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# Energy Transition: Renewable Energy-Based Combined Heat and Power Optimization Model for Distributed Communities

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**Abstract:** New energy technologies are gaining rising importance because of climate change and increasing energy demand, and they show an enormous potential to mitigate environmental issues. With the purpose of maximizing the renewable energy utilization, combined heat and power systems are considered more effective, economical, and ecological. However, renewable energy-based combined heat and power systems are still in the development phase. Hence, this study presents a new methodology to produce combined electricity and heat from wind and solar PV systems to meet the energy demand of small, distributed communities. For this scope, an optimization model is developed to exploit rationally the power generation from renewables and meet the electricity and heating demand of two selected communities. The curtailed energy of solar and wind systems is used to produce heat by a thermal load controller combined with a natural gas boiler. The developed model is also integrated with the grid station for energy exchange. This study contributes also to evaluate the economic and environmental feasibility of combined heat and power systems, and determine the best optimal operational strategies to extend the renewable energy utilization and minimize energy costs. The obtained results show that a significant amount of clean energy can be produced, covering the 79% of the energy demand of the selected communities, at the lowest levelized cost of energy of 0.013 €/kWh; meanwhile, the proposed system reduces 4129 tons of $CO_2$ emissions annually.

**Keywords:** combined heat and power system; solar and wind energy; economic and environmental analysis; distributed energy communities

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**Citation:** Gul, E.; Baldinelli, G.; Bartocci, P. Energy Transition: Renewable Energy-Based Combined Heat and Power Optimization Model for Distributed Communities. *Energies* **2022**, *15*, 6740. https://doi.org/10.3390/en15186740

Academic Editors: Doug Arent, Xiaolei Yang and Adam Warren

Received: 18 August 2022
Accepted: 13 September 2022
Published: 15 September 2022



## 1. Introduction

The world economy is heavily reliant on conventional energy sources and the extensive utilization of fossil fuels is causing climate change issues [1,2]. Furthermore, the COVID-19 pandemic and the Russia–Ukraine war create energy security and supply chain problems, causing energy and food challenges around the globe and threating global climate objectives [3]. The current energy, economic, and climate crises demand a rapid clean energy transition to new energy technologies, which produce low emissions and result more sustainable [4]. New energy technologies are playing an essential role to mitigate environmental problems, limiting greenhouse gas emissions (GHG), and increasing energy production from renewable energies [5,6]. However, due to the uncertain and variable nature of renewable energy sources (RES), it is highly challenging to maximize the utilization of RES, especially solar and wind energy [7]. In addition, the inconsistency and uncertainty in energy production from RES also poses technical issues for grid stations for the efficient management of the available energy [8]. Energy storage and conversion technologies are adopted on a large scale to increase power system flexibility and reliability, especially for intermittent renewable energy sources. Combined heat and power (CHP) technologies produce electricity and convert waste energy into thermal energy; this conversion process increases the system energy utilization and efficiency [9]. Currently, a wide range of CHP technologies such as steam and combustion turbines, reciprocating engines, and fuel cells are being largely adopted for cogeneration [10,11]. Similarly, utilizing CHP technologies, the curtailed/surplus energy of RES can be adopted to produce thermal energy, dedicated to a heating system, and for the supply of domestic hot water [12,13].

A CHP system can effectively contribute to diversify the energy mix from a small scale to a substantial extent and it can reduce the energy cost and capital costs [14]. Numerous research studies [15–18] present technical and economic analyses of small-scale CHP systems to produce electricity and heat at the industrial scale by capturing the waste/exhaust heat of thermal power plants and producing heat. R. Lacko et al. [19] presented a small-scale standalone CHP system model to produce electrical and thermal energy by harnessing energy from RES. However, RES integration and optimization at a large scale, specifically for solar and wind energy, requires highly efficient operational flexibility to match the energy demand and supply causing possible fluctuations in power system production [20]. The improvement in energy system flexibility and reliability solves the technical difficulties associated with the integration of variable energy sources; furthermore, it increases the penetration of RES [21]. The CHP techniques can significantly raise the overall efficiency, thermodynamic performance, and economic advantages [22]. Zhang et al. [23] presented an energy system model for microgrid and CHP generation systems by stochastic non-convex optimization, with the aim of minimizing the operating cost of the system. In [24], a thermo-electric decoupling method to produce CHP from a wind energy system is presented, where heat pumps and electric boilers for thermal energy production for a short-term scheduling period were used. The implementation of a renewables-based CHP energy system model in small-scale distributed communities can increase renewable energy utilization, improve the power system flexibility, and reduce the cost of energy, as well as the burden from the grid station [25–27]. Bioenergy and biofuels are playing a critical role to decarbonize existing energy systems, especially in power generation and transport sectors. The author Sarkar et al. [28,29] presented a sustainable manufacturing process for multi-type biofuels production from renewable biomass, which could be an alternative to the fossil fuels system. Moreover, the author presents a multi-setup-multi-delivery (MSMD) concept for biofuels and bioenergy generation for the transportation sector. For the robust and reliable operation of energy systems, the supply chain management has a significant importance, as the timely availability and utilization of resources improves the system reliability and flexibility [30].

Several studies presented the local-scale distributed energy system model [31–33]; they primarily focused on electricity distribution modeling for small communities, while the proposed research work shows a model to supply both electricity and heat to the distributed communities. Bartolini et al. [34] presented a multi-sources energy system model for the local community for cogeneration, electricity, and hydrogen energy storage, adopting power-to-gas storage systems for renewable energy storage. Moreover, in the Italian region, Wieler et al. [35] presented a central energy generation system with combined heat and power generation for a building, developing multiple scenarios using the 3D Urban Modeling Tool. Furthermore, Ahn et al. [36] created an hourly CHP model for small-scale commercial buildings in New York City, increasing the utilization of renewable energy, as well as improving the grid station flexibility. Grid stations with a high contribution of renewable energies demand higher flexibility to meet the variable electricity demand; besides, to cope with the hourly varying load, spinning reserves and thermal peak plants are required, with the consequent increase of the energy cost and the overall system net present cost. Demand-side energy management strategies and optimal operation and scheduling of home appliances can significantly contribute to maximize the utilization of renewables. Waseem et al. [37,38] presented a new technique for optimal operation and scheduling of home appliances and its impacts on distributed energy sources. Moreover, authors also present a GWCSO algorithm for effective energy management. Table 1 presents the latest published articles on renewables and CHP systems.

**Table 1.** Literature review of latest published articles of renewable energy systems.

| Location/Software | Developed System/Operating Strategies | Findings | Ref |
|---|---|---|---|
| Germany/ASPEN | CHP system for geothermal and biogas | • Annual electricity generation 4.3 MW<br>• LCOE 15.42 ¢€/kWh, and 16.4 ¢€/kWh | [39] |
| Nigeria/HOMER Pro | Hybrid energy system for educational institute | • Annual energy production 722 MWh<br>• LCOE 57.14 ¢€/kWh | [40] |
| Ghana/SAM | 20 MW solar PV system with and without energy storage system | • Annual energy production is 43 GWh<br>• LCOE 8.84 ¢€/kWh, 9.88 ¢€/kWh and 10.05 ¢€/kWh | [41] |
| Dubai UAE MATLAB/SAM | Domestic solar PV-storage model in a distribution network | • Simplified method for optimizing battery size in solar PV systems<br>• LCOE: 0.043 $/kWh, NPV: 12,417 $, | [42] |
| USA/HOMER Pro | Solar PV battery-based CHP model for Michigan | • LCOE 0.22 $/kWh, at 0% interest and discount rate | [43] |
| Saudi Arabia HOMER Pro | Grid connected PV battery system and techno economic analysis | • NPC $12,662 million and LCOE is 0.0543 $/kWh<br>• Tracking system generated 34% more power than fixed axis PV system | [44] |
| China/HOMER Pro | Stand-alone hybrid PV and biomass CHP system | • Total annualized cost 651,000 $<br>• LCOE 0.355 $/kWh<br>• Annual electricity output 937.6 MWh | [45] |

In contrast to previous studies, the present research work provides a better solution to meet the heat and power demand of distributed communities, which not only increases the clean energy utilization but also provides energy at the lowest levelized cost. The present research work's main objective is to identify the applicability of a renewable energy-based CHP system for distributed communities at a small scale. The contributions and significance of the presented research work are described as follows: (a) new optimization method for CHP system; (b) socio-economic and environmentally sustainable energy solution for distributed communities; (c) wind and solar PV-based energy system model; (d) maximize the renewable energy utilization.

Section 2 presents the methodology, objective functions, and mathematical models of the developed energy system, while Section 3 describes the system architecture, mathematical models of wind and solar PV, and economic and environmental analysis. Sections 4 and 5 present the obtained results and their discussion, with the relative conclusions.

## 2. Methodology

At the aim of achieving the set objectives of this research, an optimization model is developed; it integrates solar PV and wind energy system with the HOMER microgrid [46] and it optimizes the power produced by these sources and supplied to the load centers. A combined dispatch strategy HOMER cycle charging and load following techniques are implemented to maximize the power generation from solar and wind systems and supply power to the connected load centers. Additionally, the surplus power is transferred to the local grid station. Moreover, the curtailed power of the system is used to produce heat by means of a thermal load controller and a boiler, which is also operated by using propane liquid gas to produce heat during the absence of renewable energy. If renewable energy is insufficient to meet the load demand, the energy is imported from the local grid station to satisfy the load demand. At the aim of testing and validating the performance of the system, a simulation and optimization software, HOMER Pro, developed by the National Renewable Energy Laboratory (NREL) [47] is employed, while for data for the wind and solar resources, NASA metrological data are utilized to model the system [48].

HOMER Pro is a powerful optimization and simulation software that presents new standards for present energy system modeling. It can model highly complex hybrid power systems consisting of multiple renewable energy systems from small to large scale;

moreover, it compares all potential combinations in a single run and produces large data sets of information and highlights the system technical and economic details such as lifetime, cashflow and levelized cost of energy. In addition, the software can be integrated with other programming tools which enhance its operational capabilities and diversify the analysis of energy system modeling. The electric load data are obtained from the Italian National Electricity Distribution Company TERNA website and scaled down to the community scale [49,50]. Figure 1 presents a flowchart that describes the step-by-step framework of this study, which consists of four different stages. In the first step, required input data for the modeling are collected. The input data includes the hourly energy demand and power produced by the solar PV and wind system, while the second step describes the modeling techniques of solar and wind turbine systems. In the third stage, the simulation and the optimization is performed and dispatch strategies are implemented. The fourth stage shows the obtained results of the developed system.

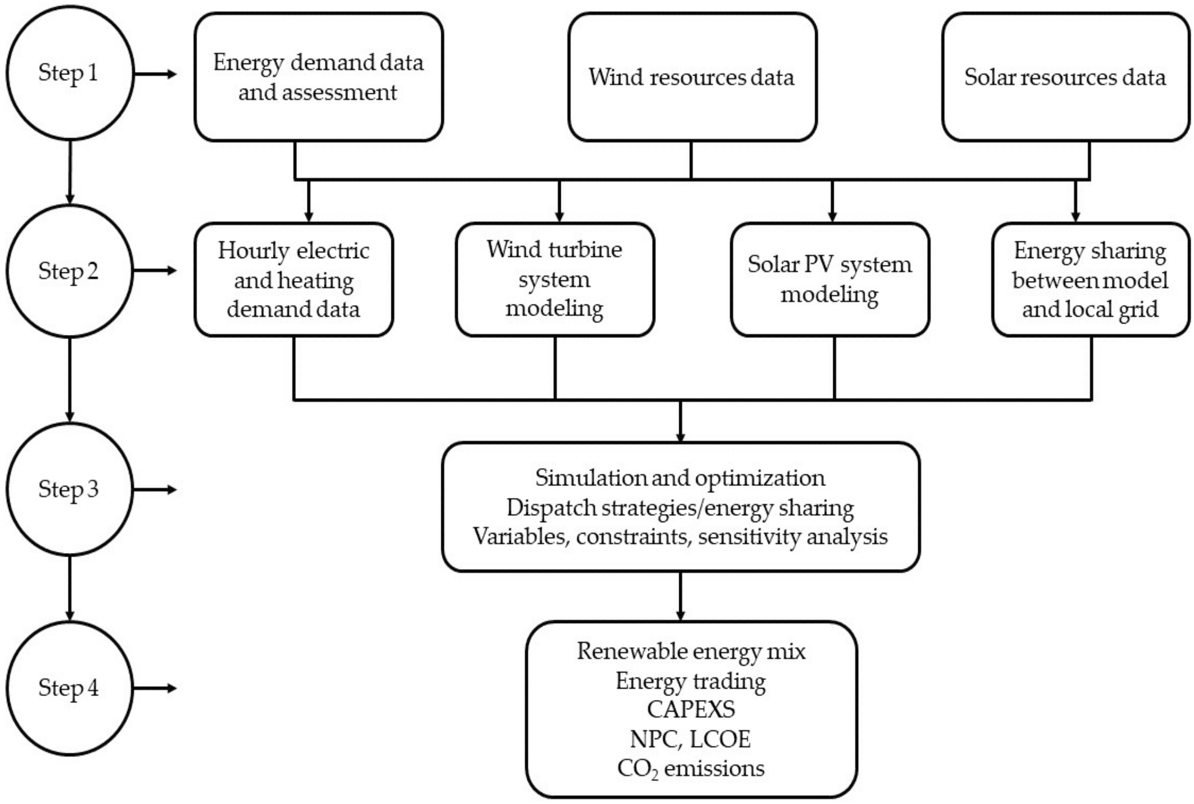


**Figure 1.** Process flowchart of the developed energy system model.

### 2.1. Model Formulation

The presented energy system model is designed to reach three objectives: (A) to maximize the power generation from the solar and wind power system presented in Equation (1); (B) to balance the electricity load demand while mixing the renewable power with energy purchased from the grid and meet the instantaneous load demand, Equation (2); (C) to supply the heat produced by the thermal load controller and boiler which balances the heat demand at each time interval over the scheduling horizon, Equation (3). The model is structured on the three objective functions presented in Equations (1)–(3) and the HOMER microgrid used the operational strategies based on the anticipated data and perform optimization. Firstly, the software maximizes and sums the power produced from the solar and wind system. In the second step, the microgrid balances the power generation with the load demand by mixing the power imported from grid station. Similarly, in the third step, the microgrid meets the heating demand of the system, summing up the heat produced by the thermal load controller and boiler and feeds the load center. Furthermore, Equation (1) represents the sum of the output power of solar and wind energy during operational periods in MWh, where $P^t_{\max}$ is the maximum power, $P^W_m$ and $P^S_m$ represent the power produced by the wind turbines and solar PV system, while $\boldsymbol{M}$ is the operational period which is one year. $P^t_d$ is the electricity demand, $P^t_R$ is the HOMER microgrid power and $P^t_{grid}$ is the energy imported from the local grid station. In Equation (3), $H^t_d$ is the thermal energy/heat demand of the community, while $H^t_{TLC}$ and $H^t_{boiler}$ are the heat produced respectively by thermal controllers and the boiler.

**Objective A**. To maximize the renewable power generation:

$$P^t_{\max} = \sum_{m=1}^{M} P^W_m + P^S_m \tag{1}$$

**Objective B**. To balance the load demand:

$$P^t_d = \sum_{m=1}^{M} P^t_R + P^t_{grid} \tag{2}$$

**Objective C**. Thermal energy balance:

$$H^t_d = H^t_{TLC} + H^t_{boiler} \tag{3}$$

*2.2. Constraints*

The energy produced by the solar and wind system is supplied to the HOMER microgrid and supplied to the connected load centers, while the surplus power is transferred to the connected grid station. Moreover, the curtailed energy of solar and wind systems is shifted to the thermal load controller for heat production, which is supplied to the selected buildings for heating purposes, as shown in Equation (4). $P^t_{Microgrid}$ is the power supplied from HOMER microgrid, $P^t_{Load}$ is the total load demand, $P^t_{grid}$ is the power export to the local grid station, and $P^t_{TLC}$ is the power supplied to the thermal load controller. During the high load demand, the power purchased from the local grid station is mixed with renewable energy and supplied to the load centers, as expressed in Equation (5).

$$P^t_{Microgrid} \xrightarrow{\text{sup}} \begin{cases} P^t_{Load} \\ P^t_{grid} \\ P^t_{TLC} \end{cases} \tag{4}$$

$$P^t_{grid} \xrightarrow{deficit} P^t_{Microgrid} \tag{5}$$

The annual capacity shorted and the minimum renewable fraction of the developed system is expressed in Equations (6) and (7). $CP_{shortage}$ is the annual capacity shortage, while $RE_{fraction}$ is the minimum renewable energy fraction.

$$CP_{shortage} \leq 2\% \tag{6}$$

$$RE_{fraction} \geq 30\% \tag{7}$$

## 3. System Architecture

This section presents the system architecture and the connected components. With the purpose of optimally combining all the integrated sources and components, HOMER load following dispatch strategies were used. Figure 2 presents the model diagram of the developed energy system model, where all energy generation and consumption components are connected with the HOMER microgrid. Furthermore, the microgrid optimizes the power generation from the solar and wind systems and supplies required energy to the interconnected load centers. The figure shows that the microgrid is also connected with the local grid station for energy sharing. The two communities' load centers, Community 1 and Community 2, are connected with the system microgrid which supplies the electricity. Moreover, to meet the thermal energy demand of load centers, a natural gas-based boiler and thermal load controller are used. The maximum installed capacity of the solar PV system is 2500 kW, while the wind system installed capacity is 2640 kW.

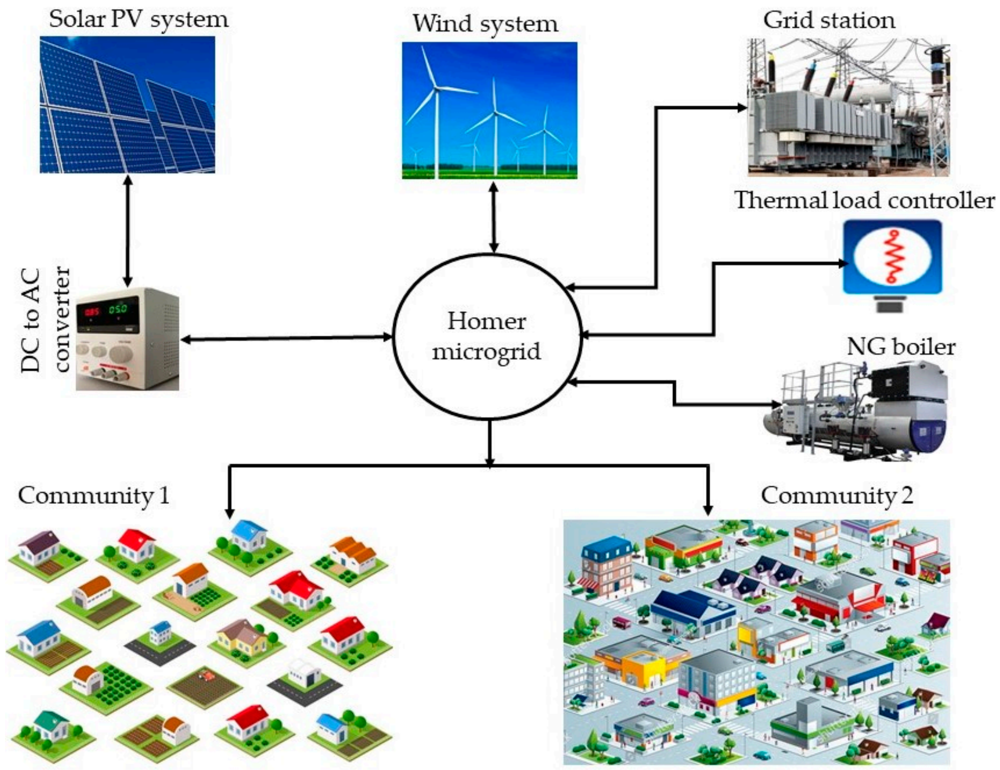


**Figure 2.** Schematic representation of developed energy system model.

Figure 3 shows the annual solar and wind resources at the selected location, through the solar global irradiance (W/m$^2$) and the wind speed (m/s).

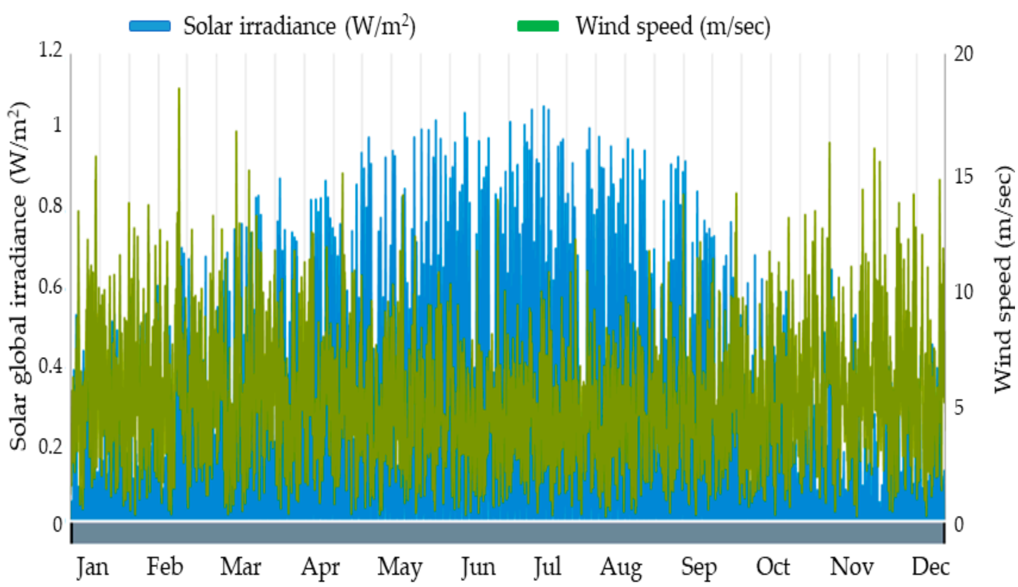


**Figure 3.** Solar and wind energy resources at the selected location.

The purpose of the developed energy system is to focus on small, distributed communities, and satisfy the energy demand by harnessing renewable energy from the solar and wind systems. Figure 4 illustrates the 24-h electrical and thermal energy demand of the two communities.

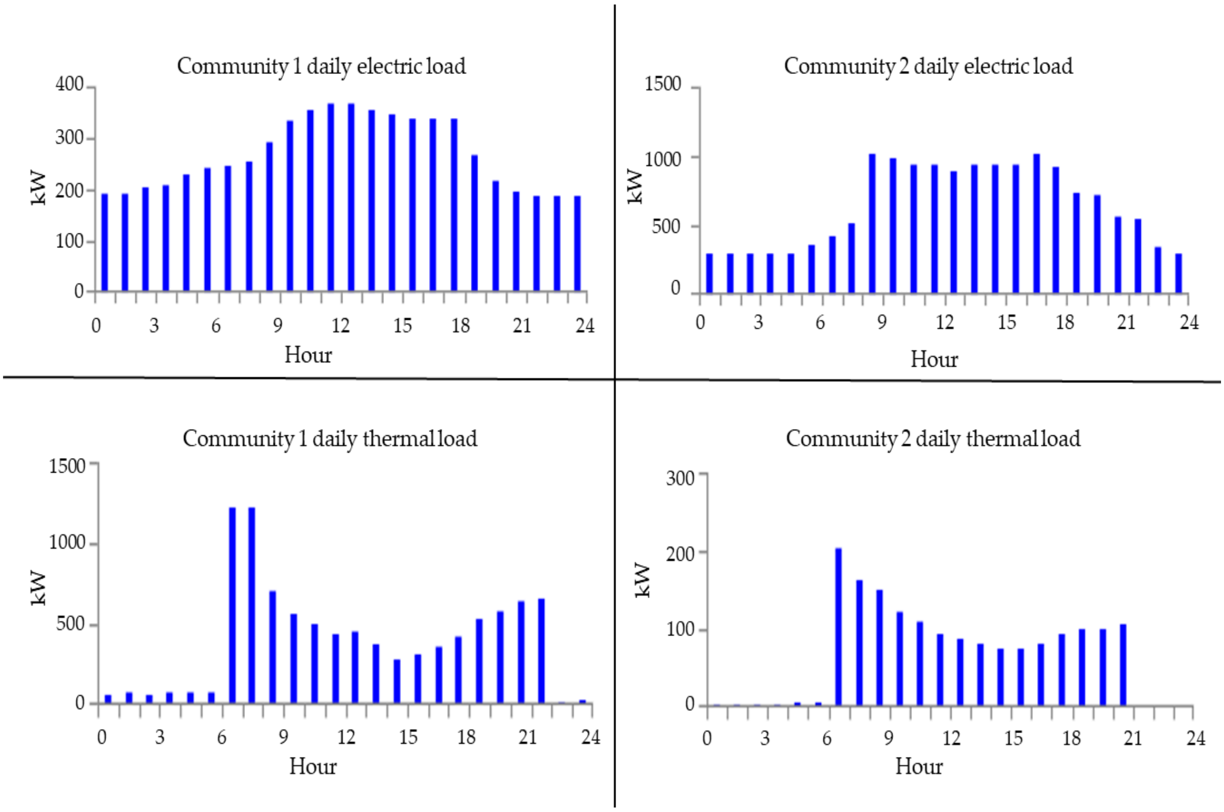


**Figure 4.** Daily electrical and thermal energy demand of distributed communities.

### 3.1. Wind System Model

Integration of wind power is a key part of this work. In the proposed optimized model, eight small commercial wind turbines are installed, with a hub height of 50 m. The power produced from wind turbines is expressed in Equation (8) [51]:

$$P = \frac{1}{2}\sigma A V^3 C_p(\lambda;\theta) \tag{8}$$

where $P$ is the aerodynamic power directly proportional to the air density $\sigma$, the speed of wind $V^3$, the area $A$ of rotor and the aerodynamic efficiency $C_p$. The aerodynamic efficiency $C_p(\lambda;\theta)$ depends upon the pitch blade angle $\theta$, and the tip speed ratio $\lambda$. Furthermore, Figure 5 shows the wind turbine power curve which describes the power generated (kW) as a function of the wind speed (m/s).

### 3.2. Solar System Model

In the analyzed system, the solar power is estimated by using a solar PV model developed by the National Renewable Energy laboratory [52,53] and expressed in Equation (9):

$$P_m^{PV} = x(\frac{R_m}{R_{stc}})[1 + \alpha_p(T_m - T_{stc}) \tag{9}$$

$R_m$ is the actual solar radiation intensity (W/m$^2$); $R_{stc}$ is solar radiation intensity under standard test conditions (1000 W/m$^2$), $T_{stc}$ is the temperature of the standard test conditions (25 °C), $T_m$ is the real temperature of the solar cell, and $\alpha_p$ is the temperature power coefficient for the solar cell module (−0.35%/°C). The output power of the inverter after the DC/AC conversion is expressed as follows [54]:

$$P_{AC} = P_{DC,stc} \times \eta_{inverter} \quad (10)$$

Equation (10) shows the estimated outpower of the inverter, where $P_{AC}$ is the output power of DC inverter (kW), $\eta_{inverter}$ is the conversion efficiency of the inverter, and $P_{DC,stc}$ is the rated DC power under STC (kW).

Figure 6 shows the operational curve of the solar PV cell. The maximum power is around 510 Wdc, the PTC value is about 480 Wdc and the temperature at NOCT is 45 °C at STC. The reference conditions for the cell temperature is 25 °C and total irradiance is 1000 W/m$^2$.

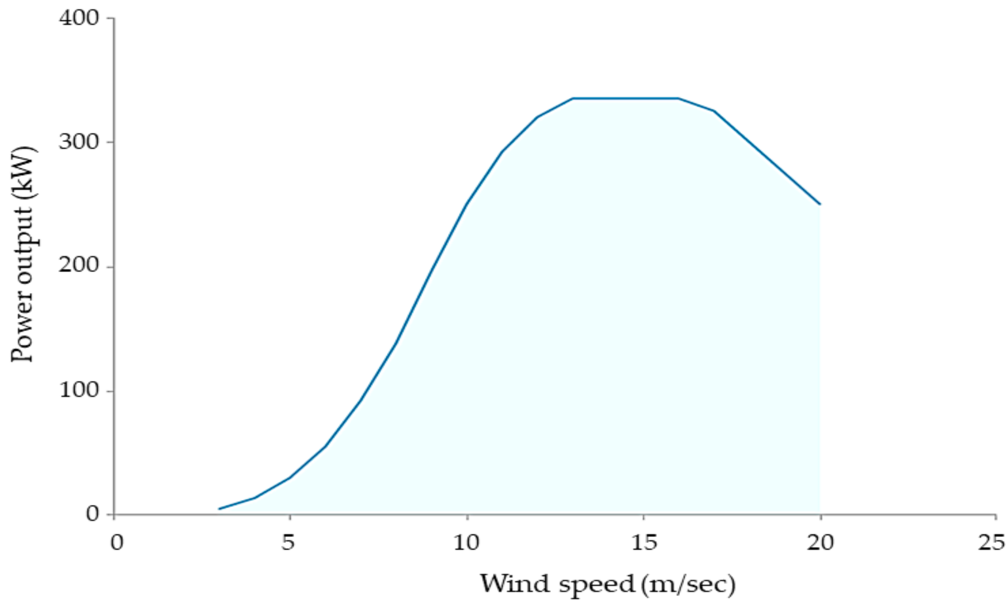


**Figure 5.** Power curve of the wind turbine vs. wind speed.

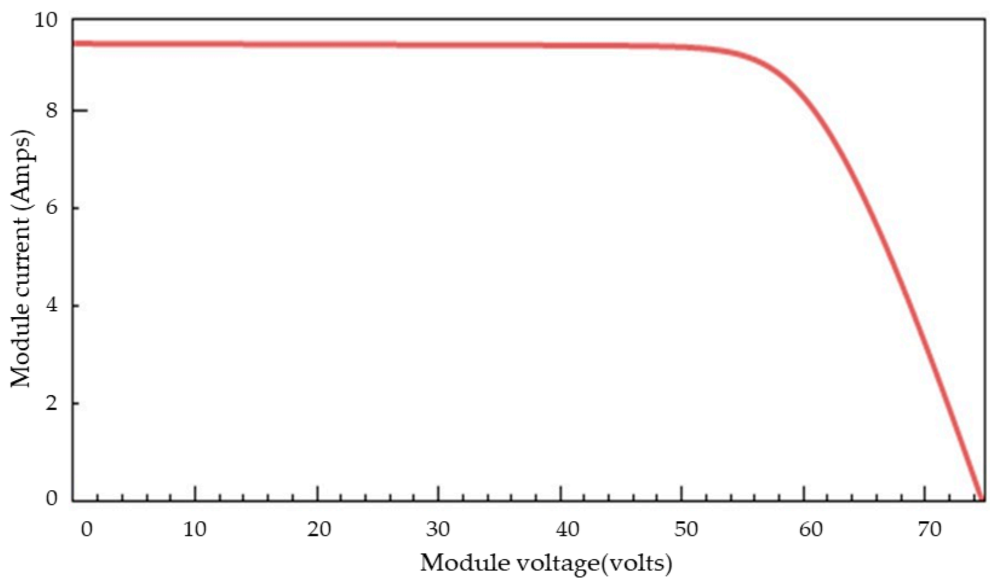


**Figure 6.** Solar cell current vs. voltage.

### 3.3. Economic and Environmental Analysis

This section explains the economic and environmental analysis of the proposed energy system. The economic assessment involves the comparison of the initial and final cost, the maintenance and operational costs of the system; the environmental assessment considers the $CO_2$ emissions reduction. Numerous research articles [55–57] presented the economic and environmental estimation of hybrid energy systems by determining the net present value (NPV), levelized cost of energy (LCOE), and operation and maintenance cost (O&M). The NPV of the proposed system is calculated by Equation (11):

$$NPV = \frac{Cashflow}{(1+i)^t} - I_{investment} \quad (11)$$

The NPV of the proposed system describes the potential profit generated by the system, where $i$ is the required rate of return, $t$ is the number of time periods, and $I_{investment}$ is the initial investment on the project. With the objective of determining the LCOE of the presented model, the system divides the annualized cost of producing electricity by the total electric load served (total annualized cost minus the cost of serving the thermal load) expressed in Equation (12):

$$LCOE = \frac{C_{ann,total} - C_{boiler}H_{served}}{E_{served}} \quad (12)$$

where $C_{ann,tot}$ is the total annualized cost of the system (€/Year), $C_{boiler}$ is the marginal cost of the boiler (€/kWh), $H_{served}$ is the total thermal load served while $E_{served}$ is the total electrical load served. Furthermore, the operating cost of the system is the annualized value of all costs and revenues other than initial capital costs estimated by Equation (13):

$$C_{operate} = C_{ann,tot} - C_{ann,cap} \quad (13)$$

$C_{ann,tot}$ is the total annualized cost of the system (€/Year), and $C_{ann,cap}$ the total annualized capital cost (€/Year). The total O&M cost of the proposed system is the sum of the O&M costs of each system component.

The environmental impact of the proposed system is evaluated by the reduction of $CO_2$ emissions, considering that the emission factor of thermal power plants in Italy is 367.3 $gCO_2$/kWh, according to the Italian Institute for Environment Protection and Research 2020 report [58,59]. The total clean energy produced by the proposed system is 10,197,929 kWh/year, which is estimated to reduce 4129 tons/year of $CO_2$.

## 4. Results

This section presents the obtained results of the proposed system. Tables 2 and 3 show the energetic scenarios of the system. Table 1 indicates that a significant amount of clean energy, estimated in about 10 GWh, is produced by the developed model during the first year of operation, covering a large portion of the energy demand of the distributed communities. Table 2 shows the total electricity load demand and the energy export to the grid station.

**Table 2.** Energy production from renewables and grid import.

| System | Energy Production kWh/year | % |
|---|---|---|
| Solar PV System | 3,714,797 | 29.0 |
| Wind Energy | 6,483,132 | 50.7 |
| Grid Purchases | 2,600,943 | 20.3 |
| Total | 12,798,873 | 100.0 |

**Table 3.** Energy demand and grid export.

| Consumptions | kWh/year | % |
|---|---|---|
| AC Primary Load | 8,446,003 | 67.0 |
| DC Primary Load | 0 | 0.0 |
| Grid Sales | 4,165,510 | 33.0 |
| Total | 12,611,513 | 100.0 |

Figure 7 shows the annual electricity and thermal load demand of the selected communities. Data indicate that, as expected, during the winter season, the thermal load demand increases, while in summer season, the electric load demand results higher.

Figure 8 indicates the monthly net energy generated by the solar PV and wind systems, and the energy imported from the local grid station. The given data describes that the energy produced by the renewable energy sources satisfies the 79% of the total electricity demand of both communities, while the remaining 21% of the electricity demand is given by the grid station.

Data presented in Table 4 illustrate the energetic scenarios of the solar PV system, highlighting the significant amount of energy produced by the solar PV system at the lowest levelized cost of energy. Results also indicate that the capacity factor and the PV penetration rate are significantly high, meaning that the system supplies a large amount of energy to the load centers. Moreover, Figure 9 presents the hourly solar power generation during the first year of operation.

**Table 4.** Description of the solar PV system model.

| Quantity | Value | Units |
|---|---|---|
| Rated Capacity | 2500 | kW |
| Mean Output | 424 | kW |
| Mean Output | 10,178 | kWh/d |
| Capacity Factor | 17.0 | % |
| Total Production | 3,714,797 | kWh/year |
| PV Penetration | 44.0 | % |
| Hours of Operation | 4374 | h/year |
| Levelized Cost | 0.00128 | €/kWh |

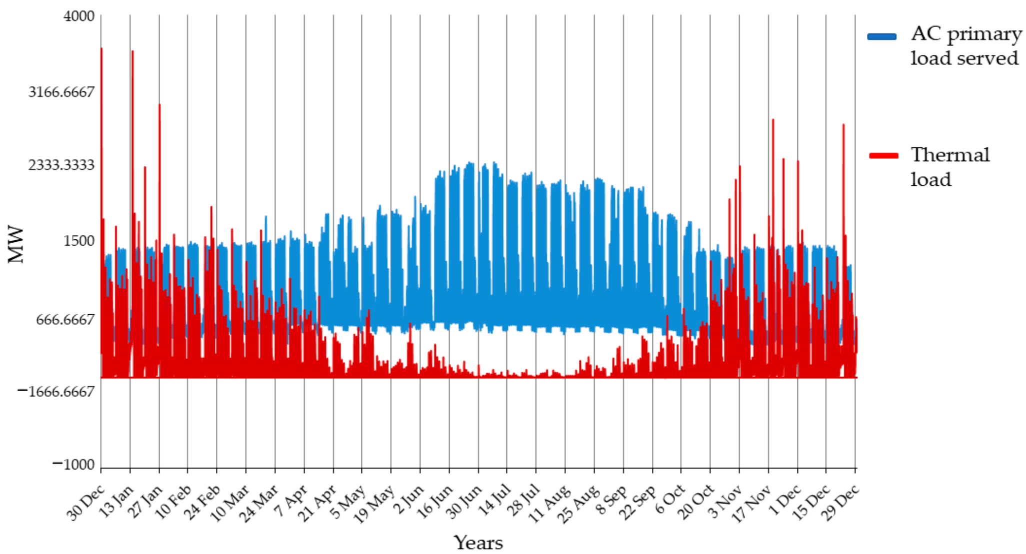


**Figure 7.** Electrical and thermal load of the selected communities.

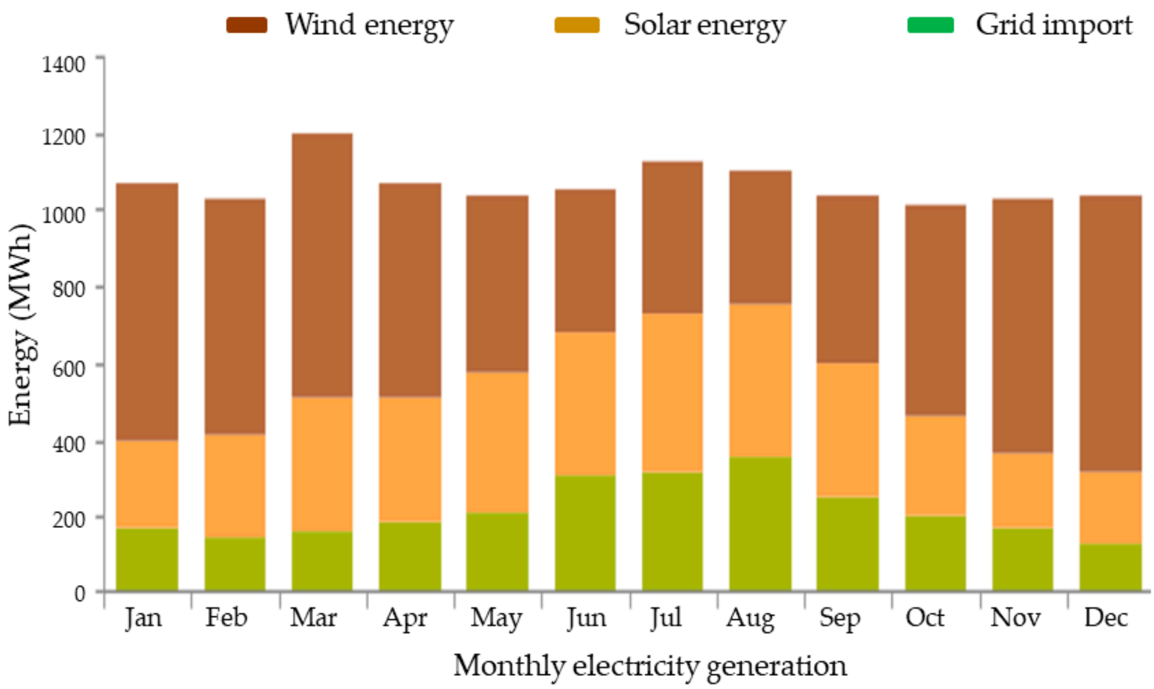


**Figure 8.** Monthly electricity production by renewable sources and grid imports.

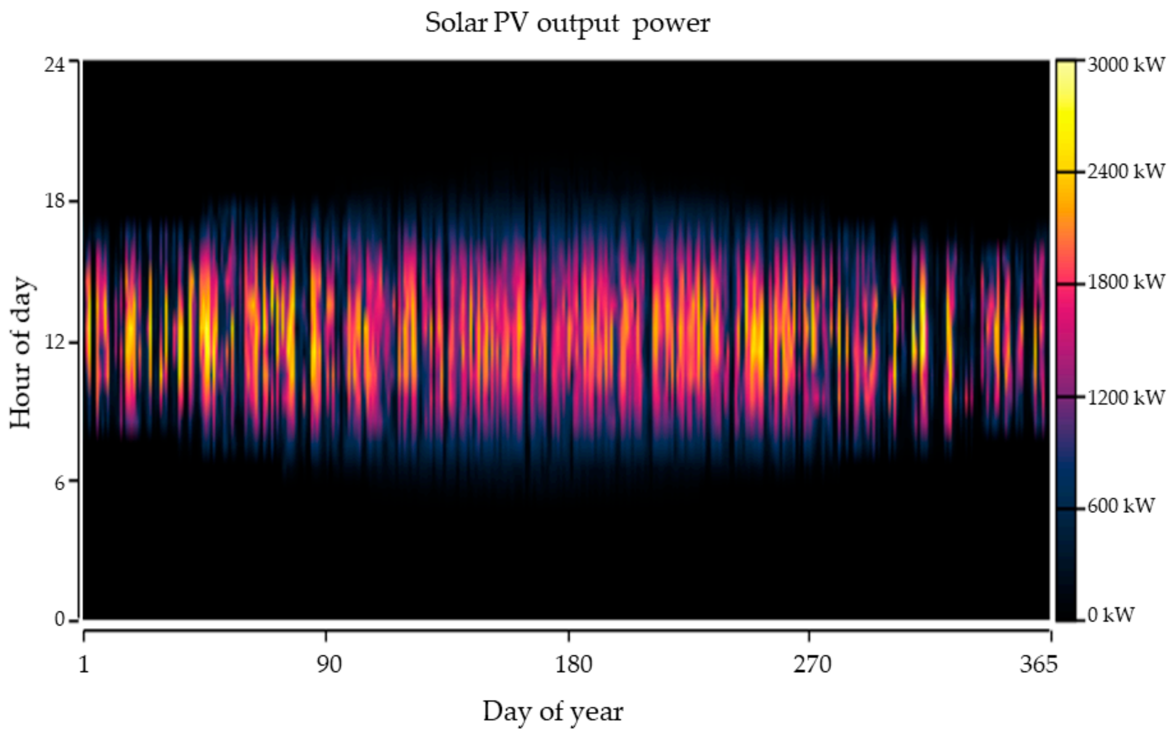


**Figure 9.** Annual electricity production by the solar PV system.

The results in Table 5 and Figure 10 show the operation and energetic analysis of the wind system. The power produced by the wind turbine is quite high and the penetration and capacity factor is also elevated. Figure 10 shows the hourly power generation by the wind system during the first year of operation.

**Table 5.** Characteristics and parameters of wind turbines.

| Quantity | Value | Units |
|---|---|---|
| Total Rated Capacity | 2640 | kW |
| Mean Output | 740 | kW |
| Capacity Factor | 28.0 | % |
| Total Production | 6,483,132 | kWh/year |
| Minimum Output | 0 | kW |
| Maximum Output | 2580 | kW |
| Wind Penetration | 76.8 | % |
| Hours of Operation | 7341 | h/year |
| Levelized Cost | 0.00167 | €/kWh |

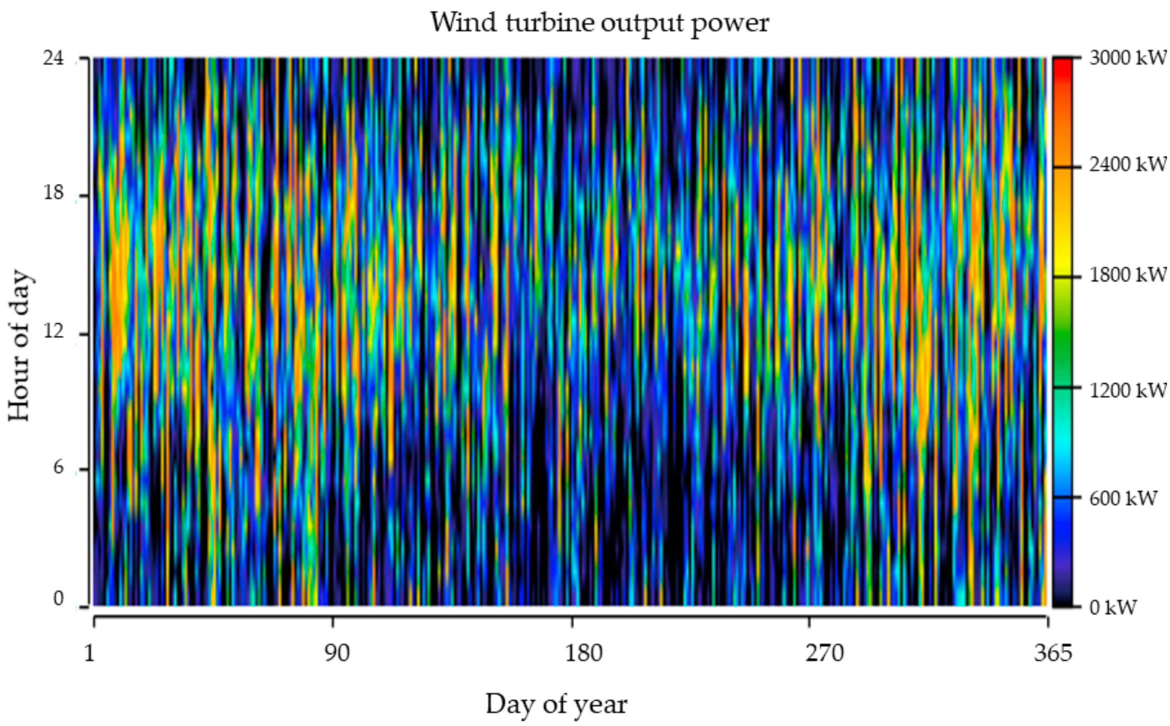


**Figure 10.** Annual electricity production by the wind system.

One of the core objectives of this research is to design a system that supplies thermal energy to the selected communities, also using the curtailed energy of renewable sources. A liquid gas propane-based boiler is integrated to meet the total heat energy demand (Table 6). Figure 11 presents the monthly thermal energy production for the first year of operation.

**Table 6.** Thermal energy demand and production.

| Production | kWh/year | % |
|---|---|---|
| Boiler | 1,288,115 | 99.9 |
| Thermal load controller | 1705 | 0.132 |
| Total | 1,289,819 | 100 |
| Excess thermal | 225 | 0.0174 |

The integration of the developed system with the local grid station increases the system reliability and flexibility. Data reported in Table 6 show that during the period of high energy production, the surplus energy is transferred to the grid station at the flat-rate tariff, while during the energy deficit period, energy is imported from the local grid station to meet the load demand. Table 7 indicates the monthly energy imports and exports during the first year of operation. Furthermore, Table 8 lists the greenhouse gas emissions during the operation of the system.

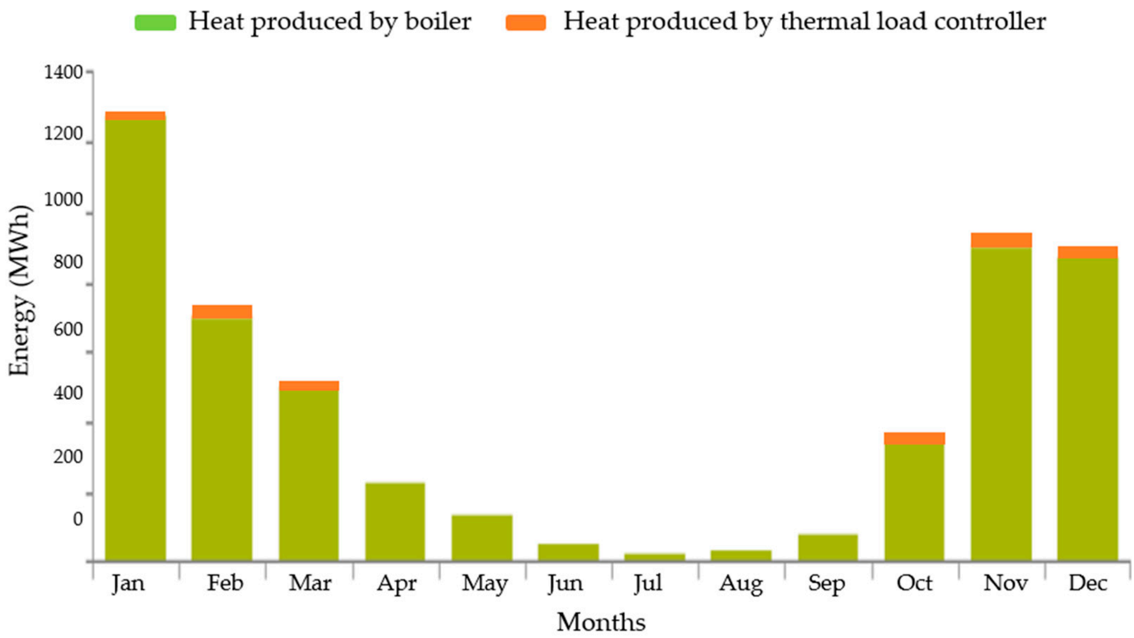


**Figure 11.** Annual thermal energy production by the system.

**Table 7.** Energy import and export with local grid station and peak load demand.

| Quantity | Energy Import (kWh) | Energy Export (kWh) | Peak Load (kW) |
|---|---|---|---|
| January | 171,199 | 455,752 | 1330 |
| February | 144,537 | 436,012 | 1370 |
| March | 161,248 | 506,721 | 1352 |
| April | 187,251 | 376,420 | 1281 |
| May | 206,644 | 300,447 | 1599 |
| June | 305,434 | 186,604 | 2054 |
| July | 315,915 | 189,620 | 2127 |
| August | 359,084 | 187,552 | 1898 |
| September | 249,184 | 266,851 | 1698 |
| October | 198,900 | 344,611 | 1532 |
| November | 168,773 | 451,427 | 1392 |
| December | 132,775 | 463,493 | 1183 |

**Table 8.** Greenhouse gas emission of the developed model.

| Quantity | Value | Units |
|---|---|---|
| Carbon Dioxide | 1,524,701 | kg/year |
| Carbon Monoxide | 0 | kg/year |
| Unburned Hydrocarbons | 0 | kg/year |
| Particulate Matter | 0 | kg/year |
| Sulfur Dioxide | 7904 | kg/year |
| Nitrogen Oxides | 3485 | kg/year |

As far as the economic analysis, Figures 12 and 13 describe the economic assessment which includes the capital cost, the operation and maintenance cost, the fuel cost, and the salvage values of the system are presented. Figure 12 illustrates the cash flow over the lifetime of the projects, where the results indicate the operational and maintenance cost, the replacement, and salvage values. Figure 13 shows the initial cost, the cost of used resources, and the annual operational costs.

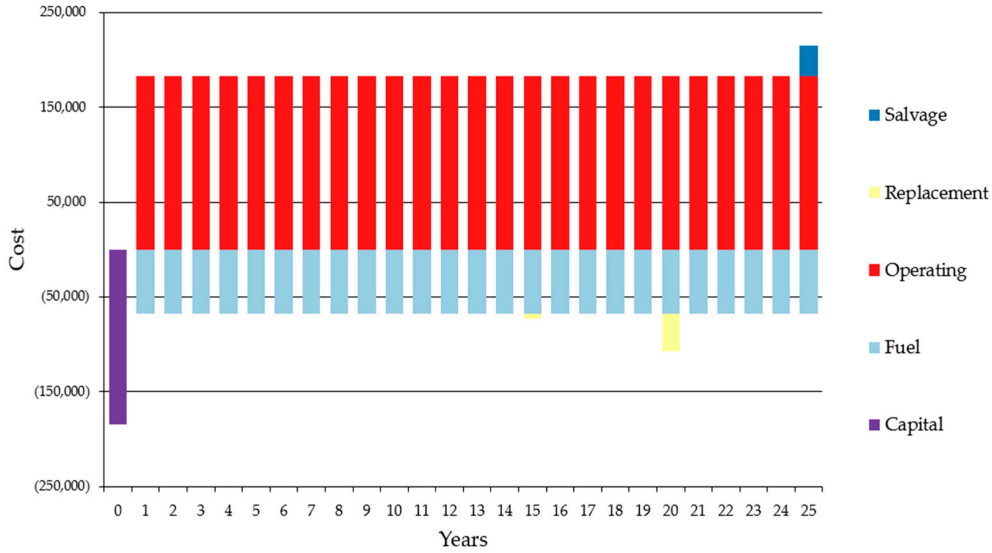


**Figure 12.** Economic analysis and cashflow of the developed system.

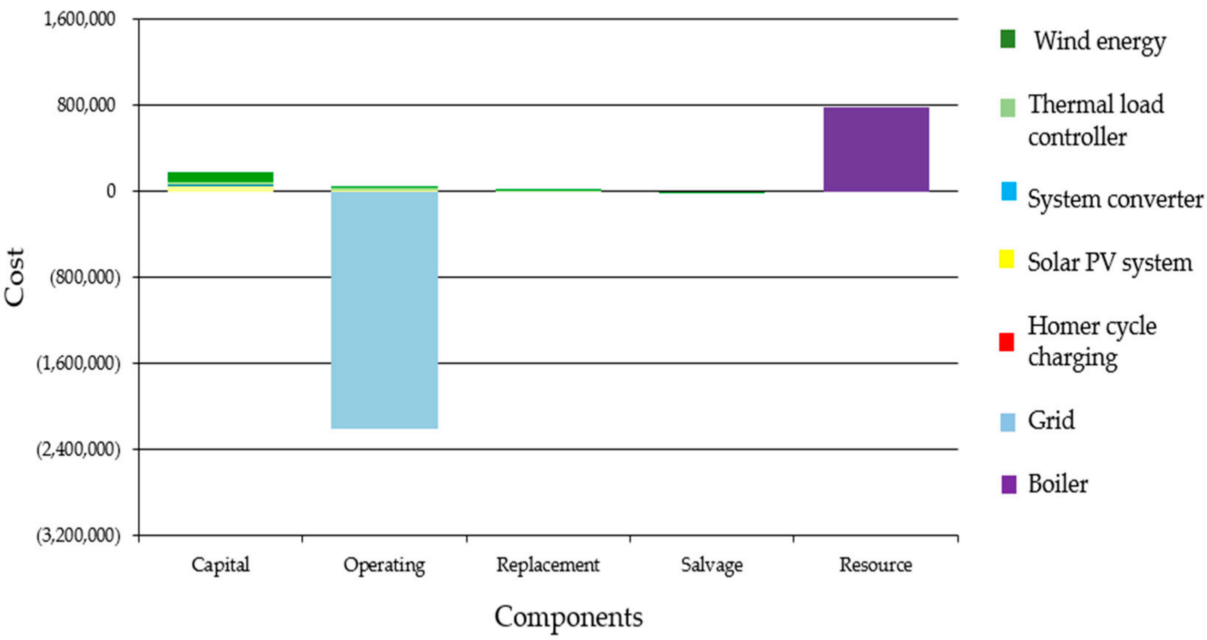


**Figure 13.** Total cost of proposed system and resources values of the project.

Table 9 shows the economic analysis of the developed system, showing that the levelized cost of energy is significantly low; the net present value and other economic indicators describe the benefits of the model. In comparison with the latest published articles presented in Table 1, this solution reduces the LCOE of the hybrid system (0.013€/kWh), especially for CHP systems. Articles [39–41] present LCOEs of 0.15 €/kWh, 0.57 €/kWh, and 0.08 €/kWh, respectively, while other works [42–45] presented LCOEs of 0.043 $/kWh, 0.22 $/kWh, 0.0543 $/kWh and 0.355 $/kWh, respectively.

Therefore, this research outcome would be highly applicable and beneficial for small-scale distributed communities, where both electricity and heat are required, because of its lowest cost of energy, marginal operation and maintenance, as well as lower $CO_2$ emissions, if compared to conventional power systems.

**Table 9.** Economic values of proposed system.

| Quantity | Value |
|---|---|
| Net present value | € 1,168,842 |
| LCOE | € 0.013/kWh |
| Operating cost | € 115,364 |
| Discount rate | 8.0% |
| Annual capacity shortage | 2.0% |
| Project lifetime | 25 years |

## 5. Conclusions

The main focus of this study is to accelerate the energy transition and identify the applicability and influence of renewable energy sources in the CHP system, especially for distributed communities. For this objective, this research work presented a combined heat and power system model and proposed a layout for a sustainable, socio-economic, and environmentally feasible energy management solution for small, distributed communities. This study fills the research gap in the existing literature and provides an alternative solution to meet the energy demand of small, distributed communities by producing energy from renewable energy-based CHP systems. Moreover, this study contributes to evaluate the economic and ecological impacts of new energy technologies, which is an effort to decarbonize the existing energy sectors. The design system integrates and optimizes the power produced by the solar PV and wind system and maximizes the total power generation, meeting the electric and thermal load demands of small communities. The obtained results show that the system produces a large amount of clean electricity: 10 GWh annually at 0.013 €/kWh levelized cost of energy. The optimal combined dispatch strategies and efficient resources management mutually increase the penetration and utilization of energy produced by the developed system, and the results show that 79.2% of the energy demand of selected communities can be satisfied by the proposed system. With the aim of improving its flexibility and reliability, the system is integrated with the local grid station for energy trading, and the results unveil a significant amount of energy exchanged between the system and the grid station. The environmental analysis estimates that a large amount of greenhouse gas emissions is reduced: 4129 tons of $CO_2$ each year. Moreover, the economic assessment of the proposed system indicates its economic feasibility, as it decreases the cost of energy. Moreover, this research work may support policy makers and investors to make decisions and understand the potential and prospects of new energy technologies. This study only encompasses the small-scale energy systems and it is limited to the small, distributed communities. In a future development, the model will be used for the realization of a large-scale energy system, integrating further renewable energy sources, and considering also other load sectors such as industrial, agricultural, and electric vehicle load centers, integrating also new energy storage technologies.

**Author Contributions:** All the authors made important contributions in the paper. E.G.: writing, conceptualization, and formulation of methodology. G.B.: formulation of methodology, review, proofreading, and supervision, P.B.: conceptualization review and proofreading. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Acknowledgments:** All authors highly acknowledge the Biomass Research Center, CIRIAF and University of Perugia for providing the facilities and support to conduct this research work.

**Conflicts of Interest:** The authors declare no conflict of interest.

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