AN INTEGRATED COMPUTATIONAL METHOD FOR THE OPTIMUM SIZING OF A WIND-BASED PUMPED HYDRO STORAGE SYSTEM

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Abstract

The electricity generation in the Aegean Archipelago islands is determined by increased electricity production costs due to its dependency on imported oil. On the other hand, these islands are favored with considerable wind potential that encourages the realization of wind energy projects. However, due to the stochastic behavior of wind, the respective electricity generation cannot always provide firm capacity to an autonomous electrical power system. To encounter the existing situation, system operators are obliged to limit wind power penetration, this resulting in significant wind energy curtailments. In an attempt to face these problems, the idea of an integrated water pumping energy storage strategy is examined. To investigate the optimum size of a Pumped Hydro Storage (PHS) system, an integrated computational algorithm is developed, based on a well-established sizing procedure methodology that also considers boundary conditions. The numerical code is prepared in "Visual-Basic" environment and a user-friendly computational tool is created, presenting among others the hourly operational status as well as the annual energy yield of the plant. Finally, an application of the proposed numerical code is presented, based on real data like the long-term renewable energy curtailments of existing wind parks (operating in a representative North Aegean island) and the operational characteristics of the PHS system components. By applying the proposed numerical code, the operational parameters of a PHS system may be investigated in detail, while based on the application results obtained, the ability of the wind energy to remarkably contribute in the remote islands' energy balance is illustrated.

Keywords: Wind Energy Curtailments; Hybrid Systems; Pumped Hydro Storage; Island Electrical Grids

1. Introduction

Remote regions and isolated areas such as several islands encountered in the Aegean Sea (Greece) face considerable infrastructure limitations that hinder the local communities' development. Among these limitations, electrification problems -mainly owed to the fact that most of these areas comprise small scale autonomous electrical grids- are quite usual. The common practice applied to cover electricity demand in these regions calls for the operation of Autonomous Power Stations (APSs) based on oil-fuel imports and diesel electric generators. As a result, the vast majority of the specific power stations exhibit high electricity production costs [1] (approaching 0.25€/kWh), in direct relation with the oil-dependence noted [2]. On the other hand, there is a constant annual increase of the local electricity demand, at an average rate of 5% [2,3], and a highly variable seasonal load [3] that is hard to confront (i.e. summer demand appears to be considerably higher due to tourist arrivals), both determining the electricity pattern of the entire area and the requirements accruing for the local electric generators. In this context, an argument may be made that in order to satisfy the future electricity needs of the local consumers in an environmentally friendly and cost-effective way, an alternative electricity generation plan must be implemented.

Taking into account that the wind energy potential of the entire Aegean Sea is of high quality [4], exploitation of wind power may under certain conditions suggest an alternative, cost-effective electricity generation solution [5]. Nevertheless, based on the up to now experience, technical minima and dynamic stability problems [6] prescribe the enforcement of upper limits to the instantaneous wind energy penetration, set by the local network administrators. It is these penetration limits that along with the stochastic availability of wind and the high variability of electricity demand result to remarkable wind energy curtailments that question the financial viability of operating wind farms [7] and discourage any future investments. To solve the problem encountered and establish wind power as a trustworthy electricity generation solution, the recovery of wind energy curtailments is prerequisite. A widely applied solution concerns the implementation of appropriate energy storage systems [8], able to largely exploit any wind energy surplus.

For considerable exploitation of wind energy curtailments bulk energy storage technologies such as Pumped Hydro Storage (PHS), offering the necessary energy storage capacity should be first considered. Optimum sizing of these systems may remarkably improve the interaction between wind power and the local grid, thus allowing for the improvement of economic performance as well. To obtain optimum PHS configurations, an integrated computational algorithm is currently presented. The algorithm is based on a well-established sizing methodology that also considers boundary conditions, while the respective numerical code is prepared in "Visual-Basic" environment. A user-friendly computational tool is eventually created that provides among others the hourly operational status and the annual energy yield of the plant. Finally, the use of real data such as the long-term renewable energy curtailments of existing wind parks (operating in a representative North Aegean island) and the operational characteristics of a typical PHS system’s components allows for the validation of the proposed numerical code.

2. Position of the Problem

As already made clear, the problem investigated in the present study concerns the optimization of a PHS system used for the maximum exploitation of wind energy curtailments in an autonomous island network. The methodology currently developed is presented in the following paragraphs and is accordingly applied to a representative North Aegean island, i.e. the island of Lesbos (Figure 1). The island of Lesbos is located on the North-East side of the Aegean Archipelagos, comprising also the third biggest Greek island, with an area of 2,154 km^2 and a permanent population of 108,000 inhabitants, presenting an increase of 4% between the two last censuses (1991 and 2001). Note that apart from the fact that Lesbos comprises a large-scale island, its capital, Mytilene, is the administrative centre of the North Aegean Prefecture. The local economy is based on rural production and tourism, while the island lacks any indigenous fossil energy resources, thus largely depending on energy imports to cover the local population and the tourist needs.

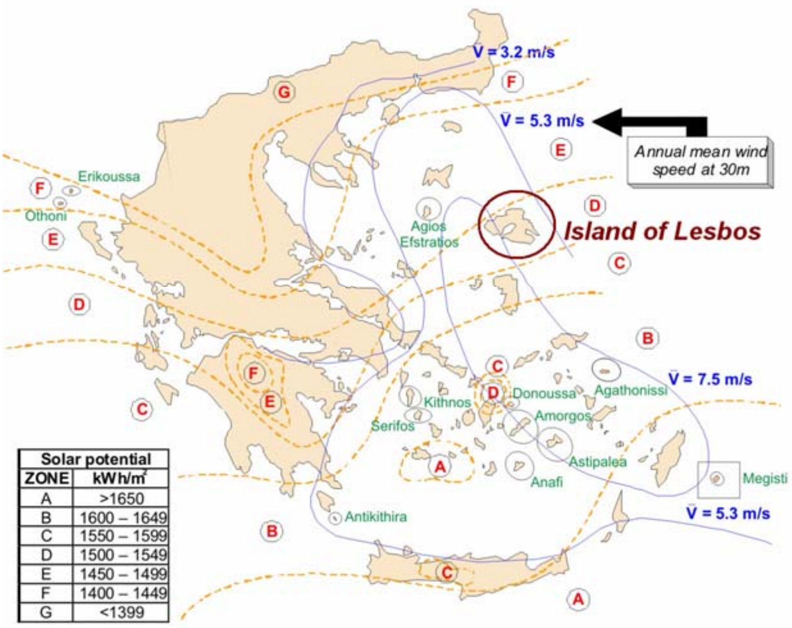

Figure 1: Location of the Lesbos island

On the other hand, the island appreciates excellent wind speeds and considerable solar potential during the entire year [4], both designating the opportunity for the employment of RES technologies. Nevertheless, the up to now electricity generation system is based on the operation of 80MW of thermal power stations and only 12MW of installed wind power capacity. In fact, the existing APS's operation is found responsible for the consumption of approximately 60,000tn of oil-fuel imports on an annual basis, entailing also the emission of severe air pollutants that considerably diminish the quality of the local environment [9]. In this context, one should also note that the local APS comprises of eight quite old internal combustion engines that mainly operate on heavy-oil (mazut) and one gas turbine consuming diesel-oil, with the corresponding real maximum power available dropping from 80MW (i.e. the official rated power of the APS) to 60MW. Additionally, the specific fuel consumption (SFC) of the existing internal combustion engines varies between 0.2 and 0.25kg/kWh, while the local gas turbine presents an average SFC value of 0.35kg/kWh.

Contrariwise, there are four wind parks operating on the island (three of medium size and one of small-scale), with a total capacity of 12MW. The operation of the small scale wind park, owned by the Mytilene Municipality, dates back to 1995, while during 1997, its rated power was increased from 600kW to 825kW. According to the official data for the period 1995-2004 [10], the corresponding long-term average value of the wind park capacity factor (CF) was slightly above 12.5%. However, during 2003 major failures were encountered for the two HMZ-300 wind turbines with the second wind turbine being completely destroyed. Since then the only machine operating is a Micon-225kW. The second wind park of the island was installed in 1999 by the Greek PPC. Nine V-27 wind turbines of 2025KW total were added to the wind power capacity of the island. Although the park did present an efficient operation during the first two years [10], in 2002 one of the machines broke down and three others presented serious malfunctions. It was in 2004 that the problems encountered in the three wind turbines were solved, thus leaving a total of 8 wind turbines operating (rated power of 1800kW). Finally, it was not up until recently that two private wind parks were erected on the island, 4.8MW and 4.2MW respectively. Both wind parks comprise of E-40 (600kW) wind turbines (a total of fifteen machines) while their excellent performance may be validated by CF values exceeding 35% on an annual average [10].

What should also be noted concerning the existing situation on the island is the public opposition encountered by the local inhabitants to the operation of the APS. Local people acknowledge the health risk from the resulting atmospheric pollution [9] and are actually negative even towards its relocation to a less densely populated area of the island. The environmental impacts and the negative influence on the tourist development accruing suggest main considerations for the local population. In addition to this, the annual energy contribution of local wind parks is currently not exceeding 10% [11] of the island's electricity demand, mainly owed to the disharmony noted between the wind energy production and the local electricity demand. As a result, both considerable amounts of clean wind energy are wasted (especially during low electricity demand periods [12]) and substantial financial losses for local wind park owners occur [7]. Anyhow, the considerable wind potential of Lesbos, with long term average wind speeds that even reach 9m/sec [4], cannot be neglected. The implementation of an appropriate energy storage system that may exploit a large portion of the existing wind energy curtailments may ameliorate the situation encountered and thus improve both the energy and the economic performance of local wind parks.

3. Proposed Solution

In order to ameliorate the current situation and maximize wind energy penetration in the island of Lesbos, an integrated wind-powered pumped hydro storage (wind-hydro) solution is proposed (Figure 2).The solution is based on [13,14]:

- a number of wind turbines spread over the island
- a water pump station able to absorb the wind power surplus of the system
- a small hydroelectric power plant [15] able to meet the local grid maximum demand through the recovery of wind energy curtailments and

- two water reservoir groups (an upper and a lower one) working in closed circuit along with the corresponding pipelines.

Besides, during the long-lasting operation of the proposed energy solution, the following situations may appear:

- The wind energy production is higher than the local electricity demand. In that case, any wind energy surplus is used to feed the pumps and drive water to the upper reservoir for storage. However, if the energy amount of curtailments exceeds the capacity of the pumping station or the storage level of the upper reservoir does not allow for full absorption of the wind energy surplus, the residual wind energy (i.e. the energy that cannot be stored) is forwarded to low priority loads.

- The wind energy production is lower than the local electricity demand. In that case, the energy reserves of the upper water reservoir are used to drive the existing small hydro turbines in order to cover the local electricity demand deficit.

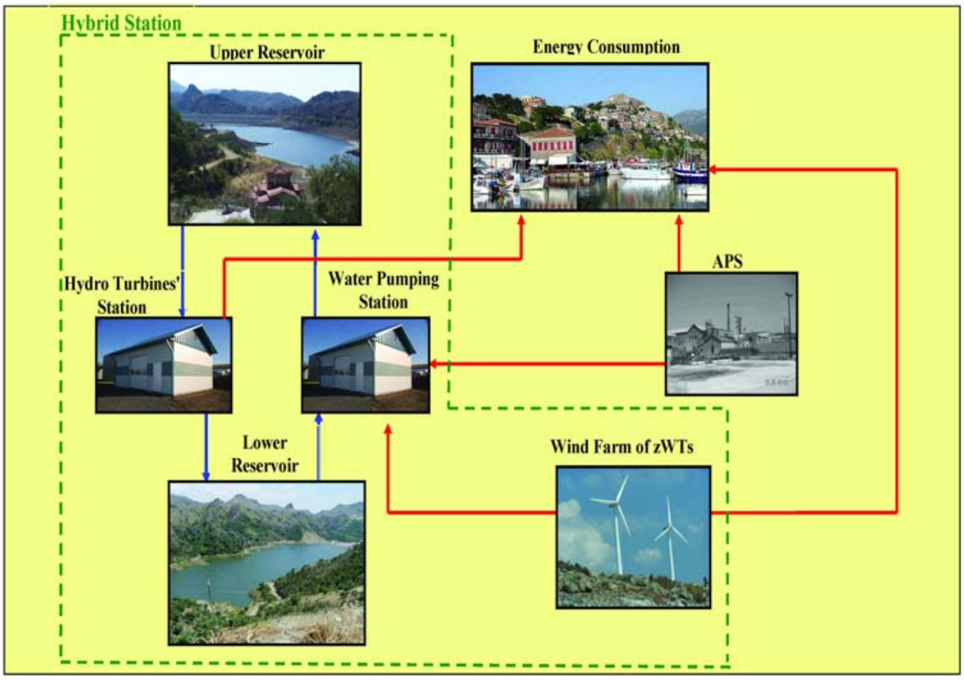

Figure 2: Proposed wind-hydro solution

For the most efficient performance of the integrated energy solution proposed, optimization of the employed PHS system is currently undertaken. Real data of long-term renewable energy curtailments of existing wind parks and operational characteristics of the PHS system components are both used for applying the developed sizing methodology according to the following steps.

- **Estimation of the existing wind parks' curtailments**: To obtain the exact amount of wind energy curtailments one must compare the actual wind power production of local wind parks with the recorded wind power absorbed by the local electrical grid. Using the available analytical wind speed measurements and estimating the power curve of local wind parks, the actual wind power production may be calculated. Based on the aforementioned comparison, detailed wind energy curtailments may be produced (Figure 3).

- **Calculation of the grid's capability concerning wind power penetration**: In order to determine the maximum wind energy absorption from the local grid on an annual basis and therefore the opportunity of adding extra wind power on the island, the annual hourly mean power production time series were modelled according to the synthesis of the island's existing thermoelectric production system. For this purpose, the characteristics of all the thermal units are taken into account, such as their technical minima, specific fuel consumption and incorporation sequence into the production procedure. According to the thermal units' technical minima, their incorporation sequence into the production procedure and their SFC, the maximum and the minimum electric power production are estimated. The wind power penetration ability is equal to the difference between the load demand and the minimum electric power provided by the on duty thermal engines, which are the on duty thermal engines' technical minima [6,16].

- **Determination of PHS optimum size:** To obtain optimum PHS configurations, an integrated computational algorithm is currently presented (Figure 4). The algorithm is based on a well-established sizing methodology that also considers boundary conditions, while the respective numerical code is prepared in "Visual-Basic" environment (Figure 4). A user-friendly computational tool is eventually created that provides among others the hourly operational status and the annual energy yield of the plant.

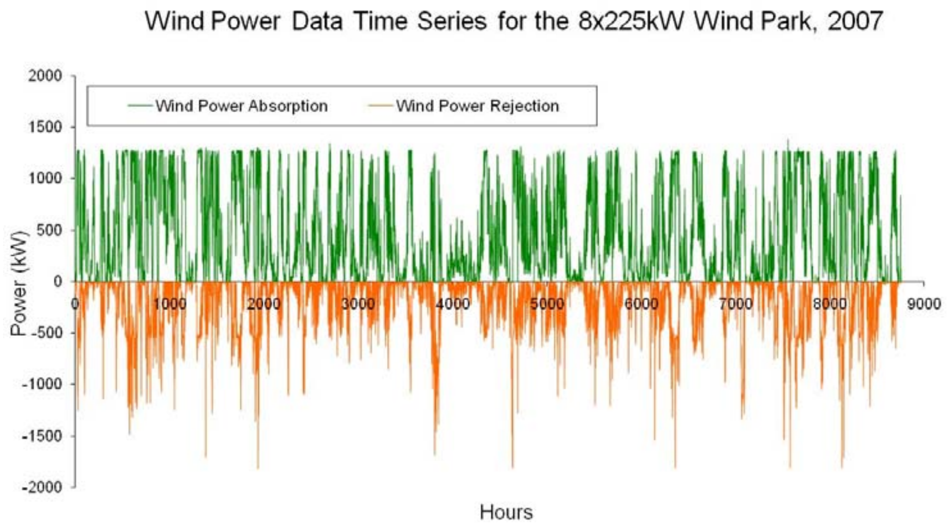

Figure 3: Profile of wind energy curtailments and wind energy absorbed by the local network

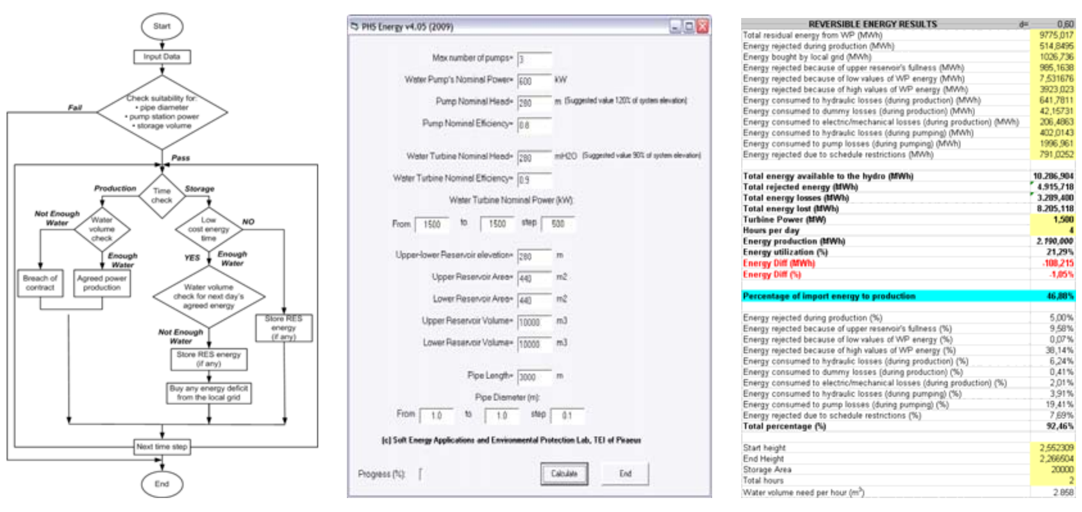

Figure 4: Proposed algorithm; input and output screens of the computational tool

Finally, note that in the specific case study the pattern of guaranteed energy production by the PHS system on a daily basis, i.e. during certain periods of the day, is currently adopted. More precisely, the developed numerical code is applied using different values of daily guaranteed energy provided to the local electricity grid at peak hours, for both existing and future wind park installations (an increase in the wind power capacity is considered). In case that the water stores cannot fulfill the condition of guaranteed energy delivered to the local grid, the proposed PHS system interacts with the local grid and absorbs any energy deficit during low consumption periods (i.e. from1:00 am to 8:00 am).

4. Application Results

The methodology previously analyzed is currently applied to the electrical network of Lesbos, considering installed wind power capacity equal to 18MW. Based on the comparison between the actual wind energy production and the corresponding wind energy penetration (30% limit is presently adopted for wind energy penetration to the local grid), wind energy curtailments may easily be obtained. Using the results of these wind energy curtailments for a certain time period investigated, both the frequency and the cumulative probability may be drawn (Figure 5). According to the figure, the most frequently rejected wind power ranges between 9MW and 10MW, while if considering the cumulative probability of rejected wind energy the dimension range of the PHS main system components may be narrowed down as well (e.g. there is no point in operating a pumping station greater than 12MW) [11].

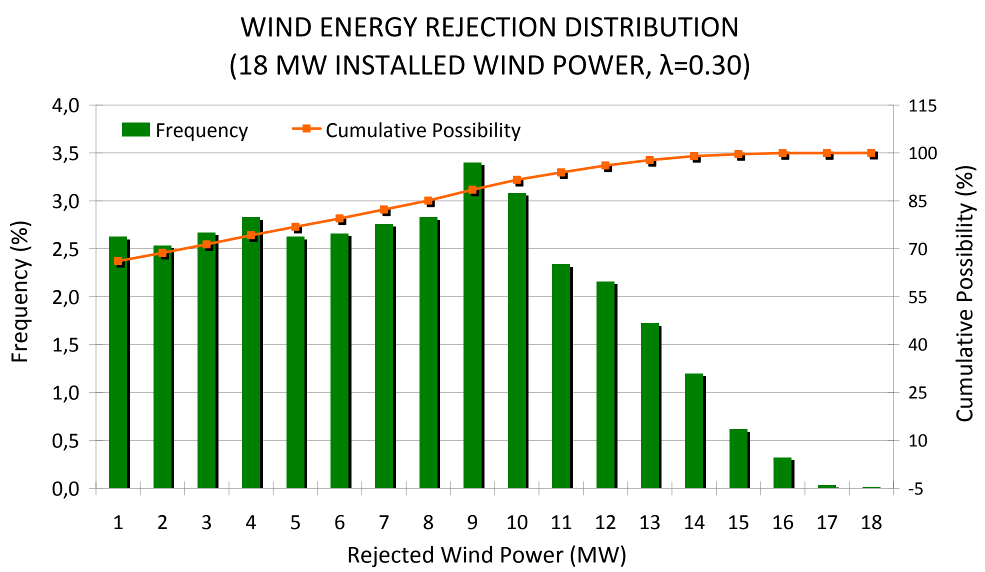

Figure 5: Distribution of wind energy curtailments

Proceeding to the parametrical analysis of the problem, in Figure 6 one may obtain the effect of the upper reservoir's size on the resulting recovery of wind energy curtailments for different hydro turbines' power. Note that recovery is directly related to the energy provided to the local grid by the employed hydro turbines, i.e. the product of the hydro turbines' station average output power for a given time period of operation and the hours of operation. In particular, a four hours' energy production per day case is analyzed (during the peak period), while the pumping station size is predetermined at 9MW.

As shown in the figure, by increasing the volume of the upper reservoir, wind energy absorption is enhanced. In fact, by tripling the minimum selected upper reservoir size (3xV_{upmin}), the increase of wind energy absorption exceeds 40% in all cases; the most pronounced encountering the recovery of more than 8GWh (4.5MWx4h case). So, what may be noted here is that the effect of the upper reservoir becomes stronger in cases of higher guaranteed power. On the other hand, when considering the 6MWh guaranteed energy case (1.5MWx4h), the increment of the wind energy absorbed is gradually reduced, clearly showing that there is a limit on the absorbed wind energy for a given system component size, the same applying to the 3MW and the 4.5MW cases as well.

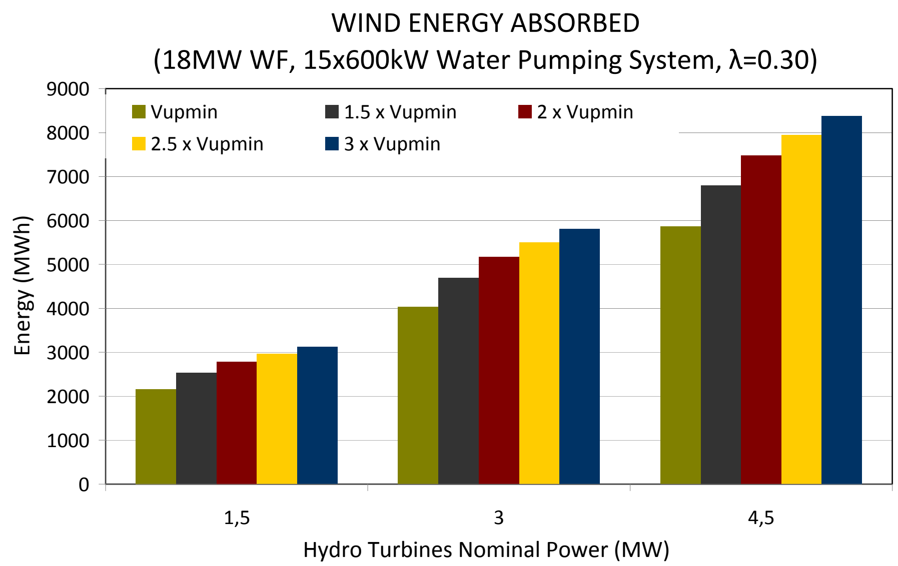

Figure 6: Wind energy exploitation Vs the variation of the hydro turbine and the upper reservoir size

Furthermore, in Figure 7 one may also obtain the percentage of wind energy curtailments recovered by the PHS system. As it may be concluded, by limiting the power of the hydro station, the impact of increasing the upper reservoir's size is minimized. On the contrary, by allowing the employment of a bigger-scale hydro station, exploitation of more water stores available is not restricted by the limited power of the hydro turbines. In fact, there is a marginal difference noted in the case of 1.5MW between doubling and tripling the upper reservoir size, gradually increasing to reach 4% in the case of 4.5MW. Besides, achieving approximately 40% of wind energy recovery for a 4.5MW hydro power plant is considerably greater than the corresponding 15% concerning the 1.5MW hydro power case, this clearly showing the dominant role of the hydro turbine power parameter.

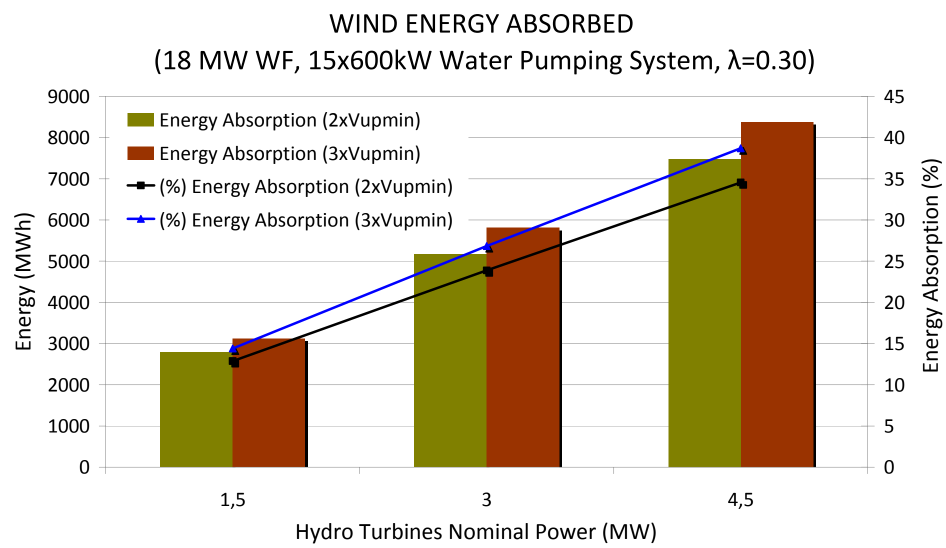

Figure 7: Percentage of wind energy exploitation Vs the variation of the hydro turbine and the upper reservoir size

The proposed algorithm is accordingly applied for a 3MW hydro turbine and a constant volume upper reservoir (double the minimum), while the pumping station size varies from 4.8MW to 10.2MW. The calculation results regarding the absorption of wind energy by the PHS system are given in Figure 8. As it may be concluded from the figure, there is a gradual increase of wind energy absorbed by the system (reaching approximately 5.17GWh), up to the point of 9MW, followed by almost constant numbers for higher pumping power values. Besides, in the specific figure the percentage of energy imports by the local grid in order to satisfy the guaranteed energy condition is also provided, currently ranging between 40% and 50% (i.e. 1800MWh and 2200MWh respectively).

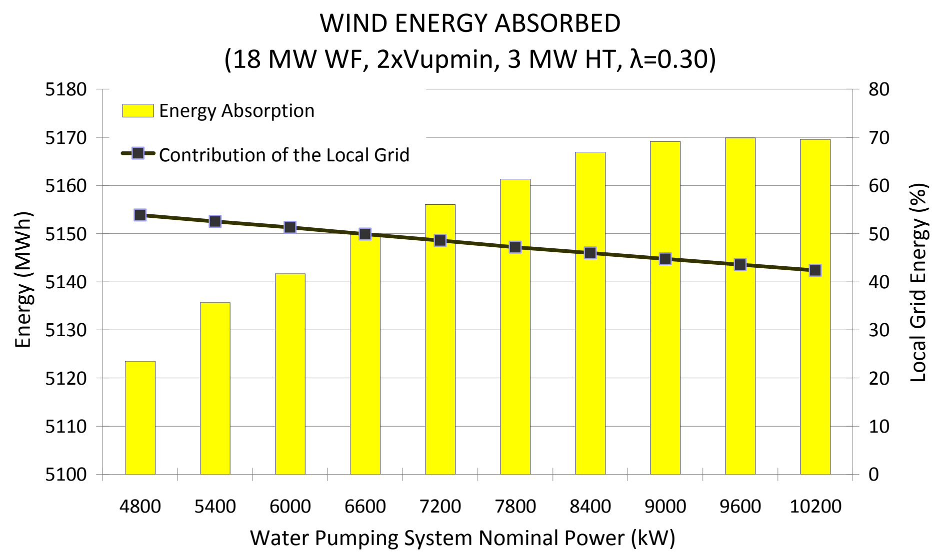

Figure 8: Wind energy exploitation Vs the variation of the water pumping station's power

Similar results may be obtained in case that the volume of the upper reservoir is reduced to its minimum size. However, in case that "V_{upmin}" is used, the absorption of rejected wind energy drops by more than 20% (if a comparison is undertaken between Figure 9 and Figure 10), i.e. from 5.17GWh to 4.03GWh, while the power of water pumps corresponding to the almost maximum wind energy absorption is now reduced to 8.4MW. What is configured therefore is that by providing a larger reservoir, the ability of the pumping station to absorb wind energy curtailments is stretched, potentially rationalizing even the use of a 9MW water pump station. Nevertheless, for the argument to be validated a complete cost-benefit analysis is required [17], this however comprising the subject of a forthcoming study.

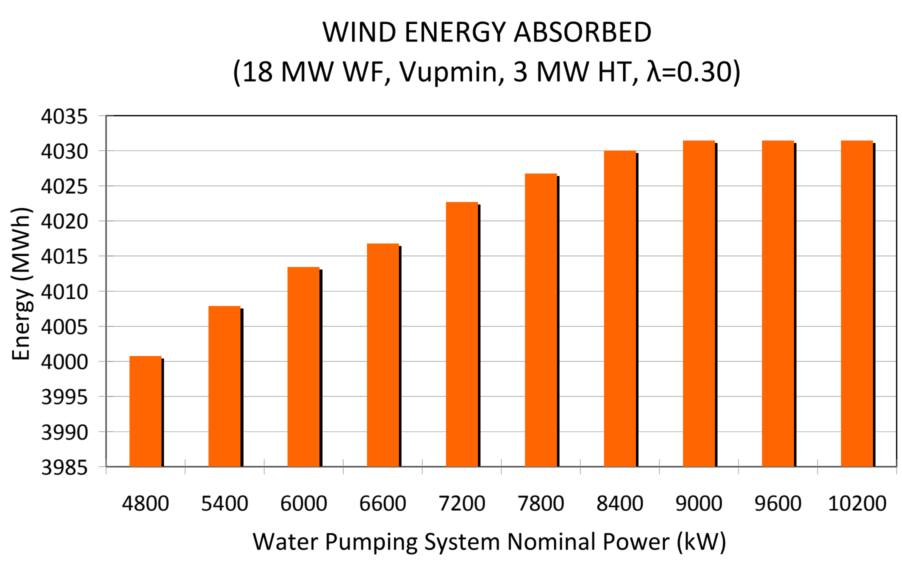

Figure 9: Wind energy absorption in relation to the variation of the water pumping system power (V_{upmin})

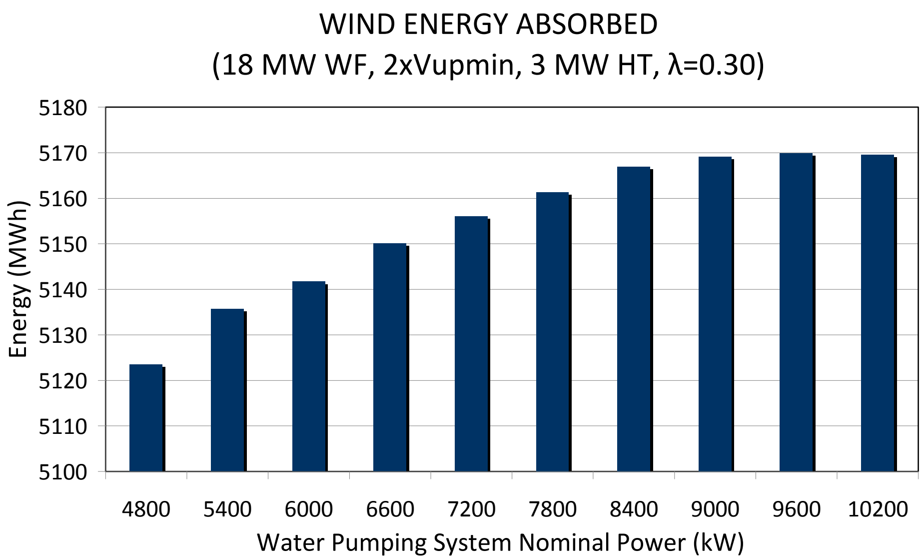

Figure 10: Wind energy absorption in relation to the variation of the water pumping system power (2xV_{upmin})

5. Conclusions

A properly sized pumped hydro storage station collaborating with a corresponding wind park may comprise a considerable integrated energy solution for the electrification of remote islands on the basis of wind potential exploitation. More precisely, the proposed solution utilizes the rejected wind energy that cannot be absorbed by the local network in order to replace heavy polluting gas turbines and diesel-oil engines. In this context, an integrated numerical algorithm is developed that is able to estimate the optimum size of the PHS installation on the basis of wind energy absorption criteria. The numerical algorithm currently established is thought to comprise a reliable calculation tool that may efficiently perform the corresponding energy related analysis. Note that the algorithm has been designed to cover guaranteed electrical energy on a daily basis, while in absence of sufficient wind energy rejection electrical energy is provided to the system by the local grid during low consumption periods.

By applying the proposed numerical code, the operational parameters of a PHS system may be investigated in detail, while based on the application results obtained, the ability of wind energy to remarkably contribute in covering the remote islands' energy demand via the implementation of PHS systems is well reflected. Based on the investigation of the PHS main parameters, their effect on the resulting wind energy exploitation has been configured; nevertheless these initial results are not sufficient to designate optimum configurations since a complete cost benefit analysis is required to determine the best outcome.

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