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TECHNICAL AND FINANCIAL OPTIMIZATION OF AN AUTONOMOUS RENEWABLE POWER SYSTEM FOR A MEDIUM-SIZED DAIRY FARM

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ABSTRACT

This paper presents an analysis of the technical and financial feasibility of an autonomous stand-alone renewable power system configuration for a medium-sized dairy farm. In this study, photovoltaic (PV) modules, wind turbines (WTs), and PV/WT power systems were analyzed to determine the optimal system. HOMER software was used for this assessment process, and viability was determined according to the net present cost (NPC) and levelized cost of energy (COE). The NPC and the COE were found to be $500,291 and 0.265 $/kWh, respectively. According to the optimization results, a PV/battery system with 264 kW of PV arrays, 202 battery units, and a 28.6-kW converter was the optimal power system for the dairy farm. For the optimized system, the initial costs and operating costs were $363,077 and $7447, respectively. In addition, the proposed system reduced the NPC by $43,602 and $165,359 compared with the PV/WT and WT power systems, respectively. Finally, the payback period was calculated to be 4.40 years, and the internal rate of return was 14.4%, meaning that this system appears economically feasible.

KEYWORDS:
Stand-alone renewable energy, Optimization, Net present cost (NPC), Cost of energy (COE), HOMER, Dairy farm.

INTRODUCTION

In Turkey, the number of modern milk processing plants has increased in recent years. Significant high-tech investment has been made in the dairy-processing industry, particularly over the last decade. Most of the workforce on the approximately 1.16 million dairy farms in Turkey consists of family workers [1]. Cow milk is processed to produce drinking milk, cheese, yogurt, ayran (a drink made of yogurt and salt) and other dairy products like butter, kefir, milk cream, and ice cream [2].

The Turkish provinces that produce the most milk are Izmir, Balıkesir, Konya, Aydın, Canakkale, Denizli, and Burdur, all of which produce more than 300,000 tons of milk annually [3]. There are 529,402 small-scale ruminant production farms, which have an average number of cows per farm of 46.8 heads; 366,082 of these farms raise less than 50 head of cattle, while 163,320 farms raise more than 50. Given that over 50% of the dairy farms in Turkey have 10 cows or fewer, the average cost of production remains relatively high [4]. To compare, in the EU, large-size enterprises account for 83% of total dairy production. From this, it is clear that the size of the dairy farming units in Turkey is very small. To improve the dairy industry, economies of scale need to be strengthened.

Data from the Turkish Statistical Institute (TURKSTAT) show that the total number of cattle in 2018 was 17,220,903; 48.89% of these were pure-bred, 40.82% were cross-bred, and 9.25% were domestic breeds. The number of milking cows was reported to be 6,413,789 in 2018, yielding 20,112,619 tons of milk [5]. In the province of Burdur, there are around 16,000 active livestock farms, and 378,935 tons of raw milk are produced yearly. This accounts for 1% of the total number of cattle in Turkey and 1.88% of the milk production. The district of Tefenni had 4690 dairy cows in 2018, which represented 5% of the dairy cattle in Burdur, with 92.60% of these pure-bred; 6.44% cross-bred, and 0.96% domestic breeds [5]. In Tefenni, 85% of the labor force is employed in the agriculture and livestock industry, and there are around 1450 livestock farms. Milk production in Tefenni was reported to reach 18,025 tons in 2018, representing 5% of the total milk production in Burdur [5].

Dairy farms today face challenges fueled by rapidly rising energy costs. Dairy farms use more energy than almost any other agricultural operation [6,7]. In generally, the highest energy consumption in a dairy farm (Figure 1) comes from milk cooling, ventilating, and milking [8, 9]. Regulating the energy efficiency of dairy farms would thus help to reduce energy costs and increase productivity and profitability [10].

It has been calculated that the energy per milk farm can be reduced to 180,000 kWh per year for farms of more than 100 cows and 61,000 kWh for fewer than 100 cows. The increase in oil and electricity prices and the increase in farm size further raise energy costs. The cost of energy for dairy farms is 2 to 3

times higher than for other agriculture enterprises. Electrical energy accounts for 37.9% of the total energy consumption on a dairy farm [11], and the average energy consumption is 87 kWh/t-year [12]. In Turkey, the annual specific electricity consumption on dairy farms is 114.14 kWh/ton milk and 741.32 kWh/cow [13]. Most of the energy is used for moving equipment, vehicles, cooling, and lighting.

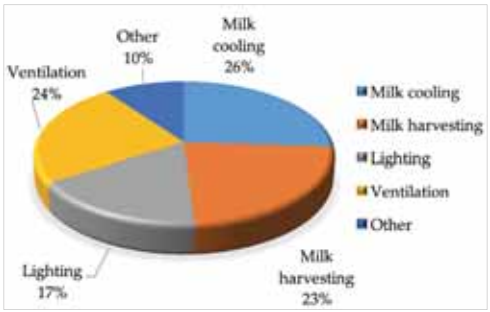


FIGURE 1
Dairy farm electrical energy consumption [8]

Ranchers and farmers are heavily dependent on the energy sector and are impacted by any changes it experiences [14]. Agriculture accounts for about 3% of the national primary energy consumption, with approximately 11% of this energy used in the form of electricity [9,15]. In recent years, energy production from renewable energy sources such as biogas, solar, and wind has become increasingly widespread on farms as a way to reduce energy costs and increase profitability [16]. In addition, autonomous renewable energy systems such as photovoltaic (PV) cells and wind have become a particular focus of research, and attempts have been made to develop these energy technologies for agricultural uses. For this reason, there is a need to understand the current status and future developments of renewable energy system configurations and to evaluate optimization strategies, system models, and performance.

The present study outlines the design process for the selection of components for a renewable hybrid energy system to provide electricity for a dairy farm (214 dairy cows) in Tefenni in Burdur Province, Turkey, and analyzes the economic feasibility of the design. HOMER Pro Version 3.11 [17] software is used to determine the most effective power system. HOMER simulates various system permutations and identifies potential solutions by ranking them based on their net present cost (NPC). In addition, it identifies the arrangement of components that both meets the specified electrical loads and minimizes costs [18].

MATERIALS AND METHODS

Site Description. In this study, the feasibility of a hybrid solar–wind energy techno-economic system in meeting the energy requirements of a medium-scale dairy farm is investigated in Tefenni in Burdur Province. Tefenni (37° 50'N, 29° 24'E) is a district and town in the Mediterranean region of Turkey (Figure 2) [19]. The average annual temperature in Tefenni is 11.7 °C, with an average annual rainfall of 515 mm. With an average temperature of 21.9 °C, July is the hottest month of the year, while January has the lowest average temperature (1.7 °C) [20]. Tefenni is considered to have a *Csb* climate according to the Köppen-Geiger climate classification (i.e., a warm-summer Mediterranean climate, with the coldest month averaging above 0 °C or −3 °C, all months averaging temperatures below 22 °C, and at least four months averaging above 10 °C) [20, 21]. Tefenni has the potential to meet the electricity demand [22] for dairy farm machinery using wind and solar energy.



FIGURE 2
Geographic location of Tefenni

HOMER Software. HOMER is a software application used to design and technically and financially evaluate the options for autonomous and grid-connected power systems for remote, stand-alone, and distributed generation applications [23]. The optimization and sensitivity analysis functions within HOMER allow the economic and technical feasibility of numerous technology options (i.e., wind turbines [WTs], PV modules, hydropower, biomass power, generators, fuel cells, batteries, and hydrogen storage) to be evaluated and to account for variation in technology costs, electricity load, and energy resource availability [24].

Assessment Criteria. The annual real interest rate was used as an input; it can be determined using the following equation [25]:

$$i = \frac{i_0 - f}{1 + f}, \quad (1)$$

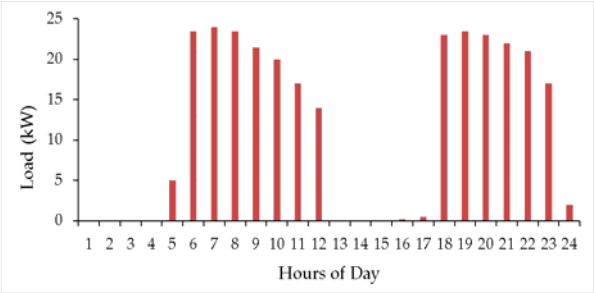


FIGURE 3
The daily load profile for the dairy farm

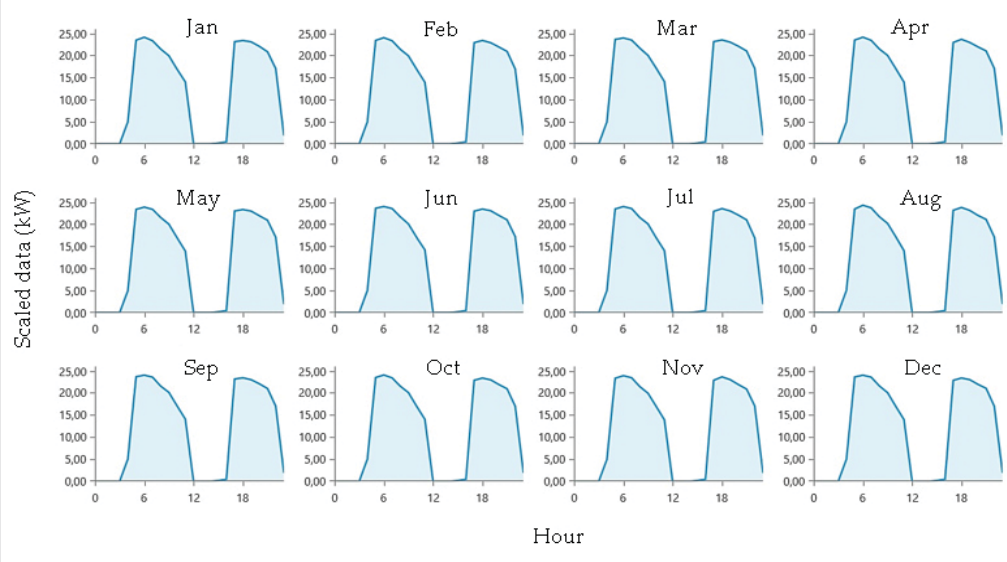


FIGURE 4
Scaled daily profile for the dairy farm

where i is the real interest rate, i_o is the nominal interest rate, and f is the annual inflation rate. For Turkey, i_o = 22.50% and f = 19.71% were used [26]. As a result, the real interest rate was calculated to be 2.33%.

Net Present Cost. The Net Present Cost (NPC) is calculated by summing the total discounted cash flow in each year of the project lifetime [27]. All systems were ranked according to the NPC, and all other economic outputs were calculated with the purpose of determining the NPC, which can be calculated using Equation (2) [28]:

$$NPC = \sum_{n=0}^{N} \frac{B_n}{(1+i)^n} - \sum_{n=0}^{N} \frac{C_n}{(1+i)^n} \quad (2)$$

where B_n is the expected benefit at the end of the year, C_n is the expected cost at the end of the year, i is the discount rate, n is the project duration in years, and N is the project period.

Salvage Value. The salvage value (S), which is the remaining value of the system components at the end of the project lifetime, is taken into consideration in NPC calculations [28]. The S can be determined by Equation (3):

$$S = C_{RC} \frac{T_{rem}}{T_{com}} \quad (3)$$

where C_{RC} is the cost of replacement ($), T_{rem} is the remaining life of the component (years), and T_{com} is the component lifetime (years).

Payback Period. The payback period (PBP) is the number of years until the energy savings from the PV system offsets the initial cost of investment. The more quickly the cost of an investment can be recovered, the more desirable the investment [29]. The PBP of a project depends on whether the cash flow for each time period is equal or not. If it is equal, the PBP [30] is calculated as follows:

$$PBP = \frac{Initial\ Cost\ (\$)}{Annual\ Production\ (kWh/year) \times (Value(\$/kWh) - O\&M(\$/year)} \quad (4)$$

Levelized Cost of Energy. The average cost of producing 1 kWh from a particular electricity generation system is defined as the levelized cost of energy (COE) and is calculated as follows [31]:

$$COE = \frac{C_{tot}}{E_{tot}}, \quad (5)$$

where C_{tot} is the annual cost of the system ($/year), and E_{tot} is the total electricity consumption per year (kWh/year).

Data Input. Load Profile. Electrical power usage and energy consumption by the farm equipment was obtained from monthly energy bills. The average daily energy demand for the dairy farm was about 280.70 kWh. HOMER software simulates the operation of a system by making hourly energy balance calculations over the course of a year [25]. Both day-to-day randomness and time-step-to-time-step randomness were assumed to be 2% in the present study. During the early hours of the day (00:00–04:00) and between 13:00 and 16:00, the power consumption was almost zero because the equipment was not in use. The load profile and scaled daily profile of the farm are presented in Figures 3 and 4, respectively.

Solar Energy. Climate data was referenced from the NASA climate database provided by HOMER. The software collects atmospheric information from ground monitoring stations and from NASA's worldwide satellite database. NASA climate data is based on 22 years of data collection. Solar radiation data for Tefenni obtained from NASA's website [32] are displayed in Figure 5. The annual solar clearness index averaged 0.569 and the daily radiation averaged 4.75 kWh/m^2/h [33].

Wind Energy. In wind-generated power systems, kinetic wind energy is converted into mechanical power by the turning of the turbine blade, which produces electricity in the shaft connected to the alternator [34]. Monthly average wind speed data over a 10-year period (July 1983 to June 1993) measured using an anemometer set 50 m above the land surface was obtained from the NASA database [32] based on the latitude and longitude of Tefenni. The average monthly wind speed for Tefenni is presented in Figure 6, showing that it ranged from 4.44 to 6.90 m/s. The peak wind speed occurred at 15:00 h over this 10-year period. For the present study, the diurnal pattern strength was set at 0.25, while the 1-h autocorrelation factor was 0.85 and the Weibull parameter (K) was 2 [35].

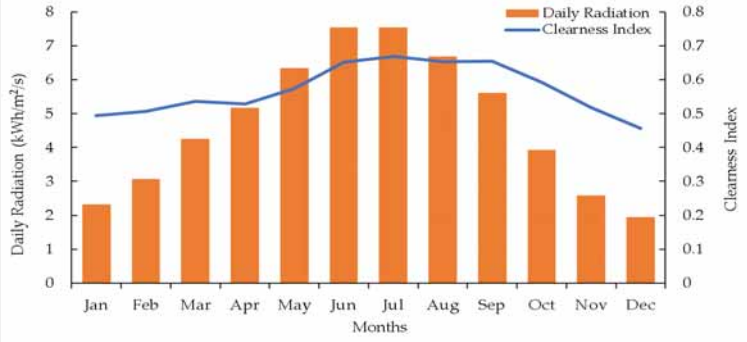


FIGURE 5
Monthly average solar global horizontal irradiance for Tefenni

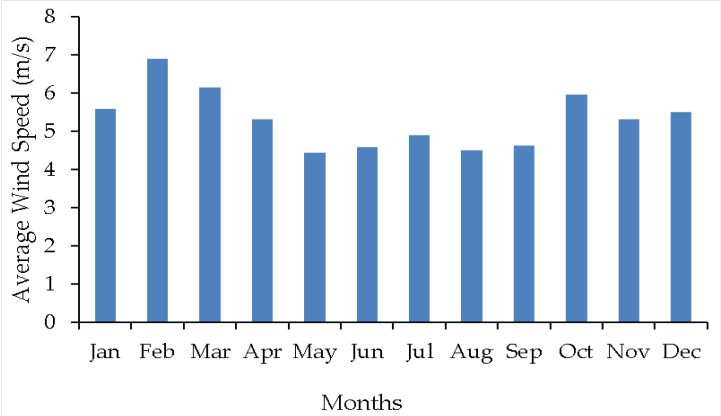


FIGURE 6
Monthly average wind speed data for Tefenni

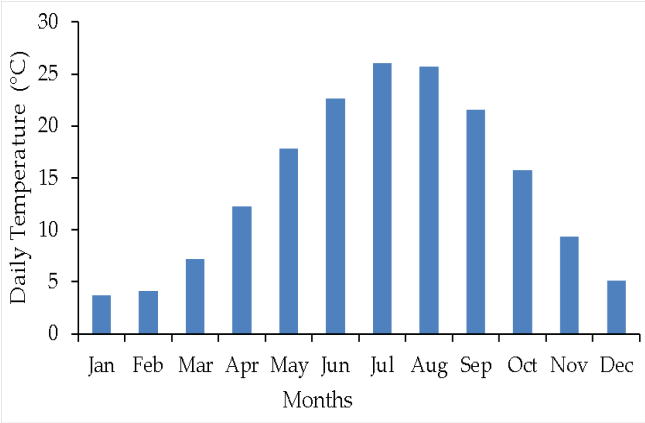


FIGURE 7
Monthly average temperature data for Tefenni

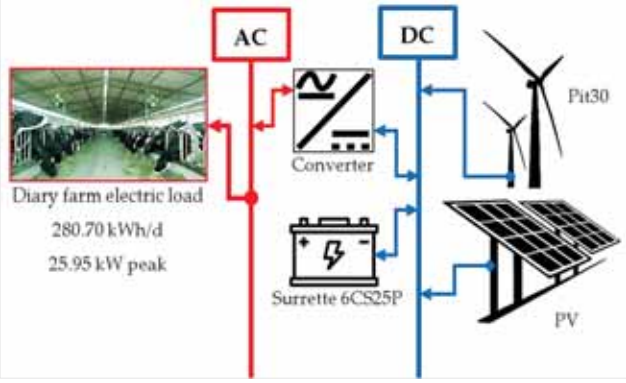


FIGURE 8
Configuration of the proposed autonomous stand-alone hybrid PV/WT system

TABLE 1
Technical data for the generic flat-plate photovoltaic (PV) module

Parameters	Value
Rated capacity	1 kW
Derating factor	80%
Nominal operating cell temperature	47.5 °C
Temperature coefficient	-0.5%/°C
Efficiency under standard test conditions	11.9%
Ground reflectance	20%
Tracking system	No tracking
Slope	37°
Azimuth	0°

Ambient Temperature. NASA temperature data [32] was also used in this study (Figure 7). The average annual temperature for the study location is 14.27 C (min. 3.72 °C, max. 26.08 °C).

System Components. In this study, the proposed autonomous stand-alone renewable energy system consists of four components: PV modules, WTs, a converter, and batteries. A schematic diagram of the energy system is presented in Figure 8.

Photovoltaic (PV) Modules. The model selected from the HOMER library was the generic flat-plate PV module with a generic lifetime of about 25 years. The installation costs were assumed to be 722 $/kW, which included the cost of the panel, wiring, and mounting hardware, the replacement costs were assumed to be 722 $/kW, and the operating and management (O&M) costs were assumed to be 10 $/kW. The technical specifications for the PV module are shown in Table 1.

The power output (P_{PV}) of the PV module is given by the following equation [36]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\dot{G}_T}{\dot{G}_{T,STC}} \right) [1 + \alpha_P (T_c - T_{c,STC})] \quad (6)$$

where Y_{PV} is the rated capacity of the PV array, which represents its power output (kW) under standard test conditions (STC), which are a radiation of 1 kW/m^2, a cell temperature of 25 °C, and no wind. f_{PV} is the PV derating factor (%), $\dot{G}_T$ is the solar radiation incident to the PV array at the current time step (kW/m^2), $\dot{G}_{T,STC}$ is the incident radiation at STC (1 kW/m^2), α_p is the temperature coefficient of power (%/°C), T_c is the PV cell temperature at the current time step (°C), and $T_{c,STC}$ is the PV cell temperature under STC (at 25 °C) [37].

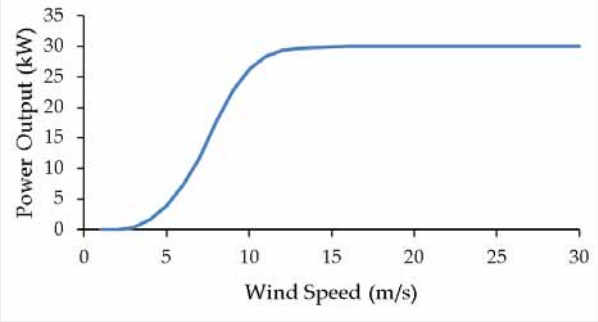


FIGURE 9
Wind turbine power curve

Wind Turbines (WTs). The Pitchwind 14m 30 kW (Pit30) [38] was selected as the WT in this study. The technical specifications for this WT are given in Table 2. The power curve in Figure 9 indicates the amount of power produced by the WT as a function of wind speed at hub height. The cost of this WT was set at $40,000 which included tower and installation costs, and the cost of replacing the generator was set at $35,000. Maintenance was assumed to be $400 per year.

TABLE 2
Technical specifications for the Pitchwind 14m 30 kW (Pit30) wind turbine (WT) [38]

Parameters	Value
Rotor diameter	14 m
Number of rotor blades	3
Cut-in wind speed	3 m/s
Cut-out wind speed	50 m/s
Nominal wind speed	16 m/s
Rated power	30 kW
Lifetime	20 years

TABLE 3
Technical specifications of the Surrette 6CS25P battery [40]

Parameters	Value
Battery model	Kinetic battery
Nominal voltage	6 V
Nominal capacity	6.91 kWh
Capacity	820 Ah
Maximum capacity	1150 Ah
Round trip efficiency	80%
Minimum state of charge	40%
Maximum charge current	279 A
Minimum storage life	4 years
Float life	12 years

Converter. Generally, electric machines on a farm run on alternating current (AC), but the power generated from the PV modules, WTs, and batteries is direct current (DC). Therefore, converters are needed to convert DC energy to AC energy. For this system, a converter with 1 kW of power and a 95% efficiency was selected. The capital cost per kW was estimated to be $420, while the replacement and the O&M costs were $420 and $7, respectively. The lifetime of this converter was set at 15 years [39].

Storage Battery. The battery model selected from the HOMER library was the Surrette 6CS25P, which has an efficiency of 80%. The initial cost was set at $1150, which included the cost of installation and power electronics, with replacement costs of $1000 per battery and O&M costs of 10 $/year. The technical specifications for the selected battery model are presented in Table 3.

RESULTS AND DISCUSSION

In this study, various combinations of the PV modules, WTs, converter, and battery described above were evaluated for a renewable power system. To determine the optimal power system design, a total of 149,072 simulations, 9317 optimization cases, and 16 sensitivity cases were analyzed using HOMER. To simulate the hybrid system, 8760 hours of actual hourly load data were collected [33]. This study hypothesized a project lifetime of 25 years.

Optimization Results. The simulated optimization results for the PV, PV/WT, and WT power systems are summarized in Table 4. The PV system with 264 kW of PV arrays, 202 battery units, and 28.6-kW converters was found to be the optimal power system for the farm. This system had an initial capital (IC) of $363,077, an annual operating cost (OC) of 7447 $/year, a total NPC of $500,291, and a COE of 0.265 $/kWh.

PV power reduced the NPC by $43,602 and $165,359 compared with the PV/WT and WT power systems respectively. The annual electricity production from the PV system was 410,293 kWh per year. The average monthly electricity production from the PV power system is shown in Figure 10. The highest electricity generation was between June and September because the solar radiation in this region is the highest at this time.

TABLE 4
The simulated optimization results for the proposed power systems

Power Systems	PV (kW)	WT (Pit30)	Battery (S6CS25P)	Converter (kW)	COE ($/kWh)	NPC ($)	OC ($/year)	IC ($)
PV	264	-	202	28.6	0.265	500,291	7447	363,077
PV/WT	265	1	194	29.3	0.288	543,893	8095	394,751
WT	-	7	170	28.6	0.353	665,650	9668	487,528

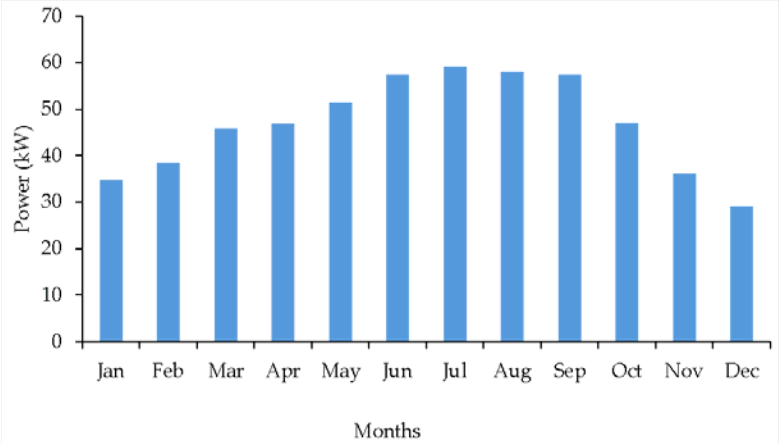


FIGURE 10
Average monthly electricity production for the PV power system

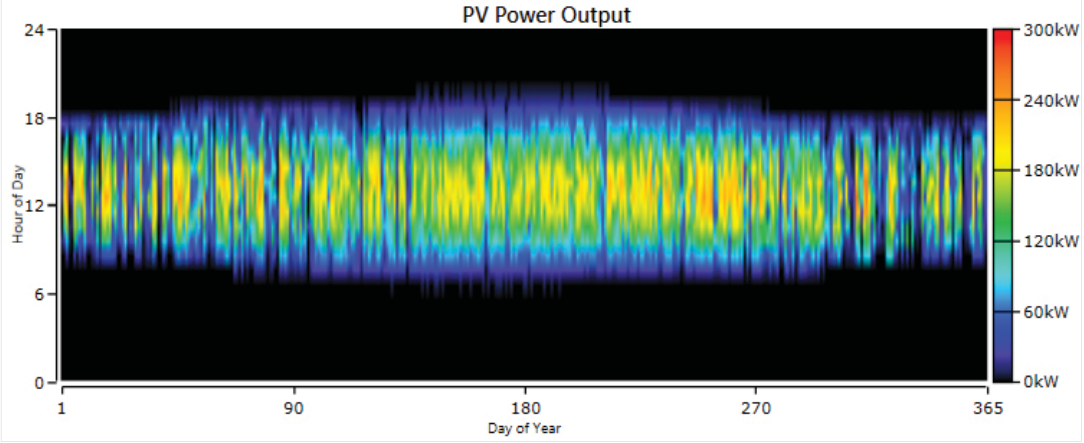


FIGURE 11
Generic flat-plate PV array output (kW)

The suggested optimal system produced an unmet electricity load of 49.6 kWh/year (0.05%), a capacity shortage of 102 kWh/year (0.1%), and excess electricity of 287,512 kWh/year (70.1%). On the other hand, the energy consumption of the AC primary load was 102,406 kWh/year. It is assumed that a DC load is not used in the proposed system. The excess electricity produced by the system always exists, which can then be reused [31]. The selected PV module array had a rated capacity of 264 kW and a capacity factor of 17.7%, resulting in a mean output of about 46.8 kW. Figure 11 presents the power output of the generic flat-plate PV model array, and Table 5 summarizes the statistics for the optimized energy system.

Economic Analysis. The cash flow of the components in the PV power system is shown in Figure 12. The capital, operating, replacement, and salvage costs are presented in Table 6, and economic descriptors of the system are summarized in Table 7.

TABLE 5
Statistics for the PV power system

Component	Quantity	Value	Units
Generic flat-plate PV array	Rated capacity	264	kW
	Mean output	46.8	kW
	Mean output	1124	kWh/d
	Capacity factor	17.7	%
	Total production	410,293	kWh/year
Converter	Capacity	28.6	kW
	Mean output	11.7	kW
	Minimum output	0	kW
	Maximum output	26.0	kW
	Capacity factor	40.9	%
Battery (Surrette 6CS25P)	Autonomy	71.6	h
	Storage wear cost	0.163	$/kWh
	Nominal capacity	1396	kWh
	Usable nominal capacity	837	kWh
	Lifetime throughput	1,380,638	kWh
	Expected life	20	year

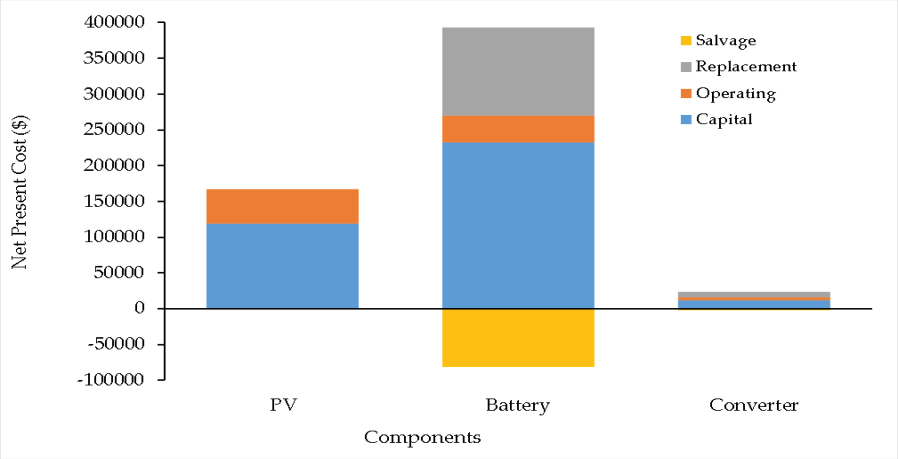


FIGURE 12
Cash flow of the components in the PV system

TABLE 6
Costs for the PV power system

Component	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)
PV Module	118,785	0	48,634	0	167,420
Battery	232,300	123,275	37,217	-81,718	311,074
Converter	11,991	8280	3682	-2156	21,797
System	363,077	131,554	89,534	-83,874	500,291

TABLE 7
Economic descriptors of the proposed system

Metric	Value
Present worth	$800
Annual worth	43 $/year
Return on investment	26%
Internal rate of return	14.4%
Simple payback	4.12 years
Discounted payback	4.40 years

The capital cost of the suggested power system was $363,077, with a replacement cost of $131,554, and an OC of $89,534. Figure 13 presents the NPC and COE in relation to the number of batteries.

The NPC increased from $500,291 to $1,122,439, and the COE also increased from 0.265 $/kWh to 0.595 $/kWh with an increase in the number of batteries from 264 to 792.

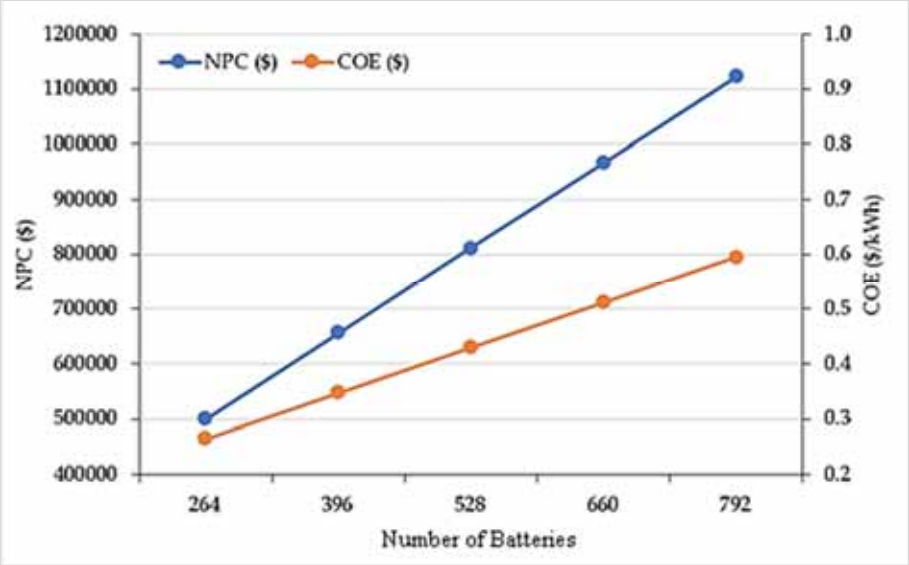


FIGURE 13
NPC and COE in relation to the number of batteries [22]

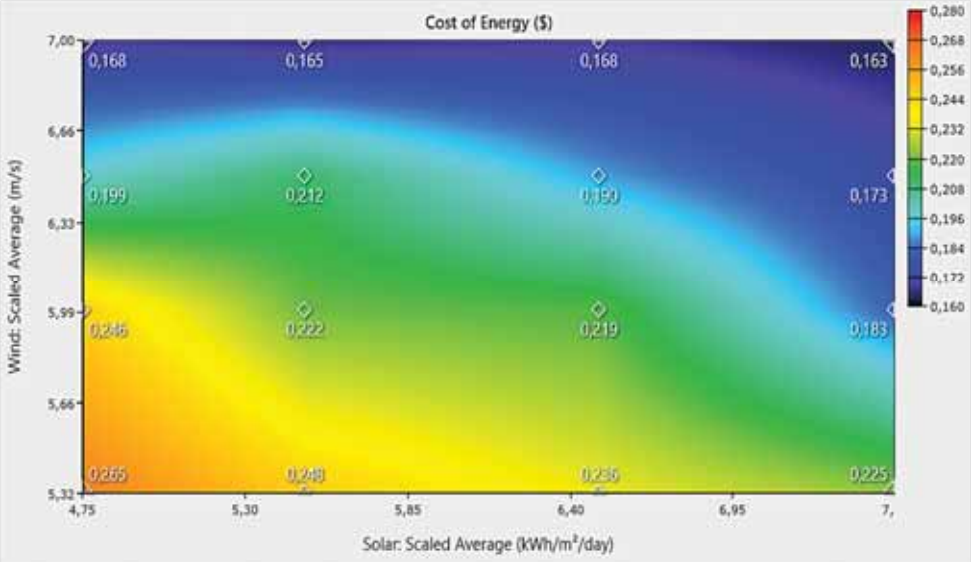


FIGURE 14
Surface plot of solar radiation intensity and wind speed for the optimal power system

Sensitivity Analysis. A sensitivity analysis was conducted to study the effect of variation in solar radiation intensity (4.75, 5.5, 6.5, and 7.5 kWh/m^2/day) and wind speed (5.32, 6.0, 6.5, and 7.0 m/s) on the COE of the optimal power system (Figure 14). Previous research has reported that the COE decreases with increasing wind speed and solar radiation [33]. Similarly, for the proposed system, the highest COE (0.265) was obtained at a solar radiation intensity of 4.75 kWh/m^2/day and a wind speed of 5.32 m/s, while the lowest COE (0.163) was obtained at a solar radiation intensity of 7.5 kWh/m^2/day and a wind speed of 7.0 m/s.

CONCLUSIONS

This paper presented the design process for the selection of components for a renewable hybrid energy system and conducted an economic analysis on the electricity generated for a dairy farm in the Tefenni district of Burdur, Turkey. In this study, PV, PV/WT, and WT power systems were analyzed to identify the optimal system. HOMER software was used for feasibility assessment, with the viability of the proposed system determined according to the NPC and the COE.

According to the simulation results, the autonomous PV power system was more cost-effective than the PV/WT and WT power systems. The PV system with 264 kW of PV arrays, 202 battery units, and 28.6-kW power converters was the optimal power system for the farm. The suggested optimal system was found to require an initial capital outlay of $363,077 and to have an annual OC of 7447 $/year, a total NPC of $500,291, and a COE of 0.265 $/kWh. The suggested system reduced the NPC by 8.72% and 33.00% compared with the PV/WT and WT power systems, respectively. A sensitivity analysis was also employed to study the effect of variation in solar radiation intensity (4.75, 5.5, 6.5, and 7.5 kWh/m^2/day) and wind speed (5.32, 6.0, 6.5, and 7.0 m/s) on the COE of the optimal power system. It was found that the COE decreased with increasing wind speed and increasing solar radiation.

According to the simulation results, the discounted PBP was 4.40 years, and the internal rate of return was 14.4%, thus this system appears feasible. The simulation indicates that installing this power generation system in this district would require high initial capital costs. Nevertheless, the system would significantly reduce overall costs in the long term.

The utilization of renewable sources of energy will reduce greenhouse gas emissions and also reduce the dependency on fossil fuels. If farms employ this system, it will provide significant gains in the long term. Therefore, incentives should be increased to encourage the use of renewable energy resources in the agricultural industry.

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