# Turning Crete into an Energy Independent Island

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***Abstract*—This article examines the technical and economic aspects for the energy transition of the electrical system in Crete from fossil fuels to Renewable Energy Sources (RES). Despite the forthcoming Crete's interconnection with the Greek mainland grid, high secure RES penetration can be only achieved with the support of strategically designed and sited electricity storage plants, formulating together with the RES electricity production projects the so-called "hybrid power plants". Pumped Hydro Storage (PHS) systems feature as the optimum storage technology, from a technical and economic point of view, given the available intensive land morphology in the island and the size of the Cretan electrical system. Fourteen candidate sites for PHS installations were located in the Cretan territory. All of them were thoroughly sited on digitized maps and the required volumetric calculations were computationally executed. At the same time, fourteen favorable sites for wind parks installations were selected, with annual average wind velocity higher than 8.5 m/s, as documented with certified annual wind potential measurements, captured by wind meteorological stations installed at these particular sites. The applied methodology was based on the computational simulation of the annual operation of the involved PHS and wind parks plants, using annual time series of average hourly values of the involved magnitudes. The number of the employed RES and PHS systems was gradually increased at each iterative simulation, concluding, each time, at the achieved annual RES penetration and the economic efficiency of the required investment. The article proves that annual RES penetration percentages higher than 90% can be easily achieved in Crete with high economic feasibility of the required projects.**

***Keywords-component; hybrid power plants; insular autonomous systems; wind parks; pumped hydro storage***

## I. INTRODUCTION

Crete currently constitutes an autonomous insular system. The Hellenic Independent Power Transmission Operator, responsible for the mainland grid's operation in Greece, has planned and already started the construction of the island's electrical interconnection with the mainland Greece [1]. Normally, the interconnection of the island will contribute to the improvement of the insular system's energy supply security and the dynamic security of the electrical grid. On a second stage, an essential objective of this interconnection is also the reduction of the existing electricity production cost in Crete's insular system, achieved by shutting down specific thermal generators, currently operating with diesel oil and exhibiting considerably increased production cost (above 0.20 €/kWh) [2]. However, the secure electricity supply in the island imposes the maintenance under cold stand-by mode, and most possibly not only, of the most cost-effective available thermal generators, especially if we account that the island's interconnection will boost the installation of wind parks and photovoltaics [3, 4]. This task, in turn, implies that the "fixed" electricity production cost, related to the regular maintenance of the remaining generators, the staff salaries etc, will not be avoided. Additionally, every time these thermal generators are put on-duty, their variable cost will also contribute to the final configuration of the total electricity production cost in the island. Conclusively, one of the main objectives of the island's interconnection is simply not achieved, at least at the desirable extent, while, at the same time, the insular system still remains dependent on imported, exhaustive energy resources. The above arguments justify that the necessity for the support of the Crete's electrical system with hybrid power plants based on Renewable Energy Sources still remains after its interconnection, given the definite decision for energy transition from fossil fuels to renewables.

On the other hand, during the last decade, the development of Renewable Energy Sources (RES) projects in the insular Greece was inappropriately approached. This approach was formulated by the submission in the Regulatory Authority of Energy of plenty of applications for the licensing of mainly wind parks and secondary photovoltaic stations of considerably large size, with regard to the insular systems' size, leading to serious reactions against these projects and, in several cases, against RES projects in general [5]. Indicatively, it is mentioned that only in Crete more than 5 GW of wind parks and photovoltaic stations projects have been submitted for licensing, covering almost all the most favorable available locations, when the annual peak power demand in the island remains at the range of 650 MW. Among all these contradictory trends (applications for large RES projects, interconnection, massive reactions against these projects etc), a sensible question has in several cases come up: which are the required production and storage projects that can guarantee high and secure energy transition from fossil fuels to RES in the island?

This article focuses on the study of a potential solution towards the 100% coverage of the currently existing electricity needs in the island from a series of wind parks and Pumped Hydro Storage (PHS) plants. Actually, this article aims to provide an answer to all these questions and constitute a reference study towards the sustainable, realistic and feasible energy transition in Crete from fossil fuels to RES.

## II. Adopted Approach

### *A. Features of Existing Electricity Production*

Electricity production in Crete is accomplished today by three thermal power plants, equipped with steam turbines, diesel generators, gas turbines and a combined cycle, with roughly 800 MW total nominal power, and approximately 220 MW of wind parks and 88 MW of photovoltaic panels. Thermal generators operate with imported heavy fuel and diesel oil, purchased at final prices (including transportation cost, taxes, public rates etc) roughly at 0.5 €/kg and 0.95 €/lt respectively. The considerably high fossil fuels procurement prices lead to a final, total electricity production specific cost higher than 0.20 €/kWh (including variable and fixed cost). The annual electrical power demand time-series is depicted in Figure 1, provided by the grid operator for 2016. The effect on the power demand annual profile from the intensive seasonality of the professional activities in the island (maximized in summer due to tourism), is clearly depicted in this Figure.

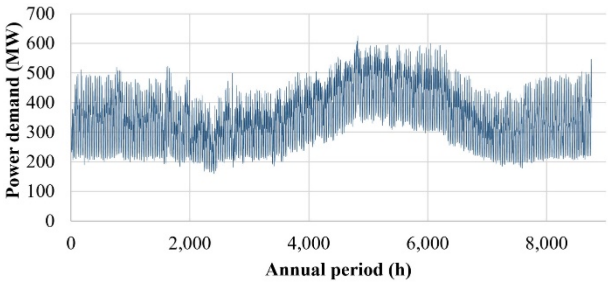


Figure 1. Annual electrical power demand fluctuation in Crete.

Given the introduced annual time-series, the annual electricity consumption is calculated at 3,074,690 MWh. The annual peak and minimum power demand are 623 MW and 160 MW respectively. The daily average electricity consumption, calculated by dividing the above annual consumption with the days' number of the year, is calculated at 8,423 MWh.

In Figures 2 and 3 the annual final power penetration time-series (after wind production curtailments) of the existing wind parks and photovoltaic stations in the island are depicted respectively. These annual time series have been computationally developed, following the computational simulation of the system's annual operation, given the installed nominal power of the involved thermal and RES technologies in the island, the dispatch sequence of the involved thermal generators and the available wind potential and solar radiation [6]. More on the available wind potential in Crete is given in a next section.

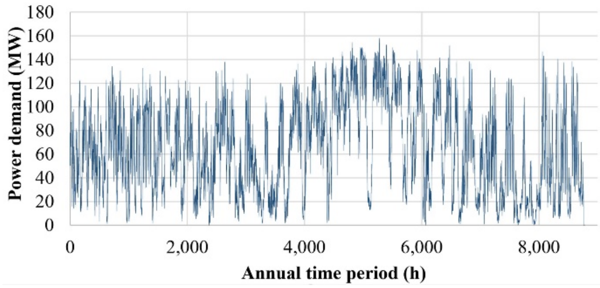


Figure 2. Annual electricity production from the existing wind parks in Crete.

The annual electricity production from the wind parks and the photovoltaic stations, based on these time-series, is calculated at 574,772 MWh and 123,429 MWh respectively. For 220 MW and 88 MW of wind parks and photovoltaics installed power respectively, the total, annual, average capacity factors are calculated at 29.8% for the wind parks and at 16.0% for the photovoltaic stations. It must be underlined that the capacity factor for the wind parks appears relatively low, because it was calculated for the final penetrated wind energy in the electrical grid (after wind power rejection from the grid's operation, due to system's stability and security reasons).

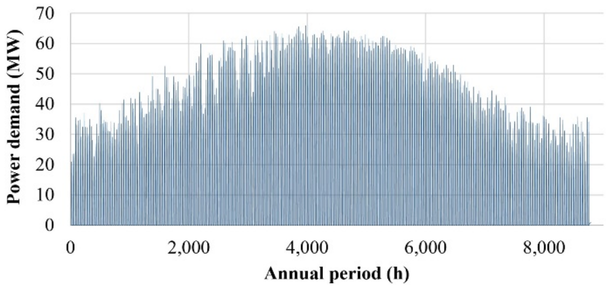


Figure 3. Annual electricity production from the existing photovoltaic stations in Crete.

The total annual electricity production from both the wind parks and the photovoltaic stations is calculated by adding the above presented amounts at 698,200 MWh, which corresponds at 22.7% of the annual electricity consumption in Crete.

### *B. Aiming at 100% Electricity Needs Coverage from RES*

It is well known that the approach of high RES penetration in autonomous insular systems requires the support of the non-guaranteed RES production technologies with electricity storage plants. As documented in the introductory section of this article, this necessity still remains even in interconnected islands, especially in cases of long distances from the mainland grid, in order to approach improved electricity supply security and claim lower production cost.

In case of large size systems, it has been widely proved that the optimum storage technology is Pumped Hydro Storage (PHS) [7-10]. This technology is the only one which can provide large storage capacity (at the range of GWh) with set-up specific cost as low as 30 €/kWh of storage capacity [11] and autonomy period more than 10 days [7]. With the term "autonomy period", the time period is defined during which the storage plant can exclusively support the power demand, starting from full charge level and without any intermediate charge during this period.

On the other hand, the remarkably high wind potential met in the Aegean Sea Islands, documented by capacity factors higher than 40% in several locations [12-15], along with the relatively higher power density, compared to photovoltaics, lead to the selection of wind parks as the essential RES technology on which the energy transition in Crete should be based. Finally, the already existing photovoltaic stations will be certainly taken into account in this article. The annual production fluctuation, presented in Figure 3, will be maintained in the simulation study, reducing respectively the power demand which should be covered by the wind – PHS systems.

## III. DOCUMENTING THE AVAILABLE WIND POTENTIAL

Crete has been blessed with remarkable wind potential. Annual average wind velocities higher than 8 m/s are often met in plenty of sites, while, in several cases, this feature can exceed 9 m/s or even 10 m/s. For this particular study, fourteen (14) annual wind velocity measurements, captured in different locations from the eastern to the western Crete, were employed for the wind potential evaluation and the simulation of the annual electricity production from the introduced wind parks. All these wind measurements were either captured during the last fifteen years by the Wind Energy and Power Plants Synthesis Laboratory of the Technological Educational Institute of Crete, certified according to the relevant 17025:2005 standard, or delivered by wind parks' owners in the island. The locations of these time series are presented in Figure 4. In Table I, the sites' local geographical names are presented, together with the corresponding annual average wind velocities.

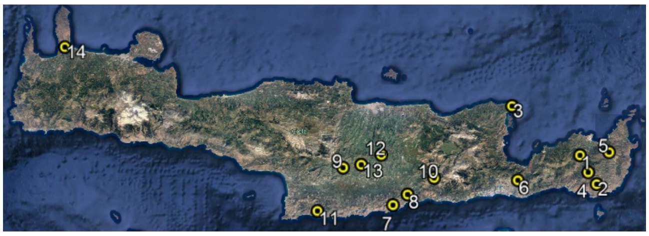


Figure 4. Locations of wind potential measurements sites.

TABLE I. EMPLOYED WIND MEASUREMENTS FEATURES.

| No | Site name | Prefecture | Annual average wind velocity (m/s) |
|---|---|---|---|
| 1 | Maronia Sitias | Lasithi | 9.6 |
| 2 | Apidi Sitias | Lasithi | 9.0 |
| 3 | Vrouhas | Lasithi | 9.5 |
| 4 | Chandras | Lasithi | 9.0 |
| 5 | Xirolimni | Lasithi | 9.5 |
| 6 | Ierapetra | Lasithi | 8.0 |
| 7 | Tsivi Achentrias | Heraklion | 10.5 |
| 8 | Agios Charalampos Kasteliana | Heraklion | 8.7 |
| 9 | Prinias | Heraklion | 8.8 |
| 10 | Kynigos Viannou | Heraklion | 9.6 |
| 11 | Antiskari Moiron | Heraklion | 7.8 |
| 12 | Partheni | Heraklion | 8.9 |
| 13 | Melidochori | Heraklion | 8.8 |
| 14 | Aspra Nera | Chania | 9.2 |

The high available wind potential is documented by the annual average wind velocities presented in the above Table. This favorable condition, namely the availability of abundant primary energy resource potential, is significantly critical, regarding the achievement of high annual RES penetration.

## IV. THE AVAILABLE SITES FOR PUMPED HYDRO STORAGE SYSTEMS INSTALLATION

Apart from the wind potential, Crete has been also blessed with excellent land morphology for PHS systems installation. These sites are characterized with flat hills or mountains tops, easily formulated as the reservoirs' basins with relatively low amounts of digging works, and mild mountains slopes, enabling the on-surface penstock installation, avoiding, thus, the expensive underground tunnels construction.

Crete, being a large, mountainous island, accepts every year considerable rainfalls, with annual heights from 400 mm (in the eastern Crete) to 700 mm in the western Crete and even above 1,000 mm in the mountainous areas and in the plateaus [16]. This means that the construction of PHS system with potable water is possible in several sites.

In this study, in total fourteen (14) sites for PHS systems installation were selected, all of them after thorough investigation and, for the most of them, after on-site inspection. Two of these cases will operate with potable water, involving, normally, an upper and a lower reservoir. The other twelve (12) PHS systems have been sited next to the coastline and will operate with seawater. In these cases, only the upper reservoir will be constructed, since seawater will be pumped directly from the sea, where it will be also disposed. All PHS systems will be equipped with double penstock, enabling, in this way, the concurrent water falling and pumping, a crucial feature for the adequate support of the grid's dynamic security and stability, especially under high RES penetration.

The locations of these fourteen sites are presented in Figure 5. It is seen that a considerable geographical dispersion has been properly achieved with the selected sites, another crucial feature for the appropriate topology of the local grid, contributing to both reduced operation cost (lower electricity transfer losses) and improved functionality and stability.

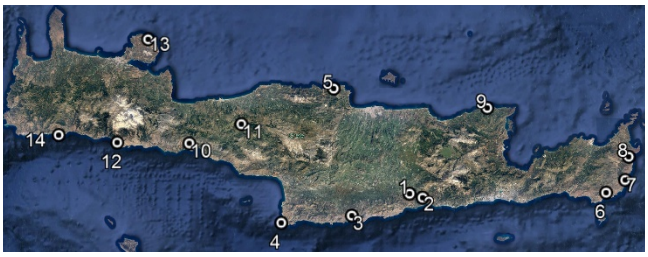


Figure 5. Locations of PHS system installation sites.

In Table II, the essential technical features of the selected sites for PHS systems installation are presented.

TABLE II. FEATURES OF THE SELECTED PHS SITES.

| No | Site name | Reservoirs altitude (m) | Reservoirs volume ($m^3$) | Penstock length (m) | Storage capacity (MWh) |
|---|---|---|---|---|---|
| 1 | Anapodaris[a] | 560 | 2,851,868 | 1,865 | 3,139 |
| | | 156 | 22,085,319 | | |
| 2 | Chondros Viannou | 404 | 1,538,603 | 2,632 | 1,693 |
| 3 | Gortynas | 300 | 1,100,243 | 2,440 | 899 |

| | | | | | |
|---|---|---|---|---|---|
| 4 | Martsalo | 220 | 1,148,871 | 1,317 | 689 |
| 5 | Bobias Heraklion | 380 | 2,045,672 | 1,383 | 2,118 |
| 6 | Atherinolakkos | 520 | 1,926,722 | 2,444 | 2,729 |
| 7 | Kato Zakros | 212 | 2,143,919 | 1,457 | 1,238 |
| 8 | Lagkada | 380 | 1,750,807 | 2,370 | 1,812 |
| 9 | Lithomandra | 268 | 1,514,808 | 749 | 1,106 |
| 10 | Plakias | 820 | 1,941,964 | 4,728 | 4,338 |
| 11 | Potamon Dam[a] | 580 | 1,463,788 | 2,804 | 957 |
| | | 200 | 22,500,000 | | |
| 12 | Agios Ioannis, Sfakia | 640 | 1,737,917 | 1,961 | 3,030 |
| 13 | Akrotiri Chanion | 280 | 1,703,754 | 1,846 | 1,300 |
| 14 | Sougia | 264 | 1,778,473 | 1,465 | 1,279 |
| | | | | ***Total storage capacity (MWh) :*** | 26,327 |

a. Operation with potable water. Two reservoirs are involved.

All figures presented in Table II are the results of detailed siting of the PHS systems' fundamental components (reservoirs, penstock) on digitized land terrain and of subsequent computational volumetric calculations. Two characteristic cases are presented in Figures 6 and 7, for the sites No 2 and 11 respectively.

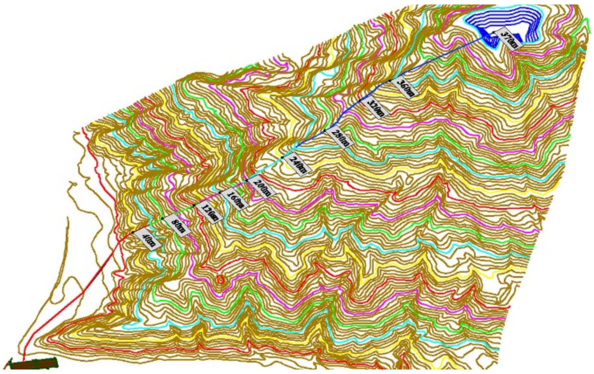

Figure 6. Siting on digitized land terrain of the PHS system in the Chondros Viannou location.

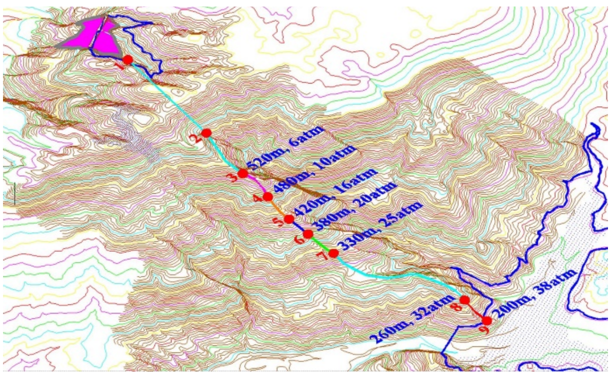


Figure 7. Siting on digitized land terrain of the PHS system in the Potamon Dam location.

Most of the selected sites combine high geostatic head and upper reservoir's volume, leading to a total energy storage capacity of 26.3 GWh (from all 14 storage plant). Given the average daily electricity consumption (8.423 GWh) and assuming an average hydro turbines' efficiency of 85%, this total storage capacity corresponds to an autonomy period of 2.6 days. PHS systems No. 1 and 11 operate with potable water. All the rest operate with seawater.

It is also certain that, due to the size of the electrical system in Crete, the coverage of the energy storage requirements could be fulfilled with much fewer storage plants, maybe two – four, each one of them with much larger size. Nevertheless, the introduction of more PHS systems, properly distributed in the overall geographical insular territory, was selected in order to approach a more secure grid's layout, by evenly distributing the guaranteed power production throughout the whole grid. Additionally, in this way any special constructions of considerably large size are avoided, which could require special technical solutions, not available in the island. Finally, although Crete in general is characterized by intensive land morphology, it is highly doubtful whether appropriate sites could be found for the installation of PHS systems with nominal guaranteed power production above 200 MW, without affecting significantly the neighboring environment and raising serious reactions in the local communities.

## V. Simulation Of The Introduced Wind-PHS Systems – Operation Algorithm

### *A. Fundamental Approach*

From the above analysis it is revealed that fourteen sites for wind parks installation and fourteen sites for PHS systems installation have been selected. In order to simplify the overall simulation process, the following approach is adopted:

- Firstly fourteen hybrid power plants, consisting of one wind park and one PHS system, are formulated, by combining each one of the 14 wind parks with each one of the 14 PHS systems. The 14 hybrid power plants will be considered, at a first step, independent between them, in the sense that each one of them will operate regardless any other.
- Secondly, the net power demand time-series, derived by subtracting the existing photovoltaic power production from the gross power demand presented in Figure 1, is divided in fourteen parts, with a division factor for each part equal with the percentage contribution of the storage capacity of each PHS system to the total storage capacity provided by all PHS systems. For example, the division factor for the first PHS system will be equal to 3,139 / 26,327 = 0.119, for the second PHS system 1,693 / 26,327 = 0.064 etc (see Table II).
- Each one of the as such formulated power demand parts is assigned to the corresponding hybrid power plant, which should cover this power demand part at a first stage on its own, namely without the support of the other hybrid power plants, following the operation algorithm presented in the following section.
- Finally, once the simulation of the above described process has been fulfilled, at a second stage, any inadequacies on the assigned power demand coverage by the corresponding hybrid power plant, due to low wind potential availability or low charge level in the storage plant, are investigated whether they can be covered by the other hybrid power plants.

The above described process is executed iteratively, varying each time the nominal power of the involved wind parks, given that the storage capacities and the geostatic heads of the PHS systems are fixed, imposed by the available land morphology. The goal is to achieve annual RES penetration at least higher than 90%, versus the annual electricity consumption.

*B. Operation Algorithm*

The adopted operation algorithm aims at the maximisation of the RES penetration throughout the daily period and, subsequently, on annual basis. It is realized with the computational simulation of the hybrid system's annual operation, based on annual time-series with average hourly values. In short terms, it is analyzed below [17]:

1. For each calculation time step, the total available power production from the RES units $P_{RES}$ and the current power demand $P_d$ are introduced. The maximum RES direct penetration percentage versus the power demand $p_{max}$ is defined at 40%.
2. The RES direct penetration $P_{RESp}$ is calculated from the following relationships:
   a. If $P_{RES} > p_{max} \cdot P_d$, then $P_{RESp} = p_{max} \cdot P_d$.
   b. If $P_{RES} \leq p_{max} \cdot P_d$, then $P_{RESp} = P_{RES}$.
3. Once the R.E.S. direct penetration has been defined, there will be:
   a. a potential R.E.S. power production surplus: $P_{RES} – P_{RESp}$
   b. a remaining power demand still uncovered: $P_d – P_{RESp}$.
4. The water volume $V_p$ is then calculated, required to be pumped in the PHS upper reservoir, in order to store the power surplus $P_{RES} – P_{RESp}$, available for the duration t of the calculation step ($H_p$ the available net pumping head, γ the water's specific weight, $\eta_P$ the pump units average overall efficiency during the current calculation time step):

$$V_p = \frac{(P_{RES} - P_{RESp}) \cdot t \cdot \eta_p}{\gamma \cdot H_p} \quad (1)$$

5. Similarly, the water volume $V_h$ is calculated, required to be removed from the PHS upper reservoir, so as the remaining power demand $P_d$ – $P_{RESp}$ will be produced by the hydro turbines for the duration t of the calculation step ($H_T$ the available water falling net head):

$$V_h = \frac{(P_d - P_{RESp}) \cdot t}{\gamma \cdot H_T \cdot \eta_h} \quad (2)$$

`

6. The remaining water volume stored in the PHS upper reservoir after the end of the current calculation time step j will be:

$$V_{st}(j) = V_{st}(j\text{-}1) + V_p – V_h.$$

7. The remaining water volume $V_{st}(j)$ in the PHS upper reservoir is checked whether it exceeds or not the reservoir's maximum storage capacity $V_{max}$:
   a. If $V_{st}(j) > V_{max}$, then:
      $P_h = P_d – P_{RESp}$
      $P_{th} = 0$
      $P_{st} = 0$
      $P_{rej} = P_{RES} – P_{RESp}$
      $V_{st}(j) = V_{st}(j\text{-}1) – V_h$.

   where $P_h$ the power produced by the hydro turbines, $P_{th}$ the power produced by the thermal generators, $P_{st}$ the power absorbed by the pump units and $P_{rej}$ the R.E.S. units rejected power.

   b. If $V_{st}(j) \leq V_{max}$, then we proceed to the following step.
8. The remaining water volume $V_{st}(j)$ in the PHS upper reservoir is checked whether it is lower or not than the minimum water volume $V_{min}$ which always remains stored in the reservoir, mainly due to constructive reasons (e.g. due to the position of the water's intake):
   a. If $V_{st}(j) < V_{min}$, then:
      $P_h = 0$
      $P_{th} = P_d – P_{RESp}$
      $P_{st} = P_{RES} – P_{RESp}$
      $P_{rej} = 0$
      $V_{st}(j) = V_{st}(j\text{-}1) + V_p$.
   b. If $V_{min} \leq V_{st}(j) \leq V_{max}$ then:
      $P_h = P_d – P_{RESp}$
      $P_{st} = P_{RES} – P_{RESp}$
      $P_{th} = 0$
      $P_{rej} = 0$
      $V_{st}(j) = V_{st}(j\text{-}1) + V_p – V_h$.

The above operation algorithm has been realized with a relevant software application developed by the authors. The results from its execution are presented in the next section.

## VI. Results

In this section the fundamental results from the executed simulations and calculations are presented, regarding the dimensioning of the introduced systems (wind parks and PHS systems) and the annual energy production and storage.

*A. Dimensioning of the involved technologies*

Given that the storage capacities and the penstock lengths of the introduced PHS systems are defined by the available land morphology in the selected installation sites, the dimensioning of the involved components refers to the required installed power of the wind parks, the hydro turbines and the pumps, as well as the nominal diameters of the water falling and pumping pipelines. The dimensioning results regarding the wind parks' required nominal power are presented in Table III. Given the size of the wind parks' required power, a 3 MW wind turbine model has been assumed for each wind park.

TABLE III. Fundamental Results Of The Wind Parks' Dimensioning.

| Wind park's site | Wind turbines' number | Wind park's power (MW) |
|---|---|---|
| 1 | 40 | 120 |
| 2 | 20 | 60 |
| 3 | 15 | 45 |

| | | |
|---|---|---|
| 4 | 10 | 30 |
| 5 | 30 | 90 |
| 6 | 45 | 135 |
| 7 | 20 | 60 |
| 8 | 25 | 75 |
| 9 | 17 | 51 |
| 10 | 75 | 225 |
| 11 | 25 | 75 |
| 12 | 30 | 90 |
| 13 | 17 | 51 |
| 14 | 22 | 66 |
| ***Total*** | 391 | 1,173 |

With regard to the PHS systems, the main dimensioning results, regarding the hydro turbines and the pumps nominal power and the inner diameter of the water falling and pumping pipelines, are presented in Table IV. The hydro turbines' and pumps' required power is derived from the annual maximum power produced by the hydro turbines or absorbed by the pumps. The required pipelines' diameter are calculated following the essential theory, aiming at the minimisation of the water flow losses through the pipelines [18].

TABLE IV. FUNDAMENTAL RESULTS OF THE PHS SYSTEMS' DIMENSIONING.

| PHS site | Hydro turbines' required power (MW) | Pumps' required power (MW) | Falling pipeline diameter (m) | Pumping pipeline diameter (m) |
|---|---|---|---|---|
| 1 | 68.1 | 102.0 | 4.0 | 3.0 |
| 2 | 38.3 | 63.3 | 2.8 | 2.2 |
| 3 | 19.2 | 36.5 | 2.6 | 2.0 |
| 4 | 14.9 | 26.5 | 2.5 | 2.0 |
| 5 | 45.7 | 82.9 | 3.2 | 2.5 |
| 6 | 58.5 | 114.2 | 3.2 | 2.5 |
| 7 | 27.0 | 48.4 | 3.5 | 2.5 |
| 8 | 40.6 | 59.2 | 3.0 | 2.5 |
| 9 | 24.4 | 40.4 | 3.0 | 2.2 |
| 10 | 97.1 | 182.5 | 3.2 | 2.5 |
| 11 | 32.0 | 60.2 | 3.0 | 2.2 |
| 12 | 64.0 | 94.5 | 3.0 | 2.2 |
| 13 | 28.3 | 42.8 | 3.0 | 2.4 |
| 14 | 26.3 | 53.5 | 2.8 | 2.2 |
| ***Total*** | 584.4 | 1,007.0 | | |

## *B. Annual Energy Production and Storage*

In this section, the results regarding the annual energy production from the involved generators, namely the wind parks, the hydro turbines and the existing thermal generators, as well as the annual electricity absorbed by the storage units (pumps) are summarized in Table V.

TABLE V. ANNUAL ENERGY PRODUCTION AND STORAGE RESULTS.

| Wind park / PHS site | Wind parks' direct penetration (MWh) | Hydro turbines production (MWh) | Pumps absorbed power (MW) | PHS systems' efficiency (%) |
|---|---|---|---|---|
| 8 / 1 | 137,273 | 159,807 | 257,078 | 62.16 |
| 10 / 2 | 82,208 | 91,054 | 149,487 | 60.91 |
| 11 / 3 | 36,068 | 51,048 | 95,492 | 53.46 |
| 12 / 4 | 34,164 | 35,462 | 61,141 | 58.00 |
| 7 / 5 | 99,639 | 120,006 | 204,792 | 58.60 |
| 2 / 6 | 133,887 | 139,641 | 239,021 | 58.42 |
| 4 / 7 | 60,286 | 69,369 | 123,354 | 56.24 |
| 3 / 8 | 88,082 | 95,891 | 155,656 | 61.60 |
| 5 / 9 | 54,700 | 59,980 | 95,823 | 62.60 |
| 9 / 10 | 196,981 | 252,527 | 441,165 | 57.24 |
| 13 / 11 | 70,449 | 79,554 | 147,986 | 53.76 |
| 14 / 12 | 131,205 | 146,653 | 229,954 | 63.77 |
| 1 / 13 | 65,702 | 69,242 | 113,116 | 61.21 |
| 6 / 14 | 60,861 | 63,807 | 116,840 | 54.61 |
| ***Total*** | ***1,251,505*** | ***1,434,039*** | ***2,430,904*** | ***58.99*** |
| Thermal generators' production (MWh) | | | 265,719 | |
| Existing photovoltaics production (MWh) | | | 123,427 | |
| Total annual energy production (MWh) | | | 3,074,690 | |
| Annual wind production surplus (MWh) | | | 276,535 | |
| Annual RES penetration percentage (%) | | | 91.4 | |
| Annual wind surplus percentage (%) | | | 7.0 | |

In Table V:

- The annual RES penetration percentage is calculated as the ratio of the sum of the wind annual penetration, the hydro turbines' production and the existing photovoltaics production, over the total annual electricity consumption. Given the results presented in Table V, it is seen that the achieved annual RES penetration percentage is higher than 91% with the conclusive dimensioning.

- The wind annual surplus comes from the electricity that could be potentially produced by the wind parks, given the available wind potential, but is not produced because of maximum direct penetration percentage exceedance and, concurrently, fully charged storage plants. The relevant percentage is calculated as the ratio of the as such annual electricity surplus versus the sum of this surplus, the wind annual direct penetration and the annual electricity provided for the pumps to be stored. The annual RES production surplus is restricted below 7%. This remarkably low percentage, in combination with the high achieved RES penetration percentage, confirm the validity of the proposed dimensioning, the selection of the involved technologies and the sites for both RES and storage power plants installation.

In Table V, in the first column the selected wind parks and PHS systems combinations for the formulation of the hybrid power plants are also presented. These combinations were selected taking into account several parameters, such as the vicinity of the corresponding locations, the combination of sites with high wind potential with PHS systems with large storage capacity and the available space for wind turbines installation at each involved site.

The annual power production synthesis is presented in Figure 8. In Figure 9, the power production synthesis is also presented for a focused time period during the peak demand season (summer).

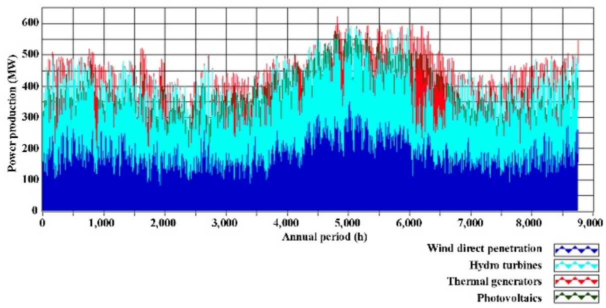


Figure 8. Annual power production synthesis with the proposed hybrid power plants in Crete.

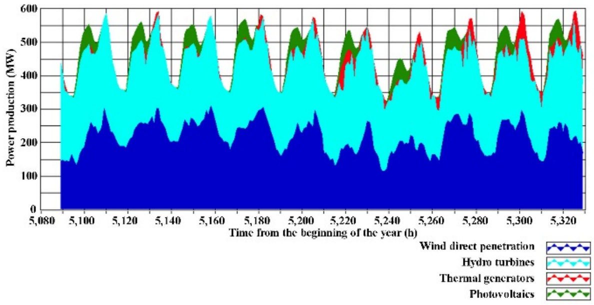


Figure 9. Power production synthesis with the proposed hybrid power plants from the 1st to the 10th of August in Crete.

From these Figures we may conclude to the following remarks:

- During summer, despite the maximized power demand, the thermal generators production is remarkably restricted. As seen in Figure 9, there are days during the peak power demand period with null thermal generators production. This is due to the certain production from the photovoltaic stations, given the abundant solar radiation availability during the daytime period, which fully undertake the early daily peak load and, additionally, due to the remarkably high wind potential, almost constantly available during summer, in the form of the local north-west winds, known as “meltemia”, formulated during the whole summer period above Aegean Sea by the warm climate in the Sahara desert and the cold air masses above Balkans.
- The main thermal power generators production is concentrated after 6,000 hours from the beginning of the year, which falls in September. This is because during this specific period, the local north-west winds in the Aegean weaken, while the power demand still remains relatively high, due to the still on-going tourist activities. This inadequacy could be treated with the construction of storage plants with higher autonomy operation periods (longer than 2.6 days), however affecting negatively the economic efficiency of the overall project. This observation also highlights the significance of the availability of high RES potential during the peak power demand period.
- Finally, from both Figures 9 and 10 it is seen that wind direct penetration is always restricted below 40% versus the current power demand.

In Figure 10 the annual fluctuation of the water volume stored in the PHS systems 1 and 6 upper reservoirs is depicted. In this Figure it is also seen the low stored water volume during September (between 6,000 and 7,000 hours), which leads to the thermal generators’ involvement in the production process. What is also observed in this Figure is that for the rest time period during the year, the wind parks’ geographical distribution offers power available for storage almost constantly, enabling high RES penetration with the minimum possible installed wind power, confirmed by the calculated low annual wind energy surplus.

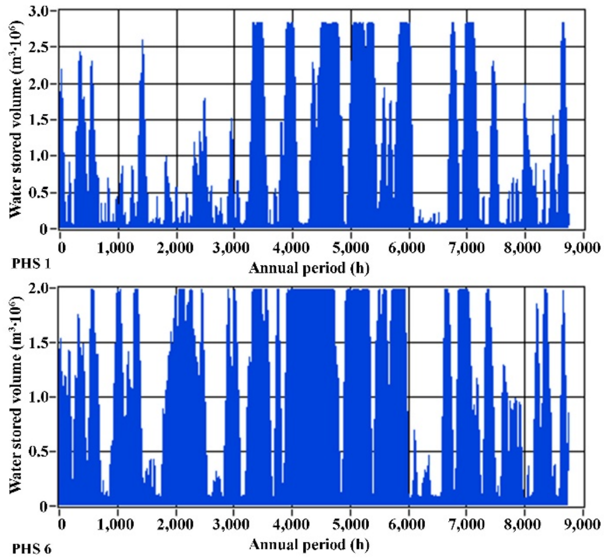


Figure 10. Annual fluctuation of the water stored volume in the PHS systems’ 1 and 6 upper reservoirs.

Indeed, the thermal generators annual production after the 1st stage of the simulation process, namely the independent hybrid power plants operation (see section V.A.), is calculated at 418,323 MWh, corresponding to 13.6% of the annual electricity demand in Crete. The wind parks annual electricity production surplus after this 1st stage is calculated at 540,520 MWh, which corresponds to 12.8% of the total annual electricity production from the wind parks. After the 2nd stage of the simulation process, during which the initial wind power surplus is investigated whether it can be stored in anyone of the available storage power plants, the thermal generators annual production and the wind parks’ annual production surplus are restricted in the amounts presented in Table V, corresponding to 8.6% and 7% of the annual electricity demand and wind parks’ production respectively. This observation highlights the significance of the wind parks dispersion throughout the geographical territory of Crete on the final achievement of as high RES annual penetration percentage as possible.

## VII. Economic Evaluation

The last step of this study is the economic evaluation of the overall proposed project, through which its economic feasibility will be examined. The economic evaluation includes the estimation of the total set-up cost, the estimation of the annual operation and maintenance cost, the pricing of the electricity produced by the hybrid power plants, the calculation of the annual revenues and, finally, the calculation of characteristic economic indices. Particularly in this study, a short sensitivity analysis will be performed for specific economic indices, versus the produced electricity pricing, introduced as the independent parameter. The above tasks are analyzed in the following sections.

### *A. Set-up cost estimation*

The set-up cost estimation is executed separately for the wind parks and the PHS systems. The wind parks set-up cost is estimated based on gained experience and awareness arisen from the study and the installation of a large amount of wind parks in the insular Greece and, particularly, in Crete. Given these facts, an average set-up specific cost at

1,200 €/kW of installed wind parks' power is adopted specifically for the installation conditions and the available infrastructure in Crete (available grid's facility, access roads etc). For a total wind parks' nominal power of 1,173 MW, the corresponding total set-up cost is calculated at 1,407,600,000 €.

The set-up cost of the PHS systems cannot be approached on the basis of an average set-up specific cost, as with wind parks. This is because each PHS system is designed, sited and, eventually, installed under different circumstances, imposed mainly by the locally available land morphology. Additionally, the size of the PHS systems affects its specific set-up cost. Hence, the PHS systems set-up costs were thoroughly estimated given their detailed siting on the digitized maps, the experience gained by the accomplishment of similar commercial projects [18, 19] and the available information in the relevant literature on this specific topic [9, 20].

The total set-up cost of the overall project is presented in Table IV. As seen in this Table, the overall cost is analyzed specifically per each involved PHS system and for the total proposed wind parks.

TABLE VI. SET-UP COST ESTIMATION OF THE OVERALL PROJECT

| Set-up cost component | Cost (€) |
|---|---|
| Wind parks | 1,407,600,000 |
| Anapodaris[a] | 170,000,000 |
| Chondros Viannou | 95,000,000 |
| Gortynas | 105,000,000 |
| Martsalo | 99,000,000 |
| Bobias Heraklion | 100,000,000 |
| Atherinolakkos | 98,000,000 |
| Kato Zakros | 95,000,000 |
| Lagkada | 102,000,000 |
| Lithomandra | 90,000,000 |
| Plakias | 112,000,000 |
| Potamon Dam | 120,000,000 |
| Agios Ioannis, Sfakia | 115,000,000 |
| Akrotiri Chanion | 92,000,000 |
| Sougia | 90,000,000 |
| ***Total*** | 2,890,600,000 |

## B. *Operation and maintenance cost*

The overall project's operational and maintenance cost is calculated following the Greek legislation and the statistical data base configured from existing similar projects worldwide. The projects' annual operation and maintenance cost consists of the following components:

- Revenues: the investment's annual revenues are calculated by the product of the total annual electricity production from the hybrid power plants (wind energy direct penetration and hydro turbines production) with the electricity selling price.
- Public rates equal to 3% of the investment's total annual revenues.
- Wind parks' maintenance annual cost equal to 0.010 €/kWh produced by them (direct penetration or storage).
- PHS systems' annual maintenance cost equal to 100,000 € per system, on average.
- Loan annual payment. The total set-up cost is assumed to be covered by 50% equities and 50% loan capitals, with a payback period of 15 years and a load rate of 2%.
- Total annual salaries: 7 employees per hybrid power plant (14 plants in total), with 25,000 € annual income per employee on average.
- Equipment insurance 4‰ of the projects' equipment procurement cost, estimated equal to 50% of the total set-up cost.
- Several other annual costs: 50,000 € per hybrid plant.
- Constant amortization over 15 years, calculated over the 70% of the total set-up cost.
- Tax coefficient 29%.
- Projects' life period 20 years.
- Discount rate 3%.

Following the above presented assumptions, the project's annual cash flows are calculated.

## C. *Sensitivity analysis – economic indices*

Given the above assumptions and parameters, a sensitivity analysis is executed versus the electricity selling price and characteristic economic indices are calculated on the investment's equities. The calculated economic indices are:

- The Net Present Value (N.P.V.) in €.
- The Internal Rate or Return (I.R.R.) in %.
- The Payback Period in years.
- The Discounted Payback Period in years.
- The Return On Investment (R.O.I.) in %.
- The Return On Equities (R.O.E.) in %.

The results are presented in Table VII.

TABLE VII. ECONOMIC ANALYSIS RESULTS.

| Electricity selling price (€/kWh) | N.P.V. (€·$10^9$) | I.R.R. (%) | Payback period (years) | Discounted payback period (years) | R.O.I. (%) | R.O.E. (%) |
|---|---|---|---|---|---|---|
| 0.12 | 0.9 | 8.5 | 10.1 | 12.8 | 81 | 162 |
| 0.14 | 1.4 | 11.5 | 8 | 9.3 | 100 | 200 |
| 0.16 | 2 | 14.5 | 6.6 | 7.4 | 119 | 238 |
| 0.18 | 2.5 | 17.3 | 5.6 | 6.2 | 138 | 276 |
| 0.2 | 3.1 | 20 | 4.9 | 5.6 | 157 | 314 |

For the above presented results, the economic feasibility of the proposed projects is definitely justified, even for electricity selling prices lower than 60% of the currently existing total electricity production specific cost in Crete (above 0.20 €/kWh).

# VIII. CONCLUSIONS

This article anticipates to provide justified answers on the very specific question with regard to the optimum transition plan in Crete towards its energy independency. With the accomplished work, it has been proved that Crete has both the RES potential (both wind potential and solar radiation) and the appropriate sites for PHS systems installation, required for the development of the fundamental electricity production and storage plants for high RES annual penetration. It was also proved, following a detailed siting of the introduced plants and a corresponding estimation of the overall investments' set-up and operation cost, that the proposed project is absolutely economically feasible, offering a considerably lower electricity selling price, compared to the existing electricity production specific cost in the islands.

It must be underlined that the interconnection of Crete with the mainland Greece does not cancel these projects, if the main objectives high energy supply security and low electricity production cost are to be satisfied. The best approach to satisfy these ultimate targets has been proved to be the hybrid power plants proposed in this article.

The proposed hybrid power plants do not in any way cancel the perspectives for alternative RES systems installations in the island, or the extensive involvement of the final consumers in the energy production and management processes, through the implementation of Demand Side Management (DSM) strategies, integrated in the frame of Smart Grids formulation. On the contrary, these approaches can have only positive supplementary contribution towards the achievement of a clear, 100% energy independence in the island, based on RES.

Finally, it is more than obvious that the social and economic benefits for the island and the local communities will be maximized in case these projects are implemented with massive participation of local investors and firms, in the form, maybe, of energy cooperative schemes. This is the optimum and the only secure way, not only to develop a series of developmental perspectives for the insular communities, but also to facilitate the fast and unobstructed realization of the required projects, by ensuring the positive common opinion and avoiding any potential negative reactions from the local inhabitants against the proposed projects.

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