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Photovoltaic and biogas based renewable energy applications in livestock farms in Karaman province

Merve YILMAZER[1], Yavuz Selim OZEN[1], Halil Ibrahim VARIYENLI[1], Mert OKTEN[2]

[1]Gazi University, Faculty of Technology, Department of Energy Systems Engineering, 06560, Ankara
[2]Manisa Celal Bayar University, Faculty of Hasan Ferdi Turgutlu Technology, Department of Energy Systems Engineering, 45400, Manisa

Corresponding author: M. Okten, e-mail: mert.okten@cbu.edu.tr
Author(s) e-mail: merve.ylmzr52@gmail.com, yvzslmozn174@gmail.com, halilv@gazi.edu.tr

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ABSTRACT

This study evaluates the economic and environmental advantages of integrating renewable energy systems into livestock farms in Karaman province,Türkiye. A hybrid model combining biogas and photovoltaic (PV) systems was developed and simulated for a representative cattle farm. Biogas production potential was calculated based on local livestock waste data, and a rooftop PV installation was modeled using region-specific solar radiation values. The results demonstrate that such a hybrid system can produce both electrical and thermal energy sufficient to meet on-farm demands, while significantly reducing greenhouse gas emissions. Economic analysis reveals a feasible payback period, and sensitivity tests show resilience against energy price fluctuations. This study is one of the first to model an integrated PV and biogas hybrid energy system at the provincial level in Türkiye, demonstrating its economic and environmental viability.

1. Introduction

Increasing industrialisation with the Industrial Revolution has led to an increase in CO_2 emissions. The increase in CO_2 emissions has led to global warming as a result of air pollution and ozone depletion, while industrial waste has caused environmental pollution and serious damage to natural life. The United Nations Framework Convention on Climate Change, the Paris Agreement signed in 2015, which sets out legal responsibilities for mitigation, adaptation and financing of climate change, aims to limit the increase in global average temperature to 2°C above pre-industrial levels (United Nations 2024). According to the results of the greenhouse gas inventory, total greenhouse gas emissions decreased by 2.4% to 558.3 million tonnes of CO_2 equivalent in 2022 compared to the previous year (TÜİK 2024). As a result of these negative figures, the search for clean and renewable energy sources has begun. The global effort to raise awareness about clean energy is the result of the popularity of renewable energy sources such as solar, wind, biomass, geothermal, hydropower and wave in recent years. According to the International Energy Agency's "Renewable Energy 2023" report, global renewable energy capacity will reach 510 GW in 2023, an increase of almost 50 per cent and a new record. One third of the increase in global renewable capacity will come from solar power plants (IEA 2024a). In Türkiye, the installed power generation capacity reached 108 GW by the end of March 2024. with 29.6% hydro, 23.2% natural gas, 20.2% coal, 11.2% wind, 11.7% solar, 1.6% geothermal and 2.5% from other sources (ETKB 2024). In light of the data obtained, it can be seen that approximately 55% of the installed capacity in Türkiyeis provided by renewable energy sources.

Biomass is an energy source with high potential for heating and electricity generation. It can be produced worldwide from sewage treatment plants, landfills, animal wastes, agricultural wastes with no food or feed value, forest products other than industrial timber, and by-products from the processing of used tyres. Biogas is a sustainable energy carrier consisting mainly of 60% methane and 35-40% carbon dioxide (Ökten 2021).

When reviewing the literature, there are both provincial and regional studies on biogas production from cattle waste inTürkiye: Ağrı (Erhan 2019), Balıkesir (Salihoğlu et al. 2019), Bilecik (Yerel Kandemir and Açıkkalp 2019), Kırklareli (Kalaycı et al. 2019), Sivas (Polat Bulut and Topal Canbaz 2019), Erzincan (Kurnuç Seyhan and Badem 2021), Bitlis (Demir Yetiş et al. 2019), East Anatolian provinces (Çağlayan 2020), Kahramanmaraş (Ay and Kaya 2020), Kayseri (Nuralan Poyraz et al. 2020), Mersin (Gülşen Akbay and Kumbur 2020), Adana (Erkan Can 2021), Antalya (Atılgan et al. 2021), Central Anatolian provinces (Topal Canbaz and Polat Bulut 2021), Çorum (Seyitoğlu and Avcıoğlu 2021), Düzce (Kurt 2021), Eskişehir (Kaynarca et al. 2021), Mardin (Yenigün et al. 2021), Bingöl (Demir and Çulun 2022), Iğdır (Tırınk 2022), Aksaray (Et Yapılcan and Bakırtaş 2023), Şırnak (Gündüz and Bayrakdar Ateş 2024).

In this study on energy consumption in dairy farming, three different dairy farms were analysed for 30 weeks and it was found that 37% of the electricity consumption of the farms was for cooling, 31% for water heating, 19% for vacuum pump and 10% for lighting systems (Cucchiella et al. 2015). Velo et al. (2014) compared an independent battery-wind-diesel hybrid system with a grid-only system in their economic study of electricity supply to a dairy farm in Spain. The farm's electricity demand was 63 kWh day^{-1} and the hybrid system designed to supply it consisted of a 20 kW wind turbine, a diesel generator and a battery. They calculated that in a location with an average wind speed of 7.39 m s^{-1}, the consumption costs would be reduced by 18% if 800 Ah batteries were used instead of 200 Ah.

A study on the design of modular hybrid renewable energy systems including biogas and solar PV for different dairy farms in the Konya, Erzurum and Izmir provinces of Türkiyeconcluded that the grid-connected system including PV and biomass is more feasible than the biomass system alone in terms of net present cost, return on investment, energy cost and annual value (Kirim et al. 2022). Bilgili (2018) developed a rooftop solar energy system designed to meet electrical energy with PV solar panels and reduce carbon dioxide in modern dairy farms in Çukurova conditions. In a solar energy system with an installed capacity of 330 kW, the payback period of the system was calculated to be 6 years and the economic life to be 20 years. The application of solar energy in a livestock farm in Konya was found to prevent 750 tonnes of CO_2 emissions per year (Orhan and Şahin 2022). It was calculated that the combined use of solar and animal biogas energy in Eskişehir-Sarıcakaya will reduce 22 thousand tonnes of CO_2 emissions compared to other energy sources (Kaynarca and Onay 2024). The modeling of hybrid power systems based on solar, wind and biogas to meet the electrical energy demand of a cattle farm in Afyonkarahisar has been estimated with Genetic Algorithm in different scenarios considering sustainable energy and environmental goals (Oz et al. 2023).

The aim of this study was to evaluate the applicability of PV and biogas systems in cattle farms in the Karaman province in terms of energy efficiency, environmental impact, and economic feasibility. Karaman was selected due to its favorable solar radiation levels and significant cattle population, making it a representative region for rural renewable energy applications. The biogas potential of cattle farming in the Karaman province of Türkiye was investigated and a rooftop SPP installation on the roof of a cattle farm, that produces its own energy with PV solar energy systems and uses the energy it produces, was simulated and analysed economically and environmentally. This study modeled the PV + biogas hybrid system in Karaman for the first time in the literature from an integrated economic and environmental perspective. While the literature often presents independent studies on either biogas production or photovoltaic systems, this study considers these two renewable energy sources as a hybrid system and presents an integrated solution. The distinguishing aspects of the study are as follows;

- Local focus: Unique data for Karaman Province based on local climate, sunshine duration and animal waste potential were used.
- Hybrid system approach: Photovoltaic and biogas systems weredesigned in an integrated manner and optimised for energy efficiency and environmental sustainability.
- Economic and environmental analysis: Both economic and carbon footprint analyses were included in the same study to more comprehensively assess the feasibility of hybrid systems.
- Scaling factor: The system was scaled according to the total cattle population in Karaman province, demonstrating its general applicability.

While many studies in the literature focus on a specific energy source (e.g. only biogas or PV systems), the combination of these two systems in this study offers a new perspective in terms of environmental impact and cost analysis.

2. Materials and Methods

The methodology was structured in the following steps (Figure 1):

i. Data Collection: Provincial animal population data (2022), climatic data (solar radiation, sunshine duration), and technical specifications of PV and biogas systems were compiled from official databases (TÜİK, MGM, EPİAŞ).

ii. Biogas Calculation: Manure production was calculated, followed by an estimation of biomethane potential and sizing of the biogas reactor using literature-based assumptions.

iii. PV System Simulation: A rooftop solar PV system was designed using PVsyst software based on local radiation data and farm dimensions.

iv. Economic and Environmental Analysis: Payback period, sensitivity scenarios, and carbon footprint comparisons were performed.

2.1. Biogas energy

Biogas is produced naturally as a result of anaerobic digestion, which is the biological conversion of organic carbon to carbon dioxide and methane (Eq. 1) (Yurtekin 2023). Figure 2 shows the production of biogas from animal waste (Chowdhury et al. 2020).

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 \qquad [1]$$

A typical biogas composition consists mainly of 55-70% methane (CH_4), 30-45% carbon dioxide (CO_2) and small amounts of hydrogen, hydrogen sulphide, carbon monoxide and nitrogen gases. Although the composition of biogas varies and has different characteristics depending on the raw material used, the type of plant and the environmental conditions, the calorific value of biogas containing 99% methane can generally be accepted as 37.3 MJ m^{-3} and the calorific value of biogas containing 65% methane as 24.0 MJ m^{-3} (EİE 2024). The biomethane potential (BMP) of waste that can be used in biogas processing plays a crucial role in determining the biogas production capacity of waste (Erkan 2020). Biogas yield refers to the amount of biogas obtained from a given amount of organic waste and indicates the production capacity of the plant. A high biogas yield provides more energy production and more efficient waste management. The methane volume fraction determines the percentage of methane gas in the biogas. High methane content increases the energy value of biogas and provides more efficient use in energy production processes (Kaya and Kılıç 2017). Biogas yields and methane volume ratios of biomass sources are shown in Table 1 (Akman 2023).

Table 2 shows the equations used in the biogas production plant during biogas production (Akman 2023).

2.2. Solar energy

Karaman has a continental climate with cold and snowy winters and hot and dry summers. The average annual maximum and minimum temperatures are 5.6-18.9°C. The average daily sunshine is 7.9 hours (MGM 2024). Figure 3 shows the solar energy potential of Karaman Province. It can be seen that the total annual solar radiation in Karaman is 1700-1800 kWh m^{-2} and the longest sunshine period is in July (EİGM 2024).

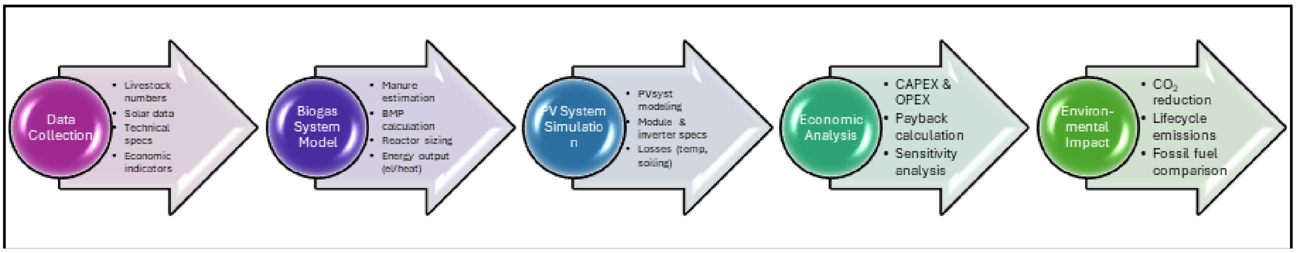

Figure 1. Methodological flowchart.

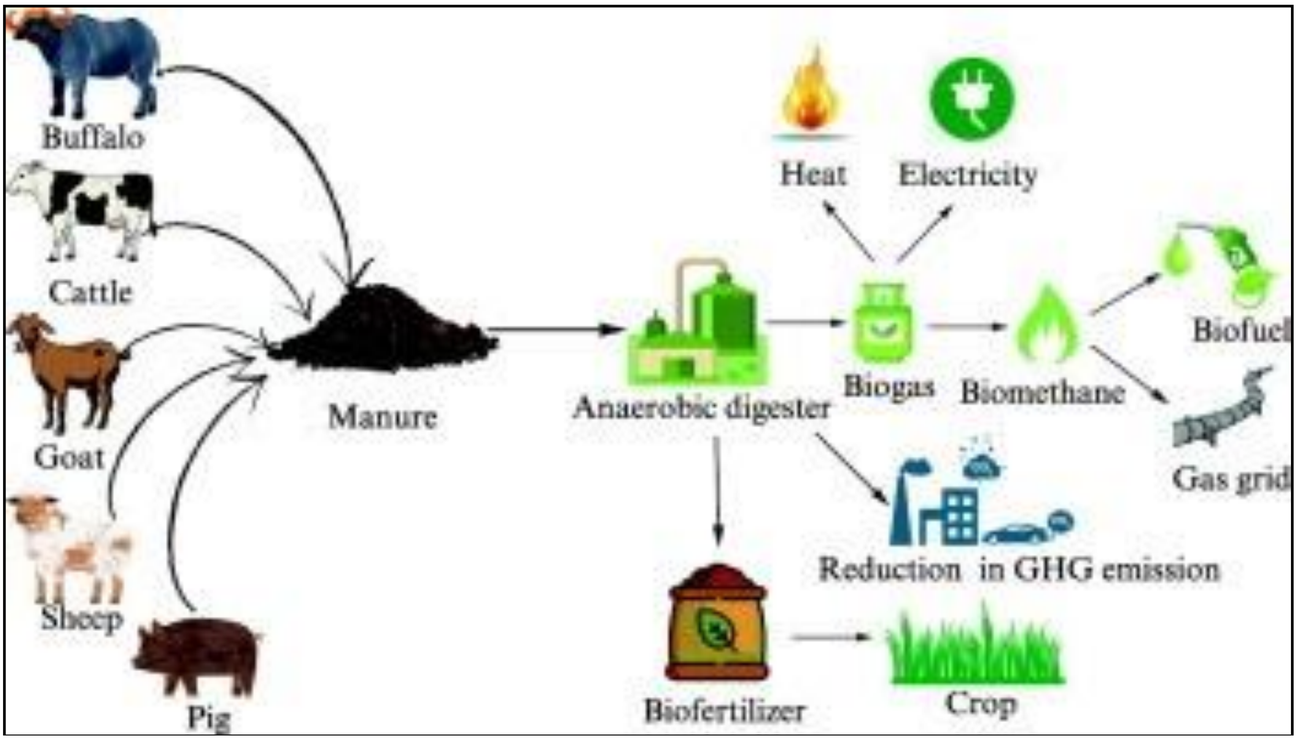

Figure 2. Biogas production from animal waste (Chowdhury et al. 2020).

Table 1. Biogas yields and methane volume fractions of biomass sources (Akman 2023)

Sources	Biogas yield (l kg^{-1})	Methane volume fraction (%)
Cattle manure	90-310	65
Poultry manure	310-620	60
Pig manure	340-550	65-70
Wheat straw	200-300	50-60
Rye straw	200-300	59
Barley straw	290-310	59
Maize stalks and waste	380-460	59
Flax, hemp	360	59
Grass	280-550	70
Vegetable waste	330-360	Variable
Variable agricultural waste	310-430	60-70
Fallen tree leaves	210-290	58
Algae	420-500	63
Waste water sludge	310-800	65-80

Table 2. Equations used in biogas energy systems (Akman 2023)

Equality Name	Equality	Equality No
Wet weight potential of animal manure	$WF = \sum NA \times \frac{LW \times FP \times CRM}{1000}$	2
Biomethane potential of the plant	$MP = \sum WP \times \frac{DM \times ODM \times MPR}{1000}$	3
Amount of diluted waste to be loaded into the reactors	$RW = WW \times \frac{DM}{DM_{pr}}$	4
Densities of waste mixtures	$\rho = 998 \times (1 - 0.004094DM_{pr\%})^{-1}$	5
Active volume of pre-storage	$FTAV = UD \times \frac{\rho}{WW}$	6
Volume of pre-storage	$FTV = FTAV \times tfh_{ca} = 5.7 + 3.8v$	7
Waste volume	$Q_h = \frac{RW}{\rho}$	8
Active reactor volume	$RVa = Q_h \times HWT$	9
Nominal reactor volume	$RVn = RVa \times tr$	10
Electrical energy obtained from biomethane	$E_e = MP \times M_E \times \eta_e$	11
Thermal energy obtained from biomethane	$E_t = MP \times M_E \times \eta_t$	12
Installed power of the biogas cogeneration plant	$P = \frac{E_e}{t}$	13

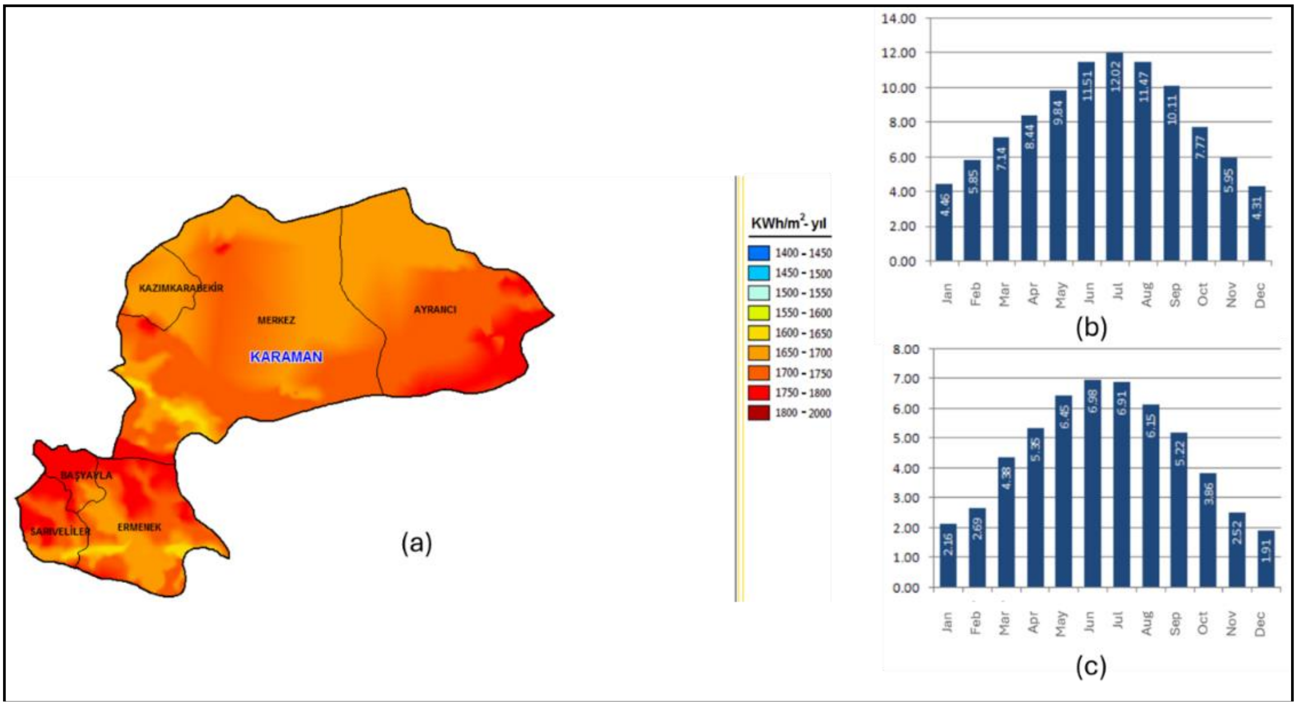

Figure 3. Karaman province: (a) Solar radiation map; (b) Sunshine hours; (c) Global radiation values (kWh $m^{-2}day^{-1}$) (EİGM 2024).

In this study, a PV solar power plant generating 300 kWe of electrical energy was modeled considering data such as the average electrical energy requirement of 0.6-1.2 kW for one cattle per day (Cucchiella et al. 2015), a barn with a barn area of 5000 m^2 and a roof area of 5300 m^2 for 250 cattle, regional climatic conditions and sunshine duration. SketchUp (SketchUp 2024) was used to model the system (Figure 4). Considering the existing environmental conditions at the project site and today's technology, it was preferred to use half-cell and multi-busbar large-cell PV modules with monocrystalline structure and higher efficiency. In order to make more efficient use of the available space in the system, PV modules with a power of 550 Wp, which can generate more power per unit area, were preferred. The PV modules used are Elin's ELNSM72M-550-HC-HV monocrystalline model, and 648 units were used. In the inverter group, our models were created by using the system parts that we call series inverters. 3 Huawei's SUN2000-100KTLM1-400 V model 100 kW array inverters were placed in the system. The main advantage of using array inverters in partial systems is that in case of any malfunction or change, instead of using a central inverter and stopping the whole system, intervening in a small area on the array will both extend the life of the system and eliminate energy loss.

The energy of a photovoltaic system depends on two basic variables: electrical and thermal. While electricity is generated by the photovoltaic effect, solar cells also heat up due to the thermal energy generated by solar radiation. Since the thermal energy generated on PV surfaces cannot be used for any useful purpose, it is lost to the environment as heat loss (Joshi et al. 2009a).

The equations used in PV systems are given in Table 3 (Joshi et al. 2009a; b).

3. Results

The total number of cattle in Karaman province was estimated to be 63515 in 2022 (Karaman Agriculture and Forestry 2024). In this study, based on the examples in the literature and established examples (Erhan 2019; Nuralan Poyraz et al. 2020; Kurnuç Seyhan and Badem 2021), the electrical efficiency of the electrical unit of the reactor is 40%, the thermal energy conversion efficiency is 42%, the annual operation time of the cogeneration system is 8200 hours, the number of daily loads is 2, the process dry matter content is 10%, the pre-storage tolerance coefficient is 1.15, the reactor tolerance coefficient is 1.15, and the hydraulic standby time is 25 days. Accordingly, the annual wet manure is calculated to be 828824.4 tonnes and the biomethane potential produced in the plant is calculated to be 20.4 million m^3. As a result of the calculation made for the sizing of the forebay, the daily amount of diluted waste to be

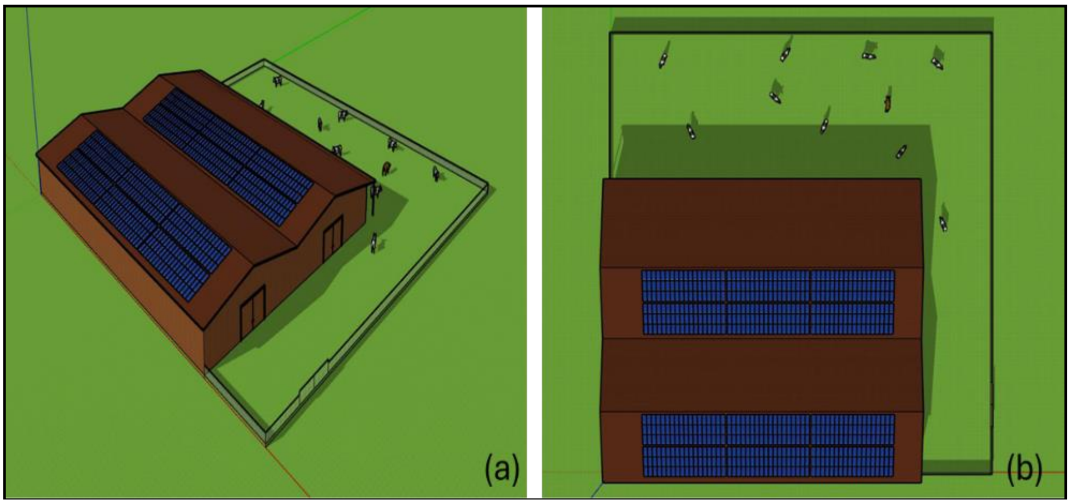

Figure 4. Karaman SPP: (a) 3D model; (b) 3D model top view.

Table 3. Equations used in PV solar energy systems (Joshi et al. 2009a; b)

Equality Name	Equality	Equality No
Maximum output power	$P_{max} = V_{max} I_{max}$	14
Open circuit voltage under atmospheric conditions	$V'_{oc} = V_{oc} \frac{100 + (T_{cell} - 25)(\tau_{ec})}{100}$	15
Open circuit current under atmospheric conditions	$I'_{sc} = I_{sc} \frac{\sigma_T}{1000}$	16
Filling factor	$FF = \frac{V_{max} I_{max}}{V'_{oc} I'_{sc}}$	17
PV system output energy	$E_o = \frac{P_{max}}{FF} + \dot{Q}$	18
Thermal energy	$\dot{Q} = h_{ca} A (T_{cell} + T_{amb})$ $h_{ca} = 5.7 + 3.8v$	19
Energy efficiency	$\eta = \frac{\frac{P_{max}}{FF} + \dot{Q}}{\sigma_T A}$	20
Performance ratio	$PR = \frac{Real\ energy\ output}{Theoretical\ energy\ output}$	21

loaded into the reactor was found to be 3167.8 tonnes, the active volume of the forebay was found to be 6088.1 m^3 and the required volume of the forebay was found to be 6998.4 m^3. The daily waste input to the reactor is 3044.3 m^3. The required active reactor volume for the biogas plant should be 76103.2 m^3 and the net volume should be 87518.4 m^3.

The amount of electricity to be produced by burning the biomethane produced in the plant is 78.73 GWh per year and the amount of thermal energy to be produced is 321.73 GWh per year. The installed capacity of the CHP plant is 9.57 MWe. The economic equivalent of the electrical energy and thermal energy to be produced by the plant annually is ₺224.1 billion and ₺820.4 billion respectively (EPİAŞ 2024).

In the design of the farm with a capacity of 250 cattle, 648 photovoltaic (PV) modules with a power of 550 Wp were used in the PVsyst programme (Mermoud and Wittmer 2014), and an annual energy production of 577 MWh was achieved. The largest losses in PV system efficiency were due to temperature (4.91%) and pollution (3%) (Figure 5).

The annual electrical energy demand of a cattle farm depends on parameters such as heating, ventilation, lighting, milking, milk tank, feeding (Çiçekli 2019). The annual energy demand of the farm where this study was conducted was calculated to be 233.4 MWh. In this case, the energy produced was equal to the energy required. The initial investment cost of installing a PV solar power plant on an existing barn roof is ₺ 6.4 million, depending on parameters such as panels, inverters, cables. The payback period can be calculated as 5.21 years by adding operational maintenance, staff salaries and the average inflation rate (20%) added to the electricity price each year to the initial investment cost (Energy Agency 2024).

The sensitivity analysis was carried out to assess the impact of changes in energy prices on the cost-benefit balance (CBA) of the system. In the analysis, the average unit price of electricity for 2024 is ₺ 0.9 kWh^{-1} (EPİAŞ 2024) and scenarios of 20% increase and 20% decrease in this price are analyzed. The economic returns of the biogas plant and the PV system were evaluated separately (Table 4).

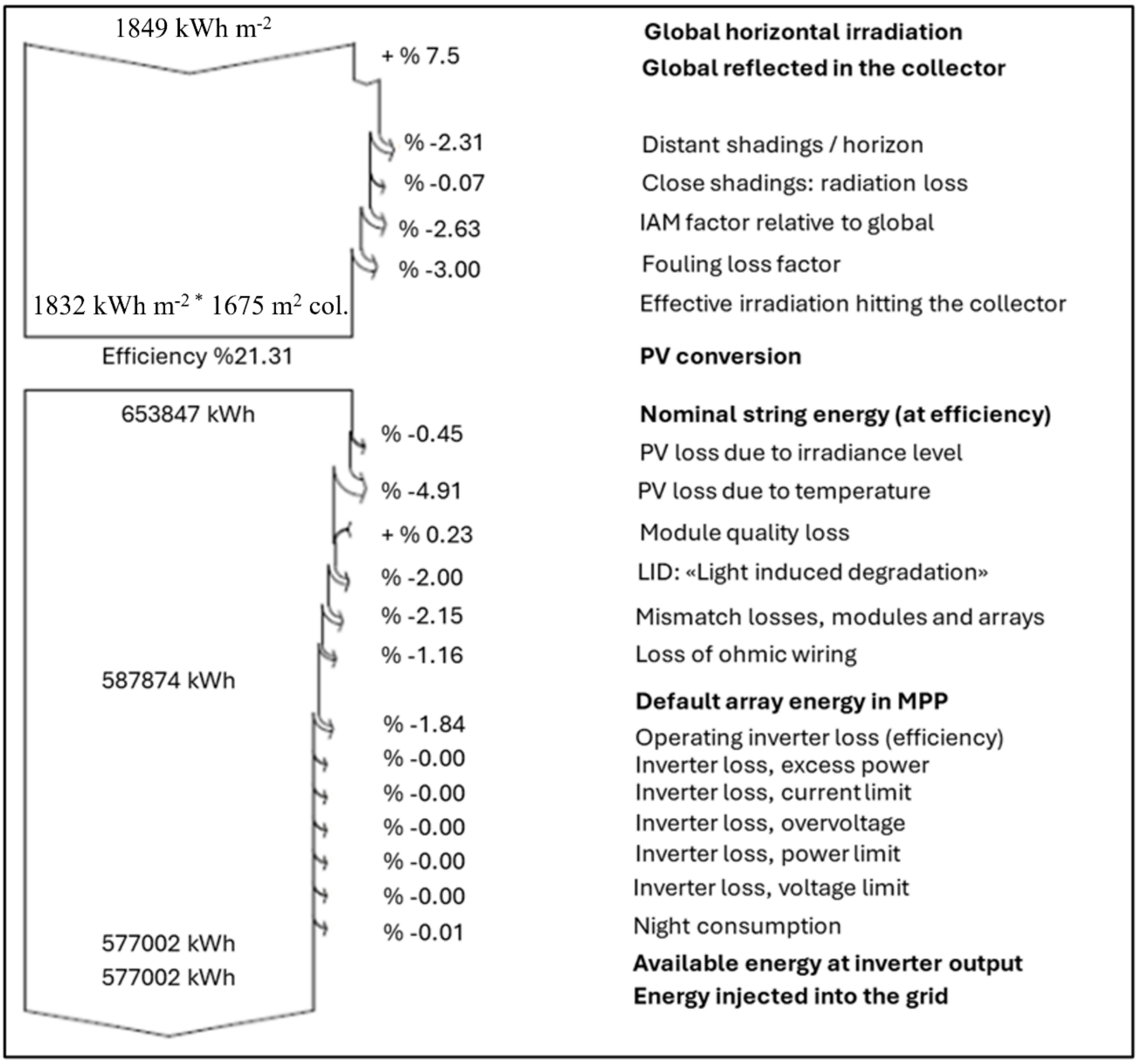

Figure 5. Grossman diagram.

Table 4. Sensitivity analysis for hybrid system CBA

Parameters	-20% price decrease	Current status (0,9 ₺)	+20% price increase
Annual revenue of PV system (million ₺)	0.415	0.519	0.623
Annual revenue of biogas plant (million ₺)	70.85	88.56	106.27
Annual revenue of hybrid system (million ₺)	71.27	89.08	106.89
Payback period (years)	7.22	6.5	5.8

A 20% price increase reduces the payback period of the hybrid system from 6.5 to 5.8 years. A 20% price decrease increases the payback period to 7.22 years, reducing the economic viability. The sensitivity analysis shows that the PV system is less vulnerable than the biogas system. This suggests that the biogas system has a greater financial impact. The hybrid system, which integrates both energy sources, provides an economic return independent of energy price fluctuations. This analysis shows that the hybrid system is able to protect its financial and environmental benefits against possible fluctuations in the energy market. In this context, hybrid systems offer an important opportunity for energy security and economic sustainability.

Carbon footprint is the total amount of greenhouse gases emitted directly or indirectly into the atmosphere by an individual, organization or product. This measurement is usually expressed in tonnes of carbon dioxide equivalent (tCO_2e). Renewable energy systems, particularly solar energy systems, have a much lower carbon footprint than fossil fuels. Solar energy systems do not directly emit CO_2 during electricity generation and therefore do not contribute to increasing atmospheric greenhouse gas concentrations (IEA 2024b). For example, a coal-fired power plant emits approximately 820 kg of CO_2 per megawatt hour (MWh) of energy produced (IPCC 2024). In contrast, solar PV systems emit only 20-50 kg CO_2e/MWh over their life cycle (NREL 2024). Equation 22 can be used to calculate the amount of CO_2 that would be emitted into the atmosphere if a fossil fuel system were to produce the same amount of electricity (IPCC 2024).

$$CO_2\ emission\ (kg\ CO_2) = Electricity\ production\ (kWh) \times Emission\ factor\ (\frac{kg\ CO_2}{kWh}) \quad [22]$$

According to this calculation, 473.14 tonnes of CO_2 would be emitted annually if a fossil fuel system were to generate the same amount of electricity. However, with the PV solar power system, this amount is greatly reduced and only 11.54-28.85 tonnes of CO_2 are emitted, taking into account the lifecycle emissions. In other words, when PV solar power systems are used for production, 94-98% less carbon dioxide is emitted compared to fossil fuels. As a result, the PV solar power plant significantly reduces carbon emissions compared to energy systems powered by fossil fuels. This contributes significantly to environmental sustainability by reducing the carbon footprint of the farm. In the long term, such investments in renewable energy play a vital role in combating climate change and offer economic as well as environmental benefits.

When calculating the carbon emissions of biogas plants, the amount of CO_2 produced as a result of biogas combustion should be taken into account (Eq. 23) (IPCC 2024).

$$Total\ CO_2\ emissions\ \left(\frac{kg}{year}\right) = Biomethane\ potential\ \left(\frac{m^3}{year}\right) \times 2.75(\frac{kg\ CO_2}{m^3\ CH_4}) \quad [23]$$

The total CO_2 emission of the biogas production plant is 55.4 thousand tonnes per year. If the electricity produced in this plant was generated using natural gas (Eq. 22), the CO_2 emissions would be 334.4 thousand tonnes per year. It emits 83% less CO_2 per year than a natural gas power plant.

4. Discussion and Conclusions

In this study, renewable energy applications on livestock farms in the Karaman Province were investigated in detail. The results clearly demonstrate the advantages of hybrid renewable energy systems in terms of both economic and environmental benefits. The biogas and PV systems used in the study increased the energy independence of the farms while significantly reducing the carbon footprint.

The annual amount of wet manure used for biogas production in this study was 828824 tonnes and the biomethane production potential was calculated to be 20.4 million m3. The combustion of this biomethane in the CHP unit produced 78.73 GWh of electricity and 321.73 GWh of thermal energy. In addition, 648, 550 Wp PV modules were designed using PVsyst software for a farm with a capacity of 250 cattle. This system produced 577 MWh of energy per year, meeting all the farm's energy needs, with losses of 4.91% due to temperature and 3% due to pollution.

In the economic analysis of the system, the initial investment cost of the PV solar power plant was determined to be TL 6.4 million and the payback period was calculated to be 5.21 years. In the analysis of the environmental impact of the renewable energy systems, the PV system reduces CO_2 emissions by 94-98% compared to fossil fuels, while the biogas plant provides 83% lower carbon emissions compared to the natural gas plant. As a scaling factor, the energy production and environmental benefits of the plant were confirmed by the number of cattle in Karaman province (0.394%).

The findings of the present study demonstrate the considerable potential of renewable energy systems, not only in terms of energy production, but also with regard to environmental sustainability and economic feasibility. These results can serve as an incentive for the more widespread use of renewable energy sources.

In addition to the technical and economic evaluations, policy support mechanisms could enhance the practicality of such systems. For instance, incentives under the Ministry of Agriculture and Forestry's sustainable agriculture programs could help promote the adoption of PV and biogas systems in livestock farms. Local governments could also support such transitions through infrastructure and permitting facilitation.

This study has several limitations. The calculations were based on static livestock population data from 2022, which may vary annually. Panel pollution and temperature effects were assumed to be constant, and inflation rates used in economic estimates are subject to change. Future studies should incorporate dynamic data and scenario-based modelling for more robust conclusions.

Future studies could investigate the use of optimization algorithms for the integrated management of biogas plants and photovoltaic (PV) systems. Furthermore, the effects of different organic waste mixtures could be analyzed to increase the efficiency of biogas production plants. Active cooling systems for temperature management or thermal energy recovery methods can be investigated to improve the performance of PV systems. Extensive field studies can be conducted to assess the potential of hybrid systems in different geographical regions. Finally, extending the economic analysis with scenarios depending on the fluctuations in energy prices would be useful to demonstrate the feasibility of the system under different market conditions.

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Nomenclatures

A	: PV module surface area
CRM	: Collectability rate of manure
DM	: Dry matter content of the waste
DMpr	: Dry matter ratio to be used in the process
Ee	: Amount of electricity generated from the plant (kWh year^{-1})
Et	: Thermal energy produced from the plant (kWh year^{-1})
FP	: Daily fertiliser production (kg day^{-1})
FTAV	: Front tank active volume (m^3)
FTV	: Front tank volume (m^3)
h_{ca}	: Convection and radiation heat transfer coefficient between the solar cell and the atmosphere
HWT	: Hydraulic waiting time (days)
I_{sc}	: Short circuit current
LW	: Live weight
Me	: Energy content of methane gas (kWh m^{-3})
MP	: Amount of methane produced from the plant (m^{3}CH$_4$ year^{-1})
MPR	: Specific methane production rate of the waste (m^{3}CH$_4$ kg^{-1} ODM)
NA	: Number of animals
ODM	: Organic dry matter content of the waste
P	: Installed power of cogeneration system (kWe)
$\dot{Q}$	: Thermal energy
Qh	: Waste volume to be loaded to the reactor in one day (m^3 day^{-1})
RVa	: Reactor active volume (m^3)
RVn	: Reactor net volume (m^3)
RW	: Amount of reconstituted waste to be loaded in one day
T_{amb}	: Ambient temperature
T_{cell}	: PV module cell temperature
t	: Annual operation time of the cogeneration system (hours)
tf	: Front tank tolerance coefficient (1.1-1.15)
tr	: Reactor tolerance coefficient (1.1-1.15)
UD	: Number of uploads per day
v	: Wind speed (m s^{-1})
V_{oc}	: Open circuit voltage
WF	: Wet fertiliser amount (kg day^{-1})
WP	: Waste potential (tonnes year^{-1})
WW	: Wet weight of incoming waste in one day
σ_T	: Total solar radiation
ρ	: Density of the mixture (kg m^{-3})
τ_{ec}	: Temperature dependent voltage coefficient of variation
η_e	: Electricity conversion efficiency of the cogeneration system
η_t	: Thermal energy conversion efficiency of cogeneration system