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Techno-Economic Analysis of a Farm's Hybrid Energy System: The Case of Konya Rural

Bir Çiftliğin Hibrit Enerji Sisteminin Tekno-Ekonomik Analizi: Konya Kırsalı Örneği

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ABSTRACT

In this study, the optimum hybrid systems to meet the electrical and thermal load needs of a farm with a capacity of 100 cattle, off-grid, which is considered to be located in a rural part of Sarayköy District of Konya Province, Turkey, with PV/Wind/Biomass/Diesel energy sources have been investigated with HOMER-Pro software. The hybrid system will meet the electrical load of the barn and the farmhouse and the thermal load of the farmhouse and biogas unit. The heating energy requirement of the farmhouse has been calculated with the IZODER TS 825 thermal insulation program developed according to the Turkish Standards Institute Thermal Insulation Standard 2164. In determining the biogas unit's thermal load, the biogas reactor's heat energy requirement, which is sized according to the amount of waste material of the farm, has been taken into account. According to the results obtained depending on the meteorological characteristics of the examined region, it has been determined that a solar panel with a capacity of 0.213 kW, a wind turbine with a capacity of 9.6 kW, a biogas generator with a capacity of 10 kW, 4 lead-acid batteries with a capacity of 12V-67 Ah and a converter with a capacity of 0.465 kW must be present in the optimum hybrid system. In addition, it has been determined that the thermal load controller is very important in reducing CO2 emissions among the hybrid system components.

Keywords: Renewable energy, Hybrid energy systems, HOMER Pro software, Biomass, Biogas, Off-grid electricity.

ÖZET

Bu çalışmada, Konya İli Sarayköy İlçesi kırsal kesiminde yer alan 100 büyükbaş hayvan kapasiteli, şebekeden bağımsız bir çiftliğin, elektrik ve ısıl yük ihtiyacını karşılayacak optimum hibrit sistemler HOMER-Pro yazılımı ile PV/Rüzgar/Biyokütle/Dizel enerji kaynakları ele alınarak incelenmiştir. Hibrit sistem ahır ve çiftlik evinin elektrik yükünü, çiftlik evi ve biyogaz ünitesinin ısıl yükünü karşılayacaktır. Çiftlik evinin ısıtma enerjisi ihtiyacı, çiftliğin atık madde miktarı dikkate alınarak, Türk Standartları Enstitüsü Isı Yalıtım Standardı 2164'e göre geliştirilen İZODER TS 825 ısı yalıtım programı ile hesaplanmıştır. İncelenen bölgenin meteorolojik özelliklerine bağlı olarak elde edilen sonuçlara göre optimum hibrit sistemde 0,213 kW kapasiteli güneş paneli, 9,6 kW kapasiteli rüzgar türbini, 10 kW kapasiteli biyogaz jeneratörü, 12V-67 Ah kapasiteli 4 adet kurşun asitli akü ve 0,465 kW kapasiteli konvertör bulunmalıdır. Ayrıca hibrit sistem bileşenlerinden CO_2 emisyonlarının azaltılmasında, ısıl yük kontrolörünün çok önemli olduğu tespit edilmiştir.

Anahtar Kelimeler: Yenilenebilir enerji, Hibrit enerji sistemleri, HOMER Pro yazılımı, Biyokütle, Biyogaz, Şebekeden bağımsız elektrik.

1. INTRODUCTION

The interest in renewable energy sources is increasing since it is a well-known fact that fossil-based energy sources are limited in today's world. In particular, meeting the energy needs of the increasing population from fossil fuels causes environmental disasters such as global warming and climate changes. For this reason, in countries with clean and sustainable environmental policies, various incentives are applied to increase the interest in the use of renewable energy. Promoting renewable energy sources is a viable option to meet energy demand and reduce greenhouse gas (GHG) emissions (Das et al., 2021; Das et al., 2019). Since renewable energy sources do not show continuity, there is a need for systems created with several renewable energy sources or hybrid energy systems integrated with fossil-based energy sources.

The use of renewable energy sources not only reduces greenhouse gas emissions, but also enables active use of rural areas where there is no electricity grid (off-grid) and which are far from the city. Thus, the crowding of the increasing population in big cities can be prevented and fertile lands can be used for agriculture or animal husbandry. In this respect, researchers have been conducting many studies on renewable energy hybrid systems. Some of these studies have been examined in terms of the hybrid system, methodology, grid connection, performance parameters and selected region. According to Mandal et al. (2018), investigated the feasibility of an off-grid hybrid system created with a PV-Wind-Diesel-Battery system in the northern region of Bangladesh with HOMER Pro software. According to their findings, they reported that the unit cost of the energy to be obtained from the hybrid system would be \$0.37/kWh, and there would be a 67% reduction in CO_2 equivalent emissions compared to the grid-connected system. In a study by Khan et al. (2022), the situation of meeting an electrical load of 55.14 kWh/day, which is considered to be in a rural area in the north of India, with a hybrid renewable energy system created with solar photovoltaic and wind energy was examined. It was determined that the unit cost of the energy to be obtained from this system would be \$0.152/kWh, and the employment that would be created by the use of rural areas was discussed regarding its social aspects. In a study conducted by Shahsavari et al. (2022), the optimum energy cost of a hybrid system to be formed with PV, wind turbine, generator, battery and combined heat-power system to meet the electricity, heat and water needs of rural areas was investigated. They determined that the unit energy cost of this system to be established would be \$0.236/kWh, the combined heat-power unit would reduce the fuel consumption by 224 m3 per year and cause 58.4% less CO_2 emissions compared to a natural gas-fired system. Vendoti et al. (2021), investigated renewable hybrid systems with HOMER Pro software to meet the electricity load continuously and safely in an off-grid village in India. According to the results of their studies based on net present cost (NPC) and unit energy cost (COE), they reported that the most efficient system could be obtained with the combination of PV-Wind-Biomass-Biogas-Fuel cell. Cano et al. (2020), investigated the optimal configuration of a hybrid system consisting of off-grid photovoltaic energy, hydrokinetic turbine, biomass gasifier and battery group in the south of Ecuador. They stated that the hybrid system they examined met the demand. Singh et al. (2015), simulated and optimized the hybrid system consisting of PV, fuel cell, biomass gasifier generator and battery set for the MANIT energy center in Bhopal (India) using HOMER Pro software. With this system, they aimed to meet the maximum load demand of 101 kWh/day, 5 kW. According to the simulation results, they determined that the unit energy cost of the system to be installed with a 5 kW biomass gasifier, a 5 kW capacity fuel cell and a 5 kW capacity PV module which are connected to the AC bus, would be 15,064 Rs/kWh. Jahangir and Cheraghi (2020), investigated a hybrid renewable energy system consisting of photovoltaic panels, wind turbines and biogas generator for rural electrification in Fars province of Iran. As a result of their simulation and optimization, they determined that the most suitable system would be obtained with a biogas generator with a capacity of 105 kW, photovoltaic panels with a capacity of 80.7 kW, a battery pack and a converter. They determined that the unit cost of the energy to be obtained from this system would be \$0.128/kWh. In addition, in terms of environmental assessment, they determined that the CO_2 emission of the hybrid system would be negligible compared to a coal system, and with the presented approach, more than $8000 could be saved per year with CO_2 reduction. In a study by Ahmad et al. (2018), the techno-economic feasibility of a grid-connected hybrid microgrid system was carried out for residents of Kallar Kahar, near the city of Chakwal, Punjab province of Pakistan. It was stated that more than 50 MW of energy could be obtained from the hybrid system in which wind, PV and biomass energies were used, and in this case, the energy unit cost would be $0.057/kWh. As it can be understood from the literature studies examined, it can be seen that the use of hybrid energy systems is quite suitable not only for meeting the electricity load, especially in rural areas far from the grid, but it can also be seen that it exhibits very suitable results in terms of reducing the energy unit cost and emission values when used in grid-connected systems.

In this study, the optimization and simulation were investigated for the hybrid energy system to be established with Solar-Wind, Biomass and Diesel for a farm with 100 cattle capacity off-grid electricity, located in Sarayköy neighbourhood of Selçuklu district of Konya province of Turkey. A development project under the name of Konya Plain Project was published between 2021-2023 by Republic of Turkey Ministry of Industry and Technology for the region under consideration (Republic of Turkey, Ministry of Industry and Technology, 2021). The aim of the project is to bring the unused rural areas to the economy and social life with grants and incentives. The optimum renewable hybrid system models that will meet the electrical and thermal load needs of the farm (barn, renewable energy unit and caretaker's house) that are thought to be installed in the off-grid rural area for the examined region have been researched with HOMER Pro software.

The difference of this study from other studies in the literature, some of which were examined above, is the sizing of the biogas reactor suitable for the amount of biomass, the determination of the thermal load requirement of the reactor and the farm house according to the climatic characteristics of the region, and it is a comprehensive study that examines this determined thermal load and electrical load requirement with renewable energy cogeneration system models from a techno-economic and environmental analysis point of view.

2. MATERIALS AND METHODS

The farm that is planned to be established is the coordinates (37° 53.9'N, 32° 24.0'E) and sun, wind and temperature data are taken from NASA data integrated into HOMER Pro software. HOMER Pro software is a program developed by NREL (National Renewable Energy Laboratory, USA). This software is a tool that provides results that are very close to the real values used for techno-economic analysis of grid-connected or off-grid power systems and for optimum design, sizing and planning of hybrid renewable energy systems (Shahzad et al., 2017). After entering the required electrical and/or heating loads into the software, different hybrid system combinations are accessed, which are sorted according to the unit cost of energy (COE) and net present cost (NPC) values according to the selected components (Ghasemi et al., 2013).

The annual heat requirement of the caretaker's house, which is thought to be built in the farm to be established, is determined according to TSE (Turkish Standards Institute) 2164, TS 825, "Thermal Insulation Requirements for Buildings", the mandatory thermal insulation standard for buildings in Turkey (Turkish Standard Institute, 2008). IZODER TS 825 software was used to determine the heat requirement (IZODER TS 825, 2019). This software is a free software developed by the Association of Thermal Insulation, Waterproofing, Sound Insulation and Fireproofing in Turkey (Yeşildağ and Geliş, 2020). The software determines the heat requirement of the building through the thermal conductivity coefficient obtained according to the thickness and thermal conductivity values of each building element, taking into account the location of the building.

2.1. Examined system

The farm is 20 km away from the settlements, off-grid and has fertile pasture and grazing areas. It has been accepted that the farm has a barn with a capacity of 100 cattle with an area of 250 m^2, a 2-storey caretaker house with a gross area of 170 m^2, renewable energy sections and feed warehouses. With the energy to be obtained from the hybrid system, the electrical load of the house and barn and the heating energy of the house and biogas reactor will be met. The schematic representation of the examined system is given in Figure 1.

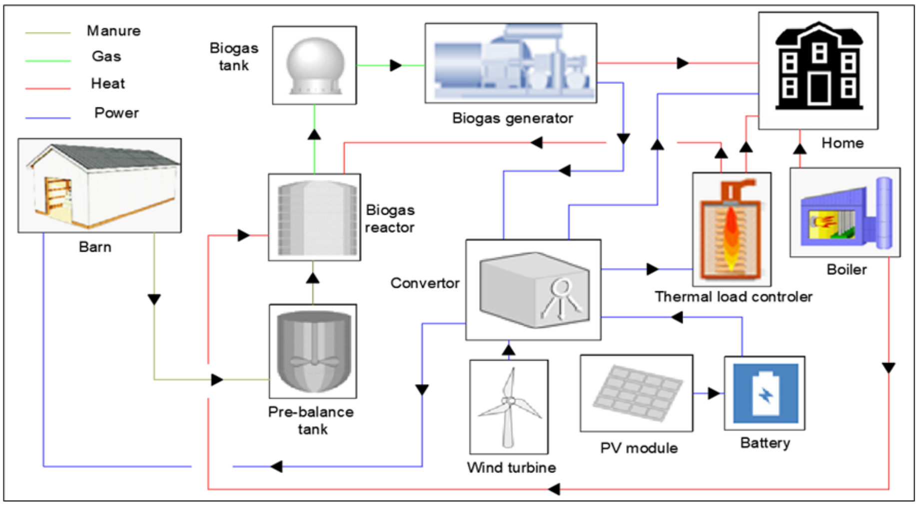


Figure 1. Schematic view of the examined hybrid energy system

2.2. Energy sources

2.2.1. Solar and wind energy potential

The region's solar energy data and wind speed profile data were obtained from NASA's database (NASA, 2023) integrated into the HOMER Pro software (HOMER Pro, 2023). The data on solar radiation is of 22 years between July 1983 and 2005, and the data on wind speed is the data obtained between January 1984 and December 2013, from a height of 50 m, as a result of 30 years of measurements. Accordingly, it has been determined that the average daily solar radiation potential for the year is 4.64 kWh/m^2, and the annual average wind speed potential is 4.76 m/s. In Figure 2, the monthly variation of the region's wind and solar energy potentials and the clearness index values are given. When Figure 2 is examined, it can be seen that although the solar energy potential of the region is high in summer, the wind energy potential is low, but both energy sources have complementary effects. In addition, it has been determined that the clearness index value, which gives the rate of solar radiation transmitted to the atmosphere by hitting the earth's surface, is higher in the summer months, and when it is examined in general, the monthly average value is 0.56.

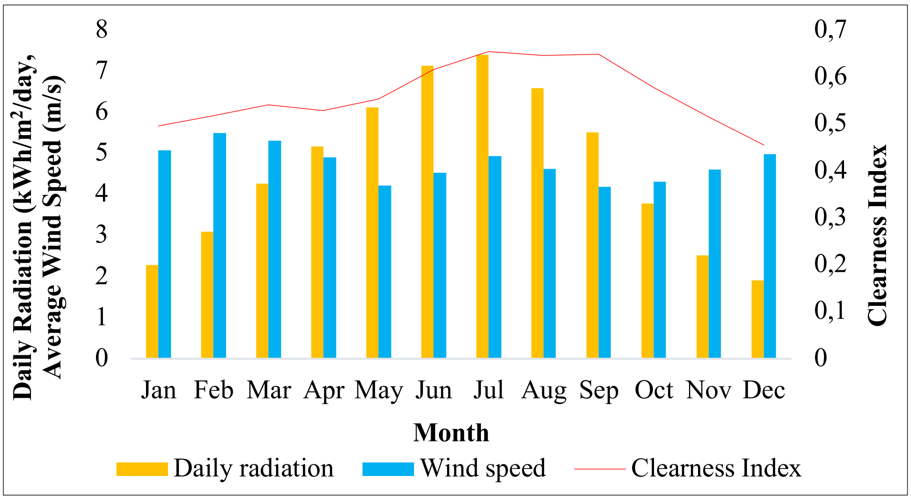


Figure 2. Change of monthly average solar - wind energy and clearness index values.

2.2.2 Biomass potential

It has been estimated that there will be 100 cattle animals with an average weight of 350 kg on the farm. Depending on the live mass of cattle, the amount of wet manure they can produce daily is between 5-10% of their mass (Özge, 2018). For this reason, it is assumed that each cattle will produce an average of 30 kg of waste. In this case, the amount of waste material was determined as 3 tons/day and this value was inputted to the HOMER Pro software as the biomass potential. In addition, it was assumed that the carbon content of the biogas was 5%, the gasification ratio was 0.70, and the lower heating value (LHV) was 5.50 MJ/kg.

2.2.3 Diesel fuel

In order to meet the thermal energy, need in the hybrid system that is planned to be established, the software requires the installation of a boiler. HOMER Pro software considers the boiler as a backup heat source that can serve any amount of thermal load as needed (HOMER boiler, 2023). For this reason, it has been accepted that the boiler added to the system operates with diesel fuel and is activated when the energy sources cannot meet the heat requirement.

2.3 The Loads of the System

2.3.1 Electrical load of the system

With the electrical energy to be provided from the hybrid system to be established, the electrical energy needs of the farm and the caretaker's house will be met. The loads determined for household and farm equipment are presented in Table 1.

Table 1. Daily electrical loads of house and farmhouse equipment (Eryaşar et al., 2016)

Equipment	Piece	Motor power (kW)	Installed power (kW)	Working hours (h/d)	Electricity consumption (kWh/d)
Electrical load of the house					
Refrigerator	1	0.2	0.2	24	4.8
Television	1	0.25	0.25	5	1.25
Computer	1	0.25	0.25	3	0.75
Iron	1	1.6	1.6	0.07	0.11
Bakery	1	1	1	0.07	0.07
Lighting	5	0.025	0.125	6	0.75
Washing machine	1	2	2	0.43	0.86

Equipment	Piece	Motor power (kW)	Installed power (kW)	Working hours (h/d)	Electricity consumption (kWh/d)
				Total	8.59
Electrical load of farm equipment					
Feed mixer	1	28	28	1	28
Feed crusher	1	3	3	1	3
Manure scraper	2	0.55	1.1	3	3.3
Manure pump	1	7.5	7.5	1	7.5
Manure mixer	1	11	11	1	11
Cattle brush	5	0.18	0.9	2	1.8
Lighting	5	0.1	0.5	3	1.5
Water pump	2	1.3	2.6	3	7.8
				Total	63.9

When determining the electrical load of the house, it is assumed that the oven and iron are used for half an hour once a week, and the washing machine is used for 1 hour and 3 times a week. In this case, the electrical load value of the house is calculated as 8.59 kWh/d and the load of the farm is calculated as 63.9 kWh/d. The electrical load of the house is entered as the primary load and the required load for the farm is entered as the deferrable load into the HOMER Pro software.

Considering the possible variations in the load values, it is assumed that the load value of the house is 9 kWh/d and the load of the farm is 65 kWh/d. In addition, considering that there is a need for heating, it is assumed that the energy need is seasonally higher in the winter months, and more energy is used for the house between 18:00 and 21:00 in daily use. In this case, the peak load value is determined 1.85 kW for the house and 14 kW for the farm by the software. Since the deferrable load profile is selected for the farm, the daily energy load is constant. A scaled sample load profile is used for the load distribution created for the house in the HOMER Pro software. The load profile of the house is given in Figure 3.

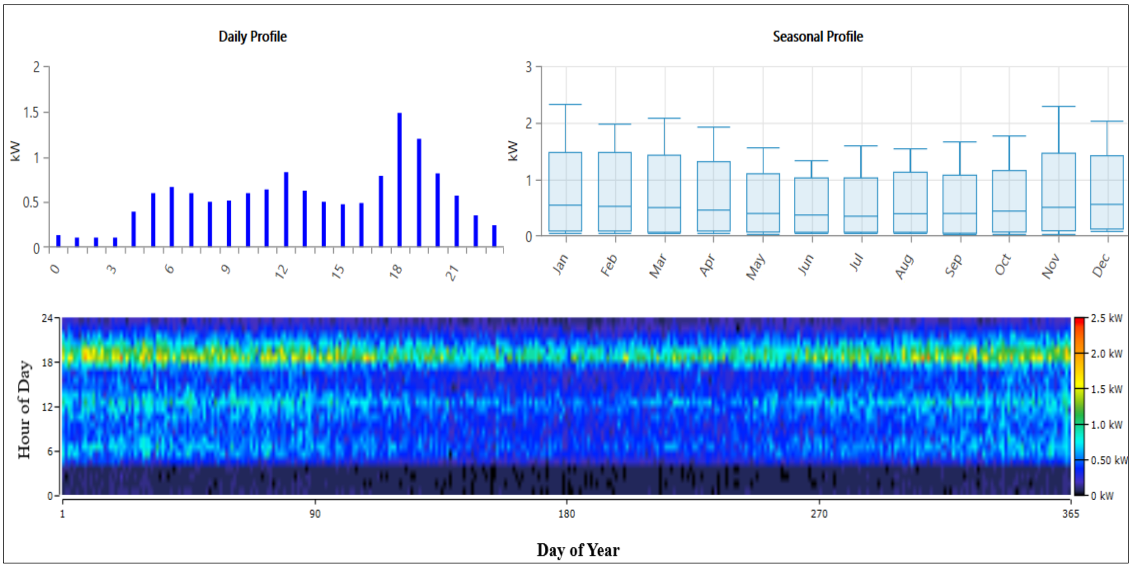


Figure 3. Variation of house electricity consumption over time

2.3.2. Thermal load of the house

The floor plan of the house, which is planned to be used as a caretaker's house on the farm, is given in Figure 4. It is assumed that the ground floor of the building will be 80 m^2 and the first floor will be 90 m^2. The heat requirement of the house was determined by the TS 825 thermal insulation calculation software designed according to the Turkish Standards Institute (TSE) 2164. Accordingly, the annual heating energy need of the building was obtained by subtracting the heat gains from the heat losses for each month (Eq. 1).

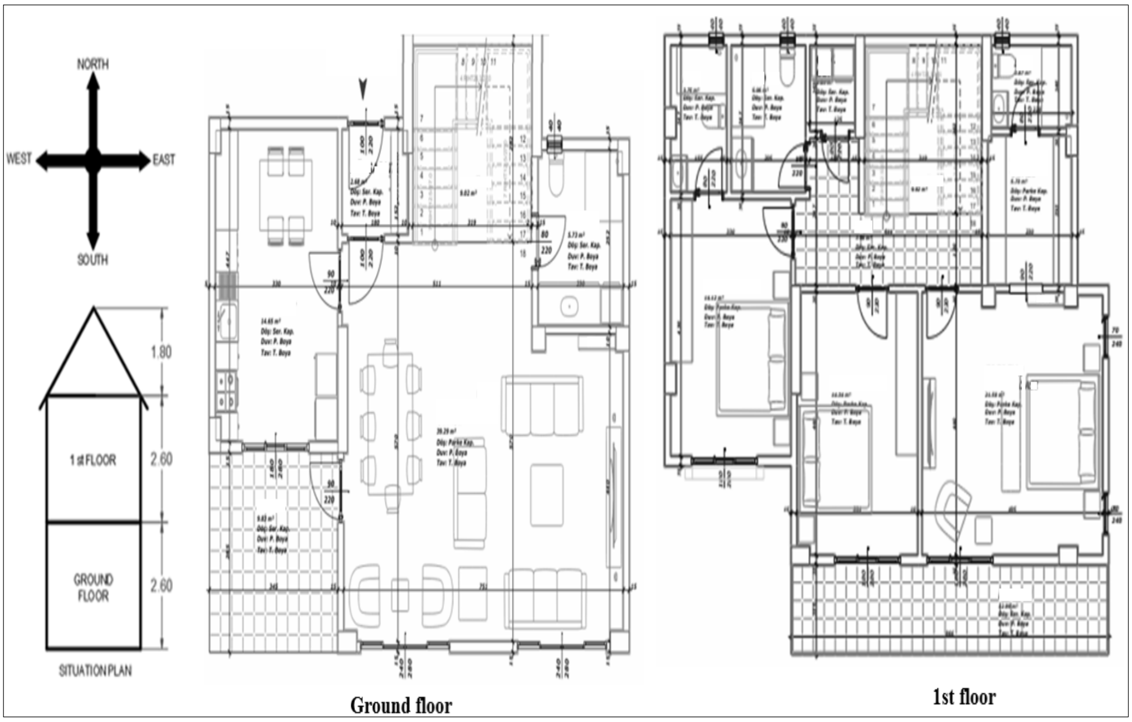


Figure 4. Floor plan of the exemplary architecture.

$$Q_{month} = \left[H(\theta_i - \theta_e) - \eta_{month}(\phi_{i,month} + \phi_{s,month})\right]t \quad (1)$$

The specific heat loss (H) of the building is obtained by summing the heat loss (HT) through conduction and convection and the heat loss (HV) through ventilation.

$$H = H_T + H_V \quad (2)$$

$$H_T = \sum AU + IU_I \quad (3)$$

In Equation 3, U is the total heat transfer coefficient (W/m^{2}K). I is thermal bridge length, and UI is the linear permeability of the thermal bridge (W/mK). The thermal bridge is the section where the composition is different compared to the adjacent surface, the heat loss is higher than the average heat loss of the building, and the interior surface temperature is lower for the steady state in winter. It is assumed that thermal bridges are not formed when insulation is made in accordance with the standards.

$$\sum AU = U_{ow}.A_{ow} + U_w.A_w + U_{od}.A_{od} + 0.8U_c.A_c + 0.5U_{ecf}.A_{ecf} + U_{ecw}.A_{ecf} + 0.5U_{ecbc}.A_{ecbc} \quad (4)$$

In Equation 4, the subscripts in the given formula are as follows: *ow* refers to outer walls, *w* refers to windows, *od* refers to outer door, *c* refers to ceiling, *ecf* refers to earth contact floor, *ecw* refers to earth contact wall, *ecbc* refers to earth contact building component. The heat loss through natural ventilation is calculated by Equation 5.

$$H_v = 0.33.\eta_h.V_h \quad (5)$$

In equation 5, η_h refers to air exchange rate (η_h =0.8 (h^{-1})), and V_h refers to the ventilated volume.

In buildings, heat gains occur as well as heat losses. For example, such heat gains are examined in two groups as monthly average internal gains from living metabolisms, lighting systems, various electrical devices, etc. ($\phi_{i,month}$), and as monthly average solar energy gains from as solar energy gains ($\phi_{s,month}$). The equation that calculates the monthly average internal gains for houses is provided in Equation 6, and the equation that calculates the average monthly gains from solar energy is provided in Equation 7.

$$(\phi_{i,month}) \leq 5xA_n \quad (6)$$

In Equation 6, A_n refers to the usage area of the building.

$$(\phi_{s,month}) = \sum r_{i,month}\, x g_{i,month} x I_{i,month} x A_i \quad (7)$$

In Equation 7, $r_{i,month}$ is the coefficient chosen according to the location of the building (0.8 for detached buildings), $g_{i,month}$ refers to the solar energy transmittance factor (0.75 for colorless insulating glass).

Internal gains and solar energy gains may not always be used as useful energy. For this reason, it is necessary to use the utilization factor (η_{month}) and the lost gains ratio (LGR_{month}). The formulas of these terms are given in Equations 8 and 9, respectively.

$$\eta_{month} = 1 - e^{(-1/LGR_{month})} \quad (8)$$

$$LGR_{month} = (\phi_{i,month} + \phi_{s,month})/H(\theta_{i,month} - \theta_{e,month}) \quad (9)$$

The thermal properties of the building elements constituting the sample building whose floor plan is given in Figure 4 are given in Table 2.

Table 2. Specific heat loss chart of the building.

Building element	Building element component	Thickness L (m)	Heat conduction coefficient λ (W/mK)	Thermal conductivity resistance R (m^2K/W)	Thermal conductivity coefficient U (W/m^2K)	Surface area A (m^2)	Heat loss (W/K)
Unreinforced exterior wall	Surface heat transfer coefficient (inner)			0.1300			
	Non-aggregate interior plaster	0.02	0.51	0.0392			
	Horizontal perforated brick wall	0.15	0.33	0.4545			
	XPS insulation material	0.03	0.03	1.000			
	Cementitious exterior plaster	0.03	1	0.030			
	Surface heat transfer coefficient (external)			0.040			
			Total	1.694	0.590	164.60	97.11
Reinforced exterior wall	Surface heat transfer coefficient (inner)			0.1300			
	Non-aggregate interior plaster	0.02	0.51	0.392			
	XPS insulation material	0.04	0.03	1.333			
	Reinforcement	0.25	2.5	0.100			
	Cementitious exterior plaster	0.03	1	0.030			
	Surface heat transfer coefficient (external)			0.040			
			Total	1.673	0.598	40.00	23.92
Attic story	Surface heat transfer coefficient (inner)			0.130			
	Cement mortar	0.03	1.6	0.018			
	Lime-cement mortar	0.03	1	0.030			
	Reinforcement	0.3	2.5	0.120			
	Heat insulation material	0.5	0.11	4.545			
	Cement mortar	0.03	1.6	0.018			
	Lime-cement mortar	0.03	1	0.030			
	Surface heat transfer coefficient (external)			0.080			
			(0.8 x A x U) Total	4.973	0.526	77.36	32.55
Ground contact foundation	Surface heat transfer coefficient (inner)			0.170			
	Granite	0.02	2.8	0.007			
	Cement mortar screed	0.02	1.4	0.014			
	Heat insulation material	0.02	0.035	0.067			

	Reinforcement	0.3	2.5	0.120			
	Pumice gravel	0.3	0.19	1.57			
	Sand, gravel, crushed stone	0.3	0.7	0.428			
	Surface heat transfer coefficient (external)			0.00			
(0.5 x A x U) Total				2.890	0.346	71.37	12.35
	Windows				2.4	30.88	74.11
	External door				4	2.4	9.6
Specific heat loss through conduction from building elements						Total	249.65

When Table 2 is examined, it is observed that the specific heat transfer from the building elements by conduction is 249.65 W/K. The specific heat transfer through ventilation has been determined as 201.38 W/K. In this case, the total specific heat transfer of the structure is determined as 451.03 W/K. As a result of the calculations, the table showing the monthly heating energy need of the building is given in Table 3.

Table 3. Monthly heat energy requirement of the building.

Months	Heat loss			Heat gains			LGR	Gain utilization factor	Monthly heating energy requirement (kJ)	Daily heating energy requirement (kWh)
	Specific heat loss (W/K)	Temperature difference (°C)	Heat losses (W)	Internal heat gains (W)	Solar energy gains (W)	Total (W)				
Jan	451.03	16.1	7262	1526	1006	2532	0.35	0.94	12653841	117.25
Feb		14.6	6585		1187	2713	0.41	0.91	10670067	98.87
Mar		11.7	5277		1262	2788	0.53	0.85	7536372	69.83
Apr		6.2	2796		1326	2852	1.02	0.62	2665577	24.7
May		1.0	451		1395	2921	6.48	0.0	0	0
Jun		0.0	0		1448	2974	0.0	0.0	0	0
Jul		0.0	0		1415	2941	0.0	0.0	0	0
Aug		0.0	0		1393	2919	0.0	0.0	0	0
Sep		0.0	0		1296	2822	0.0	0.0	0	0
Oct		4.9	2210		1165	2691	1.22	0.56	1823075	16.90
Nov		10.5	4736		939	2465	0.52	0.85	6845252	63.43
Dec		15.2	6856		892	2418	0.35	0.94	11879540	110.08

2.3.3. Biogas plant and thermal load

In this study, it is assumed that the biogas plant is a facility with continuous feed in the mesophilic temperature range of fermentation. The wastes obtained from 100 cattle animals with an average weight of 350 kg will be transferred to the pre-balancing pool with a waste scraper, and the solid matter amount will be brought to 10%. The waste will be sent into the reactor using a pump from the pre-balancing pool. The temperature inside the reactor is one of the main parameters affecting the biogas yield (Yadvika et al., 2004). It has been assumed that the average temperature in the reactor throughout the study will be 35°C. This temperature will be provided from the cogeneration system, thermal load controller and boiler (Figure 1). The gas obtained from the reactor will be stored in the gas storage tank. The gas storage tank is a tank with double membrane in the middle. Thanks to the air pressure created between the membranes, the produced biogas will be kept at a constant pressure. The obtained biogas will be sent to the cogeneration system. In order to calculate the thermal load requirement of the biogas plant, the reactor must be dimensioned. For this reason, the reactor has been dimensioned and thermal loads have been determined by using the assumptions and Equations given below.

Assuming that the density of the obtained waste is 720 kg/m^3, the amount of waste material is divided by the waste density, and the daily volumetric waste material amount is determined as 4.17 m^3/day. The total solids ratio of the wastes was assumed to be 15%. Accordingly, by taking 15% of the amount of waste material, the amount of solid matter was found to be 450 kg/day. It is assumed that the total solids ratio of the wastes in the reactor is 10%. In this case, the amount of water required for dilution of the waste was determined as 1500 kg/day (1.5m^3/day). By adding together, the volumetric waste amount and the volumetric amount of dilution water, the total volumetric waste amount was found to be 5.67 m^3/day. In addition, assuming that the total amount of volatile solids is 80%, the amount of usable volatile solids was determined as 360 kg/day. In the mesophilic zone, the holding period of cattle waste is in the range of 30-40 days (Eryaşar et al., 2016). In this study, the holding period was assumed to be 35 days. In this case, the usable reactor volume was determined as 198.45 m^3 by multiplying the volumetric solid waste amount and the holding time. When the reactor diameter is 8m, the height of the reactor was determined to be approximately 4m, and the reactor height was assumed to be 5m, taking into account the changes in the holding time or the amount of waste. The schematic representation of the reactor according to the data obtained is given in Figure 5.

The properties of the reactor and insulation materials, whose schematic representations are provided in Figure 5, are given in Table 4.

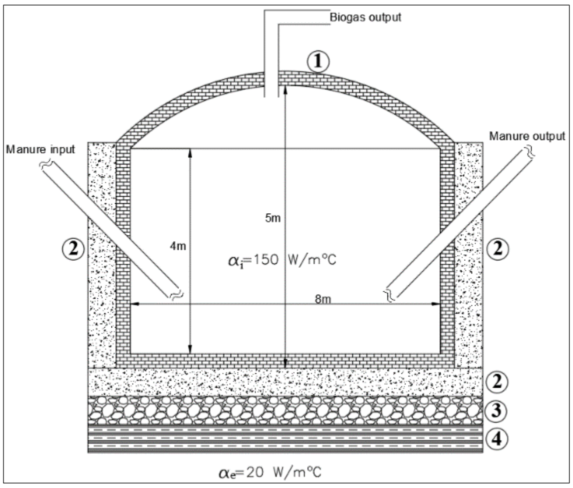


Figure 5. Schematic representation of the reactor.

Tablo 1. Characteristics of the components that make up the reactor

Number	Component	Thickness (m)	Heat conduction coefficient (W/m °C)
1	Reactor material (brick wall with bitumen coating)	0.20	0.190
2	Rock wool (heat insulation material)	0.15	0.035
3	Ceramic (floor material)	0.20	0.810
4	Concrete (ground material)	0.30	1.990

After obtaining the dimensions of the reactor and its components, the thermal load of the biogas plant was calculated with the help of the equations given below.

The thermal load of the biogas plant is calculated by adding the heat loss from the reactor surface (Q_s), the heat required to bring the feed material to the reactor temperature (Q_m), the heat loss from the biogas leaving the reactor (Q_g), the heat loss by evaporation (Q_e) and the heat required for the reaction (Q_c) (Eryaşar, 2016). In this case, the total heat requirement for the reactor facility is given in Equation 10.

$$Q_t = Q_s + Q_m + Q_g + Q_e + Q_c \tag{10}$$

Among these energies, Q_g, Q_e and Q_c have not been taken into account as they will have negligible values. The heat loss from the reactor surface (Q_s) was calculated using Equation 11.

$$Q_s = A\,.\,k_T.\Delta T \tag{11}$$

In Equation 11, A refers to total reactor surface area (m^2), k_T. is total heat transfer coefficient ($W/m^2{}^oC$), and ΔT refers to the difference between the reactor temperature and the ambient temperature (°C). The total heat transfer coefficient k_T is calculated by considering the thickness of the material layers on the reactor surface l_m (m) and the heat transmission coefficients of the materials λ_m ($W/m^2{}^oC$). The total heat transfer coefficient k_T was calculated using Equation 12 by using the heat transfer coefficient α_e (W/m^{2o}C) of the environment where the reactor is located and the heat transfer coefficient α_i (W/m^{2o}C) of the feed material inside the reactor.

$$\frac{1}{k_T} = \frac{1}{\alpha_i} + \frac{l_1}{\lambda_1} + \frac{l_2}{\lambda_2} + \frac{l_3}{\lambda_3} \dots + \frac{l_n}{\lambda_n} + \frac{1}{\alpha_e} \quad (12)$$

Using Equation 13, the amount of heat required to bring the feed material to the fermentation temperature Q_m(W), the mass flow rate of the feed material $\dot{m}_m$ (kg/s), the specific heat of the feed material c_p (J/kg^{o}C) and the difference between the reactor temperature and the ambient temperature ΔT (^{o}C) can be calculated. For the temperature of the diluent water, the mass flow rate of the feed material is assumed 5670 kg/s, and the specific heat value is assumed 4200 J/kg^{o}C, and 1m underground temperature data are taken into account (Soil temperature, 2023).

$$Q_m = \dot{m}_m \,. c_p . \Delta T \quad (13)$$

The monthly average air temperatures (NASA, 2023) and diluent water temperatures (Soil temperature, 2023) used in the calculations and the thermal loads obtained are presented in Table 5.

Table 2. Monthly average air and feed material temperatures and required thermal loads

Months	Average air temperature (^{o}C)	Feed material temperature (^{o}C)	Heat load of the reactor (kWh)	Heat load of the feed material (kWh)	Heat load of the house (kWh)	Total heat load (kWh)
Jan	1.16	7.2	1.01	7.68	117.25	125.94
Feb	1.60	7.1	0.99	7.71	98.87	107.57
Mar	5.01	8.2	0.89	7.41	69.83	78.12
Apr	10.50	10.0	0.73	6.91	24.7	32.34
May	15.69	13.6	0.58	5.92	0	6.50
Jun	20.01	18.5	0.45	4.56	0	5.01
Jul	23.50	20.6	0.34	3.98	0	4.32
Aug	22.94	21.8	0.36	3.65	0	4.01
Sep	19.21	21.1	0.47	3.84	0	4.31
Oct	13.57	18.6	0.64	4.53	16.90	22.07
Nov	6.88	15.1	0.84	5.50	63.43	69.77
Dec	2.45	11.0	0.97	6.63	110.08	117.68

2.4. Components of the Hybrid System

The required loads for the sample farm were determined with the help of the Equations given in subsection 2.3. Accordingly, the electrical load of the farmhouse was determined as 9 kWh/d, and the electrical load of the barn and biogas facility was determined as 65 kWh/d. The electrical load required for the barn and the biogas plant was accepted as a deferrable load during the day. As a result of entering the monthly total thermal load values (Table 5) required for the biogas plant and the house into the HOMER Pro software, it was determined that the scaled annual average thermal load value would be 48.13 kWh/d. The schematic representation of the hybrid system model that will meet these determined loads is given in Figure 6.

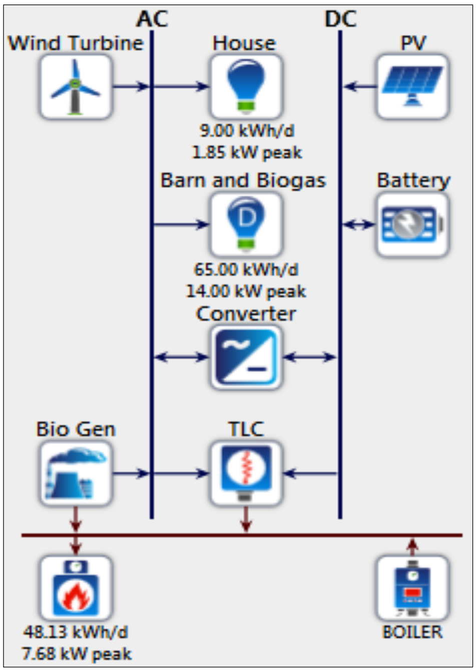


Figure 6. Schematic representation of the hybrid system

When Figure 6 is examined, it can be seen that the hybrid system consists of solar energy panels and a battery group connected to the direct current busbar, a wind turbine and a biogas generator connected to the alternating current bus. In addition to these, the system includes a converter that converts between AC and DC busbars, a thermal load controller that converts the excess electricity produced into thermal energy, and a boiler. The components that make up the system are introduced respectively.

2.4.1. Solar Panel

The solar panels used in the hybrid system are flat plate type CanadianSolar All-Black CS6K-290MS model mono-crystalline solar panels produced by Canadian Solar company (Solar panel, 2023). Technical specifications of solar panels are presented in Table 6. It is assumed that the initial installation and replacement cost of the panels per kW is 10,000 ₺, and the annual maintenance and repair costs are 50 ₺. The derating factor of the panels was taken as 88%. In the selection of the hybrid system, the alternatives of solar panels with a fixed-axis or dual-axis solar tracking system were investigated as different scenarios. In addition, MPPT (maximum power point tracking) device was also used in the system, which is used to charge the batteries at the most appropriate voltage and current values by monitoring the instant and variable energy production in the solar panels. The capacity of the MPPT device is determined by the HOMER software based on the converter load capacity. For 1 kW of the MPPT device, the initial installation and replacement cost is estimated to be 300 ₺ and the efficiency is 95%.

Table 3. Solar panel technical data

Nominal Maximum Power (W)	**290**	**Maximum System Voltage (V)**	**1000**
Optimum Operating Voltage (V)	32.10	Module Fire Performance	Type 1
Optimum Operating Current (A)	9.05	Max Series Fuse Rating (A)	15
Open Circuit Voltage (V)	39.30	Application Classification	Class A
Short Circuit Current (A)	9.67	Power Tolerance (W)	0 / +5
Module Efficiency	17.72	Operating Temperature (ºC)	-40 to +85

2.4.2. Battery

The batteries used in the hybrid system are BAE Secura PVS BLOCK Solar (Batteries, 2023) batteries selected from the HOMER Pro software. These batteries are lead-acid type batteries and their technical specifications are given in Table 7. The initial installation and replacement costs of the batteries are accepted as 5,000 ₺/piece.

Tablo 4. Technical data of batteries

Model	BAE SECURA SOLAR 12 V 1 PVS 70	Roundtrip efficiency (%)	85
Nominal Voltage (V)	12	Maximum charge current (A)	22.9
Nominal capacity (kWh)	0.804	Maximum discharge current (A)	122
Maximum capacity (Ah)	67	Maximum charge rate (A/Ah)	1
Capacity ratio	0.245	The initial state of charge (%)	100
Rate constant (1/hr)	2.09	Minimum state of charge (%)	20

2.4.3. Wind turbine

The Ennera Windera S model turbine produced by the Ennera company was chosen as the wind turbine (Wind turbine, 2023). It is assumed that the installation and replacement cost of the selected wind turbine is 4000 ₺, the maintenance cost is 100 ₺ and it works without loss. The technical specifications of the wind turbine are presented in Table 8.

Tablo 5. Wind turbine technical specifications

Model	Ennera Windera S 3.2	Sweep area (m^2)	14.9
Rated power (kW)	3.2	Number of blades	3
Cut-in wind speed (m/s)	3.0	Power density 1 (W/m^2)	214.3
Rated wind speed (m/s)	11.0	Power density 2 (W/m^2)	4.7
Cut-out wind speed (m/s)	25	Hub height (m)	12
Rotor diameter (m)	4.4	Maximum speed (U/min)	225.0

2.4.4. Converter

A power electronic converter is used to ensure the flow of AC and DC electrical energy in the system and to protect the system. It is assumed that the installation and replacement cost for 1 kW of the converter is 4000 TL.

2.4.5. Biogas generator

For 1 kW of the biogas generator used in the system, it has been assumed that the installation cost is 15,000 ₺, the replacement cost is 10,000 ₺ and the maintenance and repair cost is 0.029 ₺/op.hr. In the simulations, the minimum load ratio of the biogas generator was examined at two different values as 20% and 30%. The waste heat of the biogas generator will be used for the heat requirement of the house or reactor with the cogeneration system. For this, the heat recovery rate of the cogeneration system was taken as 15% and 20% and examined under two different scenarios. The HOMER Pro software was programmed to obtain the energy to be produced in the examined hybrid systems primarily from solar or wind energy sources. In our system, since more biogas energy is desired to be used, the working hours of the biogas generator are programmed in a way to forcefully work between 08:00 - 20:00 daily, so that the maximum possible value of the energy to be produced between the selected hours is aimed to be obtained from the biogas generator.

2.4.6. Thermal load controller (TLC)

The thermal load controller is the system element that connects the thermal load system and the electrical load system. By transferring the excess energy produced in the electrical system to the thermal load busbar, it prevents the use of excess energy for heating purposes. The calculation was made by taking the installation and replacement cost of the thermal load controller as 4000 ₺ per kW.

Tablo 9. Capacity limits of components

No	PV (kW)	MPPT (Qty.)	Wind Turb. (Qty.)	Bio Gen. (kW)		Battery (Qty.)	TLC (kW)	Conv. (kW)	Dispatch	NPC (₺)	COE (₺)	Opr. Cost (₺/yr)	İnitial Capital (₺)	Ren. Frac. (%)
1	0.213	1	3	10		4	10	0.465	CC	821,154	0.894	40,321	226,060	80.1
2			3	10		5	10	0.548	CC	823,267	0.899	40,224	229,592	79.3
3				10		5	10	0.521	CC	882,668	1.05	45,097	217,083	78.3
4	0.157	1		10		12	10	0.630	CC	903,232	1.10	43,980	254,132	76.6
5			7	10			30		CC	934,772	1.18	43,144	298,000	87.4
6	1.94	1	8	10			30	3.99	CC	972,005	1.27	42,963	337,908	88
7				10			10		CC	1.04M	1.44	57,528	190,000	82.2
8	0.324	1		10			10	2.16	LF	1.09M	1.56	59,882	201,979	79.5

2.4.7. Boiler

HOMER software uses the boiler system to meet the thermal load and diesel fuel is used as the energy source. The efficiency of the boiler used in the system has been entered as 85%. In addition, the liter price of diesel fuel is taken as 15 ₺.

2.5. Determination of Economic Parameters

In order for the simulations made by HOMER to provide more realistic results, it is necessary to determine the parameters that will affect the cost during the life of the project, such as the interest rate and inflation rate, in the calculation of economic values. While the interest rate is the rate used to calculate the present value of an economic asset, the inflation rate is the value that expresses purchasing power. The global pandemic in recent years has terribly affected the economy of our country as well, making it impossible to make forward-looking financial analyzes with the ever-increasing interest and inflation values. For this reason, it is accepted that the interest rate used in the simulations is 15% and the inflation rate is 10%. According to the assumptions made, the real interest rate has been determined as 4.55%. In addition, the project life of the system is accepted as 25 years.

2.6. Simulation and optimization model

The off-grid hybrid energy system to meet the determined electrical and thermal loads for the farm is presented in Figure 6. The simulations were determined by the HOMER Pro software for the different capacities (Table 9) of the components that make up the hybrid energy system. In addition, changes in the average wind speed, solar radiation intensity, wind turbine body height, minimum charge status of the batteries, minimum load rate of the biogas generator and heat recovery rate of the cogeneration system were taken into consideration in the simulations (Table 10). In addition, the case of solar panels with a solar tracking system has also been examined.

The capacity limits of the components are given in Table 9. With the Optimizer option of the HOMER software, the optimum capacity of the components between 0 and 100 values has been examined. The capacity of the MPPT device is obtained by multiplying the load ratio with the PV capacity.

Table 10. Variables used in sensitivity analysis

Biogas Generator Heat Recovery Raito (%)	Biogas Generator Minimum Load Raito (%)	Solar Scaled Average (kWh/m^2/day)	Battery Minimum State of Charge (%)	Wind Scaled Average (m/s)	Wind Turbine Hub Height (m)
15	20	4.64	20	4.76	20
20	30	6	30	6	30

Table 10 shows the elements selected for the optimization of the system. In order to investigate the usability of the designed system in different regions, average solar radiation and wind speed values have also been investigated.

3. FINDINGS AND DISCUSSION

HOMER software analyzes the required load values according to meteorological data (Ameen et al., 2015). As a result of the simulations carried out, many systems that may be suitable for the region have been modelled. In the selection of the systems, the number and capacities of the components are determined by considering the two economic parameters, which are Net Present Cost (NPC) and Energy Unit Cost (COE) (Aykut and Terzi, 2020; Lambert et al., 2016; Varshney et al., 2013). In Table 11, the most suitable 8 systems are presented, which are obtained using values as follows the heat recovery rate of the cogeneration system, the minimum load rate of the biogas generator and the minimum charge state of the batteries are 20%, the wind turbine core height is 20 m, and the average wind speed is 4.76 m/s and average solar radiation is 4.64 kWh/ m^2/day.

Table 61. Simulated hybrid energy models

Converter Capacity (kW)	**Biogas Generator Capacity (kW)**	**MPPT DC/AC ratio**	**Solar Panel (kW)**	**Battery (Quantity)**	**TLC Capacity (kW)**	**Wind Turbine (Quantity)**
Optimizer	Sizing	Dedicated converter capacity	Optimizer	Optimizer	Sizing	Optimizer
0	0	1	0	0	10	0
100	10		100	100	20	100
	20				30	
	30				40	
					50	

When Table 11 is examined, battery charging strategies are seen in the dispatch column. HOMER Pro follows two different paths as a battery charging strategy. These are called Load Following (LF) and Cycle Charging (CC). In LF, the generator produces enough power to feed the load, not the batteries. In CC, on the other hand, every time the generator starts to work, it works at maximum nominal capacity and charges the batteries with excess energy (Kolhe et al., 2015; Ghasemi, 2013). The systems presented in Table 11 are listed according to their NPC and COE values. Accordingly, the hybrid system with the lowest NPC and COE values ranks first. In the most suitable hybrid system offered, there will be a solar panel with a capacity of 0.213 kW, a MPPT device with a PV/Converter ratio, a wind turbine with a capacity of 9.6 kW, a biogas generator with a capacity of 10 kW, 4 batteries, a thermal load controller with a capacity of 10 kW and a converter with a capacity of 0.465 kW, and the NPC value of this system will be 821.154 ₺ and the COE value is determined to be 0.894 ₺. In the hybrid system presented in the second place, solar energy is not used. Compared to the first system, it was determined that the second system needed an additional battery and a converter with 0.183 kW more capacity. In the hybrid system presented in the third place, solar and wind energies are not used. In this case, it has been determined that the system should have a biogas generator with a capacity of 10 kW, 5 batteries, a thermal load controller with a capacity of 10 kW and a converter with a capacity of 0.521 kW. However, it should not be overlooked that the rate of renewable energy use decreases in these systems, respectively. It is seen that the hybrid system with the highest rate of renewable energy among the systems presented is the 6th system. In this system, it has been determined that 1.94 kW capacity PV Panel, 1 MPPT device, 25.6 kW wind turbine, 10 kW biogas generator, 30 kW thermal load controller and 3.99 kW capacity converter are required. In this case, it was determined that the renewable energy usage rate of the system would be 88%, and the NPC and COE values would be 972.005 ₺ and 1.27 ₺, respectively. Renewable energy sources such as wind and sun are not regular. For this reason, changes in the average power produced can be observed due to the irregular nature of renewable energy sources (Ameen, et al., 2015). Considering these changes, it should not be ignored that the loads that will be needed cannot be met instantly with a hybrid energy system that does not contain batteries. Under normal conditions, the use of battery banks is not preferred, considering that it will significantly increase the system cost.

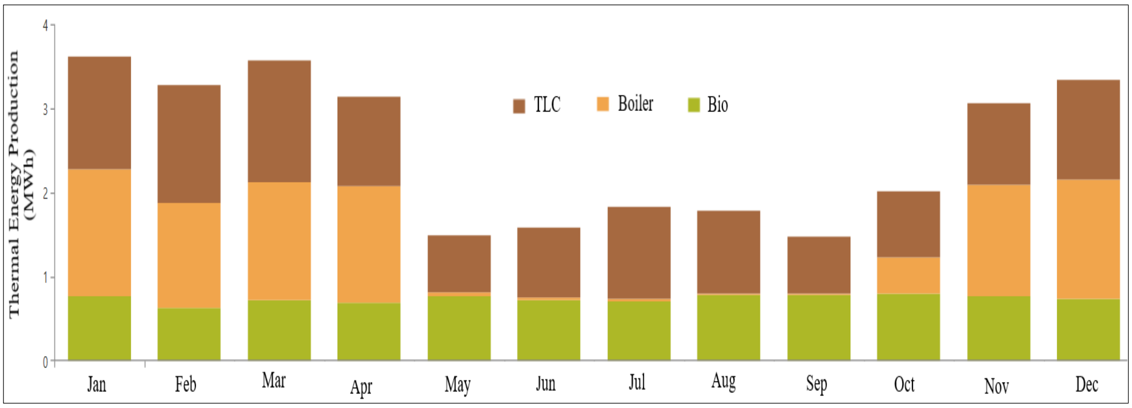


Figure 7. Monthly power generation amounts of the hybrid energy system

However, as a result of the simulations, it has been understood that the use of batteries has a positive effect on the cost, especially in off-grid systems. The fact that the solar intensity and wind speeds do not spread throughout the year increases the frequency of use of the generator in battery-free systems (Türkdoğan et al., 2020).

3.1. Investigation of the hybrid system with the lowest NPC and COE values

When the number 1 hybrid system, which is selected as the most suitable according to NPC and COE values, is examined, it has been determined by HOMER Pro that of the 39,480 kWh/yr total electrical energy to be produced by the hybrid system, 0.85% can be produced from solar panels, 45.4% from biogas generators and 53.8% from wind turbines (Figure 7). In addition, it has been determined that 31.4% of this generated energy (12,405 kWh/yr) will be the excess electricity and there will be no unmet electrical load.

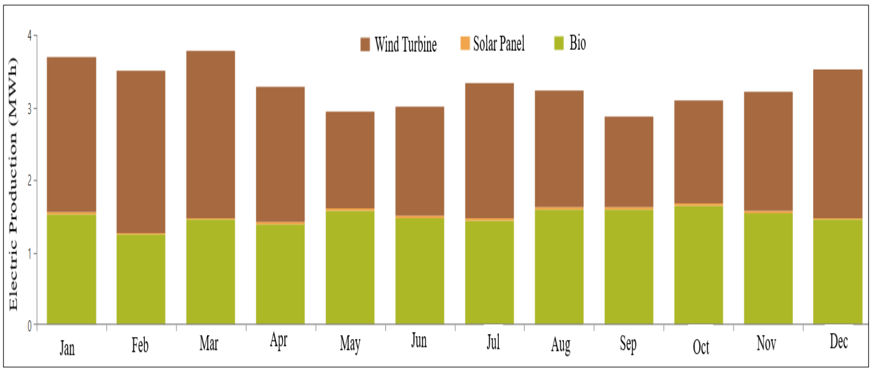


Figure 8. Monthly thermal energy production amounts of the hybrid energy system

When meeting the thermal load requirement by the hybrid system is examined, 29.5% of the annual thermal energy of 30,173 kWh to be produced by the system is obtained from the Biogas generator, 29.4% from the boiler (boiler), and 41.2% from the Thermal Load Controller (TLC) (Figure 8). In addition, it was determined that 71.8% of the thermal energy produced was extra thermal energy.

When Figure 8 is examined, it can be seen that TLC, which is used to convert excess electrical energy into heat energy, provides the highest heat energy production in all months, while the boiler operates with the lowest performance in summer.

When the contribution of the 10 kW Biogas generator to the number 1 hybrid system is examined, the data obtained are presented in Table 12, the graph showing the hourly generator output power throughout the year is presented in Figure 9a, and the average fuel consumption is presented in Figure 9b.

Table 12. Biogas generator operation data

Hours of Operation (hrs/yr)	5,055	Mean electrical output (kW)	3.54
Number of Starts (starts/yr)	426	Thermal Production (kW/yr)	8,908
Operational life (yr)	3.96	Fuel Consumption (ton/yr)	58.4
Capacity Factor (%)	20.4	Specific Fuel Consumption (kg/kWh)	2.28
Fixed Generation Cost (₺/hr)	25	Fuel Energy Input (kWh/yr)	62,453
Electrical Production (kWh/yr)	17.912	Mean Electrical Efficiency (%)	28.7

When Table 12 is examined, it can be seen that the generator operates 5,055 hours per year, the capacity factor is 20.4%, it produces 17,912 kWh of electricity, 8,908 kWh of thermal energy and consumes 58.4 tons of biogas per year.

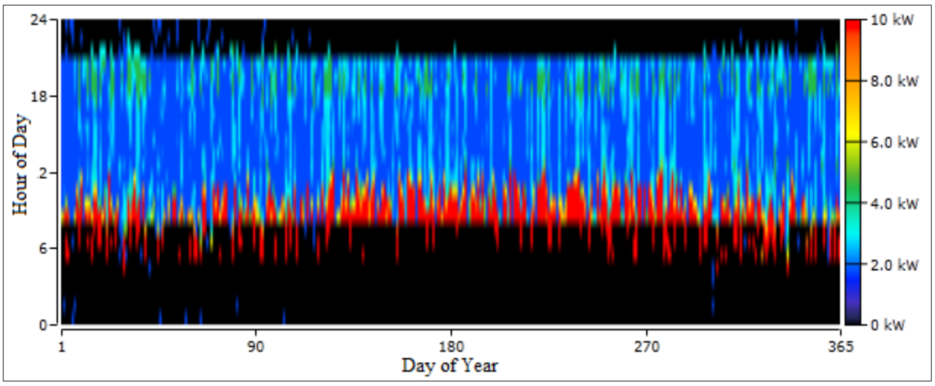


Figure. 9.a Hourly generator output power throughout the year

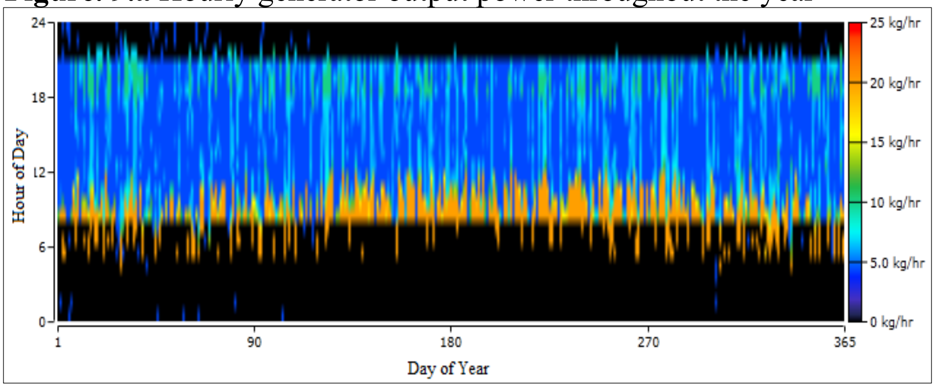


Figure. 9.b Hourly biogas consumption throughout the year

In Figure 9.a, when the hourly variation of the generator's output power throughout the year is examined, it is seen that the output power is generally around 10kW between 04.00 and 12.00 hours, and between 2 kW and 6 kW in the other hours during the year. In general, it has been determined that the average output power value of the generator is 3.54 kW. Figure 9.b shows the hourly amount of biogas consumed by the generator throughout the year. When Figures 9.a and 9.b are evaluated together, it is clearly seen that the amount of gas consumed and the power produced in the generator are directly proportional. In addition, it has been determined that the average amount of biomass used by the biogas generator daily is 0.160 tons.

3.2 Investigation of solar tracking of PV panels

Techno-economic and environmental effects of the solar tracking system compared to the fixed system were investigated by examining the case of PV panels with solar tracking in x and y axis of the hybrid system model number 1 which was examined in section 3.1. In the system, a price difference of 5000 ₺/kW for the initial installation fee of the solar panels and 950 ₺/kW for the annual maintenance and repair costs was inputted to the tracking system. For both cases, two models with the same PV panel capacity values were compared. The obtained models are shown in Table 13. In Table 13, the number 1 model belongs to the system with fixed PV panels, and the number 2 model belongs to the system whose PV panels are solar tracking.

Table 13. Techno-economic comparison of fixed and mobile PV panel models

Quantity	1st Model	2nd Model	Quantity	1st Model	2nd Model
Rated Capacity (kW)	0.280	0.280	Minimum Output (kW)	0	0
Mean Output (kW)	0.0502	0.0669	Maximum Output (kW)	0.280	0.280
Mean Output (kW/d)	1.21	1.61	PV Penetration (%)	13.4	17.8
Capacity Factor (%)	18.0	23.9	Hours of Operation (hrs./yr)	4,355	4,355
Total Production (kWh/yr)	440	586	Levelized Cost (₺/kWh)	0.481	0.977

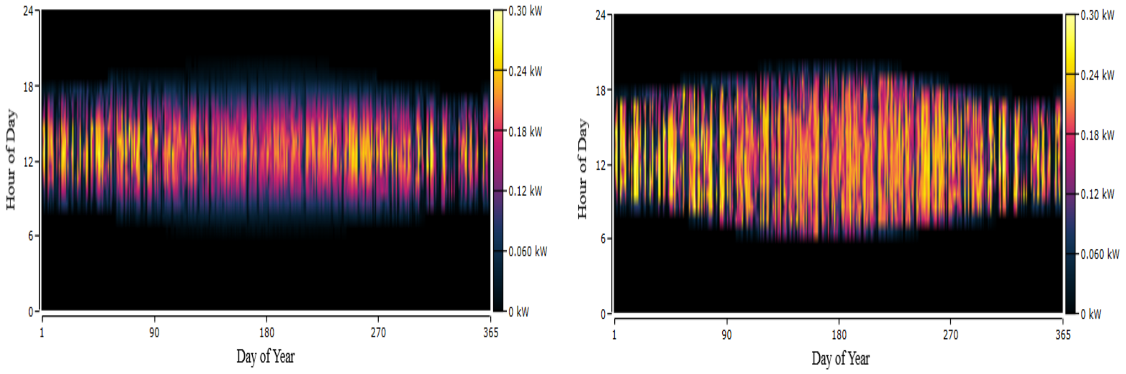
When Table 13 is examined, it can be seen that the number of wind turbines and converter capacity have increased in the solar tracking system, which is model number 2, while the number of batteries and generator capacity have decreased. When analyzed from an economic point of view, it can be seen that the financial values of the model number 2 are more appropriate than the system number 1. In addition, it can be seen that the renewable energy rates in the systems are very close to each other. The comparison of the data obtained from the PV panels for both systems is presented in Table 14.

Table 14. Comparison of data obtained from fixed and mobile PV panel models

No	PV (kW)	MPPT (Qty.)	Wind Turb. (Qty.)	Bio Gen. (kW)	Battery (Qty.)	TLC (kW)	Conv. (kW)	Dispatch	NPC (₺)	COE (₺)	Opr. Cost (₺/yr)	İnitial Capital (₺)	Ren. Frac. (%)
1	0.280	1	5	20	5	20	0.886	CC	1.30M	2.09	58,660	431,424	83
2	0.280	1	6	10	2	20	1.07	CC	858,480	0.987	39,699	272,554	83.8

As seen in Table 14, all data obtained from model 2 with solar tracking system is higher than the data obtained from system 1 in the PV panels selected with the same capacity for both models. The tracking system increased the capacity factor of the PV panels from 18% to 23.9%, and this increase caused the annual total energy produced to increase from 440 kWh to 586 kWh. Graphs showing the changes in hourly PV panel power outputs of the compared systems throughout the year are presented in Figure 10.

When Figure 10. is examined, it can be seen that fixed PV panels produce energy between 07.00 and 18.00 (Figure 10.a.), while PV panels with tracking system produce energy between 06.00 and 20.00 (Figure 10.b.). In addition, depending on the meteorological characteristics of the studied region, it is



a. *Fixed PV Panel*

Figure 10. Hourly output power variations of fixed and mobile PV panels throughout the year

understood that the energy production between the 90th and 270th days of the year is higher than the other days of the year.

3.3 Investigation of optimization and sensitivity analysis

In the analysis of the off-grid hybrid energy system, 6 different sensitivity variables were considered and all possible system configurations were investigated. Sensitivity variables used in simulation are the minimum charge state of the batteries, the minimum load rate of the biogas generator, the heat recovery rate of the cogeneration system, the turbine hub height, the average wind speed, and the variation of the average solar radiation intensity. As a result of the optimizations made with the HOMER Pro software, 64 models were developed and these models are presented in A-Table 15 given in the Appendix. In A-Table 15, model 1 is the best fit model in terms of NPC and COE. When the sensitivity variables of the model are examined, it is seen that the state of charge of the batteries, the minimum load rate of the generator and the heat recovery rate of the generator (cogeneration system) are 20%, the wind turbine hub height is 30 m, the solar radiation intensity is 4.64 kWh/m2/day and the average wind speed is 6 m/s. It has been determined that the optimum system for these conditions can be installed with a 9.6 kW wind turbine, a 10 kW biogas generator, 4 battery groups, a 10-kW thermal load controller and a converter with a 0.56 kW capacity. The renewable energy rate of this system is 83.79%. The model with the lowest NPC value created with the solar and wind potential values of the region is provided in A-Table 15. When the sensitivity parameters of this model are examined, the only difference from model 1 is that the minimum load rate of the biogas generator is taken as 30%. When the components in this model are compared with the components given in system 1, it has been determined that the converter capacity has decreased to 0.50 kW and the other components have remained at the same capacity. Renewability value of this model has been determined as 82.59%. In the system number 64 with the highest NPC value, the minimum charge state of the batteries and the minimum load rate of the generator are 20%, the heat recovery rate of the cogeneration system is 15%, the wind turbine body height is 20 m, the solar radiation intensity is 6 kWh/m2/day and the average wind speed is 4.76 m/s. Renewability rate of this system has been determined as 77.64%. As a result of the optimizations and simulations, it has been determined that solar energy is not as efficient as wind energy for the region, and only 8 of the 64 presented models require very small capacity solar panels. This confirms the statement (IRENA, 2012) that PV panels can be economically competitive at high production levels. In Figure 11, the effects of solar radiation intensity and wind speed on hybrid system configurations are examined.

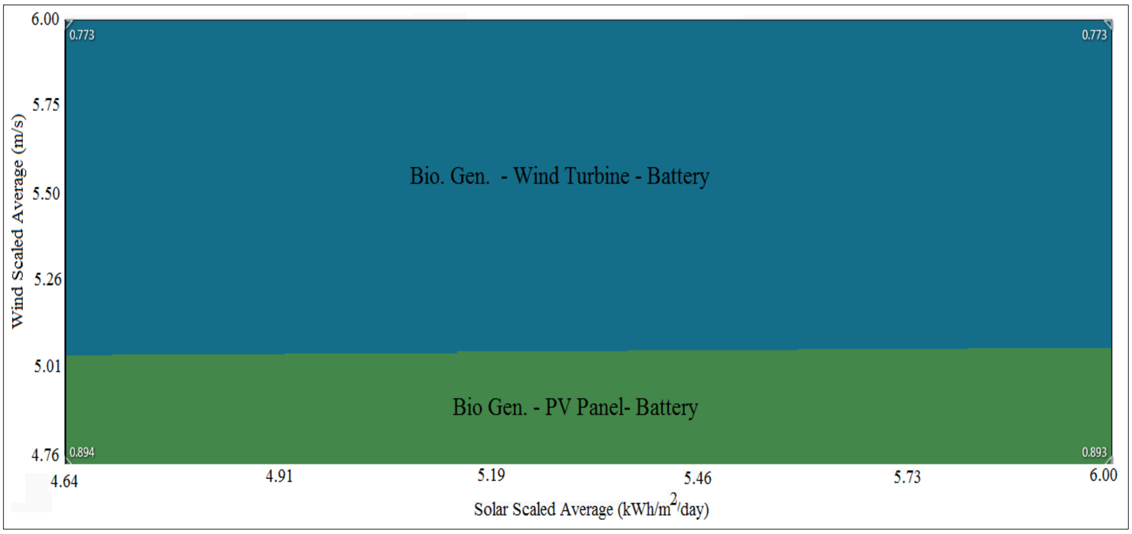


Figure 11. Effect of avarage solar radiation and wind speed on system configuration

Figure 11 shows the optimum system for the unit energy cost (COE) in which the charge of the batteries, the minimum load of the generator, the heat recovery rate are 20%, and the turbine hub height is 20 m. Accordingly, it has been determined that adding PV panels to the hybrid system will increase the NPC and COE values at wind speeds above 5.07 m/s. In addition, the variation of the NPC values of the hybrid systems depending on the component selection for the investigated sensitivity values is presented in Table 16.

Table 16. NPC values of hybrid systems selected according to sensitivity values

Condition	Sensibility	Value	Hybrid system components	NPC (₺)
1	Battery Minimum State of Charge Bio. Gen. Minimum Load Ratio Bio. Gen. Heat Recovery Ratio Wind Turbine Hub Height Solar Scaled Average Wind Scaled Average	20% 20% 20% 20 m 4.64 kWh/m^2/day 5.07 m/s	Bio. Gen. / Wind Turb. / Battery	810,857
			Bio. Gen. /PV Panel / Wind Turbine / Battery	810,862
			Bio. Gen. / Battery	882,668
			Bio. Gen. / PV Panel / Battery	903,232
			Bio. Gen. / Wind Turbine	906,290
			Bio. Gen. / PV Panel / Wind T.	944,202
			Bio. Gen.	1,039,061
			Bio. Gen. / PV Panel	1,085,788
2	Battery Minimum State of Charge Bio. Gen. Minimum Load Ratio Bio. Gen. Heat Recovery Ratio Wind Turbine Hub Height Solar Scaled Average Wind Scaled Average	30% 20% 20% 20 m 4.64 kWh/m^2/day 5.01 m/s	Bio. Gen. / Wind Turb. / Battery	813,113
			Bio. Gen. /PV Panel / Wind Turbine / Battery	813,116
			Bio. Gen. / Battery	888,047
			Bio. Gen. / PV Panel / Battery	903,232
			Bio. Gen. / Wind Turbine	911,469
			Bio. Gen. / PV Panel / Wind T.	949,255
			Bio. Gen.	1,039,061
			Bio. Gen. / PV Panel	1,085,788
3	Battery Minimum State of Charge Bio. Gen. Minimum Load Ratio Bio. Gen. Heat Recovery Ratio Wind Turbine Hub Height Solar Scaled Average Wind Scaled Average	30% 30% 15% 30 m 4.64 kWh/m^2/day 5.94 m/s	Bio. Gen. / Wind Turb. / Battery	787,668
			Bio. Gen. /PV Panel / Wind Turbine / Battery	787,854
			Bio. Gen. / Battery	840,702
			Bio. Gen. / PV Panel / Battery	846,692
			Bio. Gen. / Wind Turbine	942,425
			Bio. Gen. / PV Panel / Wind T.	946,544
			Bio. Gen.	1,112,102
			Bio. Gen. / PV Panel	1,132,884

In Table 16, three cases are examined for different sensitivity values despite the same solar radiation values. Case 1 is the case described in Figure 11. In number 2, the case where the minimum charge state of the batteries is 30% instead of 20% is examined. In this case, it was concluded that it would be economical to use PV panels in cases where the average wind speed for the studied region is lower than 5.01 m/s. In case 3, the wind speed limit value was determined as 5.94 m/s, according to the sensitivity values examined

3.4 Investigation of emission analysis of hybrid systems

In order to perform emission analysis of hybrid systems, 2000 hybrid system models created as a result of optimization and sensitivity analyzes by HOMER Pro software were compared regarding renewable energy rates. The lowest renewability rate of the developed hybrid systems is 69.7% and the highest renewability rate is 86.3%. Emission analyzes of 5 different hybrid systems were compared, starting from the hybrid system with the lowest renewability rate, with approximately 5% increments. The hybrid systems used in the comparisons are presented in Table 17, and the emission data of these systems are presented in B-Table 18 in the Appendix.

Table 17. Component capacities of hybrid systems

No	PV (kW)	MPPT (Qty.)	Wind Turb. (Qty.)	Bio Gen. (kW)	Battery (Qty.)	TLC (kW)	Conv. (kW)	NPC (₺)
1	8.3	1		10	8	20	8.33	1.23M
2				10	6	10	2.08	1.16M
3	1.80	1	6	10	2	30	5.72	992,875
4	1.40	1	8	10	3	30	0.956	912,404
5	11.8	1	7	10		50	3.82	1.18M

When B-Table 18 is examined, it can be seen that the emission values of hybrid systems are inversely proportional to the renewability rates of the systems. In addition, it has been determined that the extra electricity and thermal energy produced in systems without wind turbines (number 1 and 2) is less when compared to the other systems. The excess electricity generated by the components is converted into thermal energy by TLC. Therefore, the use of TLC significantly reduces the emission values of the systems. In the number 5 hybrid system, which does not use batteries, the annual 89,257 kWh electrical energy produced in excess has been converted into thermal energy. On the other hand, when system 5 is compared to system 2, although system 5 produces approximately 5 times more energy than system 2, annual CO_2 emissions are almost half of the system compared. When the biogas and diesel fuel consumption values of the simulated systems are examined, it is determined that they will consume between 37.9 and 53.4 tons/year of biogas and between 729 and 1612 L/year of diesel fuel. It has been concluded that these consumption values will cause CO_2 emissions between 1939 and 4273 kg/year.

4. RESULTS

In this study, optimizations and simulations of hybrid systems using diesel fuel together with biogas, solar and wind renewable energies using daily waste manure for a farm with a capacity of 100 cattle, which is considered to be independent from the grid, were carried out with HOMER Pro software. Assuming that the examined farm consists of a barn, a farmhouse and a renewable energy unit section, the electrical load of the barn and the farmhouse and the thermal loads of the biogas system and the farmhouse were determined separately, taking into account the meteorological characteristics of the studied region. In order for the study to be beneficial for different regions, solar and wind energy potentials were selected with different values, sensitivity analyzes were made, and techno-economic and environmental analyzes of the models obtained were evaluated.

According to the results obtained from the study, it has been determined by using HOMER Pro software that there should be a PV panel with a capacity of 0.213 kW, a wind turbine with a capacity of 9.6 kW, a biogas generator with a capacity of 10 kW, 4 lead-acid type batteries with a capacity of 12V-67Ah, a thermal load controller (TLC) with a capacity of 10 kW, and a converter with a capacity of 0.465 kW in the most suitable hybrid system model selected according to the average solar radiation and average wind speed values of the region and based on the sensitivity parameters. In addition, if this system is selected, it has been determined that the net present cost (NPC) will be 821,154 ₺ and the energy unit cost (COE) will be 0.894 ₺ during its lifetime. The case of the PV panels in this hybrid system to be selected with a two-axis solar tracking system has also been investigated, and it has been determined that 146 kWh more energy can be obtained annually from the PV panels. In order to expand the scope of the study, sensitivity analyzes have been carried out considering the average wind speed, solar radiation intensity, minimum load rate and heat recovery rate of the biogas generator, the wind turbine hub height and the minimum charge condition of the batteries. According to the results obtained, it has been determined that it will not be economical to add PV panels to the hybrid system if the average wind speed of the region exceeds 5.5 m/s. On the other hand, it has been determined that the TLC device used in hybrid systems can prevent a significant amount of CO_2 emissions as a result of converting the excess electricity produced into thermal energy. When evaluated in general, it has been determined that the simulated hybrid systems will consume 37.9 to 53.4 tons/year of biogas and 729 to 1612 L of diesel fuel, and these consumption values will cause CO_2 emissions between 1939 and 4273 kg per year.

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Appendix A,

A-Table 15. Sensitivity analysis results

	Sensitivity						Architecture								Cost				System
No	Minimum State of Charge (%)	Bio Gen. Minimum Load Ratio (%)	Bio Gen. Heat Recovery Ratio (%)	Wind Turb. Hub Height (m)	Solar Scaled Average ($kWh/m^2/day$)	Wind Scaled Average (m/s)	PV (kW)	MPPT (Qty.)	Wind Turb. (Qty.)	Bio Gen. (kW)	Battery (Qty.)	TLC (kW)	Conv. (kW)	Dispatch	NPC (₺)	COE (₺)	Opr. Cost (₺/yr)	İnitial Capital (₺)	Ren. Frac. (%)
1	20	20	20	30	4.64	6.00			3	10	3	10	0.56	CC	762703	0.75	36821	219256	83.79
2	20	20	20	30	6.00	6.00			3	10	3	10	0.56	CC	762703	0.75	36821	219256	83.79
3	30	20	20	30	4.64	6.00			3	10	3	10	0.56	CC	763069	0.75	36846	219256	83.84
4	30	20	20	30	6.00	6.00			3	10	3	10	0.56	CC	763069	0.75	36846	219256	83.84
5	20	20	20	20	4.64	6.00			3	10	3	10	0.56	CC	773251	0.77	37536	219256	82.97
6	20	20	20	20	6.00	6.00			3	10	3	10	0.56	CC	773251	0.77	37536	219256	82.97
7	30	20	20	20	4.64	6.00			3	10	3	10	0.56	CC	773490	0.77	37552	219256	83.02
8	30	20	20	20	6.00	6.00			3	10	3	10	0.56	CC	773490	0.77	37552	219256	83.02
9	20	30	20	30	6.00	6.00			5	10	3	20	0.50	CC	775494	0.78	34453	267002	88.34
10	20	20	15	30	4.64	6.00			3	10	3	10	0.89	CC	775727	0.78	37615	220571	82.00
11	20	20	15	30	6.00	6.00			3	10	3	10	0.89	CC	775727	0.78	37615	220571	82.00
12	30	30	20	30	6.00	6.00			5	10	3	20	0.50	CC	775828	0.78	34475	267002	88.36
13	30	20	15	30	4.64	6.00			3	10	3	10	0.89	CC	776151	0.78	37643	220571	82.04
14	30	20	15	30	6.00	6.00			3	10	3	10	0.89	CC	776151	0.78	37643	220571	82.04
15	30	30	20	30	4.64	6.00			5	10	3	20	0.59	CC	776599	0.78	34503	267364	88.25
16	20	30	20	30	4.64	6.00			5	10	2	20	0.71	CC	777431	0.78	34865	262854	88.65
17	20	30	20	20	4.64	6.00			6	10	2	20	0.39	CC	782470	0.80	35024	265544	88.85
18	20	30	20	20	6.00	6.00			6	10	2	20	0.39	CC	782470	0.80	35024	265544	88.85
19	30	30	20	20	4.64	6.00			6	10	2	20	0.39	CC	782756	0.80	35044	265544	88.87
20	30	30	20	20	6.00	6.00			6	10	2	20	0.39	CC	782756	0.80	35044	265544	88.87
21	30	30	15	30	6.00	6.00	0.05	1	5	10	3	20	0.52	CC	785523	0.80	35092	267603	87.41
22	30	30	15	30	4.64	6.00	0.05	1	5	10	3	20	0.52	CC	785554	0.80	35094	267603	87.41
23	20	30	15	30	4.64	6.00			5	10	3	20	0.78	CC	786583	0.81	35128	268128	87.25
24	20	30	15	30	6.00	6.00			5	10	3	20	0.78	CC	786583	0.81	35128	268128	87.25
25	20	20	15	20	4.64	6.00			3	10	3	10	0.89	CC	787136	0.81	38388	220571	81.22
26	20	20	15	20	6.00	6.00			3	10	3	10	0.89	CC	787136	0.81	38388	220571	81.22
27	30	20	15	20	4.64	6.00			3	10	3	10	0.89	CC	787427	0.81	38407	220571	81.27
28	30	20	15	20	6.00	6.00			3	10	3	10	0.89	CC	787427	0.81	38407	220571	81.27
29	20	30	15	20	4.64	6.00			6	10	3	20	0.69	CC	792041	0.82	35251	271764	87.34
30	20	30	15	20	6.00	6.00			6	10	3	20	0.69	CC	792041	0.82	35251	271764	87.34
31	30	30	15	20	4.64	6.00			6	10	3	20	0.69	CC	792545	0.82	35285	271764	87.37
32	30	30	15	20	6.00	6.00			6	10	3	20	0.69	CC	792545	0.82	35285	271764	87.37
33	**20**	**30**	**20**	**30**	**4.64**	**4.76**			**3**	**10**	**3**	**10**	**0.50**	**CC**	**794888**	**0.83**	**39019**	**219000**	**82.59**
34	20	30	20	30	6.00	4.76			3	10	3	10	0.50	CC	794888	0.83	39019	219000	82.59
35	30	30	20	30	4.64	4.76			3	10	3	10	0.50	CC	795381	0.83	39053	219000	82.65
36	30	30	20	30	6.00	4.76			3	10	3	10	0.50	CC	795381	0.83	39053	219000	82.65

A-Table 15. Cont. Sensitivity analysis results

37	20	30	20	20	4.64	4.76			3	10	4	10	0.61	CC	807444	0.86	39501	224440	81.12
38	20	30	20	20	6.00	4.76			3	10	4	10	0.61	CC	807444	0.86	39501	224440	81.12
39	20	20	20	30	4.64	4.76			3	10	3	10	0.42	CC	809742	0.86	40048	218668	81.06
40	20	20	20	30	6.00	4.76			3	10	3	10	0.42	CC	809742	0.86	40048	218668	81.06
41	30	20	20	30	6.00	4.76			3	10	3	10	0.53	CC	810116	0.87	40044	219107	80.68
42	20	30	15	30	4.64	4.76			3	10	3	10	0.57	CC	810345	0.87	40047	219293	81.08
43	20	30	15	30	6.00	4.76			3	10	3	10	0.57	CC	810345	0.87	40047	219293	81.08
44	30	30	20	20	4.64	4.76			3	10	5	10	0.67	CC	810436	0.87	39348	229699	80.88
45	30	30	20	20	6.00	4.76			3	10	5	10	0.67	CC	810436	0.87	39348	229699	80.88
46	30	30	15	30	4.64	4.76			3	10	3	10	0.57	CC	811012	0.87	40092	219293	81.13
47	30	30	15	30	6.00	4.76			3	10	3	10	0.57	CC	811012	0.87	40092	219293	81.13
48	30	20	20	30	4.64	4.76			3	10	2	10	0.36	CC	811979	0.87	40554	213440	81.60
49	20	20	20	20	6.00	4.76	0.21	1	3	10	4	10	0.47	CC	821045	0.89	40313	226060	80.12
50	20	20	20	20	4.64	4.76	0.21	1	3	10	4	10	0.47	CC	821154	0.89	40321	226060	80.12
51	20	30	15	20	6.00	4.76	0.02	1	3	10	4	10	0.54	CC	821358	0.89	40451	224337	79.99
52	20	30	15	20	4.64	4.76			3	10	4	10	0.58	CC	821431	0.89	40458	224304	79.90
53	30	20	20	20	6.00	4.76	0.21	1	3	10	4	10	0.47	CC	821443	0.89	40340	226060	80.14
54	30	20	20	20	4.64	4.76	0.21	1	3	10	4	10	0.47	CC	821549	0.89	40347	226060	80.14
55	30	30	15	20	6.00	4.76	0.02	1	3	10	4	10	0.54	CC	821997	0.90	40494	224337	80.04
56	30	30	15	20	4.64	4.76			3	10	4	10	0.58	CC	822126	0.90	40505	224304	79.97
57	20	20	15	30	4.64	4.76			3	10	5	10	0.53	CC	826169	0.91	40453	229121	78.56
58	20	20	15	30	6.00	4.76			3	10	5	10	0.53	CC	826169	0.91	40453	229121	78.56
59	30	20	15	30	4.64	4.76			3	10	5	10	0.53	CC	826179	0.91	40454	229121	78.58
60	30	20	15	30	6.00	4.76			3	10	4	10	0.93	CC	827230	0.91	40756	225701	78.37
61	20	20	15	20	4.64	4.76			3	10	4	10	0.65	CC	835676	0.93	41403	224604	77.70
62	30	20	15	20	4.64	4.76			3	10	4	10	0.65	CC	836586	0.93	41465	224604	77.77
63	30	20	15	20	6.00	4.76			3	10	5	10	0.53	CC	837073	0.93	41191	229133	77.87
64	20	20	15	20	6.00	4.76			3	10	4	10	0.93	CC	837560	0.93	41456	225701	77.64

Appendix B,

B-Table 18. Component and emission data of hybrid systems

No	Thermal Load (kWh/yr.)	Bio Gen. Thermal Production (kWh/yr.)	Boiler Total Production (kWh/yr.)	TLC Production (kWh/yr.)	Excess Electricity (kWh/yr.)	Excess Thermal (kWh/yr.)	Bio Fuel (tons)	Diesel Fuel (L)	Carbon Dioxide (kg/yr)	Carbon Monoxide (kg/yr)	Sulfur Dioxide (kg/yr)	Nitrogen Oxides (kg/yr)	Ren. Frac. (%)
1	17,567	5,930	13,480	95,6	95,8	1,938	50.8	1,612	4,273	0.102	10.6	0.0635	69.7
2	17,567	9,807	11,593	969	968	4,801	87.6	1,386	3,683	0.175	9.09	0.109	74
3	17,567	4,481	9,372	28,866	28,866	25,152	37.9	1,121	2,972	0.0759	7.35	0.0474	79
4	17,567	5,517	7,596	45,986	45,979	41,524	47.7	908	2,411	0.0954	5.96	0.0596	83
5	17,567	5,216	6,086	89,256	89,257	82,991	53.4	729	1,939	0.107	4.78	0.0667	86.3