Study of hybrid wind-hydro power plants operation and performance in the autonomous electricity system of Crete Island

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Abstract: This work analyses the configuration and operation principles of hybrid wind-hydro power plants with pumped storage integrated into autonomous electric grid systems, in order to support high wind energy penetration. The plant consists of wind generation units, combined with a pumped-hydro storage system. It operates on a daily basis, storing the surplus wind production by pumping water in an elevated reservoir, and re-feeding this energy to the electric grid during high load demand periods through its hydroturbines. The new concept for the operation strategy of such plants is the provision of both guaranteed power and guaranteed energy to the grid, combining high wind energy integration and improved operation of the conventional generation system. A computer algorithm is developed to simulate in detail the hybrid plant operation during a reference year and it is applied to the case of Crete Island in Greece, where the penetration limit of the great wind potential available has almost reached. Two different configurations for the pumped storage system are investigated, using reversible pump-turbine machines or separate pumping station and double penstock. The possibility of installing very large hybrid plant power is investigated, as also the effect of some main design parameters on the plant energy results, like the reservoir capacity and the wind farm power. The results showed that a hybrid plant with the new operation strategy is able to effectively substitute a significant portion of both installed power and electricity production of the conventional fossil-fuel plants in the island.

Key-Words: Hybrid wind-hydro power plant; Pumped storage; autonomous electricity grid.

1 Introduction

The use of pumped-storage energy systems concentrates an increasing interest worldwide in order to enhance the share of the renewable energy into both large and small grid electricity systems, since most of the other storage technologies are rather expensive and inefficient, and/or have reduced capacity. Especially for the local autonomous grids that can be found in many islands, the installation of hybrid pumped storage schemes in combination with wind generators and/or solar systems appears to be a promising and attractive application in order to maximize the exploitation of their abundant renewable potential [1-3].

In Greece there are more than 50 islands that are not interconnected to the mainland electricity grid, and electric energy is currently supplied by autonomous diesel power stations. The cost per KWh of these stations is very high and therefore the integration of renewable energy sources is in most cases an economically viable solution. Unfortunately, the fluctuating and intermittent behaviour of these sources imposes certain power limitations to their penetration in an isolated grid system, due to technical constraints and stability problems of the conventional generating units. For the most important, wind energy potential, a comprehensive study for Greek islands showed that penetration levels above 25–35% of the peak annual load are not economically feasible [4]. Moreover, in several islands this limited wind power level is already installed or production permits have been granted, and the possibilities of erecting new wind farms are minimal [5]. Wind energy accounts for approximately 10% of the annual electricity production in all autonomous islands of Greece, and with the current operating practices the upper limit for this share is estimated to 12-14% [3].

The operation analysis and the optimum sizing of wind-hydro Hybrid Power Plants (HPP) with pumped storage has been the target of several recent research works, for system sizes ranging from a few MW up to some hundreds MW, corresponding from small up to large island grids [6-11]. Various alternative operation strategies of a HPP plant have been investigated by some of the above researchers in order to find the most efficient one for the plant and/or the grid system. A small wind-hydro pumped

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storage scheme (13 MW) with a desalination plant is under construction in El Hierro, Canary island [6]. This project is supported by the EU and its results are expected to provide valuable practical experience. Also the first small hybrid wind-hydro plant in Greece is being constructed in Ikaria island, having 3 Pelton turbines at two levels with total power 3.7 MW and variable speed pumps of 3.8 MW [8]. Variable speed pumping can be easily adjusted to the fluctuating wind production and can contribute to even higher penetration of such energy sources, providing primary frequency control to the power system.

The present work uses a computer algorithm for the detailed simulation and analysis of such a HPP installed in autonomous power system of the Greek island of Crete. The considered operating strategy of the plant is in accordance with the current legislation in Greece (Law 3468/2006), and is based on the provision of both guaranteed power and guaranteed energy to the grid system. This is completely different than previous considerations, according to which the plant should produce at its rated hydroturbines power only during an agreed fixed period of the day [12]. Two reference pumped storage configurations are examined, with and without the capability of simultaneous pumping and turbining. The performance, the energy results and the optimum sizing of the corresponding hybrid plants are parametrically investigated and compared. Then, the algorithm is applied to investigate the possibility to integrate HPPs of large capacity and power level in the system of Crete.

2 HPP Design and Operation

A typical configuration of a wind-hydro hybrid power plant (HPP) with pumped storage is given in Fig. 1. The plant consists of two reservoirs at different elevation, a set of hydroturbines and pumps with common or separate penstock, and one or more primary wind production units installed at the same or adjacent locations. Energy exchange with the electricity system and between subsystems of the plant is carried out through separate connections of all subunits with the grid, and there is no internal interconnection. The storage capacity of the plant depends on the useful volume of the smallest of the two reservoirs and of the hydraulic head between their levels. The storage power is determined by the rated power of the pumping and turbining units.

The new concept of hybrid plants integration into island electric networks is to use them on a daily basis for storage of surplus RES production, as well as to provide guaranteed power and guaranteed energy to the system. The controllable plant production is used for peak load shaving but also to substitute conventional units, therefore the dispatch program of hydtoturbines must be adapted to the load demand curve of the system. For this reason, the storage capacity of a HPP is also expressed in terms of hours of continuous turbine operation at rated power, which in most cases is of the order of 10 to 20 hours.

The double penstock, in conjunction with a separate pumping station, increases the cost of the investment but provides flexibility to the plant, allowing for simultaneous pumping and turbining operation. In that case, the plant acts as an effective energy filter through which the fluctuating wind production is transformed to a stable and controllable hydroelectric production.

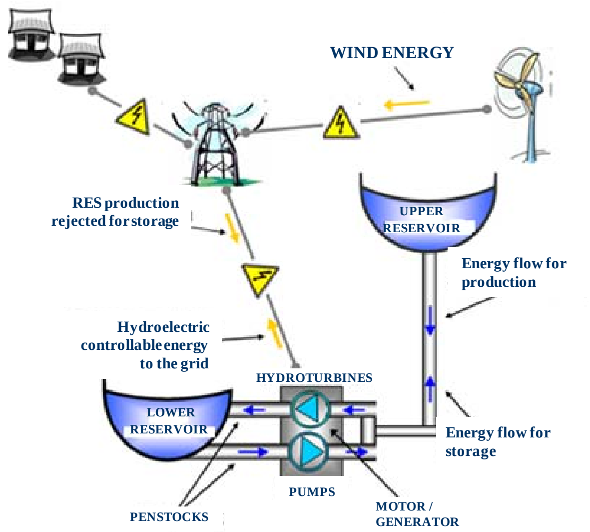

Figure 1. Sketch of a hybrid energy system.

According to the finally adopted regulatory framework and operating principles for hybrid power plants in the Greek islands, the incomes of a HPP come from the net electricity that it sells to the grid and also from a yearly remuneration for the guaranteed power it provides to the system. The latter is defined as the peak annual load demand of the system, minus the rated power of the plant controlled production units, which are the hydroturbines. The maximum such capacity credit can be computed for each particular grid system and annual load demand data, based on the maximum energy flow of a pumped-storage cycle that provides the requested power above that limit and up to the peak load demand throughout the whole year, even without any contribution of primary renewable sources.

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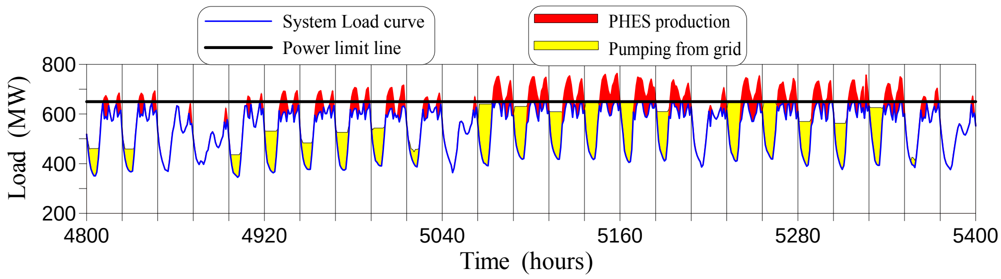

Figure 2. Determination of the power capacity credit limit for the electric system of Crete.

This concept can be explained with the aid of the following Fig. 2, which gives an example of operation of a simple pumped storage plant, which provides guaranteed power only by night-time pumping. In order to ensure this performance, the maximum energy pumped during the night (yellow areas), must cover the next day demands above the power line, plus the cumulative energy losses of the pumped-storage cycle, which may be in the range of 20 to 35%. It is obvious in Fig. 2 that if the power limit line was moved below its depicted position, then there would be one or more days of the year in which the plant would not be able to cover the day-time demands above that level. This power limit for Crete Island was computed to about 650 MW [3]. Hence, considering that the corresponding peak load is estimated to 820 MW, the maximum capacity credit for hybrid power plants in the island will be about 170 MW.

The operation strategy of the HPP is based on a daily energy planning procedure, as analysed below (see also [2, 3]):

– At the and of each day, the HPP producer submits his energy supply offer for the next day, which is based on the energy stored in the upper reservoir, but can also include part of the anticipated wind production of the next day, depending on the forecasting accuracy.
– Then, the system administrator constructs the hourly dispatch schedule for the next day, in order to absorb the HPP energy offer, at least up to the guaranteed daily energy amount. The dispatch of the hydroturbines is made in a peak-shaving manner, in order to optimize the overall system operation. Consequently, the hourly power (and loading) of the hydropower units is determined only by the system operator, and then communicated to the HPP producer. This gives great flexibility to the operator and permits the integration of large amounts of RES power into the grid.
– According to the guaranteed power concept, the HPP must be able to cover the entire demands of the system above the power limit line. Therefore, if the forecasted load exceeds this line, the operator calculates the power and energy needs that must be covered and informs the HPP. The latter, may then respond in two different ways: Verify its ability to provide the guaranteed energy if there is enough energy stored in the upper reservoir, or submit a request for pumping during the night-time hours by purchasing energy from the grid. In the latter case, the HPP cannot submit energy offer above the amount requested by the system operator.
– Although the HPP is obliged to provide the guaranteed power and energy whenever required, the system operator has the flexibility to reduce during real time operation the hydroturbines production below the scheduled, in order to retain the set-point given to the other RES producers of he island (if any). This is because the HPP substitutes conventional thermal units and must provide also ancillary services, like primary reserve. However, this is not a frequent situation, and may happen only in cases of high wind potential during moderate or low demand day-time hours.

Theoretically, the total rated power of the plant hydroturbines can be higher than the maximum capacity credit of the island. In this way, the producer may offer as much guaranteed power and energy can be absorbed in the system, and is permitted by the technical minima of the base thermal units in operation. However, the yearly power compensation cannot exceed the capacity credit power (170 MW for Crete).

The HPP production can be composed of a combination of wind and hydro power, and the PHES producer is allowed to continuously regulate this production mix in order to maximize the economic results of the plant. The only restriction is that the hydroturbines must always provide primary reserve for the wind generators of the plant, by reducing their load.

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Consequently, depending on the specific pricing policy, the HPP producer can adopt one of the following production strategies:

a. The wind production is injected directly to the grid and only the non-penetrable amount is stored in the upper reservoir. In this way, a large fraction of wind production can be exploited avoiding the losses in the pumped storage cycle.

b. The wind production is directed in priority to the pumped-storage cycle, and only the amount that cannot be stored (e.g. when the rated power of pumping station is exceeded or the upper reservoir is full), is injected to the grid.

Although from the energy point of view the first strategy is clearly advantageous, the producer may prefer to apply the second one, when the pricing of the guaranteed hydropower production is high. This is the case in Crete Island, where the recently regulated prices for hybrid PHES plants are as follows [13]:

Table 1. Regulated pricing for HPPs production in Crete island.

Hydro-turbines €/MWh	Wind Gen. €/MWh	W/G €/MWh Guaranteed	Capacity payment €/MW/year
236	120	178	127000

The pricing of hydroturbines production is determined based on the average annual variable cost of peak conventional units (operating units <30% of the time) of the island, which is very high in Crete. On the other hand, the wind production is compensated with a fixed feed-in-tariff price of 120 €/MWh (no public subsidy), and when it is supported by the hydroturbines of the plant its price rises to 178 €/MWh. Consequently, the incomes of the plant maximize when its wind production passes through the pumped-storage cycle and injected into the grid as controllable hydroelectric energy. For this reason, the present modelling of HPPs for Crete island is based on the second operating strategy.

3 Case study and simulation method

Crete is the largest Greek island, with about 600000 inhabitants. The energy consumption in 2008 was about 3 TWh, with a peak demand of 650 MW. Although there have been various plans for future interconnection with the mainland, the electric system of Crete is still autonomous (Fig. 3). Electricity is produced by three conventional power stations of total installed capacity ~800MW and several types of generators: steam turbines, gas turbines, CC, Diesel units. About 175 MW of installed wind farms operate today, providing 10-14% of the annual electricity, and about 50 MW of small PV installations have got production license. Some small hydropower schemes are also exist, with total capacity of several hundred kW. The annual energy consumption in the last decade growing at about 4-5%, therefore the load in the reference year 2015 is accordingly estimated to about 820 MW. The corresponding lowest technical minimum is taken 200 MW, whereas considering the register of licensing the installed wind power is expected to reach 220 MW [3, 13].

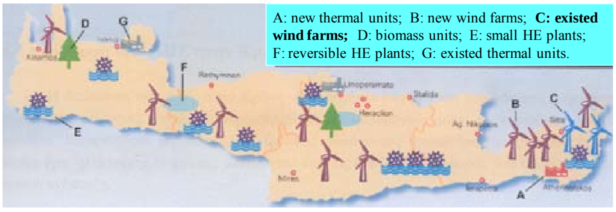

Figure 3. The electricity production map of Crete.

In the present study three different HPPs are modelled for the electricity system of Crete Island, with corresponding hydroelectric power of 75 MW, 250 MW and 500 MW. The configuration and sizing of these plants and the installed power of their subsystems is obtained following a parametric investigation that will be discussed later. The corresponding data are concentrated in Table 2. The mean hydraulic head between the reservoirs was 420 m.

Table 2. The studied HPPs schemes

Case	HPP Power (MW)	Hydro turbines (MW)	Pumps/ power (MW)	Reser-voirs (m^3)	Pens-tocks	W/G. power (MW)
A	75	3 x 25 Francis	4 x 25	1,3x10^6	2	90
A1	75	3 x 25 Revers.	1 x 25	1,3x10^6	1	90
B	250	3 x 83,3	4 x 80	4x10^6	2	300
C	500	3 x 166,7	10 x 50	6x10^6	2	450

The possibility of using singe penstock is investigated for the 75 MW plant. In that case the hydraulic machinery consists of reversible pump-turbines, which is the most cost-effective solution. All pumps and reversible machines are equipped with variable speed motors.

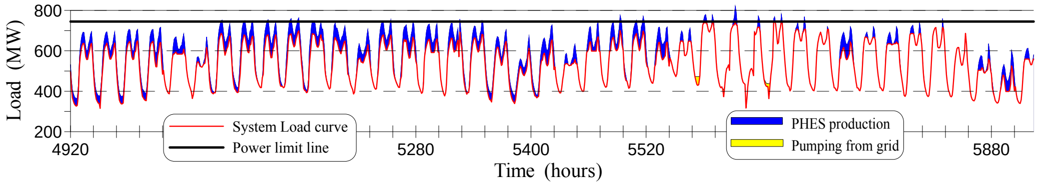

Figure 4. System load curves before and after the integration of the HPP-A.

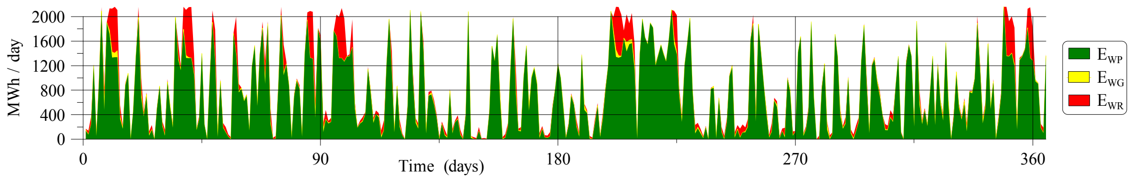

Figure 5. Annual operation diagrams of plant A: Wind production flow (upper), and reservoir content and production efficiency (lower)

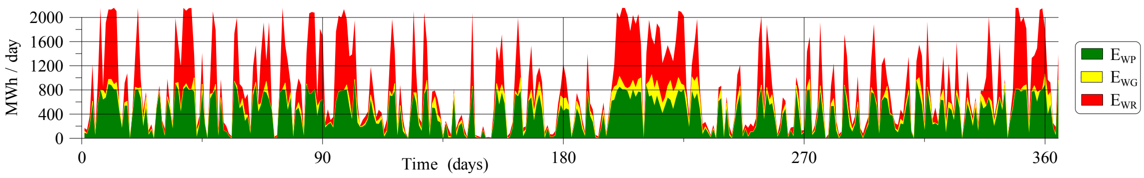

Figure 6. Annual diagrams of wind production of plant A1.

A series of 10-mins power production data of the wind farms is constructed with the aid of existing measurements from wind farms operating in the island, and after further adjustment and scaling to correspond to the estimated development by the reference year. Similar adjustment is also made for the hourly load variation data of the electric system of Crete.

The modelling of HPPs operation during the reference year is performed using the minimum resolution of available time-series data for load and wind production (10 min and 1 hour, respectively). Transmission and distribution limitations, as well as transient phenomena are not considered. The hydraulic machinery (pumps and hydroturbines) is simulated in detail, taking into account the normalized characteristic operation curves of the machines depending on the specific speed, and the effect of part load operation on their hydraulic and electric efficiency. Energy losses in the penstock are also analytically computed. The technical minimum power is taken 50% for the Francis turbines and 60% for the variable speed pumps.

The developed algorithm simulates the actual dispatch procedure of the HPP, which consists of two stages: At first, the daily schedule of the HPP operation is determined by computing the energy supply offer of the producer and the possible needs for night-time pumping from the grid for each of the next 24 hours, taking into account the stored energy in the reservoir, the wind production forecasts and the possible requests for guaranteed power by the system operator. Only part of the forecasted wind production during the next day is taken into account, according to a specifically defined and tested rule [2]. An internal optimization algorithm is used for these computations, in order to maximize the wind energy recovery, while not violating any of the operation constraints (e.g. lowest reservoir level).

Then, the simulation of plant operation starts using time steps of 10 min. For each such period an optimization loop determines the operating point of the pumps and/or turbines in order to maximize the cumulative efficiency of the both processes. The various performance data (internal and external energy flow, reservoir content, etc.) are computed at each time step and recorded in an hourly or daily basis.

4 Results and discussion

4.1 Performance of HPPs

Figure 4 shows part of the load variation curve of the electric system of Crete during the reference year, before and after the installation of a 75 MW HPP (plant A, Table 2). It can be observed that the HPP operation shaves the peaks of the load in most of the days, except of periods of low wind production. Even in those cases, however, the plant can easily provide the required guaranteed energy above the power limit line. The latter is set quite

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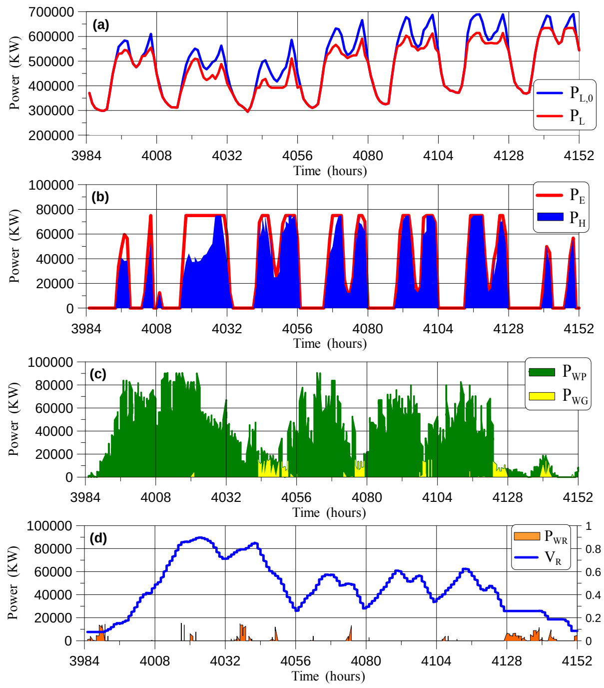

Figure 7. Indicative performance of plant A.

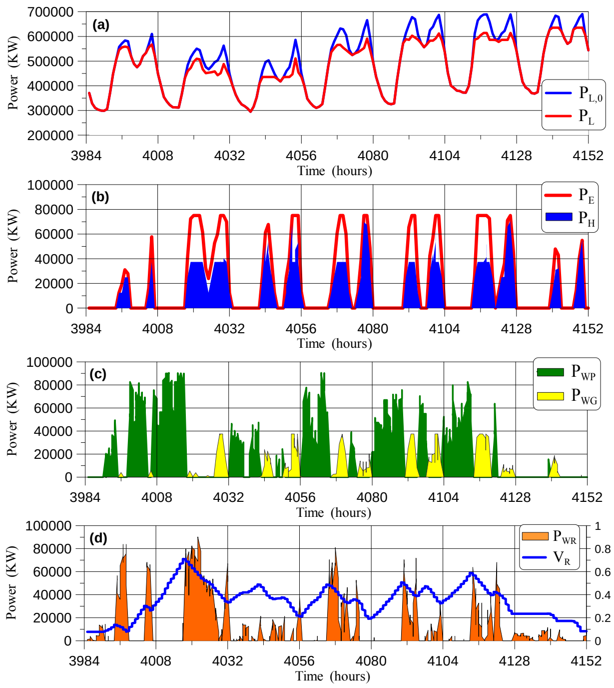

Figure 8. Indicative performance of plant A1.

high for this particular plant, at 745 MW (820-75), and hence such conditions are expected only in few days of the year. Even fewer (only 3) are the days when the HPP needs to purchase energy for pumping from the grid.

The variation and distribution of the wind production of plant A during the reference year is drawn in Fig. 5, along with the normalized water content of the upper reservoir. This figure shows at first the significant variability in wind farm produced energy, which ranges from zero to more than 2000 MWh per day. Most of this production is stored in the upper reservoir (E_{WP}), whereas a small quantity is injected directly into the grid (E_{WG}). In days of very high wind potential the storage capacity of the plant is exceeded (V_R=1) and certain amount of wind production cannot be pumped. Moreover, this amount can neither go to the grid, because the system operator reduces the load of the plant hydroturbines in order to provide reserve to the other wind farms of the island. So, eventually, the surplus production during those periods is rejected (E_{WR}).

The guaranteed production of the plant follows the variation of the stored energy, because the producer offers every day the entire energy amount that is available in the upper reservoir. However, the corresponding hydroturbines production is reduced by about 30%, due to the losses of the pumped-storage cycle. The efficiency of only the production phase is varied around 85% (Fig. 5), depending on the exact operation point of the hydroturbines.

The corresponding performance of plant A1 that has a single pipeline (Table 2) is quite different, as shown in Fig. 6. The wind production cannot be stored during the scheduled operating period of hydroturbines. As a result, part of this production is injected directly to the grid, but a much higher amount is finally rejected, although the upper reservoir is not full. Moreover, the average efficiency of the turbines production is lower, because the turbines are frequently operate at their technical minimum in order to support the penetration of wind farm production. Therefore, in spite of the reduced investment cost of a single-pipe unit, its energy and economic results are much lower than those of a double-pipe plant.

The operation and performance of the 75 MW HPP plant is analysed in more detail with the aid of Figs. 7 and 8 that show and compare weekly results of the double and single-pipe plants A and A1, respectively. The selected indicative week of the year exhibits a medium to low wind production and medium load demand. For this combination, almost the entire energy supply offer of the HPP is absorbed in the system, except of the second day, when the system operator reduces the turbines loading to their technical minimum in order to provide reserve to the other RES of the island (Fig. 7b). The water level in the upper reservoir is kept below maximum and hence almost the entire wind production is stored and exploited later. Only a very small amount cannot be pumped when the wind power is below the technical minimum of the pumps

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(10 MW). In that case the wind production is either injected to the grid supported by the plant turbines (Fig. 7c) or rejected if there is not any turbine in operation (Fig. 7d).

On the other hand, the hydroturbines of plant A1 operate almost always at their technical minimum, in order to provide reserve for direct injection of the wind production (Fig. 8b, 8c), which otherwise would be rejected. Even then however, the wind production during the operation periods of hydroturbines cannot be entirely exploited and there are considerable energy losses, especially when the system operator reduces the plant production (Fig. 8d). As a result, the reduction of conventional units loading is smaller with the plant A1 (Figs. 8a, 7a).

4.2 Parametric and optimum sizing studies

The other important design parameters of the HPP are the useful content of the reservoirs and the installed power of the wind generators. The effect of the above on the energy results of plants A and A1 are plotted in Figs. 9 and 10. The fraction of wind production injected to the grid depends mainly on the plant pipeline configuration (Figs. 9a and 10a), and it is higher for plant A1, as explained before. The reservoir capacity determines the capability of the plant to exploit the wind farm production. A drastic reduction of this capability and of the overall energy efficiency of the HPP (defined as the ratio of net energy provided to grid divided by the primary wind farm production) is evident below a certain capacity limit, which is about 1.3 hm^3 for plant A and 0.8 hm^3 for plant A1 (Fig. 9b,c,d). For larger reservoirs above that limit the performance is marginally improving, therefore this capacity constitutes a cost-effective selection.

Fig. 10 presents and compares the effect of the installed wind power of plants A and A1, for fixed reservoir capacity of 1.3 hm^3. An increased wind production causes corresponding increase of stored and produced energy in both plants (Fig. 10b), but at the same time the wind energy rejections become greater (Fig. 10c) and the overall energy efficiency of the plants deteriorates (Fig. 10d). Therefore, the wind farm power should be a compromise selection to serve the requirements for high efficiency and productivity of the plant. In this study a minimum overall efficiency level of 60% is adopted in order to define an optimum design of the examined HPPs. In Figs 9 and 10 this corresponds to reservoir capacity of 1.3 hm3 and wind power of 90 MW. The same was applied in the parametric results of the other two HPPs (B and C), and the obtained configurations are given in Table 2.

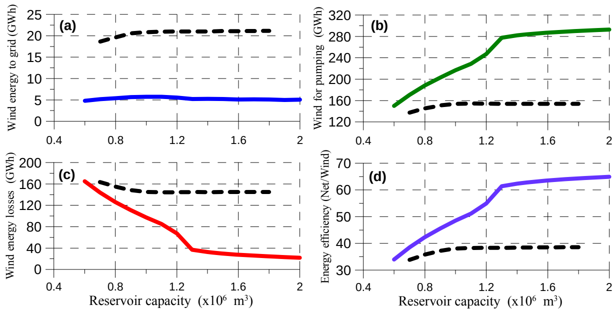

Figure 9. Effect of reservoir capacity on the energy results of HPP: A (continuous) & A1 (dashed line).

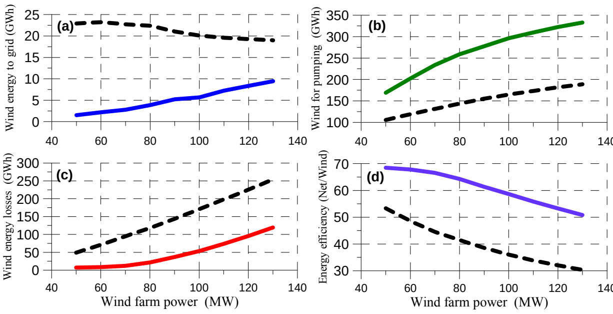

Figure 10. Effect of wind farm power on the energy results of HPP: A (continuous) & A1 (dashed line).

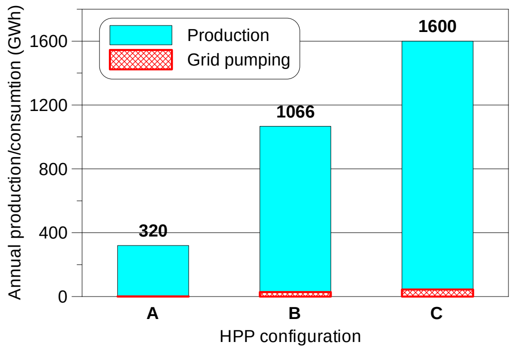

Figure 11. Annual energy results of studied HPPs.

4.3 Contribution to the island grid

The annual energy production of the studied HPPs in the system of Crete is shown in Fig. 11. Considering that the cumulative electricity production in the system for the reference year are estimated to 3800 GWh, the installation of the hybrid plants can significantly reduce the operation of conventional thermal units, replacing corresponding amounts of fossil fuel with clean wind energy. More specifically, at least 170 MW of conventional units can be phased out, and up to 42% of annual electricity needs can be covered (with the 500 MW HPP), in addition to about 15% share of the other RES units operating in the island. Moreover, the needs for pumping energy from the grid are minor, less than 3% of total HPPs production (Fig. 11).

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5 Conclusions

The computer analysis of the design and performance of hybrid wind-hydro power plants (HPP) in the autonomous grid of Crete island showed that the rated power of the plant determines its guaranteed power and annual energy share in the electricity system. The current regulatory framework for integration of hybrid plants in the Greek island networks permits the efficient operation of HPPs with significant installed storage capacity and production power, that can have more than 40% share in the electricity production, substituting conventional fossil fuelled units. Moreover, the provision of guaranteed power to the system is ensured with only minor needs for pumping energy from the grid.

Important parameters for the cost-effective design of HPPs are the reservoirs capacity and the wind farm power. The superiority of using double penstock and of separate pumping and turbining machinery was evident in all the results, concerning both the net energy production and the overall efficiency.

Finally, it was found that the net production efficiency of the HPP decreases as the primary RES power increases, for given capacity of the rest subsystems of the plant. Hence, the high plant efficiency and productivity constitute competitive targets.

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