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HYBRID RENEWABLE ENERGY SYSTEMS AND CARBON FOOTPRINT REDUCTION IN LIVESTOCK PRODUCTION FACILITIES

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Abstract: Carbon dioxide (CO_2) is an essential component for photosynthesis, and its presence within certain limits in the atmosphere is necessary for the sustainability of life on Earth. However, the intensive use of fossil fuels in industry, transportation, agriculture, and residential sectors increases atmospheric CO_2 concentrations, leading to global climate change and an expansion of the carbon footprint. In particular, coal-fired thermal power plants are among the energy production sources with the highest CO_2 emissions per unit of energy. Depending on the diversity of electricity generation sources, the average emission factor is commonly accepted as 0.478 kg CO_2 per kWh of electricity production. In this context, the widespread use of renewable energy sources such as solar and wind energy is of strategic importance for both environmental sustainability and combating climate change. The Marmara Region of Türkiye offers favorable conditions for such systems due to its high solar radiation duration and wind energy potential. In this study, the feasibility of meeting the energy demand required for the cooling system of a buffalo barn, designed with a capacity of 64 animals and located in rural Tekirdağ, was evaluated using a hybrid renewable energy system. The total power requirement for the fan–pad ventilation system was calculated as 8.04 kW, and considering production fluctuations and system losses, the installed capacity was determined as 12 kW. This capacity was designed to be equally distributed between a 6 kW photovoltaic system and a 6 kW wind turbine system. Considering the annual average daily sunshine duration of Tekirdağ (5.7 h day^{-1}), the theoretical annual energy production of the 6 kW photovoltaic system was calculated as 12483 kWh. By applying a performance ratio (PR) of 0.75 to account for system losses, the actual annual energy production was estimated to be approximately 9362 kWh. Assuming that the wind turbine operates for an average of 5 hours per day, its annual energy production was calculated as approximately 10950 kWh. Accordingly, the hybrid system provides a total annual energy production of approximately 20312 kWh, preventing the emission of approximately 9710 kg CO_2 into the atmosphere. The findings indicate that hybrid renewable energy systems offer an effective solution for meeting energy demands in rural livestock operations and contribute significantly to reducing the carbon footprint.

Keywords: Buffalo barn, Hybrid renewable energy, Wind turbine system, Solar panel system, Fan–pad system

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1. Introduction

Carbon dioxide (CO_2), although present in the atmosphere at a concentration of approximately 0.042% (about 420 ppm), is a fundamental component for plant life and the global carbon cycle. CO_2 is a colorless and odorless gas that, despite its relatively low atmospheric concentration, has significant effects on the climate system. During photosynthesis, plants convert CO_2 into organic compounds using water and solar radiation, while releasing oxygen into the atmosphere. When plants die, decompose, or are burned, carbon recombines with oxygen and is released back into the atmosphere as CO_2, thereby completing the carbon cycle (Anonymous, 2025a).

Due to its ability to trap heat energy, CO_2 is one of the most important greenhouse gases. The rapid increase in its atmospheric concentration as a result of human activities triggers the phenomenon known as global warming and leads to a series of cascading effects that threaten living organisms (Akın, 2006). Along with CO_2, gases such as CH_4, N_2O, CFC_s, O_3, CO, and SF_6 contribute directly or indirectly to the greenhouse effect, helping to maintain the Earth's surface temperature at levels suitable for life (Anonymous, 2025a).

Deforestation, organic matter decomposition, population growth, and animal respiration contribute to increased CO_2 emissions (Koç and Şahin, 2023). CO_2 is a greenhouse gas and one of the primary drivers of climate change (Karaaslan et al., 2017). Reducing fossil fuel consumption and increasing the use of renewable energy

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sources significantly decrease CO_2 emissions (Türkboyları and Yüksel, 2024a).

In Türkiye, approximately 21% of electricity generation is supplied by coal-fired thermal power plants, which emit about 0.94 kg CO_2 per kWh of electricity produced (Orhan and Şahin, 2022). This value represents one of the highest emission levels among electricity generation sources.

Emission factors for electricity generation vary depending on the energy mix; however, lower average values are reported for mixed or renewable-based systems. In this study, an average emission factor of 0.478 kg CO_2 per kWh was adopted based on national institutional assessments (SDU Yeşil Kampus, 2026).

These findings highlight the environmental importance of transitioning to renewable energy systems.

1.1. Agriculture and Energy Relationship

Agriculture is an energy-intensive sector and can be broadly classified into crop and livestock production. In crop production, almost all stages—including soil preparation, sowing, irrigation, fertilization, crop management, harvesting, and transportation—are generally carried out using fossil fuels (Türkboyları, 2023; Altuntaş and Özgöz, 2024). This dependence directly increases production costs. The use of electric tractors and other electrically powered agricultural machinery has the potential to reduce fossil fuel consumption.

One technological approach that enables the efficient use of renewable energy resources is integrating different energy sources to complement each other (Yılmaz et al., 2023a). In livestock production, energy demand is predominantly met by electricity. In buffalo housing systems, solar and wind energy technologies can be effectively utilized (Yüksel and Türkboyları, 2021; Türkboyları and Yüksel, 2023). Wind–solar hybrid systems help balance seasonal fluctuations in energy production and provide a more reliable and continuous energy supply (Rezai et al., 2018; Türkdoğan et al., 2020; Türkboyları and Yüksel, 2024b).

1.2. Anatolian Water Buffalo Husbandry

Buffaloes raised in Türkiye belong to the Anatolian water buffalo (*Bubalus bubalis*), which is classified within the Mediterranean buffalo group and the river-type buffaloes. This indigenous breed has adapted well to high temperatures and humidity conditions due to its morphological and physiological characteristics. However, because of the limited number of subcutaneous sweat glands, its thermoregulation capacity is restricted; therefore, wallowing or entering water to cool down is of critical importance for animal welfare and productivity.

The Anatolian water buffalo can be successfully raised even in wetlands, marshes, and areas with permanent access to water—environments where cattle generally show low productivity or cannot survive. Lakes, ponds, streams, and riverbanks provide suitable ecological conditions that allow buffaloes to exhibit their natural cooling behavior. During hot periods, time spent in water helps maintain body temperature balance and positively affects milk yield and reproductive performance. In addition, this breed has a high capacity to utilize fibrous and low-quality roughage, enabling economically viable milk and meat production even on poor-quality pastures (Koyuncu et al., 2021; Satılmış and Kul, 2024). Compared to other large ruminants, buffaloes are more resistant to natural environmental conditions and diseases, and their reproductive and feeding costs are generally lower (Alkoyak and Öz, 2022).

1.3. Environmental Conditions and Ventilation in Animal Barns

In water buffalo barns, excess heat, humidity, and gases such as carbon dioxide (CO_2), ammonia (NH_3), hydrogen sulfide (H_2S), and methane (CH_4) are generated as a result of animal metabolism. Elevated concentrations of these gases may adversely affect animal health as well as environmental and human health (Kocaman et al., 2018). Ventilation is therefore essential to maintain desirable environmental conditions within buffalo barns (Yüksel and Şişman, 2015; Koç and Şahin, 2023).

Ventilation can be achieved through natural or mechanical means. Since natural ventilation does not always provide sufficient effectiveness, mechanical ventilation becomes necessary, particularly during hot periods. Mechanical systems reduce indoor temperature, remove contaminated air, and supply fresh air through the use of fans and evaporative cooling pads. In rural areas, the energy demand of buffalo barns can be met by solar photovoltaic panels and wind turbine systems. Moreover, the combined (hybrid) use of these two renewable energy systems is also feasible (Türkboyları and Yüksel, 2024b).

1.4. Solar and Wind Renewable Energy Potential of Türkiye

Due to its geographical location, Türkiye has a higher solar and wind energy potential compared to many countries. The country's wind energy potential primarily arises from pressure differences formed between the cold Black Sea and Central Asian steppes and the warm Aegean and Mediterranean regions. This meteorological structure results in strong and persistent winds throughout the year, particularly in Thrace, Southern Marmara, and along the Aegean and Mediterranean coasts (Koçaslan, 2010).

Located within the solar belt, Türkiye is also highly advantageous in terms of annual sunshine duration. However, both solar and wind energy sources inherently exhibit intermittent and fluctuating generation profiles. During summer months, solar radiation is high while wind speeds are generally lower, whereas in winter months, solar radiation decreases and wind speeds increase. This seasonal complementarity enhances the importance of hybrid energy systems that integrate both resources (Özdamar et al., 2005).

Solar–wind hybrid energy systems provide more stable energy production by balancing supply and demand fluctuations. The general operating principle of hybrid renewable energy systems combining solar panels and wind turbines is based on complementary energy generation from these sources. In off-grid systems, energy storage units (batteries) are used to ensure an uninterrupted power supply during periods of insufficient solar radiation or low wind speeds. For efficient battery operation, proper system design and the use of suitable charge controllers are required. Charge controllers protect batteries from overcharging and deep discharging, thereby extending battery lifespan and improving overall system performance. Inverters, within the system, convert direct current (DC) into alternating current (AC), enabling the generated energy to be integrated into the electrical grid or used directly within animal barn systems (Şenel and Koç, 2015).

1.5. Ventilation and Cooling Systems in Animal Barns

Ventilation and cooling systems in animal barns are of critical importance for improving animal welfare and productivity. Mechanical ventilation systems typically consist of fans, evaporative cooling pads, circulation pumps, water distribution pipes, and a water supply source. In these systems, cooling is achieved through the latent heat absorbed from the surrounding air during water evaporation. As air passes through the evaporative pads, it becomes humidified and cooled before entering the barn, resulting in a reduction in ambient temperature and the creation of a more comfortable environment for animals (Yüksel and Şişman, 2015).

When the fans are in operation, carbon dioxide (CO_2) and other harmful gases generated by animal metabolism are expelled from the barn. This process creates a low-pressure zone inside the building, allowing fresh air to be drawn in. Consequently, both heat stress is reduced and indoor air quality is improved. Under the climatic conditions of Tekirdağ, ventilation systems must be supported by cooling mechanisms when outdoor temperatures exceed 22–24 °C during the summer months (June, July, and August). Although the need for ventilation decreases during winter, it does not disappear entirely (Yüksel and Şişman, 2015).

The energy requirements of these systems can be met through solar–wind hybrid energy solutions. Hybrid systems balance seasonal variability, ensuring energy supply reliability while simultaneously reducing CO_2 emissions associated with fossil fuel consumption.

This study aims to evaluate the feasibility of supplying the energy demand of mechanical ventilation and cooling systems used to maintain optimal environmental conditions in a water buffalo barn located in rural Tekirdağ through a hybrid renewable energy system integrating solar and wind resources, and to assess the potential contribution of this system to the reduction of CO_2 emissions.

2. Materials and Methods

2.1. Study Area

This study was conducted in the Thrace Region, located in the northwestern part of Türkiye, specifically in the central district (Süleymanpaşa) of Tekirdağ Province. Tekirdağ is situated between 26°–29° east longitude and 40°–42° north latitude and lies on the Thrace Peninsula. The region is bordered by the Black Sea to the north, the Bosphorus Strait to the east, the Marmara Sea and the Dardanelles to the south, and the Aegean Sea to the west. Tekirdağ has a total surface area of 6313 km² and is generally characterized by undulating topography and a semi-humid climate. Summers are typically hot and dry, while winters are cold and rainy. During the summer period, mild southwesterly winds (Lodos) are dominant, whereas cold northeasterly winds (Poyraz) prevail in winter, shaping the regional climate conditions (MCT, 2025).

From an energy potential perspective, data from Türkiye's Solar and Wind Energy Potential Atlases (GEPA and REPA) indicate that Tekirdağ Province and the Marmara coastal belt rank among the leading regions in the country in terms of solar irradiation duration and wind speed (MENR, 2025a; MENR, 2025b). Previous studies by Karık et al. (2017) and Tunus (2019) have also highlighted this potential, demonstrating that Tekirdağ possesses distinct seasonal advantages, with higher solar energy potential during summer months and increased wind energy potential during winter months.

This natural energy potential of the region enables the feasible and sustainable use of renewable energy systems to meet the electricity demand of livestock production facilities. Accordingly, the climatic and geographical advantages of Tekirdağ were taken into account in the design of the hybrid energy system evaluated within the scope of this study.

2.2. Method

Within the scope of this study, a hybrid energy system based on solar and wind energy was designed to provide ventilation and cooling in Anatolian water buffalo barns located in Tekirdağ. In this context, a mechanical ventilation and cooling system was designed for a closed, double-row water buffalo barn with a capacity of 64 animals (Figure 1).

The total enclosed area of the water buffalo barn is approximately 499 m², with dimensions of 10.1 m × 49.4 m (10.1 × 49.4 = 498.94 m²) (Avcı, 2015).

To remove indoor air contaminated with CO_2 and other harmful gases in animal barns, the energy demand of the designed ventilation and cooling system was planned to be supplied by a hybrid renewable energy system consisting of solar panels and wind turbines.

2.3. Design of Solar–Wind Hybrid Energy Systems for Water Buffalo Barns

Located at the crossroads of Europe and Asia, Türkiye consists of two peninsulas, Anatolia and Thrace. Due to its position within the solar belt, Türkiye has a significant advantage in terms of solar energy potential compared to many other countries. In addition, the presence of alternating high- and low-pressure systems formed between the cold Asian steppes and the warm Mediterranean basin provides the country with considerable wind energy potential. Consequently, Türkiye is among the countries with high renewable energy potential in terms of both solar and wind resources.

In this context, the utilization of renewable energy sources in plant and animal production contributes to reducing energy expenditures, which constitute a substantial portion of total production costs. Although renewable energy systems generally require relatively high initial investment costs, the absence of fuel expenses, long service life, and low maintenance requirements offer significant economic advantages in the long term. Previous studies have demonstrated that solar and wind energy systems can be economically viable for use in agricultural and livestock production enterprises (Türkboyları and Yüksel, 2024b; Orhan and Şahin, 2022).

Solar photovoltaic systems consist of photovoltaic cells that directly convert solar radiation into electrical energy. These cells are typically manufactured using semiconductor materials such as silicon.

Wind turbines, on the other hand, are systems that convert the kinetic energy of moving air into electrical energy. Wind turbines generally operate within wind speed ranges of approximately 2–4 m s^{-1} to 25–35 m s^{-1} (MENR, 2025a).

Hybrid systems that combine solar and wind energy offer an effective solution for mitigating the variability and intermittency inherent in renewable energy sources. These systems can be designed either as grid-connected (on-grid) or standalone (off-grid) configurations.

In off-grid hybrid energy systems, electricity generation is typically supplied by solar panels and wind turbines. In contrast, system continuity is ensured through the use of accumulators (batteries), charge controllers, inverters, protection devices, and control units (Şenel and Koç, 2015). Another important consideration in the design of hybrid energy systems is that, in addition to being environmentally friendly, they should also provide an economically sustainable solution.

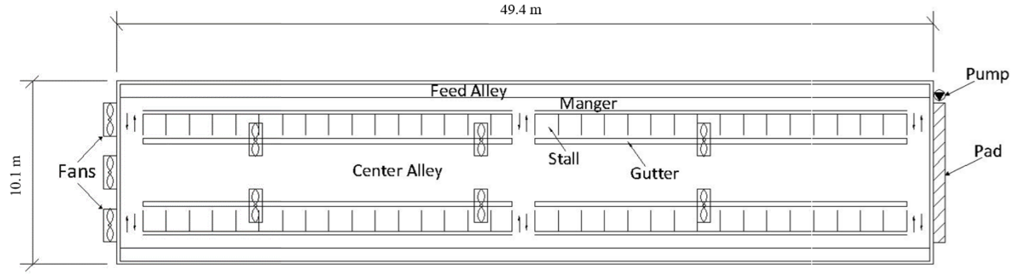

Figure 1. Plan view of the designed water buffalo barn with the ventilation and cooling system.

2.4. Energy Production Calculation

The theoretical energy production of the photovoltaic (PV) system was calculated based on panel specifications and regional solar radiation data. However, this calculation represents ideal conditions and does not include losses occurring under real operating conditions. In PV systems, actual energy production is lower due to inverter losses, temperature effects on panels, cable losses, and other system-related losses.

Therefore, the performance ratio (PR) was used to more realistically represent system performance. PR is defined as the ratio of the net energy output of the system to the theoretically obtainable reference energy and is widely used as a performance indicator for comparing different systems. According to the literature, PR values generally range between 75% and 85% (AEPC, 2022). In addition, studies based on real PV system data report average PR values of approximately 78–80% (DOE, 2021). Furthermore, model-based studies indicate that the overall system loss factor is approximately 0.77 (NREL, 2013).

In this study, a performance ratio (PR) of 0.75 was adopted to represent system losses. The performance ratio represents overall system losses, including inverter losses, temperature effects, and other system-related factors. Accordingly, the actual energy production was calculated from the theoretical energy production (e_theoretical) and the performance ratio (PR) using equation 1:

$$\mathrm{E} = \mathrm{E}_{\text{theoretical}} \times \mathrm{PR} \tag{1}$$

3. Results

In designing the fan–pad system for ventilation and cooling in water buffalo barns, it is necessary to determine the physical dimensions of the barn as well as the number of animals housed inside. Within the scope of the planned project, a stanchion-type barn housing 64 Anatolian water buffaloes was considered. The barn has a width of 10.1 m and a length of 49.4 m, resulting in a total enclosed area of approximately 499 m^2 (10.1 × 49.4 = 498.94 m^2) (Avcı , 2015).

In calculating the required pad area, the barn floor area was taken as the basis. A pad area of 1 m^2 is required for every 25 m^2 of barn floor area (A_1). Accordingly, the required pad area (A_p) for the barn with a total floor area of 499 m^2 (A_b) was calculated using the following equation (equation 2) (Yüksel and Şişman, 2015).

$$A_p = \frac{A_b}{A_1} = \frac{499}{25} = 19.96 \sim 20\ m^2 \tag{2}$$

To ensure continuous and effective cooling performance of the pad system, the pad surface must be constantly wetted with water. This process is achieved using a circulation pump with a power rating of 0.2 kW.

In the design of ventilation systems for buffalo barns, calculating the required ventilation rate based on the number of animals is of great importance. The removal of excess heat, moisture, carbon dioxide (CO_2), and other harmful gases generated by the animals within the barn is a critical requirement for both animal health and productivity.

The required ventilation rate for ruminant animals varies between 0.35 and 3.5 $m^3\ h^{-1}\ kg^{-1}$, depending on seasonal conditions, live weight, and metabolic activity. In this study, an average value of 2 $m^3\ h^{-1}\ kg^{-1}$ (Q_1) was adopted (Wathes and Charles, 1994). This basic assumption provides a sufficient initial parameter for maintaining optimal air quality within the barn.

The live weight of Anatolian water buffaloes ranges between 400 and 600 kg, and the average live weight was assumed to be 500 kg (m_1) (TAGEM, 2009). Accordingly, the total required ventilation rate (Q_t) for a barn housing 64 animals (n) with an average live weight of 500 kg was calculated using the following equation (equation 3).

$$Q_t = Q_1 \times n \times m_1 = 2 \times 64 \times 500 = 64000\ m^3h^{-1} \qquad (3)$$

The fans to be used in the barn should be capable of operating either individually or simultaneously, depending on the ventilation demand. Due to their low noise levels, fans with a diameter of 60 cm were preferred in the system. This type of fan has a unit air flow rate of 8500 $m^3\ h^{-1}$, with a power consumption (Q_a) of 0.56 kW (Anonymous, 2025b).

The required number of exhaust fans (n_a) to remove polluted indoor air from the barn to the outside environment was calculated using the following equation (equation 4):

$$n_a = \frac{Q_t}{Q_a} = \frac{64000\ m^3h^{-1}}{8500\ m^3h^{-1}} = 7.53 \sim 8 \qquad (4)$$

The considerable length of the barn (49.4 m) may result in insufficient air circulation and the formation of stagnant air zones in certain interior sections. To prevent such conditions, the installation of additional exhaust fans at regular intervals along the barn length is recommended (Yüksel and Türkboyları, 2018).

Accordingly, six additional exhaust fans were planned to be installed along the barn, with two units placed at each of the 14th, 28th, and 40th meters. Thus, together with the previously proposed eight fans, a total of 14 exhaust fans were included in the system to ensure homogeneous air circulation within the barn. This approach represents a commonly used engineering solution for achieving balanced air distribution in elongated livestock buildings.

The total power requirement (P_t) of the hybrid energy system was calculated as the sum of the power demand of the exhaust fans (P_a) and that of the circulation pump (P_s) (equation 5).

$$P_t = P_a \times 14 + P_s = 0.56 \times 14 + 0.2 = 8.04\ kW \qquad (5)$$

The annual energy production of the wind turbine system was calculated based on its average daily operating time. It was assumed that the wind turbine operates for approximately 5 hours per day on average (Türkboyları and Yüksel, 2024c). Under this assumption, the annual energy production potential of a 6 kW wind turbine was calculated as follows (equation 6):

$$\text{Annual Energy Production} = 6 \times 5 \times 365 = 10950\ kWh \qquad (6)$$

Based on this production amount, the wind turbine energy system prevents the emission of approximately 5234 kg of CO_2 annually (10950 kWh × 0.478 kg CO_2).

To evaluate the effect of the photovoltaic system on CO_2 emissions, the annual energy production potential of the system must be determined. This production is largely dependent on solar radiation duration. Therefore, the average daily sunshine durations for Tekirdağ Province were considered (MGM, 2025).

Table 1 presents the monthly average daily sunshine durations for Tekirdağ Province, with an annual average value of 5.7 h day^{-1}. With the projected 6 kW photovoltaic (PV) system, the annual electrical energy production in the study area was calculated based on the installed capacity, the average daily sunshine duration, and the number of days per year (equation 7):

$$\text{Annual Energy Production} = 6 \times 5.7 \times 365 = 12483\ kWh \qquad (7)$$

Based on these values, a 6 kW photovoltaic system can theoretically produce approximately 12483 kWh of electrical energy per year in Tekirdağ Province.

However, this value represents theoretical production. Considering system losses, a performance ratio (PR) of 0.75 was applied, and the actual annual energy production was calculated using equation 8:

$$E = 12483 \times 0.75 = 9362\ kWh \qquad (8)$$

This amount of renewable electricity prevents the emission of approximately 4474 kg of CO_2 compared to conventional electricity generation (9362 kWh × 0.478 kg CO_2). The proposed hybrid energy system, with a total installed capacity of 12 kW, consists of a 6 kW photovoltaic system and a 6 kW wind turbine system. With this configuration, a total of approximately 20312 kWh of electrical energy can be produced annually. This production prevents the emission of approximately 9710 kg of CO_2 (20312 kWh × 0.478 kg CO_2).

Table 1. Monthly average daily sunshine duration in Tekirdağ Province (hours day^{-1})

Months	1	2	3	4	5	6	7	8	9	10	11	12	Annual
Sunshine duration (hours)	2.7	3.5	4.4	6.0	7.5	8.6	9.5	8.6	6.9	5.0	3.2	2.5	5.7

4. Discussion

Due to the relatively large barn length of 49.4 m, insufficient air circulation and the formation of stagnant air zones may occur in certain interior areas. To prevent this situation, the installation of additional exhaust fans along the barn length is recommended (Yüksel and Türkboyları, 2018).

The calculated energy demand of the system to be used in the buffalo barn exceeds 8 kW. However, when solar and wind energy systems are evaluated separately, it is well known that photovoltaic systems cannot generate sufficient energy during nighttime, cloudy, or rainy conditions, while wind turbine systems may experience intermittent energy production due to fluctuations in wind speed or operation outside the optimal wind speed range (Tunus, 2019).

For this reason, in the design of renewable energy systems, it is generally recommended to install a system capacity approximately 25–30% higher than the calculated energy requirement. Accordingly, in this study, the hybrid energy system was designed with a total installed capacity of 11–12 kW, and a 12 kW system was adopted.

In cases where the investment capital of the enterprise is limited, priority should be given to photovoltaic systems, which have lower initial investment costs. This is because the initial investment costs of wind turbine systems are considerably higher than those of solar panel systems (Yılmaz et al., 2023b).

Electricity demand can be met through various energy sources such as coal, natural gas, hydroelectric, geothermal, and biomass, depending on local conditions. However, some of these sources release environmentally harmful wastes and greenhouse gases during energy production, leading to adverse impacts on ecosystems.

In particular, fossil fuel–based power plants accelerate climate change through carbon dioxide (CO_2) emissions and contribute significantly to the growth of the carbon footprint.

In Türkiye, approximately 21% of electricity production is supplied by coal-fired thermal power plants (Orhan and Şahin, 2022).

According to the Carbon Neutral Charitable Fund (CNCF, 2025), approximately 0.94 kg of CO_2 is emitted into the atmosphere for each 1 kWh of electricity generated in coal-fired thermal power plants.

According to international energy data, emission factors for electricity generation vary depending on the energy mix, with typical values reported around 400–500 g CO_2 (IEA, 2021). In this study, a representative value of 0.478 kg CO_2 was adopted based on national institutional assessments (SDU Yeşil Kampus, 2026).

Accordingly, the environmental contribution of renewable energy systems can be quantitatively demonstrated by calculating the amount of CO_2 emissions avoided based on the total electricity generated by these systems.

The proposed hybrid system results in an annual reduction of approximately 9710 kg of CO_2 emissions.

In conclusion, the use of hybrid renewable energy systems in agricultural production enables energy demands to be met through sustainable sources while significantly reducing CO_2 emissions associated with fossil fuel consumption, thereby contributing to a reduced carbon footprint and enhanced environmental sustainability.

5. Conclusion

The use of fossil fuels has been increasing in Türkiye, as in the rest of the world. This trend leads to higher carbon dioxide (CO_2) emissions, thereby increasing the risk of global climate change. In order to reduce the carbon footprint and ensure environmental sustainability, CO_2 emissions must be decreased and the use of renewable energy sources should be promoted instead of fossil fuels. This transition not only provides environmental benefits but also contributes to reducing the current account deficit by decreasing dependence on fossil fuel imports.

Energy demand is high in agricultural activities, particularly in buffalo breeding and production systems. This energy is used in various processes in livestock enterprises, primarily for ventilation, cooling, and heating systems (Aslan, 2024).

In livestock enterprises, solar and wind energy systems can be utilized to achieve both economic benefits and reductions in CO_2 emissions associated with climate change. The Marmara Region, in particular, has a high potential for both solar and wind energy in Türkiye. Although the unit cost of energy obtained from these systems is relatively low, their adoption in agricultural enterprises remains limited. The main reasons for this include high initial investment costs (Emiroğlu et al., 2021) and the limited financial capacity of such enterprises.

In buffalo barns located in the Marmara Region, solar and wind energy systems can be used to meet electricity demand. Especially in rural areas without access to the electricity grid, these systems not only supply energy but also contribute to reducing the carbon footprint. In this context, the integration of renewable energy systems into livestock enterprises has strategic importance in terms of environmental sustainability.

In this study, the technical feasibility of hybrid systems based on solar and wind energy for buffalo barns was demonstrated. In particular, the combined evaluation of energy demand and carbon footprint constitutes the original aspect of this study.

Hybrid renewable energy systems can be used in buffalo barns to reduce production and energy costs. These systems can improve animal comfort by providing effective ventilation and cooling, thereby enhancing productivity. In addition, it is recommended that such systems be designed with a capacity higher than the calculated requirement in order to prevent potential energy shortages. Excess energy produced can be utilized within the enterprise or transferred to the national grid

(Türkboyları and Yüksel, 2024c).

However, this study has certain limitations. Energy production calculations are based on theoretical data and specific assumptions. In particular, assuming a constant performance ratio (PR) may not fully reflect variations under real operating conditions. Furthermore, measurement and monitoring data required to validate the long-term field performance of the proposed system are limited. The study is limited to the conditions of Tekirdağ Province, and different results may be obtained in other regions.

Future studies should focus on implementing the system under real field conditions, monitoring its long-term performance, and conducting detailed economic analyses (e.g., investment cost, payback period). Additionally, the integration of energy storage systems and the evaluation of system applicability in different regions would contribute to a more comprehensive assessment of system effectiveness.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	E.T.	A.N.Y.
C	60	40
D	60	40
S	60	40
DCP	60	40
DAI	60	40
L	60	40
W	60	40
CR	60	40
SR	60	40
PM	60	40
FA	60	40

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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