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Article

Effect of Hybrid Power Station Installation in the Operation of Insular Power Systems

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Abstract: Greece has a large number of islands that are isolated from the main interconnected Greek power system; however, a majority of them are to be interconnected in the mainland grid over the next decade. A large number of these islands present a significant amount of wind and solar potential. The nature of load demand and renewable production is stochastic; thus, the operation of such isolated power systems can be improved significantly by the installation of a large-scale energy storage system. The role of storage is to compensate for the long and short-term imbalances between power generation and load demand. Pumped hydro storage (PHS) systems represent one of the most mature technologies for large-scale energy storage. However, their advantages have not been proven in practice for cases of medium and small-sized isolated insular systems. Regarding Greece, which contains a large number of isolated insular systems, a PHS system in the island of Ikaria started its test operation in 2019, whereas in Europe only one PHS system operates in El Hierro (Canary Islands). This paper studies the effect of installing a wind-PHS hybrid power station in the operation of the insular power system of Samos, Greece, according to the latest regulatory framework. The implemented analysis uses real hourly data for a whole year, and examines the effects of such an installation considering investors' and power system operators' viewpoints. More specifically, the economic viability of this project under different billing scenarios is compared, and its impact on the insular power system operation for various PHS sizes is examined.

Keywords: energy storage; hybrid power stations; insular power systems; pumped hydro storage; wind turbines

1. Introduction

Greek territory contains a large number of islands; the majority of these are located in Aegean Archipelagos. The submarine cable interconnection of some nearby islands to the mainland system began in the early 1960s. However, during the last decade, a procedure began to develop a sea transmission network that contains all insular systems. This network is planned to be fully developed by the end of the next decade. Currently, Greek islands consist of 32 isolated systems [1]. Regarding their peak demand, each one of these isolated systems can be included in one of the following categories: (a) "small" systems with peak demand up to 10 MW (includes 19 systems), (b) "medium" systems with peak demand from 10 MW to 100 MW (includes 11 systems), and (c) "large" systems with peak demand exceeding 100 MW (includes two systems) [2].

In many of these islands, significant amounts of wind penetration levels have been reached. Moreover, these islands present significant solar potential. As a result, significant amounts of energy can be provided by technologies that are based on renewable energy sources (RES), such as wind turbines (WTs) and photovoltaics (PVs). However, these technologies are dependent on a resource that is unpredictable and depends on weather and climatic changes, so they face increased problems related to their operation and control [3–5]. By 2017, 97 wind farms (323 MW) were in operation on all Greek non-interconnected insular systems in addition to 758 ground PV stations (136 MW), 242 rooftop PV systems (24 MW) and one small hydroelectric station (0.3 MW) [6].

More specifically, isolated insular power systems with increased RES technologies power penetration and interconnected power systems have significant differences, which include lower values of minimum to maximum demand ratio and increased stability problems, as smaller production or demand changes can lead to larger frequency deviations. Furthermore, higher uncertainties in load and RES power lead to increased spinning reserve requirements and consequently higher operating cost, whereas the technical minima of the installed thermal units often enforce limitations in RES power integration [7,8]. It is also to be mentioned that the operational cost of conventional generators in these systems can be high—in many cases and especially during peak hours they significantly exceed 200 €/MWh, while is highly dependent though on oil prices [9].

The operation of these insular systems can be improved significantly by the installation of a large-scale energy storage system [10–12]. The role of such a system is to compensate for the long and short-term imbalances between power generation and demand. More specifically, it is used to transfer energy from periods of high RES output to periods of power shortage, allowing the system to remain fully functional over a wide range of operating conditions [13–15]. It is to be noted that the installation of large scale energy storage units in interconnected systems offers significant benefits in the reduction of the amounts of rejected wind energy [16].

This paper studies the effect of installing a hybrid power station in the medium-sized insular power system at Samos Island. Hybrid power stations combine the installation and use of a large-scale energy storage technology with a renewable energy technology. During the last years, the Greek legislative framework has provided the ability to install a hybrid power station in such systems. In our case, the hybrid station combines pumped hydro storage (PHS) and WTs. The performed analysis uses real hourly data for a whole year, and studies the economic viability of this project under different billing scenarios, as well as its impact on the isolated power system operation.

The paper is organized as follows: Section 2 contains a brief description of hybrid power stations in Greece: it is mainly focused on their operation at isolated power systems and also presents interconnection plans. Section 3 provides information on the basic characteristics of the insular power system of Samos Island. Section 4 includes the basic considerations and presents the main results of the analysis, which includes economic evaluation, optimal sizing of hybrid power station, and comparison of power system operations before and after installation of hybrid power stations. Section 5 concludes the paper.

2. Operation of Hybrid Power Stations in Greek Insular Power Systems

According to the Greek legislative framework [17], a hybrid station is a power generation plant that (a) uses at least one form of RES, (b) the total amount of electricity absorbed from the Network on an annual basis does not exceed 30% of the total amount of energy consumed for the filling of the storage system of that station, and (c) the maximum output of the units of the RES station should not exceed the installed capacity of that station increased by 20% at the most.

Pumped hydro storage (PHS) units represent the most mature technology for large scale energy storage. Such a system usually consists of an upper and a lower reservoir, pump(s), hydro-generator(s), and waterways. During off-peak electricity demand hours, the water is pumped into the upper reservoir; whereas during peak hours, the water can be released back into the lower reservoir [18]. It is to be noted that hydro-generators typically have fast ramp-up and ramp-down rates, providing strong regulating capabilities, and their marginal generation cost is close to zero. Figure 1 shows the structure of a hybrid power station that uses wind power (typical case) and is connected to the electricity grid.

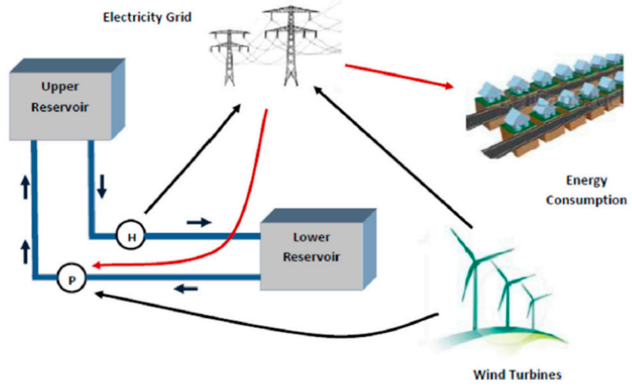


Figure 1. Structure of a hybrid power station [19].

The Greek electrical system operation code for non-interconnected islands was initially published in February 2014, and its revised version was presented in April 2018 [20]. According to this version, the hybrid power station owner declares its guaranteed energy, which is equal to the product of maximum power output of the station P_{hydro} and the number of hours of guaranteed power. Regarding the operational principle of a wind-hydro hybrid power station, the following cases can be considered:

1. Case 1: If the total power output of the wind farms is less than the pump installed capacity of hybrid power station P_{pump}, the total generated wind power can be stored in the hybrid station with respect to the reservoir's upper and lower limits.
2. Case 2: If the total power output of the wind farms is greater than P_{pump} and less than $1.2 \times P_{pump}$, the amount of wind power that cannot been stored can be provided directly to the grid when there is capability of additional power injection to the grid from RES; otherwise, it is discarded.

Other restrictions related to hybrid power stations operation include: (a) the daily produced energy has to be at least $2 \times P_{hydro}$, and (b) on certain days (especially with high loads), the hybrid station has to provide its guaranteed energy.

As mentioned before, an interconnection procedure for all Greek isolated insular systems was initiated in the beginning of this decade. It (a) allows higher levels of renewable energy penetration, (b) enhances power system reliability, (c) significantly reduces the high operational costs of conventional generators in these systems, and (d) provides environmental benefits [21,22]. The interconnection of an isolated insular system is considered a high-cost project, but when it is combined with large-scale wind power, considerable cost savings can be achieved [23]. These interconnection plans are shown in Figure 2 and, until now, have been implemented for a part of the Cycladic Islands. The ten-year plan (2018–2027) of Greek Independent Power Transmission Operator (IPTO) [24] for Crete and Dodecanese islands is expected to be interconnected with the mainland power system. Samos Island is located in the North Aegean islands cluster, which is not included in IPTO'S ten-year plan; however, it is expected to be updated over the next few months to include the examined island power system of Samos.

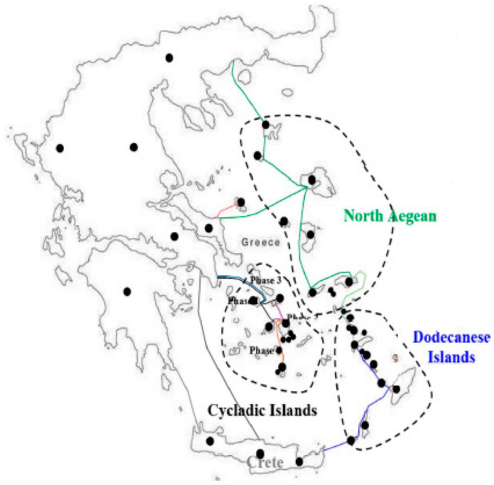


Figure 2. Interconnection plans of Greek islands [25].

3. Characteristics of Samos Insular System

The isolated power system of Samos Island is fed by a diesel power station with a total installed capacity of 47.75 MW. The station consists of six diesel generators that consume heavy fuel oil (mazut). Their technical characteristics (unit type, maximum and minimum power P_{max} and P_{min}) are given in Table 1, which also provides info regarding the priority list of these units, which is used in unit commitment. The distribution network on the island consists of several 15 kV medium voltage (MV) overhead lines [26]. Available data also include the annual time series (using an hourly time step) of net load, which is the full load minus PV production, as well as the corresponding time series of total WT production and total PV production. The data refer to 2015.

Table 1. Technical characteristics of Samos Island diesel power units.

Priority List	Unit Type	P_{max} (MW)	P_{min} (MW)	Fuel
1	Cegielski 9RTA-F58	11	6.14	Mazut
2	Cegielski 6RTAF-58	6	3.15	Mazut
3	Cegielski 6RTAF-58	6	3.125	Mazut
4	Wartsila W32-18V	8.25	4.125	Mazut
5	Wartsila W32-18V	8.25	4.125	Mazut
6	Wartsila W32-18V	8.25	4.125	Mazut

Figure 3 depicts the variation of annual net load on an hourly basis for Samos Island, with data. The peak net load is 30.2 MW, achieved through summer, whereas the minimum net load is 7.56 MW and takes place in April. As a result, the minimum-to-maximum net load ratio is equal to 0.25. The annual electricity demand is 140 GWh. Regarding WTs, several wind parks with 7.975 MW total capacity have been installed. Their annual capacity factor (CF) is equal to 29.38%. Figure 4 shows the wind power duration curve. The maximum WTs power output is 92.41%, which is related to the installed WT capacity. Moreover, in Samos Island has been installed 63 small PV parks with 4.373 MW_p rated power and maximum capacity of 70 kW_p each, as well as 23 roof PV systems with 0.113 MW_p rated power and maximum capacity of 5 kW_p each. As a result, in 2015, the total installed PV power reached 4.486 MW. The PV annual electricity production was 6950 MWh.

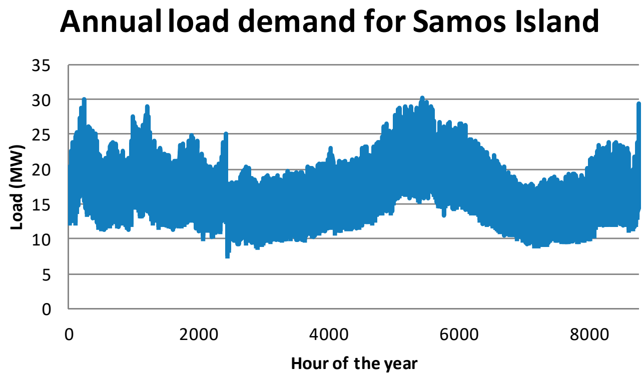


Figure 3. Annual net load demand variation for Samos Island (2015).

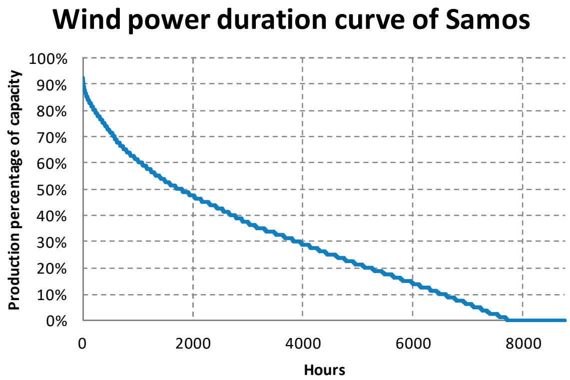


Figure 4. Duration curve of existing wind farms generated power (2015).

4. Results and Discussion

In this paper, the operation of the insular power system of Samos is implemented, using 8760 hourly time steps (one year) for net load demand and wind power production. Initially, a simulation of the system's operation in its current state (without hybrid power station installation) is implemented. For the unit commitment problem of conventional generators, the priority list method was used, according to the information provided in the first column of Table 1. A strict rule for spinning reserve has been considered as follows [18]:

$$\sum_i u_i \cdot P_{i\max} \geq 1.1 \cdot P_{Load} + 0.2 \cdot P_{WT} + 0.1 \cdot P_{PV} \quad (1)$$

where u_i is the i unit status (1 for ON and 0 for OFF), $P_{i\max}$ is the maximum power of unit i, P_{Load} is the net load demand, P_{WT} is the WTs production, and P_{PV} is the PVs production. As a first step, a simulation run was executed for the annual operation of Samos Island power system, without considering the installation of a hybrid power station. For each hour, the load that has to be supplied by diesel generators is equal to the net load minus WT production. Considering the technical data from Table 1 (power limits, priority list) and the spinning reserve constraint (1), the hourly production for each unit can be calculated. The annual results are shown in Figure 5, from which it can be concluded that almost 70% of Samos' total electricity needs are supplied by the first two units of Table 1. RES Technologies' (WTs and PVs) penetration surpasses 19%. The annual operating cost of all conventional power units is 9,887,800 €.

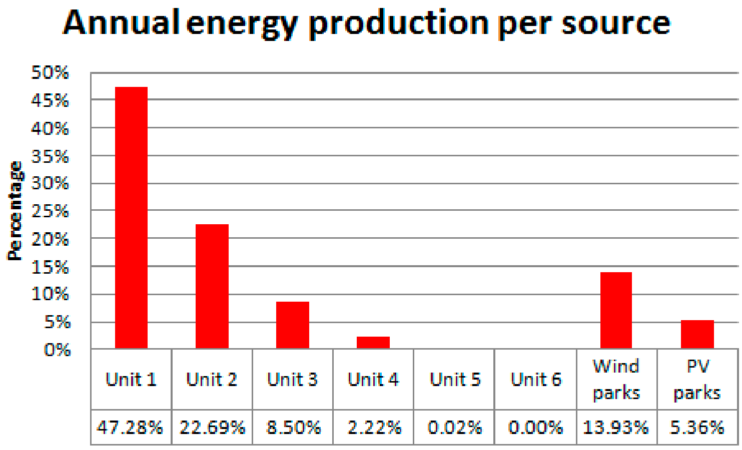


Figure 5. Annual energy production in Samos Island from different sources (no hybrid power station existence).

Regarding the modeling of the hybrid power station that consists of PHS and new installed WTs, the following assumptions were made:

1. The efficiency of a pump unit is considered to be 78% and the efficiency of a hydro unit is considered to be 90%. As a result, the total efficiency of PHS unit is $n_{\text{total}} \approx 70\%$.
2. P_{pump} is considered to be equal to $P_{\text{hydro}}/n_{\text{total}}$.
3. CF of newly installed WTs is considered to be equal to CF of the already installed wind farms (i.e., 29.38%).
4. The minimum time interval of hydro turbine daily operation at its rated power (P_{hydro}) is 2 h, as defined by the Greek operation code [17]. The time interval of hydro turbine daily operation at its guaranteed power (P_{hydro}) is 8 h.
5. The days in which the power system operator needs the guaranteed energy from the PHS system, regardless of WTs production, are considered all the days of the year in which their daily energy is greater than 90% of the maximum daily energy of the year. For the Samos Island power system, this corresponds to 34 days per year (mainly in the summer period).
6. The capacity of upper and lower reservoirs is considered to be sufficient in order to be able to provide continuous operation of hydro turbine at rated power (P_{hydro}) for 14 h.
7. The maximum WT penetration (with respect to net load) is considered to be 50%. In case of wind power shedding, newly installed WTs have priority in the reduction of their electric power.

4.1. Hybrid Power Station Financial Schemes Comparison

In order to evaluate the performance of hybrid power systems operation, two alternative financial schemes (referred as scenario 1 and scenario 2) that have been proposed in Greece were examined:

1. Scenario 1: Energy delivered by PHS to the grid is paid 200 €/MWh. Energy absorbed from the grid has a cost of 140 €/MWh, which is equal to 200 × n_{total} €/MWh.
2. Scenario 2: Energy delivered by PHS to the grid is paid 147 €/MWh and PHS power availability is paid 127,000 €/MW annually. Energy absorbed from the grid has a cost of 103 €/MWh, which is equal to 147 × n_{total} €/MWh.

For all cases, MATLAB software was used. Electricity from newly installed WTs that cannot be absorbed by PHS but it is absorbed by the grid (if maximum wind penetration is not surpassed) is paid for at 98 €/MWh. The economical index that was examined is the net present value (NPV) for discount rate i = 8%. The considered initial costs are 3,000,000 €/MW for PHS system construction (without WTs) and 1,200,000 €/MW for WTs. Seventy percent of these initial costs are covered from a bank loan of 6% interest rate and 20 years' duration. Total annual operational and maintenance (O&M) costs are assumed to be 1.5% of the initial cost. The total lifetime of the project is considered to be 50 years. Due to the fact that WTs' lifetime is approximately 25 years, reinstallation of equal capacity WTs is considered during halftime of the project life.

Figures 6–8 present the economic evaluation results for three scenarios with regards to the size of the hybrid power station: (a) P_{hydro} = 3.5 MW, (b) P_{hydro} = 7 MW, and (c) P_{hydro} = 10.5 MW. Parameter $P_{WT\mathrm{new}}$ represents the newly installed wind turbine capacity of the hybrid power station. The dotted line shows the optimal option for each scenario. In all cases, wind parks of large capacities have to be installed due to moderate annual CF value of WTs (less than 30%). The lower $P_{WT\mathrm{new}}/P_{\mathrm{pump}}$ optimal values (shown in bold italics) for higher P_{hydro} sizes can be explained by the higher wind power curtailment of new wind parks that exist when $P_{WT\mathrm{new}}$ is higher.

The results of Figures 6–8 show that all options are economically viable (NPV > 0), and that in all cases, Scenario 1 provides significantly better results. However, the implementation of such a project has to take into account additional parameters that include large durations of the project and the high installation costs of the system's components.

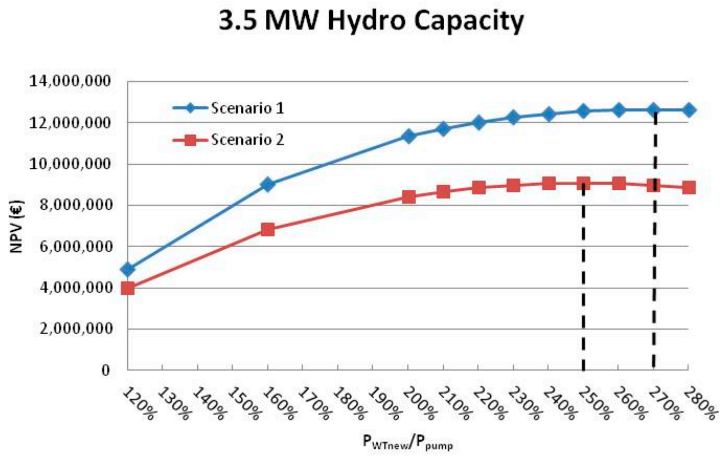


Figure 6. Comparison of the two billing scenarios considering P_{hydro} = 3.5 MW.

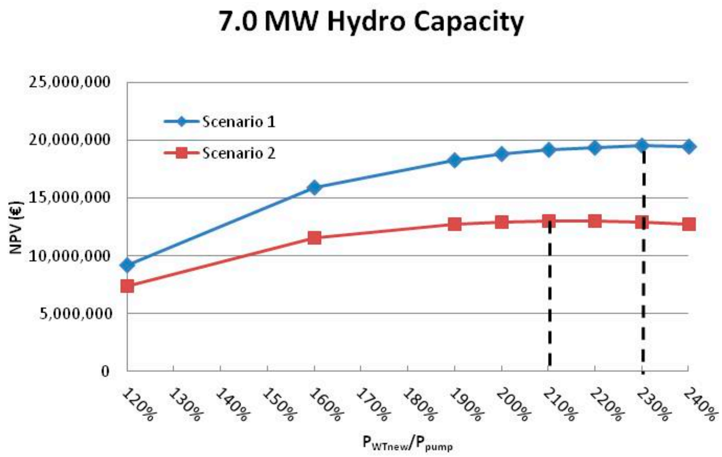


Figure 7. Comparison of the two billing scenarios considering P_{hydro} = 7.0 MW.

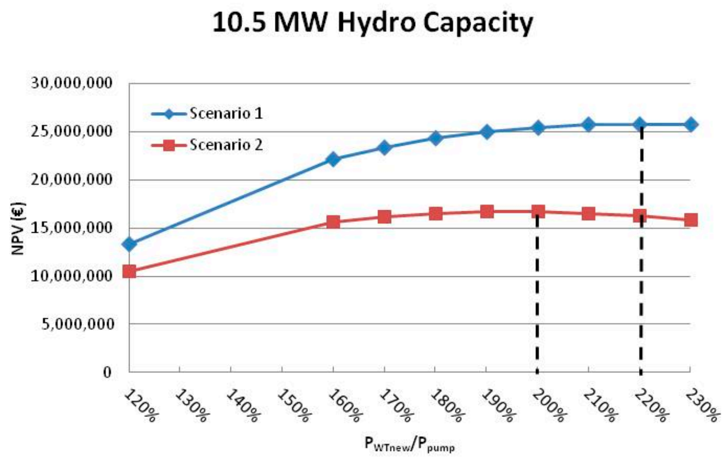


Figure 8. Comparison of the two billing scenarios considering P_{hydro} = 10.5 MW.

4.2. Power System Operation considering Hybrid Power Station Existence

In order to evaluate the effect of a hybrid wind-PHS power station installation in the isolated power system of Samos Island, the configuration that provides the highest NPV for Scenario 1 is adopted. For each one of the three PHS sizes, the effect of hybrid power station operation is evaluated with regards to the annual electricity production and the effect on load curves.

4.2.1. Small PHS Size (P_{hydro} = 3.5 MW)

Figure 9 presents the annual energy production per different type of source, and its comparison with Figure 5 shows that the hybrid power station contributes to 15.10% of the total electricity: 9.78% from PHS and 5.32% from newly installed WTs. The total amount of electricity absorbed from the Network compared to the total amount of energy consumed for the filling of the storage system is 1.05%, which is considerably smaller from the maximum allowable limit of 30% (see Section 2). With the exception of base load Unit 1, all other conventional units reduce considerably their production, or do not operate at all. The amount of electricity that is curtailed from newly installed WTs is 25.0% of the electricity that is absorbed by PHS station from new WTs. The annual operating cost of all conventional power units in this case is 8,062,833 €, which is 18.5% lower than the current cost of operation.

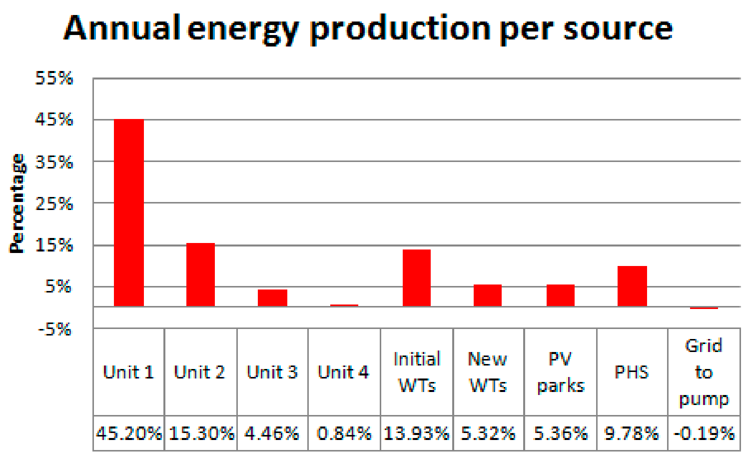
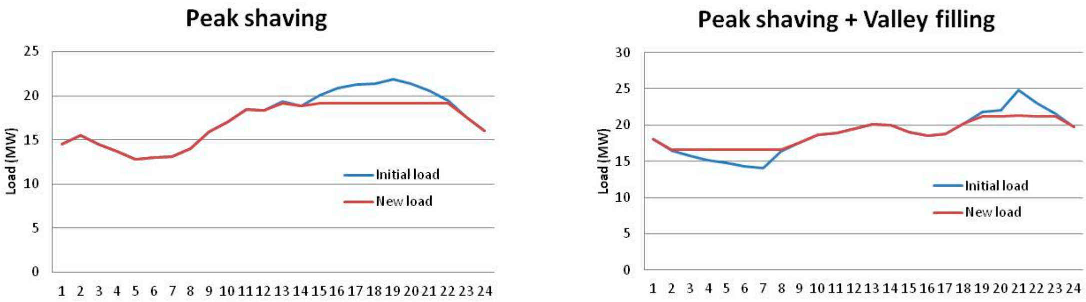


Figure 9. Annual energy production in Samos Island from different sources, considering hybrid power station operation (P_{hydro} = 3.5 MW).

Figure 10 shows the differences that occurred in daily load curves of Samos Island's isolated power system due to hybrid power station operation, which can be classified into two categories: peak shaving (Figure 10a) and a combination of peak shaving and valley filling (Figure 10b). The first case can occur every day, but it provides additional advantages in high-load days, when the cost of peak power is generally higher. The combination of peak shaving and valley filling usually occurs in a combination of a high load and low wind day, in which the charging from grid (valley filling) takes place during the first night hours, while peak shaving occurs usually at late peak hours.



(**a**) (**b**)

Figure 10. Variation of daily load curve considering P_{pump} = 5 MW and P_{hydro} = 3.5 MW: (**a**) Peak shaving operation of hybrid power station (day 4 of the year); (**b**) Peak shaving and valley filling operation of hybrid power station (day 206 of the year).

4.2.2. Medium PHS Size (P_{hydro} = 7.0 MW)

Figure 11 presents the annual energy production per different type of source, and its comparison with Figure 5 shows that the hybrid power station contributes to 24.48% of total electricity: 18.89% from PHS and 5.59% from newly installed WTs. The total amount of electricity absorbed from the network, compared to the total amount of energy consumed for the filling of the storage system, is 1.27%. Similar to the previous case, with the exception of base load Unit 1, all other conventional units considerably reduce (even more) their production, or do not operate at all. The amount of electricity that is curtailed from newly installed WTs is 24.0% of the electricity that is absorbed by PHS station from new WTs. The annual operating cost of all conventional power units in this case is 6,988,914 €, which is 29.3% lower than the current cost of operation.

The effect of hybrid power station operation in the same load curves as mentioned in Section 4.2.1 is depicted in Figure 12. It can be seen that the effect in both cases is even more intense (as expected). In the second day (high load-low wind day), especially, all load values lie in an interval of 2 MW.

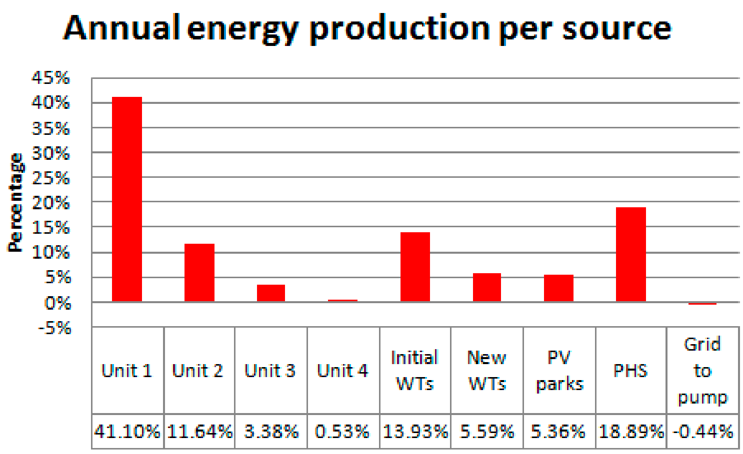
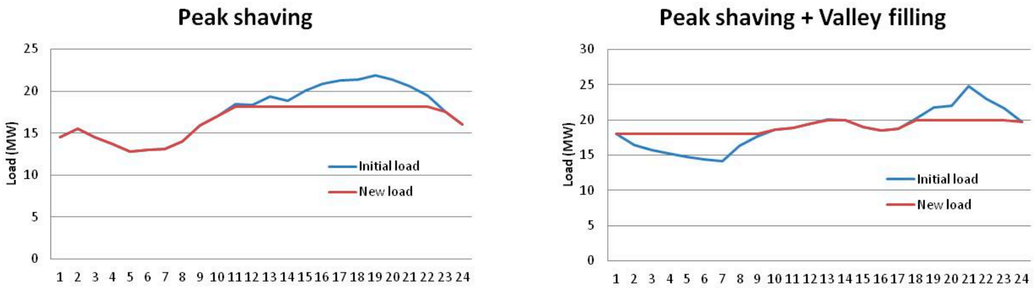


Figure 11. Annual energy production in Samos Island from different sources, considering hybrid power station operation (P_{hydro} = 7.0 MW).



(**a**) (**b**)

Figure 12. Variation of daily load curve considering P_{pump} = 10 MW and P_{hydro} = 7.0 MW: (**a**) Peak shaving operation of hybrid power station (day 4 of the year); (**b**) peak shaving and valley filling operation of hybrid power station (day 206 of the year).

4.2.3. Large PHS Size (P_{hydro} = 10.5 MW)

Figure 13 presents the annual energy production per different type of source, and its comparison with Figure 5 shows that the hybrid power station contributes to 33.89% of the total electricity: 28.01% from PHS and 5.88% from newly installed WTs. The total amount of electricity absorbed from the network, compared to the total amount of energy consumed for the filling of the storage system, is 1.33%. Regarding conventional generators, even the production of base load Unit 1 has started to considerably decrease. The amount of electricity that is curtailed from newly installed WTs is 25.2% of the electricity that is absorbed by PHS station from the new WTs. The annual operating cost of all conventional power units in this case is 6,032,105 €, which is 39.0% lower than the current cost of operation.

The effect of hybrid power station operation in the same load curves as mentioned in Section 4.2.1 is depicted in Figure 14. Notably, for the high load-low wind day in Figure 14b, all new load values are almost constant (have a very small variation of 0.2 MW).

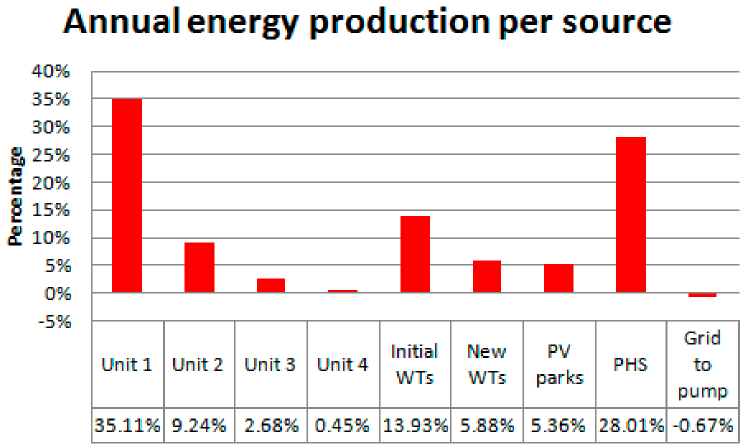


Figure 13. Annual energy production in Samos Island from different sources, considering hybrid power station operation (P_{hydro} = 10.5 MW).

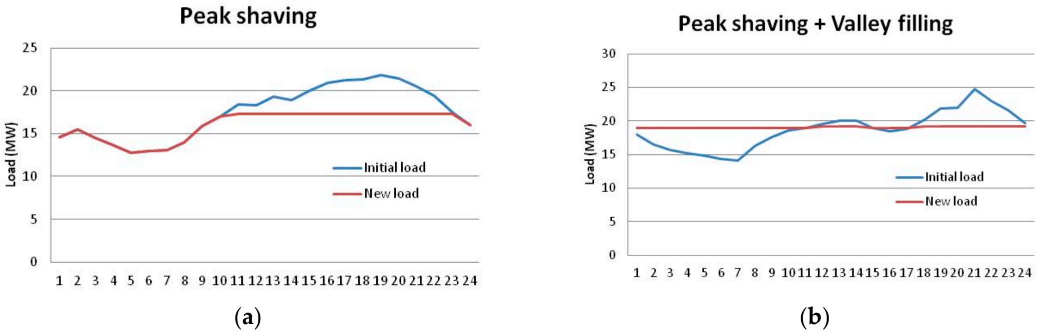


Figure 14. Variation of daily load curve considering P_{pump} = 15 MW and P_{hydro} = 10.5 MW: (**a**) Peak shaving operation of hybrid power station (day 4 of the year); (**b**) peak shaving and valley filling operation of hybrid power station (day 206 of the year).

5. Conclusions

This paper studied the impact of a WT-PHS hybrid power station in the operation of the medium sized isolated power system of Samos Island. A PHS system is a mature largescale energy storage technology that presents good efficiency, a large lifetime, fast response speed and adaptability to load curve. This impact was examined for both power system operator and hybrid power system investor viewpoints. The analysis was based on hourly real system data. Initially, a comparison of the two available billing options for PHS operation was made, considering three different sizes of hybrid power stations. In all cases, the first option that considers a price of 200 €/MWh for produced PHS electricity led to significantly better results compared to the second option that considers a price of 147 €/MWh for produced PHS electricity and annual price of 127,000 €/MW for PHS power availability. Moreover, the analysis showed the economic viability of these projects and the necessity to install new wind parks of large capacity, due to moderate CF of Samos Island. Additionally, the contribution of hybrid power station operations is examined by considering three alternative hybrid power station output capacities that are approximately equal to 1/9, 2/9 and 1/3 of the annual peak load, respectively. The results showed that the total hybrid power station penetration can achieve 34%, the annual cost reduction of generating units can achieve 39%, and the new load curves are significantly smoother. Additional benefits of PHS systems (i.e., water supply security) are not examined in this paper. Next steps could include the study of the interconnection impact and reliability evaluation. The effect of interconnection of the operation of Samos insular system that includes hybrid power station and a large amount of wind power has to be studied, in order to examine the financial and operational benefits. In such cases, it is estimated that such a power grid will turn into an energy exporter for a number of hours within a year. The evaluation of the insular power system of Samos under a reliability framework includes the estimation of proper reliability indices using probabilistic and/or simulation methods.

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