Operation of a Greek Island Power Grid Under Various Simulated Scenarios of Combined RES and Battery Based Storage Systems

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***Abstract*—In Greece there are numerous islands, with some common characteristics of their typical load profile, powered by diesel generators, at a variable cost of electricity due to the fuel consumption much higher than the cost of electricity in the mainland. On the other hand RES technologies like PVs and wind turbines have recently become even more cost effective, with the cost of energy produced by these technologies to be comparable or even lower than that of conventional centralized power plants. However the exploitation of these intermittent RES technologies is limited in the islands, due to constraints imposed by the operation of the power grid, such as the minimum technical limits of the diesel generators as well as a maximum value of instantaneous RES penetration in order to avoid unsecure operation of the electrical system.**

These issues, also present in large interconnected electrical systems, are dealt in this paper for the case of small islands. Various scenarios of the use of battery systems are examined, in order to study the energy benefits by the use of such systems, concerning the potential increase of RES share in the total electricity production of the power grid. The results are derived through the hourly simulation of the annual operation of a typical small to medium scale Greek island, based on typical profiles of consumption and RES production, and considering various sizes of storage systems and modes of operation.

Keywords- RES;Storage;Battery;Islands

I. Introduction

The integration of a significant share of renewable energy sources (RES), mainly variable RES such as wind and PVs, into the electricity mix requires significant transformations of the existing networks, leading to the concept of the so-called smart grids. A main feature of the smart grids, that will facilitate the integration of RES, is the introduction of energy storage capacity. A battery based storage system is a valuable tool, capable to provide a wide range of services to the operation of a smart grid. As a result a wide range of applications for grid-connected battery storage systems can be identified. These can be roughly distinguished to energy related applications, characterized by charge-discharge cycles of several hours, and power related applications, characterized by cycles of charge-discharge of shorter periods (seconds to minutes) [1].

The aim of this work is to study the energy benefits that can be achieved by the use of battery storage systems in the electrical system of a typical Greek island, through the reduction of the curtailments of RES energy which are imposed by the operational constraints. The study is based on the current rules of operation of the electrical system and is focused on the energy results. The economic terms of such applications are expected to change rapidly, as according to the predictions of experts, the cost of storage has a large reduction potential in the next few years, especially for technologies like lithium-ion batteries and flow batteries [2].

II. THE CASE OF GREEK ISLANDS

Most of the Greek islands currently are powered by a local power station based on conventional diesel-fueled generators, at a cost of electricity much higher than that of the interconnected system. Examples of the size of the demand and the costs of electricity for some of the islands, for the year 2017, are presented in Table I, as derived by the site of the HEDNO, the Greek Distribution System Operator (DSO).

HEDNO is responsible for the technical and economic management of the system according to the legislative framework defining the technical requirements, policy, planning, operation procedures and connection standards for generating units in the non-interconnected islands (NIIs) as included in the NIIs Code. Some main points of the operation procedures, from the NIIs Code, are presented in the followings [3], [4].

TABLE I. SIZE OF DEMAND AND COST OF ELECTRICITY FOR SOME GREEK ISLANDS.

Island	Peak demand (MW)	Annual Energy demand (MWh)	Average Total Cost of electricity (€/MWh)	Average Variable Cost of electricity (€/MWh)
AG. EYSTRATIOS	0.31	1,092.9	592.05	257.95
AMORGOS	3.15	10,233.8	359.94	217.09
ANAFI	0.50	1,296.7	617.09	253.31
ASTYPALAI A	2.21	6,447.5	374.83	221.08
IKARIA	6.70	25,219.2	422.78	254.35
KARPATHOS	11.30	32,823.3	233.26	100.31
SAMOS	29.60	112,161.5	164.41	87.20
SIFNOS	6.22	22,681.3	348.31	206.62
THIRA	42.80	180,769.5	183.24	115.33
MEGISTI	0.91	3,539.6	480.70	245.28

The current electricity market structure for the NII foresees a Day Ahead Scheduling (DAS) with the participation of all market actors (producers and suppliers). The DAS is determined by HEDNO and defines on a daily basis the dispatch algorithm of dispatchable diesel generation units, as well as calculates for every dispatch hour (t) the maximum level of power injection from all the non-dispatchable RES units, in case that this is required in order to ensure secure operation of NIIs according to the security and operational standards specified in the Code. The methodology of this scheduling process is based on RES and load forecasting data which are utilized to optimize the next day operational plans based on availability of conventional units and other factors related to the operation of the system, known to the operator of each NII, e.g. maintenance schedule, ramp up time etc., as well minimizing the total operational cost of conventional production units.

Generally, HEDNO is obliged to prioritize electricity produced by RES plants, including hybrid stations and thereafter the surplus of energy produced by an auto-producer or a high-efficiency cogeneration plant, instead of conventional units‘ production, provided that secure operation of the system is ensured. In addition, RES plants installed on NIIs are subject to operational constraints which result to curtailments of their output, when the RES penetration becomes considerable. These operational constraints are due to technical restrictions of the conventional generator units connected to the same grid. These units, using mainly light diesel or heavy fuel oil, should not operate below a specific threshold of power output in order to avoid wear and increased maintenance. This limitation, known as “technical minima” is currently relatively high. A different limitation, often referred to as “dynamic penetration limit” is dependent on the explicit characteristics of the NIIs (size, type of conventional units, load type etc.) and expresses the dynamic stability of the system, i.e. the effect of faults or unplanned units disconnection on the operation of the system in terms of voltage and frequency.

According to the legislative framework, the operation of Hybrid Stations is foreseen for NIIs. A Hybrid Station is a power station, which uses at least one form of RES and combines energy storage systems. The main goal of Hybrid Stations is to increase RES penetration in the NIIs, especially in those on which it is not possible to include additional RES capacity. Thus, the fundamental principle for the operation is to store the RES energy at first priority, instead of injecting it directly to the grid. The energy could be used later, in a controllable way, replacing expensive thermal units. The energy of the storage system is then supplied to the system as a firm energy, equivalent to the energy from a dispatchable generator, overcoming thus the constraint due to the dynamic penetration limit of RES production (maximum instantaneous penetration of RES). Furthermore, the Hybrid Stations replace not only energy but also capacity from the conventional thermal units. In order to guarantee the provision of firm capacity, it is allowed to store energy from conventional thermal units if the RES unit of the Hybrid Station cannot produce the necessary energy. Hybrid Stations receive payments for both the energy and the capacity. Namely the prices of the energy injected directly from RES are the same as the prices for RES stations of similar technology. The price of the energy coming from the storage systems is 50% higher than the RES price, this methodology however may be revised. The price for the capacity is defined based on the local characteristics of each island electrical system.

The market operation in the NIIs is less complex in comparison to standard electricity markets. Namely the thermal conventional units declare only the technical characteristics and their availability. The participation of the Hybrid Systems to the DAS is accomplished with the declaration of the amount of energy that the station is willing to inject or absorb the next day. The Hybrid station may absorb energy if there is a request for guaranteed capacity provision by the System Operator. The systems operator produces the hourly schedule for the next day by solving an optimization problem trying to maximize the RES penetration and minimize the thermal production cost, taking into account all the necessary technical constraints to ensure system safety.

Moreover, there is a consultation on the possibility for the integration of storage systems within RES plants installed on the non-interconnected islands that could facilitate the reduction of curtailments of RES plants which are caused due to system constraints.

To support the processes defined in the NIIs Code, it is foreseen the establishment of Energy Control Centers infrastructure, locally and centrally.

However in practice, for many islands, especially the small ones, the procedures foreseen in the NIIs Code, are not fully applied. On the contrary the operation of the electrical system is based on empirical rules by the operators of the local power station. These include the procedures for the dispatching of the conventional generators, while a dynamic limit of RES penetration, in relation to the instantaneous load, is always respected.

III. CASE STUDY – APPROACH

For the investigation of the various scenarios of operation, an example of a typical island was selected based on realistic data.

The load of the island corresponds to an annual demand of 8737 MWh, with a peak demand of 3.1 MW and a lowest demand of 0.4 MW. The annual load profile is shown in Fig. 1.

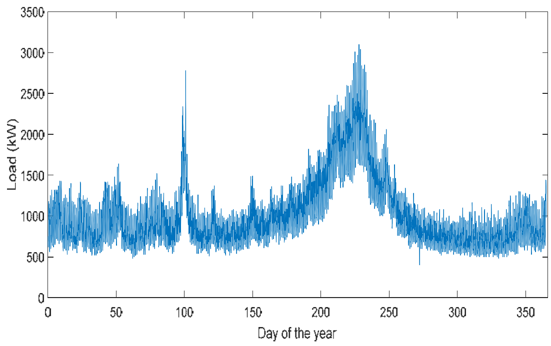

Figure 1. Annual load profile of the island of the case study.

This annual profile is very representative of many Greek islands with a touristic season. Actually a scaling of this profile to the size of another island could reproduce quite well the load of the island, assuming it has the same seasonal behavior due to tourism.

The local power station of the island is equipped with 3 similar diesel units of a maximum power of 1MW and four similar diesel units of a maximum power of 0.3MW. The technical minimum of these units is considered to be 40% of the nominal power value.

The RES units have been simulated based on hourly values of power output per installed capacity, adapted from real typical applications. The annual capacity factor for the output of a RES unit concerning PV technology accounts to 19.5%, while for wind technology it accounts to around 30%.

The simulations of the operation of the electrical system of the case island were conducted based on hourly energy values, with an own developed software tool.

The program takes as input the hourly time-series of the load, the production of the RES units, and the technical characteristics of the conventional generating units of the system, including their consumption curve. For the scenarios including storage units (battery-based), the battery model of [5], [6] was used, which is a relatively simple model based on energy values, without a detailed representation of the current and voltage of the battery. The parameters of the model which have been used concern a typical lead-acid battery cell. The size of the battery is defined in terms of its C_{10} capacity, while a 60% depth of discharge is allowed during operation.

The simulation involves the calculation for each hour of the net load and based on this value the appropriate conventional unit commitment. The conventional unit commitment is based on an hourly basis on a priority list. Due to the small size of the load, usually one unit or a small number of units should be found, as an optimum combination of units that fulfills at the same time the constraints and requirements for each hour. Based on the operating conventional units the curtailments of RES production are calculated, due to the technical minimum limits of the conventional units or due to the dynamic limit of RES production (maximum instantaneous penetration of RES). According to the typical practice in islands, a 35% dynamic limit, i.e. a maximum allowed instantaneous penetration of RES production of 35% of the current hourly load, has been used in the simulated scenarios.

IV. RESULTS OF SIMULATED SCENARIOS

The results from the simulations of the operation of the electrical system of the island of the case study, are presented in the followings, for various operating scenarios.

A. Simulated Scenario 1

First the operation of the electrical system without any storage is considered. For this base scenario it is assumed that the system is operating with the conventional generators and RES plants. More specific, a small amount of PV generation, by PV plants of a total of 240 kWp is considered, plus a wind generator. Two sizes of capacity of the wind generator are examined, one of a value of 500 kW and one of a value of 900 kW. The typical size of modern wind generators is an issue for the small size of electrical systems of many islands, and the size of the wind generator is most probable to be defined by the available models of the market. This lack of choices may result to a choice of a larger size wind generator, which will have to limit its output at a reduced level in order to overcome restrictions of the system and the grid.

Due to the aforementioned constraints part of the RES energy has to be curtailed. Actually curtailments of the RES energy are required when the size of the RES units, PV and/or wind, is such to correspond to a RES share of approx. 10%. For higher values of RES share to be achieved, curtailments will be required, given the defined system constraints. So it is important for the new RES units which are to be installed to afford the possibility of control of their output. It is interesting to note that for the same RES share value, the required curtailments are smaller for the case that two RES technologies are used, than the case when only one RES technology is used. This positive effect of the combination of the two technologies seems to be attributed to the more even distribution of the energy in time and the avoidance of high peaks of the generated power, that are prone to curtailments.

By the simulation of the operation for one year the results of Table II are derived. The calculated curtailments are applied on the production of the wind generator, according to the current practice, by using the ability of the wind generators for control of their output at an external command.

TABLE II. SUMMARISED RESULTS FOR SCENARIO 1

Wind Generator size (kW)	Wind curtailments (%-MWh)	RES share with curtailments (%)	RES share without curtailments (%)
500	17.68%-218.4	16.3%	18.8%
900	40.23%-907.8	20.1%	30.5%

In the case of the 500 kW wind generator, an energy amount of 1239 MWh could theoretically contribute to the load, raising the RES share to the annual consumption to a value of 18.8%. However due to the aforementioned constraints, a part of this energy (218.4 MWh) will have to be curtailed, resulting to actual wind generated energy of 1020.6 MWh and reducing actual RES share to the value of 16.34%.

In the case of the 900 kW wind generator, an energy amount of 2256 MWh could theoretically contribute to the load, raising the RES share to 30.5%. Due to the large amount of curtailments that are required, only 1348.73 MWh of wind energy are used, and the actual RES share is decreased to 20.1%. The corresponding fuel savings account to 308.6 tn of diesel in this case.

The main reason for most of the curtailments is the RES dynamic limit. If the constraint of the maximum value of instantaneous RES penetration is relaxed, leaving only the constraint of the technical minimum of the conventional generators, the usable wind energy for the 900 kW wind generator would account to 2049 MWh, i.e. the curtailments of the wind energy would be reduced to 9.17%. In this mode of operation of course at least one conventional generator is always operating.

An example of the operation of the system, with the 900 kW wind generator, is shown in the following Fig. 2. In this Figure the load is the red solid line. The area below the load is covered by the output of the conventional generators (blue area) and the used production of RES units (grey area). The output of the conventional generators is at least 65% of the value of the load, due to the application of the RES dynamic limit. The blue dashed line is the theoretical RES production, added to the output of the conventional generators. That is, the RES theoretical production is the area between the blue dashed line and the edge of the blue area. The part of this area which is used for the coverage of the load is the grey area, while the white area below the blue dashed line is the curtailed RES energy.

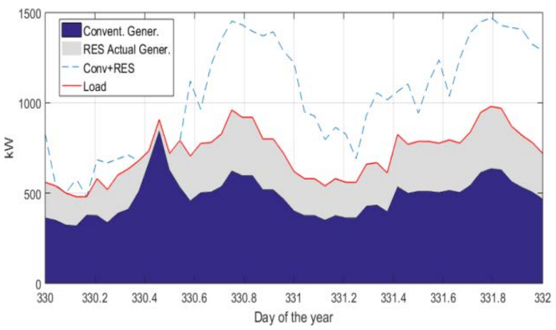

Figure 2. Plot of energy use, for two days of the operation of the system with the 900 kW wind generator.

B. Simulated Scenario 2

A battery with a converter is added to the system of the previous scenario. For this scenario, the same dynamic limit, i.e. a maximum allowed instantaneous penetration of RES production of 35% of the current hourly load, has been used. The battery is assumed to use part of the wind energy that is curtailed, whenever this is possible for the battery to accept, and then to discharge the stored energy to the system as soon as this is possible, substituting thus energy by the conventional units. The part of the wind energy which, instead of being curtailed, is used for charging of the battery is shown in the following Tables, in Column 'Energy Charged'. A 'RES' share of the consumption is calculated also, as the ratio of the RES energy directly supplied to the system plus the discharged energy, divided by the total annual consumption (the RES energy directly supplied to the system is equal to the value of the previous scenario).

The results for various sizes of converter and battery, are shown in the following Table III, regarding the case of a wind generator of 900 kW.

TABLE III. MAIN RESULTS FOR THE SCENARIO 2 WITH THE 900 KW WIND GENERATOR AND STORAGE.

Converter size (kW)	Battery size (kWh)	Energy charged (MWh)	Energy discharged (MWh)	'RES' share (%)
0	0	0	0	20.1
100	500	83.21	66.65	20.86
100	1000	116.56	93.36	21.16
250	1000	135.2	108.3	21.3
500	1000	136.02	108.95	21.34
500	2000	199.87	160.1	21.92
500	4000	289.52	231.91	22.75

Considering the case of a wind generator of 900 kW, where without any storage an energy amount of 907.8 MWh was curtailed, by using a battery storage system, only a relatively small amount of this energy can be used for the charging of the battery. For the 500 kW/4000 kWh system for example, 289.5 MWh can be exploited, a 31.9% of the curtailed energy. The RES share consequently cannot be significantly increased with the addition of a battery of a reasonable size. The energy benefit depends on the size of the battery. Regarding the size of the converter, if a too small value is selected it may be not able to absorb the required power for some periods, and so to reduce the benefit for the same size of battery. The results regarding the smaller wind generator of 500 kW show a similar trend. Only a limited amount of the curtailed wind energy can be exploited by a same size storage system, although larger as percentage (63%) compared to the wind generator of the larger size.

The operation of the system, for the case of a wind generator of 900 kW and a storage system of 500 kW/2000 kWh, is shown in Fig. 3, analogous to Fig. 2, for the same days. In this case the energy of the storage unit is shown also, the area in brown color. When the brown area is below the red solid line (load), this is energy discharged by the battery to contribute to the load. When the brown area is above the red line, this is energy charged to the battery, supplied by the wind unit. The white area below the blue dashed line is the wind curtailed energy for this scenario.

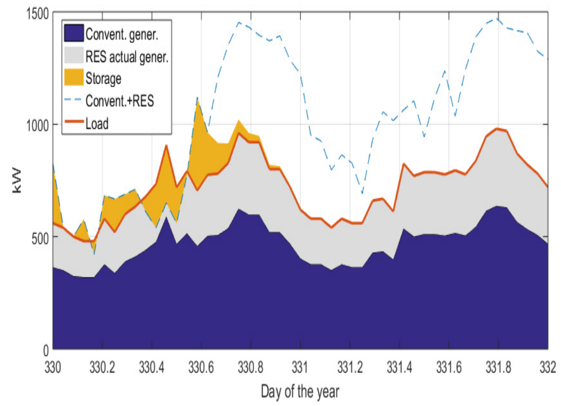

Figure 3. Plot of energy use, for two days of the operation of the system with the 900 kW wind generator and a storage system consisting of a converter 500 kW and a battery 2000 kWh.

The battery State of Charge (SOC) is shown in Fig. 4.

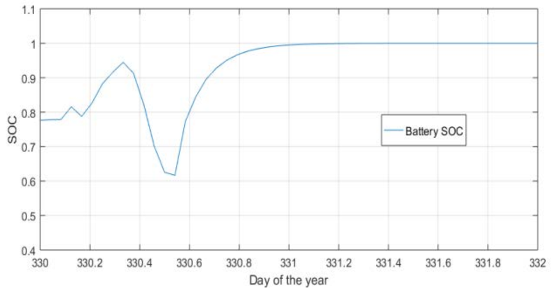

Figure 4. Battery State of Charge (SOC).

The example shown can evidence the relatively small benefit of the battery to the wind system. It is usual, as in the example, that the periods of high wind potential may cover several days, and this makes difficult the storage of the generated energy, as a reasonably sized battery will soon get full.

On the contrary the hours of energy production of a PV system are limited by the daily sunshine hours, allowing the battery to perform daily cycles of charge-discharge and avoiding prolonged periods at full state of charge and inability to accept energy.

For a PV system of a capacity of 900 kWp, the simulation results for various sizes of converter and battery are shown in Table IV. In the case without storage, an energy amount of 1554 MWh could theoretically contribute to the load, raising the RES share to the annual consumption to 22.4%. Due to the constraints however, a 47.5% of the PV energy will have to be curtailed, and only 815.8.7 MWh of the PV energy are used, resulting thus to RES share of 14%. PV curtailments account for a total of 738.5 MWh.

TABLE IV. MAIN RESULTS FOR THE SCENARIO WITH THE 900KWP PV PLANT AND STORAGE.

Converter size (kW)	**Battery size (kWh)**	**Energy charged (MWh)**	**Energy discharged (MWh)**	**'RES' share (%)**
0	0	0	0	14%
100	500	124.78	100.27	15.14
100	1000	212.18	170.6	15.94
250	1000	243.58	195.75	16.23
500	1000	243.93	196.03	16.23
500	2000	441.0	354.64	18.05
500	4000	670.7	539.8	20.17

As shown in the Table, a large amount of the PV energy which would have to be curtailed otherwise, can be used to charge the battery and be discharged later. A percentage value as high as 90% of the curtailed energy, can be achieved for the charging of a reasonably sized battery. This indicates that PV technology matches better than wind technology to be combined with battery systems, in applications concerning the storage of otherwise curtailed energy.

C. Simulated Scenario 3

This scenario concerns the operation of a hybrid system composed of a wind generator of 900 kW and storage, under the current legislative framework for hybrid systems.

For the wind generator, of nominal capacity of 900 kW, a storage system of nominal capacity of 760 kW is selected, as the wind capacity should not be higher than 120% of the installed storage capacity, according to legislation.

For this scenario a day ahead scheduling is applied, where the hybrid system is also participating. The day ahead scheduling in the simulation is based on the existing time series, assuming a 'perfect' forecasting of the load and the wind production for the next day. The main principles of the operation based on the Code of NII, which have been simulated, are the following.

The hybrid operator submits an energy offer for the next day. The system operator dispatches the value of the energy offer on the load curve, mainly at peak load hours. For the remaining load the conventional units are committed, as in the previous scenarios. For the RES energy directly fed to the system, a dynamic limit (set to 35%) is applied, in order to calculate any curtailments of RES required. The dispatched power of the hybrid system is supplied mainly by the storage unit. For this mode of operation, typically the dispatched energy delivered by the storage system has the highest price, so the RES energy of the hybrid system is used at first priority for charging of the storage, overcoming thus at the same time significantly the obstacle of the dynamic limit.

Besides this typical daily operation, in cases of high load periods, the system operator may request a guaranteed energy. In this case, the hybrid system operator may use energy from conventional units, typically during the hours of the valley of the load curve, to charge the storage system, after submitting a load declaration to the system operator.

Fig. 5 shows the load profile of the island for the day of the year with the peak load, when most probably the guaranteed energy will be requested. On the same figure the profile of the dispatched output of the hybrid system is plotted, based on the dispatch of a guaranteed energy value corresponding to 4 hours at the nominal capacity of the hybrid system. In this case the energy in the valley of the load curve is sufficient to be used for the charging of the battery, in order to meet the requirement of the guaranteed energy under a worst case scenario, i.e. if there is no wind production for this day. On the contrary, for values of guaranteed energy corresponding to a higher value of hours at the nominal capacity, this condition is not met, imposing a limit for the amount of the guaranteed energy of the hybrid system of the given size. A value of guaranteed energy corresponding to 4 hours at the nominal capacity has been defined in this case (although 8 hours are required by legislation). A battery of a size of 5500 kWh has been selected for the simulation of this scenario, which can easily meet the defined guaranteed energy value, taking into account the allowable depth of discharge value of 60%. It is noted that the peak reduction which is achieved, and which is the main aim of this guaranteed energy concept, is the same (760 kW) for the case where the 4 hours value is defined and for the case where a higher value of hours is defined.

By simulating the operation of the system based on the aforementioned mode of operation and parameters, it is calculated that the hybrid system can contribute by 1847 MWh to the load, which, if considered as RES energy, raise the 'RES' share to 25.8%. A percentage of 18.1% of wind energy is lost (409 MWh), due to curtailments on the part of the wind energy which is directly fed to the system and due to the storage conversion efficiency on the part of the wind energy that is used to charge the battery.

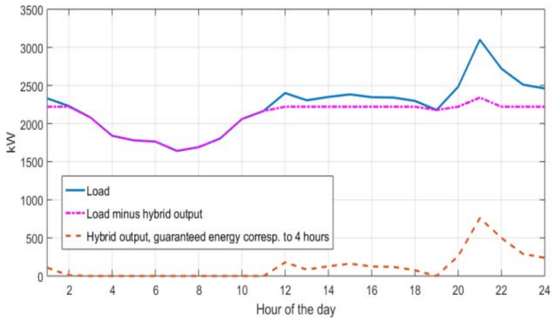

Figure 5. Profile of load, of hybrid system output for a value of guaranteed energy corresponing to 4 hours at nominal capacity of storage, and of the resulting new load curve, for the day of the year with the peak of load.

V. CONCLUSIONS

In this work some quantitative results have been presented, calculated by the simulation of the operation of the electrical system of a typical Greek island, and concerning the integration of RES units and the possibilities of increasing their share in the total electricity production by the use of battery based storage systems. It is pointed out the importance of an appropriate analysis tool which can be used in order to give an insight and assess the details of operation of the system, taking into account the special conditions that may exist for each island and the various parameters of each mode of operation. The analysis was focused in the energy results and has shown the benefits that can be achieved for the examined cases.

In terms of economics, even for the most favourable of the examined cases, the storage system could hardly be viable, from the investor's point of view, based on the current cost of storage and remuneration for the supplied energy. It is noted that the remuneration for the supplied energy is not related to the actual cost of electricity of the island. The cost of storage however has a large potential for reduction in the next years.

Besides this, additional benefits that may be introduced by the storage system have not been taken into account. Modern battery converters may utilize advanced control techniques that allow them to operate in a grid supporting mode, as often referred, offering valuable functions for the stable and secure operation of the grid. These advanced capabilities of the battery converters may allow the operation of the system at very high instantaneous penetration of RES or even allow the operation with the conventional power station shut down. Such a mode of operation allows the achievement of very high percentages of RES share. For the sizes of the examined cases, for example, if the conventional generators were allowed to shut down and the operation of the system was based on the combination of RES and storage units, RES production could be almost fully exploited.

The isolated electrical system of an island is a valuable field for the assessment of various operational scenarios and for the testing of new technological solutions. Unfortunately there is a lack of a sufficient number of such pilot projects on islands, that could test and verify such solutions and concepts of operation. The experience by such projects may be relevant and useful to larger systems also, for operation based on the concept of microgrids.

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