the upper reservoir (Covão) (m), $C_{T,h}$ is the produced hydroelectricity selling price for each hour (€/kWh), $\eta_P$ is the pump efficiency (%), $\eta_T$ is the turbine efficiency (%), h is the hour of the day.

This function represents the sum of the water level variation in the upper reservoir multiplied by the electricity costs/selling price, throughout 24 hours. When the water level rises ($dN_h$>0), the pump is operating, with an associated cost for each hour ($C_{P,h}$), and the turbine term is equal to zero due to the factor $\left(\frac{dN_h - |dN_h|}{2}\right)$. Conversely, when the water level declines ($dN_h$<0) the turbine is operating, and energy can be sold at an associated price for each hour ($C_{T,h}$), while the pump term is equal to zero due to the factor $\left(\frac{dN_h + |dN_h|}{2}\right)$. Additionally, the factor $\left|\left(dN_{h,W}/dN_h\right)-1\right|$ introduces a condition in which if the pump uses exactly the wind energy available in a given hour, then the cost of operation is equal to zero. Should the pump use more than that energy, then there is a price to be paid for the operation, since the pump needs to use the electrical grid to work. If, instead, the pump uses less than that energy, then there is also a price to be paid for, as that means that wind energy is being wasted. Since we are minimizing the function, the solver will always try to use exactly the amount of wind energy available, to bring the pumping operation cost down to zero, and use the turbine the most when the electricity tariff is higher.

The restrictions to the hourly water level variations are shown in Tables 3 and 4.

Table 3 – Hourly water level variations in the upper reservoir for Functions i and ii

| Operation | Limits |
|---|---|
| **Turbine** | [$N_{QT}$, 0], ($N_{QT}$ = -2.16) |
| **Pump** | [0, $N_{QP}$], ($N_{QP}$ = 0.72) |

Table 4 – Hourly water level limits for the reservoirs for Functions i and ii

| | |
|---|---|
| **Maximum water level in the upper reservoir (m)** | $N_{MAXU}$ |
| **Maximum water level in the lower reservoir (m)** | $N_{MINU}$ |
| **Minimum water level in the upper reservoir (m)** | $N_{MAXL}$ |
| **Minimum water level in the lower reservoir (m)** | $N_{MINL}$ |

Wind data was collected from Loiral's weather station record of July of 2014 and compiled into daily hourly averages. With the wind speed records, and using VESTAS V90 power curve, shown in Figure 16, the data was converted into kW, and subsequently to water level variation (in meters) using Equation (4).

$$P = \gamma\, Q\, Hu/\eta \qquad (4)$$

where P is the installed power (kW), γ is the specific weight of fluid (N/m³), Q is the discharge (m³/s), $H_u$ is the head (m) and η is the pump's efficiency. That is to say that a given wind speed produces a given power that is capable to elevate a given amount of water, represented by $dN_{h_w}$.

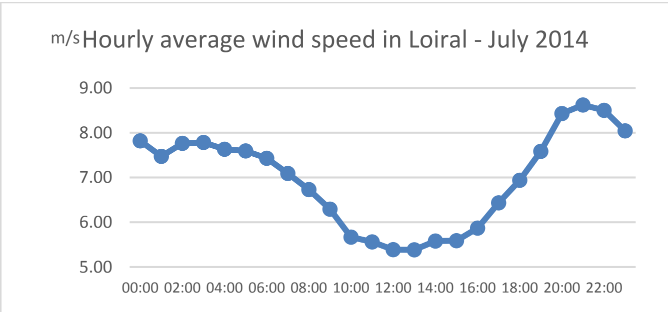


Figure 15 –Hourly average wind speed in Loiral - July 2014

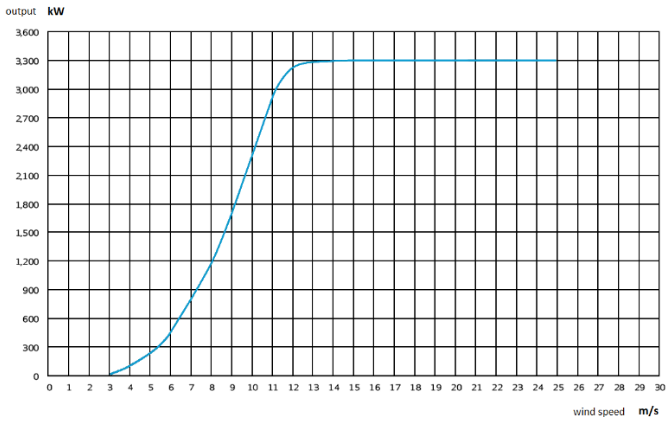


Figure 16 – VESTAS V90 wind turbine power curve

If the available wind energy exceeds the maximum value that the pump can elevate, the value will be reduced to that threshold.

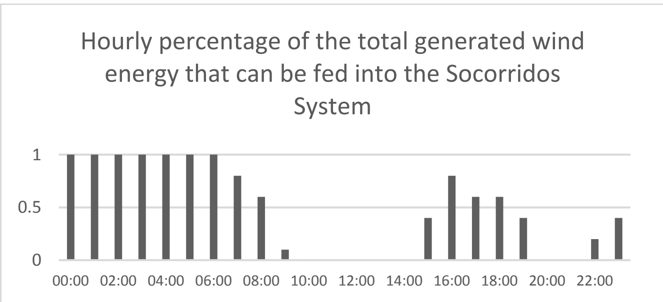


Figure 17 - Hourly percentage of the total generated wind energy that can be fed into the Socorridos System

The data for the hourly consumption derived water level variations in the upper reservoir was compiled from a record of the hourly flows to the water treatment plants of Stª Quitéria and Covão, and the irrigation flows Stª Quitéria for Ameixeira, Campanário and Covão. There is no data record for the hourly inlet derived water level variations in the upper reservoir, so it is considered constant and equal to the total amount of water consumed in a day. The water consumption and inlet in the lower reservoir is set to zero.

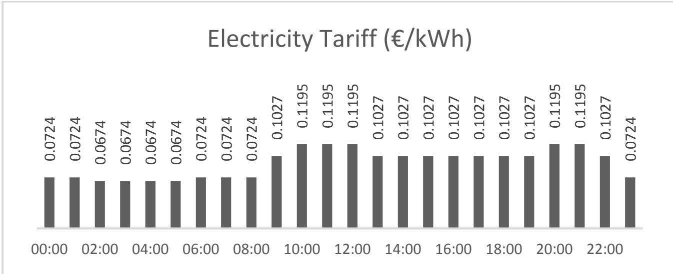


Figure.18 – Electricity Tariff (€/kWh) (EEM, 2015)

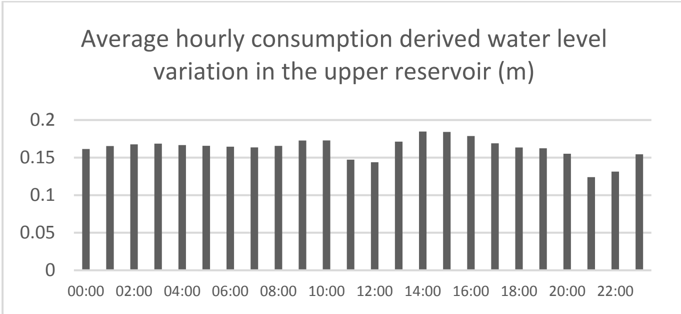


Figure 19 –Average hourly consumption derived water level variation in the upper reservoir (m)

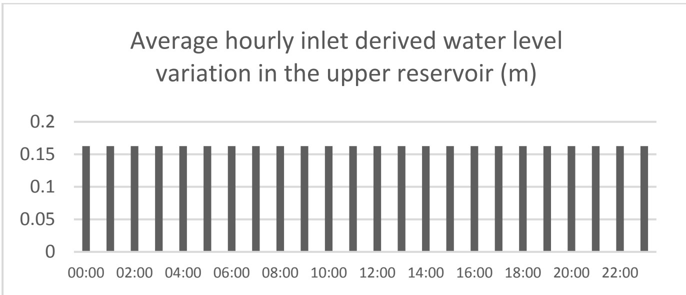


Figure 20 – Average hourly inlet derived water level variation in the upper reservoir (m)

The algorithm runs in two loops, one which sets the initial water level in the upper reservoir in ten different levels, starting from its minimum level and increasing in 0.1 m intervals. The second loop happens within each of these ten scenarios, and runs the algorithm a hundred times, minimizing the objective function, in order to get as close to the global minimum as possible, since the nonlinear solver stops running when a local minimum is found. The best results are stored in MATLAB's memory and later output to an excel spread sheet. The output contains the hourly water level variation and both reservoirs' water levels for all of the 10 scenarios, where it is treated separately for adjustable and synchronous speed technologies. A histogram is made from the results, where an average of the 10 scenarios is multiplied by 183 days, corresponding to the dry season, which tells us the number of hours the equipment has worked at a given flow on that period of time.

The specific energy that is consumed or generated by moving a certain volume of water through the system is calculated as shown in Equation (5).

$$Es = \frac{Energy}{Volume} = \frac{Time \times H \times Q \times g \times \rho}{Time \times g} \quad (5)$$

where E is the specific energy (J/m³), Time (s), Q is the discharge (m³/s), $g_u$ is the gravitational acceleration (m/s²) and ρ is the fluid density (kg/m³),

For pumping and turbining operation, and considering water with a density of 1000 kg/m³, Equation (5) translates as Equation (6) and (7) respectively

$$Es = \frac{H \times g}{3600 \times \eta_p} \quad (6)$$

$$Es = \frac{H \times g \times \eta_t}{3600} \quad (7)$$

where $\eta_p$ is the pump's efficiency and $\eta_t$ is the turbine's efficiency.

The pump efficiency curve was obtained from a test done to one of the pumps installed in the Socorridos system (Figure 21). For the calculations regarding adjustable speed technology, the efficiency of the motor and variable frequency drive (VFD) have to be taken in consideration. Pulse width modulation is a commonly used way to control the speed of the motor, which works by alternating the voltage between discrete amplitudes. When the VFD has an output voltage proportional to the frequency, the motor torque remains constant while the frequency decreases, which is desirable since motor torque is then proportional to the square of the frequency. Figure 22 shows the operating efficiency of VFD. To obtain the efficiency of the pump with adjustable speed motor, one has to multiply the efficiencies of both of these.

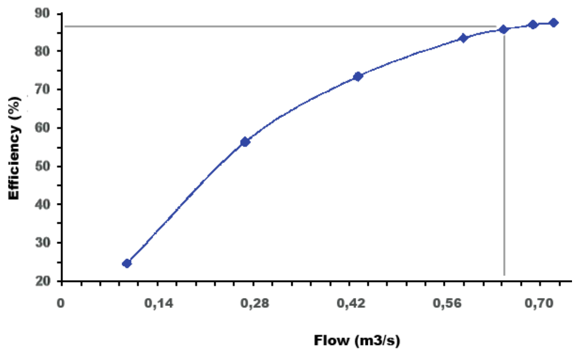


Figure 21 – Pump efficiency vs Flow

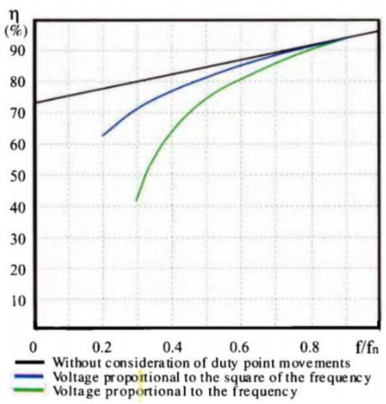


Figure 22 – Operating efficiency of VFD (FLYGT, 2011)

Since there are three pumps in the system, the efficiency will rise and fall as the flow varies an additional pump is turned on or off. The efficiency for the synchronous pump station is considered constant and equal to 0.84 at nominal flow.

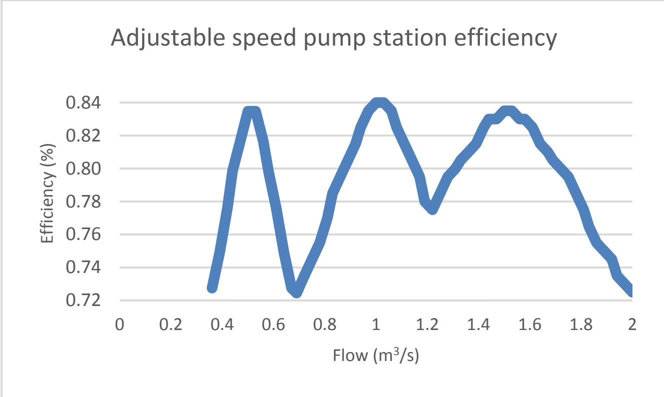


Figure 23 – Adjustable speed pump station efficiency

With a Pelton turbine there aren't much improvements in efficiency by using adjustable speed technology, since its efficiency is almost constant even for low discharges. As so, the efficiency is considered equal to 0.91 in both technologies in turbine operation.

The specific energy for every flow possible is calculated. It is worth mentioning that the specific energy in a synchronous system is constant since its efficiency is always maximum.

To calculate the energy consumed and generated by the pump and turbine station respectively, one has to use Equation (8).

$$\sum_i E_{s,i} \times T_i \times Q_i \quad (8)$$

where Es,i is the specific energy corresponding to the flow Qi (kWh/m³), Ti is the number of hours for which the flow Qi occurred and Qi is the flow (m³/s).

If the results schedule shows that there was a water level variation of half the nominal flow of the synchronous pump at a given time step of one hour, it means that the pump only worked for half an hour during that time step. In the adjustable speed pump station, the time is considered to be always one hour, meaning the pump operates continuously during that time step, except for values below 0.33 m³/s, since below that threshold the efficiency drops considerably.

The amount of wind energy absorbed is determined by subtracting the energy the pump has used from wind energy from the total wind energy available. For this, a second MATLAB model is used, which gathers data from the previously generated optimized schedule and calculates the time for which the pump station worked for synchronous and adjustable technologies. The synchronous pump station will only operate for a fraction of the time step, which means some of the wind energy will be lost.

For synchronous pump operation, the electrical grid will have to provide a surplus of energy to power the pump station when the wind energy is not enough to power it by itself, since it will only operate at nominal power. This surplus is also determined with the second MATLAB model.

**Pumped hydro storage with double penstock**

For modelling a double penstock system, a similar procedure is done, but with all the variables converted into a 48 sequence time steps in the MATLAB script, in which the odd number sequence steps correspond to the pump operation and the even number sequence steps correspond to the turbine operation.

The consumption and inlet derived water level variations is simply divided into equal parts for each sequence step, while the electrical tariff remains the same for both pump and turbine related time steps.

The available wind energy derived water level variations on the upper reservoir is converted so that it is zero on even number time steps.

The objective Function (ii) and the rest of the calculations are also adjusted to 48 sequence steps.

$$\sum_{h=1}^{48}\left[\left|\left(dN_{h,W}/dN_h\right)-1\right| \times \frac{C_{P,h}}{\eta_P}\left(\frac{dN_h+|dN_h|}{2}\right) + C_{T,h}\,\eta_T\left(\frac{dN_h-|dN_h|}{2}\right)\right] \qquad \text{(ii)}$$

## 5. ANALYSIS AND COMMENTS

The output of the 10 initial level for the reservoirs scenarios modelling for single penstock is presented in Figure 24 in an histogram, consisting of the number of hours that the equipment operated with a given flown over the time period of dry season, where 183 days are considered. The histogram suggests that only 2 pumps with 0.65 $m^3/s$ of nominal flow are effectively necessary, since the maximum registered flow is of 1.28 $m^3/s$. On the other hand, the number of turbines is seemingly adequate.

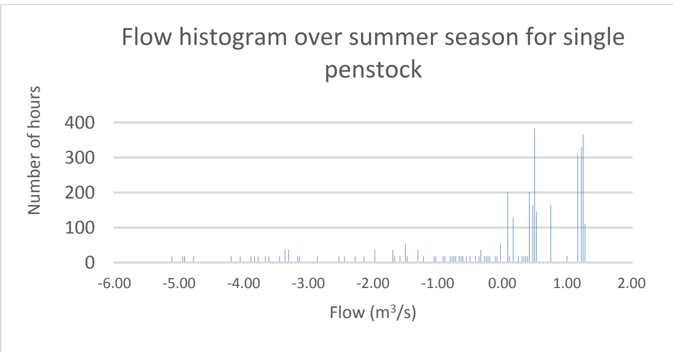


Figure 24 - Flow histogram over summer season for single penstock

A more detailed view of one of the simulated scenarios for single penstock and adjustable speed is shown in Figure 25, while Figure 26 shows the same simulation but with the use of synchronous speed equipment. By comparing the two figures, it is possible to observe that to deliver the same hourly water level variations, synchronous speed equipment must often operate with a higher flow over less time. The consequence of this is that there are gaps in which wind energy is wasted. Also, a surplus of energy over the available wind energy, must be provided by the electrical grid in order for the pump station to operate, as is indicated in Figure 26.

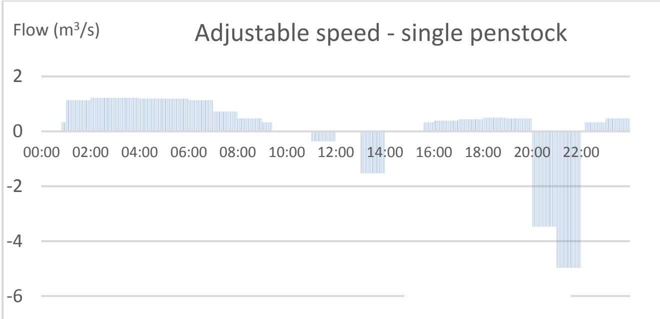


Figure 25 - Results for one scenario simulation of adjustable speed with a single penststock

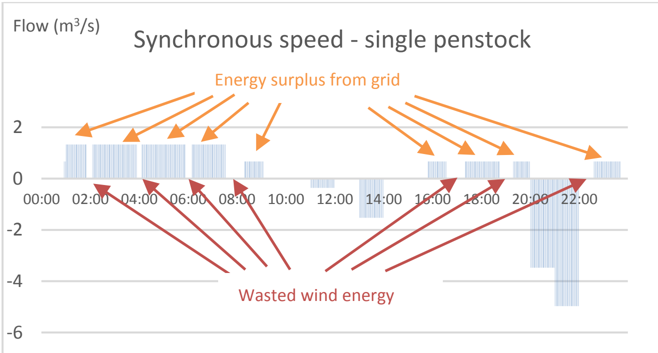


Figure 26 - Results for one scenario simulation of synchronous speed with a single penstock

The water level in the upper and lower reservoirs for the same scenario and single penstock is presented in Figure 27 and Figure 28. It is possible to identify from these illustrations the hours for which the pump and turbine stations operate, which are seemingly coherent with the previous graphics, and also with the modelling constraints.

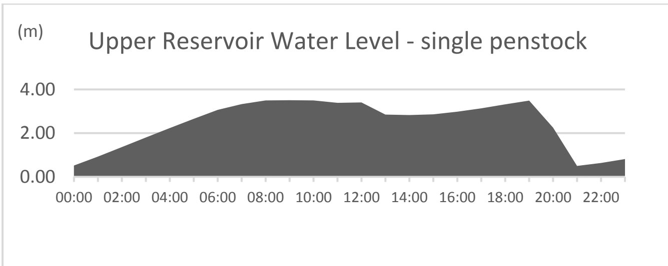


Figure 27 - Results for water level of the upper reservoir for one scenario simulation of single penstock

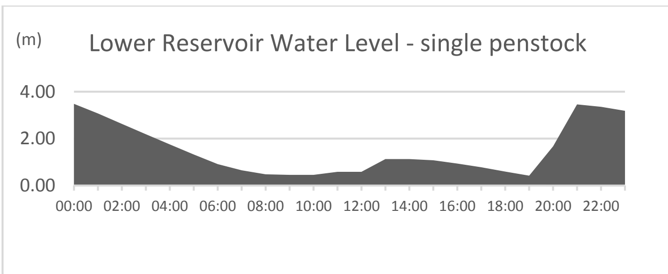


Figure 28 - Results for hourly water level of the lower reservoir for one scenario simulation of single penstock

The histogram for double penstock is presented in Figure 29, while an overview for one scenario of adjustable and synchronous speed equipment is shown in Figure 30 and Figure 31, respectively. The same behavior as single penstock is largely observed in pumping operation, shown in blue, indicating that 2 pumps of 0.65 m³/s of nominal flow would be sufficient. Because more water is pumped to the upper reservoir, due to the permanent availability of pumping operation, there is enough for the turbine station to operate at maximum capacity while maintaining the modelling constraints. It is also possible to observe that, similarly to the case of single penstock, adjustable speed technology allows for more wind power to be absorbed, while only using wind energy to feed the pumps.

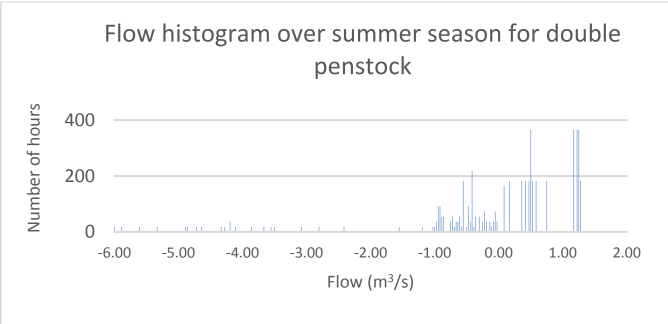


Figure 29 - Flow histogram over summer season for double penstock

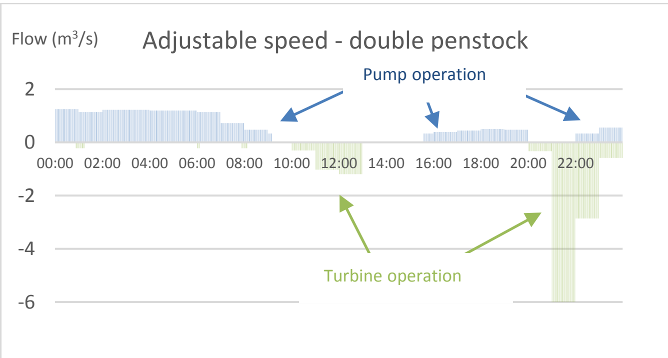


Figure 30 - Results for one scenario simulation of adjustable speed with double penststock

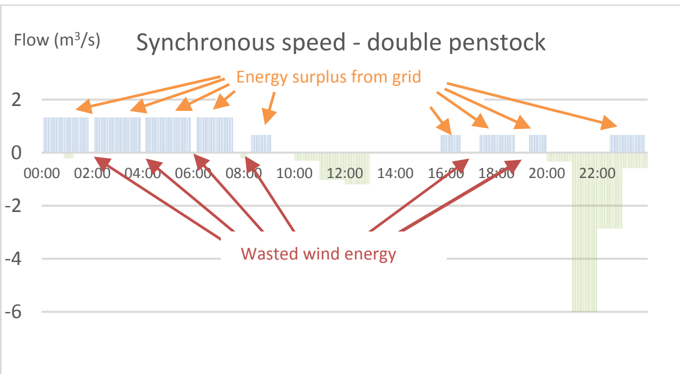


Figure 31 - Results for one scenario simulation of synchronous speed with double penstock

Figure 32 and Figure 33 show the upper and lower reservoir water levels throughout the simulation of the same scenario, where it is possible to observe that the modelling constraints are respected.

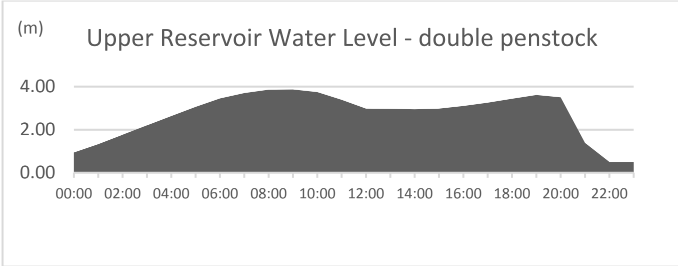


Figure 32 - Results for hourly water level of the upper reservoir for one scenario simulation of double speed

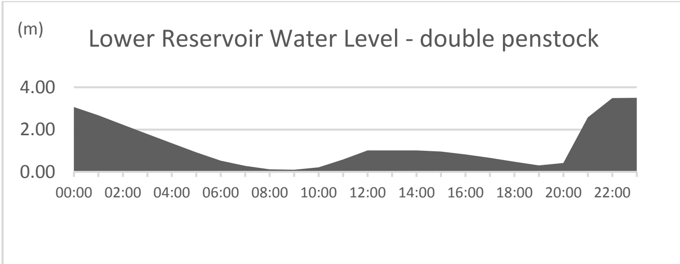


Figure 33 - Results for hourly water level of the lower reservoir for one scenario simulation of double speed

Taking into account the efficiency for adjustable and synchronous speed pump equipment, it is no surprise to observe in Table 5 that adjustable speed pumping spends more energy than synchronous speed. However, jumping to the conclusion that adjustable speed is therefore less profitable is a mistake, for there are other expenditures to be accounted for. Table 6 shows the results for the surplus of energy that synchronous speed equipment require, while Table 7 shows the percentage of wind energy that each technology can absorb. This surplus is directly taken from the electrical grid and, as so, comes at a cost.

It is remarkable that adjustable speed is able to absorb more wind energy with a single penstock than synchronous speed is with a double penstock, as Table 7 shows. As so, even though it consumes more energy overall, adjustable speed avoids the waste of fossil fuel generation by absorbing more wind power.

The combination of a double penstock with adjustable speed equipment absorbs as much as 97% of the available wind energy, which is a clear indication of its adequacy to off grid systems, such as existent in isolated regions. The total balance of costs and revenues by technology is shown in Table 8. With this table, it is clearer that adjustable speed can offer a globally more profitable solution. Not only does it generate more revenues, it absorbs more wind energy, a step closer to an ideal situation in the electricity generation.

Another conclusion to be made is that a double penstock can be less profitable than a single one, which suggests that it is only suitable for isolated regions or off the gird connections.

There are another expenditures that are not accounted for in this study which could further justify the use of adjustable speed technology, which are spinning reserves capacity from fossil fuel avoidance, and consequently GHG emissions avoidance, and the ability to provide frequency and load balance control to the grid while in pump mode

Table 5 - Results for Energy balance by technology

| Energy balance by Technology | | | | | | |
|---|---|---|---|---|---|---|
| | Pump | | | | Turbine | |
| | Single Penstock | | Double Penstock | | Single Penstock | Double Penstock |
| | Adjustable | Synchronous | Adjustable | Synchronous | - | - |
| **Summer season (GWh)** | -11308 | -10697 | -13351 | -12595 | 8507 | 9917 |
| **Electricity Tariff (€)** | 0.0724 | 0.0724 | 0.0724 | 0.0724 | 0.1027 | 0.1027 |
| **Costs/revenues (€)** | -818725 | -774493 | -966631 | -911849 | 873709 | 1018461 |

Table 6 - Results for Energy surplus by technology

| | Energy Surplus by Technology | | | |
|---|---|---|---|---|
| | Single Penstock | | Double Penstock | |
| | Adjust | Synch | Adjust | Synch |
| **Daily (kWh)** | - | 10 584 | - | 12 421 |
| **Dry season (kWh)** | | 1 936 809 | | 2 273 024 |
| **Costs (€)** | | 70 112 | | 82 283 |

Table 7 - Results for Absorbed wind energy by technology

| | Absorbed Wind Energy by Technology | | | | Total Available Wind Energy |
|---|---|---|---|---|---|
| | Single Penstock | | Double Penstock | | |
| | Adjust | Synch | Adjust | Synch | - |
| **Daily (kWh)** | 55 129 | 45 265 | 64 012 | 53 478 | 65 950 |
| **Dry season (kWh)** | 10 088 642 | 8 283 505 | 11 714 192 | 9 786 434 | 12 068 777 |
| **Total percentage** | 0.84 | 0.69 | 0.97 | 0.81 | - |

Table 8 -Results for Costs/Revenues balance by technology

| Costs/Revenues Balance by Technology | | | | |
|---|---|---|---|---|
| | Single Penstock | | Double Penstock | |
| | Adjustable | Synchronous | Adjustable | Synchronous |
| **operation (€)** | 54 984 | 99 217 | 51 830 | 106 612 |
| **surplus (€)** | - | -70 112 | - | -82 283 |
| **total (€)** | 54 984 | 29 104 | 51 830 | 24 328 |

## 6. FINAL CONCLUSIONS

PHS is the element that will allow for RES to safely increase its penetration in electrical grids, without compromising security or requiring the use of added spinning reserves, while making them a more competitive energy source. The storage of energy allows PHS to regulate load diagrams, absorbing the variability that is introduced by RES, and distributing it through time. Some improvements can be implemented to PHS systems, namely the use of adjustable speed equipment, or the use of a separate penstock for the pumping and turbining operations. These alterations can increase the overall system ability to provide ancillary services and absorb RES energy that would otherwise go to waste, which results in a cut in costs and in a potential reduction in GHG emissions.

The case study presented confirmed the claims of the initial study. With the introduction of the Multiple Purpose Socorridos System, safe renewable penetration was increased by 17 MW, corresponding to a GHG emissions reduction of 27 600 tonnes of $CO_2$ (carbon dioxide), 116 tonnes of $SO_2$ (sulfur dioxide), 478 tonnes of $NO_x$ (nitric oxide) and 7 tonnes of particles. In conjunction with the Calheta Hydroelectric Reversible System - Calheta III, renewable production is expected to reach 30% of the electricity production share, which results in the reduction of spinning reserve, avoiding 81 400 tonnes of fuel oil importing, corresponding to a 3.8 M€ savings per year, and to an avoided emission of 253 000 tonnes of $CO_2$.

The optimization algorithm further enlightens the potential for improvement by using adjustable speed equipment, with the results showing that it absorbs 15% more wind energy with a single penstock, and 16% more with a double penstock. By avoiding the use of a surplus of energy provided by the electrical grid, it can be over twice as profitable with a double penstock, and just under two times as profitable with a single penstock. Furthermore, results show that the use of adjustable speed combined with a double penstock is the ideal setting for an off the grid system, since it absorbs 97% of the available wind energy.

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