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Techno-Economic Feasibility and Operational Emission Assessment of Hybrid Renewable Energy Systems for a Large Educational Building: A Case Study in Türkiye

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Abstract

This study evaluates the techno-economic performance and operational emissions of grid-connected and off-grid hybrid renewable energy systems (HRES) for a large educational building in Türkiye. The building's hourly electricity-demand profile for 2020–2025 and local solar, wind and livestock-manure resources were modeled in HOMER (Hybrid Optimization of Multiple Energy Resources). Photovoltaic (PV), wind-turbine (WT) and biogas-generation alternatives were assessed using net present cost (NPC), cost of energy (COE), renewable fraction and modeled operational emissions. Among the grid-connected alternatives, the Grid/PV/Biomass configuration was the least-cost option, with an NPC of approximately \$1.85 million, a COE of \$0.199/kWh and a renewable fraction of 70%. Adding wind increased the renewable fraction to 72% but raised the COE to \$0.263/kWh. Among the off-grid cases, the WT/PV/Biomass/Battery configuration had the lowest COE (\$0.555/kWh) and generated 1,006,808 kWh/year, with PV, biogas and wind contributing approximately 48%, 40% and 12%, respectively. The low wind-turbine capacity factor (4.85%) indicates a supplementary role for wind at the site. Relative to the grid-only baseline, modeled operational CO₂ emissions decreased by more than 99% in the off-grid configurations and by approximately 78–81% in the grid-connected cases; these are operational rather than life-cycle savings. A separate analytical grid-only reference shows that the least-cost HRES is not necessarily cheaper than continued grid supply under the fixed 2025 reference purchase price of \$0.05/kWh. The results demonstrate a trade-off between renewable penetration, operational emission

reduction and system cost, and highlight the importance of site-specific resource quality, biomass logistics and reliability metrics.

Article Highlights

- Solar panels and manure-based biogas supplied most of the renewable power for a large university building in Türkiye
- Keeping the grid connection made hybrid renewable systems far cheaper than running the building fully off-grid
- Renewable options sharply cut operating CO₂ emissions but cost more than simply buying electricity from the grid

Keywords Hybrid renewable energy system (HRES); Techno-economic analysis; Educational buildings; Biogas; HOMER

1 Introduction

Higher-education institutions are increasingly being used as testbeds for hybrid renewable energy systems (HRES) because they combine substantial and temporally structured electricity demand with opportunities for on-site solar, wind, biomass and storage deployment. For educational facilities, however, the feasibility of HRES depends strongly on the spatial scale of analysis, the temporal resolution of the load profile, local renewable-resource quality, grid tariffs and the techno-economic assumptions assigned to individual components. Consequently, results obtained for an entire university campus cannot automatically be transferred to a single educational building, where load variability and renewable-resource constraints may be more pronounced.

Recent 2026 studies illustrate the shift from simple renewable-capacity sizing toward integrated techno-economic, reliability and decarbonization assessment in educational facilities. Ali et al. (2026a) optimized a grid-connected university student-residence microgrid combining PV, wind, biomass, battery storage and utility-grid support, with sensitivity analysis and net-metering considered alongside cost and emission performance. Ali et al. (2026b) examined a broader educational-institution HRES that included battery and hydrogen-storage pathways and evaluated reliability-related indicators together with NPC, LCOE and emissions. These developments show that contemporary HRES assessment increasingly requires least-cost optimization to be

interpreted together with reliability, resource uncertainty, storage performance and clearly defined environmental boundaries.

This trend is particularly evident in the 2026 literature. Bozkurt et al. (2026) optimized a PV-wind-biomass transition pathway for Erciyes University in Türkiye using HOMER Pro and a campus-wide annual demand of 30.4 GWh. Other 2026 university studies have coupled HOMER-based sizing with battery storage, net-metering, sensitivity analysis and grid-stability or power-system validation. Collectively, these studies demonstrate a methodological shift toward multi-dimensional evaluation of cost, renewable penetration, operational emissions, storage performance and system robustness rather than reliance on a single economic indicator.

Despite this progress, three gaps remain relevant to the present case. First, much of the recent educational-sector literature is campus-scale, whereas comparatively fewer studies examine a single large educational building using a multi-year hourly load profile. Second, studies integrating solar PV, wind and livestock-manure-derived biogas within both grid-connected and fully off-grid configurations remain limited at building scale. Third, reported COE and NPC values across studies are often difficult to compare directly because system scale, resource quality, tariff year, technology cost assumptions and reliability criteria differ. These issues motivate a case-specific assessment in which economic results are interpreted together with renewable contribution, resource limitations and operational emissions.

Accordingly, this study evaluates HRES configurations for Classroom Building-2 at Kırklareli University's Kayalı Campus using the building's hourly electricity-demand profile for 2020–2025 and local solar, wind and livestock-manure resource data. PV, wind turbine and biogas generation are examined under both grid-connected and off-grid architectures using HOMER. The study is designed to: (i) identify the least-cost configurations among the investigated HRES alternatives using NPC and COE; (ii) quantify the contribution of individual renewable resources and the resulting renewable fraction; (iii) compare modeled operational emissions with a grid-only baseline while explicitly distinguishing operational emission assessment from life-cycle assessment; and (iv) examine how local resource conditions—particularly weak wind availability and manure-based biogas potential—affect the interpretation of the optimized configurations.

The contribution of the study therefore lies not in claiming a universally optimal HRES architecture, but in providing a building-scale, resource-specific comparison of grid-

connected and off-grid PV-wind-biogas alternatives under Türkiye-specific conditions. The use of a multi-year hourly building load, explicit treatment of manure availability, separate analytical interpretation of the grid-only economic reference, and transparent discussion of missing off-grid reliability and storage metrics are intended to improve the reproducibility and interpretability of the case study. The results are consequently presented as conditional on the adopted technical and economic assumptions rather than as directly transferable benchmarks for other campuses or buildings.

2 Materials and Methods

This study employs the HOMER software to evaluate the techno-economic feasibility of various HRES configurations. The target site is the Kayalı Campus of Kırklareli University, located in north-western Türkiye. The methodology includes the collection of site-specific input data, component modelling, and economic evaluation.

2.1 Input parameters

HOMER requires site-specific input parameters to simulate the performance of the proposed HRESs.

2.1.1 Site Characteristics

Classroom Building-2 (CB-2), a large educational building on the Kayalı Campus of Kırklareli University in north-western Türkiye, was selected as the case study. The study area is located at 41.791° N and 27.162° E. The campus spans 3.58 million m² and hosts approximately 26,643 students. A satellite image of the campus and CB-2 is presented in Fig. 1.



Fig. 1 Kırklareli University Kayalı Campus and the CB-2

2.1.2 Load profile

CB-2's electricity consumption data were obtained from Kırklareli University's institutional electricity records for the period 2020–2025 and were available at hourly resolution. The building exhibits a peak electrical demand of 277 kW, with an average daily energy consumption of approximately 2,000 kWh. The measured hourly data were used to characterize the building load in HOMER. As shown in Fig. 2, demand is lowest between 23:00 and 07:00, when the building is largely unoccupied. Weekend consumption is also at minimum levels because the building is rarely used on Saturdays and Sundays.

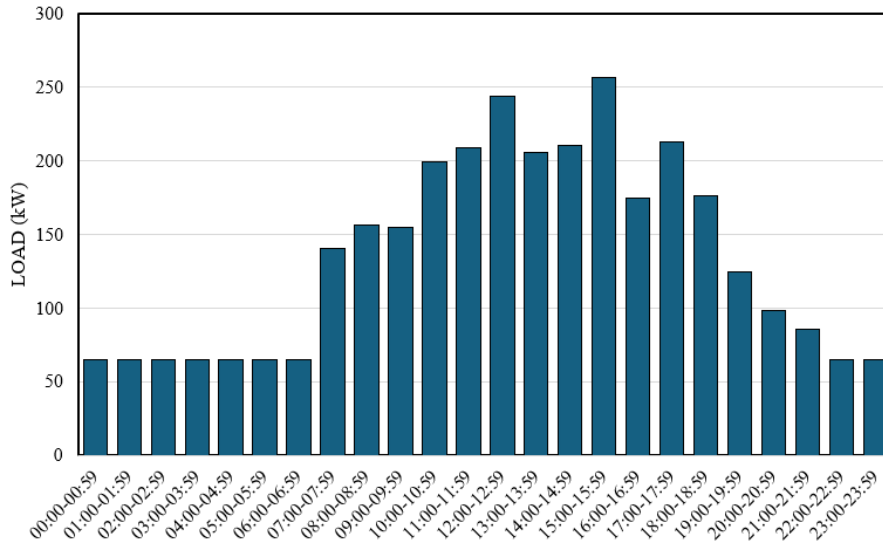


Fig. 2 Daily load curve of the CB-2

2.1.3 Solar data

Solar radiation data were obtained from NASA and verified with Turkish State Meteorological Service (TSMS) datasets (Stackhouse 2017; TSMS 2021). The annual average daily solar irradiation is 3.943 kWh/m²/day, with an average clearness index of 0.515 (Fig. 3).

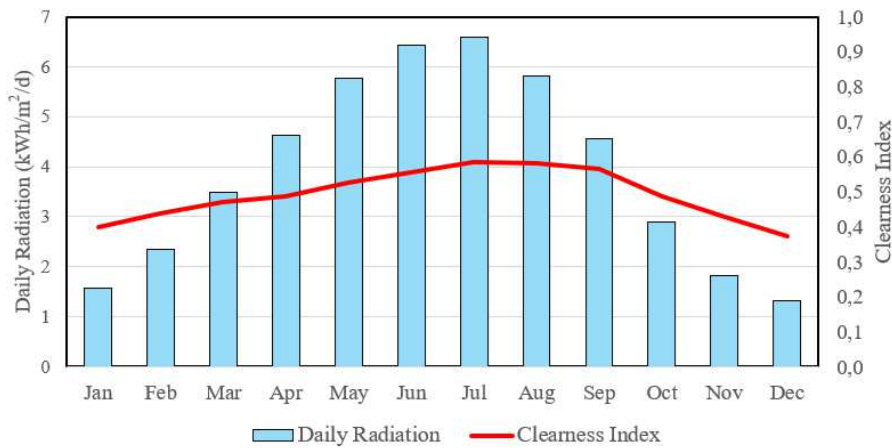


Fig. 3 Monthly average solar radiation and clearness index of CB-2

2.1.4 Wind data

The wind resource data used in the HOMER model were obtained through HOMER from the NASA Prediction of Worldwide Energy Resources (POWER) database (NASA POWER 2026). The dataset represents monthly average wind speed at 50 m above the Earth's surface for the 41-year period from January 1984 to December 2025. For the study

location, the NASA POWER grid-cell midpoint reported by HOMER is 41.25° N and 28.75° E. The long-term annual average wind speed used in the model is 2.97 m/s at 50 m, with monthly averages ranging approximately between 2.5 and 4.0 m/s. The highest monthly average occurs in February and the lowest in October (Fig. 4). The wind-speed frequency distribution used by HOMER is represented by a Weibull probability density function (Fig. 5), for which HOMER reports a shape parameter $k = 1.71$ and a scale parameter $c = 3.37$ m/s. Thus, the wind input should be interpreted as a long-term NASA POWER reanalysis-derived resource dataset used within HOMER rather than as a site-specific anemometer measurement.

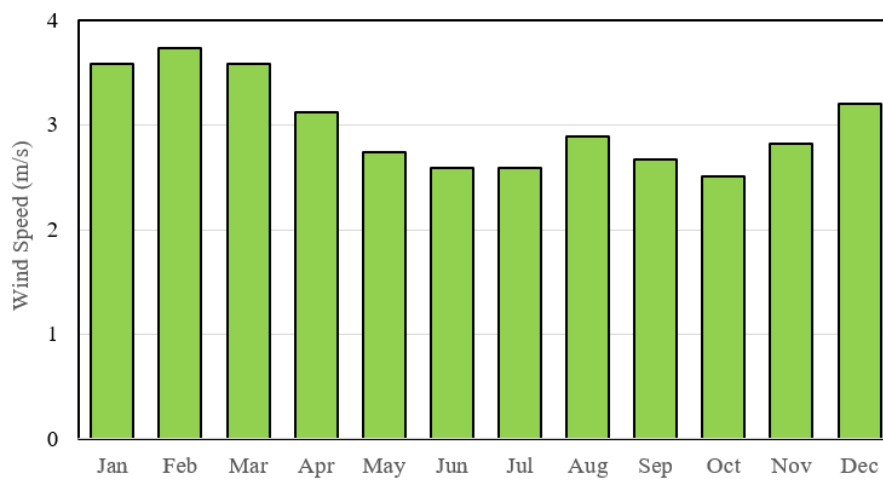


Fig. 4 Long-term monthly average wind speed at 50 m for the study location (NASA POWER data used in HOMER, January 1984–December 2025)

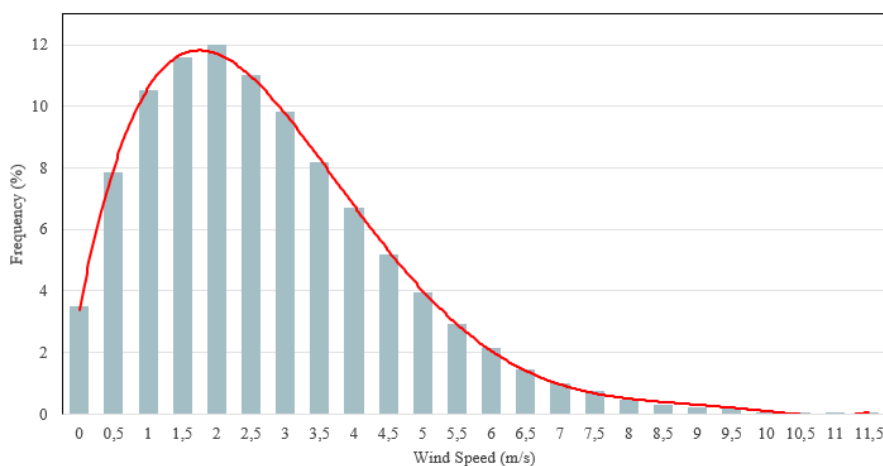


Fig. 5 Weibull wind-speed frequency distribution for the study location generated in HOMER

2.1.5 Biomass Availability

Animal manure is a biomass resource that can be converted into biogas through anaerobic digestion. According to the Kırklareli Provincial Directorate of Agriculture and Forestry, the province had 154,098 cattle in 2025 (Kırklareli Provincial Directorate of Agriculture and Forestry 2026). To test whether the 30 t/day fresh-manure input used in the HOMER model is physically plausible at the regional scale, a manure-availability calculation was performed using literature coefficients. Ertop et al. (2023) report an average fresh-manure production rate of 43 kg cattle⁻¹ day⁻¹ and a manure availability coefficient of 50% for cattle. Accordingly, the potentially collectable fresh manure in Kırklareli can be estimated as;

$$M_{col} = N_c \times m_d \times f_c, \quad (1)$$

where N_c is the cattle population, m_d is the daily manure production per animal, and f_c is the collectable fraction. Using $N_c = 154,098$ cattle, $m_d = 43$ kg cattle⁻¹ day⁻¹, and $f_c = 0.50$ gives $M_{col} = 154,098 \times 43 \times 0.50 = 3,313,107$ kg/day, or approximately 3,313 t/day. Therefore, the 30 t/day feedstock assumed in the HOMER model corresponds to only 0.91% of the estimated collectable manure at the provincial scale. Equivalently, 30 t/day would require the collectable manure of approximately $N_{req} = 30,000 / (43 \times 0.50) = 1,395$ cattle, corresponding to about 0.91% of the provincial cattle population. A second consistency check was performed for gas production. Using the cattle-manure parameters reported by Ertop et al. (2023)—13.95% dry matter, 83.33% volatile dry matter in dry matter, and a methane production coefficient of 0.18 m³ CH₄ kg⁻¹ volatile dry matter—the 30 t/day feedstock corresponds to approximately 628 m³ CH₄/day. Assuming a representative methane share of about 60% in cattle-manure biogas, this is equivalent to approximately 1,046 m³ biogas/day, or 34.9 m³ biogas per ton of fresh manure. This independently calculated value is close to the approximately 30 m³/t reference value adopted in the model, supporting the order of magnitude of the assumed biogas yield. These calculations demonstrate regional feedstock plausibility, but they do not constitute evidence of a secured 30 t/day supply to the campus. Actual recoverable manure depends on farm location, housing and collection practices, seasonal availability, moisture content, transport distance, competing uses, and contractual access. Because farm-level inventory and logistics data were unavailable, the model represents the regional supply as an aggregate feedstock scenario, and the techno-economic results remain conditional on continuous availability of 30 t/day at the assumed cost and conversion performance.

2.2 HRES components modelling

2.2.1 Photovoltaic Panel

The output power of the PV array is calculated using Equation (2). It depends on four parameters: the installed capacity of the PV array, the solar radiation incident on the panels, the derating factor representing various system losses, and the cell temperature (Jahangir et al. 2021; Aykut et al. 2023; Zahid et al. 2023; Pamuk 2024).

$$P_{pv} = Y_{pv} \cdot f_{pv} \cdot \left(\frac{G_T}{G_{T,stc}} \right) \cdot [1 + \alpha_p (T_C - T_{C,stc})] \quad (2)$$

In this context, P_{PV} represents the rated output power of the PV panels in kW, and Y_{PV} denotes the PV system's rated capacity. The parameter f_{PV} is the derating factor accounting for system losses (%), while G_T is the solar irradiance incident on the PV surface (kW/m²), and $G_{T,stc}$ refers to the standard temperature and irradiance, taken as 1 kW/m². The coefficient α represents the power temperature coefficient, T_C is the operating temperature of the PV module (°C), and $T_{C,stc}$ is the module temperature under STC (25°C). If the effect of temperature on PV module performance is neglected (i.e., $\alpha=0$), the output power of the PV system can be calculated using a simplified expression.

$$P_{pv} = Y_{pv} \cdot f_{pv} \cdot \left(\frac{G_T}{G_{T,stc}} \right) \quad (3)$$

The PV system's efficiency can be expressed as in Equation (4) (Aykut et al. 2023; Pamuk 2024). Where η_{stc} is the efficiency of the PV systems (%) and A_{pv} is surface area of PV panels (m²) (Demirci et al. 2022).

$$\eta_{stc} = \frac{Y_{pv}}{A_{pv} \cdot G_{T,stc}} \quad (4)$$

2.2.2 Wind Turbine

A wind turbine generates electricity by converting the kinetic energy of the wind, captured by its rotating blades, into electrical energy. The electrical power output of wind turbines is influenced by several environmental and site-specific parameters, including wind speed, air density, wind direction, site elevation, ambient temperature, and surrounding topography. Among these, wind speed is the most important input. The wind speed at hub height is estimated from the wind speed measured at a lower height using the Hellmann (power-law) equation (Sharma et al. 2022).

$$V_{hub} = V_{data} \left(\frac{h_{hub}}{h_{data}} \right)^\alpha \quad (5)$$

Here, V_{hub} is the wind speed at the wind-turbine hub height, V_{data} is the reference wind speed available to the model, h_{hub} is the turbine hub height, h_{data} is the reference height of the wind dataset, and α is the Hellmann coefficient. In the present study, the NASA POWER wind resource supplied through HOMER is referenced at 50 m; therefore, any height adjustment performed within the wind-turbine model should be interpreted relative to this 50 m reference rather than to a 10 m ground measurement. Since moving air has kinetic energy, wind-turbine output power (P_r) is calculated from the kinetic-energy flux of the moving air (Sharma et al. 2022).

$$P_r = \frac{1}{2} \cdot \rho_a \cdot A \cdot V_{hub}^3 \quad (5)$$

In the equation, ρ_a refers to the density of air under standard temperature and pressure (STP) conditions (1.225 kg/m³). A is the rotor swept area (m²). Equation (6) is used to calculate the output power of the wind turbine at STP. Under actual (non-standard) atmospheric conditions, the output power of wind turbines (P_{WT}) is calculated as in Equation (7) (Sharma et al. 2022). Here, ρ is the actual air density.

$$P_{WT} = \left(\frac{\rho}{\rho_a} \right) \cdot P_r \quad (7)$$

2.2.3 Biogas Generator

The main routes for converting biomass into energy are shown in Fig. 6. In a biogas power plant, electrical energy is produced by burning the gas obtained through the fermentation of organic waste in a biogas generator. The output power of the biogas generator is calculated using Equation (8) (Agajie et al. 2023).

$$P_B(t) = \frac{V_B(t) \cdot CV_B \cdot \eta_B}{860 \cdot t_B} \quad (8)$$

In this regard, P_B denotes the electrical output generated by the biogas generator, while V_B signifies the total volume of biogas produced during the process. The term CV_B corresponds to the calorific (energy) value of the biogas, η_B stands for the conversion efficiency of the biogas generator, and t_B indicates the operational time span over which biogas is produced. The fuel consumption of the biogas generator is calculated using Equation (9) (Zahid et al. 2023).

$$m_{biogas} = Z_{biogas} \cdot \rho_{fossil} \cdot (F_{0,biogas} \cdot Y_{biogas} + F_{1,biogas} \cdot P_{biogas}) \cdot (1 - x_{fossil}) \quad (9)$$

Where Z_{biogas} is the substitution ratio of biogas in fuel, ρ_{fossil} is the density of fossil fuel, Y_{biogas} is the rated capacity of the biogas generator, $F_{0,biogas}$ is the fuel curve intercept, P_{biogas} is the maximum generator output at minimum fossil fuel fractions, $F_{1,biogas}$ is the rate of change of fuel consumption with respect to output, x_{fossil} is the minimal fossil fuel fraction. Since the generator in this study is fuelled solely by biogas, no fossil fuel is used in the simulations.

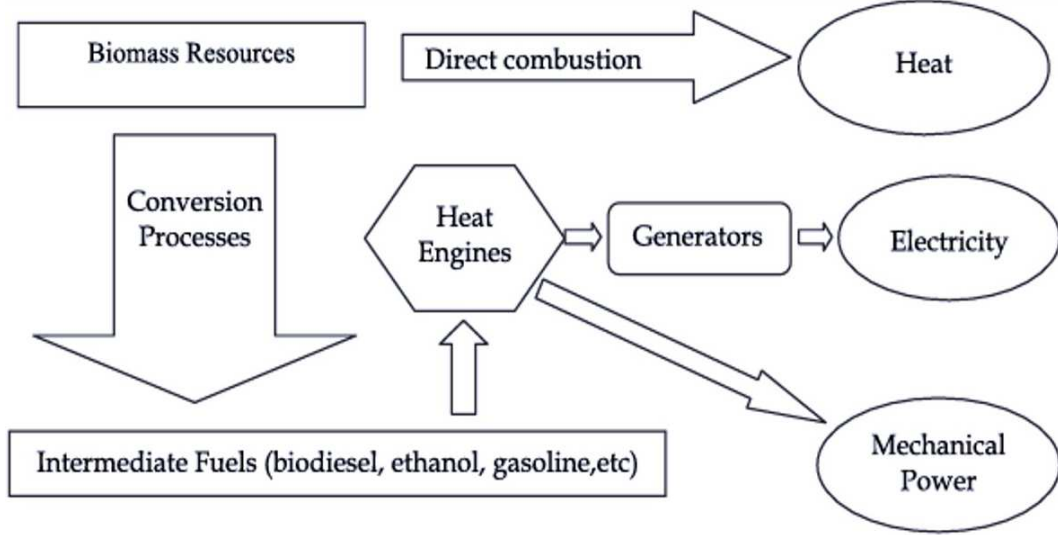


Fig. 6 Methods of using biomass for energy (Hosseini and Wahid 2014)

2.2.4 Storage Batteries

In off-grid HRESs, surplus electricity must be stored for use when generation does not meet the demand, and batteries are used for this purpose. Lead-acid batteries are the oldest and most mature storage technology. During the charging phase, the instantaneous capacity of the battery bank can be determined using the following expression (Sharma et al. 2022):

$$E_{B,t} = E_{B,(t-1)} \cdot (1 - \sigma_i) + \left[E_{T,t} - \frac{E_{L,t}}{\eta_i} \right] \cdot \eta_B \quad (10)$$

Where, $E_{B,t}$ is battery energy storage capacity, $E_{T,t}$ is produced energy, $E_{L,t}$ is energy demand for the load, (t) is time. When generation falls short of the load demand, the batteries are discharged to supply the load. During the discharge process, the instantaneous capacity of the battery at any time t can be calculated using the following expression (Sharma et al. 2022):

$$E_{B,t} = E_{B,(t-1)} \cdot (1 - \sigma_i) - \left[E_{T,t} - \frac{E_{L,t}}{\eta_i} \right] \quad (11)$$

where $E_{B,t}$ and $E_{B,(t-1)}$ are the energy available in the battery at time (t) and (t-1) respectively. σ_i is battery self-discharge rate, η_B and η_i are efficiency of battery charger and the inverter, respectively.

2.2.5 Converter

The converters used in HRESs are bidirectional. They operate as rectifiers (AC–DC) to charge the batteries and as inverters (DC–AC) when the load is supplied from the batteries. Converter efficiency, defined as the ratio of output power to input power, is the most important parameter in these conversions. The inverter and rectifier efficiencies are given by Equations (12) and (13).

$$\eta_i = \frac{P_{i0}}{P_{ii}} \quad (12)$$

$$\eta_r = \frac{P_{r0}}{P_{ri}} \quad (13)$$

Where, the inverter output power and input power are P_{i0} , P_{ii} (kW) respectively (Jahangir et al. 2021; Aykut et al. 2023). Similarly, the rectifier output and input powers are P_{r0} , P_{ri} (kW). η_i and η_r are inverter and rectifier efficiency (%) respectively (Demirci et al. 2022; Sharma et al. 2022).

2.3 Economic parameters

For contextual comparison, a grid-only analytical reference case (S0) was calculated separately from the HOMER optimization using the same fixed 2025 reference purchase-price assumption of 0.05 USD/kWh. With an annual electricity demand of approximately 730,000 kWh, the corresponding electricity-purchase expenditure is 36,500 USD/year. Assuming a constant real electricity price over the 25-year project horizon and the study's 6% real discount rate, the present-value factor is approximately 12.783, giving an analytical discounted grid-purchase cost of approximately 0.467 million USD. This S0 value is not a HOMER-derived NPC and excludes tariff escalation, demand charges, taxes, fees and other billing components; it is used only as a transparent economic reference for interpreting the modeled HRES costs.

Among the economic inputs utilized in hybrid system optimization, the annual real interest rate and project lifetime are important parameters. HOMER ranks configurations according to total NPC (Ngan and Tan 2012), while COE is reported as a complementary metric. Component costs are expressed in US dollars, the annual real interest rate is 6%,

and the project lifetime is 25 years. For all grid-connected simulations, the grid purchase price was set to 0.05 USD/kWh and the sell-back price to 0.04 USD/kWh as fixed 2025 reference tariff assumptions. These values are scenario inputs rather than direct reproductions of a specific regulated tariff category (EPDK 2025).

2.3.1 Annual real interest rate

The annual real interest rate, also called the real discount rate, is used to convert between lump-sum and annual costs. HOMER requires a discount factor that considers the time value of money, not inflation. Accordingly, HOMER employs the annual real interest rate to derive the discount factor and compute the annualized cost based on the total NPC. HOMER can derive the annual real interest rate from the nominal interest rate and the expected inflation rate using Equation (14) (Ngan and Tan 2012; Jahangir et al. 2021; Sharma et al. 2022).

$$i = \frac{i' - f}{1 + f} \quad (14)$$

Where i , i' , f are the annual real interest rate, the nominal interest rate and the expected inflation rate (%).

2.3.2 Net present cost (NPC)

The total NPC of a hybrid system is the present value of all costs incurred over its lifetime, including installation, replacement and O&M costs, minus the present value of all revenues. The total NPC is the main economic output of HOMER and is used to evaluate all system configurations in simulation results. HOMER calculates the NPC of each component and of the entire system. The total NPC, also referred to as the life-cycle cost, is calculated using Equation (15) (Islam 2018; Demirci et al. 2022).

$$C_{NPC,tot} = \frac{C_{ann,tot}}{CRF(i,N)} \quad (15)$$

Where $C_{NPC,tot}$ is the total net present cost in USD, $C_{ann,tot}$ corresponds to the total yearly cost in USD, $CRF(i,N)$ represents the capital recovery factor, i stands for the annual real interest rate (%), N is the project lifetime in years. The $CRF(i,N)$ is an expression to estimate the present value of yearly income within a specific time and it is calculated by equation 16 (Dursun and Aykut 2019; Jahangir et al. 2021; Demirci et al. 2022; Sharma et al. 2022).

$$CRF(i, N) = \frac{i(1+i)^N}{i(1+i)^N - 1} \quad (16)$$

2.3.3 Levelized cost of energy (COE)

The levelized cost of energy (COE) is defined as the average cost per kWh of useful electrical energy produced by the system. As shown in Equation (17), HOMER calculates the COE by dividing the annualized cost of producing electricity by the total electrical load served (Mandal et al. 2018; Jahangir et al. 2021; Sharma et al. 2022).

$$COE = \frac{C_{ann,tot}}{E_{served}} \quad (17)$$

Where E_{served} is the total electrical load served (kWh/yr).

2.4 Limitations and Uncertainty Considerations

The input data used in the HOMER simulations were obtained from institutional records and publicly available resource datasets. The wind resource was obtained through HOMER from NASA POWER as a 20-year (January 2005–December 2025) monthly climatological series at 50 m for the model grid cell centered at 41.25° N, 28.75° E. NASA POWER meteorological wind products are reanalysis-derived and are intended to characterize regional mean wind conditions; they do not replace site-specific, hub-height anemometer measurements. Consequently, local effects of terrain, buildings, surface roughness and microclimatology may not be fully represented. The solar input was likewise based on publicly available resource data and cross-checked against TSMS information. Manure is assumed to be sourced from livestock farms in the vicinity of the university campus, with an aggregate supply of 30 tons/day. Farm-level inventory and logistics data, including farm locations, collection efficiency and transport distance, were unavailable and are not explicitly modelled. Site-specific anaerobic-digestion performance and biogas-yield variability are also not quantified. The results should therefore be interpreted as conditional on the adopted resource datasets, regional feedstock availability and component-cost assumptions.

3 Hybrid Renewable Energy System Modelling

3.1 System Components

3.1.1 Photovoltaic Panel

A PV array consisting of monocrystalline silicon modules was used in this study. Since the PV array produces DC power, a converter is required to supply the AC loads. In the

HOMER optimization, the PV capital cost was assumed to be \$3,000/kW, with the replacement cost equal to the initial investment cost and an annual O&M cost of \$10/kW-year. This cost input was applied consistently to all PV-containing configurations. Recent commercial-scale PV benchmarks indicate lower installed costs (U.S. Department of Energy 2025); therefore, the adopted value should be regarded as a conservative economic assumption rather than a representation of the lowest contemporary PV market cost. No NPC, COE or optimal-capacity results are inferred here from updated PV cost benchmarks. Lower contemporary PV investment costs would be expected to improve the relative economic performance of PV-containing configurations, but the magnitude of this effect is outside the scope of the present analysis. The PV lifetime was assumed to be 25 years, and a derating factor of 90% was applied to account for soiling, temperature, shading, snow and ageing effects (Lambert et al. 2006).

3.1.2 Wind Turbine

The Northern Power NW 100/19 wind turbine, with a rated power of 100 kW, a rotor diameter of 19 m and AC output, was used in this study. The initial capital cost of the 100 kW wind turbine is estimated at \$240,000, with the replacement cost assumed to be equivalent to the initial investment. The annual O&M cost of the turbine is approximately \$3,000, and its lifetime is assumed to be 15 years. To determine the optimal number of turbines, 0, 1, 2 and 3 turbines were considered, where zero indicates a system without a wind turbine (NPS 2022). Figure 7 shows the power-speed characteristic of the wind turbine generated using HOMER.

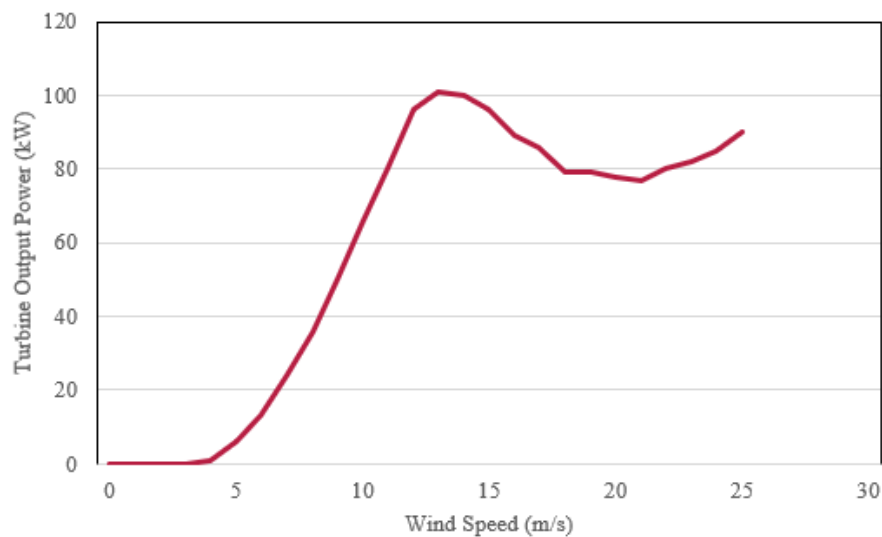


Fig. 7 The power curve of the wind turbine Northern Power NW/100/19

3.1.3 Biogas Generator

The initial investment cost of the biogas generator is \$ 1,000 per kW. The replacement cost is equal to the initial cost, and the O&M cost is assumed to be 0.020 \$/kWh. The generator has a lifetime of 15,000 operating hours and a minimum load ratio of 30%. Biogas produced from dairy cattle manure is used as fuel, and the generator capacity was varied between 0 and 150 kW (Mahalakshmi and Latha 2015). The biomass-to-biogas economic boundary requires explicit qualification. The model is based on the 30 tons/day feedstock-availability scenario and the biogas-generator cost parameters given above; a separately itemized biomass feedstock price and a complete anaerobic-digestion balance-of-plant cost are not reported in this study. HOMER can incorporate an assigned biomass price into generator fuel cost according to the quantity of feedstock consumed (HOMER Energy 2026a, b), whereas digester capital and O&M costs must be entered separately or embedded explicitly in other system-cost inputs (HOMER Energy 2026c). Accordingly, no separate cost is assigned for manure purchase, collection, transport, anaerobic digestion, gas cleaning or storage, digestate handling, or methane-leakage control. The reported NPC and COE values should be interpreted within this biomass-cost boundary rather than as a complete project-level investment estimate for a new manure-to-biogas facility.

3.1.4 Storage Batteries

Batteries store the surplus energy generated by the system and supply it back when generation is insufficient. The Hoppecke 24 OPzS 3000, a vented lead-acid battery with tubular positive plates, was selected for this analysis. It has a nominal capacity of 3,000 Ah (6 kWh). The nominal voltage is 2V and the minimum charge level is 30%. The initial capital and replacement costs are \$150 per battery, and the annual O&M cost is \$2. To determine the optimal battery bank size, 0, 150, 200, 300 and 400 batteries were considered (Hoppecke 2024). The storage component was represented by the Hoppecke 24 OPzS 3000 lead-acid battery available in the HOMER component library. Each unit was modeled with a nominal capacity of 3000 Ah (approximately 6 kWh at 2 V) and a minimum state of charge of 30%. The reported battery sizing and economic results are therefore technology-specific and should not be generalized to alternative storage chemistries. In particular, no lithium-ion or lithium iron phosphate (LFP) alternative was included in the optimization.

3.1.5 Converter

The converter has a lifetime of 15 years and an assumed efficiency of 90%. The initial investment and replacement costs of the converter are \$ 800 per kW and \$ 750 per kW, respectively, and the annual O&M cost is \$10. Converter capacities of 0, 150 and 300 kW were considered in the optimization (Dursun 2012). The load is primarily supplied by the wind turbines, PV panels and biogas generator, and any surplus energy is stored in the batteries. Since the PV panels produce DC power, it must be converted to AC by the inverter to supply the AC load. When the PV panels, wind turbines and biogas generator cannot meet the load demand, the batteries switch from charging to discharging mode and supply the load.

3.2 Operating Strategies and Assumptions

- Grid-connected and off-grid systems were modeled separately.
- The main system components are 100 kW NW 100 wind turbines, a 200 kW PV array, a 150 kW biogas generator, Hoppecke 24 OPzS 3000 batteries and a 150 kW converter.
- The load demand of CB-2 and the wind speed and solar radiation data for the site were used as inputs to HOMER.
- In the HOMER sensitivity analysis, wind speed was varied between 3 and 7 m/s, biomass supply between 15 and 70 tons/day, and solar radiation between 3 and 7 kWh/m²/day. The sensitivity results presented in this study (Figs. 12 and 13) resolve system selection as a function of solar radiation and wind speed at the base-case biomass supply of 30 tons/day; therefore, no separate quantitative conclusion is drawn here for biomass-supply sensitivity.
- Grid-connected configurations were evaluated with the grid retained as a backup supply. The economic analysis uses 2025 as the reference year for electricity prices. In the HOMER model, electricity purchased from the grid was fixed at 0.05 USD/kWh and surplus electricity exported to the grid was assigned a sell-back price of 0.04 USD/kWh. These values are treated as fixed 2025 reference tariff assumptions for scenario comparison and are not presented as a direct reproduction of a specific EPDK-regulated retail or feed-in tariff category. This distinction is important because electricity charges in Türkiye vary with consumer category, consumption level, supply arrangement and tariff period. EPDK's 2025

framework applied a 15,000 kWh/year threshold to public and private services and other relevant non-residential consumer groups for the high-consumption last-resort supply regime (EPDK 2025). Given the approximately 730 MWh/year demand of the investigated building, the fixed USD-denominated purchase and sell-back prices should therefore be interpreted as modeling assumptions normalized to the 2025 economic reference year rather than as the building's exact regulated bill. The same prices were applied consistently to all grid-connected scenarios.

- The operating reserve was set to 10% of the hourly load.
- The operating reserve was set to 25% of the solar power output and 40% of the wind power output. HOMER allows this setting only for variable sources such as solar and wind, not for the biogas generator.
- Since all component costs in this study are expressed in US dollars, a USD-based real discount rate was adopted. Applying Turkish lira nominal interest and inflation rates to USD-denominated costs would introduce a currency inconsistency.
- The annual real interest rate was set to 6 % for all simulations, consistent with the value adopted by Kumar and Channi (2024).
- The project lifetime was set to 25 years for all configurations.
- For CO₂, the latest electricity consumption-point emission factor published by the Turkish Ministry of Energy and Natural Resources (ETKB) in 2025 for distribution-connected consumption points (0.469 tCO₂-eq/MWh) was used (ETKB 2025).

For SO₂ and NO_x, the factors used in the simulation were the default HOMER grid-emission factors (2.74 g/kWh for SO₂ and 1.34 g/kWh for NO_x), rather than Türkiye-specific official emission factors. These pollutants are therefore retained to preserve consistency within the HOMER simulation, but their absolute values should be interpreted as model-based estimates rather than country-specific emission inventories. Accordingly, the SO₂ and NO_x results are used primarily for relative comparison among the modeled configurations.

The environmental component of this study is limited to operational emissions associated with electricity purchased from the grid and pollutants represented by HOMER for biogas-based electricity generation. It is therefore an operational emission assessment

rather than a life-cycle assessment (LCA). Embodied emissions associated with manufacturing PV modules, wind turbines, batteries, converters and generators, as well as construction, manure transportation, component replacement, decommissioning and end-of-life processes, are outside the system boundary. Accordingly, the reported emission reductions should be interpreted as operational reductions relative to the modeled grid-only baseline and not as life-cycle greenhouse-gas savings.

4 Results and discussion

Beyond the HOMER sensitivity analysis, the economic uncertainty assessment in the present study is interpretive. The principal uncertain inputs include the grid electricity tariff, PV capital cost, biomass availability and collection cost, wind-resource conditions, component replacement costs, and the real discount rate. These variables can affect the absolute NPC and COE values and, in some cases, the relative ranking of configurations. No additional NPC, COE, component sizing, or optimal-system outputs are generated from altered inputs, and the HOMER sensitivity results are kept separate from the additional uncertainty discussion presented here.

For the off-grid cases, the present manuscript reports the system configurations, annual component-level electricity generation, operating hours, capacity factors, NPC, and COE obtained from the HOMER simulations. However, detailed reliability and storage-performance outputs such as annual unmet electrical load, capacity shortage, excess electricity, loss-of-power-supply probability (LPSP), battery autonomy, battery throughput, and replacement count are not reported in this study, and these indicators are not inferred from the reported annual energy balances.

The performance of the HRES configurations was evaluated using HOMER under both off-grid and grid-connected scenarios in terms of NPC, COE, renewable fraction and emission reduction potential.

4.1 Off-grid HRES

The off-grid HRES consists of wind turbines (WT), photovoltaic panels (PV), biogas generators (BG), batteries (BT) and converters. This system is designed to meet the electrical load of CB-2 entirely from renewable sources, and its configuration is shown in Fig. 8.

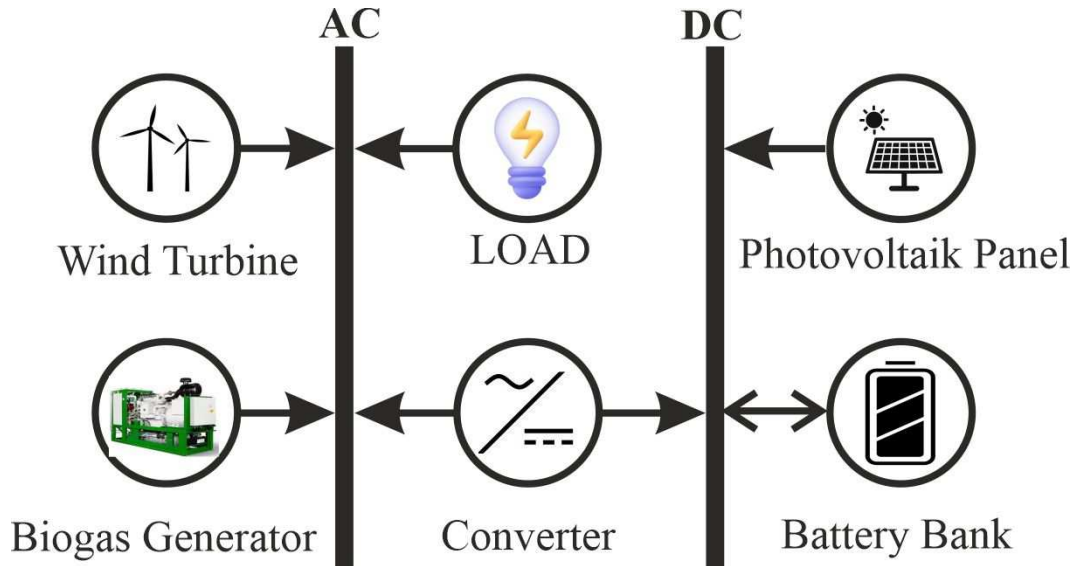


Fig. 8 The off-grid HRES

For an average solar radiation of 4 kWh/m²/day, an average wind speed of 3 m/s and a biomass supply of 30 tons/day, the optimal component sizes of the off-grid configurations are presented in Table 1.

Table 1 Optimal component sizes and economic results of the off-grid HRES configurations

Configuration	WT (kW)	PV (kW)	BG (kW)	Bat (unit)	Conv (kW)	IIC (\$)	OC (\$/year)	NPC (\$)	COE (\$/kWh)
PV-BG-BT (S1)	-	200	150	300	150	915,000	336,186	5,212,591	0.559
WT-BG-BT (S2)	200	-	150	300	150	795,000	419,920	6,162,983	0.663
WT-PV-BG-BT (S3)	200	200	150	300	150	1,395,000	295,547	5,173,077	0.555

Note: WT, wind turbine; PV, photovoltaic; BG, biogas generator; Bat, battery; Conv, converter; IIC, initial investment cost; OC, operating cost; NPC, net present cost; COE, cost of energy.

Figure 8 and Table 1 illustrate the optimal system configurations for standalone scenarios. The WT/PV/BG/BT system yielded the lowest COE (0.555 \$/kWh) and NPC (\$5.17 million) among all off-grid setups. In this configuration, photovoltaic panels, biogas and wind turbines accounted for 48%, 40% and 12% of the total annual electricity generation, respectively. The respective capacity factors were 27.9% (PV), 30.6% (biogas), and 4.85% (wind), indicating biomass as the most stable contributor. Despite its fully renewable modeled generation mix, the off-grid system exhibits a relatively high COE

compared to grid-connected configurations, highlighting the economic trade-offs of autonomy from the grid.

The total annual energy output generated by the WT/PV/BG/BT-HRES system amounts to 1,006,808 kWh. The wind turbine (WT) exhibited a capacity factor of 4.85% and operated for a total of 4,510 hours, contributing 116,993 kWh/year to the system. This output corresponds to approximately 12% of the total annual electricity generation. The wind penetration level, defined here as the share of a component in the total annual electricity generation, was calculated as 11.6%. The biogas generator (BG) achieved a capacity factor of 30.6% and operated for 2,679 hours annually. It generated 401,850 kWh/year, accounting for approximately 40% of the total annual electricity generation. The photovoltaic (PV) system operated for 4,389 hours and had a capacity factor of 27.9%. Its annual energy contribution was 487,965 kWh, accounting for 48% of the total annual electricity generation. The penetration level of the PV system was determined to be 48.5%. According to Table 1, the lowest COE and total NPC for a 100% renewable supply are 0.555 \$/kWh and \$5,173,077, respectively. Figure 9 shows the average electricity production.

The off-grid results should therefore be interpreted as techno-economic outcomes of the modeled configurations, rather than as a complete quantitative demonstration of supply reliability. Although S3 produces 1,006,808 kWh/year in total and is reported as the least-cost option among the modeled off-grid configurations, annual generation exceeding annual demand does not by itself demonstrate hourly adequacy because renewable generation and building demand are time dependent and storage constraints may produce both excess generation and short-duration deficits. As unmet-load, capacity-shortage and battery-performance outputs are not reported, no numerical claim regarding LPSP, autonomy, curtailment, or storage cycling is made.

Battery technology is an additional source of uncertainty in the off-grid results. The modeled OPzS lead-acid battery reflects the storage assumptions of the present analysis, whereas contemporary LFP systems can differ materially in usable depth of discharge, cycle life, round-trip efficiency, replacement frequency and capital cost. Since no alternative battery model was optimized, this study does not quantify how an LFP system would change optimal storage capacity, NPC, COE or off-grid reliability. Any such numerical comparison would require a new optimization using technology-specific cost and performance inputs.

The very low wind-turbine capacity factor (4.85%) requires careful interpretation. It is consistent with the weak wind resource represented by the long-term NASA POWER dataset used in HOMER (mean wind speed 2.97 m/s at the 50 m reference height) and indicates that wind energy is a weak resource at this location for the selected turbine. Accordingly, the inclusion of wind in S3 should not be interpreted as evidence that wind is independently attractive at the site. Rather, S3 is the least-cost configuration among the modeled off-grid combinations under the HOMER search space and assumptions adopted, in which wind provides 116,993 kWh/year (11.6% of total annual generation), while PV and biogas provide the dominant shares. Because NASA POWER wind data represent regional reanalysis conditions rather than on-site measurements, the wind-related results should be treated as a resource-screening outcome. Site-specific wind monitoring at the intended hub height would be required before an investment decision. Alternative turbine, hub-height or wind-exclusion optimizations are outside the scope of this study.

In the grid-connected cases, the same low wind-resource condition applies. Therefore, the presence of wind in S6, which raises the renewable fraction only modestly relative to S4, should be interpreted as a supplementary renewable contribution within the modeled configuration rather than as evidence of strong standalone wind-resource suitability.

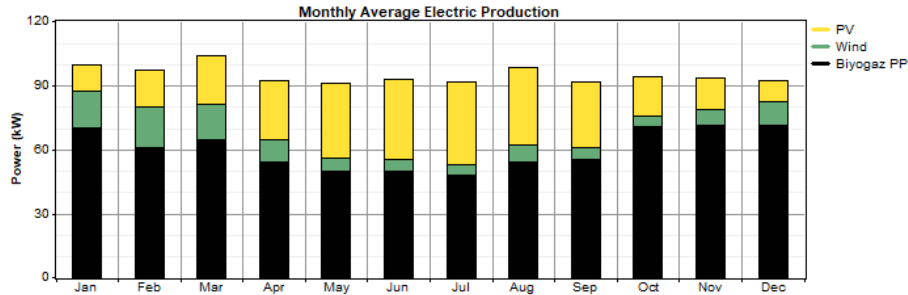


Fig. 9 The average production of electrical energy for off grid

4.2 On-grid hybrid systems

The grid-connected HRES consists of the grid, wind turbines (WT), photovoltaic panels (PV), biogas generators (BG) and converters. Its purpose is to meet the electrical load of CB-2 without interruption at the lowest COE, and its configuration is shown in Fig. 10.

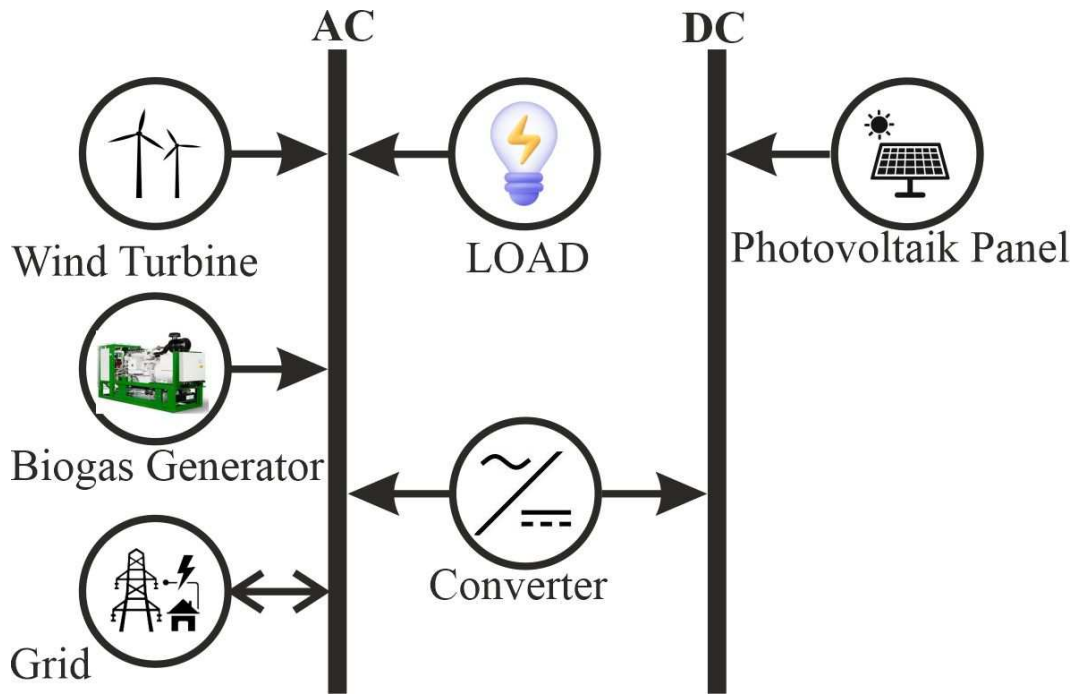


Fig. 10 The on-grid HRES

For the same resource conditions and a grid capacity of 250 kW, the optimal component sizes of the grid-connected configurations are given in Table 2.

Table 2 Optimal component sizes and economic results of the grid-connected HRES configurations

Configuration	WT (kW)	PV (kW)	BG (kW)	Conv (kW)	Grid (kW)	IIC (\$)	OC (\$/year)	NPC (\$)	COE (\$/kWh)	RF (%)
Grid-PV-BG (S4)	-	200	150	150	250	870,000	77,005	1,854,379	0.199	70
Grid-WT-BG (S5)	200	-	150	150	250	750,000	103,286	2,070,347	0.222	70
Grid-WT-PV-BG (S6)	200	200	150	150	250	1,350,000	85,869	2,447,688	0.263	72

Note: WT, wind turbine; PV, photovoltaic; BG, biogas generator; Conv, converter; IIC, initial investment cost; OC, operating cost; NPC, net present cost; COE, cost of energy; RF, renewable fraction.

For the Grid/WT/PV/BG configuration (S6), the renewable fraction is 72% and the electricity generated by the renewable components is 943,358 kWh/year. The capacity factor of the wind turbine was calculated as 4.85 % and it operated for 4,510 hours. Wind penetration was determined to be 12.4 %. The wind turbine generated 116,993 kWh/year, corresponding to approximately 12 % of the total electricity generation. The photovoltaic

system's capacity factor is 27.9 % and it operated for 4,389 hours. The PV penetration was 51.7 %. The photovoltaic system generated 487,965 kWh/year, corresponding to approximately 52 % of the total electricity generation. The capacity factor of the biogas generator is 25.8 % and it operated for 2,256 hours. The biogas generator generated 338,400 kWh/year, corresponding to approximately 36 % of the total electricity generation. As shown in Table 2, Grid/PV/BG (S4) yields the lowest COE (0.199 \$/kWh) and NPC (\$1,854,379), with a renewable fraction of 70%. The Grid/WT/BG configuration (S5, 0.222 \$/kWh) ranks second, reflecting the modest wind potential of the site. Grid/WT/PV/BG (S6) achieves the highest renewable fraction (72%), but its COE is approximately 32% above that of S4. Figure 11 shows the average electricity production.

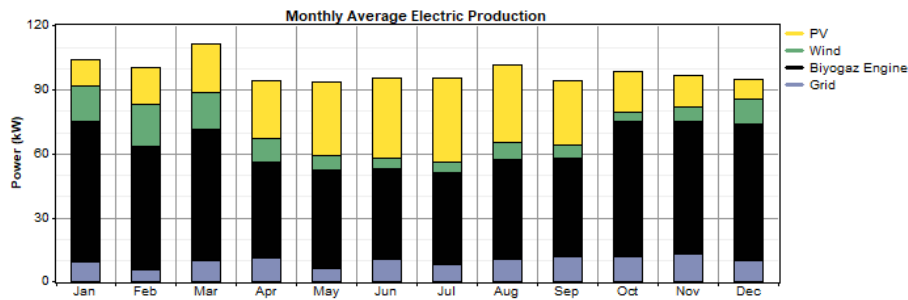


Fig. 11 The average production of electrical energy for on grid

4.3 Emissions

An important distinction is required when interpreting the economic ranking. S4 (Grid/PV/BG) has the lowest NPC and COE among the investigated HRES alternatives, but this does not imply that it is less expensive than continued grid-only electricity supply under the fixed 2025 reference tariff assumptions. The separate analytical S0 reference gives an annual grid-purchase cost of approximately \$36,500 and a 25-year discounted present value of approximately \$0.467 million under a constant real tariff and a 6% real discount rate. In comparison, the HOMER-derived NPC of S4 is approximately \$1.85 million. Because the S0 value is an analytical electricity-purchase reference rather than a HOMER-derived NPC, the two values should not be interpreted as a strict like-for-like optimization comparison. Nevertheless, the reference calculation shows that the economic motivation for the modeled HRES is not lower direct electricity cost under the assumed tariff alone; the configurations instead involve a trade-off between higher system

cost, increased renewable penetration, and substantial reductions in grid-related emissions.

The economic results should consequently be interpreted as conditional on the adopted input assumptions rather than as deterministic forecasts. In particular, the fixed 2025 reference grid purchase-price assumption of \$0.05/kWh strongly influences the comparison between grid-connected renewable configurations and continued grid supply, while the adopted PV capital cost of \$3,000/kW is conservative relative to more recent commercial PV benchmarks. Biomass economics are additionally sensitive to the actual cost and continuity of manure collection, transport and handling, none of which were represented as a detailed logistics model. The low modeled wind capacity factor (4.85%) also makes wind-containing configurations sensitive to site-specific wind-resource and turbine-selection assumptions. These uncertainties do not invalidate the HOMER optimization; rather, they define the conditions under which its numerical NPC and COE results should be interpreted.

Fossil fuels are still widely used for electricity generation and emit gases that pollute the air and contribute to global warming. Table 3 compares the annual pollutant emissions of the grid-only baseline (S0) with those of the proposed HRES configurations. The grid-only baseline supplies the entire annual load of about 730 MWh from the grid and emits 342,370 kg CO₂, 2,000 kg SO₂ and 978 kg NO_x per year. The off-grid configurations reduce CO₂ emissions by more than 99% and eliminate SO₂ emissions, while the grid-connected configurations reduce CO₂ and SO₂ emissions by 78–81% owing to the substantial decrease in net grid purchases. NO_x emissions are also reduced in all configurations, by 69–74% in the grid-connected and 83–88% in the off-grid configurations. In contrast, CO, UHC and PM emissions, which are not associated with grid electricity in the model, arise in all HRES configurations from the combustion of biogas. These findings indicate substantial modeled operational-emission reductions for the investigated HRES configurations. Among the modeled HRES alternatives, the Grid/PV/BG configuration (S4) combines the lowest HRES cost with a 78% CO₂ reduction relative to the grid-only baseline, while S6 achieves a slightly higher reduction of 81% at a higher cost.

Table 3 Modeled annual operational pollutant emissions of the grid-only system and the proposed HRES configurations

Scenarios	Pollutant Emissions (kg/yr)					
	Carbon Dioxide CO ₂	Carbon Monoxide CO	Unburned Hydrocarbons UHC	Particulate Matter PM	Sulphur Dioxide SO ₂	Nitrogen Oxides NO _x
S0 Grid	342,370	0	0	0	2,000	978
S1 PV-BG-BT	410	15.4	1.71	1.16	0	137
S2 WT-BG-BT	501	18.8	2.09	1.42	0	168
S3 WT-PV-BG-BT	352	13.2	1.46	0.996	0	118
S4 Grid-PV-BG	75,318	9.32	1.03	0.703	439	298
S5 Grid-WT-BG	65,338	12.7	1.41	0.957	380	299
S6 Grid-WT-PV-BG	64,210	7.78	0.862	0.587	374	252

If the load is supplied entirely from the grid, 342,370 kg CO₂, 2,000 kg SO₂ and 978 kg NO_x are released into the atmosphere annually. By using the WT-PV-BG-BT configuration (S3) instead of the grid, CO₂, SO₂ and NO_x emissions can be reduced by 99.9%, 100% and 88%, respectively. With the grid-connected Grid-WT-PV-BG configuration (S6), CO₂, SO₂ and NO_x emissions can be reduced by 81%, 81% and 74%, respectively. In both cases, however, biogas combustion results in additional CO, UHC and PM emissions (e.g., 7.78 kg CO, 0.862 kg UHC and 0.587 kg PM per year for S6).

The SO₂ and NO_x results require additional caution. Unlike the CO₂ calculation, which uses the ETKB electricity consumption-point factor, the SO₂ and NO_x values originate from HOMER default grid-emission factors. They should therefore not be interpreted as Türkiye-specific measured or official emission estimates. Their main value in this study is comparative: they indicate the direction and approximate relative magnitude of operational-emission changes across the modeled scenarios. Future work should replace these defaults with temporally matched, Türkiye-specific pollutant factors where reliable data are available.

These emission results should not be interpreted as a complete environmental footprint comparison. In particular, the analysis does not quantify upstream and embodied impacts of renewable-energy equipment or the collection and transportation of cattle manure. A full comparative LCA could therefore modify the relative magnitude of the environmental advantages reported here, especially for material-intensive components and biomass logistics.

At the building scale, increased use of on-site renewable resources can reduce electricity drawn from the grid. However, the broader energy-security implications cannot be quantified from this single-building case. The local air-quality impacts of biogas combustion, particularly CO, UHC and particulate matter emissions, should also be considered alongside the modeled greenhouse-gas reductions, for example through appropriate exhaust-gas treatment.

4.4 Sensitivity Analysis

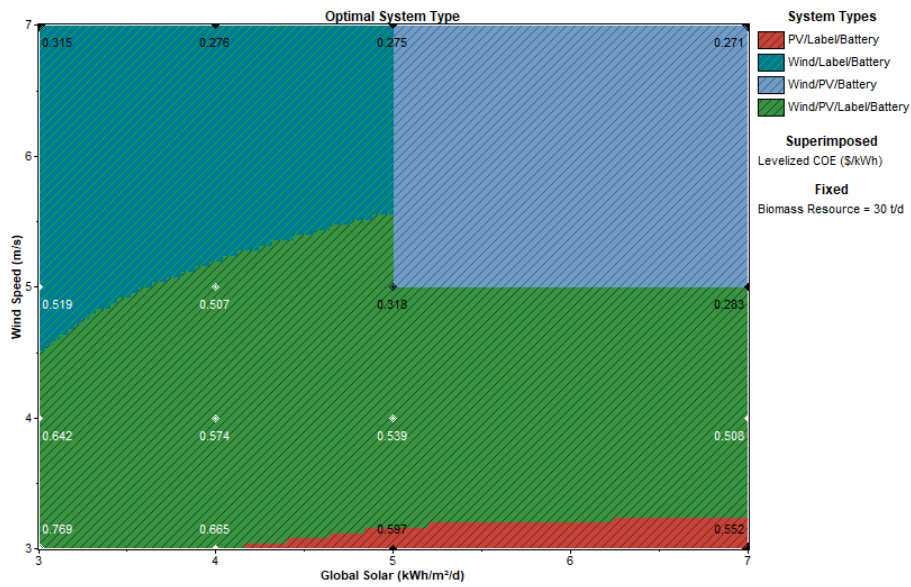


Fig. 12 Sensitivity analysis of off-grid HRES according to solar radiation and wind speed change

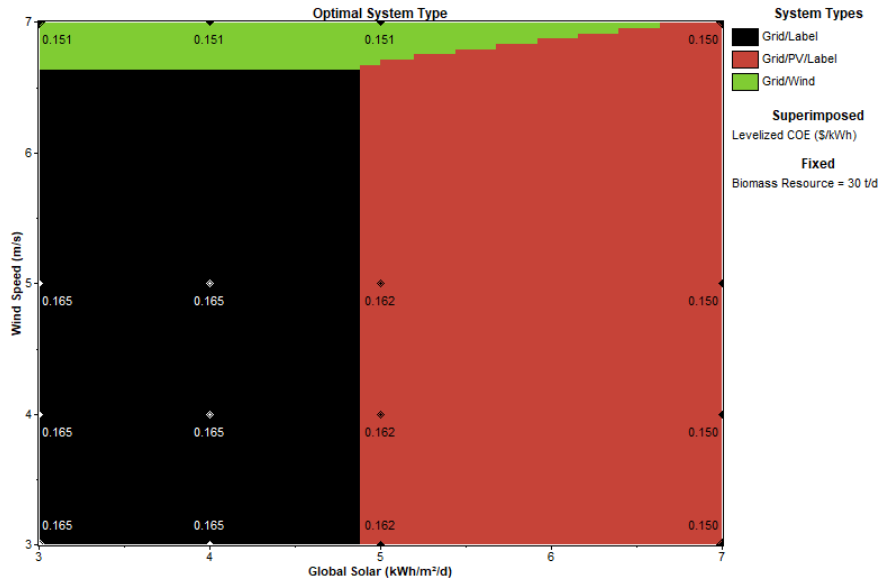


Fig. 13 Sensitivity analysis of on-grid HRES according to solar radiation and wind speed change

Sensitivity analyses were conducted by varying wind speed and solar radiation under both grid-connected and off-grid scenarios. The results, shown in Figs. 12 and 13, can be summarized as follows:

- For off-grid systems, PV/BG/BT becomes optimal under high solar radiation (4.2–7 kWh/m²/day) and low wind speeds (3.0–3.2 m/s).
- For grid-connected systems, Grid/PV/BG emerges as optimal under solar radiation >4.8 kWh/m²/day, irrespective of wind speed.

These results underscore the importance of local resource assessment for optimal system selection. Under the base-case resource conditions, the Grid/WT/PV/BG configuration (S6) provides the highest renewable fraction (72%), but at a considerably higher COE (0.263 \$/kWh) than the cost-optimal Grid/PV/BG configuration (S4, 0.199 \$/kWh).

4.5 Comparison with Previous Studies

A further economic boundary concerns the manure-to-biogas pathway. HOMER can include biomass feedstock price directly in generator fuel cost, whereas anaerobic-digester capital and O&M costs require explicit additional cost inputs. Since the biomass price and digester balance-of-plant costs are not itemized separately in this study, the reported NPC and COE are presented as HOMER outputs and the biomass-cost boundary is identified as an uncertainty. A bankable project assessment would require site-specific

quotations for manure collection and transport, digester construction and operation, pretreatment, gas cleaning and storage, digestate handling, and methane-leakage control.

A further limitation is that a probabilistic uncertainty analysis (e.g., Monte Carlo simulation) and a full one-at-a-time economic sensitivity analysis were not performed in this study. Accordingly, the study does not assign confidence intervals or probability distributions to NPC and COE, nor does it claim robustness of the configuration ranking outside the modeled parameter space. Future work should evaluate tariff escalation, contemporary PV and battery costs, biomass logistics, discount rate, component replacement costs, and alternative wind-turbine/hub-height choices using systematic sensitivity or probabilistic methods.

Accordingly, a complete future assessment of off-grid feasibility should report hourly supply-demand adequacy together with unmet load, capacity shortage, excess electricity, battery state-of-charge distribution, annual throughput, autonomy, and replacement requirements. These indicators are particularly important for S1-S3 because economic autonomy from the grid is meaningful only when the required reliability criterion is simultaneously demonstrated.

Future work should therefore compare the existing lead-acid storage case with contemporary LFP and other relevant battery technologies using consistent assumptions for usable capacity, depth of discharge, round-trip efficiency, calendar and cycle ageing, replacement cost, and end-of-life. Such a comparison would be particularly important for the off-grid scenarios, where storage performance directly affects both reliability and lifecycle cost.

Comparison with the 2026 literature should be made cautiously because system scale, resource quality, tariff structures, technology portfolios and economic assumptions differ substantially. For example, Bozkurt et al. (2026) considered a 30.4 GWh/year campus-scale PV–wind–biomass transition in Türkiye, whereas the present study addresses an approximately 0.73 GWh/year individual building load. Ali et al. (2026a) examined a smaller student-residence load but included battery storage and net-metering, while Ali et al. (2026b) incorporated hydrogen production and long-duration storage together with explicit robustness indicators. Consequently, their NPC and LCOE/COE values are not directly transferable benchmarks for the present case. The more informative comparison is methodological: recent studies increasingly combine cost optimization with reliability, storage, sensitivity and decarbonization metrics. In this context, the present results

provide a building-scale PV–wind–biogas case under Türkiye-specific load and resource conditions, while the missing reliability and probabilistic metrics define clear priorities for subsequent work.

The results of this study are broadly consistent with recent campus-scale HRES assessments, although the absolute cost values differ. The COE of the cost-optimal grid-connected configuration (S4, 0.199 \$/kWh) is higher than the values reported for larger grid-connected campus systems in Türkiye, such as 0.107 \$/kWh for the Burdur Mehmet Akif Ersoy University campus (Aykut et al. 2023) and 0.043–0.114 \$/kWh for the Erciyes University campus (Bozkurt et al. 2026), and it also exceeds the grid-only LCOE of 0.135 \$/kWh reported by Bozkurt et al. (2026). This difference may reflect, among other factors, the smaller scale of a single building, different cost and tariff assumptions, and the relatively low wind potential of the site. For fully renewable off-grid operation, the COE obtained here (0.555 \$/kWh) is considerably higher than the 0.327 \$/kWh reported for a hydrogen-supported off-grid system at Aksaray University (Demir 2024), the 0.333 \$/kWh reported for a PV/biomass/battery system in Morocco (Choukri et al. 2025) and the 0.179 \$/kWh obtained for the off-grid scenario of Erciyes University (Bozkurt et al. 2026). Within the assumptions and configurations examined here, full grid independence is substantially more costly than the modeled grid-connected HRES alternatives. Consistent with the findings of Akindeji and Ewim (2023) and Bozkurt et al. (2026), the present results show that the modeled grid-connected hybrid configurations achieve lower COE than the modeled off-grid alternatives while retaining substantial operational-emission reductions. In line with Bozkurt et al. (2026), the present analysis shows substantial reductions in CO₂, SO₂ and NO_x emissions; however, it also shows that biogas-based configurations introduce local CO, UHC and particulate matter emissions, which should be taken into account in the environmental assessment of manure-based HRES.

5 Conclusions

This study assessed grid-connected and off-grid PV-wind-biogas HRES configurations for a large educational building at Kırklareli University using the 2020-2025 hourly electricity-demand profile and local renewable-resource data. Under the adopted HOMER assumptions, the Grid/PV/Biomass configuration (S4) was the least-cost option among the investigated grid-connected HRES alternatives, with an NPC of approximately \$1.85 million, a COE of \$0.199/kWh and a renewable fraction of 70%. Adding wind in

S6 increased the renewable fraction to 72% but also increased the COE to \$0.263/kWh. For the off-grid alternatives, S3 (WT/PV/BG/BT) had the lowest reported COE (\$0.555/kWh) and generated 1,006,808 kWh/year, with PV, biogas and wind contributing approximately 48%, 40% and 12%, respectively.

The results emphasize that local resource quality is decisive for system interpretation. The modeled wind-turbine capacity factor of only 4.85% indicates that wind is a supplementary rather than a dominant resource at this site, whereas PV and biogas provide the principal renewable contributions. The 30 t/day manure input is technically plausible relative to the estimated collectable provincial manure potential, but it remains a scenario assumption rather than a verified site-specific supply contract; collection continuity, transport distance and handling costs therefore remain important implementation uncertainties.

The economic findings should also be interpreted conditionally. S4 is the least-cost configuration among the modeled HRES alternatives, but it should not be interpreted as less expensive than continued grid-only supply under the fixed 2025 reference purchase-price assumption of \$0.05/kWh. The separate analytical grid-only reference corresponds to an annual electricity-purchase expenditure of approximately \$36,500 and a 25-year discounted present value of about \$0.467 million under a constant real tariff and a 6% real discount rate. This analytical value is not a HOMER-derived NPC and is therefore not a strict like-for-like optimization metric; nevertheless, it demonstrates that the modeled HRES configurations involve a trade-off between additional system cost, renewable penetration and reduced dependence on grid electricity. The HRES cost results also remain conditional on the adopted biomass-cost boundary; because the feedstock price and anaerobic-digester balance-of-plant costs are not itemized separately, the reported NPC and COE should not be interpreted as a complete investment estimate for a new manure-to-biogas plant.

Operational CO₂ emissions were reduced by more than 99% in the modeled off-grid cases and by approximately 78-81% in the grid-connected HRES cases relative to the grid-only baseline. These values represent operational emissions rather than life-cycle impacts. Moreover, the SO₂ and NO_x results are based on HOMER default grid-emission factors and should be interpreted primarily as comparative model outputs rather than Türkiye-specific official pollutant inventories. A complete environmental evaluation would

require life-cycle boundaries that include equipment manufacture, replacement and end-of-life processes as well as manure collection and transportation.

Several limitations define the scope of the conclusions. The present study does not report the detailed off-grid reliability and storage outputs required to quantify unmet load, capacity shortage, excess electricity, LPSP, battery autonomy, throughput or replacement count. The storage results are also specific to the modeled OPzS lead-acid battery, and no LFP alternative was optimized. Similarly, updated PV costs, alternative wind turbines or hub heights, and probabilistic economic uncertainty were not included in the analysis.

Future work should therefore extend the optimization with contemporary technology costs, alternative battery chemistries, detailed biomass logistics, Türkiye-specific pollutant factors and explicit hourly reliability indicators. Systematic sensitivity or probabilistic analysis should additionally test tariff evolution, discount rate, component replacement costs and resource uncertainty. Within these boundaries, the present study provides a building-scale Türkiye case showing how PV, wind and manure-derived biogas interact differently under grid-connected and off-grid architectures, and why cost, renewable penetration, operational emissions and reliability should be evaluated jointly rather than through a single performance metric.

Statements and Declarations

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Author contributions Conceptualization: Sureyya Kocabey; Methodology: Sibel Ülker Dursun; Data curation: Sureyya Kocabey; Formal analysis: Sureyya Kocabey; Investigation: Sureyya Kocabey; Software: Sureyya Kocabey; Visualization: Sureyya Kocabey; Writing – original draft: Sureyya Kocabey; Writing – review and editing: Sibel Ülker Dursun. All authors read and approved the final manuscript.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics approval Not applicable. This study did not involve human participants or animals.

References

- Agajie TF, Fopah-Lele A, Amoussou I, Ali A, Khan B, Tanyi E (2023) Optimal design and mathematical modeling of hybrid solar PV–biogas generator with energy storage power generation system in multi-objective function cases. *Sustainability* 15(10)
- Akindeji KT, Ewim DRE (2023) Economic and environmental analysis of a grid-connected hybrid power system for a university campus. *Bulletin of the National Research Centre* 47:75
- Ali MF, Rony MMH, Biswas D, Azam ME, Shezan SA, Kamwa I (2026a) Hybrid renewable microgrid optimization for cost reduction, emission mitigation, and net-metering grid-connected stability in university student residences for developing countries. *Energy Nexus* 21:100649. <https://doi.org/10.1016/j.nexus.2026.100649>
- Ali A, Abdul Wahab NI, Qureshi ZUA, Azmat U, Muqet HA, Aghamolaei R (2026b) Hybrid renewable energy systems in educational institutions: pathways to sustainability and cost-effectiveness. *Results in Engineering* 30:111083. <https://doi.org/10.1016/j.rineng.2026.111083>
- Aykut E, Dursun B, Görgülü S (2023) Comprehensive environmental and techno-economic feasibility assessment of biomass-solar on grid hybrid power generation system for Burdur Mehmet Akif Ersoy University Istiklal Campus. *Heliyon* 9(11):e22264
- Bozkurt A, Kaan M, Genç MS, Azgın ŞT, Kaan L (2026) Sustainable energy transition in higher education: optimization of a hybrid renewable system under Türkiye's 2053 net-zero target. *Sustainability* 18(9):4584
- Choukri NE, Touili S, Azzaoui A, Merrouni AA (2025) Techno-economic analysis for a 100% renewable hybrid energy systems integration in a research facility in Morocco. *iScience* 28:113132
- Demir H (2024) Design and optimization of hybrid renewable energy systems for hydrogen production at Aksaray University campus. *Process Safety and Environmental Protection* 192:543–556
- Demirci A, Akar O, Ozturk Z (2022) Technical-environmental-economic evaluation of biomass-based hybrid power system with energy storage for rural electrification. *Renewable Energy* 195:1202–1217

- Dursun B (2012) Determination of the optimum hybrid renewable power generating systems for Kavakli campus of Kırklareli University, Turkey. *Renewable and Sustainable Energy Reviews* 16(8)
- Dursun B, Aykut E (2019) An investigation on wind/PV/fuel cell/battery hybrid renewable energy system for nursing home in Istanbul. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 233(5):616–625
- EPDK (Energy Market Regulatory Authority) (2025) Electricity tariff and last-resort supply framework for 2025. Energy Market Regulatory Authority, Ankara. Accessed 1 October 2026
- Ertop H, Atılgan A, Kocięcka J, Krakowiak-Bal A, Liberacki D, Saltuk B, Rolbiecki R (2023) Calculation of the potential biogas and electricity values of animal wastes: Turkey and Poland case. *Energies* 16(22):7578. <https://doi.org/10.3390/en16227578>
- ETKB (Ministry of Energy and Natural Resources) (2025) https://enerji.gov.tr/Media/Dizin/EVCED/tr/%C3%87evreVe%C4%B0klim/%C4%B0klimDe%C4%9Fi%C5%9Fikli%C4%9Fi/EmisyonFaktorleri/2023_Turkiye_Elektrik_UretimveElektrik_Tuketim_Noktasi_Emisyon_Faktorleri.pdf
- HOMER Energy (2026a) Biomass module. HOMER Pro documentation. Accessed 1 October 2026
- HOMER Energy (2026b) Generator fuel cost. HOMER Pro documentation. Accessed 1 October 2026
- HOMER Energy (2026c) Capital cost—anaerobic digester biogas. HOMER Knowledge Base. Accessed 1 October 2026
- Hoppecke (2024) Hoppecke 24 OPzS 3000 model battery specifications. <https://www.hoppecke.com/>
- Hosseini SE, Wahid MA (2014) Utilization of palm solid residue as a source of renewable and sustainable energy in Malaysia. *Renewable and Sustainable Energy Reviews* 40:621–632
- Islam MS (2018) A techno-economic feasibility analysis of hybrid renewable energy supply options for a grid-connected large office building in southeastern part of France. *Sustainable Cities and Society* 38:492–508

- Jahangir MH, Eslamnezhad S, Mousavi SA, Askari M (2021) Multi-year sensitivity evaluation to supply prime and deferrable loads for hospital application using hybrid renewable energy systems. *Journal of Building Engineering* 40:102733
- Kırklareli Provincial Directorate of Agriculture and Forestry (2026) Kırklareli 2025 provincial activity report, Table 7: Animal population. Republic of Türkiye Ministry of Agriculture and Forestry, Kırklareli
- Kumar P, Channi HK (2024) Evaluating resilience: a HOMER-based sensitivity analysis of electric vehicle charging infrastructure. In: 2024 International Conference on Integrated Circuits and Communication Systems (ICICACS). IEEE, Raichur, pp 1–6. <https://doi.org/10.1109/ICICACS60521.2024.10499066>
- Lambert T, Gilman P, Lilienthal P (2006) Micropower system modeling with HOMER. In: Farret FA, Simões MG (eds) *Integration of alternative sources of energy*. Wiley, Hoboken, pp 379–418
- Mahalakshmi A, Latha S (2015) An economic and environmental analysis of biomass-solar hybrid system for the textile industry in India. *Turkish Journal of Electrical Engineering and Computer Sciences* 23(6):1735–1747
- Mandal S, Das BK, Hoque N (2018) Optimum sizing of a stand-alone hybrid energy system for rural electrification in Bangladesh. *Journal of Cleaner Production* 200:12–27
- NASA POWER (2026) Prediction of Worldwide Energy Resources (POWER): meteorological wind-speed data. NASA Langley Research Center, Hampton, VA. Data accessed through HOMER; 50-m monthly average wind speed, January 1984–December 2025, grid-cell midpoint 41.25° N, 28.75° E. Accessed 1 October 2026
- Ngan MS, Tan CW (2012) Assessment of economic viability for PV/wind/diesel hybrid energy system in southern Peninsular Malaysia. *Renewable and Sustainable Energy Reviews* 16(1):634–647
- NPS (Northern Power Systems) (2022) Northern Power NW/100/19 model wind turbine specifications. <http://nps100.com/>
- Pamuk N (2024) Techno-economic feasibility analysis of grid configuration sizing for hybrid renewable energy system in Turkey using different optimization techniques. *Ain Shams Engineering Journal* 15(3):102474

- Sharma S, Sood YR, Sharma NK, Bajaj M, Zawbaa HM, Turkey RA, Kamel S (2022) Modeling and sensitivity analysis of grid-connected hybrid green microgrid system. Ain Shams Engineering Journal 13(4):101679
- Stackhouse PW (2017) NASA surface meteorology and solar energy. NASA Langley Research Center, POWER Project. <https://power.larc.nasa.gov/>
- TSMS (Turkish State Meteorological Service) (2021) Solar radiation data for Kırklareli. https://www.mgm.gov.tr/kurumici/radyasyon_iller.aspx?il=Kırklareli
- U.S. Department of Energy (2025) Solar photovoltaic system cost benchmarks: 2025 Q1 PV system cost model. U.S. Department of Energy, Washington, DC
- Zahid A, Shahzad MK, Jamil SR, Iqbal N (2023) Futuristic feasibility analysis and modelling of a solar-biomass on-grid hybrid system for Hattar Industrial Estate Phase (VII), Pakistan. Cleaner Energy Systems 4:100053