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Contribution of pumped hydro energy storage for more RES utilization on autonomous power systems

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Abstract. This paper addresses the performance issues of autonomous power systems under high renewable energy sources (RES) penetration. Renewable energy sources could be the main option for isolated power generation at remote locations in case that energy storage introduced. At the moment, pumped hydro storage (PHS) units and batteries storage systems (BSS) represent the most mature technologies for large scale energy storage. The basic criteria for this kind of energy storage unit installations include, (a) the existence of an autonomous power system with local power stations, (b) the high electricity production cost, (c) the potential of renewable energy sources (mainly wind and solar), and (d) the non-flat terrain morphology (for PHS). Greek islands represent ideal cases for large scale energy storage installations, as they fulfil all the above criteria. This paper shows the effect of the installation of a planned PHS unit in Crete island. The calculations are based on real data provided by the Cretan power system operator, whereas the results show the effect of energy storage units operation on the energy mix, as well as the economic viability of the project, which is combined with significant environmental benefits.

Key words: Isolated power systems, energy storage, pump hydro systems, renewable energy sources.

INTRODUCTION

Currently diverse challenges have emerged, such as climate change, economic recession, and security of energy supply. Furthermore, the rapid depletion of fossil fuels and their high and volatile prices have necessitated an urgent need for alternative energy sources to meet the corresponding energy demands (Ilić et al., 2011). Renewable energy sources (RES), such as wind and solar, are clean, inexhaustible and environmental-friendly alternative energy sources with negligible fuel cost (Kymakis et al., 2009). However, RES technologies, such as wind turbines (WTs) and solar photovoltaics (PVs), are dependent on a resource that is unpredictable and depends on weather and climatic changes, and the production of WTs and PVs may not match with the load demand (Annuk et al., 2011a; Annuk et al., 2011b), so there is an impact on the reliability of the electric energy system. This reliability problem can be solved by a proper combination of the two resources (WTs and PVs) together with the use of an energy storage system, such as batteries, as a type of energy-balancing medium (Brekken et al., 2011).

The Greek power system consists of the mainland interconnected system, which consumes the largest portion of total electricity demand (≈ 90%), and a large number of isolated autonomous power systems, with the vast majority of them located in the Aegean Archipelago islands (Hatziargyriou et al., 2006). In most of these systems, the cost of electricity production is much higher than in interconnected systems due to the high operating costs of their thermal generating units, mainly diesel and gas turbines, and the import and transportation costs of the fuel used.

More of these islands present significant wind and solar potential, which make ideal the exploitation of these renewable energy sources by using technologies such as wind turbines (WTs) and photovoltaics (PVs), and significant progress has been made till now. These technologies, when installed properly, may provide significant benefits to the system (Papadogiannis et al., 2009). Unfortunately, production fluctuation from RES may not match the demand. Usually, the demand is higher in early night hours, with simultaneous decrease in case of solar power production.

In such systems, contrary to interconnected ones, mismatches in generation and load and/or unstable system frequency control might lead to system failures much easier. Increased share of intermittent RES, may be economically attractive (Tsikalakis et al., 2003) but unless special precautions are made, dynamic security of the whole system may deteriorate (Karapidakis & Hatziargyriou, 2002).

Energy storage may be an interesting solution to alleviate technical barriers for increasing intermittent RES penetration. One of the main disadvantages of energy storage is its high initial cost. However, when sized properly, energy storage can provide an economically viable solution, especially in the cases of autonomous power systems that present high operating costs.

Although many technologies are available for energy storage, pumped hydro storage (PHS) represent the most mature technology for large scale energy storage. This paper includes a brief presentation of PHS technology, analyses the effect of the installation of the examined PHS unit in Crete island and concludes with the main considerations and results of the analysis.

MATERIALS AND METHODS

A wide variety of energy storage technologies are commercially available and include PHS systems, rechargeable batteries, flow batteries, and compressed air. Potential benefits include capacity reduction, frequency support, standing reserve provision and black start capability. Depending on technical requirements and geographical settings, a particular utility may avail of one or more of these technologies. Research effort has also focussed on ultra-capacitors, high-speed flywheels and superconducting magnetic energy storage. While these are highly responsive, their energy storage capabilities are limited, making such approaches more suitable for power quality applications and for improving system reliability.

The most widely established large-scale form of energy storage is PHS. Typically, such plant operates on a diurnal basis – charging at night during periods of low demand (and low-priced energy) and discharging during times of high or peak demand. A PHS plant may have the capacity for 4–8 hours of peak generation with 1–2 hours of reserve, although in some cases the discharge time can extend to a few days. Worldwide capacity is almost 100 GW, with facilities ranging up to 2,000 MW. The high construction costs, long development times and environmental considerations (most feasible locations are already being exploited) suggest that future growth in this area will be limited. Traditionally, PHS is utilised for energy management and the provision of standing reserve, but more recent installations possess the ability to provide frequency support and operate at partial capacity (Fox et al., 2007).

Hydroelectric plants typically have fast ramp-up and ramp-down rates, providing strong regulating capabilities, and their marginal generation cost is close to zero. In many countries, a natural synergy exists between hydroelectric generation/pumped storage and wind power. Clearly, if hydro generation is being replaced by wind energy then emission levels will not be directly affected, but the hydro energy can be transformed into potential energy stored for later use. The existing hydroelectric plant can reduce their output, using the reservoirs as storage, to avoid wind energy curtailment.

PHS systems usually consist of the following parts: an upper reservoir, waterways, reversible (pump/generator) turbines or separated units of peltons and pumps as in this examined case**,** and a lower reservoir, shown schematically in Fig. 1.

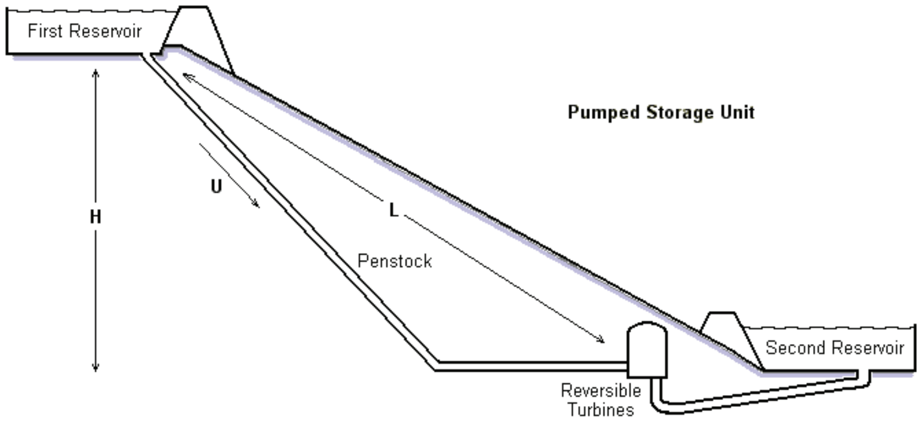

Figure 1. Components and structure of pump hydro storage system.

As in any hydraulic system, in PHS there are losses during operation, such as frictional losses, turbulence and viscous drag, and the turbine itself is not 100% efficient. The water retains some kinetic energy even when it enters the tailrace. For the final conversion of hydro power to electricity, generator losses have to be also accounted. The overall efficiency of a PHS system is defined as the ratio of the energy supplied to the consumer while generating, and the energy consumed while pumping, and it usually lies in the range of 65–75%.

Unit commitment is a very significant optimization task, which plays a major role in the daily operation planning of power systems, especially in the framework of the deregulated power markets. The objective of unit commitment is to minimize the total operating cost of the generating units during the scheduling horizon, subject to a number of system and unit constraints. The overall problem can be divided into two sub-problems: the mixed-integer nonlinear programming problem of determining the on/off state of the generating units for every hour of the dispatch period (usually 24 hours) and the quadratic/cubic programming problem of dispatching the load among them. The simultaneous solution of both problems is a very complicated procedure, the difficulty of which grows proportionally to the number of units and constraints taken into consideration (Simopoulos et al., 2006; Katsigiannis & Karapidakis, 2007).

The total operating cost of the generating units consists of Fuel costs, Start-up costs and Shut-down costs. Fuel costs are calculated using unit heat rate and fuel price information. The use of dual fuels for flame stabilization when the unit operates at low output levels, for example during start up ramps, further complicates the fuel cost computation. Start-up costs are expressed as a function of the number of hours the unit has been down (exponential when cooling and linear when banking). Shut-down costs are defined as a fixed amount for each unit per shut-down. The constraints which must be satisfied during the optimization process are (Kazarlis, 1996):

- *System constraints*: They include system power balance (demand + losses + exports), and system reserve requirements.
- *Local constraints*: They include unit initial conditions, unit high and low power limits (economic, operating), unit minimum-up time, unit minimum-down time, unit status restrictions (must-run, fixed-MW, unavailable, available), unit rate limits, unit start-up ramps, unit shut-down ramps, unit flame stabilization fuel mix, unit dual or alternate fuel usage, unit or plant fuel availability, and plant crew constraints.

On the island, in many locations average wind speed is higher than 8.5 m sec^{-1}. Moreover, Crete presents one of the highest solar potentials in whole Europe reaching up to 2,100 kWh m^2 per yr. These characteristics make Crete ideal for the installation of wind and solar technologies. As a result, already 33 wind farms have been installed with rated power of 187.1 MW. Moreover, Cretan topology is quite suitable for PHS installation. The terrain is very mountainous with altitudes more than 2 km. Additionally, more than 1,000 small PV parks (mainly of 80 kW each) and 1,800 roof PVs have been installed, reaching a total of 95.5 MW. Table 1 presents the percentage of annual energy production in 2015 for all installed units of the island (conventional and RES), in which RES penetration exceeds 20%. The annual load demand is almost stable within the last seven year and approximately 3T Wh.

Table 1. Characteristics of Crete Island's electricity units (year 2015)

Technology	Fuel	Annual share
Steam turbines	Mazut	36.70%
Diesel generators	Mazut	24.85%
Gas turbines	Diesel	3.85%
Combined cycle (CC)	Diesel	14.47%
WTs	-	16.03%
PVs	-	5.11%

The basic solution methods of unit commitment problem include the priority list method, dynamic programming, branch-and-bound, Lagrangian relaxation, and numerous artificial intelligence methods. In Cretan power system, the priority list method is used, which mimics the scheduling practices followed by system operators. The units are committed in ascending order of the unit average full load cost so that the most economic base load units are committed first and the peaking units last in order to meet the load demand. Priority list methods are very fast but they are highly heuristic and give schedules with relatively high production costs. Table 3 presents the main technical characteristics and priority list for Cretan power system's thermal (conventional) units.

The examined PHS system will have the ability to provide guaranteed power through three (3) hydro turbines with an installed capacity of 25 MW each (as a corresponding hydro power station with nominal output of 75 MW) for 8 hours per day, producing at least 600 MWh daily. In parallel, the system includes four (4) wind farms, with total capacity of 166 MW that aren't in the same place. This capacity will be limited to 120 MW during wind farm production, following the Greek legislative framework. The main technical characteristics of the examined project are presented in Table 2 and the basic single line diagram is depicted in Fig. 2.

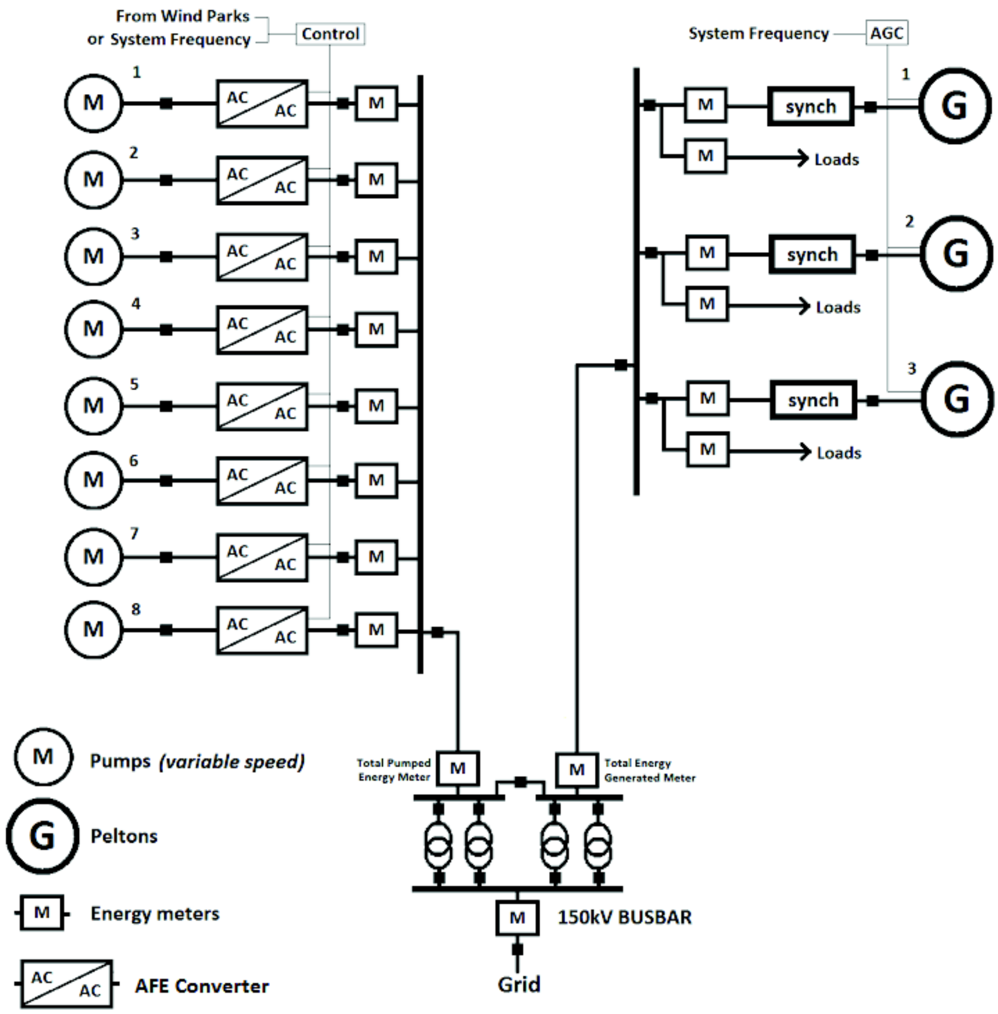

Figure 2. Single line diagram of the examined project.

Table 2. Main technical characteristics of the project

Wind Farms	
Total Installed Capacity	166 MW
Maximum Permitted Capacity (Injected)	120 MW
Pumping & Hydroelectric Station	
Pumps (8 pumps x 12.5MW)	100 MW
Hydroelectric station (installed capacity)	100 MW
Hydroelectric station (guaranteed capacity)	75 MW
Upper & Lower reservoir tank (total storage)	1,250 MWh
Upper & Lower reservoir tank (actual storage)	1,100 MWh

According to the national operational code for the non-interconnected islands (RAE, 2014), all the PHS should submit an overall daily bid of energy supply, which is available to offer in the network for the next day (24 hours time interval). By this action, the network administrator is required to absorb this energy supply prior to the energy produced by conventional units, as energy produced by RES technologies.

Furthermore, in cases that the network administrator considers that more power is needed to meet the power demand that cannot be satisfied by other production units, only then can he require from the PHS to provide the next day into the grid part or the whole of its capacity in 'guaranteed energy'. More specifically, in this case if the PHS is not able to provide the required stored energy in order to adequately meet the given requirement and cannot cover it directly from its own RES units, it has the ability to consume energy (by pumping) directly from the network during the night. This energy is considered as energy that absorbed from the network, and is billed in a different way. Table 3 shows the different billing options that exist in PHS operation, according the Greek legislative framework.

Table 3. Billing options for PHS system

Energy & Power Compensation	Revenues
Energy delivered by the hydro turbines	236 € MWh^{-1}
Energy delivered by the WFs directly to the network	100 € MWh^{-1}
Energy absorbed from the network	186 € MWh^{-1}
Power compensation availability	127,000 € MW^{-1}

RESULTS AND DISCUSSION

The results show that on annual basis the hydro turbine produces at least 220 GWh of electricity (75 MW guaranteed power for 8 hour per day for all year around). By considering a total PHS system efficiency of 72%, the electricity needed for pump operation is 304 GWh. The simulation results show that 88% of this electricity is covered from the WFs of PHS system. From the remaining produced WFs electricity, 5.5% is delivered directly to the network, whereas 6.5% cannot be absorbed.

This study used the well-known and reliable economical indices that include net present value (NPV), after tax internal rate of return (IRR with 29% tax rate), benefit to cost (B/C) ratio, simple payback and equity payback for discount rate i = 6%. The considered costs are 3,000,000 € MW for PHS system construction (without the WFs) and 1,200,000 € MW for WTs. The 75% of these initial costs are covered from a bank loan of 7% interest rate. Total annual operational and maintenance (O&M) costs are assumed to be 2% of the initial cost (these costs do not include the cost of absorbed electricity from the network). The total lifetime of the project is considered to be 40 years (Kousksou et al., 2014). Due to the fact that WFs lifetime is approximately 20 years, reinstallation of equal capacity WTs is considered during halftime of the project life.

Concluding, the conducted capital budgeting study concludes that the examined PHS project is economically viable as it is shown in Table 4. It has to be taken into account that the considerations for hydro turbine electricity production are pessimistic, so during real operation the results could be significantly improved. The environmental results show the amount of annual greenhouse gases (GHGs) emission reduction for the specific fuel mix of Cretan power system.

Table 4. Economical and environmental evaluation of the examined project

NPV	60,710,000 €
IRR (after tax)	8.8%
B/C ratio	1.49
Simple payback	10.3 years
Equity payback	11.2 years

CONCLUSIONS

In this paper, the effect of PHS units installation on the (largest in Greece) autonomous power system of Crete Island is examined. The analysis showed the significant effect of PHS units operation on the energy mix, as it produces 7.5% of total energy production in Crete (considering a modest scenario). Moreover, the analysis proved that the project is economically attractive, while it provides significant environmental benefits. The viability of this project also shows that additional PHS stations can be installed in the Cretan power system, increasing the wind power penetration and decreasing the dependence on expensive fossil fuels (diesel and crude oil). This study proves that in the majority of small autonomous power system, the target of reliable operation with high penetration of renewable technologies and low initial cost is feasible. The analysis of results showed the significant contribution of further wind turbines installations combined with energy storage, projects which will be widely applied in the near future.

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