

Article

Modeling and Optimal Dimensioning of a Pumped Hydro Energy Storage System for the Exploitation of the Rejected Wind Energy in the Non-Interconnected Electrical Power System of the Crete Island, Greece

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Abstract: The aim of the present paper is to investigate the use of the site “Potamon” Dam in the Prefecture of Rethymnon, Crete island, Greece, as a “virtual” renewable electricity supply of a pumped storage plant (PSP) in order to save and exploit the maximum possible part of the rejected wind energy of the autonomous power system of the Crete island. Taking into account the annual time series of the rejected power of the Crete power grid, the present research work targets the optimal configuration of the proposed PSP power station, including the sizing of its individual components as well as the determination of the capacity it could guarantee in order to be economically viable. The rejected electric energy from the actually operating wind farm production, which is not possible to be absorbed by the grid of Crete due to its stable operation limitations, could be absorbed by the here proposed pump storage plant (PSP) and converted to hydraulic energy. This can be achieved by pumping the water from the lower reservoir, which is the existing reservoir of the site “Potamon” Dam, with a storage capacity of about 22.5 million m³, up to the upper reservoir, which must be constructed accordingly. For the proposed PSP’s optimal size determination, established financial indices are used as an evaluation criterion for an investment life cycle of 25 years. The proposed PSP optimization is based on the dynamic mathematical model of the simulation results of the PSP’s hourly operation when incorporated in the Crete power grid for a whole year, performed in the Matlab 2016b computational environment (The MathWorks, Inc., Natick, MA, USA). The results of this research demonstrate the PSP’s technical feasibility and determine the PSP’s optimal CAPEX and the PSP’s whole life-time financial indicators in order that the whole investment be viable. Furthermore, the appropriate selling prices of the electricity produced from the proposed PSP were determined to achieve the PSP’s financial viability. The results comprise the key elements to prove the necessity for the establishment a.s.a.p. of the appropriate legal framework in order to have authorization to exploit the rejected RES (renewable energy sources) electric energy or the major part of it through PSPs, in priority in both the non-interconnected, as well as the interconnected power systems.

Keywords: non-interconnected power systems; pumped storage hydro power plants; optimization of isolated power grid including pump storage hydro plant; rejected wind energy electricity; isolated power grid stability; guaranteed capacity; water–energy nexus

1. Introduction

In power grids, in general, in order not to cause instability due to the high fluctuation of the wind power high penetration and consequently not to cause imbalance between electric power

production and demand, there is always a limit on the penetration of Renewable Energy Sources (RES). In non-interconnected islands the problem of absorbing RES energy production is greater and more crucial. In these cases, any amount of the RES produced electricity exceeding the acceptable penetration threshold must be obligatorily rejected. The need to store electric energy generated by RES and especially by wind farm production is emerging, even in strong interconnected networks, where wind energy participation approaches several limits beyond which the penetration of the wind produced electricity could cause serious instability in the electricity grid. The excess of the RES produced electricity, which is rejected from the grid, could then be stored for later use. This energy could be used during the electricity demand peak, while at the same time maintaining the stability of the whole grid [1]. A technologically advanced solution involves pumping to convert the rejected RES energy into hydraulic energy. This is achieved by pumping water from a lower reservoir to a higher reservoir using the obligatorily rejected RES produced excess electricity. The purpose of this paper is first to optimize the design and the determination of the key components of the appropriate Pumping Storage Plant (PSP), namely the number of pumps, rated pump supply, the hydro turbines nominal power, the capacity of the upper reservoir of the project and to determine the minimum CAPEX and the produced electricity selling price in order to achieve a viable and profitable PSP investment. The Net Present Value (NPV) at the end of investment life-time (25 years) is used as the main optimization criterion for PSP sizing. The optimal sizing of the above components is based on the simulation results of the dynamic mathematical model of the PSP for its hourly operation incorporated in the Crete power grid for a whole year, performed in the Matlab computational environment. Water and energy are two basic and important resources directly linked together. Correspondingly, significant amounts of energy are required for the pumping and/or collection, treatment, transportation of water and the treatment of waste-water before returning it to the environment. The reduction of energy consumption in water networks is directly linked to economic and environmental benefits. By reducing the energy costs, a reduction of the water management costs is obtained, which is in turn translated to reduced tariffs for consumers. In addition, the replacement of conventional energy with renewable energy has enhanced the environmental benefits associated with reducing CO₂ emissions, greenhouse gases, and climate change factors. The PSP under consideration is a high-profile project of the “Water Energy Nexus” policy. The project utilizes already existing dam infrastructure and existing water quantities stored to generate electricity. Consequently, the operating costs of the Organization for the Development of Crete S.A. (OAK SA, www.oakae.gr), which is the main water service provider in the water district of the Crete island, will be significantly reduced.

The use of wind-hydro hybrid plants for power production in isolated grids, appears to be the best solution for the maximization of the wind energy penetration and the minimization of the electricity production cost, in order to overcome the various problems and obstacles of the increased RES penetration to the grid [2,3]. The optimal technical and economic sizing of the combined wind-hydro storage hybrid power plants as well as the wind-battery storage hybrid plants, whose operation will be based on the rejected electric energy from already operating wind farms, which cannot be absorbed by the local isolated power grid, was initially studied in [1,4–7]. In Greece, the definition of hybrid systems has been clarified with the Greek Law no 3468/2006 and later related legislation, where constraints for the RES and storage unit size and the supplementary energy purchased from the grid, if necessary, have been set. In these works [8–10] simulation models were created in Matlab to incorporate the above law restrictions in order to investigate the optimal techno-economic sizing and design of pumped-storage wind-hydro power plants to be potentially installed in dams on the island of Crete. In fact, according to the results of several recent studies, installation of large-scale PSPs in the mainland grid is considered necessary over the next years in order to avoid remarkable wind energy rejections [11] and electricity rejections in general, thus to achieve the desired high levels of RES penetration [12–16]. Until now, a significant number of projects involving pumped storage hydro units have been submitted to the Greek Regulatory Authority of Energy (RAE) for licensing [17].

In continuation of the aforementioned studies, the present research investigates for the first time the optimal sizing and the techno-economic viability and determines the pricing policy of a PSP that absorbs only the rejected electricity or the maximum possible part of it of the existing wind farms interconnected to the isolated electrical grid of Crete. This rejected electricity is not possible to be consumed due to the strict grid stability limitations, especially during the late evening and the night period, using the infrastructure and the excessive water volume available in the reservoir at the site “Potamon” with an already existing dam in Rethymnon Prefecture, Crete, Greece.

2. The Case Study and the Methodology

2.1. The Proposed PSP's Optimal Design and Operation

A typical configuration of a hybrid wind-hydro PSP is given in Figure 1. The plant consists of two reservoirs at different elevation, a set of hydro turbines, pumps with common 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, while there is no internal interconnection between the hydro and the wind sub-plants. The electric energy storage capacity of such a plant depends on the useful volume of the smallest of the two reservoirs and of the hydraulic head between their levels. The storage capacity is determined by the rated power of the pump and turbine units [13].

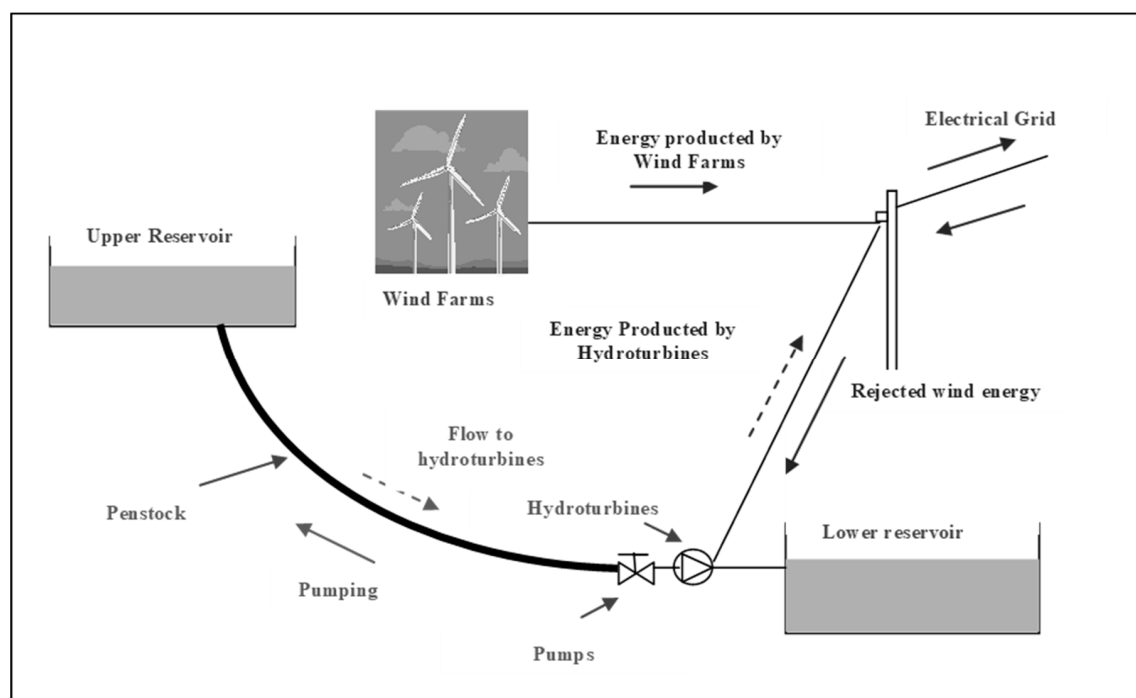


Figure 1. The parts of the proposed Pumped Storage System which absorbs the total daily rejected wind produced electricity.

In the present study, the wind electricity produced by the wind farms on the island of Crete is injected directly into the grid and only the non-penetrable amount, i.e., the non-absorbed by consumption, will be saved and stored in the upper reservoir through the pumps of the proposed PSP. In this way, an important fraction of the wind energy production, which otherwise would have been rejected, can be saved and exploited further. The hydro turbine produces and delivers electricity to the network according to a pre-agreed contract signed with the local TSO (Transmission System Operator) of the Crete island, for a constant time period every day, i.e., for eight hours during the peak demand hours of each day. This electric energy will be sold to the main grid. According to the Decision No.

1333/2010 of the Greek Regulatory Authority of Energy, the pricing of 236 €/MWh for the guaranteed wind-hydropower PSP production in Crete can be considered quite satisfactory. Crete is the largest Greek island with approximately 600,000 permanent inhabitants. The energy consumption in 2017 was 3,019,581 MWh with a peak demand of 637.9 MW. The electricity is produced by three conventional power stations (Linoperamata-Heraklion, Atherinolakos-Lasithi, and Xilokamara-Chania conventional power plants) of total installed power of 824.6 MW, by wind farms of total installed power of 200.3 MW and by photovoltaic installations of installed power of 95.5 MW [17,18]. Although the national project of the electric interconnection of Crete with the mainland has been initiated by the Independent Power Transmission Operator of Greece (ADMIE: www.admie.gr), the power system of Crete is still expected to remain autonomous until at least the end of the year 2025.

2.2. Simulation Methodology and Data

The simulation methodology first established in the present research includes the following steps:

- Step 1: Selection of the necessary data for the management and operation scenarios of the energy system of Crete from the most recently approved Energy Planning Study of the Region of Crete [19].
- Step 2: Generation of the rejected wind power time series. A rather difficult issue in the present research is the statistically valuable forecasting of the hourly time series (8760 values) of the rejected wind power in the power system of Crete for the year 2025 from the available rejected wind power time series of the reference year 2015. The determination of that time series used in the present research work is based on the combination of the data of the Energy Planning Study of the Region of Crete with the data of the HEDNO S.A. (Hellenic Electricity Distribution Network Operator) Annual System Operation Report-2017 as well as on the appropriate adaptation and application of the related algorithms and methodology developed by the Laboratory of Hydraulic Turbomachines-LHT/National Technical University of Athens (www.ntua.gr), Greece [14,20].
- Step 3: Development of the simulation model for the PSP scenarios realization study. In order to simulate the PSP annual operation a new dedicated algorithm was developed in Matlab, based on previous relevant research [9,10,21,22] with the appropriate modifications and updates. Changes and modifications concerning both the technical and the cost aspects of the individual subsystems of the PSP are presented in the following sections.
- Step 4: Simulations and results. The simulations of the scenarios under consideration are implemented and the results related to the technical issues, the optimal sizing, and the financial issues of the proposed PSP are derived.
- Step 5: Evaluation of the results and conclusions. The results are evaluated w.r.t. qualitative as well as quantitative and economic profitability indicators and documented conclusions are drawn on the feasibility and viability of the proposed scenarios for the proposed PSP realization.

The theoretical and computer implementation details of the above Steps 1 to 5 are presented in the following sections of the paper.

2.3. Step 1: Selection of the Necessary Data and Scenarios for the Realistic Crete Power System Management at the Year 2025

In order for the present study to be valuable and realistic, the selection of data sources is a crucial issue. The required forecasted operation values of the energy system of Crete in 2025 are obtained from the official and most recent Energy Planning Study of the Region of Crete approved by the Prefecture of Crete [19]. In the study [19] a long-term energy plan was scheduled, which thoroughly analyzed alternative strategies and options for future energy mixture, for the development of the energy infrastructure and the goals for the security of energy supply and the environmental protection. All sectors of consumption and energy production in Crete were covered and finally twelve feasible forecasting scenarios were proposed until the year 2050 (i.e., five scenarios without electrical interconnection consideration and seven alternative scenarios with electrical interconnection with

the mainland electrical system). The year under consideration in the present study is the year 2025 because at the end of that year the Crete island will be interconnected to the mainland grid. Thus, the five scenarios examined refer to the time period during which the Crete island will still remain non-interconnected. Finally the three possible and feasible scenarios selected for the needs of the present study are those including significant decentralized wind project development [19]:

- Scenario Business as Usual (BAU): It concerns persisting with the current situation. The estimated total gross electricity consumption for the year 2025 is then 3,137,000 MWh and the installed power of wind farms remains 215 MW, i.e., persistent prediction.
- Scenario OIL-GREEN: Maintenance and keeping in operation all the existing oil conventional units and decentralized RES are considered. The estimated total gross electricity consumption for the year 2025 is then 3,247,000 MWh and the installed power of the wind farms is decentralized 210 MW.
- Scenario GREEN-Advance (GREEN-ADV): Introduction of natural gas and decentralized RES are considered. The estimated total gross electricity consumption for the year 2025 is 3,374,000 MWh and the installed power of the wind farms is decentralized 210 MW.

More details about the forecasted installed power of all the electricity sources, as well as the forecasted gross electricity consumption in Crete in 2025 according to the study [19] is summarized in Table 1.

Table 1. The forecasted installed power of all kind of energy units in the Crete power grid in the year 2025 for the three scenarios.

Forecasted Installed Power in the year 2025 [MW]	BAU	OIL-GREEN	GREEN-Advance
Thermal Units	796	696	600
Natural Gas	0	0	540
Wind Farms	215	210	210
Photovoltaics	110	300	275
Other RES (small hydro, solar thermal, hybrid)	35	52	52
Total RES	360	562	537
Total Power	1156	1258	1677
Forecasted gross electricity consumption in the year 2025 [MWh]	3,137,000	3,247,000	3,374,000

The forecasted total gross electricity consumption for the year 2025 is different in each scenario due to the following reasons:

- Each energy planning scenario includes different estimations of the Crete Island economic growth.
- In the reference study [19] the different electricity consumption increases due to the partial or the complete substitution with electricity from hydrocarbons used for heating and transportation.

2.4. Step 2: Generation of the Rejected Wind Power Time Series

A rather difficult issue in the present research is the estimation of the time series (8760 values) of the rejected wind power in the power system of Crete for the year 2025. The creation of that time series used in the present research is based on the combination of the data of the Energy Planning Study of the Region of Crete with the data of the HEDNO S.A.'s (Hellenic Electricity Distribution Network Operator) Annual System Operation Report-2017, as well as the methodology developed in [14], properly modified. In Figure 2, the annual rejected wind power production for the reference year 2015 is depicted, as it was given by the Laboratory of Hydraulic Turbomachines-LHT/National Technical University of Athens [14] and it is registered as 184,888 MWh. In the year 2015 the installed wind power in Crete was 169 MW and the total gross electricity consumption was 2,904,000 MWh.

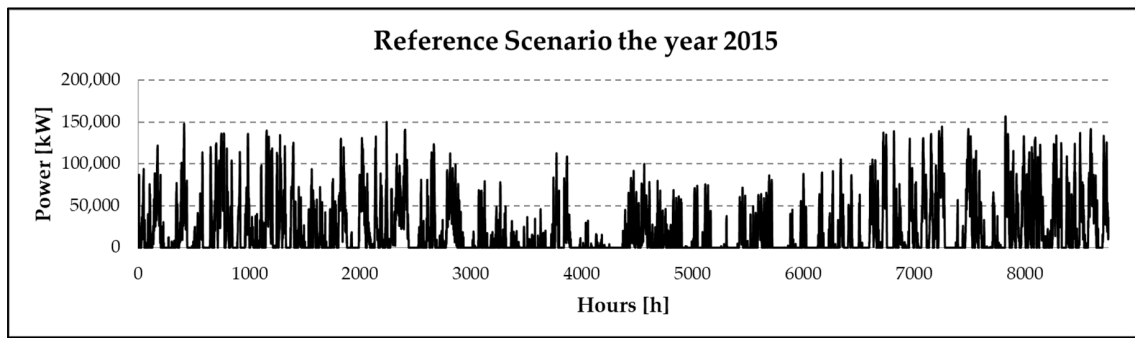


Figure 2. The annual rejected wind power time series for the reference year 2015 [14].

The method to forecast the rejected wind power time series of the year 2025 based on that recorded for the reference year 2015, is described below.

In the first step, the average hourly load \bar{L}_d of the power system of Crete for the year 2015 is calculated by the division of the registered total gross electricity consumption of the power system of Crete (by HEDNO) with 8760 h/y, i.e.,:

$$\bar{L}_d = \frac{2,904,000 \text{ MWh}}{8760 \text{ h/y}} = 331.5 \text{ MW} \quad (1)$$

With the same formula the forecasted average load for the year 2025 for each energy planning scenario (see Section 2.3 above) is estimated:

- Business as Usual: the forecasted total gross electricity consumption for 2025 is 3,137,000 MWh thus $\bar{L}_d = 358.1 \text{ MW}$
- OIL-GREEN: the forecasted total gross electricity consumption for 2025 is 3,247,000 MWh, thus $\bar{L}_d = 370.7 \text{ MW}$
- GREEN-Advance: the forecasted total gross electricity consumption for 2025 is 3,374,000 MWh, thus $\bar{L}_d = 385.2 \text{ MW}$

In the following, the dimensionless parameter R is introduced as the ratio of the total installed wind power in the island of Crete $N_{\text{wind}} [\text{MW}]$ to the average hourly load \bar{L}_d for each year (i.e., scenario) under consideration:

$$R = \frac{N_{\text{wind}}}{\bar{L}_d} \quad (2)$$

The parameter R signifies the relative (percentage) participation of the installed wind power to the average hourly load covering. In other words the ratio R could be considered as a simplified estimation of the average hourly penetration of the wind energy in the isolated power system for each year under consideration.

In the last step, the parameter F_{ct} is introduced below that can be used to create the forecasted wind production time series from the registered one of a past (reference) year, until the future year under consideration. In that way, the additional wind power installed due to any new wind farm installation during the corresponding time period is considered and defined as follows [13]:

$$F_{\text{ct}} = \frac{\text{Parameter R of the future year X}}{\text{Parameter R of the reference year}} \quad (3)$$

In this way, by multiplying all the values of the reference wind power rejection time series with the defined above parameter F_{ct} , a realistic forecasting of the rejected wind power time series can be created for each energy planning scenario under examination of the Crete power grid for the year 2025. In the case of the present study the parameter F_{ct} is used to create the rejected wind power time series,

one for each scenario examined, for the year 2025, by taking as reference the known rejected wind power time series of the reference year 2015. The parameter F_{ct} could then be expressed as:

$$F_{ct} = \frac{R_{2025}}{R_{2015}} \quad (4)$$

where R is defined in Equation (2).

The above parameters calculated for each examined scenario are presented in Table 2.

Table 2. The main parameters values calculated by Equations (1)–(4) for each energy planning scenario for the reference year 2015 and the forecasted year 2025.

Year	Scenario	Average Load- L_d [MW]	Installed Wind Power in Crete- N_{wind} [MW]	R Parameter	F_{ct} Parameter
2015	Reference year (registered)	331.5	169	0.51	1
2025	BAU	358.1	215	0.60	1.17
2025	OIL-GREEN	370.7	210	0.57	1.11
2025	GREEN-ADV	385.2	210	0.55	1.07

By applying the above algorithm to the known reference wind power rejection time series of the year 2015, the forecasting of the wind power rejection time series for the year 2025 can be produced. At the year 2025, the forecasted wind power rejection time series of the still autonomous power grid of Crete for the above under examination scenarios have been finally estimated as: 218,000 MWh, 205,000 MWh and 198,000 MWh for the Business as Usual, the OIL-GREEN and the GREEN-ADV scenarios respectively. In Figure 3 the new time series for Business as Usual energy planning scenario is presented indicatively.

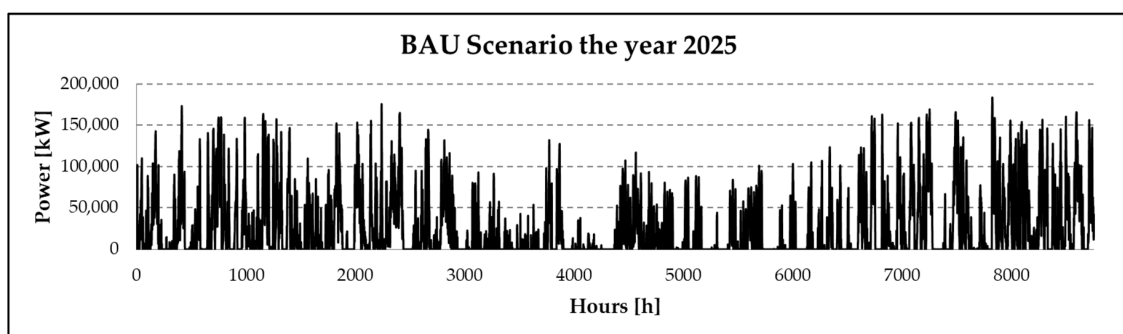


Figure 3. Rejected wind power time series for Business as Usual energy planning scenario under examination forecasted for the year 2025.

2.5. Pump Storage and Hydro Turbine Physical Operation Mathematical Background and Formulation

The main machinery of a PSP are its pumping and its hydro-turbine-generator sub systems. For the reservoir-pump-pipeline system of the proposed here PSP, the stored energy equation from the lower reservoir to the upper reservoir yields the total pump head H_p calculated by the relation:

$$H_p = H_0 + h_f \quad (5)$$

where: H_0 : is the static head i.e., the height difference between the two reservoirs [m]; Q : water flow rate [m^3/s]; k : the friction factor [dimensionless]; h_f : is the friction head i.e., the friction loss in the pipes [m] given by the equation bellow:

$$h_f = k \cdot Q^2 \quad (6)$$

The centrifugal pump has an operational curve where the head falls gradually with the increase of the flow. This is called the pump's characteristic curve, i.e., the hydraulic head H w.r.t. the flow rate Q . When a pumping system is installed in a PSP the effect can be illustrated graphically by superimposing the pump characteristic curve and the pump head curve. The pumping system operating point will be at the point where those two curves intersect (Figure 4).

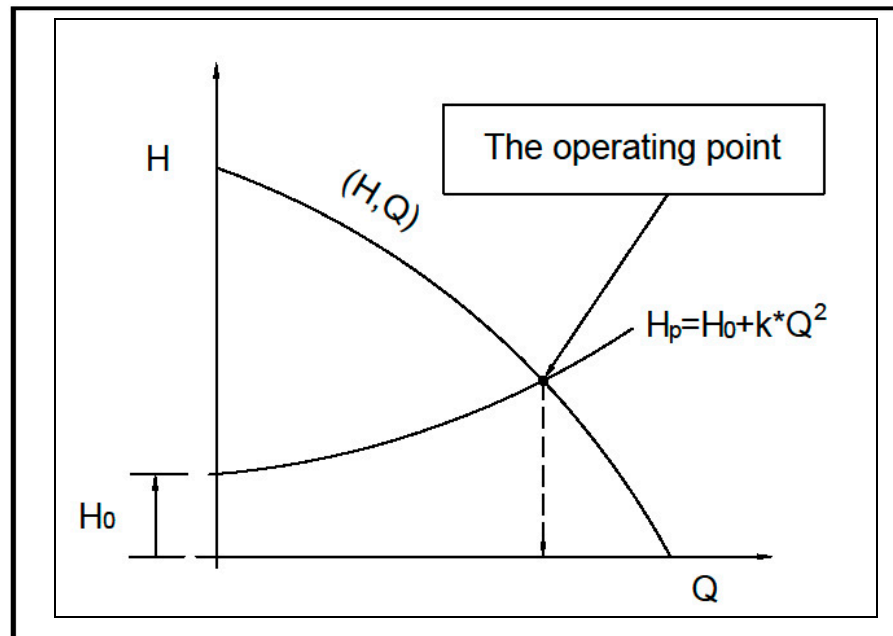


Figure 4. Schematic representation of the pumping system operating point [20].

It is considered that the pump system installation usually consists of N pumps connected in parallel. The pumps parallel coupling is preferable because of the existing possibility of a significant variation in the water flow (Q) supply. In the pumping system characteristic curves the variables (H , Q , η) are inserted dimensionless with respect to the corresponding values of the nominal operating point (H_{ref} , Q_{ref} , η_{ref}), see Figure 5 below. H is the hydraulic head, Q the water flow, and η the pump system efficiency.

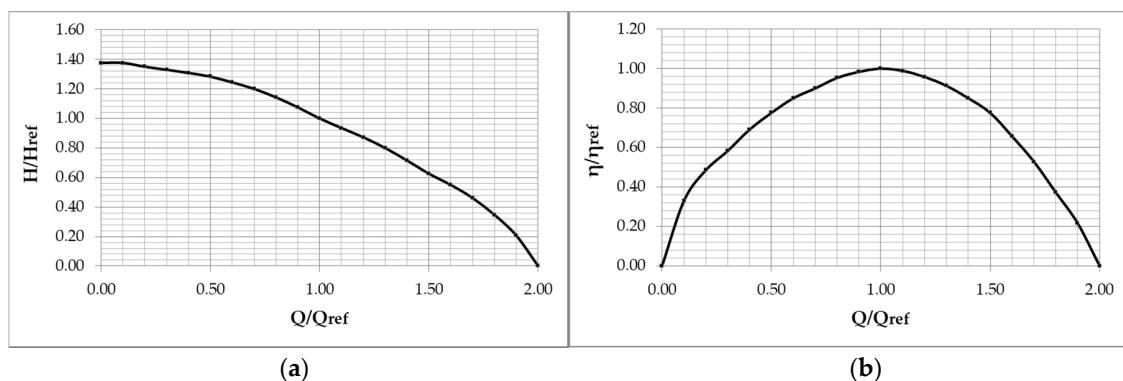


Figure 5. (a) Dimensionless head of pump and (b) pump efficiency as a function of the dimensionless water flow [20].

The pump storage hydro station operation has been modeled by the equations below [5,20]. Each pump and each turbine unit are characterized by the corresponding efficiency curve. Given the

electrical power at the terminals of the unit, the required water flow rate is calculated using the following equations, for the pumps and turbines units [5]:

$$P_{\text{pump}} = \frac{\rho \cdot g \cdot Q (H_0 + h_f)}{1000 \cdot \eta_{\text{pump}} \cdot \eta_{\text{el}}} \quad (7)$$

$$P_{\text{turb}} = \frac{\rho \cdot g \cdot Q (H_0 - h_f)}{1000} \cdot \eta_{\text{turb}} \cdot \eta_{\text{el}} \quad (8)$$

where: P_{pump} : power consumed by the pump [kW]; P_{turb} : power produced by the turbine [kW]; ρ : water density ($\times 1000$) [kg/m^3]; g : gravity acceleration [$9.81 \text{ m}/\text{s}^2$]; Q : water flow rate [m^3/s]; H_0 : is the height difference of the two reservoirs or static head [m]; η_{pump} : the pump efficiency; η_{turb} : the hydro turbine efficiency; η_{el} : the electrical machines efficiency (motor/generator).

The friction loss is also given by the more accurate Darcy–Weisbach formula below, which is the formula used in the present study:

$$h_f = f \frac{L}{D} \frac{V^2}{2g} \quad (9)$$

where: f : a numerical friction factor [–]; L : length of pipe [m]; D : diameter of the water carrying pipe [m]; V : velocity of flow in pipe [m/s].

The numerical factor f is calculated by the Colebrook–White equation:

$$\frac{1}{\sqrt{f}} = -2 \log_{10} \left[\frac{K_s}{3.71D} + \frac{2.51}{\text{Re} \sqrt{f}} \right] \quad (10)$$

where: Re : is the Reynolds Number [–] and K_s is the Roughness Coefficient of the pipe [m] considered to be $1.5 \times 10^{-3} \text{ m}$ in the present study case, as a typical value for steel pipes [23].

Equation (9) may be rewritten in terms of the water flow rate as following:

$$h_f = \frac{f \cdot L}{2g(\pi/4)^2 D^5} Q^2 \quad (11)$$

Equations (9)–(11) have been incorporated in (7) and (8) for the hydropower calculation in the present study.

Regarding the operation of the here proposed PSP, the following alternatives of its operation are considered depending on the rejected wind power and the hydro turbine operation conditions and limitations:

- If the rejected wind power P_R is less than the minimum pumping power P_{Pmin} , the pumping station cannot operate and therefore the absorbed power is equal to zero. In that case, the PSP's operator may choose to use a variable speed pump for small supply rates.
- If the rejected wind power is greater than the maximum power that the pump can absorb, noted P_{Pmax} , then the pump operates at its full power of P_{Pmax} , so the difference ($P_R - P_{\text{Pmax}}$) cannot be absorbed, thus this amount of rejected wind energy is not possible to be converted into hydraulic energy and it will be definitively lost. It should be noted that the maximum absorbed power of a steady speed pumping station is approximately equal to the one of variable speed and the slight difference between them is due to the increased losses of the Variable Speed Inverter.

At each time step δt [h] the rejected wind energy E_R [kWh] during each step is calculated as follows:

$$E_R = P_R \cdot \delta t \quad (12)$$

where: P_R is the rejected wind power [kW].

When this rejected wind energy is converted to hydraulic energy it will be equal to:

$$E_H = \rho \cdot g \cdot Q_P \cdot \delta t \cdot H_0 \quad (13)$$

where Q_P [m^3/s] is the pumped water flow supplying the upper reservoir, representing also the ability (i.e., the pumping station capacity) to convert the rejected wind energy. Thus, the amount of water pumped δV [m^3] during each time step δt is equal to:

$$\delta V = Q_P \cdot \delta t \quad (14)$$

So, the following energy balance equation applies between the rejected wind energy and the part of it possible to be converted to hydraulic energy:

$$E_R = E_H + \text{losses} \quad (15)$$

Specifically, the term “losses”, i.e., the amount of the rejected wind energy non-convertible in hydraulic energy (i.e., unable to be absorbed), taken into account in the hourly simulation for a whole year operation of the proposed PSP, is estimated as following:

- Rejected wind energy amount that cannot be absorbed because the corresponding rejected wind power P_R is less than the minimum P_{Pmin} of the pump station operational capacity.
- Rejected wind energy amount that cannot be absorbed because the rejected wind power is greater than the maximum of the pump station operational capacity, so the difference ($P_R - P_{\text{Pmax}}$) is not possible to be exploited (i.e., to be converted to hydraulic energy).
- Rejected wind energy amount that cannot be absorbed in the case of a steady speed pump station due to the gradual shape of the absorbed power-pumped flow curve.
- Rejected wind energy amount lost due to the hydraulic losses in the pipeline.
- Rejected wind energy amount lost due to the power losses of the motor pump and of the inverter for the variable speed pump station.

The average values of the power losses of the transmission network are about 2%–4% [IEC document “Efficient Electrical Energy Transmission and Distribution” (2007)]. These losses compared to the gross energy consumption are considered negligible, thus they have not been taken into account in this study.

2.6. Mathematical Background of the Economic Analysis and of the Viability Analysis of the Proposed PSP Investment

In order to apply the method of economics and the viability analysis of the proposed PSP, the following technical and economic data must be known [20]:

- Installed hydro turbines nominal power [MW].
- Annual energy production estimation [MWh].
- Total amount of investment (total project budget-CAPEX) [€].
- Electric energy delivered to the power grid selling price [€/MWh].
- Banking interest on loans and deposits [%].
- Inflation [%].
- Time period (total life) of the financial management [y].
- Duration of the construction of the project [y].
- Annual operating expenses (maintenance, insurance, salaries, depreciation etc. OPEX) [€/y].

The economic evaluation of each possible scenario for the proposed PSP realization in the present study is based on the two well-known and worldwide established financial indices of any investment's financial and viability evaluation: The Net Present Value (NPV) and the Internal Return Rate (IRR).

The NPV is the difference between the present value of cash inflows and the present value of cash outflows over the whole life period of time of the investment. NPV is used in capital budgeting and investment planning to analyze the profitability of a projected investment or project.

The following formula is used to calculate the NPV [in €]:

$$NPV = \sum_{i=1}^N \frac{R_t}{(1+r)^i} - C \quad (16)$$

where: R_t : the net cash inflow-outflows during a single period [€], which is calculated by Equation (17)

$$R_t = \text{annual incomes} - \text{annual expenses} = E_{HT} \cdot T - C_{O\&M} \quad (17)$$

where: E_{HT} : is the annual energy produced by the hydro turbine-generators [MWh]; T : is the tariff (selling price) of the electricity produced by the hydro turbine-generators [€/MWh]; $C_{O\&M}$: is the annual operating and management costs of the PSP [€], calculated by Equation (39); r : the discount rate or return that could be earned in the under evaluation alternative investments [%]; i : the number of time periods [y]; N : the lifetime of the investment [y]; C : the initial cost (i.e., the CAPEX) of the investment [€].

The decision rule of the NPV criterion for the evaluation of the investment is:

$NPV \geq 0$: accept the under evaluation project

$PV < 0$: reject the under evaluation project (18)

The IRR is a metric used in capital budgeting to estimate the profitability of potential investments. The internal rate of return is a discount rate that makes the net present value (NPV) of all cash flows from a particular project equal to zero. IRR calculations rely on a similar formula to NPV [20].

The decision rule of IRR is:

$IRR \geq r$: accept the under evaluation project

$IRR < r$: reject the under evaluation project (19)

For reasons of comparison, all the costs of the various scenarios of realization of the proposed PSP are expressed in relation to the dimensions and the size of the project in each trial for the optimal selection of its basic components—subsystems and of the project's size, using the criteria of NPV and IRR presented above. All the following formulas of partial costs can be found in [20].

Cost of the pumps:

$$C_P = 1814 \cdot \left(\frac{P_{\text{pump}}}{H_{\text{ref}}^{0.3}} \right)^{0.82} \quad (20)$$

where P_{pump} is the nominal power of pump and H_{ref} the nominal pump head.

Cost of the motor:

$$C_{\text{MOTOR}} = 11,370 \cdot \left(\frac{\pi \cdot P_m^{1.1}}{\text{RPM}^{0.776}} \right) \quad (21)$$

where $P_m = 1.2 P_{\text{pump}}$ is the nominal power of the motor and the RPM = 1500 rotations per minute.

Cost of the inverter:

$$C_{\text{INV}} = 1160 \cdot (P_{\text{inv}}^{0.7}) \quad (22)$$

where $P_{\text{inv}} = 1.25 P_m$ the power of inverter

Cost of the penstock:

$$C_{\text{PENST}} = C_M + C_E + C_I + C_W + C_{SP} \text{ [€]} \quad (23)$$

where: C_M : Cost of the material:

$$C_M = 0.6 \text{ [€]/kg m} \quad (24)$$

where m is the mass of the material [kg]

C_E : Cost of the excavation:

$$C_E = 1.5 \frac{\pi D^2}{4} L \cdot 5 \quad (25)$$

where L is the length of penstock [m]

C_I : Cost of the installation:

$$C_I = 15\% C_M \text{ [€]} \quad (26)$$

Cost of the welding:

$$C_W = 19.5 \text{ [€]/inches [in] of diameter} \quad (27)$$

where:

$$1 \text{ in} = 2.54 \text{ cm} \quad (28)$$

C_{SP} : Cost of the surface protection:

$$C_{SP} = 22 \text{ [€]/m}^2 \text{ surface [in m}^2\text{]} \quad (29)$$

Cost of the reservoir:

$$C_R = 420 \cdot V_R^{0.7} \text{ [€]}, \text{ where } V_R \text{ is the reservoir volume in m}^3 \quad (30)$$

Cost of the hydro turbine:

$$C_T = 52,000 \cdot P_T^{0.444} \cdot H_T^{-0.186} \quad (31)$$

where P_T is the hydro-turbine nominal power [kW] and the H_T is the turbine head [m]

Cost of the grid connection:

$$C_{GC} = 4\% \cdot (C_P + C_T + C_R + C_{PENST}) \text{ [€]} \quad (32)$$

Cost of the control systems:

$$C_{CS} = 1.6\% \cdot (C_P + C_T + C_R + C_{PENST}) \text{ [€]} \quad (33)$$

Cost of the equipment transportation:

$$C_{TR} = 2.4\% \cdot (C_P + C_T + C_R + C_{PENST}) \text{ [€]} \quad (34)$$

Cost of the road construction:

$$C_{ROAD} = 1,125,000 \text{ [€]} \quad (35)$$

Cost of the licensing and consulting:

$$C_{GEN} = 0.25 \cdot (C_P + C_T + C_R + C_{PENST}) \text{ [€]} \quad (36)$$

Cost of the substation construction:

$$C_{SUB} = 8,000,000 \text{ [€]} \quad (37)$$

Other costs:

$$C_{OTHER} = 2\% \cdot (C_P + C_T + C_R + C_{PENST}) \text{ [€]} \quad (38)$$

Annual operating and management costs:

$$C_{O\&M} = 2\% \cdot (C_P + C_T + C_R + C_{PENST} + C_W) \text{ [€]} \quad (39)$$

The above various partial cost formulas are used to calculate the investment CAPEX (see Equation (40)) introduced in the NPV and the IRR formulas in order to perform the annual PSP operation simulation and the investment evaluation simultaneously for each PSP realization scenario tested in this work.

$$CAPEX = C_P + C_{MOTOR} + C_{INV} + C_{PENST} + C_R + C_T + C_{GC} + C_{CS} + C_{TR} + C_{ROAD} + C_{GEN} + C_{SUB} + C_{OTHER} \text{ [€]} \quad (40)$$

2.7. The Site of the Case Study Project

The site “Potamon” existing Dam (Figure 6) was constructed in 2008 by the OAK SA in the municipality of Amari in the Prefecture of Rethymnon, Crete island, Greece [9,10]. It is an earth dam with a height of 55 m and its reservoir capacity is 22.5 million m³. The project was initially designed to irrigate an area of 2400 ha of the plain of Rethymnon Prefecture as well as to ensure the water supply of the city of Rethymnon. Concerning the proposed PSP case study project of the preset research, the lower reservoir is the existing reservoir of the existing dam at the “Potamon” site, while the upper reservoir will be located in a neighboring higher situated plane, with a height difference of about 450 m and a distance of 2.5 km from the “Potamon” site existing reservoir.



Figure 6. The existing dam at the site “Potamon”, Amari, Prefecture of Rethymnon, Crete, Greece.

3. Simulations, Results and Discussion

3.1. Simulation Procedure

A dedicated algorithm was developed in the Matlab computational environment of all the algorithms and the procedures presented above in order to simulate the annual operation of the pumped storage unit, the hydro turbine, and the hydroelectric power plant operation as a whole on an hourly basis for a period of one year. Also, a Graphical User Interface was developed in Matlab by the Laboratory of Electric Circuits and Renewable Energy Sources/School of Electrical and Computer Engineering (ECE) of the Technical University of Crete, Greece (TUC) [7], see Figure 7, for the visual presentation of the results. Statistical data correlating the specific rotational speed with the characteristic operation curves of the hydraulic machinery and other technical data as well as limitations of the electromechanical equipment are utilized in order to compute—at each time step—the operating points and the efficiency of the pumps and hydro turbines and the losses in

the pipelines and the rotating machinery [7,22]. The reservoir levels are computed every hour from their volume-level curves in order to obtain the exact available hydraulic height for the calculations. The developed algorithm also performs simultaneously the economic evaluation of the plant and computes the financial indices of the project investment (Net Present Value—NPV, Internal Return Rate—IRR, etc.).

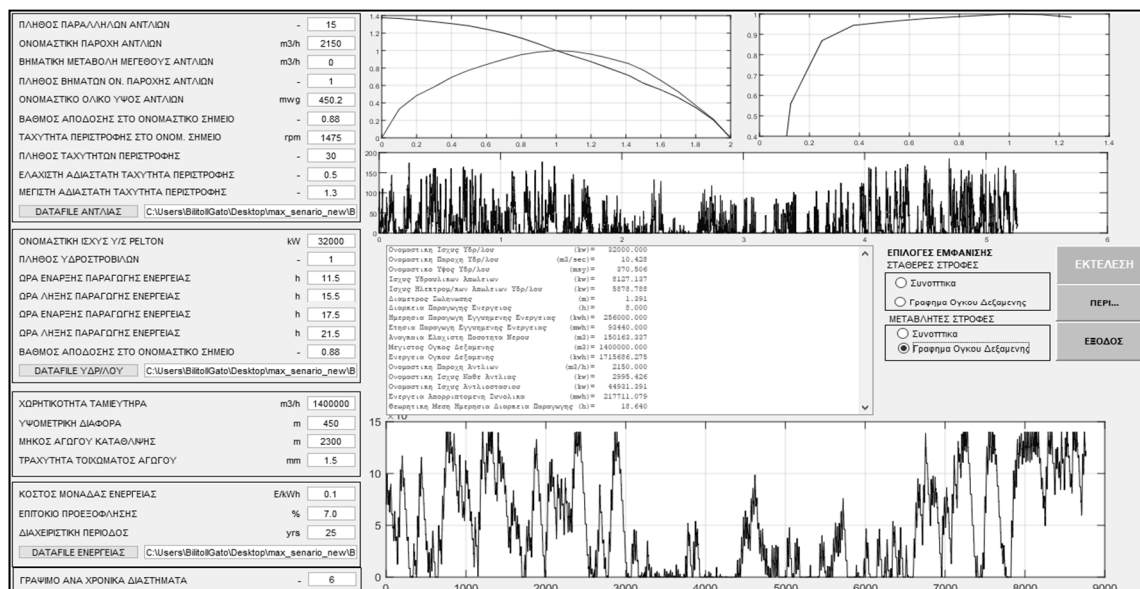


Figure 7. Graphical interface of the developed simulation model for the proposed PSP in Matlab.

The proposed PSP technical design and viability is optimized using as criterion the maximization of the NPV over a 25 year life cycle but at the same time as design variables to be determined in terms of: the number of pumps with variable speed, the nominal pump flow, the upper reservoir volume, and the nominal hydro turbine power. The nominal head (hydraulic head) of the pumps is 450.2 m their efficiency is 0.88, the nominal rotational speed is 1.475 rpm, the dimensionless rotational speed range is from 0.5 to 1.3. The operating time of the hydro-turbines i.e., the electricity production time is 8 h per day, i.e., from 11.5 h to 15.5 h and from 17.5 h to 21.5 h. The height difference between the two reservoirs is 450 m, the length of the penstock is 2,300 m, and the roughness of the drain pipe is 1.5 mm. The selling price of the guaranteed electric energy produced is considered to be 0.1 €/kWh (i.e., about 55% lower than that adopted by the Greek Regulatory Authority of Energy, in order to consider and assess the “worst case” selling price risks), the discount rate is 7% and the operation management period is 25 years.

Parametric optimization based on exhaustive analysis was applied and the combinations of the basic components which were simulated and evaluated in order to obtain the proposed PSP configuration are presented in Table 3 for each of the three scenarios under examination (see Section 2.3). A restriction of the volume of the upper reservoir is also considered as it cannot exceed the 1,500,000 m³, due to the land limitations available for its construction area. The amount of the wind energy rejected and stored as hydraulic energy is continuously changing during the PSP operation. Thus, the pumping block of the PSP must be able to track a continuously changing pumping power demand. The selection of 15 non-reversible pump units (more than usual) and of a separate hydro turbine-electric generator unit is made in order to achieve high reliability, redundancy and flexibility of the PSP operation.

Table 3. The parameter boundaries, steps and combinations of the proposed PSP's realization.

Parameters	MIN	MAX	Step	Combinations
Number pumps	15	26	1	12
Nominal pump flow [m ³ /h]	1500	2200	50	15
Reservoir volume [m ³]	500,000	2,000,000	50,000	31
Nominal hydro turbine power [kW]	10,000	60,000	1000	51

The total combinations are 284,580. However, only 145,080 were selected for each scenario considering only positive NPV. The results of the optimization are shown in Table 4 for each scenario.

Table 4. The dimensions of the optimal PSP for each scenario.

Scenario	No of Pumps	Nominal Pump Flow [m ³ /h]	Reservoir Volume [m ³]	Nominal Hydro Turbine Power [MW]	NPV [€]
BAU	15	2150	1,400,000	32	35,646,830
OIL-GREEN	16	1900	1,400,000	31	34,154,520
GREEN-ADV	16	1900	1,350,000	31	33,116,430

3.2. Results and Discussion

In Table 4 the optimal values of the proposed PSP design parameters that lead to maximum NPV in each examined scenario are presented. The number of pumps is determined to be 15 or 16 of a nominal power between 3 to 3.3 MW each, the nominal pump flow is 2150 m³/h for the Business as Usual scenario and 1900 m³/h for the other two scenarios and the nominal hydro turbine-generator power is 32 MW and 31 MW respectively. The required volume of the upper reservoir is about 1,400,000 m³, thus below the maximum acceptable limit, and the resulted NPVs give feasible investment for all the scenarios examined. The initial costs C for the optimal PSP for each scenario are about 42,130,000 € (Business as Usual), 41,760,600 € (OIL-GREEN and 41,474,700 € (GREEN- ADV).

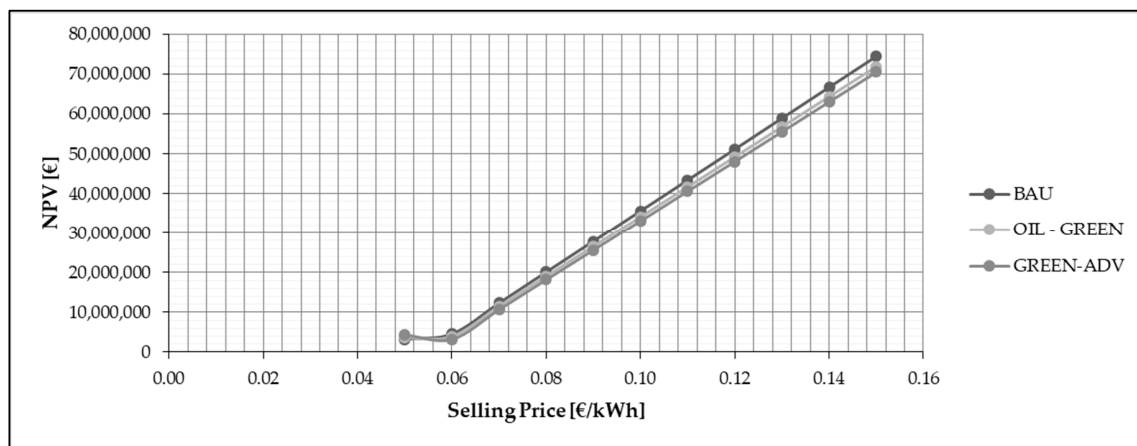
Since the techno-economical optimal PSP realizations of Table 4 have been selected among the thousands of possible combinations through the aforementioned procedure, the developed dedicated algorithm estimates the hourly and annual wind energy rejected possible to be absorbed in each examined scenario. According to Table 5, for the Business as Usual scenario the wind energy rejected in the Crete electrical grid is estimated at the year 2025 to be 218,000 MWh. An amount of 43,000 MWh of that rejected energy cannot be absorbed due to a time-limited operation of the hydro turbine that produces the guaranteed power contracted with the TSO of Crete, i.e., the energy to be delivered to the grid during the 8 h of the peak daily. The remaining 175,000 MWh is the available rejected wind produced electric energy for storage, while only 101,000 MWh are eventually converted to hydraulic power, due to the pumping and storage losses that were modeled by applying the here established algorithm, see Section 2.5. Eventually, the guaranteed produced and sold electrical energy by the proposed PSP would finally be 70,000 MWh given also the losses of conversion of the stored energy to electricity by the hydro-turbine and the generator up to the grid connection transformer.

Table 5. The annual energy results of the optimal PSP for each scenario.

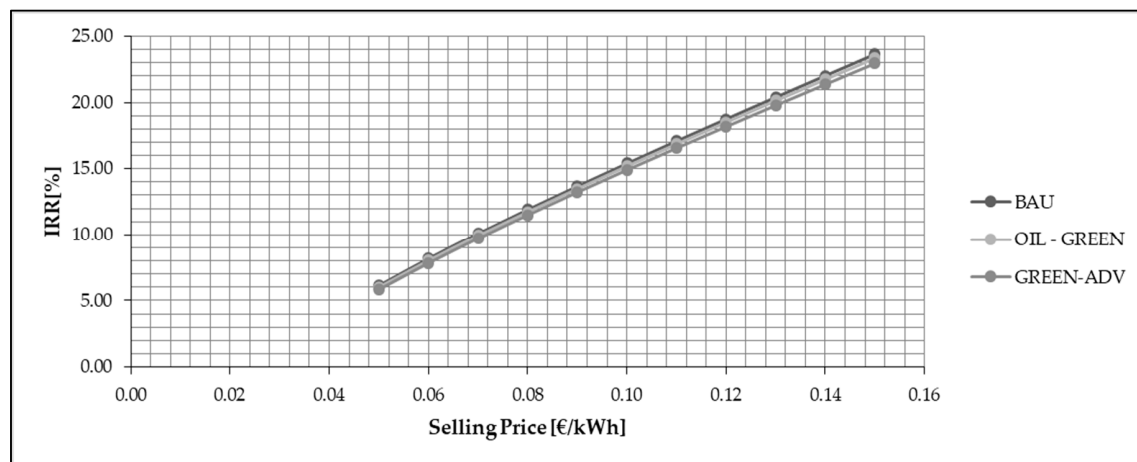
Scenario	Total Annual Rejected Wind Energy [MWh]	Annual Rejected Wind Energy No Possible to Be Converted, i.e., Definitively Lost [MWh]	Annual Rejected Wind Energy Possible to Be Converted [MWh]	Annual Energy Converted to Hydraulic and Stored to the Upper Reservoir [MWh]	Annual Energy Produced by the PSP's Hydro Turbine [MWh]
BAU	218,000	43,000	175,000	101,000	70,000
OIL-GREEN	205,000	41,000	164,000	101,000	68,000
GREEN-ADV	198,000	39,000	159,000	95,000	67,000

3.3. Sensitivity Analysis of the Pricing of the Produced Proposed PSP Electricity

The feasibility of the proposed PSP is based on a substantial number of variables and assumptions. The previous results were obtained with a “pessimistic” fixed selling price of 100 €/MWh (lower in any case than any other selling price of the electricity produced by hybrid power plants, discussed in the Greek deliberated energy market until today). As a legal framework in Greece for the wind rejected energy storage and exploitation does not exist, the most uncertain parameter is the selling price of the produced PSP guaranteed daily electricity. Thus, since the selling price for Hybrid Power Stations according to the Law 3468/2006 and later relative legislation seems to be a barrier for the development of such plants in Greece, it is significant to investigate the range of the selling price for which such projects become feasible. To this end, a sensitivity analysis was performed with respect to possible values (Figure 8) of the PSP produced electricity selling price.



(a)



(b)

Figure 8. (a) NPV and (b) IRR indices for each scenario and for the PSP produced energy selling price variation from 0.05 to 0.15 €/kWh.

As observed from Figure 8, the PSP projects have positive NPV values in all cases. The index IRR is also calculated for each case. The IRR criterion considers the investments profitable when the IRR is greater than the minimal discount rate acceptable of 7%.

Regarding this criterion, as well as the results of Figure 8, selling prices from at least 60 €/MWh lead to feasible and viable investments. This is due to the fact that, when replacing the energy generated by a new wind farm needed to pump the water to the upper reservoir, which is the usual

case of a pumping storage hydro plant, with zero or very low cost of the rejected wind energy of the already operating wind farms, this reduces the investment budget (CAPEX) of the PSP proposed here dramatically. It is therefore demonstrated in the present research that the solution to replacing the wind energy generation necessary annually for PSP operation with the rejected wind energy of the already operating wind farms of the Crete island power grid, thus avoiding the additional cost of a new wind farm investment, leads to viable PSP projects by doubtlessly offering the possibility of lower selling prices of the contracted guaranteed electricity produced by the PSP proposed in the present work.

4. Conclusions

In the present research work the possibility to develop pumping storage electricity projects which will be viable even with relatively low selling prices of their produced electricity, by exploiting the rejected wind produced electricity in an isolated power grid, is examined. Although today this possibility is not foreseen in the current legislation in Greece and also in EU countries, it is nevertheless considered very important to investigate the technical feasibility and the economic viability of such a new approach for PSPs, especially in non-interconnected power systems such as those of the Crete island, for the following crucial reasons:

- The creation of hybrid power stations under the terms established in the Greek Law 3468/2006 and later legislation as well as similar EU guides have not materialized in Crete, although significant projects have been licensed by the Greek RAE since 2013, without any progress towards their construction since then. A major social opposition to the construction of new large wind farms required by these projects under the current legislation has been an important hindrance.
- The periodic electricity auctions established during recent years in Greece, in the EU, and worldwide [24], in order to significantly reduce the RES produced electricity pricing, prevents the development of wind farm-pumping storage hybrid power plants which are capital intensive and expensive investments in general.
- The pumping storage plants absorbing only the rejected wind energy from the already operating wind farms could play a decisive role in offering electricity at low and competitive cost, comparable to that achieved in the auctions, achieving in the same time increased penetration of the already operating wind energy farms. Moreover important energy savings can be made, which otherwise would be definitively rejected and lost, ensuring after all grid stability, especially during the important time period in the future when the island grid will still remain isolated, as well as after its electrical interconnection with the mainland [25].
- The research work presented in this paper responds positively, by scientifically justifying all the related aspects to the above key issues by providing a reliable and feasible PSP proposition in the case study of the Crete island, since:
- The PSP under investigation in this research does not require the installation of any new wind farms to support its operation, but takes advantage of the exploitation–absorption of the annually rejected wind produced energy of the existing wind farms. Such a project will have significantly lower construction cost and it could be sustainable and viable with a significantly lower selling price of the electricity produced, similar to that achieved in the periodic electricity auctions of the interconnected power system.
- Such a PSP without the need for the construction of a new wind farm as its necessary RES electric power/energy supplier (as currently is in force with at least the Law 33468/2006 in Greece) could play an important role in the new interconnected electricity grid of Crete island after the year 2025. In particular, it would replace old conventional production units, which will obligatorily be put out of operation by then, given that these units are very close to the end of their life cycle and with very high CO₂ emissions. This is because the storage unit of such a PSP will provide flexibility in demand congestion management, i.e., by balancing load-spaced valleys in the load curve and by

daily optimizing the power flow during peak hours, offering important support to the local TSO to maintain the stability of the island grid within the limits imposed by the international regulations.

- The contribution of the proposed PSP to the annual gross electricity consumption is estimated to be about 2%. Moreover, the CO₂ emission reduction for the non-interconnected electrical grid of Crete in the year 2025 is estimated by taking into account an average unitary CO₂ emission in Crete to be 760 kg/MWh [10], which proves that it could be very significant, See Table 6.
- Finally, the economic analysis of the present study was carried out with the available and the forecasted operation data of the isolated power grid of Crete. However, the specific PSP could also play a crucial role after the interconnection with the mainland grid, due to:
 - a. The need for the excess produced renewable energy, even after the interconnection, to be saved and stored locally.
 - b. The need for the produced excess electric energy during the technical minimal operation of the conventional power generation units to be also saved and stored. Moreover, the excess electric energy, saved and stored as above, provides numerous ancillary services which can have a direct additional economic benefit to the grid.

Table 6. The proposed PSP contribution in the gross electricity consumption coverage and in the CO₂ emission reduction.

Scenario	Annual Gross Electricity Consumption Estimation of the Crete Island in the Year 2025 [MWh]	Electric Energy Produced by the Proposed PSP [MWh]	Annual Electricity Demand Coverage from the Proposed PSP [%]	CO ₂ Emission Reduction [tn]
BAU	3,137,000	70,000	2.2%	53,200
OIL-GREEN	3,247,000	68,000	2.1%	51,680
GREEN-ADV	3,374,000	67,000	2.0%	50,920

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Nomenclature

\bar{L}_d	average hourly load [MW]
h_f	head friction or pipe friction loss [m]
H_p	pump head [m]
H_T	turbine head [m]
N_{wind}	total installed wind power [MW]
P_{pump}	power consumed by the pump [kW]
P_T	hydro-turbine nominal power [kW]
P_{turb}	power consumed by the turbine [kW]
C	the initial cost of the investment [€]
C_{CS}	cost of the control systems [€]
C_E	cost of the excavation [€]

C_{GC}	cost of the grid connection [€]
C_{gen}	licensing and consulting cost [€]
C_I	cost of the installation [€]
C_{INV}	cost of the inverter [€]
C_M	cost of the construction material [€]
C_{MOTOR}	cost of the motor [€]
C_{other}	other costs [€]
C_P	cost of the pumps [€]
C_{penst}	cost of the penstock [€]
C_R	cost of the reservoir [€]
C_{road}	cost of the road construction [€]
C_{SP}	cost of the surface protection [€]
$C_{substation}$	substation construction cost [€]
C_{TR}	equipment transportation cost [€]
C_W	cost of the welding [€]
C_T	cost of the hydro turbine [€]
D	penstock diameter [m]
E_R	rejected wind energy [kWh]
f	numerical friction factor [–]
F_{ct}	fraction of the average value of year X to the average value of reference year
g	gravity acceleration [9.81 m/s ²]
H	hydraulic head [m]
H_0	static head [m]
H_{ref}	hydraulic head of the nominal operating point [m]
i	the number of timer periods [y]
k	friction factor [–]
K_s	pipe Roughness Coefficient [m]
L	length of the pipe [m]
N	the lifetime of the investment [y]
P_{inv}	power of the inverter [kW]
P_m	nominal power of the motor [kW]
P_{Pmax}	full power of the pump station [kW]
P_{Pmin}	minimum pumping power [kW]
P_R	rejected power [kW]
Q	water flow rate [m ³ /s]
Q_P	pumped water flow [m ³ /s]
Q_{ref}	water flow rate of the nominal operating point [m ³ /s]
R	fraction of the total installed wind power to the annual average load [–]
r	the discount rate or return [%]
Re	Reynolds Number [–]
R_t	net cash inflow-outflows during a single period [€]
V	velocity of the flow inside the pipe [m/s]
V_R	reservoir volume [m ³]
δt	time step [h]
δV	the amount of water pumped [m ³]
Greek letters	
η_{pump}	pump efficiency
η_{turb}	turbine efficiency
η_{el}	electrical machines efficiency (motor/generator)
η	efficiency [–]
η_{ref}	efficiency at the nominal operating point
ρ	water density (×1000) [kg/m ³]
CO_2	carbon dioxide

Abbreviations

CAPEX	Capital Expenditure
ECE	Electrical and Computer Engineering
EU	European Union
HEDNO	Hellenic Electricity Distribution Network Operator
IRR	Internal Return Rate
LHT	Laboratory of Hydraulic Turbomachines- www.ntua.gr
NPV	Net Present Value
OAK SA	Organization for the Development of Crete S.A.- www.oakae.gr
PSP	Pumped or Pumping Storage Plant
RES	Renewable Energy Sources
TSO	Transmission System Operator
TUC	Technical University of Crete
RPM	Rotations per Minute

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