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Hybridization of photovoltaics with pumped storage hydroelectricity. An approach to increase RES penetration and achieve grid benefits. Application in the island of Cyprus

Pavlos Tsamaslis[a], George Karagiorgis[b,c,*], Athanasios Katsanevakis[a,d]

[a] *ESTIA consulting & engineering S.A., 1st km Thermi—"Macedonia" Airport, Thessaloniki 57001, Greece*
[b] *Associate Professor, Mechanical Engineering Department, Frederick University 7, Y frederichou Str.,Pallouriotissa 1036, Nicosia 2643, Cyprus*
[c] *Senior Researcher, Hystore Technologies Ltd, Spyrou Kyprianou 30, Ergates Industrial Area Nicosia 2643, Cyprus*
[d] *Associate Professor, Mechanical Engineering Dept, Technology Institute of Central Macedonia, Terma Magnisias Av., Serres 62124, Greece*

Abstract

The penetration of renewable energy resources in small isolated grids can be significantly enhanced by introducing energy storage facilities into the system. This work presents the application of pumped storage in an autonomous island with intense solar irradiation but low wind resources. The proposed system hybridizes photovoltaics with pumped hydroelectric energy storage. Taking into account all significant electrical grid and power stations operating parameters, a customizable smart algorithm was developed to simulate the effects of various scenarios of PV-hydro hybrid power plants applied in the autonomous grid of Cyprus. The tools developed can be applied in any other case where hybridization of pumped storage and PVs can be used. This novel approach provides significant benefits for both the penetration of renewables and the stabilization of the autonomous grid, offering numerous technical and commercial benefits to power system operators and stakeholders.

Keywords: Storage technologies; Hybrid PV-hydro plants; Renewables penetration; Grid stabilization; Smart customizable algorithm

1. Introduction

The penetration of renewables in Cyprus, with a 7% share of the overall electricity balance, has resulted in significant grid instability and operation issues. The low electrical power required—In light of—power load—during certain periods of the year, together with the priority access or guaranteed access to the grid system afforded to electricity produced by the installed wind and photovoltaic power plants, made secure operation of the Cyprus grid a difficult task. During low grid demand in the range of 270 MW, the operation of around 150 MW of wind farms which, depending on the local wind conditions, may operate at near nominal capacity, makes it difficult for the operator to safeguard system stability.

Recent research shows that the increase in Renewable Energy Sources (RES) penetration, can be achieved alongside operational safety of the grid if (i) the predictability of renewable power generation is increased, (ii) energy storage is incorporated into the grid system, and (iii) a smart algorithm can be used to produce a generation unit operation schedule [1–4]. Additionally, sustained increases in RES penetration may reduce or even marginalize the need for new power generation capacity.

Based on the above needs, a preliminary study has been performed to identify specific actions that can be taken to overcome the various obstacles. The results are summarized below.

The most widely available RES in Cyprus is solar irradiation [5, 6]. Sunshine is abundant during the whole year, thus lowering the uncertainties of both centralized and decentralized solar generation forecasting [7–9]. In terms of energy potential availability and stability, PVs are less site specific than wind farms. PV plant output can be accurately predicted one (1) or two (2) days ahead. This gives the operator time to arrange the operational schedule of the other power plants. Lastly, considering the typical grid demand profiles, solar irradiation is often available during high demand hours of the day.

Appropriate energy storage could help resolve the variability in demand and improve reliability in distribution, thus relaxing the grid and the operation of the conventional power plants. Sufficient storage capacity will increase both (i) power demand during low demand periods and (ii) power generation during high demand periods. This will give the operator the independence needed to produce an efficient operation

*Corresponding author
Email address: eng.kg@frederick.ac.cy (George Karagiorgis)

schedule for the grid's conventional units.

Producing the operation schedule of the conventional power units and existing renewable power plants is an important task. Net metering introduces key new parameters which will affect the demand profile, thus creating additional difficulties. The development of a smart algorithm that takes into account all the above mentioned parameters will assist the operator's efforts to produce an efficient operation schedule.

The present study focused on the use of renewables to perform smart energy storage in order to achieve the grid benefits analyzed above. Taking into account the benefits and the assessment of market potential for current energy storage technologies along with their potential for commercial applications in the near future, it was shown that the most promising approach is to use PV plants in hybrid mode coupled with pumped storage. Pumped storage plants can be built in Cyprus using the existing water reservoirs of various capacities spread all over the island. Furthermore, technical and economic analysis results concerning the integration of pumped energy storage plants in the Cypriot power system indicate that under certain parameters the use of pumped energy storage systems can be beneficial for the large scale integration of renewable energy sources [10]

2. Cyprus climate data and RES potential

Cyprus has a typical Mediterranean climate with mild winters, long hot, dry summers and short autumn and spring seasons. Sunshine is abundant during the whole year, with a daily average of 11.5 hours in summer and 5.5 hours in winter. Average annual rainfall is about 500 millimeters. The variation in rainfall is not only regional but annual and often two- and even three-year droughts are observed [11].

Wind resources are not as favorable, but there are a few areas where further wind power can be installed. On the other hand, solar irradiation in Cyprus is one of the highest in Europe (Fig. 1), making PVs the most promising RES installations.

Cyprus does not have abundant potable water from natural resources. Water demand is met by dams, springs, desalination plants, recycling, reuse of water and imports.

At present, Cyprus has over 100 dams, 56 of which are included in the Register of the International Committee on Large Dams (ICOLD) [14]. Thus, there is a strong potential for the implementation of medium and large scale pumped storage projects.

3. Hybrid plant design and operation

A typical configuration of a PV-hydro hybrid power plant with pumped storage is presented in Fig. 2.

The plant consists of two reservoirs at different altitudes and a set of hydro turbines and pumps with common or separate penstock. The volume of the upper reservoir and the

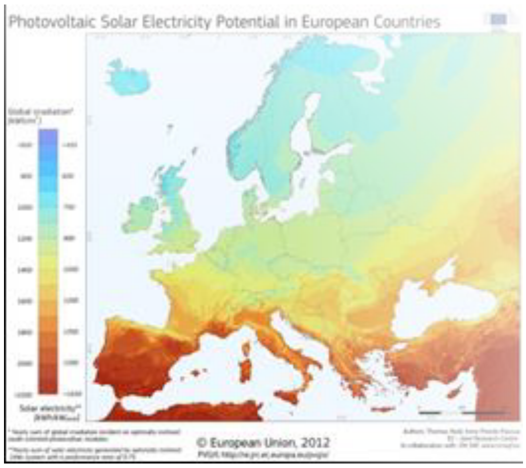

Figure 1: Photovoltaic Electricity Potential in European Countries [12, 13]

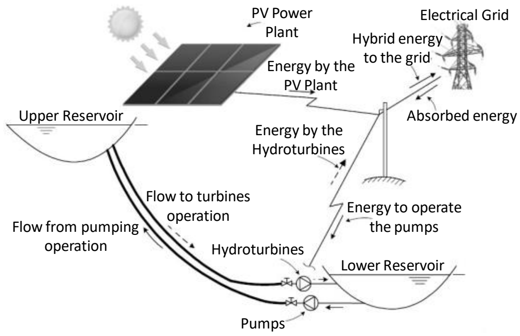

Figure 2: Sketch of a pv-hydro hybrid power plant

nominal power of the hydro turbines determine the storage capacity and the storage power of the plant respectively [15]. A PV power station of appropriate nominal power is installed at a neighboring site.

Separate connections of the hybrid units with the grid and internal interconnections ensure the energy exchanges with the electricity system and between subsystems of the hybrid power station.

The concept of hybrid plant integration into the grid is to use them on a daily basis for both storing RES production and supplying power to the system [16, 17].

The operation strategy of the PV-hydro hybrid plant is based on a daily energy planning procedure. Based on the special legal and regulatory framework developed for the introduction of storage to non-interconnected island systems in Greece [18–20] and taking into account the special characteristics of the annual energy load, an innovative daily energy planning procedure was adopted, as analyzed below:

- At the end of each day, the hybrid plant producer submits its energy supply capability for the next day, which is based on both the energy stored in the upper reservoir and the anticipated solar production of the next day, depending on forecasting accuracy.

- Then, the grid administrator produces the hourly schedule for the next day, in order to increase the participa-

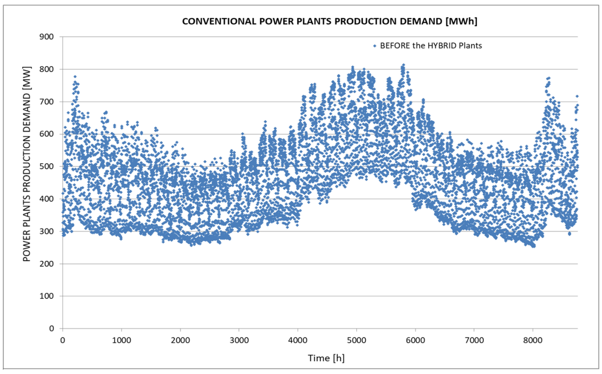

Figure 3: Conventional units' power generation data for 2013 (reference year)

tion of RES and simultaneously improve the operating parameters, thereby ensuring grid stability and safety.

- The hourly power and loading of the hydro turbines are defined only by the system operator. The turbines operate in a peak-shaving manner, in order to optimize the overall system operation.

- The hourly operation of the plant's pumping units (during night hours) is also determined by the system operator, giving the operator great flexibility to permit large amounts of RES energy to flow into the grid even during low grid demand periods.

Although the above concept may not be suitable for direct implementation in large systems with standard market organization, it could lay the groundwork for a regulatory framework for hybrid power stations in Cyprus, providing clear rules and responsibilities concerning the technical modalities and the financial conditions of hybrid power stations based on large storage capacity.

4. Cyprus electrical power system

Electricity generation in Cyprus is currently based exclusively on imported fuels, mainly crude oil. In 2013, the total installed capacity of the power plants was 1598 MW. In addition to the conventional units, there was also 146.9 MW of wind, 33.9 MW of PV and 9.7 MW of biomass installed capacity. During 2013, the reference year for the simulations, annual energy consumption was 4499 GWhs and the penetration of renewables achieved a 7% participation in the overall electricity balance [21–23]. The total hourly power generation data of the conventional units are presented below.

The modeling of the hybrid plant operation during the reference year is performed using the minimum resolution (1 hour) of the available time series data for load and existing RES power plants—wind, PV, biomass.
The monthly minimum, maximum and range of power generated by the conventional power plants is presented below:

Table 1: Monthly power produced by Cyprus' power plants for the reference year

Month	Min. Demand, MW	Max. Demand, MW	Range, MW
Jan-13	286.8	777.0	490.3
Feb-13	276.0	643.5	367.5
Mar-13	265.0	618.3	353.3
Apr-13	256.5	549.5	293.0
May-13	290.3	638.5	348.3
Jun-13	313.0	753.8	440.8
Jul-13	386.8	807.0	420.3
Aug-13	437.3	813.3	376.0
Sep-13	321.5	791.0	469.5
Oct-13	284.0	605.8	321.8
Nov-13	252.5	578.3	325.8
Dec-13	253.5	773.3	519.8

As seen in Fig. 3 and Table 1 the electricity demand met by the power plants is characterized by significant daily and seasonal variations. The lowest monthly demand reported for the reference year is less than 270 MW while the maximum is over 800 MW. Typical daily variation is in the range of 400 MW while the integration of non stable RES units increased grid stability problems [23, 24].
Moreover, widespread integration of distributed energy resources in the distribution network will produce a number of power quality problems, such as overloading of network components, overvoltage and undervoltage situations, voltage dips and harmonic distortion [25–27].
Taking into account parameters like the possible failures of generation units, the various interconnections with major consumers and producers and the resulting implications for grid safety devices, safe operation of the grid becomes a difficult task.

5. Scenarios studied and simulation methodology

A customizable algorithm was developed for the purposes of the present work. It takes into account all significant operating parameters of the conventional and RES power stations affecting the operation of the electrical grid . The algorithm was used to simulate the operation of all the power production units of the autonomous Cyprus grid and the effects of various scenarios of the renewable power plants and hybrid water pumped storage capacities to be used. The Raw Data along with the basic intermediate calculation results that were used as the algorithm's input data are presented below.
The developed algorithm was customized according to the Cyprus grid operator's main criteria relating to operating cost, start up cost, maintenance requirements, fuel costs and grid stability regarding the conventional units' integration order.
The upper water reservoirs are considered to be full at the start of the simulations. The PV-Hydro plants give priority to filling the upper reservoirs of the pumped storage whenever their water levels drop below 50% of the nominal mark.
Existing water reservoirs of Cyprus which meet capacity, grid, topographic (available height differences) and environmental criteria were selected as the lower reservoirs, while new water reservoirs constitute the upper reservoirs of the

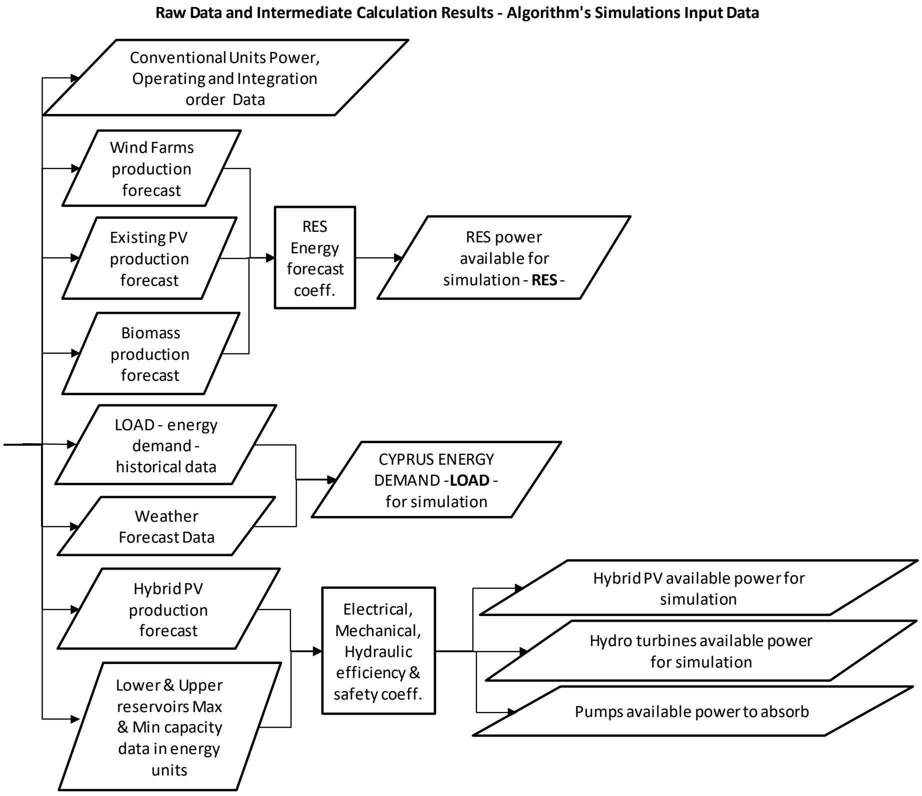

Figure 4: Algorithm's input data and intermediate results

Table 2: Capacities of the Lower and Upper reservoirs

Existing Water Dams - Lower Reservoirs		New Upper Reservoirs
Kouris	115.000	0.550
Dipotamos	15.500	0.500
Lefkara	13.850	0.500
Arminou	4.300	0.300
Germasoyeia	13.500	0.780
Kalavasos	17.100	0.450
Asprokremmos	52.375	0.450
Kannaviou	17.168	0.450
Mavrokolimpos	2.180	0.250
Evretou	24.000	0.450
Kalopanagiotis	0.363	0.180
Ksiliatos	1.430	0.250
Klirou	2.000	0.300
Total Capacity [MCM]	**278.766**	**5.410**

hybrid power plant. The water capacities data in Million Cubic Meters (MCM) for the various reservoirs are presented in Table 2.

Two different scenarios of hybrid plants are modeled for the electricity system of Cyprus.

Scenario A. 165 MW of hydro pumped storage capacity + 195 MWp of PV power plants based on 2 axis tracking.

Scenario B. 85 MW of hydro pumped storage capacity + 85 MWp of PV power plants based on 2 axis tracking.

Simulations were performed for the reference year 2013 taking into account the real grid demand of that year, the actual power generation of the existing RES plants of Cyprus and the actual solar irradiation.

Simulations using the PVsyst software (Databases Meteonom 7.1 and NASA-SSE satellite data) were performed for the purposes of calculating the annual energy produced by the PV power plants sited near the lower reservoirs of the storage facilities.

Typical PV and pumped storage electrical, mechanical and hydraulic efficiency levels were taken into cosideration.

The developed software performed all analyses on an hour-by-hour time frame.

6. Results and discussion

The main results of the simulations performed in the context of the present report are summarized below.

Fig. 5 shows the real demand curve of the Grid in Cyprus during a typical summer day: 2 August 2013. In the same figure grid demand grid is shown when applying scenario A or scenario B.

By incorporating the approach described above, the operation of the conventional power units is flattened out markedly, reducing the peaks and increasing the power during the low power demand periods.

The typical daily variation of more than 300 MW which should be faced by the conventional power plants is drastically reduced, thus improving operational stability and safety.

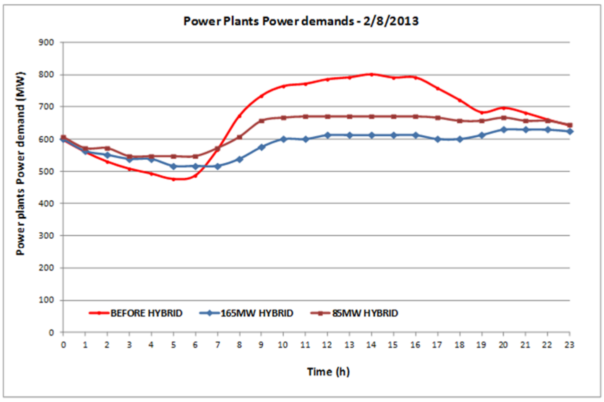

Figure 5: Existing (red) and achieved daily operation of the conventional units, during a typical summer day, after the implementation of scenarios A (blue) & B (brown)

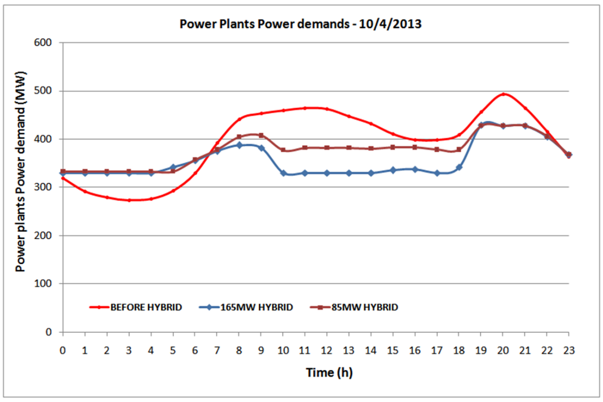

Figure 6: Existing (ed) and achieved daily operation of the conventional power plants, during a low demand day, after implementation of scenarios A (blue) & B (brown)

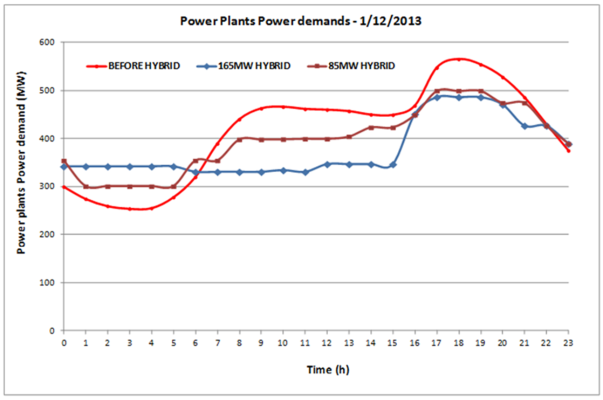

Figure 7: Existing (red) and achieved daily operation of the conventional power plants, during a typical winter day, after the implementation of scenarios A (blue) & B (brown)

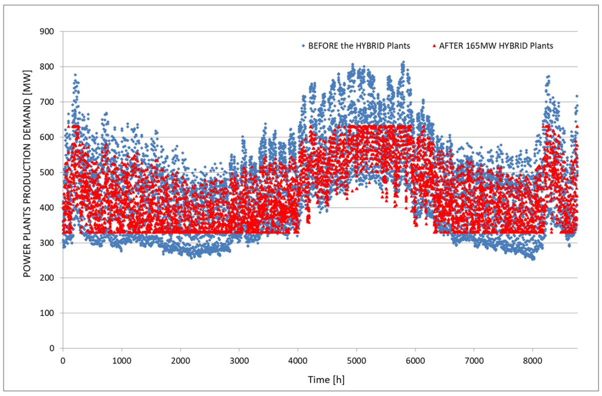

Figure 8: Existing (blue) and achieved (red) yearly operation of the conventional power plants after implementation of scenario A

Fig. 6 shows the corresponding results during a typical low demand day—spring, 10 April—and Fig. 7 during a typical winter day, 1 December 2013. Fig. 8 shows the all-year conventional power plant operation when scenario A is applied and Fig. 9 if scenario B is the choice. In both figures the existing power generation data of the conventional power plants is shown at the back of the red data which show the achieved results when applying the hybridization scenarios described above.

RES penetration during the reference year (2013) was almost 7%. A significant increase in RES penetration is achieved when the hybrid plants are integrated in the energy system of Cyprus.

Table 3 shows that by applying the proposed approach the Cyprus targets for RES penetration are met.

As shown in the previous figures, incorporation of the proposed hybrid power plants reduces the needs for spinning reserve and improves operational safety back-up.

The PV-Hydro solution will facilitate the adoption of multiple strategies to utilize more wind energy and reduce RES curtailment, including reducing minimum loads on must-run units, modifying units so that they can turn off daily, reducing reserves for quick start units, running units at lower load levels, and incorporating demand response into reserves. The additional reservoir storage acquired will be used to reduce both balancing and oversupply related curtailments.

If all the above measures were taken, it would result in a drastic reduction of the units' operating cost and of Cyprus' dependency on fossil fuels.

The annual variation in power output of the existing conventional power plants is reduced from 560 MWs to (i) 300 MWs and (ii) 370 MWs in scenarios A and B respectively. This eliminates the need for building and operating additional conventional power plants.

Table 3: RES penetration before & after hybrid plant integration

Scenario	RES Penetration, %
Before Integration	7.0
B	13.0
A	17.1

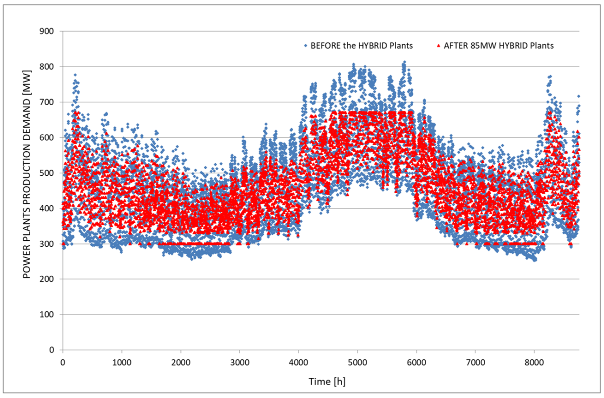

Figure 9: Existing (blue) and achieved (red) yearly operation of the conventional power plants after implementation of scenario B

7. Conclusions

The use of existing storage methodologies, such as pumped storage combined with photovoltaics, can have significant benefits in isolated grids where solar irradiation resources are significant and where stabilization of the grid should be ensured.

If the discussed measures are applied in Cyprus, our study shows that not only would the RES penetration goals of Cyprus be met but the island would achieve enhanced grid stability and secure operation of the existing RES power plants.

Taking into consideration Cyprus' willingness to apply the European Target model in the Energy Market, the present methodology could lay the groundwork for a regulatory framework to develop and integrate hybrid power stations, providing clear rules and responsibilities concerning the technical modalities and the financial conditions of hybrid power stations based on large storage capacity.

Moreover, the need for new conventional power plant development would be minimized.

The proposed methodology can be applied in any autonomous grid where increased RES penetration and stabilization of the grid are needed.

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