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Simulation and evaluation of a hybrid concentrating-solar and wind power plant for energy autonomy on islands

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ABSTRACT

Renewable energy sources can offer isolated communities the opportunity to regulate their energy use in a manner that best suits their needs. This paper presents the simulation and thermodynamic evaluation of a stand-alone hybrid power plant exclusively using renewable energy sources and storage technologies for the energy autonomy of a Mediterranean island. The study assumes stand-alone dynamic operation and investigates the sustainable and robust energy independence of the community under consideration, a remote area not connected to a centralized electrical grid. The analysis shows that the evaluated hybrid concentrating solar-wind power plant is a reliable alternative for satisfying the fluctuating electricity demand of the island. The plant achieves stable and controlled autonomous performance using the complementary character of solar and wind energy, combined with energy storage.

1. Introduction

Among the International Energy Agency (IEA) member countries, Greece has the most carbon-intensive primary energy supply, because of its strong reliance on oil and lignite [1]. 55% of the country's domestic energy demand is met with oil, approximately 99% of which is imported. For the oil energy needs of the islands in the Aegean alone, Greece pays more than 500 million Euro a year, in order to generate electricity at local power plants [2].

The relatively high cost of electricity of isolated areas and non-interconnected islands increases the competitiveness and promotes the wider incorporation of renewable energy technologies that may, in other cases, seem economically inferior to business-as-usual energy solutions. With this in mind and accounting for the high potential of the country in renewable sources, it is expected that appropriate energy policies could make a significant contribution to the economic recovery of Greece, while these policies could also be used as a European example on energy metamorphosis.

The present paper presents part of the outcome of the European project GENERGIS (Green ENERGy for ISlands) [3]. The goals of the project were to: (1) address the renewable energy autonomy of an island, including energy storage systems, (2) involve the people of the community in the decision-making process, (3) perform detailed technical calculations through simulations, as well as economic and environmental analyses, (4) propose a concrete energy plan for achieving 100% sustainable living and (5) create the first guide on sustainable development based on social, environmental and economic data.

This paper presents the dynamic simulation and thermodynamic analysis of a hybrid power plant based on renewable energy sources (RES) for the energy autonomy of the Greek island Skyros. Published work on a similar basis can be found in Refs. [4–6]. The proposed power plant in this work aims to fully satisfy the electricity energy demand of Skyros with 100% use of RES. To develop such a stand-alone RES plant and at the same time minimize the probability of operational failures, the system must be tested under extreme conditions of energy demand and climatic conditions. To achieve reliable and robust operation, the power plant is substantially oversized, combines renewable technologies with

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complementary character and includes energy storage systems. The existing diesel generator on the island is expected to be used as a theoretical back-up technology initially to ensure no power outages in the case of unpredicted events, not accounted for or evaluated in this paper. This has a twofold purpose: to provide the necessary time and space 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. The hybrid renewable power plant is planned to be built in the same location as the existing diesel power plant operating on the island currently. Thus, it is expected that the transmission and distribution of electricity will follow similar patterns as in the current situation, while the associated grid connection and reinforcement costs will be kept to a minimum. This work does not consider grid-related infrastructure but it focuses on the thermodynamic analysis of the power-plant equipment.

2. Presentation of the case study

The case study chosen in the project GENERGIS was the island of Skyros. The current reported cost of electricity of Skyros is one of the highest among the Greek islands [7]. This high expenditure undermines the financial condition of the island itself, as well as that of the Greek state. Large public subsidies are required to balance the cost for both the energy company and the inhabitants of the island. In addition it belies the potential for energy development and environmental quality of the island. The incorporation of new renewable energy applications on Skyros provides the possibility to use local energy resources in order to face future changing energy requirements in a sustainable manner. Wider incorporation of stations based on RES can make the island energy self-sufficient, while providing significant environmental advantages and promoting economic growth. In addition, the incorporation of RES in the energy portfolio of the island can provide a better standard of living, better quality of energy services and help to achieve national and international goals associated with the wider incorporation of renewable sources into the global energy portfolio.

The current electricity energy needs of Skyros are covered today through the combustion of diesel oil. The electricity generated is used to cover part of the space and water heating needs of the island, as well as operate lighting and electrical and cooling appliances. Skyros is characterized by a low population density that reveals good potential for developing applications with RES. The future electricity energy demand of Skyros, as anticipated in 2012 by the Hellenic Electricity Distribution Network Operator (HEDNO/DEDDIE), is shown in Table 1 [8]. Assuming an approximate annual energy increase of 1.4%, the energy demand of the island is further projected to selected years of importance for the present study.

Table 1
Projected energy demand on Skyros.

Year	Total energy demand [MWh]	Peak demand [MW]
2013	15,531	4.668
2014	15,918	4.737
2015	16,055	4.807
2016	16,207	4.876
2017	16,369	4.946
2018	–[a]	5.015
2019[b]	16,698	5.085
2020[b]	16,865	5.156
2045[b]	21,628	7.300

[a] Missing value from the dataset provided by DEDDIE.
[b] Data projected using an annual energy increase of 1.4%.

3. Methodology

Exergy is an important tool in the analysis and evaluation of thermodynamic systems. It is a measure of departure of a system from the state of its thermodynamic environment and shows the maximum theoretical useful work that can be obtained by bringing the system into equilibrium with the environment. In contrast to energy, exergy can be destroyed, it is thus not conserved and reveals the real thermodynamic inefficiencies of a system that cannot be determined using an energy analysis alone.

Physical exergy depends on the pressure and temperature of a material stream. Chemical exergy, on the other hand, is determined by the chemical composition of a stream and depends on the defined standard chemical exergy of the standard environment consisting of a set of reference substances. The main two standard chemical exergy reference environments widely used in the engineering field are the models of Ahrends and Szargut [9,10]. The kinetic and potential exergy are equal to the kinetic and potential energy.

The exergy of solar power received by the sun in the case of the solar-based plants can be calculated using the following equation [11]:

$$\dot{E}_{sun} = \dot{Q} \cdot \Psi_s$$

where, $\dot{Q}$ is the solar irradiation available from the sun and Ψ_s is the ratio between exergy and energy. This ratio is calculated as:

$$\Psi_s = \left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right]$$

where, T_a is the ambient temperature and T_s is the apparent black body temperature of the sun (5600 K).

The input exergy of wind, that is also the exergy of fuel of the wind turbines used in this work, is the kinetic power of the wind calculated as:

$$\dot{E}_{wind} = \frac{1}{2} \cdot m \cdot v^2 = \frac{1}{2} \cdot \rho \cdot A \cdot v^3$$

where, m is the mass flow rate of the air going through the wind turbine's swept area, ρ is the density of the air (1.23 kg/m^3), A is the total swept of the wind turbines and v is the wind speed.

An exergetic analysis reveals the cause, location and quantity of irreversibilities within a system [12]. It is a very useful tool both for minimizing inefficiencies in the design and planning stage when evaluating new energy conversion systems and for proposing ways to improve operational efficiencies when evaluating existing systems.

To realize an exergetic analysis, the system boundary of the analyzed plant must be first defined. This boundary allows the definition and distinction between exergy destruction and loss. When the system boundaries of the analysis include a complete thermodynamic system, exergy loss ($\dot{E}_L$) is only defined for the overall system, while the exergy destruction ($\dot{E}_D$) is defined and calculated for each of the components within the system.

Each component k within a thermodynamic system under evaluation is defined by an exergy of the fuel and an exergy of the product ($\dot{E}_{F,k}$ and $\dot{E}_{P,k}$). The fuel of a process/component/system depicts the resources that must be used to generate the desired product, while the product is the result itself. The exergy of the fuel and product are defined based on the operation and purpose of each component within an analyzed system [13,14].

The ratio of the exergy of the product to the exergy of the fuel, ε_k, is the exergetic efficiency of a component, which demonstrates its thermodynamic performance. The difference between the exergy of the fuel and product at the component-level represents the exergy destruction within a component ($\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k}$), while at the system-level it represents the sum of exergy destruction and exergy loss of the overall system ($\dot{E}_{D,tot} + \dot{E}_{L,tot} = \dot{E}_{F,tot} - \dot{E}_{P,tot}$).

4. Simulation of the hybrid power plant

The hybrid power plant proposed in this paper combines a concentrating solar power (CSP) plant [15] including thermal storage with wind energy coupled with electricity storage. According to the International Renewable Energy Agency, IRENA [16], a CSP is considered an economically-viable option in regions with direct normal irradiance levels (DNI) at the level of 2000 kWh/m^2/year and above. The annual average DNI of Skyros is 1960 kWh/m^2/year, which places Skyros at the low end of the desired range for the implementation of CSP technologies [17].

The simulation of the plant is realized using the commercial software EbsilonProfessional [18]. The operational characteristics of the system can be found in Table 2. For the purpose of this paper a quasi-steady state simulation is realized, driven by hourly meteorological input data sets over the course of a year. The final capacities of the renewable technologies and storage facilities are determined after sensitivity analyses using developed code written in the programming language R. This simulation was based on given input meteorological data with the condition that the hybrid plant should autonomously cover the annual energy requirement and maximum energy peaks of the island, in order to minimize the probability of power shortages. The peak energy demand and total annual demand are determined from the hourly demand time series of the island, as projected to the last year of the economic life of the power plant (2045). The plant is assumed to start operation in 2020 with an economic life of 25 years. The 2012 hourly time series of electricity demand on Skyros was extrapolated to 2045 with an annual energy increase of 1.4% [8]. The daily time series, as well as the distribution of the annual electricity demand of the island in the future for four selected years is presented in Fig. 1. The proposed hybrid plant has an annual net energy output equal to the energy demand of the island that same year (approximately 25,000 MWh/a).

All of the input data used in the simulation of the hybrid plant are shown in Fig. 2. The solar data were derived from Ref. [19]. The wind speed time series (third panel) represents the mean wind speed of the years 2010–2013. The wind speed was averaged over the 4 years of available data because one year is not representative of such a volatile variable. The wind speed data [20] were 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 [21]:

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

Table 2
Operational characteristics of the hybrid power plant.

CSP design conditions	
Solar field collectors	
Type [–]	Parabolic trough
Total number [–]	56
Collector length [m]	150
Average efficiency [%]	60
Thermal storage	
Type [–]	Indirect two-tank system
Storage medium [–]	Molten salt
Thermal oil [–]	Therminol VP-1
Energy capacity [MWh]	350
Discharge time at maximum capacity [h]	14
Steam turbine (incl. generator)	
Isentropic efficiency [%]	88
Mechanical efficiency [%]	99
Electrical efficiency [%]	95
Pressure levels [bar]	33.5; 16.5; 14.0; 6.3; 3.1; 1.2; 1.6; 0.03
Live steam temperature [°C]	380
Power output [MW]	10
Pumps (incl. motors)	
Isentropic efficiency [%]	80
Mechanical efficiency [%]	99
Electrical efficiency [%]	85
Condenser	
ΔT_{min} [K]	5
Operational pressure [bar]	0.032
Wind turbines	
Model [–]	Vestas V112 (IEC IB/IEC S)
Rated power [MW]	3.3
Efficiency [%]	32
Hub height [m]	84
Rotor diameter [m]	112
Swept area [m^2]	9852
Cut-in speed [m/s]	3
Cut-out speed [m/s]	25
Electricity storage	
Type [–]	Sodium-sulfur (NaS) battery
Energy capacity [MWh]	60
Discharge time at capacity max of 14 MW [h]	4
Efficiency [%]	95

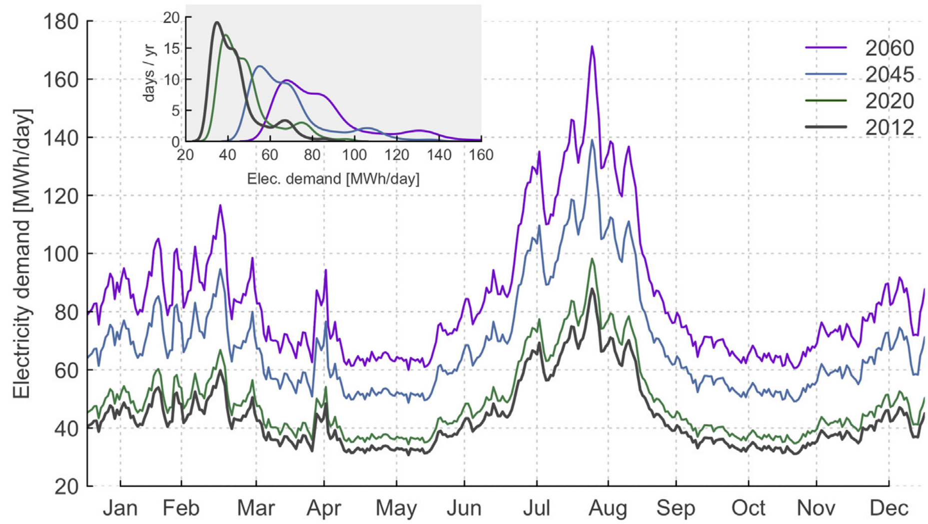

Fig. 1. Daily time series and annual distribution of electricity demand on Skyros for selected years.

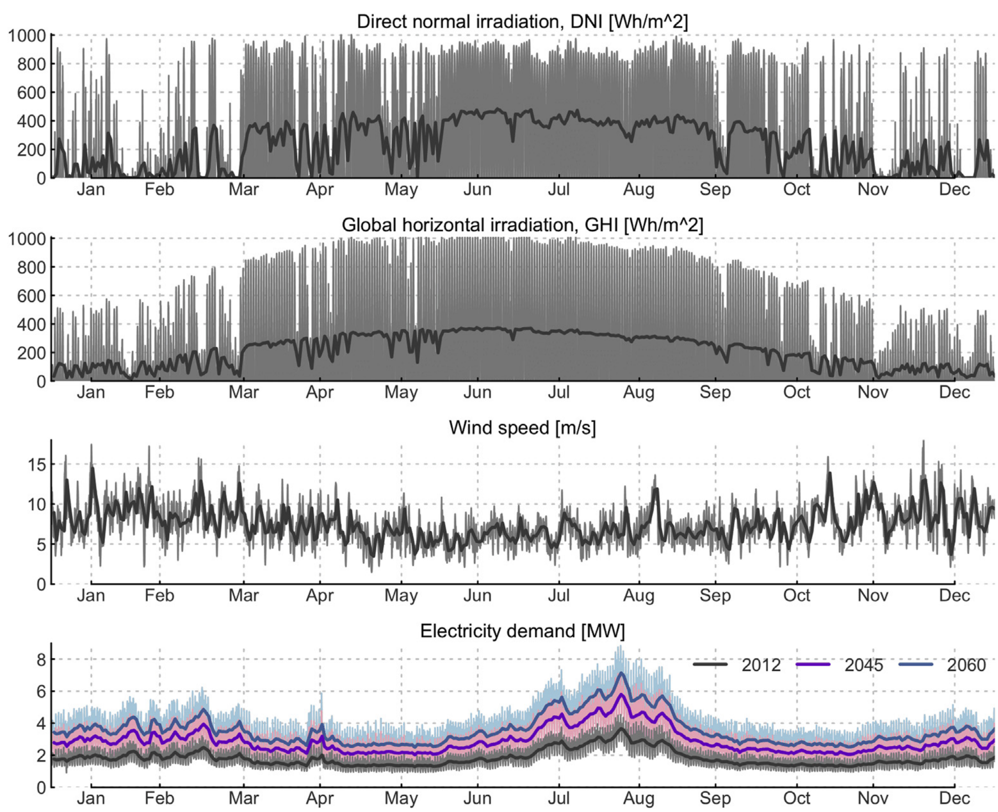

Fig. 2. Input hourly data used in the dynamic simulation of the hybrid power plant (daily mean shown by thick darker lines).

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

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. 3). 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, the electric battery of the wind farm is used. Generated energy surpluses from the wind turbines (that imply wind speeds higher than those required

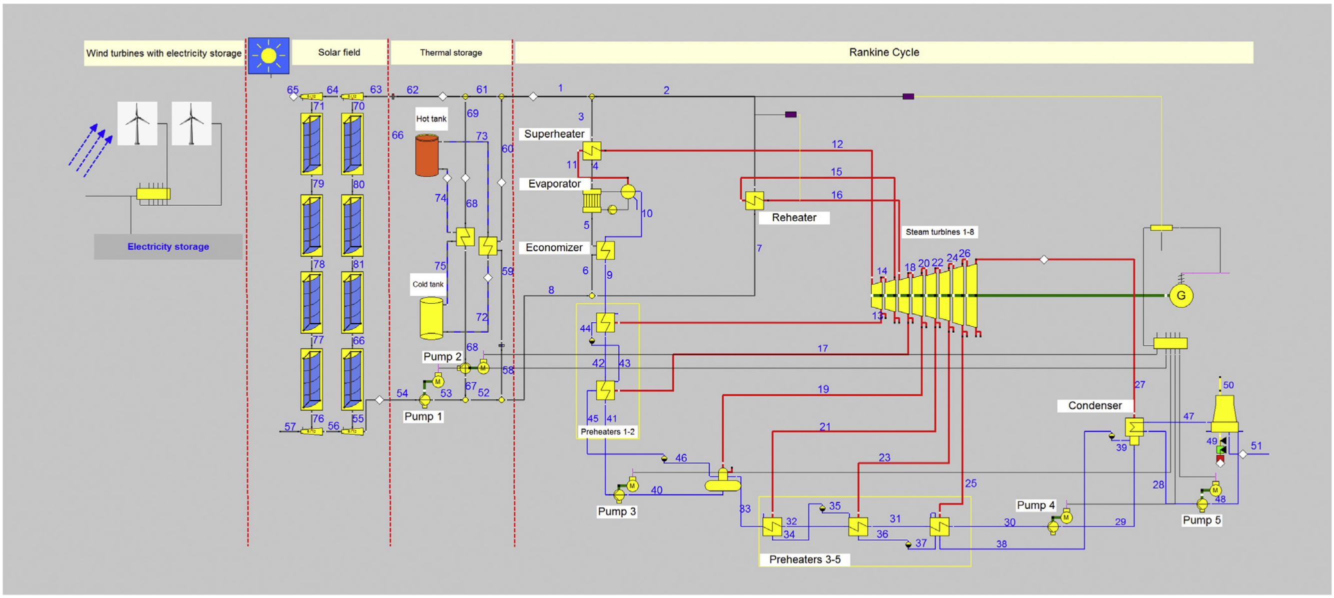

Fig. 3. Simulation flow diagram of the CSP-wind power plant supported by thermal and electricity storage.[2]

to cover the remaining energy demand) are stored in the electric battery. The number of the wind turbines and the size of the associated electricity storage 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 [22]. 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 energy generated by the solar field with $n = 56$ solar collectors is calculated as:

$$Q_{solar\_field} = \sum_{n=1}^{n} Q_{coll,n} = DNI \cdot \left(\sum_{n=1}^{n} A_{net,n} \right) \cdot \eta_{coll}$$

where, $A_{net,n}$ is the net aperture area of each collector (817.4 m^2), *DNI* is the direct normal irradiation and η_{coll} the average efficiency of the collectors (60%)[1].

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 MWh$_{th}$ (124.7 MWh$_e$) 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 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). 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 with the power curve shown in Fig. 4 [23].

Each wind turbine has a 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, respectively. 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 optimal capacities of the plants and storage facilities are determined after the simultaneous variation of their capacities over a wide range, with the restriction that the electricity requirements of the island are fully covered. 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: diameter) crosswind (4D + D = 560 m), while for safety reasons 1D of empty space is kept in the front and 1D in the rear side of the turbines. This spacing ensures array efficiency higher than 90% [24,25]. 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

[1] An average collector efficiency is used to facilitate the application of the program used, not suited to calculate dynamically-varying collector efficiencies. It is assumed that changes in the efficiency of the collectors will not affect the overall conclusions of this work that is based on average annual performance.

[2] Wind turbine image from: http:/imgarcade.com/1/how-to-draw-wind-turbine/.

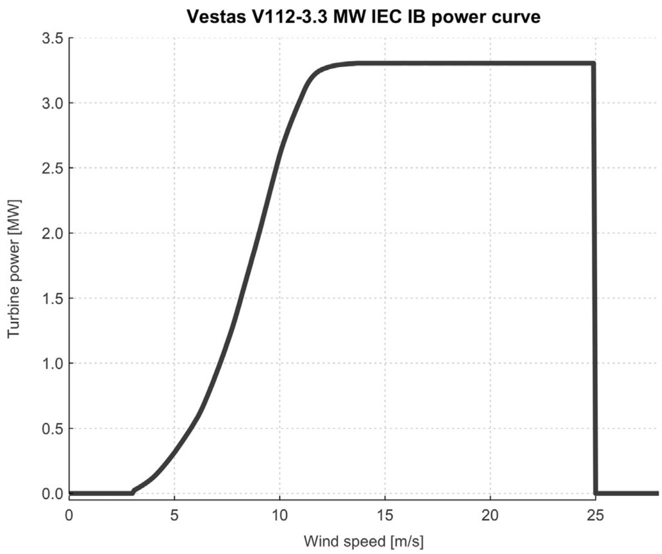

Fig. 4. Power curve of the wind turbines.

operation is supported by an electricity storage system.

The incorporated sodium-sulfur (NaS) battery storage system has an energy capacity of 60 MWh 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 kWh/m^3 and 100–200 kWh/t, respectively [26]. This means that for the proposed hybrid plant a 200–300 m^3 NaS battery system is needed. It should be noted that, for simplicity, no daily battery losses have been included in the simulations.

5. Results and discussion

The performance of the CSP-wind hybrid power plant over the course of the year is presented in Fig. 5. The months of December and August are depicted in the zoomed panels of Fig. 6. It should be noted that the CSP power output (second panel) represents the operation of the steam turbines related to directly converted solar irradiation and it does not include operation using the thermal storage. The overall operational capacity of the turbines of the CSP plant includes the discharge of the thermal storage as well (fourth panel). Energy deficits exist both in the winter period, because of low irradiation levels, and in the summer season, because of high energy demand despite the high irradiation levels. In the winter period, it is also possible to have several consequent cloudy days resulting in an accumulation of energy deficit. Throughout the year, energy deficits from the operation of the CSP plant are covered by the wind turbines of the plant.

With the exception of periods with high energy peaks (August–September), solar and wind residual are adequate to keep the thermal and electricity storage systems of the hybrid plant fully charged throughout the summer season. During the winter period when the solar irradiation and wind energy are not adequate to satisfy the demand of the island, the stored thermal energy is used. The hybrid plant relies on the overall more constant performance of the wind turbines and electricity storage system. Thus, although the storage systems are not used continuously throughout the year they are necessary to ensure stable operation during high energy peaks and demanding weather conditions.

The average capacity factors, defined as the mean ratio of power output (including the mean wind residual of 0.6 MW) to the maximum power output, of the CSP and wind plants are found to be 16.1 and 34.2%, respectively. It is seen that approximately 48% of the annual electricity demand of the hybrid plant is generated in the

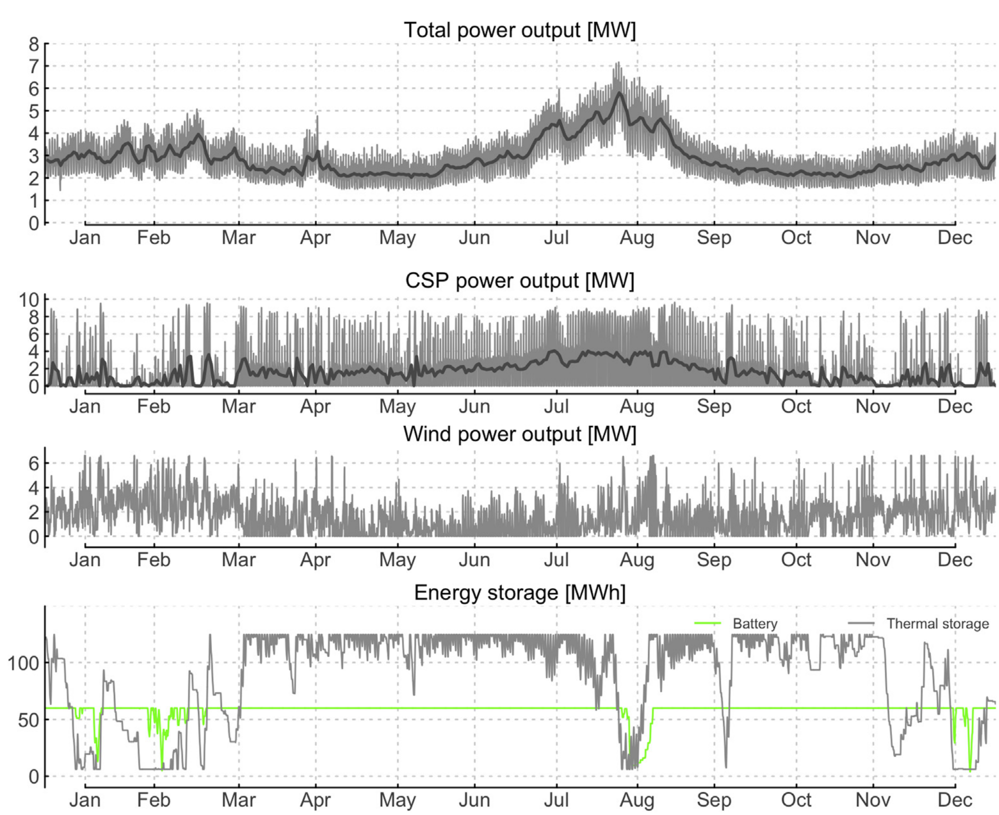

Fig. 5. Performance of the CSP-wind power plant with electricity storage (daily mean shown by thick darker lines; CSP power output represents sun availability).

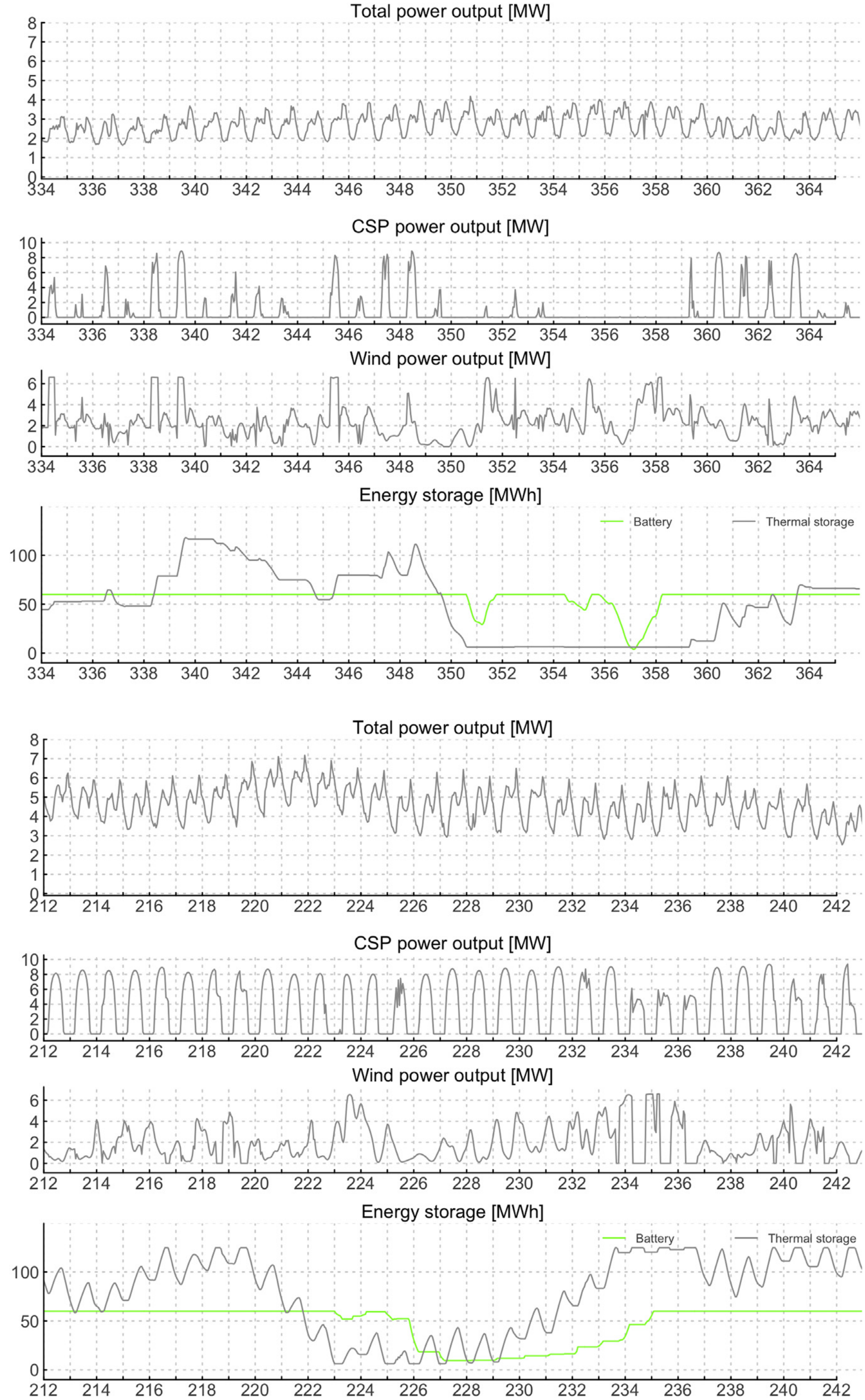

Fig. 6. Operation over winter and summer months (December is presented in the solid panel and August is presented in the dashed panel). The x-axis shows the numbered day of the year.

CSP system and 52% by the wind turbines. The plant does not generate any additional electricity surplus.

The power plant is examined with an exergetic analysis at the component-level while operating at full load. The system boundaries of the analysis include the complete hybrid power plant. Time-related equipment degradation and its influence on the operational effectiveness of components has not been considered in this work.

The exergy of the fuel of the solar field is the exergy received from the sun $\dot{E}_{sun}$ calculated using the DNI. The exergy of the product of the field is the exergy generated and stored in the thermal oil of the power plant ($\dot{E}_{thermal\_oil} = \dot{m}_{thermal\_oil} \cdot e_{thermal\_oil}$, with the $\dot{m}_{thermal\_oil}$ the mass flow rate of the thermal oil and $e_{thermal\_oil}$ the increase of the specific physical exergy of the thermal oil). The definition of the exergy of the product and fuel of the other components follow known rules [13,27].

The results at the component-level of the CSP plant at full-load operation are presented in Table 3. The calculation of the physical exergy of the individual components is based on an ambient temperature and pressure of 20 °C and 1.013 bar, respectively. Full-load operation is achieved with the maximum input, i.e., solar irradiation (DNI). As seen, the overall efficiency of the plant is found to be 22.9% with 90% of the exergy destruction stemming from the operation of the solar collectors. The operation of the solar field is thus vital for the efficiency of the CSP plant. The remaining plant components operate within expected and acceptable limits.

It should be noted that the plant is frequently required to operate in partial load, due to design restrictions associated with the energy demand and weather variations. These variations cause significant fluctuations to its efficiency. To include these operational fluctuations in the overall evaluation of the plant, a mean annual efficiency is calculated based on the generated time series of energy input and output over one year. The annual efficiency of the hybrid plant combines the net mean contributions of each incorporated technology.

The mean annual operation of the plant is estimated with the mean DNI value of 233.5 W/m^2. With this solar irradiation (exergy input: 9940 kW), the CSP plant generates 1550 kW. These values result in a total CSP plant efficiency of 15.6%. The efficiency of the solar field in this case is found to be 22.6%, which is significantly reduced when compared to full-load conditions. Nevertheless, as in the full-load operation, the exergy destruction of the solar field dominates the plant's irreversibilities, being responsible for 91% (7.7 MW) of the plant's total exergy destruction.

The exergetic efficiency of the wind turbines at full load operation (3.3 MW) is 31.6%. It should be noted that this is not the maximum efficiency the wind turbines can reach, since their efficiency depends on the relative increase of the ratio of the exergy of the fuel and product. Their maximum efficiency is found to be 45.7% and it is achieved with a wind speed of 8.3 m/s and a power output of 1.6 MW. The mean annual exergetic efficiency of the wind turbines is found to be 24.6% (with wind speed of 7.5 m/s) with mean power output for each wind turbine at 825 kW.

Accounting for the exergy values shown in Table 4, the overall annual mean efficiency of the hybrid plant (CSP – wind plant with storage) is calculated as:

$$\varepsilon_{mean,hybrid} = \frac{\dot{E}_{P,hybrid}}{\dot{E}_{F,hybrid}} = \frac{\dot{E}_{P,CSP,mean} + \dot{E}_{P,wind,mean}}{\dot{E}_{F,sun,mean} + \dot{E}_{F,wind,mean}}$$

with $\varepsilon_{elec.stor}$ the roundtrip exergetic efficiency of the electricity storage system, $\dot{E}_{F,sun,mean}$ the mean annual solar exergy received from the sun calculated with the mean value of DNI (233.5 W/m^2), $\dot{E}_{F,wind,mean}$ the mean exergy of the fuel of the wind, $\dot{E}_{P,CSP,mean}$ the net mean annual exergy of the product of the CSP plant and $\dot{E}_{P,wind,mean}$ the net mean exergy of the product of the wind turbines.

The mean annual exergetic efficiency of the overall hybrid CSP-wind power plant is consequently calculated at 19.2%, a value that lies in the range between reported efficiencies of CSP and wind plants.

The dynamic simulation presented here is subject to some caveats. First, a lack of longer time series of input data made more robust testing of the plant under realistic conditions difficult. While the simulation does cover a wide range of conditions, weather conditions and energy demand can vary from year to year. This type of simulation would greatly benefit from the availability of more data.

Second, we made reasonable assumptions concerning the physical limitations of the components of the hybrid power plant (temperatures, maximum loads, etc.). Nonetheless, we did not consider some technological limitations related to the operation of the CSP plant. Current technologies may require several hours or days to shutdown or restart the turbines. However, new turbines developed specifically for CSP plants can be restarted within the course of a day (e.g., [28]). Given the uncertainty of this aspect of the technology, such a limitation was not considered.

Within the framework of the project GENERGIS two more alternatives for the 100% renewable energy autonomy of the island of Skyros were examined. All hybrid plants were based on similar assumptions and boundary conditions. The first option included a photovoltaic array and wind turbines coupled with electricity storage and an electrolyzer unit for hydrogen generation, while the second choice included photovoltaic panels, wind turbines and a pumped-storage hydropower plant coupled with an electrolyzer. When comparing the CSP-wind power plant with the two other alternatives, it is seen that this plant achieves the best exergetic

Table 3
Results of the exergetic analysis at the component level of the CSP plant at full-load/maximum operation.

	$\dot{E}_F$ [MW]	$\dot{E}_P$ [MW]	$\dot{E}_D$ [MW]	ε [%]
Solar collectors	42.04	13.92	28.12	33.1
Steam turbine 1	2.17	1.94	0.24	89.1
Steam turbine 2	1.13	1.05	0.07	93.8
Steam turbine 3	0.39	0.38	0.01	98.3
Steam turbine 4	1.65	1.48	0.17	89.9
Steam turbine 5	1.22	1.12	0.10	91.8
Steam turbine 6	1.32	1.18	0.14	89.4
Steam turbine 7	0.83	0.75	0.08	90.7
Steam turbine 8	2.63	2.25	0.38	85.5
Reheater	2.49	2.20	0.29	88.4
Superheater	1.22	1.14	0.08	93.8
Evaporator	7.15	6.77	0.38	94.7
Economizer	1.90	1.76	0.14	92.9
Preheater 1	0.90	0.82	0.08	91.5
Preheater 2	0.46	0.42	0.04	90.6
Preheater 3	0.29	0.25	0.04	86.2
Preheater 4	0.15	0.13	0.02	85.1
Preheater 5	0.35	0.19	0.16	53.8
Pump1	0.31	0.13	0.18	40.8
Pump2	0.00	0.00	0.00	40.7
Pump3	0.17	0.12	0.05	68.8
Pump4	0.01	0.01	0.00	61.3
Pump5	0.01	0.01	0.00	67.3
Deaerator	0.54	0.33	0.21	60.8
Condenser	0.24	–	0.12	–
Total	**42.04**	**9.63**	**31.10**	**22.9**
$E_{L,tot}$	1.31			

Table 4
Calculated exergy values at full-load/maximum and mean annual operation of each RES technology.

	$\dot{E}_F$ [MW]	$\dot{E}_P$ [MW]	$\dot{E}_D$ [MW]	ε [%]
Solar field				
Full load/maximum	42.0	13.9	28.1	33.1
Mean annual	9.9	2.3	7.7	22.6
CSP plant				
Full load/maximum	42.0	9.6	32.4	22.9
Mean annual	9.9	1.6	8.4	15.6
Wind turbines				
Full load/maximum	20.9	6.6	14.3	31.6
Mean annual	6.7	1.7	5.1	24.6
Electricity storage[a]				
Full load/maximum	15.0	14.3	0.8	95.0
Mean annual	1.6	1.5	0.1	95.0

[a] The operation of the electricity storage is fully based on the operation of the wind turbines.

efficiency and has the smallest land requirement (16% smaller that of the second choice and 24% smaller that of the third choice).

The evaluation of energy projects is largely influenced by their associated economic expenditure. The cost of electricity (COE) published for Skyros in the years 2012 and 2013 was at 420.2 and 400.8 €/MWh, respectively [7]. 77% of the direct cost of electricity is associated with fuel cost. The COE of the renewable hybrid plant presented is 400 €/MWh [3]. Although the COE of the presented plant is higher than that of conventional power plants connected to the main grid of the country, it is lower than that of the diesel generation plant presently operating on the island. This confirms the economic feasibility of the proposed technology. Last but not least, it should be mentioned that the COE of renewable plants may be further reduced in the future through the adoption of governmental climate change measures (e.g., CO_2 taxes).

6. Conclusions

Hybrid power plants, like the one proposed in this study, are a promising alternative in locations where the extension of the electrical grid is difficult or not economical, where the cost of electricity is high, or where the electricity generation is associated with significant environmentally harmful emissions.

The evaluated renewable hybrid plant combined concentrating solar power with wind turbines and storage facilities. It was designed accounting for the non-interconnected character of the island, i.e., it was based on stand-alone requirements. This led to the adaptation of three factors that determine the efficiency and cost of the plant: net energy output restrictions, capacity oversizing and large storage facilities. When 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 low.

During the optimization of the operation of the power plant, it was found that more than one renewable technology must be combined to ensure stable and secure operation. 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 a more consistent operation. The combination of wind and large storage facilities are seen to be very good supplements to solar energy.

Comparing the power plant presented here with other alternatives for the 100% renewable energy autonomy of remote areas [3], the concentrating solar power-wind plant is found to achieve promising operation with a relatively lower land-use requirement and higher exergetic efficiency. In addition, the zero residual electricity of the plant makes it a solution that is easy to manage with a relatively more reliable and secure operation.

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