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Full-Scale Implementation of RES and Storage in an Island Energy System

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Abstract: The field of energy, specifically renewable energy sources (RES), is considered vital for a sustainable society, a fact that is clearly defined by the European Green Deal. It will convert the old, conventional economy into a new, sustainable economy that is environmentally sound, economically viable, and socially responsible. Therefore, there is a need for quick actions by everyone who wants to move toward energy-efficient development and new environmentally friendly behavior. This can be achieved by setting specific guidelines of how to proceed, where to start, and what knowledge is needed to implement such plans and initiatives. This paper seeks to contribute to this very important issue by appraising the ability of full-scale implementation of RES combined with energy storage in an island power system. The Greek island power system of Astypalaia is used as a case study where a battery energy storage system (BESS), along with wind turbines (WTs), is examined to be installed as part of a hybrid power plant (HPP). The simulation's results showed that the utilization of HPP can significantly increase RES penetration in parallel with remarkable fuel cost savings. Finally, the fast response of BESS can enhance the stability of the system in the case of disturbances.

Keywords: energy transition; renewable energy sources; island power systems; hybrid power plants; wind turbines; battery energy storage systems

1. Introduction

The integration of renewable energy sources (RES) is interesting to designers of isolated island power systems, presenting significant opportunities especially for fuel cost savings. Islands are usually very dependent on fossil fuel imports, which are typically expensive due to transport costs. Hence, the utilization of RES via the exploitation of the island's RES potential can assist the load demand–supply, reducing the cost derived from fuel consumption, as well as pollutant emissions [1,2]. Two strategies have been developed by the European Union (EU) in view of climate change and sustainable development on islands [3,4] with the aim to maximize the share of RES. In this respect, such island power systems seek to improve their independence from conventional units, promoting an environmentally friendly profile.

However, RES integration traditionally brings operating issues in power systems. Due to their strong weather dependence, such as in the cases of solar irradiation and wind speed, RES generation can have large fluctuations. These unpredictable variations affect the stability and power quality of power systems. These issues are primarily related to voltage and frequency deviations [5]. In comparison with interconnected power systems, such issues are increased in isolated island communities, as fluctuations in production or demand changes can lead to larger frequency deviations [6,7]. Therefore, to avoid problems that can affect the safety and stability of the power supply system, intermittent RES power has to be limited to a higher specific percentage of the system's load, compared with interconnected power systems. These actions arise from the need for ensuring adequate frequency and voltage regulation, which are traditionally provided by conventional synchronous units. Subsequently, in scenarios of high RES penetration, the operator of the system may give the command of RES curtailment with respect to the operational requirements of conventional units and the spinning reserve criteria [8].

A solution in RES power curtailment is the utilization of energy storage systems (ESSs). ESSs are mainly used to maximize the RES penetration [9–13] by storing RES power/energy in periods that cannot be absorbed by the power systems, providing it in periods when it is required. Furthermore, ESSs can be integrated as a technique to maintain stability in cases of power system stress. Due to their fast response, ESSs can be used from the operator of a system to regulate frequency [14,15] and voltage [16,17], maintaining them at the desired limits, either via power injection (frequency/voltage increase) or power absorption (frequency/voltage decrease). Therefore, the utilization of RES in combination with energy storage systems can lead to near-zero or 100% RES island power systems. In such systems, the dependence on conventional units is almost eliminated, resulting in them practically being used as backup systems for ancillary service provision [18].

Creek territory consists of 32 isolated island power systems with the vast majority of them in the Aegean Archipelagos [19]. 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. Most of these isolated power systems present significant wind and solar potential. Hence, considerable amounts of RES penetration levels have been reached. By 2017, 97 wind farms (323 MW) were in operation on all Greek noninterconnected insular systems in addition to 758 PV parks (136 MW), 242 rooftop PV systems (24 MW), and one small hydroelectric station (0.3 MW) [20]. Additionally, extensive research has been carried out on large-scale energy storage development in those islands. The operation of wind-pump storage units in the Cretan power system was examined in [21,22], while, in [23,24], the impact of hybrid power systems was evaluated for the Samos island power system; in [25], a hybrid power plant was utilized for Sifnos island to reach 100% energy autonomy. Currently, Ikaria island is the only Greek isolated island with a large-scale hybrid power system in operation [26].

This paper investigates the technical and economical optimal generation scheme in a specific real grid that belongs to the small Greek island power system of Astypalaia, utilizing a hybrid power plant (HPP). Taking into account similar research studies [24,27–29], isolated island power systems, such as that of Astypalaia which presents significant wind potential, could be representative case studies for further RES implementation, not only in European isolated islands but also worldwide. The utilization of such a large-scale HPP represents an energy planning strategy for further RES implementation on islands, which contributes to the full-scale deployment of green power technologies. More specifically, different scenarios of battery energy storage systems (BESSs) and wind turbines (WTs) are combined to significantly reduce the operation of the existing conventional units of the island. Therefore, an extensive analysis is made presenting annual data for the electricity production of the existing thermal units and the BESS; the purchased annual energy needed for BESS charging, as well as the annual discarded WT energy and WT energy injection to the grid, is also calculated. Furthermore, the annual fuel costs savings for each examined scenario are presented while an extensive economic analysis is also made using financial indicators. Finally, a stability analysis for the examined power system is conducted, after the installation of the HPP.

This paper is organized as follows: Section 2 presents the most significant features and restrictions of the Greek legislation framework regarding the operation of HPPs in insular power systems. Section 3 contains a general description of the island power system of Astypalaia, Section 4 contains the methodology adopted, while Section 5 contains the main simulation results and the economic analysis for HPP utilization. Section 6 contains the analysis for the dynamic performance of the power system after the installation of the HPP, while Section 7 concludes the paper.

2. Greek Legislation for Hybrid Power Plants in Insular Power Systems

In general, hybrid power plants (HPP) consist of a storage system, a controllable generation unit, and at least one form of RES power generation unit. A wide range of technologies can be used for an HPP's electricity storage and production. Pumped hydro storage units and battery stations represent the most common and mature technologies for large-scale energy storage, in terms of HPP. In Greece, according to [30], a power plant is defined as an HPP if it meets the following requirements/criteria:

- The plant comprises at least one RES unit and a storage system;
- The total electricity absorbed from the grid, on a yearly basis, does not exceed 30% of the total stored electrical energy;
- The maximum installed capacity of the HPP's RES units does not exceed the respective installed capacity of the storage units, increased by 20%.

The installation of a wind-battery HPP on the Greek noninterconnected insular power system (NIIS) of Astypalaia is examined in this paper. According to [31], the operator of the NIIS is obliged to absorb the electricity produced by the RES with priority, including the HPP's units, over conventional units without prejudice to the secure operation of the NIIS. Within this frame, this priority is not valid when the HPP's production violates the restriction for the technical minimum of the must-run conventional units. Additionally, there is not a priority in HPP's commitment over conventional units when their production is deemed necessary to meet ancillary service requirements which are not possible to be met by RES and HPPs.

In terms of HPP utilization from the operator of the NIIS, the declaration of its guaranteed energy, which is equal to the product of maximum battery capacity P_{bat}, and the number of hours of guaranteed power are required. Regarding the operational principle of a wind-battery HPP, two basic case scenarios can be considered:

- Case 1: if the total power output of the wind farms is less than the installed capacity of HPP P_{bat}, the total generated wind power can be stored in the HPP with respect to the battery minimum and maximum state of charge (SoC).
- Case 2: if the total power output of the wind farms is greater than P_{bat} and less than $1.2 \times P_{bat}$, the amount of wind power that cannot be stored can be provided directly to the grid, in the case that there is the capability of additional power injection to the grid from RES; otherwise, it is discarded.

Other restrictions related to HPP operation include that (a) the provided energy from the HPP the first 12 h of the day cannot exceed the provided energy of the last 12 h of the day, (b) the daily produced energy has to be at least $2\text{h} \times P_{bat}$ (otherwise must be equal to zero), (c) on certain days (especially with high loads), the HPP has to provide its guaranteed energy, and (d) the price of the electricity taken from the battery station is higher compared to the price of electricity sold by wind farms to the grid.

3. Description of Astypalaia Island Autonomous Power System

Astypalaia is a small island that belongs to the Dodecanese complex in the southeastern Aegean Sea, Greece. Its permanent population is 1334 inhabitants (2011 data); however, during summer months there exists a significant increase, which is depicted in load consumption. The annual peak load reached 2.22 MW (2014 data) on 15 August at 9:00 p.m. Currently, the autonomous power system of Astypalaia island is fed by a diesel power station that consists of three identical diesel generators (Mitsubishi S16R-PTA) with 1 MW peak power each (3 MW in total). Moreover, 320 kWp of photovoltaic (PV) power has been installed on the island, with annual electricity production of 531.38 MWh in 2019 (18.96% annual capacity factor) [32]. Figure 1a shows the net load duration curve, which is the full load minus PV production, and Figure 1b depicts the annual load demand, which shows the significant load increase (more than double in some periods) during summer months.

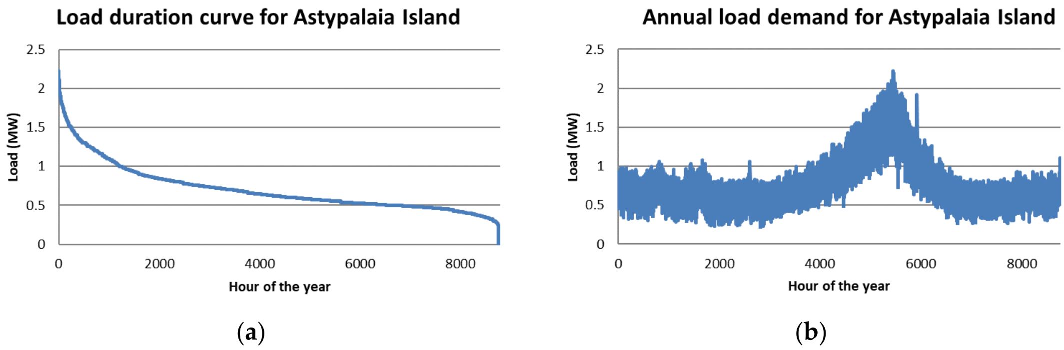

Figure 1. Net load on Astypalaia Island for the year 2014: (**a**) load duration curve; (**b**) annual load demand.

The island of Astypalaia presents significant wind potential, as with the majority of locations in the Dodecanese complex. Although no wind turbines have been installed, there is a large number of approved wind farms (by the Greek Regulatory Authority for Energy) for electricity generation on the island (on the scale of several tenths of megawatts) [33]. For a typical mountainous location on Astypalaia Island, although the annual mean wind speed is around 6.5–7.0 m/s (for a 10 m anemometer height), there are no high wind speed values that surpass 20 m/s. This characteristic makes this location ideal for a WT that is suitable for medium to high wind speeds. The proposed WT for installation is the Siemens Gamesa onshore model SG 2.6-114, with 2.625 MW rated power, a hub height of 88 m (other hub height alternatives are also available), and wind class IEC IA/IIA/S [34], which corresponds to medium and high wind speeds [35]. Figure 2a,b show the mean monthly wind speed and wind speed duration curve, respectively, taken from a mountainous location in the northwest of Astypalaia, using typical model year (TMY) data provided in [36]. Figure 3 shows the power curve of the SG 2.6-114 WT model.

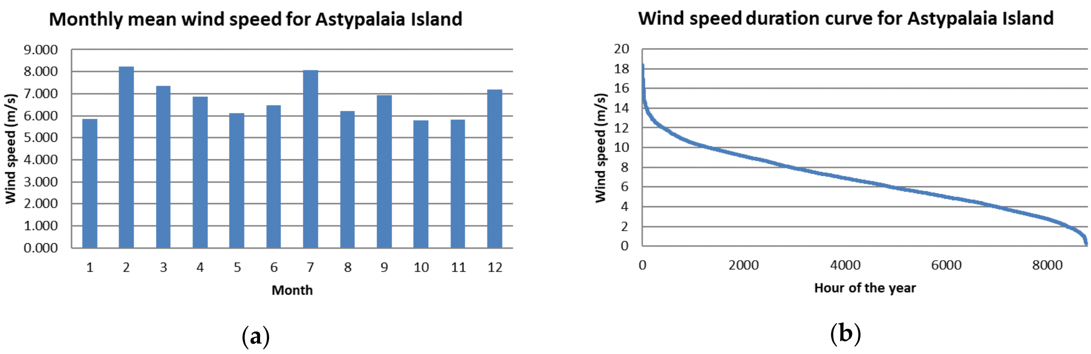

Figure 2. Wind data for a mountainous location in the northwest of Astypalaia (10 m anemometer height with annual mean wind speed of 6.73 m/s): (**a**) monthly mean wind speed; (**b**) wind speed duration curve.

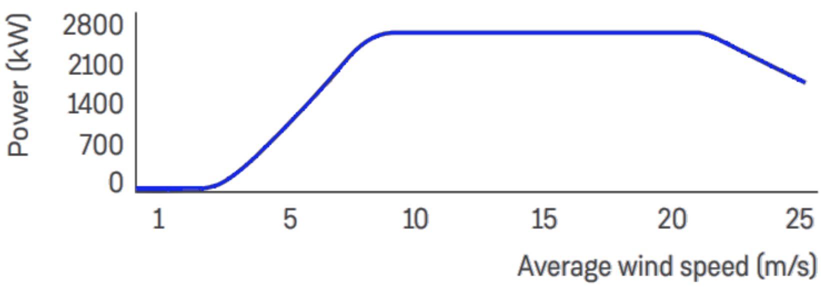

Figure 3. Power curve of SG 2.6-114 wint turbine (WT) model [34].

4. Methodology

In the following analysis, time-series data with an hourly time step (i.e., 8760 annual values) were used, which include net load, total WT production, and total PV production. WT production was calculated by combining the annual wind data (Figure 2) and WT power curve (Figure 3). Moreover, the effect of WT hub height was also taken into account using the power law with a power law exponent value a = 1/7 [37]. The annual capacity factor for each WT was equal to 41.03% (around 3600 equivalent hours per year operating at rated power). PV production data were used only in unit commitment calculations (see Equation (1)) and were estimated by PV-GIS [36]. The difference between the annual estimated and observed PV electricity production was only 0.8%.

Initially, a simulation of the system's operation in its current state (without HPP installation) was implemented. For the unit commitment problem, the priority list method was used for the three identical diesel generators. A strict rule for spinning reserve was considered as follows [22]:

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

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 WT production, and P_{PV} is the PV production. As a first step, a simulation run was executed for the annual operation of Astypalaia island power system, without considering the installation of the HPP. For each hour, the load to be supplied by diesel generators was equal to the net load minus WT production ($P_{Load} - P_{WT}$). Considering the technical data of diesel generators and the spinning reserve constraint described in Equation (1), the hourly production for each unit could be calculated.

Next, the operation of Astypalaia Island operation was evaluated considering the installation of the HPP units. Each HPP unit consisted of a combination of Siemens Gamesa onshore WT model SG 2.6-114 and a Narada lead-carbon BESS of 1 MW alternating current (AC) output power [34]. In each case, multiples of this combination could be used. The technical characteristics of Narada BESS were as follows:

- Output energy (AC): typically 8 MWh, whereas other capacities could be used (usually in the range of 4–12 MWh);
- Single-way efficiency equal to 0.96, which means that the roundtrip efficiency (n_{total}) was equal to 0.9216;
- Typical battery lifetime: 5000 (daily) cycles (more than 13.5 years).

The basic criterion for choosing lead–carbon batteries for the proposed BESS of the HPP was economic. According to brief calculations, the utilization of lithium-ion batteries would have given a nonviable solution for the proposed investment, as they are significantly more expensive than lead–carbon batteries. Therefore, it was preferable to use lead–carbon batteries which also promote a well-proven technology as they are the next generation of the older lead–acid technology. Furthermore, this paper proposes the integration of an HPP with the aim of providing an indicative energy planning strategy for the energy transition of island power systems, making them more energy-efficient, economically efficient, and environmentally friendly. Taking into account the restriction of an environmentally friendly power system, the advantage of lead–carbon batteries is that they can be recycled in contrast with lithium batteries, where the issue of their recycling remains an unresolved problem.

Regarding the operation of HPP, the WT electricity production for each hour of the year was initially calculated. The maximum WT penetration (concerning the net load) was considered to be 60%, such that if the WT production surpassed this limit for a specific hour, the surplus energy was curtailed. Then, the charging procedure of the BESS from WTs was estimated, according to the rules described in Cases 1 and 2 of Section 2. In cases when, during charging, the BESS SoC reached 100%, the WT energy that was used for BESS charging was reduced properly and it was absorbed from grid if possible.

The load demand of each day was assumed to be known (zero-load forecasting error); thus, during each day that the BESS was operating, its discharging schedule could be estimated by considering that the BESS discharged during peak load hours (usually evening and early night hours). As a result, peak load was reduced (peak-shaving). On days when the power system operator needed the guaranteed energy from the BESS, regardless of WT production, if the WT production was not sufficient to fully charge the BESS, power from the grid also had to be absorbed. This usually happened during night hours, when the load presented its minimum daily values (valley-filling). In this paper, this was considered to take place on all days of the year where the daily energy demand was greater than 80% of the maximum daily energy demand of the year. For the Astypalaia Island power system, this corresponded to 25 days per year (mainly in the summer period).

Taking into account the load reduction during WT production and peak-shaving, as well as the load increase during valley-filling, the new load curve could be estimated; thus, the operating points of diesel generators considering the HPP installation could be calculated using Equation (1). The flowchart of the abovementioned methodology is presented in Figure 4.

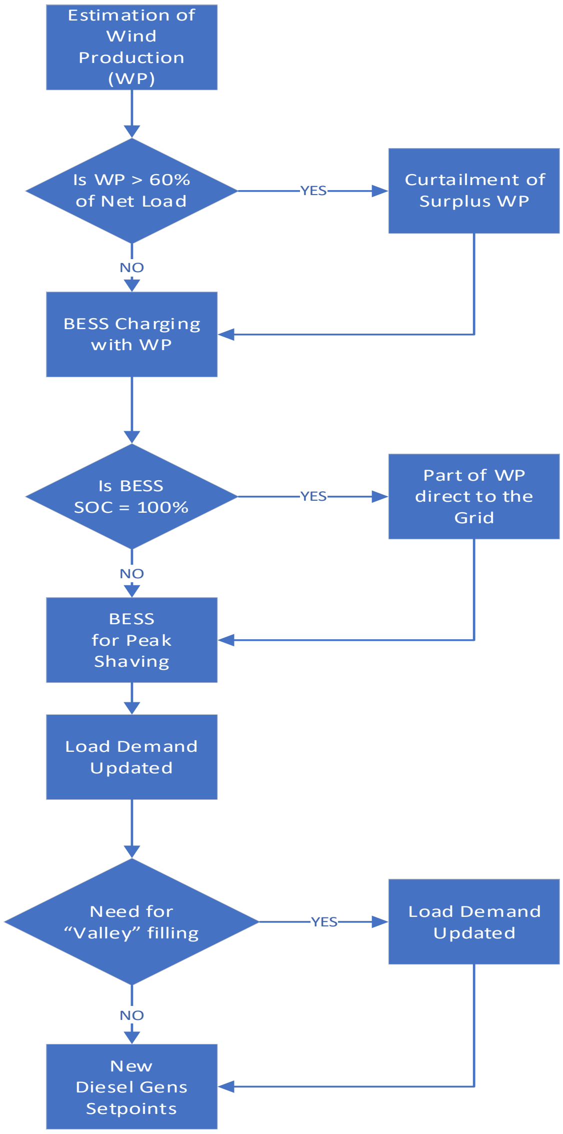

Figure 4. Flowchart of Astypalaia non-interconnected insular power system (NIIS) operation considering hybrid power plant (HPP) installation.

5. Economic Analysis, Results

The economic analysis was based on the directives of the Greek legislative framework for noninterconnected islands. The energy delivered from BESS to the grid had a cost of EUR 147/MWh. Energy absorbed from the grid had a cost of EUR 135.47/MWh, which was equal to EUR 147 × n_{total}/MWh. Electricity from the installed WTs that could not be absorbed by the BESS but was absorbed by the grid (if maximum wind penetration was not surpassed) had a cost of EUR 98/MWh. The considered initial costs were EUR 250,000/MWh for the BESS (without WTs) and EUR 1,200,000/MW for the WTs. Seventy percent of these initial costs were covered from a bank loan at a 7.5% interest rate with a 15 year duration. Total annual operational and maintenance (O&M) costs were assumed to be 1% of the initial cost. The annual discount rate i was 6%, whereas the total project lifetime was considered to be 25 years, which is equal to the WT lifetime. Batteries were replaced during the 14th year of system operation (5000 daily cycles). For WTs and BESSs, during the end of their lifetime, a salvage value equal to 20% of their initial cost was assumed.

For all developed scenarios, MATLAB software was used. The following financial indicators were calculated:

1. Net present value (NPV): positive NPV values (in Euros) are an indicator of a potentially feasible project; however, NPV also has to be compared with the size of the project (initial investment).
2. Internal rate of return (IRR): a project is acceptable if the IRR is greater than the discount rate (i = 6%).
3. Benefit-to-cost (B/C) ratio: this is the ratio of the net benefits to costs of the project. B/C ratios greater than 1 are indicative of profitable projects.
4. Simple payback (in years): contrary to the previous indices, simple payback does not consider the time value of money. It is useful, however, as a secondary indicator to indicate the level of risk of an investment.

NPV was used as the primary financial indicator for the evaluation of HPP installation. All scenarios with two WTs led to large negative NPV values (see, for example, the last column of Table 1) and significantly higher amounts of discarded wind energy (approximately three times more for the same BESS capacity). Figure 5 shows the total NPV for HPP projects with one WT and different BESS capacity. The results show that the most beneficial case was the installation of the 8 MWh BESS. Table 1 shows the financial indicators for a number of considered scenarios, including a typical one that contains two WTs. All three indicators that took into account the time value of money showed that the optimal scenario was that highlighted in Figure 5.

Table 2 gives a more detailed analysis for the four scenarios with one WT that presented the highest (positive) NPVs. The parameters that were calculated include the total net load, the annual electricity production of diesel generators and BESS, the annual energy purchased from the grid (in the case of valley-filling at night hours), the annual wind energy fed directly to the grid (without being stored to BESS), and the annual discarded wind energy (i.e., the wind energy not absorbed by the BESS or the grid). The last two parameters of Table 2 provide information about the annual energy penetration of HPP in Astypalaia Island. The results show that the increase in BESS capacity decreased conventional generation and WT energy fed directly to the grid or discarded and increased the penetration of HPP. Although the increase in BESS capacity improved the operational characteristics of the studied insular system, the high initial cost of batteries did not lead to better financial performance of the HPP for very large BESS capacities.

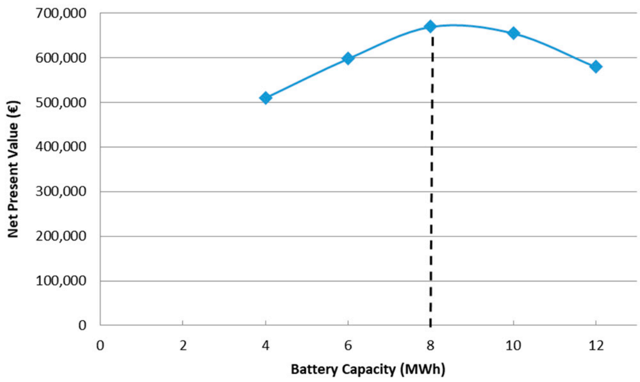

Figure 5. Total net present value (NPV) of HPPs containing one WT and different battery energy storage system (BESS) capacity.

Table 1. Financial indices for a number of considered scenarios. IRR, internal rate of return; B/C ratio, benefit-to-cost ratio.

Index	1 WT, 1MW, 6 MWh BESS	1 WT, 1MW, 8 MWh BESS	1 WT, 1MW, 10 MWh BESS	2 WTs, 2MW, 8 MWh BESS
NPV (EUR)	597,893	669,507	654,782	−1,829,710
IRR	8.49%	8.57%	8.32%	2.12%
B/C ratio	1.43	1.43	1.39	0.27
Simple payback (years)	17.62	17.80	18.17	24.07

Table 2. Annual electricity production and consumption for Astypalaia Island.

Parameter	1 WT, 1MW, 6 MWh BESS	1 WT, 1MW, 8 MWh BESS	1 WT, 1MW, 10 MWh BESS	1 WT, 1MW, 12 MWh BESS
Total load (MWh)	6188.43	6188.43	6188.43	6188.43
Diesel generators (MWh)	2089.25	1741.17	1427.55	1130.53
BESS (MWh)	2082.31	2690.96	3230.63	3706.77
Purchased from grid (valley-filling, in MWh)	9.75	9.76	9.75	9.91
WT energy directly provided to grid (MWh)	2026.61	1766.06	1540.00	1361.04
Discarded wind energy (MWh)	5157.86	4758.01	4398.47	4060.95
BESS penetration	33.65%	43.48%	52.20%	59.90%
BESS + WT penetration	66.40%	72.02%	77.09%	81.89%

Table 3 compares the annual fuel costs of diesel generators for all examined profitable scenarios, as well as for the current situation (operation without WTs or HPPs). Even the installation of an HPP with small BESS capacity significantly decreased (50% or more) annual fuel costs. Figure 6 shows the duration curves of BESS SoC for the four most dominant scenarios that were also included in Table 2. In the case of a small BESS capacity, there were several hours during the year in which the BESS was fully charged: more than 2800 h for the 6 MWh capacity (see Figure 6a) and more than 4000 h for the 4 MWh capacity. This usually happened on high-wind night and morning hours, during which the BESS was being charged by WTs. The small BESS capacity led to an inability to fully exploit the available wind potential, which also affected the financial indicators, significantly reducing revenues that could be received from the energy sold to the grid.

Table 3. Comparison of annual fuel costs for considered scenarios in Astypalaia Island.

Title 1	Annual Fuel Costs (EUR)
Current state	1,092,703
1 WT, 1MW, 4 MWh BESS	521,933
1 WT, 1MW, 6 MWh BESS	476,754
1 WT, 1MW, 8 MWh BESS	430,233
1 WT, 1MW, 10 MWh BESS	387,582
1 WT, 1MW, 12 MWh BESS	347,990

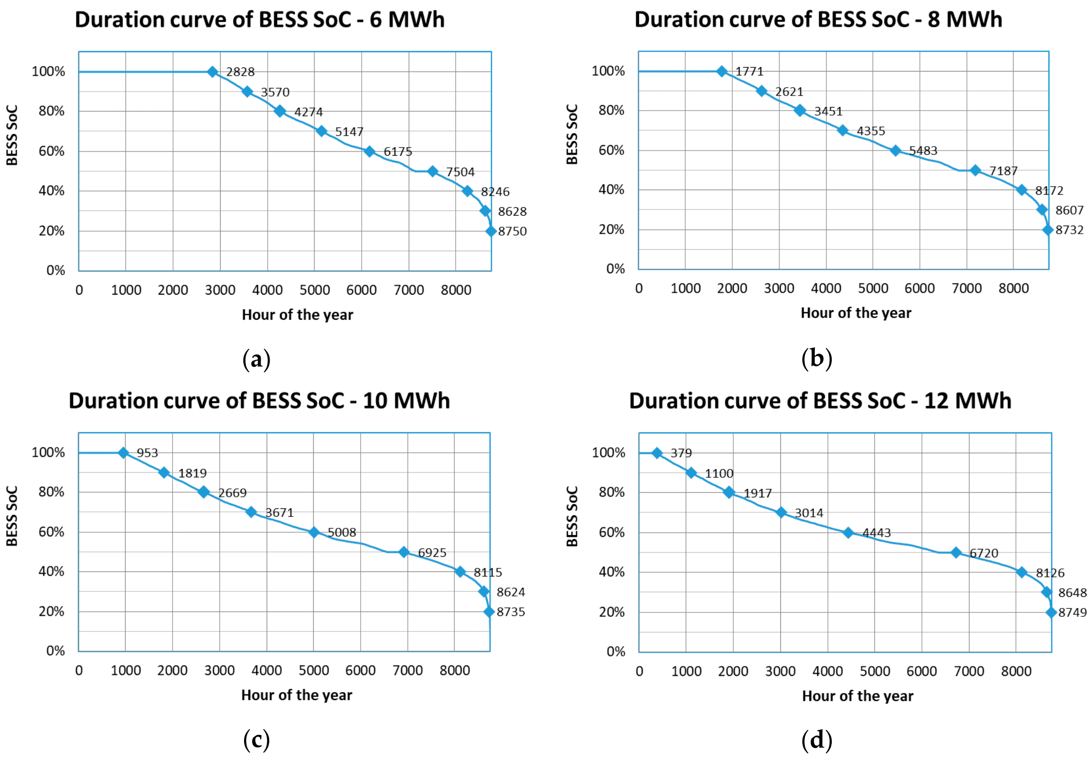

Figure 6. Duration curve for state of charge (SoC) for systems with 1 WT and different BESS capacity: (**a**) 6 MWh; (**b**) 8 MWh; (**c**) 10 MWh; (**d**) 12 MWh.

6. Dynamic Performance of the System with HPP

In this section, a preliminary stability analysis of the proposed production scheme was conducted. The profile of the HPP that was investigated through simulations (using Powerworld Simulator version 21 software) consisted of one WT of 2.625 MW and a BESS of 1 MW power and 8 MWh energy capacity. Previous power flows were used and basic disturbances were assessed. In more than 7000 h (cases A) of operation under the preselected specific disturbances, the island grid could be considered substantially safe, due to the fast response of the 1 MW BESS, while most of the remaining cases (cases B) retained their robustness under the precondition of sufficient wind power generation (equipped with Fault Ride Through (FRT)). Concluding, a few cases (cases C) with high load demand more than 1.5 MW and inadequate wind power production less than 0.3 MW were assessed as unsafe. This could be counterbalanced by the contribution of spinning reserves of the existing internal combustion units of the island. Therefore, the vital role of accurate real-time load and wind forecasting was once again confirmed.

In Figure 7, the variations in frequency profiles for several operation cases are depicted as described previously. The system was considered to operate with adequate energy storage power capacity (cases A) and with sufficient wind turbine generation (cases B), and it seemed to be quite stable. In cases C with insufficient wind production and storage power, the generation system could be supported by conventional units such as the current diesel generators (fast spinning reserve), which could clearly contribute to grid robustness.

Concluding, as a next step of this research, extensive simulation of the proposed HPP should be carried out to identify specific real-time operation guidelines and regulations, aiming at the most stable profile, which would cover all the frequency, voltage, and power quality requirements of weak grids as island power systems.

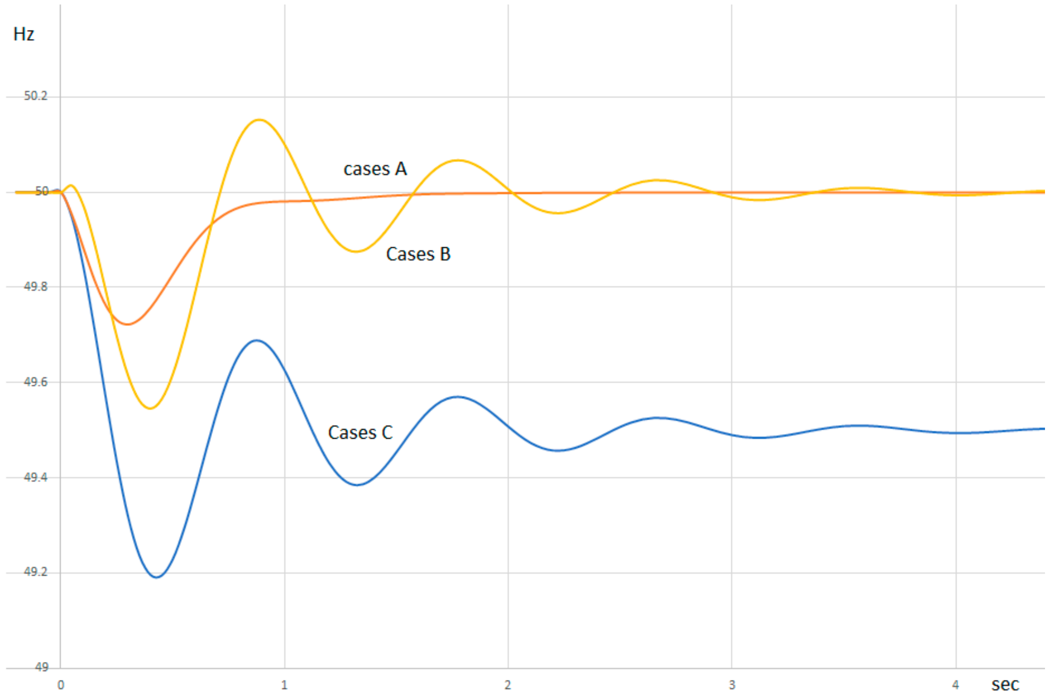

Figure 7. Frequency variations.

7. Conclusions

In this paper, the operation of the Greek insular power system of Astypalaia was examined, after the installation of an HPP consisting of WTs and BESSs. Due to the annual mean wind speed of 6.5–7.0 m/s observed on the island, a WT suited for medium to high wind speeds was selected to be installed. This WT was a Siemens Gamesa onshore model SG 2.6-114, with 2.625 MW rated power and 88 m hub height. Additionally, a Narada lead-carbon BESS of 1 MW AC output power was selected. For the needs of the simulation, combinations of those WTs and BESS were evaluated to find the optimal technical and especially economical generation scheme.

The criterion used to find this optimal scheme was the results of economic analysis using financial indicators. The relevant calculations were made considering the following initial costs: EUR 250,000/MWh for BESS (5000 daily cycles) and EUR 1,200,000/MW for WTs. Furthermore, the energy injected from the BESS to the grid had a cost of EUR 147/MWh, the cost of energy absorbed from the grid was assumed as EUR 135.47/MWh, and the total project lifetime was considered to be 25 years. Other considerations for the investment were that 70% of these initial costs were covered from a bank loan of 7.5% interest rate with a 15 year duration. The total annual O&M costs were assumed to be 1% of the initial cost, and the annual discount rate *i* was 6%. Taking into account those investment considerations, an analysis was made calculating the indicators of NPV, IRR, B/C ratio, and simple payback for different scenarios of BESS capacity with one SG 2.6-114 WT.

The results for all four indicators showed that the most beneficial combination was the installation of the 8 MWh BESS with one SG 2.6-114 WT. Consequently, a simulation was made to examine the annual energy penetration of the HPP in the Astypalaia island power system. Keeping as a basic scenario the utilization of one SG 2.6-114 WT, different scenarios of BESS capacity were examined for this purpose. The results showed that the increase in BESS capacity led to a decrease in the thermal unit's annual electricity production. A decrease was also observed in discarded WT energy or WT injection to the grid, while the penetration of HPP was also increased. However, due to the high initial cost of batteries, the increase in BESS capacity could not lead to a better financial performance of the HPP. In the case of a small BESS capacity (4 MWh and 6 MWh), it was almost impossible for wind potential to be fully exploited, thus reducing revenues that could be received from the energy sold to the grid. Thus, the capacity of 8 MWh BESS was confirmed as the optimal selection.

Finally, the stability analysis showed that the Astypalaia island power system could become much more robust after the installation of the examined HPP. More specifically, in more than 7000 h of operation in annual level, the island grid could be considered substantially safe, as the scheme of the 1 MW BESS would immediately respond to a possible disturbance. An unsafe situation was observed only in a few cases (less than 300 h annually) of load demand higher than 1.5 MW. In such cases, the spinning reserves of fast response units such as the existing internal combustion units could act to keep the robustness of the system.

As an overall conclusion, the island of Astypalaia was used as a case study with the aim of proposing an indicative energy planning strategy for the energy transition of isolated and weak interconnected islands and complexes of islands. This planning strategy could be included in policies for Green Energy in Europe and worldwide, such as the European Green Deal. More specifically, this paper proposed the integration of an HPP which follows the energy-efficient development and the new environmentally friendly behavior of insular power systems. The penetration level of both BESSs (8 MWh) and WTs exceeded the rate of 70%, achieving almost the maximization of RES penetration. At the same time, the operation of HPP achieved a reduction in fuel costs of more than 60%, making the power system more economically efficient, in addition to being more energy-efficient and environmentally friendly. Additionally, the fast response of the BESS could keep the system safe, from a stability perspective, during probable disturbances. As a novelty of this paper, the installation of an economically efficient HPP was proposed to contribute to the energy transition of island power systems, with the potential to also provide services for maintaining safety during unexpected events.

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