Operation of a Hybrid Power Station in an Isolated Power System: The Case of Samos Island

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***Abstract*— Greece includes a large number of islands that are isolated from the main interconnected Greek power system. A large number of these islands present significant amount of wind and solar potential. The nature of load demand and renewable production is stochastic, so the operation of such isolated power systems can be improved significantly by the installation of a large scale energy storage system. The role storage is to compensate for the long and short-term imbalances between power generation and load demand. Pumped hydro storage (PHS) units represent one of the most mature technologies for large scale energy storage. This paper studies the effect of installing a wind-PHS hybrid power station in the operation of the isolated power system of Samos Island. The implemented analysis compares the economic viability of this project under different billing scenarios, as well as its impact to the isolated power system operation.**

Keywords-energy storage; hybrid power stations; isolated power systems; pumped hydro storage; wind turbines

I. Introduction

The majority of Greek islands in Aegean Archipelagos are not interconnected with country's continental system. The electricity market of these islands consists 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 (contains 19 systems), b) "medium" systems with peak demand from 10 MW to 100 MW (contains 11 systems), and c) "large" systems with peak demand exceeding 100 MW (contains 2 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 to 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]-[4].

More specifically, an isolated power system with increased RES techologies power penetration has significant differences from an interconnected power system. First, the isolated power system presents low minimum to maximum demand ratio and significantly larger frequency deviations with relatively small production or demand changes compared to an interconnected power system. Furthermore, quite often the installed thermal units have significant values of technical minimum that introduce problems in co-operation between thermal units and wind power making the operators disconnect some of the wind power production in order to avoid technical limits violations [5]. It has also to be noticed that the operational cost of conventional generators in these systems can be high – in many cases and especially during peak hours exceeds 200 €/MWh, while is much depending though on oil prices [6].

The operation of an isolated system can be improved significantly by the installation of a large scale energy storage system [7]. 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 [8].

This paper studies the effect of installing a hybrid power station in the medium sized isolated power system of Samos Island. Hybrid power stations combine the installation of a (usually) large scale energy storage technology with a renewable energy technology. During the last years, the Greek legislative framework provides 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 it studies the economic viability of this project under different billing scenarios, as well as its impact to the isolated power system operation.

The paper is organized as follows: Section II contains a brief description for hybrid power stations in Greece and it is mainly focused in their operation at isolated power systems. Section III provides information for the basic characteristics of the isolated power system of Samos Island. Section IV includes the basic considerations and presents the main results of the analysis, which include economic evaluation, optimal sizing of hybrid power station, and comparison of power system operation before and after the installation of hybrid power station. Section V concludes the paper.

II. Operation of Hybrid Power Stations in Greek Isolated Power Systems

According to the Greek legislative framework [9], 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 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 [10]. It has 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.

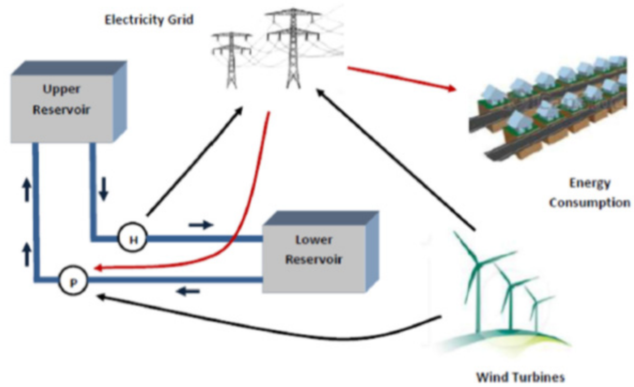

Fig. 1. Structure of a hybrid power station [11].

The hybrid power station owner declares the 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 hybrid station with respect to reservoirs 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, in the case that 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 that [12]: a) the daily produced energy has to be at least $2 \times P_{hydro}$, and b) in certain days (especially with high loads) the hybrid station has to provide its guaranteed energy.

III. Description of Samos Island Power System

The isolated power system of Samos Island is fed by a diesel power station had a total installed capacity of 47.75MW. 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 I. Moreover, Table I presents the priority list of these units, which is used in unit commitment. The distribution network on the island consists of several 15kV medium voltage (MV) overhead lines [13].

TABLE I. 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 2 depicts the net load duration curve (without considering PV production) for Samos Island, with data referring to year 2015. The peak load is 30.2MW and it is achieved through summer, whereas the minimum load is 7.56MW and takes place in April. As a result, the minimum to maximum load ratio is equal to 0.25. The annual electricity demand is 140GWh. Regarding WTs, several wind parks with 7.975MW total capacity have been installed. Their annual capacity factor (CF) is equal to 29.38%. Figure 3 shows the wind power duration curve. The maximum WTs power output is 92.41% related to the installed WT capacity. Moreover, in Samos Island have been installed 63 small PV parks with 4.373MW rated power, as well as 0.113MW roof PVs. As a result, the total installed PV power for year 2015 reaches 4.486MW. The annual CF for PV installations is 17.7%.

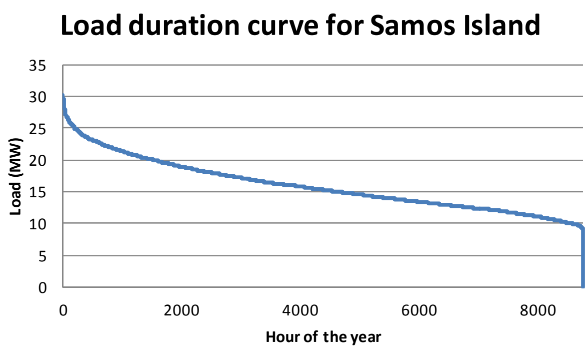

Fig. 2. Net load duration curve for Samos Island (year 2015).

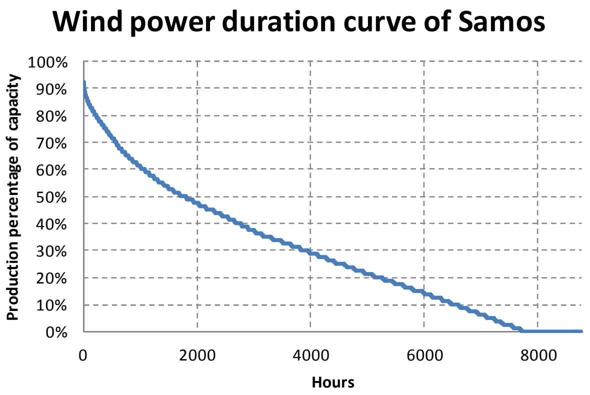

Fig. 3. Duration curve of existing wind farms generated power.

IV. Results and Discussion

In this paper, the operation of the isolated power system of Samos Island is implemented, using 8760 hourly time steps (one year) for net load demand and wind power production. Initially, a simulation of system's operation in its current state (without hybrid power station) 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 I. A strict rule for spinning reserve has been considered as follows:

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

where u_i is the i unit status (1 for ON and 0 for OFF), P_{imax} 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. Initially, a simulation run was executed for the annual operation of Samos Island power system, without considering the installation of hybrid power station. The results are shown in Fig. 4, for which it can be concluded that almost 70% of Samos total electricity needs are supplied by the first two units of Table I. The RES technologies (WTs and PVs) penetration surpasses 19%. The annual operating cost of all conventional power units is 9,887,800 €.

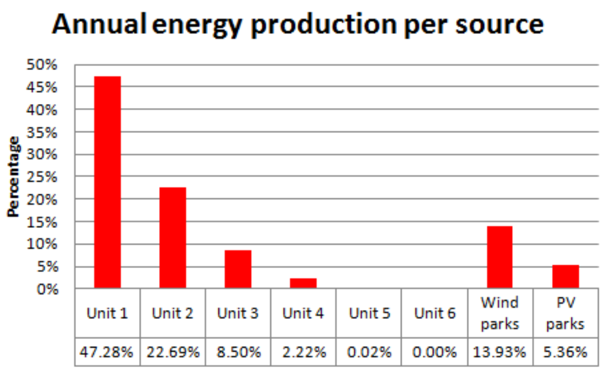

Fig. 4. Annual energy production in Samos Island per different source (no hybrid power station existence).

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

- The efficiency of pump unit is considered 78% and the efficiency of hydro unit is considered 90%. As a result, the total efficiency of PHS unit is n_{total}≈70%.
- P_{pump} is considered to be equal to P_{hydro} / n_{total}.
- The CF of newly installed WTs is considered to be equal to CF of the already installed wind farms (i.e., 29.38%).
- 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.
- The minimum time interval of hydro turbine daily operation at its rated power (P_{hydro}) is 2 hours, as defined by the Greek operation code [12]. The time interval of hydro turbine daily operation at its guaranteed power (P_{hydro}) is 8 hours.
- The days in which the power system Operator needs the guaranteed energy from the PHS system, regardless of the 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 on the summer period).
- 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 hours.

A. Economic Analysis

In order to evaluate the performace 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 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 annualy 127,000 €/MW. Energy absorbed from grid has a cost of 103 €/MWh, which is equal to 147 × n_{total} €/MWh.

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 98€/MWh. The economical indices that were examined are the net present value (NPV) and the internal rate of return (IRR), 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. The 70% 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.

Tables II-IV present the economic evaluation results for three scenarios regarding 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_{WTnew} represents the newly installed wind turbine capacity of the hybrid power station. In all cases, wind parks of large capacity have to be installed due to moderate annual CF value of WTs (less than 30%). The lower P_{WTnew}/P_{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_{WTnew} is higher.

TABLE II. EVALUATION OF THE TWO BILLING SCENARIOS CONSIDERING HYDRO CAPACITY EQUAL TO 3.5 MW

P_{WTnew}/P_{pump}	NPV_1[a] (€)	NPV_2[b] (€)	IRR_1[a]	IRR_2[b]
120%	4,909,683	3,981,900	14.08%	12.83%
160%	9,020,303	6,844,639	18.58%	15.79%
200%	11,343,356	8,427,785	20.21%	16.81%
210%	11,722,110	8,665,929	20.34%	***16.86%***
220%	12,021,393	8,840,636	***20.37%***	16.83%
230%	12,264,786	8,974,999	20.34%	16.77%
240%	12,438,974	9,047,851	20.24%	16.64%
250%	12,549,807	***9,067,006***	20.07%	16.46%
260%	12,611,698	9,044,869	19.86%	16.25%
270%	***12,631,382***	8,984,814	19.62%	16.01%
280%	12,596,287	8,875,455	19.34%	15.74%

a. Index 1 refers to scenario 1

b. Index 2 refers to scenario 2

TABLE III. EVALUATION OF THE TWO BILLING SCENARIOS CONSIDERING HYDRO CAPACITY EQUAL TO 7 MW

P_{WTnew}/P_{pump}	NPV_1 (€)	NPV_2 (€)	IRR_1	IRR_2
120%	9,226,887	7,371,415	13.67%	12.44%
160%	15,872,273	11,520,944	17.18%	14.44%
190%	18,286,535	12,769,403	17.89%	***14.66%***
200%	18,789,855	12,958,713	***17.93%***	14.60%
210%	19,137,361	***13,024,999***	17.88%	14.47%
220%	19,346,454	12,984,939	17.75%	14.30%
230%	***19,502,106***	12,922,530	17.60%	14.12%
240%	19,477,345	12,695,098	17.36%	13.86%

TABLE IV. EVALUATION OF THE TWO BILLING SCENARIOS CONSIDERING HYDRO CAPACITY EQUAL TO 10.5 MW

P_{WTnew}/P_{pump}	NPV_1 (€)	NPV_2 (€)	IRR_1	IRR_2
120%	13,283,615	10,500,408	13.42%	12.20%
160%	22,169,407	15,642,415	16.48%	13.78%
170%	23,338,191	16,168,454	16.73%	***13.83%***
180%	24,274,530	16,524,649	16.88%	13.81%
190%	24,921,215	16,645,516	***16.90%***	13.71%
200%	25,407,742	***16,661,029***	16.86%	13.58%
210%	25,681,577	16,513,034	16.74%	13.39%
220%	***25,786,125***	16,243,852	16.56%	13.17%
230%	25,752,692	15,883,328	16.35%	12.93%

The results of Tables II-IV show that all options are economically viable, 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 the large duration of the project and the high installation costs of system's components.

B. 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 considering P_{hydro} = 7 MW (see Table III) is adopted. Figure 5 presents the annual energy production per different type of source. The comparison of Fig. 4 with Fig. 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%, which is considerably smaller from the maximum allowable limit of 30% (see Section II). 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 24% 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 from the cost of Section IV.A configuration.

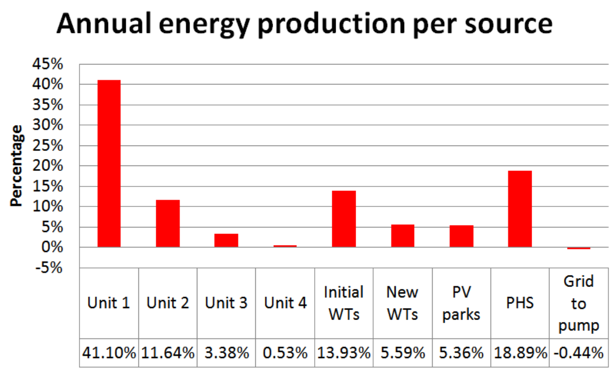

Fig. 5. Annual energy production in Samos Island per different source considering hybrid power station operation.

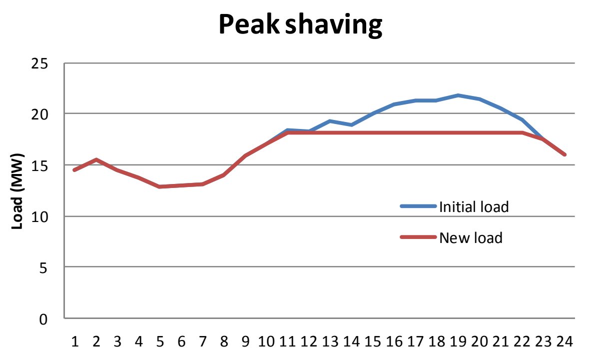

Fig. 6. Peak shaving operation of hybrid power station (day 4 of the year).

Figures 6 and 7 show the differences that occur in daily load curves of Samos Island isolated power system due to hybrid power station operation. More specifically, Fig. 6 shows the load peak shaving during high load hours for a typical day, in which the Operator does not need the guaranteed energy. In Fig. 7, a case of high load-low wind has been considered, in which the charging from grid occurs at the first hours of the day (valley filling), whereas peak shaving occurs the late hours of the day.

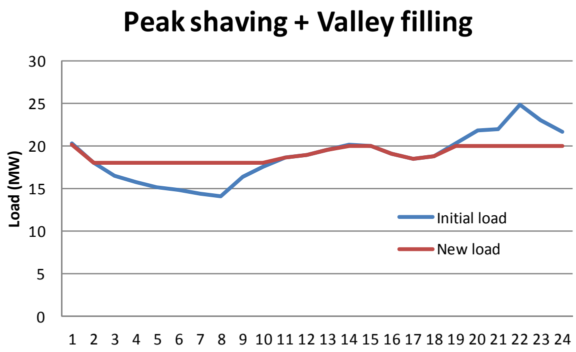

Fig. 7. Peak shaving and valley filling operation of hybrid power station (day 205 of the year).

V. 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. 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 station. In all cases, the first option that considers price of 200 €/MWh for produced PHS electricity led to significantly better results compared to the second option that considers 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 is examined, by considering HPS output capacity of 7 MW, which is 23% of the annual peak load. The results showed that the total hybrid power station penetration surpassed 20%, the annual cost reduction of generating units was almost 30%, and the new load curves were significantly smoother.

References

[1] G. N. Psarros, S. I. Nanou, S. V. Papaefthymiou, and S. A. Papathanassiou, "Generation scheduling in non-interconnected islands with high RES penetration," Renew. Energ., vol. 115, pp. 338–352, 2018.

[2] Regulatory Authority for Energy – Greece. Available: http://www.rae.gr/site/en_US/portal.csp

[3] Y. A. Katsigiannis, P. S. Georgilakis, and E. S. Karapidakis, "Hybrid simulated annealing–tabu search method for optimal sizing of autonomous power systems with renewables," IEEE Trans. Sustainable Energy, vol. 3, no. 3, pp. 330–338, 2012.

[4] E. S. Karapidakis and N. D. Hatziargyriou, "Online preventive dynamic security of isolated power systems using decision trees," IEEE Trans. Power Syst., vol. 17, no. 2, pp. 297–304, 2002.

[5] A. G. Tsikalakis, N. D. Hatziargyriou, Y. A. Katsigiannis, and P. S. Georgilakis, "Impact of wind power forecasting error bias on the economic operation of autonomous power systems," Wind Energy, vol. 12, no. 4, pp. 315–331, 2009.

[6] M. Kapsali, J. S. Anagnostopoulos, and J. K. Kaldellis, "Wind powered pumped-hydro storage systems for remote islands: a complete sensitivity analysis based on economic perspectives," Appl. Energ., vol. 99, pp. 430–444, 2012.

[7] Y. A. Katsigiannis, E. S. Karapidakis, A. G. Tsikalakis, and A. Katsamaki, "A review of the proposed large-scale energy storage applications on the autonomous power system of Crete," [Proc. Recent Advances in Energy, Environment, Economics and Technological Innovation, pp. 45–54, 2013].

[8] I. Hadjipaschalis, A. Poullikkas, and V. Efthimiou, "Overview of current and future energy storage technologies for electric power applications," Renew. Sust. Energ. Rev., vol. 13, iss. 6, pp. 1513–1522, 2009.

[9] Hellenic Republic Ministry of Development, "Law 3468/2006: Generation of Electricity using Renewable Energy Sources and High-Efficiency Cogeneration of Electricity and Heat and Miscellaneous Provisions," Athens, October 2006.

[10] K. E. Fiorentzis, Y. A. Katsigiannis, E. S. Karapidakis, and A. G. Tsikalakis, "Evaluating the effect of wind-hydro hybrid power stations on the operation of Cretan power system," [52nd International Universities' Power Engineering Conference (UPEC 2017), Heraklion, Crete, Greece, pp. 1–6, 28-31 August 2017].

[11] S. Rehman, L. M. Al-Hadhrami, and M. M. Alam, "Pumped hydro energy storage system: A technological review," Renew. Sust. Energ. Rev., vol. 44, pp. 586–598, 2015.

[12] Regulatory Authority for Energy (RAE), "Electrical system operation code for non-interconnected islands (version 2)," April 2018 (in Greek). Available: https://www.deddie.gr/el/themata-tou-diaxeiristi-mi-diasundedemenwn-nisiwn/ruthmistiko-plaisio-mdn/kwdikas-diaxeirisis-ilektrikwn-sustimatwn-mdn/kwdikas-diaxeirisis-mdn/

[13] Y.A. Katsigiannis and E.S. Karapidakis, "Operation of wind-battery hybrid power stations in autonomous Greek islands," [52nd International Universities' Power Engineering Conference (UPEC 2017), Heraklion, Crete, Greece, pp. 1–5, 28-31 August 2017].