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On the economics of stand-alone renewable hybrid power plants in remote regions

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ABSTRACT

In recent years ever more examples of regions that have managed to achieve or orientate themselves toward renewable energy sufficiency are emerging. However, actions to create energy autonomy are mainly the result of isolated activities and they are less driven from fully organized movements. In addition, total energy independence without the support of a centralized electrical grid is yet to be achieved. The objectives of this work are to investigate the associated costs of stand-alone renewable hybrid power plants on a Greek island and compare them to the cost of the currently used fossil-fuel-based conventional plant. The plants examined here are designed to fully cover the electricity needs of the island. Islands may face numerous energy problems and rely heavily on foreign and environmentally-harmful fuels. It is shown that the relatively high cost of electricity of such a remote region can increase the competitiveness and promote the wider incorporation of technologies based on renewable energy sources that may, in other cases, seem economically inferior to business-as-usual energy solutions.

1. Introduction

The increase of the world population and industrialization in developing countries continuously raise global energy needs. Without significant change in present energy practices, greenhouse gas emissions related to energy use will continue to increase, stressing the climate to extreme and, until today, unknown conditions [1]. The European Union has committed to reducing anthropogenic greenhouse gas emissions from the combustion of fossil fuels by implementing energy-saving measures [2]. Measures proposed to reduce man-made emissions include reducing energy demand, increasing the efficiency of energy conversion and/or energy utilization, switching to less carbon-intensive fuels, increasing the use of renewable energy resources (RES) and nuclear energy and utilizing carbon capture and storage [3]. While none of these measures can directly solve the energy problem on its own, their appropriate combination can help us achieve more sustainable living.

Although the use of renewable resources is increasing, it is mainly the result of the initiative of isolated activities of individual communities and less from fully organized movements at the national level [4]. The relatively high cost of electricity of isolated areas and non-interconnected islands requires large amounts of public subsidies to balance the cost for both the energy company and the inhabitants of the regions. This may undermine the overall financial condition of a community. At the same time, this situation increases the competitiveness and promotes the wider incorporation of renewable energy technologies (e.g., [5,6]) that may, in other cases, seem economically inferior to business-as-usual – fossil-based – energy solutions [7].

In recent years, several islands – both connected to their country's national grid and non-interconnected – have been studied for renewable energy self-sufficiency and a few have achieved it. The island of Samsø in Denmark is an example of a community connected to a mainland grid with electricity generation fully based on wind energy. In addition, the energy surplus of the island is further used for powering renewable-based heating systems [8]. Other examples of islands in the process of renewable energy autonomy are the islands of Graciosa in Portugal, Gotland in Sweden, Bozcaada in Turkey, Maldives, Sumba in Indonesia, the

Abbreviations: COE, cost of electricity; CSP, concentrating solar power plant; EH, electric heat exchanger; FCI, fixed capital investment; HX, heat exchanger; O&M, operating and maintenance cost; PEC, purchased-equipment cost; PV, photovoltaic; TCI, total capital investment.

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Cook islands and the isle of Wight in the UK [9–11]. The island of Hierro in Spain is equipped with a hybrid wind/pump hydro storage facility to serve the electricity needs of its residents, its tourist needs and the requirements of three water desalination plants [12]. However, the Red Eléctrica de España (REE) reports that renewable energy use is much lower than 100% [13]. Total renewable energy independence without the support of a centralized electrical grid is yet to be achieved.

Hybrid power plants initially attracted scientific attention as energy systems that combined conventional fuels with RES, with the purpose to reduce the environmental impact of conventional fuels, increase the penetration of renewables in national energy schemes and balance their relatively high cost. Bernardos et al. [14] suggest that the combination of fossil fuels with solar energy can be energetically advantageous, when compared to the operation of individual conventional or renewable technologies. Also, Peng et al. [15] show that hybridization scenarios operate more satisfactorily, when compared to renewable-only solutions. Solar-coal hybridization was found to have a more efficient and economical performance when compared to solar-only operation [15]. Depending on the area of application and the magnitude of renewable energy penetration, government subsidies may be required to realize a large-scale hybrid plant [16].

Renewable hybrid power plants combine more than one renewable source with complementary character for more reliable and continuous operation. An important factor in the operation of renewable hybrid power stations is the choice of energy sources and their sizing for robust operation and relatively reduced costs. Ayub et al. [17] study the economics of a hybrid solar–geothermal system involving organic Rankine cycle, Ebaid et al. [18] evaluate the costs of the hybridization of PV with a hydrogen gas turbine plant and Nixon et al. [19] evaluate the costs of the hybridization of solar with biomass. These studies show that hybridization is not yet economical enough or it is economically less favorable than the individual systems. It has been shown that such structures can only become competitive under specific conditions (e.g., [20]).

The profitability of hybrid renewable plants increases when stand-alone conditions apply (e.g., [5,6]). Off-grid operation of hybrid power plants implies particular operational characteristics and restrictions. In addition to the environmental benefits, stand-alone and fully renewable-based plants can have a positive socio-economic impact on an isolated community [21].

Wind energy is a very important resource for islands, but it requires advanced systems to control its inconsistent nature (e.g., [22]). Ntomaris and Bakirtzis [23] present the stochastic optimization of hybrid stations based on wind and hydropower for insular systems in Greece. Papaefthymiou et al. [24] also deal with the combination of hydropower with wind energy for higher wind penetration on islands. They present the case of a real hybrid power plant planned to operate on the autonomous island of Ikaria in Greece. Furthermore, the combination of solar and wind has been studied widely due to the complementary character of the two energy sources. A review of solar–wind energy systems and the analyses based on which each plant was evaluated, can be found in Ref. [25]. For example, a micro-grid system combining solar and wind energy in Brazil was found to be a good solution for isolated communities such as islands [5]. Other promising technologies for future applications, such as fuel cells, have been studied as well. A hybrid micro-grid based on solar PV, fuel cells and batteries was studied by Patterson et al. [26] and different scenarios based on these three technologies were optimized using the modeling software HOMER.

This paper presents the economic analysis of three stand-alone renewable hybrid power plants for the sustainable energy self-sufficiency of a Greek island (e.g., [27–30]). The proposed power plants aim to fully satisfy the electricity demand of the island with 100% use of renewable resources. The combination of four factors comprise the novelty of this work: (a) real case-study data for a relatively large population, (b) fully renewable operation of new plant structures, (c) stand-alone considerations for energy autonomy and (d) estimates and comparison of the associated costs of three alternatives under similar conditions.

To develop and optimize the stand-alone RES plants, while at the same time minimizing the probability of operational failures, the systems are tested under extreme conditions of energy demand and climatic conditions [31,32]. To achieve reliable and robust operation, the power plants are substantially oversized, combine renewable technologies with complementary character and include storage systems. The existing diesel generator currently used on the island is expected to be used only as a back-up technology for the prevention of power outages in the case of unpredicted events. Theoretically, this has a twofold purpose: to provide the necessary time to the personnel operating the new plants to familiarize themselves with the function and requirements of the new technologies and to replace the diesel generator in a more gradual manner.

2. The hybrid power plants

The simulations of the power plants are realized using the commercial software EbsilonProfessional [33], while their operational characteristics are determined through sensitivity analysis realized in the programming language R [31,32]. The proposed systems aim to fully satisfy the electrical energy demand of the Greek island of Skyros with 100% use of renewable resources throughout their economic life (25 years). The RES technologies incorporated in the power plant analysis include solar–thermal, solar photovoltaic, wind turbines and hydroelectric generators.

The nominal capacity of each RES technology incorporated in a hybrid plant depends on parameters specified individually for each case. The most important factor that determines the capacity of the hybrid plants is the maximum demand on Skyros. To ensure construction and operation able to fully cover the electricity needs of the island, the peak energy demand and total annual demand are derived from the hourly demand time series of the island. These are adjusted to the year 2045, the last year of the economic life of the power plants, i.e., the year with the highest demand.

The plants are assumed to start operation in 2020. The 2012 hourly time series of electricity demand on Skyros was extrapolated to 2045 with an annual energy increase of 1.4% [34]. The examined hybrid plants have an annual net energy output equal to the predicted energy demand of the island in 2045 (approximately 25,000 MW h/a).

The input data used in the simulation of the hybrid plants are shown in Fig. 1. The solar data were derived from Ref. [35]. The wind speed time series (third panel) represents the mean wind speed of the years 2010–2013. The wind speed data [36] was extrapolated from the height of the meteorological station (4 m) to the height of the hub of the considered wind turbines (84 m) using the logarithmic profile of wind sheer [37]:

$$V = V_{ref} \cdot \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)} \tag{1}$$

where V is the velocity of the wind to be calculated at the height z, V_{ref} is the known velocity at the height z_{ref}, z is the height above ground level for velocity V (84 m), z_{ref} is the reference height (4 m) and z_0 is the roughness length in the current wind direction

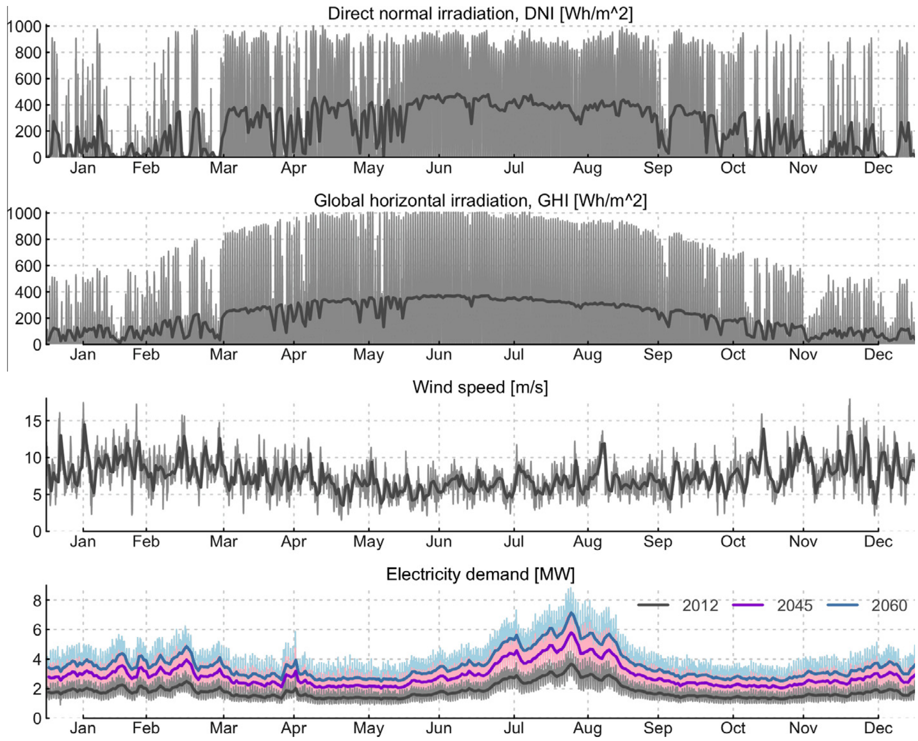

Fig. 1. Daily time series and annual distribution of electricity demand on Skyros for selected years.

(0.03 m for "open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills").

2.1. Scenario 1

The first hybrid power plant examined combines a concentrating solar power (CSP) plant including thermal storage with wind turbines coupled with an electricity storage system.

CSP systems are based on the concentration of solar irradiation by programmed mirrors onto a receiver, where the heat is collected by a thermal energy carrier, the heat transfer fluid [38]. When compared to other renewables that cannot be stored effectively, CSP with thermal storage is a reliable and stable alternative for energy generation [39].

To assure continuous operation, the scenario presented here considers the hybridization of CSP with wind energy. Wind energy can have a supplementary role to solar energy. However, the main drawback of wind energy is its high volatility. Output fluctuations in the time range of a minute for wind generators can cause frequency and voltage variations [40]. Combining an electricity storage system with a wind turbine, as realized in this work, can minimize the challenges present and mitigate the effects of power fluctuations [40,41].

The hybrid plant consists of 5 blocks: the solar field, the thermal storage system, the power block, the wind turbines and the electricity storage system (Fig. 2). When the solar irradiation is adequate the plant generates the required electricity using the solar field, while, at the same time, charging the thermal storage system. Lower energy requirements that can be covered from the CSP plant are achieved by adjusting the mass flow of the thermal oil of the plant, assuring, in this way, zero electricity surplus. At night or during cloudy days, the necessary electricity is generated using the wind turbines and then, if necessary, the thermal energy system (down to a safety limit of 5% capacity). If the thermal storage is not enough to cover the remaining energy demand, it is covered by the electricity storage system of the wind farm. Generated energy surpluses from the wind turbines (that imply wind speeds higher than those required to cover the remaining energy demand) are stored in the electricity storage system. The number of the wind turbines and the size of the associated electricity storage system are optimized to eliminate any energy deficits and ensure no additional surpluses in the hybrid plant overall.

The collectors used in the power plant are parabolic though collectors. The thermal oil used as heat transfer fluid in the plant is the Therminol VP-1. The simulated solar field has a solar multiple (thermal energy generated by the solar field divided by the net power output of the CSP plant) of 2.5 [42]. The total number of collectors used in the solar field is 56, positioned in 14 parallel rows of 4 collectors. The length of each collector is 150 m with a gross aperture width of 5.8 m. The distance of the axes of two parallel collector rows is 17.3 m. It is thus calculated that the solar field of the plant occupies a space of 0.12 km^2 with a specific land use of 12,218 m^2/kW.

The thermal storage system used in the CSP plant is an indirect two-tank system using molten salt as storage medium. The molten salt used in the thermal system exchanges heat with the thermal oil of the plant in two heat exchangers. The total thermal energy to reach the maximum required power output is calculated from the simulation of the plant. A fully charged storage system can provide 350 MW h_{th} (124.7 MW h_e) daily (operation for 14 h at maximum capacity). Using the energy required by the storage system and the enthalpy difference between its hot and cold states, the mass flow of the molten salt at full load is calculated at 120.9 kg/s or 6094.4 tonnes. The tanks used for its storage are 9 m high and 22 m in diameter with a total volume of 3420 m^3. A distance of one diameter is kept between the two tanks for the placement of the necessary heat exchangers of thermal oil and molten salt and 5 m of empty space is kept on the sides of the tanks. The total area of the storage facility is 2432 m^2.

The power block of the plant operates with live-steam pressure and temperature of 100 bar and 380 °C and a total thermal-to-power conversion efficiency of 35.6% (based on simulation data).

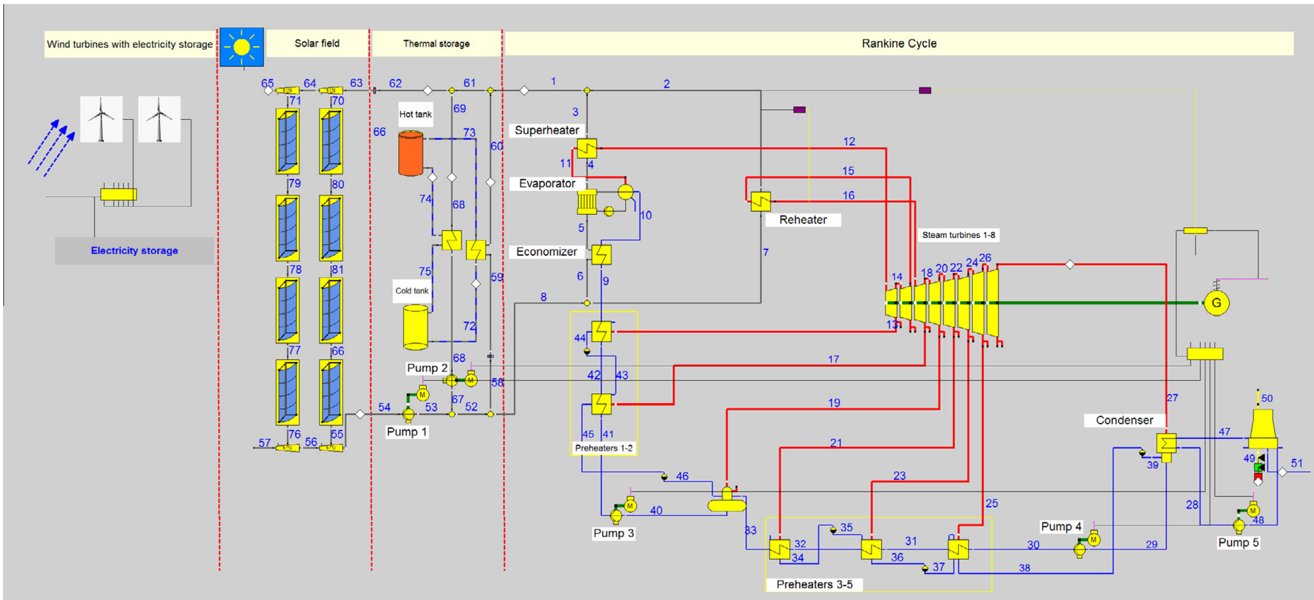

Fig. 2. Simulation flow diagram of the CSP–wind power plant supported by thermal and electricity storage (Wind turbine image from: http://imgarcade.com/1/how-to-draw-wind-turbine/).

The heat exchangers used in the Rankine cycle are three low-pressure and two high-pressure water preheaters, an economizer, an evaporator, a superheater and a reheater. The net power output of the power block of the CSP plant is 10 MW.

The simulation of the wind turbines assumes wind turbines of the type Vestas V112-3.3 MW™ IEC IB [43]. Each wind turbine has rated power output of 3.3. MW, a hub height of 84 m, a rotor diameter of 112 m with swept area 9852 m^2 and cut-in and cut-out speeds of 3 and 25 m/s. The elements constituting the wind plant are: turbines (generators, nacelles, blades), turbine foundations (towers), power transformers (at each turbine and a substation), cables for carrying power and electronic signal, a substation and switching equipment for interconnection into a high-voltage grid and other electrical equipment.

The optimization of the power plant structure shows that only two wind turbines placed upwind (facing against the wind direction) are required for the robust operation of the hybrid plant. The space kept between the wind turbines is 4D (D: wind turbine diameter) crosswind (4D + D = 560 m), while for safety reasons 1D of empty space is kept in the front and 1D in the rear sides of the turbines. This spacing ensures array efficiency higher than 90% [44,45]. The total area needed for the wind turbines is 0.12 km^2. To ensure continuous and reliable performance of the wind plant during energy peaks and challenging weather conditions (long cloudy periods in the winter season and low wind speeds) its operation is supported by an electricity storage system.

The incorporated sodium-sulfur (NaS) battery has an energy capacity of 60 MW h with a discharge time of 4 h at its maximum capacity of 15 MW. The efficiency of the battery is 95%. The volume and weight energy densities of NaS batteries are between 200 and 300 kW h/m^3 and 100–200 kW h/t, respectively [46]. This means that for the proposed hybrid plant a 200–300 m^3 NaS battery is needed. It should be noted that no daily battery losses have been included in the simulations.

2.2. Scenario 2

The second power plant studied involves the hybridization of a photovoltaic (PV) array with wind turbines, coupled with electricity storage and a hydrogen-generating electrolyzer that operates using electrical surpluses (Fig. 3) [31].

PV panels are noiseless, they do not emit greenhouse gas emissions and have relatively simple operation and maintenance [47]. Factors that influence the performance of a PV system are geographic conditions (weather conditions, altitude and latitude) and design factors, such as system selection, orientation, location, panel area and tilt angle [48]. As also mentioned in Scenario 1, wind energy can complement solar energy and with the support of electricity storage can assure continuous and robust operation.

The sizes of the PV system, wind turbines and electricity storage facilities are optimized for maximizing power coverage. When there is enough solar irradiation, the electrical demand is produced with the PV array and existing surplus is stored in the electricity storage system. At night or during cloudy days the energy demand is covered primarily by the wind turbines. Any generated energy surplus from the turbines is also stored in the electricity storage system, if necessary. The electricity storage system ensures continuous operation in the case that the solar irradiation and wind are not adequate to cover the energy demand. Any energy surplus remaining after covering the energy demand and charging the electricity storage system is sent to the electrolyzer unit to generate hydrogen.

The PV plant is composed of the PV modules (PV generator), an inverter for converting the direct current of the PV output into alternating current, mounting and racking components, a combiner box and other electrical components (wires, conductors, data monitoring system, etc.). The PV array is simulated with a power output of 10.5 MW. The panels incorporated are monocrystalline silicon panels (model EP156M/60-250W of the company Eoplly New Energy Technology Co., Ltd). Each panel includes 60 cells, has a peak efficiency of 15.3% and generates 153.0 W/m^2 under standard test conditions [49].

The wind plant includes three wind turbines of the turbine model used in Scenario 1 (Vestas V112-3.3MW™ IEC IB). The turbines are placed upwind in one row with a 4D distance between them ((2 × 4D) + D = 1008 m), 1D empty space in their front and 1D in their rear sides. The area needed for the three wind turbines is 0.23 km^2.

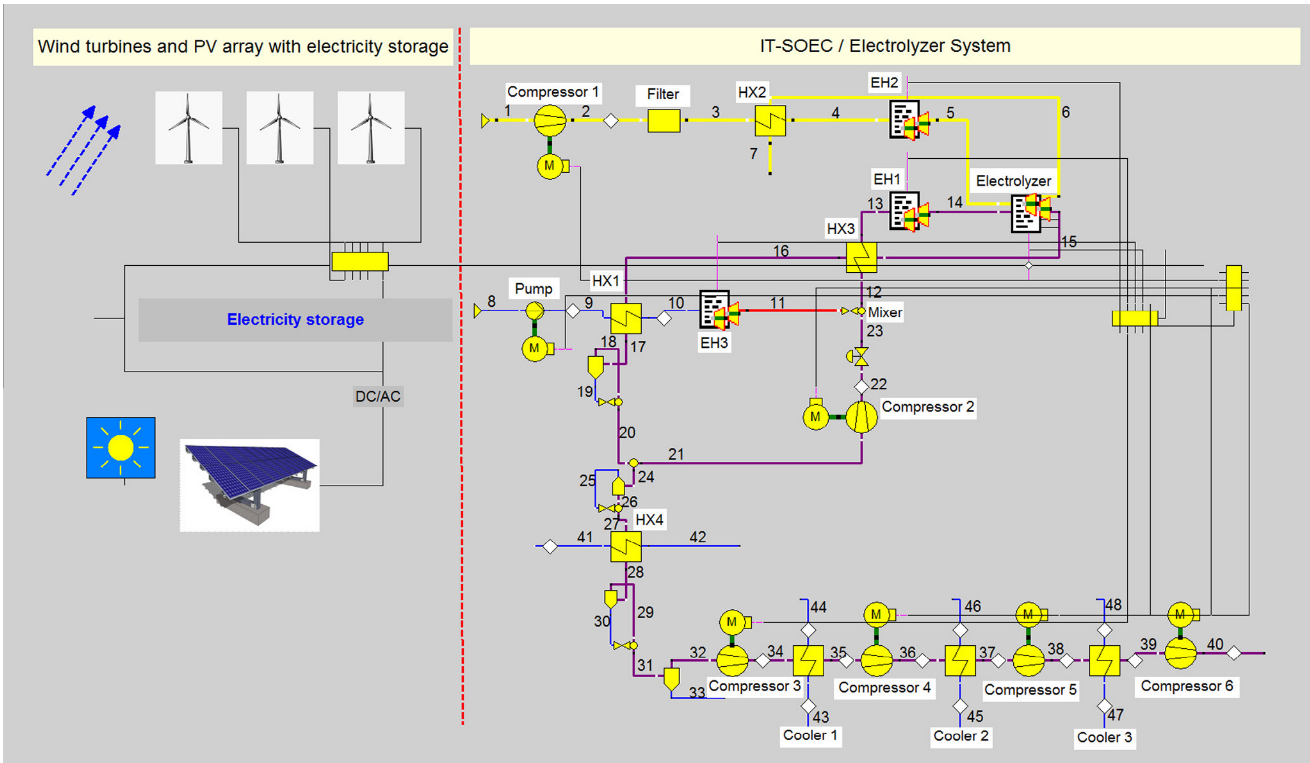

Fig. 3. Simulation flow diagram of the PV–wind power plant supported by electricity storage and a H_2-generation facility (PV array image from http://www.solarbrownfields.com/solar-brownfield-solutions-for-utility-providers/) [31].

The NaS battery storage incorporated in the hybrid plant has a storage potential of 140 MW h (10 2-MW units with discharge time of 7 h). With volume energy densities of sodium-sulfur batteries between 200 and 300 kW h/m^3 the proposed hybrid plant requires 793–1190 m^3 of sodium-sulfur batteries to cover the required needs of the simulated plant.

Any electricity residual after covering the energy demand and charging the electricity storage system is lead to the electrolyzer coupled to the plant. The electrolyzer, an intermediate-temperature solid-oxide electrolysis cell [50], uses electricity to generate hydrogen through water electrolysis. The electrolysis cells work at thermoneutral voltage, at a temperature of 700 °C, with a steam conversion rate in the cathode chamber of 61% and a molar ratio between the anode and cathode of 1:1. The generated hydrogen is finally compressed to 150 bar and stored [51]. The ultimate purpose is to sell the generated H_2 for use in other chemical processes (e.g., ammonia, methane generation) or for other purposes (e.g., future filling stations of H_2-driven vehicles) and achieve, in this way, an additional financial benefit from the power plant.

2.3. Scenario 3

The third power plant evaluated assumes the hybridization of PV and wind (same capacities as in Scenario 2) with a pumped-storage hydropower plant. Positive aspects of hydropower include the wide resource availability, efficient energy conversion with proven technology, relatively low operating and maintenance costs (although with high capital cost) and a long life span. Hydropower is also a renewable energy resource without fluctuations and can be used for irrigation and flood control [52,53]. The idea behind the power plant proposed here is to replace the electricity storage facility of Scenario 2 with the hydropower plant and to also use it to generate electricity when solar and wind energy are not adequate.

The lower reservoir of the hydropower plant will be the water dam constructed in the area of Ferekampos on the island of Skyros (was expected to start operation by the end of 2015 [54]). The capacity of the reservoir is 1,000,000 m^3 and it is built at an altitude of approximately 80 m. The upper reservoir (proposed) will be situated northwest of the existing reservoir at a height of approximately 380 m (Map 1) with a capacity of 300,000 m^3. The two reservoirs are planned to be connected with pipes of 1500 m.

The flow diagram of the simulated hybrid power plant can be seen in Fig. 4 [32]. The electromechanical equipment of the hydropower plant includes a pump-turbine, a generator/motor, a transformer and cabling and control systems. The turbine included in the hydropower plant is a Francis pump-turbine with reversible operation and a variable-speed motor/generator. The variable operation of the hydropower plant offers the possibility to regulate its power output and pumping power requirement based on the needs and electricity availability of the hybrid plant.

When the solar irradiation is adequate, the electric demand is covered by the PV plant. If that is not the case, the wind turbines are used to supplement the energy demand of the island. The hydropower plant is used when the energy demand cannot be covered by the combination of PV and wind plants. When there is a surplus from the PV or wind systems, the operation of the hydropower plant is reversed to pump water to the upper reservoir, as needed. Any additional surplus generated by the plant is sent to the electrolyzer of the plant (similar process to that of Scenario 2) to generate hydrogen.

3. Methodology

3.1. Economic analysis

The revenue requirement method is used to determine the economic feasibility of the power plants proposed in this study [55]. In

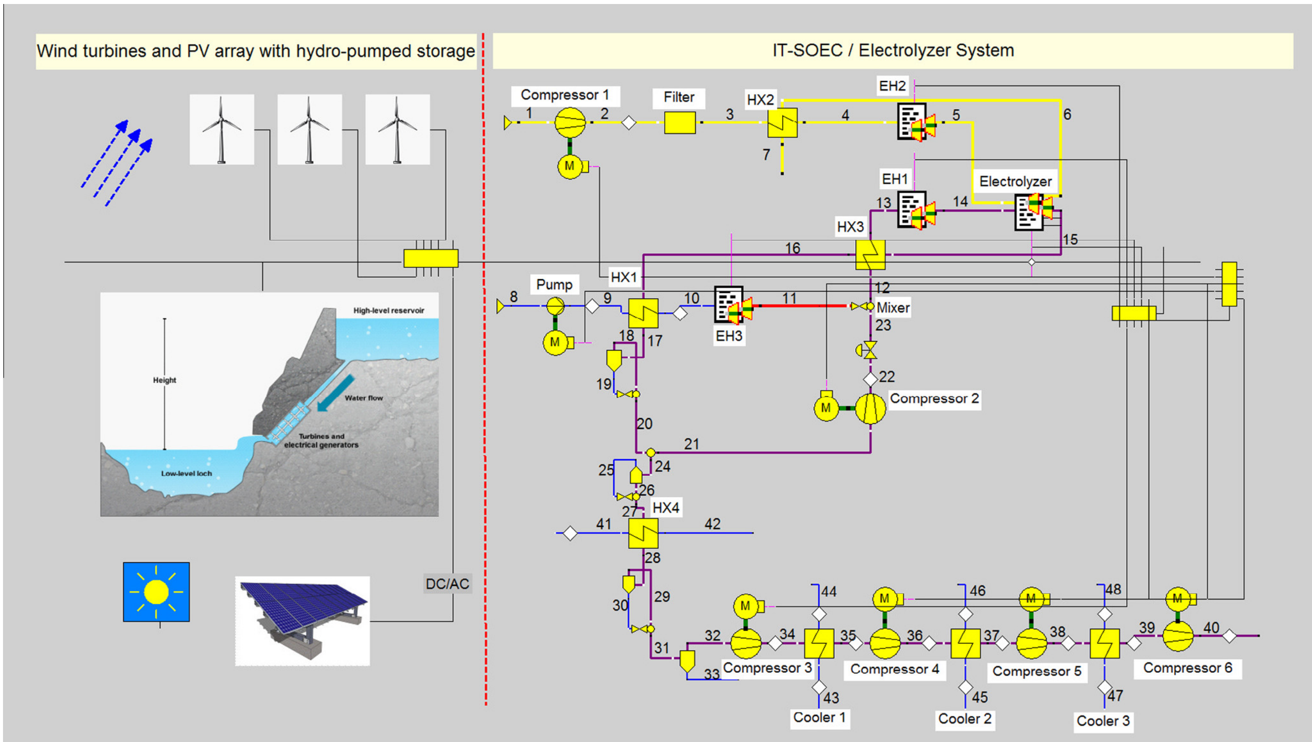

Fig. 4. Simulation flow diagram of the PV–wind plant with pumped-storage hydropower (Image of hydro-pumped power plant from: http://pixshark.com/hydroelectric-power-plant-diagram.htm) [32].

Map 1. Map of upper and lower reservoirs.

this method, the cost of the product/s (electricity or electricity and hydrogen) is calculated by (1) estimating the total capital investment that includes the fixed-capital investment and other outlays, (2) determining economic, operating and market input parameters for the cost calculations, (3) calculating the total revenue requirement, i.e., the revenue that must be collected in a year through the sale of the product/s to compensate for all expenditures and ensure secure economic operation and, finally, (4) calculating the levelized product cost.

The detailed steps and guidelines for the method can be found in Ref. [55], while specific assumptions for the analyzed energy scenarios are presented below.

4. Results

The reported cost of electricity (COE) for the island of Skyros in 2012 and 2013 was at 420.2 and 400.8 €/MW h, respectively [56]. This high cost stems mainly from the very high diesel fuel costs, responsible for 77% of the direct cost of electricity. To counterbalance the difference between this high cost and the average lower cost of the mainland, the Greek state subsidizes the electricity sector of Skyros with approximately 5 million Euro per year. Another negative aspect to account for is that the current energy generation, entirely based on diesel fuel, emits large amounts of greenhouse gases significantly burdening the climate.

The power plants proposed in this study have no direct CO_2 emissions during the generation of electricity, while the fuel costs (solar energy, wind and water) are considered to be zero. Thus, the cost of electricity of these plants is dominated and determined by the investment cost of the incorporated renewable technologies. It is also important to mention that the cost of these zero-emission power plants can be significantly decreased if future public subsidizing mechanisms associated with CO_2 abatement measures are accounted for. The general assumptions for the realization of the economic analysis realized without the consideration of subsidies are presented in Table 1.

The investment cost of each power plant depends, among others, on the capacity of the plant and the size of the incorporated storage system, if any. Reported total installed costs and COE in OECD countries of the different renewable technologies and storage systems used in the present work are [57,58]:

- *CSP:* in the range 4000–9000 $/kW, with COE in the range 180–310 $/MW h. These costs make this technology the most expensive solution when compared to other renewable-based plants.
- *Onshore wind projects:* between 800 and 3800 $/kW, with COE in the range of 30–170 $/MW h.
- *PV plants:* between 1000 and 7500 $/kW, with COE 70–330 $/MW h.
- *Hydro power stations:* in the range 800–6200 $/kW, with COE between 30 and 240 $/MW h.
- *NaS batteries projected investment cost:* between 100 and 2000 $/MW h.

It should be remembered that the proposed renewable hybrid plants proposed are designed for energy autonomy and their design accounts for the non-interconnected character of the island. In the case that the island were interconnected to the main electricity grid of the mainland and under the right circumstances, operational off-grid limitations of the power plants could be largely avoided. The scenarios given Skyros connected to the mainland grid are also briefly investigated and presented in the *Discussion*.

Table 1
Basic assumptions of the economic analysis.

Plant economic life (years)	25
Plant life for tax purposes (years)	20
Average general inflation rate (%)	2
Average real cost of money (%)	9
Date of commercial operation	2020
Reference year of cost calculations	2013

4.1. Scenario 1

For the purpose of the analysis, the total capital investment (TCI) of the CSP plant has been shared among the different plant components and equipment as shown in Table 2. These percentages, derived from Ref. [59], are adjusted to the power output and storage capacity of the analyzed plant.

To account for capacity scaling of the thermal storage system the following equation was used [55]:

$$C_{PEC,Y} = C_{PEC,W}\left(\frac{X_Y}{X_W}\right)^a \quad (2)$$

with $C_{PEC,W}$ the known purchased-equipment cost (PEC) of a component W, $C_{PEC,Y}$ the unknown PEC of a component Y, X_Y the capacity of component Y, X_W the capacity of component W and a the exponent associating the capacities of components Y and W (here assumed equal to 0.8).

The calculations resulted in a specific total capital investment cost of the CSP plant of 5282 €/kW.

The total cost of a wind system in Europe in 2010 was between 1423 and 1615 €/kW, while in 2015 between 1308 and 1500 €/kW [60]. Knowing that the installed cost of a wind farm in Greece in 2010 was between 1123 and 1429 €/kW and accounting for a 6% reduction between 2010 and 2013, a specific 2013 installed cost of a wind system at 1056–1343 €/kW is found. For the following calculations the maximum value of 1343 €/kW has been used as the TCI of the wind turbines. The TCI of the wind plant has been shared among the plant components, as shown in Table 3.

Lastly, the investment cost of the electricity storage system has been assumed to be 500 €/kW$_e$ [58].

Table 2
Sharing the TCI among the CSP plant components.

	(%) of investment
Solar field and HTF system	36.6
Mirrors	6.1
Receivers	6.7
Steel construction	10.2
Pylons	1.0
Foundations	2.0
Trackers	0.4
Swivel joints	0.7
HTF system (piping, installations, heat exchangers, pumps)	5.1
Heat transfer fluid	2.0
Electronics, controls, electrical and solar equipment	2.4
Thermal storage system	15.0
Salt	7.3
Storage tanks	2.6
Insulation materials	0.3
Foundations	0.9
Heat exchangers	2.0
Pumps	0.6
BOS	1.4
Conventional plant components and power system	13.6
Power block	5.4
BOP	5.4
Grid connection	2.8
Labor costs	16.3
Solar field	2.9
Site preparation and infrastructure	5.5
Steel construction	2.4
Piping	1.7
Electric installations and others	3.8
Others	18.5
Project development	2.8
Project management	7.3
Financing	5.7
Other costs (allowances)	2.8

Table 3
Sharing the TCI among the wind system plant components.

	(%) of TCI
Wind turbine	64
Tower	25
Blades	22
Gearbox	13
Other (generator, transformer, power converter, control system, buildings, consult...)	40
Grid connection	11
Construction cost	16
Other (development, engineering, licensing, permits, monitoring)	9

The operating and maintenance (O&M) costs of the CSP plant are assumed to be 2% of the total investment, with an allocation of 10% to the variable O&M costs and 90% to the fixed costs [59]. The total O&M costs of the wind turbines, on the other hand, are 0.03 €/kW$_e$ with 1/3 linked to the variable and 2/3 to the fixed costs [57]. The fixed and variable O&M costs of the electricity storage are 3 €/kW and 7×10^{-2} €/kW h, respectively [61]. Table 4 shows the fixed capital investment (FCI) and the O&M costs, as well as the required land for the construction of the hybrid power plant.

Using the costs of Table 4 and under the basic assumptions presented in Table 1 a detailed economic analysis is realized [55]. The annual total revenue requirement of the power plant is found to be 10.2 million Euro, 17% of which stems from the plant's O&M costs. The analysis results in the significant overall COE of 402.3 €/MW h, which mainly reflects the high investment and COE of the CSP system. Although the installed CSP system could generate more electricity that would lead to a substantial decrease in its COE, its operation is restricted (through mass flow adjustments) by the existing energy demand on the island and the requirement of zero overall energy surplus. These restrictions lead to a relatively high cost when compared to the resulting net power generation. The operation of the wind turbines is also restricted but in a less disruptive manner, while the size of the wind plant is much smaller in comparison to the CSP. Lastly, the stand-alone operation of the plant calls for capacity oversizing and large storage facilities to ensure safe operation. Both of these factors increase the investment and, consequently, the COE of the plant.

4.2. Scenario 2

The TCI of the PV system is shared as shown in Table 5 [62]. The resulting FCI of the PV plant has been found to be 1706 €/kW.

The relative FCI of the wind turbine plant and the cost of the electricity storage system are the same as in Scenario 1.

The cost of the components of the electrolyzer unit, shown in Table 6, were based on detailed calculations presented in Ref. [63]. The total cost of the unit is estimated at 15.4 million Euro, including four replacements of the electrolyzer during the lifetime of the plant.

The O&M costs of the wind turbines are calculated based on the same strategy followed for Scenario 1. The O&M costs of the PV system are assumed to be 1.5% of the capital investment, 2/3 associated with fixed and 1/3 with variable costs [64]. The O&M costs of the electrolyzer unit are 3% of the FCI with a 70% and 30% share between fixed and variable costs. Lastly, as in Scenario 1, the fixed and variable O&M costs of the electricity storage are 3 €/kW and 7×10^{-2} €/kW h, respectively [61].

The costs of the plant, as well as the land requirement for its construction are shown in Table 7.

The generated hydrogen in the electrolyzer of the plant is considered as a by-product for the plant and its annual total revenues are subtracted from the total revenue requirement of the plant. With an initial TRR of 9.6 million Euro (14% of which is associated with O&M costs) and an assumed 25-year levelized unit value for hydrogen of 5 €/kg, the resulting revenue requirement of the plant decreases to 8.3 million Euro. This cost results in a COE of 321.2 €/MW h.

Table 5
Sharing the TCI among the PV plant components.

	(%) of TCI
PV module	50
Silicon production	8
Silicon wafer production	14
Solar cell production	11
PV module production	17
Inverter DC/AC	16
Mounting & ranking components	6
Combined box & other electrical equipment	2
Site preparation & installation	25
System design, overheads and any up-front financing	1

Table 6
FCI of the components of the electrolyzer system.

Component	Power (kW)	Cost (€)
Electrolyzer	5790	11,580,000
Compressor 1	20.55	7468
Compressor 2	8.07	21,509
Compressor 3	290.33	773,930
Compressor 4	330.12	879,994
Compressor 5	260.84	695,299
Compressor 6	290.33	895,223
EH1	122	10,980
EH2	28	2520
EH3	1628	146,520
Component	Surface, A (m^2)	Cost (€)
HX1	41.60	13,605
HX2	201.24	107,253
HX3	355.56	175,981
HX4	269.30	69,095
Cooler 1	52.10	16,551
Cooler 2	55.35	17,443
Cooler 3	55.97	17,614

Table 4
FCI, O&M costs and land requirement of the hybrid CSP–wind plant with electricity storage.

	FCI (€)	O&M cost (€/a)	Fixed O&M cost (€/a)	Variable O&M cost (€/a)	Land (m^2)
Scenario 1					
CSP (incl. storage)	41,449,819	1,017,346	915,611	101,735	183,104
Wind turbines	8,068,922	436,072	290,715	145,357	120,000
Electricity storage system	7,500,000	45,420	45,000	420	746
Total	57,018,741	1,498,838	1,251,326	247,512	303,851

Table 7
FCI, O&M costs and land requirement of the hybrid PV–wind plant with H_2 generation.

	FCI (€)	O&M cost (€/a)	Fixed O&M cost (€/a)	Variable O&M cost (€/a)	Land (m^2)
Scenario 2					
PV plant	17,915,100	408,240	272,160	136,080	123,529
Wind turbines	12,103,384	535,772	357,182	178,591	225,800
Electricity storage system	10,000,000	60,980	60,000	980	995
Electrolyzer unit	15,430,987	347,400	243,180	104,220	11,264
Total	55,449,471	1,352,392	932,522	419,871	361,588

Table 8
Sharing the TCI among the hydropower plant components.

	(%) of TCI
Civil costs	
Dam & reservoir	15
Tunneling & canal	10
Powerhouse	10
Site access infrastructure	10
Connection	5
Developer/owing costs (incl. planning, permits, etc.)	20
Electro-mechanical costs	30

Table 9
FCI of the components of the electrolyzer system.

Component	Power (kW)	Cost (€)
Electrolyzer	5330	10,660,000
Compressor 1	18.90	6870
Compressor 2	7.43	19,806
Compressor 3	267.27	712,444
Compressor 4	303.90	810,082
Compressor 5	240.11	640,061
Compressor 6	309.16	824,101
EH1	112	10,080
EH2	26	2340
EH3	1499	134,910
Component	**Surface, A (m^2)**	**Cost (€)**
HX1	38.38	12,686
HX2	185.25	99,797
HX3	327.37	163,780
HX4	248.14	64,348
Cooler 1	48.04	15,422
Cooler 2	50.94	16,230
Cooler 3	51.52	16,388

As in the previous power plant, the power output of the wind plant is restricted by the imposed energy requirements. This increases the COE of the wind turbines that would otherwise drive the overall costs down. The need to incorporate a storage system into the plant is also a factor that increases the total cost and could be avoided if the plant was not required to operate autonomously.

4.3. Scenario 3

The relative FCI of the PV system, wind plant and electrolyzer unit are the same as in Scenario 2. The TCI of the pumped-storage hydropower plant is shown in Table 8 [65]. The relative FCI of the plant is found to be 1867 €/kW. The cost of the lower reservoir is not included in the calculations, since it is already built and ready for use.

The cost of the electrolyzer unit is shown in Table 9. The total FCI of the unit is estimated at 14.2 million Euro, somewhat lower that of Scenario 2 due to its relatively smaller size.

The O&M costs of the PV plant, the wind turbines and the electrolyzer are calculated as in Scenario 2. The O&M costs of the hydropower plant are 0.001 €/kW h, 17% of which is associated to fixed and 83% to variable costs [65,66].

The costs and land requirement of the individual parts of the hybrid power plant are presented in Table 10.

As in Scenario 2, the generated hydrogen is considered as a by-product of the plant and its annual total revenues can be subtracted from the total revenue requirement of the plant. With an initial TRR of 9.8 million Euro and an assumed 25-year levelized unit value for hydrogen of 5 €/kg, the resulting revenue requirement decreases to 9.3 million Euro. This cost results in a COE of 369 €/MW h. As in the previous two scenarios, this increased COE is a result of the operational limitations on the wind and hydropower plants, as well as the required combination of different technologies and storage facilities in order ensure safe operation in stand-alone mode. The large investment of the required infrastructure and its maintenance costs increases the COE of the hybrid plant significantly.

5. Discussion

The overall results of the exergetic and economic analyses of the three proposed scenarios are summarized in Table 11.

As seen in the above table, the best exergetic efficiency is achieved by Scenario 1. Scenario 2 results in a lower efficiency due to the additional conversion losses of the residual electricity

Table 10
FCI, O&M costs and land requirement of the hybrid PV–wind–hydro plant with H_2 generation.

	FCI (€)	O&M cost (€/a)	Fixed O&M cost (€/a)	Variable O&M cost (€/a)	Land (m^2)
Scenario 3					
PV plant	17,915,100	408,240	272,160	136,080	123,529
Wind turbines	12,103,384	397,659	265,106	132,553	225,800
Hydro-pumped plant	14,396,667	8483	1442	7040	40,071
Electrolyzer unit	14,209,346	319,800	223,860	2	8556
Total	58,624,496	1,134,182	762,568	275,675	397,957

Table 11
Results of the exergetic and economic analyses of the three proposed hybrid power plants.

	Scenario 1	Scenario 2	Scenario 3
Exergetic efficiency (%)	19.2	17.9	14.4
FCI (10^6 €)	57.7	55.5	58.6
TRR (10^6 €/a)	10.1	8.3	9.3
O&M costs 10^6 €/a)	1.50	1.35	1.13
Land requirement (10^3 m^2)	303.8	361.6	398.0
Cost of electricity (€/MW h)	402.3	321.2	369.3

of the plant to hydrogen, while the performance of Scenario 3 is mostly burdened by the relatively low round trip efficiency of the storage-pumped hydropower plant.

Scenario 1 is also presented as the best solution from a land requirement viewpoint, a factor very important in locations with limited available area. The area Scenario 1 requires is approximately 16% smaller that of Scenario 2 and 24% smaller that of Scenario 3.

When looking at the costs of the plants it is seen that all three scenarios result in a similar fixed capital investment. The lowest investment is estimated for Scenario 2, followed by Scenario 1 and, lastly, Scenario 3. Although Scenario 3 is the most expensive alternative, it is found to have the second best TRR (after Scenario 2) due to the additional revenue gained through the sale of the generated hydrogen.

Since the power plants generate the same amount of power, the TRR determines the best alternatives. As also verified by the calculation of the cost of electricity, the best solution economically is Scenario 2, followed by Scenario 3 and, last, Scenario 1. Although the initial TRR of Scenario 3 is very similar to that of Scenario 2, it generates less hydrogen due to its smaller power surplus and it results in a relatively higher COE. It should be mentioned, however, that the lifetime of the hydro-power plant is much longer than the 25 years accounted in the analysis presented. Thus at the end of the economic life of the PV and wind plants in Scenario 3, the storage-pumped hydropower plant has remaining value and it could be used further.

Although the calculated COE for the three plants is relatively high when compared to conventional power plants connected to the main grid of the country, they are comparable to and even lower than that of the diesel generation plant currently functioning on the island of Skyros. This makes all of the proposed technologies economically feasible. In addition, the proposed plants have zero direct emissions and can eventually be subsidized by already allocated public subsidies solely based on environmental reasons. In addition, it should be mentioned that the COE from renewable plants will not be adversely affected by the adoption of any future climate change measures (e.g., CO_2 taxes), which will increase the cost of conventional power stations significantly.

The renewable hybrid plants presented here have been designed accounting for the non-interconnected character of the island, based on stand-alone requirements. This leads to the adoption of three factors that determine the efficiency and cost of the plants: net energy output restrictions, capacity oversizing and large storage facilities. If the energy power output of a plant is limited to exclusively serve the energy demand, energy residuals are avoided, but the capacity factor of the plant is significantly decreased. If, on the other hand, the energy power output of a plant is not limited, any surpluses must be used within the operational limits of the plant increasing the investment cost of the plant, in order to generate secondary products that can be stored or sold.

If the island were connected to the grid of the mainland, the operational restrictions of the renewable stations would change significantly and the results of the efficiencies and costs would become more favorable. In order to briefly investigate the operation of the three main technologies used in the hybrid plants (CSP, PV and wind), a second analysis was performed assuming that the island is inter-connected to the main grid of the country. The main operational restriction imposed in this case is that the annual energy generated from the renewable sources is net positive (i.e., the island generates at least as much energy as it uses). This means that the plants can feed electricity to the grid, whenever they generate surplus, and obtain electricity from the grid, when necessary, without capacity limitations. This implies priority is always given to RES for the operation of the grid and that the grid is able to operate securely without restrictions on renewable power input. These simplifications were made to facilitate this first-order analysis, although they also imply upgraded capacity and service of the mainland grid.

When connected to the grid, each of the individual technologies used in the hybrid plants can satisfy the annual energy demand without significant complications. For example, only two wind turbines connected to the grid could provide an annual positive renewable surplus for the island of Skyros with a mean operating exergetic efficiency of 38.3%. Assuming that the prices of selling and buying electricity to and from the grid are equal, this solution could generate electricity at a 25-year levelized COE of 67 €/MW h. A PV plant would need a higher capacity than it does within the hybrid plants to achieve the same results. Its capacity must increase by approximately 80% when compared to Scenarios 2 and 3 and its costs would result in a 25-year levelized COE of 221 €/MW h. A CSP plant (without thermal storage) is similar: the capacity of the plant would need to be 36% higher than that of Scenario 1 with accordingly higher costs. The plant would operate with a mean annual efficiency of 23% and would result in a COE of 395 €/MW h.

It is seen thus that the COE generated with the three technologies differs significantly for on-grid applications. Overall wind is found to be the most efficient and economical solution, while PV is found to be relatively expensive when compared to conventional power plants. Lastly, CSP is still a very expensive renewable alternative for on-grid applications mainly due to its high investment cost and the less continuous nature of solar energy when compared to wind.

6. Conclusions

Renewable hybrid power plants constitute a promising alternative for electricity generation in locations where the extension of the electrical grid is difficult or not economical, where the cost of electricity is high or where the current technology is associated with significant environmentally harmful emissions.

In this paper three renewable hybrid plants were analyzed based on their economic performance as stand-alone systems covering the electricity demand of the island of Skyros in Greece. Scenario 1 combined concentrating solar power with wind turbines and storage facilities; Scenario 2 coupled a photovoltaic array with wind turbines, storage facilities and a hydrogen generation system; and, Scenario 3 included a photovoltaic array with wind turbines, a pumped-storage hydropower plant and a hydrogen generation system.

The three plants were compared both to one another and the currently existing conventional fossil-fuel facility on the island. Accounting for the non-interconnected character of the island (stand-alone operation) led to the adoption of three factors that determine the efficiency and cost of the plant: net energy output restrictions, capacity oversizing and large storage facilities. When the power output of a plant is limited to exclusively serve the energy demand, energy residuals are avoided, but the capacity factor of the plant is significantly lower.

The optimization process of the operation of the power plants showed that it is vital to combine more than one renewable technology to ensure stable and secure operation. Solar and wind energy were found to be good complementary energy choices, the operation of which is further stabilized with the incorporation of storage facilities. Wind energy depends on wind speed and is, thus, highly volatile. In many places, however, as in Skyros, it can be considered more stable than solar. In addition, although solar may generally be considered more predictable than wind, it requires supporting systems for more consistent operation.

The most exergetically efficient performance was achieved by Scenario 1 [67]. In addition, the structural facilities of Scenario 1 required approximately 16% and 24% less land than Scenario 2 and Scenario 3, respectively, a factor very important in locations with limited available land area [31,32]. The lowest investment cost, on the other hand, was calculated for Scenario 2, followed by Scenario 1 and, lastly, Scenario 3. The best solution based on the cost of electricity is Scenario 2, followed by Scenario 3 and, lastly, Scenario 1. Although the initial total revenue requirement of Scenario 3 is very similar to that of Scenario 2, the lower amount of the hydrogen generated in the plant resulted in a relatively higher COE.

The calculated COE for the three plants is relatively high when compared to conventional power plants connected to the main grid of the country. However, the calculated costs of electricity are comparable to and even lower than that of the diesel generation plant currently functioning on the island of Skyros. This implies that all of the proposed renewable technologies are economically viable. Lastly, the zero direct emissions of the proposed renewable hybrid plants is an additional advantage to be accounted for in future environmental measures.

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