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Effect of Energy Storage in Increasing the Penetration of RES in the Remote Island of Agios Efstratios

I. Kyriakidis, P. Braun, S. K. Chaudhary

Abstract—Most of the inhabited Greek islands are not connected to the central electricity grid and their energy needs are satisfied by diesel power stations. The operation of such stations has negative economic and environmental effects related to the high transportation cost of fuels, increasing oil prices and CO_2 emissions. The replacement of fossil fuelled stations with hybrid ones that combine renewable energy technologies with energy storage systems will provide a promising clean energy generation alternative and contribute to the limitation of the aforementioned drawbacks. The current paper deals with the integration of such a hybrid power system in the autonomous power system (APS) of the Greek island Agios Efstratios. The objective is to study the effect of energy storage (ES) in increasing the penetration of renewable energy sources (RES) in the hybrid system. Two storage technologies, based on lead-acid batteries and compressed hydrogen, have been studied for this purpose.

Index Terms—batteries, energy management, hydrogen storage, islanding operation, microgrids, photovoltaics, renewable penetration, wind power.

I. INTRODUCTION

Several autonomous power system (APS) have been installed worldwide for the electrification of remote regions where interconnection to a transmission network is economically not feasible or impossible. Agios Efstratios is a small Greek island located in the northern part of the Aegean Sea. Due to its remote location, it is not connected to the grid. Diesel engine generators (DG) are installed for electricity supply. In order to save its fragile ecosystem, national authorities have decided to establish a fossil-fuel-independent energy profile on the island.

According to annual time series provided by the Center for Renewable Energy Sources and Savings (CRES), the island is endowed with a good wind profile, with average wind of approximately 9 m/s and solar insolation with an annual average of 170 W/m^2 as shown in Fig. 1. Therefore, wind turbine generators and photovoltaic (PV) panels have been proposed as the renewable energy sources (RES) for the island. Since such RES have stochastically variable generation pattern, battery and hydrogen based energy storage technologies have been envisaged as the enabling technologies to balance the power generation and demand. The objective of this study is to investigate different scenarios regarding their co-ordinated operation and the reduction of the diesel generation to raise the

RES penetration level. Under these scenarios, DGs can be utilized as a back-up power source when the combined generation from the RES and the storages fall short of the demand.

Similar projects for designing the hybrid renewable energy systems in isolated interconnected / stand-alone locations have been successfully accomplished in many countries and several others are under development [1]-[4].

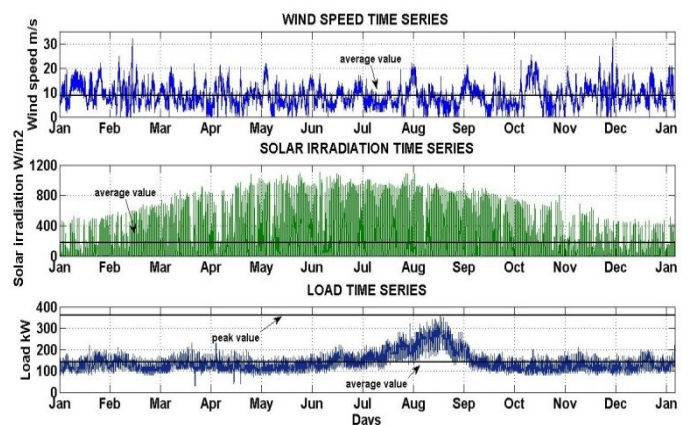


Fig. 1. Annual load, wind and solar profile on Agios Efstratios

This paper is divided into four sections. Section II describes the models of generation and storage units. In Section III, the operation of the energy management control algorithm is described. Section IV presents the simulation results for different operation scenarios of the hybrid system and Section V contains concluding remarks about the high level of RES penetration that can eventually be achieved.

II. LOAD AND GENERATION ON AGIOS EFSTRATIOS AND PROPOSED RES WITH STORAGE PLANT

As illustrated in Fig. 1, the island has a peak load demand of 360 kW and according to data provided by the Public Power Corporation (PPC) the annual energy demand of 1221 MWh. The island is supplied by the five diesel engines of total 840 kW capacity. Wind turbine generators of 680 kW total capacity and PV farm of 100 kWp power along with energy storages using lead-acid battery and hydrogen generation, as shown in Table I, have been proposed by CRES.

The capacities of the PV and wind plant have been chosen such that, in times of adequate wind and solar power potential, the RES units are able to cover the peak demand. For average wind speed and solar irradiation, the 680 kW wind power plant and 100 kWp PV farm would produce approximately 365 kW and 10 kW respectively.

TABLE I.
AUTONOMOUS POWER SYSTEM COMPONENTS AND RATINGS

RES/Storage Component	Power/Energy Rating
Wind turbines	2x330 kW & 1x20 kW
Photovoltaic farm	100 kWp (200 Wp x 500 modules)
Electrolyzer & gas compressor	100 kW, 10 Nm ³ /h
Hydrogen storage tank	200 kg max. volume (≈2.14 MWh)
Hydrogen generation sets	2x75 kW
Lead-acid batteries bank	2.5 MWh (3000 Ah x 2 V x 417 batteries)
Diesel generation sets	2x90 kW 3x220 kW

Apart from the excellent wind power potential of the island, there is also abundant solar irradiation (average: 4.08 kWh/m²/day) which justifies the installation of the PV farm. Furthermore, those technologies are complementary to each other [5]. PV supply power close to their rated value during periods of low wind power potential and the opposite.

The different components of the hybrid power system and their simulation model are described below.

A. Generators

1) Photovoltaic System

A photovoltaic system converts solar irradiation into electricity. The fundamental component of a PV system is the photovoltaic cell. The most commonly used model for a PV cell is the one-diode equivalent circuit shown in Fig. 2. Since a single PV cell can produce no more than a few Watts, modules and arrays are required in order to supply the electrical grid with larger amounts of energy. Modules are series-parallel connections of cells while an array is a group of modules connected in series and parallel circuits.

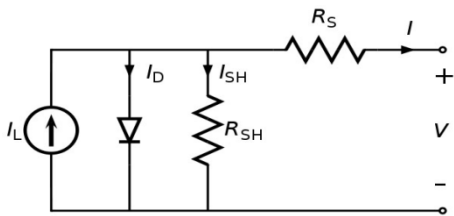
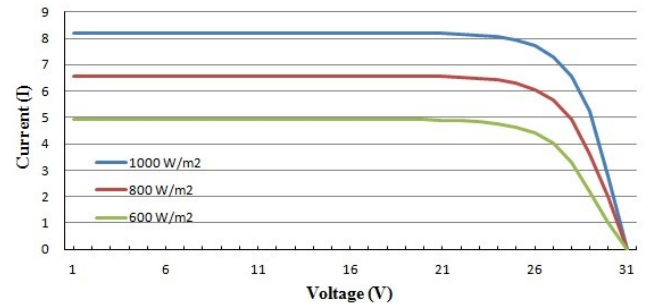


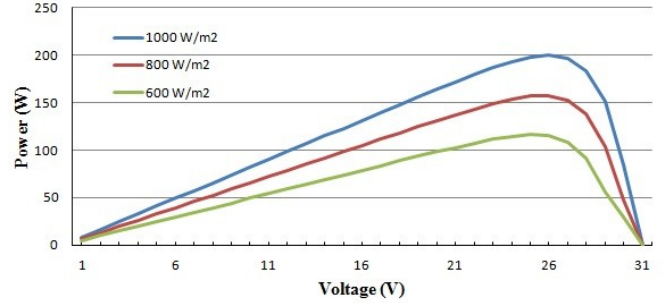
Fig. 2. Equivalent one-diode circuit model of a PV cell

The model consists of a diode, a series resistance which describes the internal resistance, a parallel one that depicts a leakage current and a photo current. The parallel resistance R_{SH} can be assumed to approach infinity without leakage current [6]. The PV model can be expressed by the characteristic between output voltage V and load current I as illustrated at Fig. 3.

For the model development, the technical characteristics of a multicrystal PV module are used as indicative values [7].



(a)



(b)

Fig. 3. Typical curves of a PV module $V-I$ (a) and $P-V$ (b) and characteristics for various irradiation levels

The maximum power that can be generated from each module of this type is 200 W under standard test conditions of 1000 W/m² and 25 °C. Furthermore, it is assumed that each module functions constantly at the maximum power point except for the cases of power curtailment when the output is set by the controller.

2) Wind Energy Conversion System

For this study, steady-state wind power plant models are used. Each wind turbine is represented by its power curve. The power curve of a variable speed 330 kW wind turbine is shown in Fig. 4. These curves are suggested by the wind turbines manufacturers and are considered to depict their power output at the maximum power point. The power production of the wind farm can be regulated through pitch control according to the decisions made by the controller.

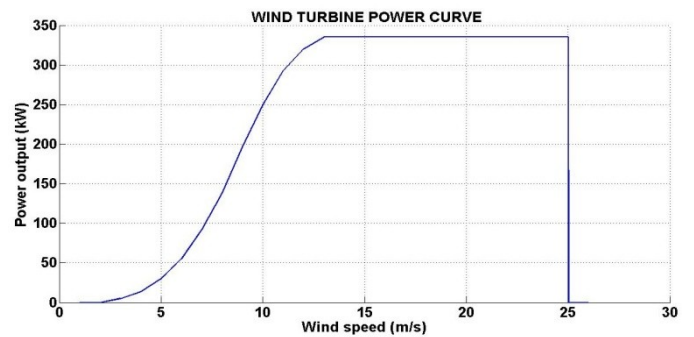


Fig. 4. Power curve of a 330 kW Enercon E33 wind turbine

3) Diesel Generation units

Diesel engines are frequently used as back-up generators at stand-alone systems due to their reliability, long lifetime and fast response. When in stand-by mode, they are able to supply

electrical power within approximately 10-15 s [8]. On the contrary, cold-start takes normally a few minutes according to the generator's capacity. In this project, it is assumed that they can be fully loaded within 10 minutes. The minimum load ratio is set by their operator to be 50% in order to avoid excessive wear out of the engine's mechanical parts and reduction of its lifetime. The ratings of the two diesel engines are given in Table II. There were used in the modelling of the diesel engines.

TABLE II
TECHNICAL CHARACTERISTICS OF DIESEL GENERATION UNITS

Unit	Nominal power (kW)	Minimum operation point (kW)	Fuel consumption rate (g/kWh)		
			50%	75%	100%
MAN DE2566/ME	90	45	291.9	265.8	263.3
HYUNDAI KD8AX	220	110	250.7	240.3	242.8

B. Energy Storage Systems

1) Hydrogen generation and storage system

A typical hydrogen generation and storage system comprises of an electrolyzer, a gas compressor, a tank and one or more generation units.

a) *Electrolyzer*: The electrolyzers split the water molecules in hydrogen and oxygen using electricity. An alkaline electrolyzer is modeled for this study as described in [9].

Its minimum operating point is 20% of its rated power [9]. The parameters used for the model development are based on [10].

b) *Hydrogen compressor and storage tank*: The hydrogen produced by the electrolyzer is compressed and stored into a tank at high pressure of 200 bars. This storage container is assumed to have a maximum capacity of 200 kg. The state of charge of the tank is calculated by dividing the amount of stored hydrogen with the tank's capacity and it is assumed that it cannot be discharged less than 10%.

c) *Hydrogen generation units*: The hydrogen generation sets are internal combustion engines (ICE) that use pressurized hydrogen gas as the fuel. It is assumed that two identical H_2 engines are included in the hybrid system of the island for reasons of security of supply and their nominal capacity is 75. The average efficiency of these engines is around 35% [11].

Despite the high cost and low overall efficiency (<30%) of hydrogen storage, its utilization is justified by the fact that it is the only ES system that allows a wide range of applications in all the three important sectors of an energy system (electricity, heating and transportation) and energy storage for long periods [12]. It is planned that hydrogen cars will be operated on the island [13].

2) Battery

Among the available types of storage technologies, lead-acid batteries are the oldest, most developed and common solution used in hybrid energy systems. Its largest advantages are the high reliability and efficiency, the fast response time

and low cost compared to other storage systems [14], [15]. For the model development of the battery bank it is assumed that each unit's rated capacity and voltage is 3000 Ah and 2 V respectively.

Since the peak power demand coincides with the zero generation from RES, the battery power capacity must be able to satisfy this peak demand. Moreover, its energy capacity must be adequate to supply full power for at least 2-3 hours since the average duration of deficit periods is 2.5 hours. The indicative storage device of 2.5 MWh is assumed to have 417 deep-cycle units with a round-trip efficiency of 85% and a power rating of 500 kW, which means that max C rate of the battery is 0.2. The upper and lower state of charge is considered as 90% and 10% respectively.

III. DESIGN OF THE ENERGY MANAGEMENT CONTROL ALGORITHM

An energy management controller is developed to balance the variations between supply and demand and maximize the production share that comes from renewables. On the basis of the unbalance in supply and demand, it decides what kind of regulations should be imposed to the hybrid system. In case of excess generation, the surplus energy is used for charging the storage devices. Among the two ES devices, batteries are set as a higher priority (for both charging and discharging) due to their faster response and higher efficiency. In practice, the charging process can be limited due to their state of charge or technical limitations. If there is still surplus power left, the output of the units must be curtailed or, in some extreme cases, the units have to be disconnected. On the contrary, in case of power deficit, one or both storage devices are activated depending on the amount of power required. Likewise charging, the discharging capability can be restrained as well. When the RES and storage cannot meet the demand, diesel reserve units are switched on in order to supply the rest of the power. Fig. 5 depicts the flowchart of the controller.

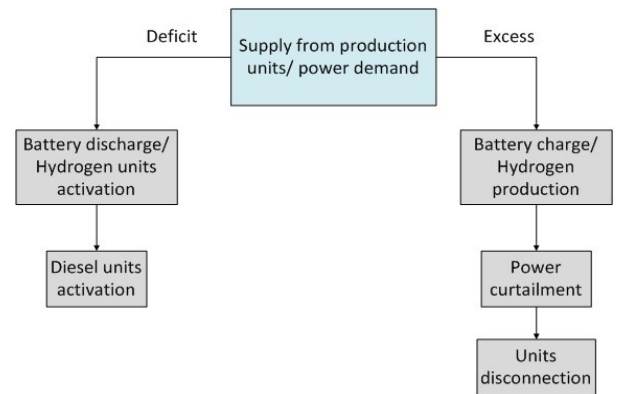


Fig. 5. Flowchart of the control algorithm

A block diagram of the controller is provided in Fig. 6. The controller receives the load and generation data in time steps of ten-minute duration. The connection, disconnection or the power regulation of the RES and the ES is decided on the

basis of supply and demand variations. Any decision would be implemented in the next time step.

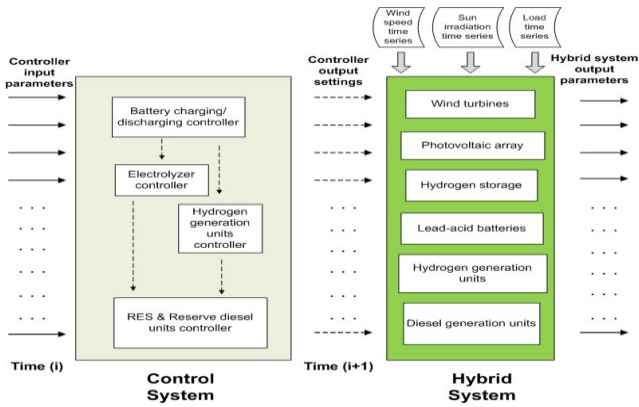


Fig. 6. Overall function of the controller

IV. SIMULATION AND RESULTS

All the components of the hybrid system and the energy management controller were modeled in Matlab/Simulink. Wind turbines, PV, DG, hydrogen storage and batteries were modeled as discussed in Section II. The generation and demand data is selected from the annual data of Fig. 1 for the last week of July which is the period with the highest demand. The average load is around 250 kW as shown in Fig. 7. The peak demand is 360 kW and there are significant deviations of RES production. Studies were carried out for a selected week in the month of July as well as for the whole year.

A. Weekly simulations

Two scenarios were considered with respect to the operation of DG.

1) *Scenario-1*: The DG was continuously operated at the minimum operation limit of 45 kW. The DG generation would increase when the power from RES and storages cannot meet the demand. This kind of operation strategy is likely to restrain the production share of RES units.

2) *Scenario-2*: The diesel engines were exclusively used as back-up when power production from RES and storages was insufficient. Figures 7, 8, 9 and 10 demonstrate the response of RES, diesel and storage units for both scenarios.

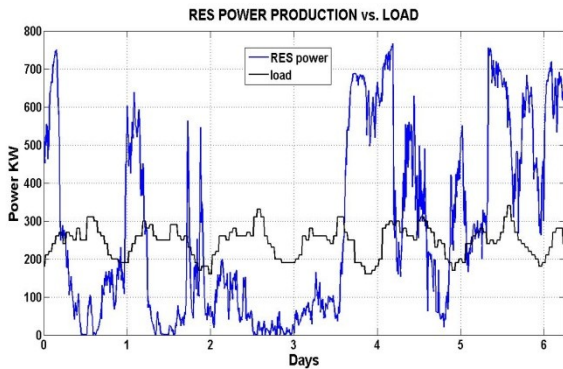


Fig. 7. Power output from RES compared to demand

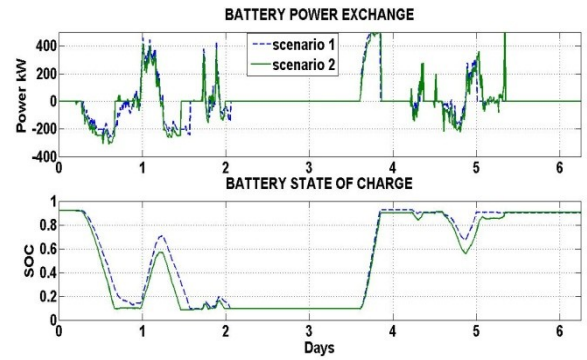


Fig. 8 Battery power exchange and state of charge

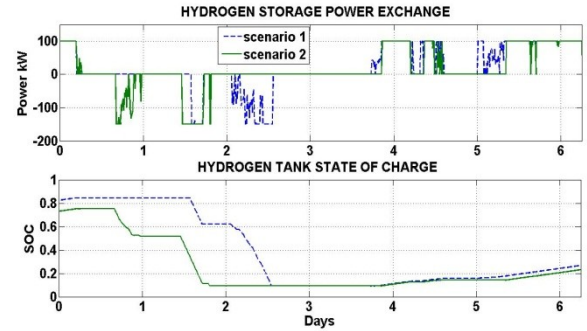


Fig. 9 Hydrogen storage power exchange and tank's state of charge

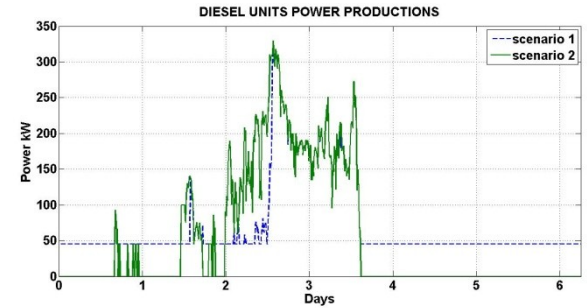


Fig. 10 Diesel units power output

As shown in Fig. 7, periods of excess (up to 515 kW) and shortage (up to 330 kW) of generation occurred in that week. As illustrated in Fig. 8, the batteries were discharged during power deficit as long as the state of charge (SOC) was above the lower limit of 10%. Similarly, they got charged when there was surplus generation until the upper limit of 90% was reached. When the operation of the battery was limited due to their power capacity or state of charge, the hydrogen storage was activated. As shown in Fig. 9, the electrolyzer absorbed the excess energy, produced hydrogen and stored the pressurized gas in the tank. When there was a shortage of generation from the RES and the batteries, the hydrogen generators were operated and the tank's SOC dropped. When the generation from RES and storages could not meet the demand, diesel engines were activated as shown in Fig. 10.

The energy storages got fully discharged in both the scenarios. The batteries reached the SOC limits of 90% and 10% in both cases. Due to the continuous operation of the diesel generator in Scenario-1, some differences regarding the

system's behavior can be observed and the results of one year operation are stated in Table III.

B. Yearly simulations

Even though peak power production was 800kW and the RES potential (3054 MWh) was more than two times the demand (1221 MWh), 100% RES penetration could not be achieved as shown in Fig. 11. This happened due to the fact that during extended periods of low RES power, the energy capacity of the batteries (2.5 MWh) and hydrogen storage (2.3 MWh) was not enough to cover the demand. The energy production from the DGs was 352 MWh more in Scenario-1 compared to that in Scenario-2 because of the continuous operation of DG at the minimum point (50% of rated capacity).

TABLE III.
ANNUAL RESULTS FOR BOTH SCENARIOS

	Scenario 1	Scenario 2
Energy demand (MWh)	1,221	1,221
Potential RES production (MWh)	3,054.64	3,054.64
RES production (MWh)	1337.9	1612.1
Capacity factor WT1 (%)	35.4	41
Capacity factor WT2 (%)	8	11
Capacity factor WT3 (%)	4	7
Capacity factor PV (%)	9	10
Hydrogen units production (MWh)	6.12	20.56
Hydrogen fuel consumption (kg)	524.3	1,762
Hydrogen fuel production (kg)	4,331	3,705
Diesel units production (MWh)	420.25	68.11
Diesel fuel consumption (kg)	121,557	18,091
Energy stored at batteries (MWh)	104.8	166.8
Energy discharged from batteries (MWh)	101.5	164.4

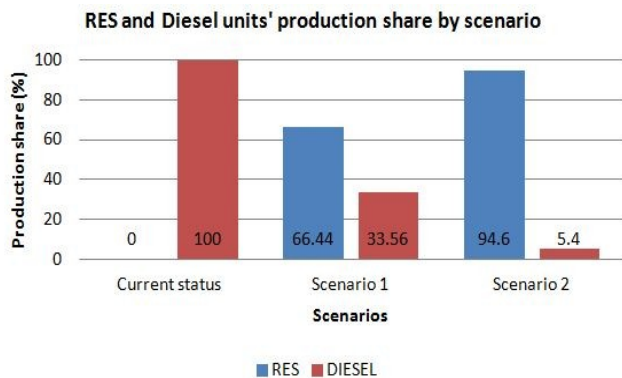


Fig. 11. Comparison between RES and diesel units' production share by scenario

Furthermore, in Scenario-1, 104.8 MWh were stored in the battery and 101.5 MWh were recovered. In Scenario-2, 166.8 MWh and 164.4 MWh of energy were respectively stored in and discharged from the battery because it was more actively involved in absorbing the power deviations when the DG was not running continuously. On the contrary, in the first case, the batteries remain fully charged for a longer period of time, and their role was diminished. For the same reason, 1238 extra kg of hydrogen gas were consumed in Scenario-2. The capacity factors of wind and PV generators are greater in Scenario-2 since smaller percentage of RES production is curtailed. Also, since power production priority is set for WT1, the output of

the other generators (WT2, WT3 and PV) is imposed to significant curtailment and for this reason their capacity factors are relatively low.

Although the Scenario-2 case triples the energy production from H_2 engines, there is still a considerable quantity of hydrogen fuel that is not used. In both cases, large amounts of energy are consumed in the electrolyzer to produce hydrogen. At the second one, though, 14.4% less energy and hydrogen are consumed and produced respectively due to less energy excess.

C. Sensitivity analysis

Moreover, a sensitivity analysis was performed for the battery unit energy capacity and hydrogen tank's volume so as to evaluate the impact of increasing the storage capacity upon RES penetration. The results are shown in Figures 12 and 13. By increasing the battery's energy capacity from 0.5 MWh to 15 MWh, the RES penetration increased from 64.15% to 69% in Scenario-1 and from 88.56% to 98.8% for Scenario-2. For battery capacity values above 5 MWh, there was not any significant increase of the RES share due to the existence of long periods where there is very low wind speed and high demand at the same time.

Similarly, considering 2.5 MWh batteries as high priority, the increment of tank's volume from 100 kg (1.16 MWh) to 1000 kg (11.6 MWh) increased the RES penetration from 66.3% to 67.1% for Scenario-1 and from 94.2% to 95.5% for the second one. Moreover, an increase of the tank's volume would almost not increase the RES level. This fact is justified by the low efficiency of hydrogen storage and the minimum power requirement of the hydrogen generators.

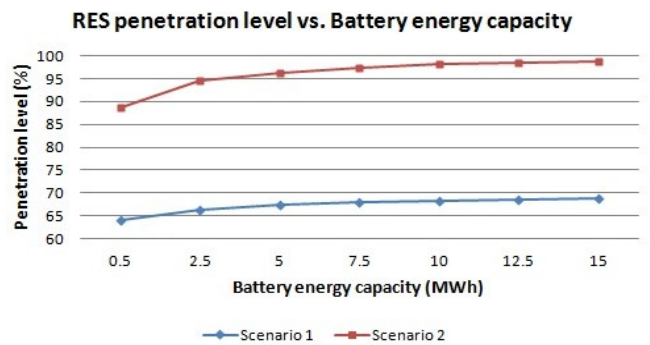


Fig. 12. RES penetration level vs. Battery energy capacity

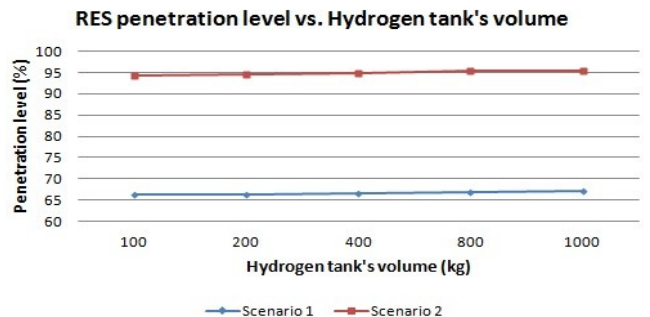


Fig. 13 RES penetration level vs. Hydrogen tank's volume

Larger capacities were not studied here in detail since their cost would be prohibitive. However, it was found through simulations that 100% RES penetration could be attained either by using batteries capacity of approximately 35 MWh or simultaneously 30 MWh batteries and 1000 kg hydrogen tank.

V. CONCLUSIONS

The issue of increasing the penetration of RES was discussed and this study shows that energy production from the diesel station can be significantly reduced by RES and its penetration can be increased by the inclusion of energy storage. However, with the components selected in this study, the diesel generation could not be eliminated due to prolonged periods (up to 12 days) of low RES potential, specifically during the high load season in summer. Under the more favourable scenario 2 – when switching the diesel units on only when absolutely needed – a maximum RES share of 94.6% could be reached. The demerit of this scenario is the frequent start ups and shut-down of the DGs. On the other hand, continuous operation of the DG under Scenario-1 restrains the production share from renewables to 66.4% and increases the diesel fuel consumption significantly. This drawback could be limited by using a smaller DG. In order to reach 100% of the supply from RES, around 30 MWh of battery capacity and a hydrogen tank of 1000 kg would be required but the high cost of such big storage devices would make it financially unattractive. Finally, the power exchange and operation time of the battery is increased in Scenario-2 and this fact will result in a shorter lifetime of the batteries compared to the Scenario-1 due to more cycles imposed on them.

A possible future work may be to investigate the dynamic phenomena and evaluate the hybrid system's operation from an economic point of view so as to decide which scenario, control strategy and units' capacities are likely to create an optimum combination from both technical and economic point of view.

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