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Techno-Economic and Environmental Assessment of On-Grid and Off-Grid Renewable Energy Systems for Çanakkale, Türkiye Using HOMER Pro

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WHAT IS ALREADY KNOWN ON THIS TOPIC?

- *Hybrid systems combining solar and wind are widely studied to reduce fossil fuel dependence and enhance sustainability, especially in remote areas.*
- *HOMER Pro is a commonly used simulation tool for evaluating the technical, economic, and environmental performance of these systems.*

WHAT DOES THIS STUDY ADD ON THIS TOPIC?

- *This study provides a contextualized assessment by comparing economic indicators like NPC and COE.*
- *It also quantifies environmental benefits, enabling multidimensional decision-making.*
- *Unlike national-level or purely technical studies, it integrates simulation, economics, and sustainability in a local case.*

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ABSTRACT

The increasing depletion of fossil fuel resources and their detrimental impact on the environment have heightened the demand for renewable energy sources in the power generation sector. Renewable sources are favored for their sustainability, reliability, and eco-friendliness. This study evaluates the technical and economic viability of both on-grid and off-grid hybrid renewable energy systems for Çanakkale, Turkey, using HOMER Pro software. The analysis incorporates solar photovoltaic (PV) panels, wind turbines, and storage components, assessing key metrics such as Net Present Cost (NPC), Cost of Energy (COE), Operating Cost (OC), and emissions. Results reveal that the on-grid system has an NPC of $25.1M, COE of $0.0257/kWh, and OC of $3.33M, while the off-grid system's NPC is $9.88M, COE $0.371/kWh, and OC $106.1M. The off-grid system reduces carbon emissions by 99.3% compared to the on-grid system but at higher costs. Annual electricity production for the on-grid system is 77.886.964 kWh, with 69.8% from wind turbines, 29.5% from PV, and 0.8% from the grid. The off-grid system generates 7.813.622 kWh annually, predominantly from PV (76.6%). The findings highlight a trade-off between economic feasibility and environmental sustainability, with the on-grid system offering cost advantages and the off-grid system excelling in emission reductions. This study aids in strategic decision-making for renewable energy investments.

Index Terms—Homer Pro, HESs, off-grid, on-grid, hybrid renewable energy, optimization, solar PV, wind

I. INTRODUCTION

Given global technological advancements and the expansion of energy infrastructure, the demand for energy resources continues to grow steadily. Energy consumption is rising in line with the country's economic development, technological advancement, and population growth [1]. Projections indicate that the upward trend in energy consumption is expected to persist in the coming decades. According to research, primary energy consumption is expected to increase by 56% globally between 2010 and 2040 [2].

Fossil fuels, as primary energy sources, pose significant global challenges by disturbing the ecological equilibrium. In addition, the rapid depletion of reserves has increased the demand for renewable energy sources. Turkey's energy consumption is rising in parallel with global trends. Turkey imports 72% of its energy needs from abroad [3]. In addition to the 3.58 million tons of crude oil produced in 2022, 33.49 million tons of crude oil were imported. These figures indicate that approximately 90% of Turkey's crude oil supply relies on imports [4].

Turkey's reliance on imported energy has led to numerous political and economic challenges, particularly price volatility. To minimize its dependence on foreign energy, Turkey conducts exploration studies for fossil energy resources within its borders. Turkey's producible reserves are approximately 70 million tons as of 2022. In the same year, 421.408 meters of drilling were conducted, and 191 crude oil wells were drilled [4].

According to data from September 2023, Turkey's installed power capacity by energy source is illustrated in Fig. 1: 27.8% from hydraulic energy, 21.3% from natural gas, 18.9% from coal, 11.1% from wind, 17.1% from solar, 1.5% from geothermal, and 2.3% from other sources.

As of the end of September 2023, Turkey's installed capacity has reached 105.668 MW. According to the same data, among the 12.562 electricity generation plants in Turkey, 753 are hydroelectric, 68 are coal-based, 363 are wind-powered, 63 are geothermal, 343 are natural gas plants, 10.479 are solar-based, and 493 use other sources [3]. Fig. 2 shows the hourly distribution of power plant production by resource [5].

Turkey ranks seventh globally in electricity production [6]. Despite its substantial installed capacity, the country remains unable to fully meet domestic energy demand. Additionally, Turkey ranks twelfth globally and fifth in Europe in renewable energy production [3]. Similar to other countries with high energy demand, Turkey's renewable energy potential is being explored and actively developed [7]. Thus, Turkey is one of the leading countries in the renewable energy sector and aims to expand its mission further.

Despite the growing body of literature on hybrid renewable energy systems (HRESs), several limitations remain unaddressed, particularly in the context of region-specific applications. Many existing studies focus on generic techno-economic evaluations or simulations that lack integration with real consumption profiles and locally sourced meteorological datasets. Moreover, most prior works do not simultaneously assess both environmental impact (i.e., CO_2, SO_2, NO_x emissions) and financial feasibility in a harmonized framework, especially for Turkish provinces with distinctive renewable potential like Çanakkale. For instance, while studies such as [8–11] explored off-grid systems in rural or tropical settings, and others [12, 13] analyzed hybrid models using HOMER Pro, there remains a lack of comprehensive analysis combining local consumption data, real capacity profiles, and multi-objective optimization tailored to semi-urban Turkish contexts.

This study addresses that gap by conducting a dual-scenario simulation (on-grid and off-grid) using HOMER Pro, enriched with authentic electricity consumption statistics from Çanakkale and high-resolution wind and solar datasets. The novelty of this work lies in its contextualized assessment: it not only compares economic indicators such as NPC and COE, but also quantifies environmental benefits, thus offering a multi-dimensional decision-making basis for policymakers and investors. Unlike most literature focusing on national-level modeling or isolated technical metrics, our contribution bridges simulation, economics, and sustainability in a locally grounded case study. Hence, this research provides a replicable and scalable model for optimizing hybrid renewable systems in other Turkish regions with similar topographic and demographic conditions.

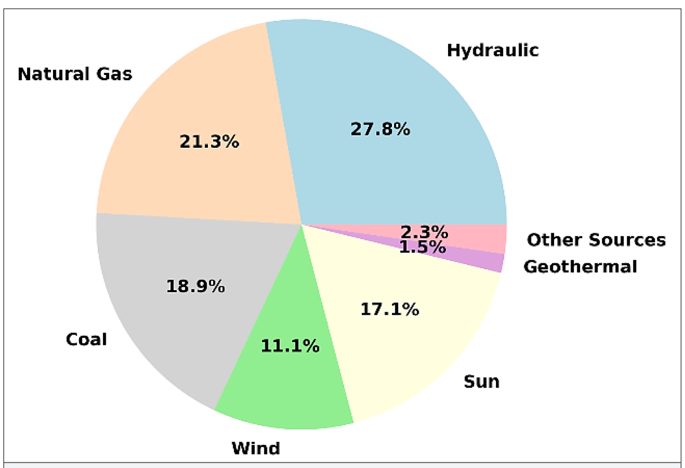


Fig. 1. Distribution of Turkey's installed power capacity in 2024.

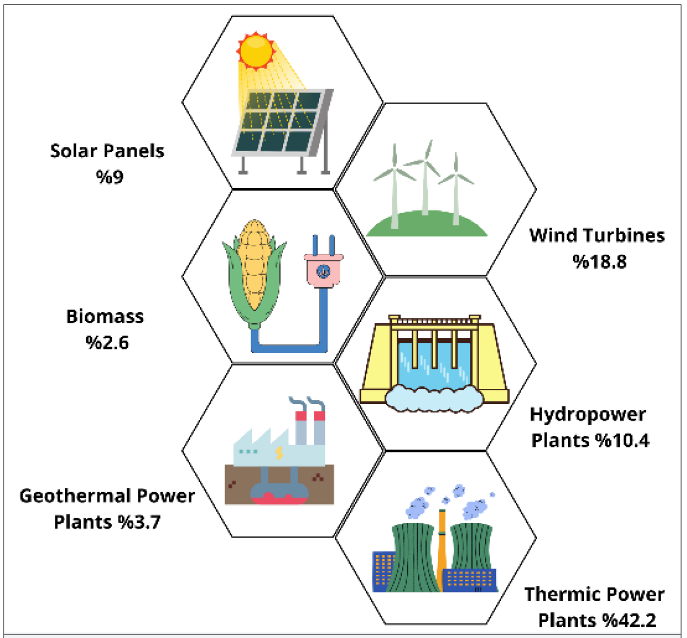


Fig. 2. Distribution of hourly production by sources (MWh).

Renewable energy systems—such as wind farms and photovoltaic (PV) plants—primarily depend on wind and solar radiation, resulting in intermittent energy generation. To ensure continuity in energy supply, renewable energy systems can be integrated into hybrid systems [14]. Hybrid energy systems (HESs) are designed to operate under varying conditions and combine multiple energy sources to meet continuous energy demands [15].

Hybrid energy systems can be installed either as grid-connected or off-grid systems [16]. In remote and hard-to-reach areas, off-grid systems are preferred [17, 18]. For these regions, photovoltaic systems, wind energy, or other renewable energy sources are combined with generators to form hybrid systems [14, 19]. Such hybrid configurations offer shorter payback periods, enhanced supply continuity, and substantial reductions in CO_2 emissions. Consequently, HESs contribute to reducing the effects of global warming and climate change by producing energy with lower carbon emissions [20].

II. THE ROLE OF RENEWABLE ENERGY: GLOBAL TRENDS AND TURKEY'S POTENTIAL

According to the analysis of the Outlook for Energy, it is estimated that producers in the energy sector will make effective decisions to reduce CO_2 emissions by 2040. The damage caused by CO_2 gas to the environment and climatic conditions is well-known. Accordingly, manufacturing companies in the sector are transitioning to renewable, environmentally friendly energy sources instead of fossil-based energy production to reduce carbon emissions. In this direction, a 45% reduction in carbon emissions globally is targeted by 2040. It is also among the goals of the energy sector to reduce carbon intensity by 30% by utilizing renewable and sustainable resources in electricity generation.

For this reason, wind and solar energy—both types of renewable energy—are growing in popularity. Additionally, hybrid systems, created by combining wind and solar energy systems, are increasingly preferred in the sector due to their sustainability, reliability, and adaptability to specific needs [21]. As illustrated in Fig. 3, renewable energy systems are expected to become the fastest-growing energy source globally, accounting for approximately two-thirds of investments in the production sector by 2040 [22].

According to the criteria determined by the Turkish Wind Energy Potential Atlas (REPA), regions with an annual average wind speed of 50 meters above ground and over 7.5 m/s in Turkey are considered suitable for wind power plant installation. As of the end of June 2022, Turkey's installed wind energy-based electricity capacity reached 10.976 MW, constituting 10.81% of the total installed capacity. The year-on-year changes in installed wind power capacity and its share in total capacity are presented in the graphs in Fig. 3.

Similarly, Turkey possesses significant solar energy potential due to its geographic location. Solar energy is both environmentally friendly and sustainable. According to the Solar Energy Potential Atlas of Turkey (GEPA), the country has an annual average sunshine duration of 2741 hours and an annual average total radiation value of 1527.46 kWh/m^2. The general potential outlook and monthly average global radiation distribution are shown in GEPA's data.

Consequently, numerous studies are being conducted in Turkey to explore renewable energy resources. There has been a significant increase in the use of photovoltaic, wind, biomass, and hydroelectric energy sources for electrical energy generation. As demonstrated in Figs. 4 and 5, Turkey's geographic location offers high wind and photovoltaic energy potential, making it suitable for hybrid renewable power plants.

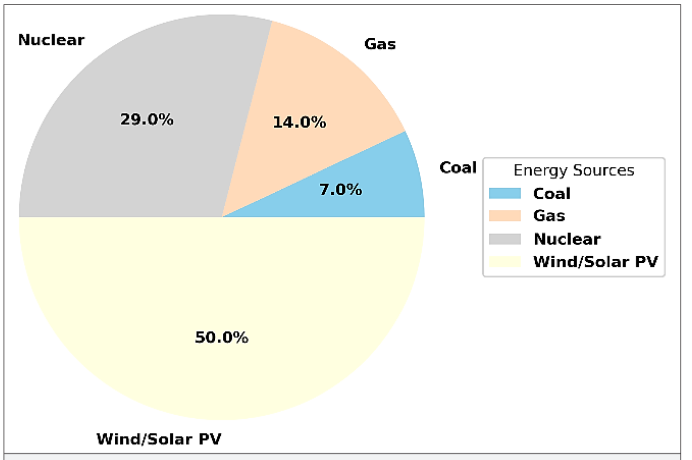


Fig. 3. Distribution of energy sources by fuel type (2017–2040).

When the solar radiation and wind potential in Turkey are analyzed, it is evident that their contributions to the total installed capacity grew substantially between 2011 and 2021. According to data from the Ministry of Energy and Natural Resources of Turkey, solar energy contributed 7.83% and wind energy 7.36% to the installed power during this period.

III. THE POTENTIAL OF RENEWABLE ENERGY IN ÇANAKKALE

Wind and solar energy, as renewable energy sources, vary depending on factors such as region, climate, and time. Therefore, the location where energy production is planned must undergo thorough analysis, and installations should be tailored accordingly. In this context, when analyzing the advantages and disadvantages of wind and solar energy for Çanakkale:

The province of Çanakkale, covering an area of 1016 km^2, spans both the European and Asian continents. Located at the westernmost edge of the Marmara Region, Çanakkale is one of the provinces with the highest energy consumption due to its regional dynamics and geographical positioning. Cape Baba, situated at the westernmost tip of Anatolia in the Aegean Sea, has coordinates 39° 28′ 45″ north latitude and 26° 03′ 50″ east longitude.

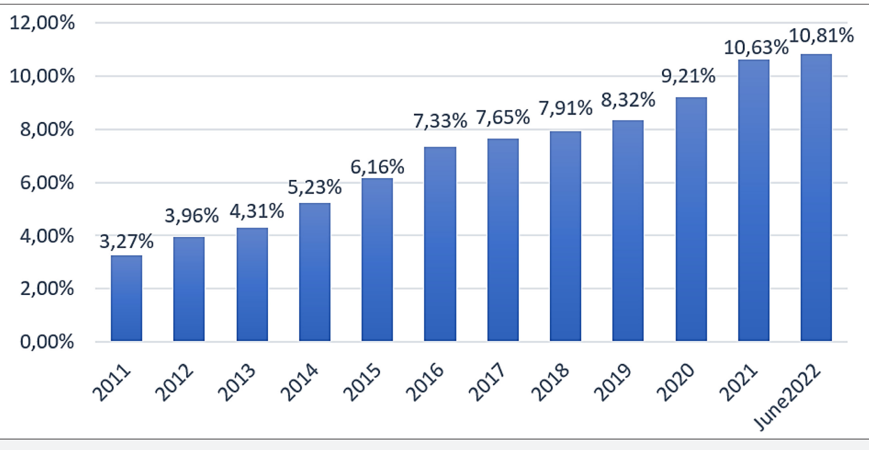


Fig. 4. The contribution of wind energy to Turkey's total installed electricity generation capacity.

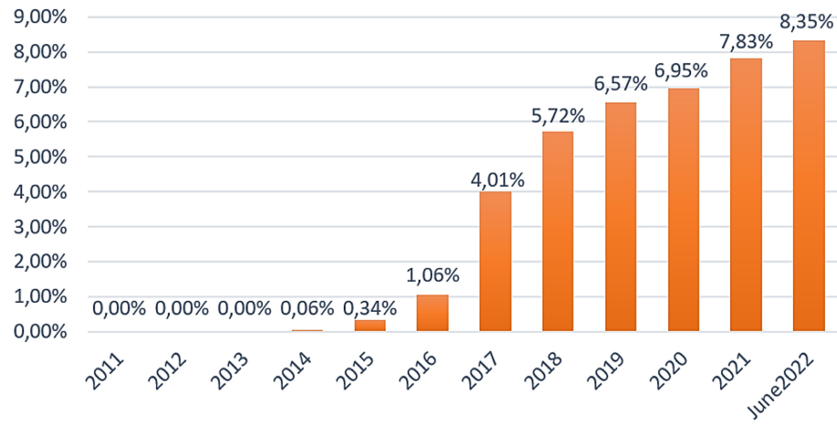


Fig. 5. The contribution of photovoltaic energy to Turkey's total installed electricity generation capacity.

According to data from REPA, Çanakkale possesses a high wind energy potential due to its geography. Similarly, based on GEPA's data, analyses indicate that the amount of sunshine in Çanakkale is sufficient for energy production through solar power plants. While wind energy in Çanakkale has some disadvantages, such as variability in capacity factors for power generation plants, it offers numerous benefits. These include being clean, renewable, environmentally friendly, and sustainable, as well as having low maintenance and operating costs and shorter commissioning times compared to other energy generation plants.

As shown in Fig. 6, the wind potential map of Çanakkale, published by the General Directorate of Renewable Energy, highlights the province's exceptional wind intensity and energy potential. This figure details the variation of wind intensity at an altitude of approximately 100 meters within the study area. The western regions of Çanakkale, in particular, demonstrate a notably high energy potential.

Considering these statistics, it has been determined that Çanakkale is a suitable location for establishing a renewable hybrid power plant [15].

IV. OVERVIEW OF HOMER PRO FOR HYBRID RENEWABLE ENERGY OPTIMIZATION

Hybrid renewable energy systems can be utilized in both grid-connected and off-grid configurations. To design such systems effectively, many optimization programs are available. These programs offer economic and technical advantages to designers [23]. In this study, HOMER Pro (Hybrid Optimization Model for Electric Renewables) was selected as the optimization tool for hybrid power plant design.

The HOMER Pro stands for Hybrid Optimization Model for Electric Renewables [24, 25]. When designing in HOMER Pro, the location of the system to be designed must first be determined and selected. Subsequently, energy source data must be uploaded to the system. HOMER Pro retrieves wind, solar, and temperature data from NASA's POWER database for the selected region [26].

HOMER Pro includes many components necessary for system design. Depending on the intended design, the user can either utilize the preconfigured components provided by HOMER Pro or customize each element based on specific criteria. Once the system is simulated, HOMER Pro provides a comprehensive optimization experience by performing comparisons and presenting technical and economic graphs.

The program calculates the total NPC to represent the maintenance cost of the system [12]. In this context, costs are considered positive values, while revenues are negative. Additionally, the discount rate, inflation rate, and simulation period must be defined as they significantly impact economic outcomes. These rates, in particular, directly influence the payback period of the system [13].

Finally, based on the results provided by HOMER Pro, the best option is determined, and design outputs are generated. A review of the literature on HOMER Pro optimization studies, including investment analyses and scenarios, is summarized in Table I.

V. METHODOLOGY

In this study, carbon emissions from different hybrid systems for renewable energy potential in Çanakkale province were compared. This comparison was based on the payback period, NPC, and current system cost, calculated using the HOMER Pro program. The following formulations were applied to determine the most suitable system.

To calculate the payback period of the system, the ratio of the initial investment cost to the cash flow is used. A shorter payback period indicates a more efficient scenario and suggests that the system is economically viable.

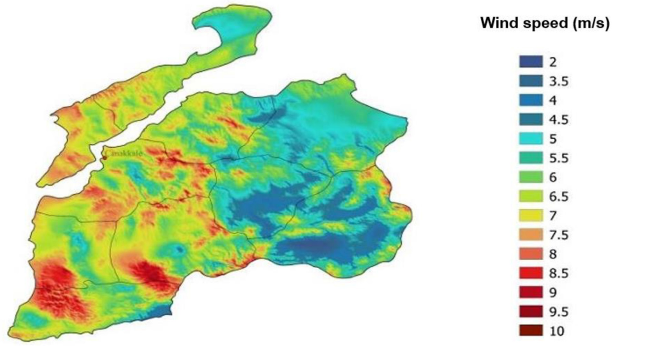
For the NPC value, the difference between the total project costs over its lifetime and the total income generated is calculated. A negative NPC value signifies that the system is profitable.

$$\textit{Payback Period} = \frac{\textit{Initial Investmentor Or iginal Cost of the Asset}}{\textit{Cash Inflows}}$$

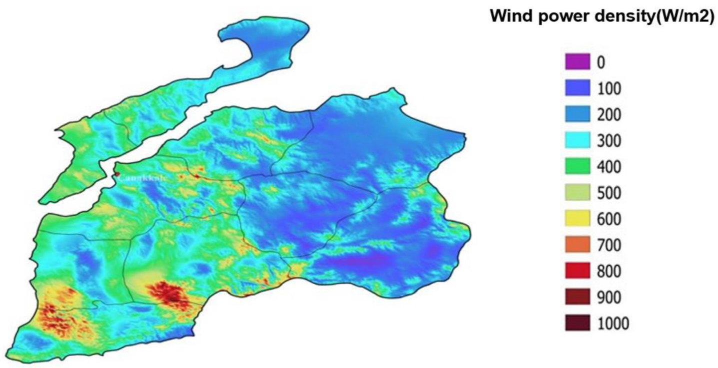
NPC = All-time present value over project lifetime – revenues earned over the project lifetime

Present worth = NPC base system – NPC current system

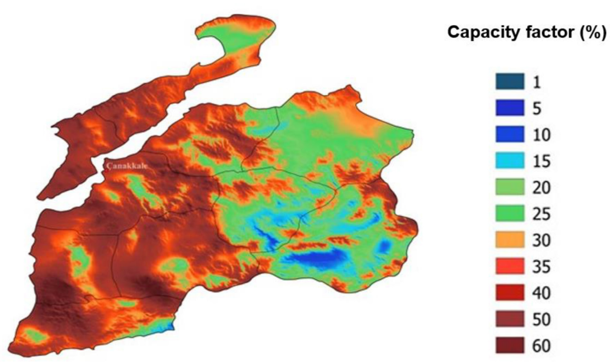
To ensure economic realism in the simulation, key financial parameters were incorporated into the HOMER Pro model. Specifically, an annual interest rate of 8% and an inflation rate of 2% were assumed, based on historical averages and recommendations by the Central



Minimum wind speed (m/s)	3.06
Maximum wind speed (m/s)	9.86
Average wind speed (m/s)	6.14
Variance	1.23
Standard deviation	1.11



Minimum power density (W/m2)	54.94
Maximum power density (W/m2)	994.23
Average power density (W/m2)	305.25
Variance	17887.19
Standard deviation	133.74



Minimum capacity factor (%)	6,66
Maximum capacity factor (%)	63,2
Average capacity factor (%)	34,63
Variance	114,490
Standard deviation	10,700

Fig. 6. Distribution of annual average wind speeds, wind power density, and distribution of capacity factor at 100 meters.

Bank of the Republic of Turkey and prior studies on renewable energy economics in the region [13]. These values influence the real discount rate used in NPC calculations and directly affect the Levelized COE estimations. The simulation horizon was set to 25 years to reflect the typical service life of the PV and wind systems, enabling a long-term assessment of cost-effectiveness.

The steps followed for system analysis are outlined below:

TABLE I. OVERVIEW OF RECENT STUDIES ON PROJECT SCENARIOS USING HOMER PRO FOR ENERGY OPTIMIZATION

References	Years	Scenarios	Investment Analysis
[8]	2016	Standalone hybrid energy system (PV + wind turbine + battery + converter)	N_{PV} = 26 = 5 N_W N_{bat} = 8 E_{inv} (kW) = 1.5 *COE* (€/kWh) = 0.3757 *NPC* (€) = 37.818 *OC* (€/y) = 774.380 *IC* (€) = 25360
[9]	2017	Load = 97.68kWh/dkWpeak (On grid + PV + converter) • Load = 98.03 kWh/d 29.90 kW peak Off grid + PV + battery (1 kWh Li)	COE (cost of energy) = 0.525 RS, NPC (net present cost) = 429.346 RS Initial cost for the system = 1.92 M. COE (cost of energy) = 242.980 RS, NPC (net present cost) = 64.4 M initial cost for the system = 2.99 M. PV system = 64.403 kWh/year and the consumption = 24.840 kWh/year The results of the optimization studies conducted using HOMER Pro reveal that the grid-connected system is more economical compared to the off-grid system when evaluated for identical loads Economically, the grid-connected system offers significant advantages; however, from an environmental perspective, the off-grid system emerges as a more favorable option
[10]	2018	• Load = 336.00 kWh/d 25.69 kW peak (Off grid + PV + diesel generator + battery + wind turbine + converter) – (current diesel price (0.95$/L)) • For 100% renewable fraction (PV + battery)	For standalone hybrid system: NPC (net present cost) = $270.781 COE (cost of energy) = $185.000 For 100% renewable fraction NPC (net present cost) = $398. 529 COE (cost of energy) = $286. 166 For stand-alone applications, a PV + wind + diesel + battery system is more suitable For 100% renewable fraction PV + battery system would be more suitable
[11]	2022	• Load = 42000.00 kWh/d 5053.98 kW peak (Off grid + PV + HPP (Hyd1MW) + wind turbine (LTW90) + battery (100LI) + converter) • Load = 42000.00 kWh/d 5053.98 kW peak (On grid + PV + HPP (Hyd1MW) + wind turbine (LTW90) + converter)	For standalone hybrid system: NPC (net present cost) = M$41.4 COE (cost of energy) = $/kWh0.167 OC (operating cost) = M$/year1.12 IC (initial cost) = M$26.9 For on grid hybrid system: NPC (net present cost) = M$51.7 COE (cost of energy) = $/kWh0.269 OC (operating cost) = M$/year1.40 IC (initial cost) = M$33.6 The optimization studies indicate that the grid-connected system is more economical compared to the off-grid system. However, the off-grid system has a lower environmental impact
[13]	2024	• 100% penetration with no sales to grid • 75% penetration with no sales to grid • 50% penetration with no sales to grid	The most profitable system is on-grid PV-wind turbine system with an NPC of $52.8 M. 100% penetration systems would save $1.281 M per year For 0% and 25% sale constrained systems low penetration systems are optimal. For 75% penetration systems would save $1.211 M per year For systems of different sizes, sales to the grid are 0%, 25%, 50%, and there is no restriction on sales. Sensitivity analyses have been performed for 10% and 20% more power required by the load. The 50% penetration systems would save $1.101 M per year The optimal system has the lowest NPC of all scenarios with $52.8 M. Fire hawk optimizer, Grey Wolf optimizer, and particle swarm optimizer are used to size the system by power flow analysis The sensitivity analysis for the scenarios where the load consumes 10% and 20% more power shows an increase in NPC, COE, and OC costs

A. Retrieval of Input Data

Data on installed power and electrical energy consumption, obtained from the Energy Market Regulatory Authority (EMRA), were utilized to design system scenarios. Table II presents the installed power and consumption data for Çanakkale. Using this data as a constraint, various scenarios involving different renewable energy (RE) technologies were planned. The locations for these scenarios, shown in Fig. 7, was derived from Google Maps. In Fig. 7, the components planned for the on-grid system are displayed and the components designed for the off-grid system are presented.

B. Creation of Scenarios for Hybrid Systems

Based on the electrical energy consumption data obtained from the Energy Market Regulatory Authority (EMRA), two different hybrid system scenarios (grid-connected system and off-grid system) were developed to address the energy needs of Çanakkale, as shown in Fig. 8. In both system designs, the primary energy sources considered are photovoltaic (PV) solar panels and wind turbines.

The input parameters for the components used in the development of these scenarios are provided in Table III. This table outlines the

TABLE II. MONTHLY VARIATIONS IN INSTALLED POWER AND ELECTRICITY CONSUMPTION IN ÇANAKKALE PROVINCE

Months	Installed Power (MWh)	Power Consumed (MWh)
January	4517.47	248.409
February	4524.97	242.892
March	4524.97	259.296
April	4524.97	252.594
May	4536.22	117.801
Jun	4545.09	126.630
July	4545.09	123.699
August	4545.09	129.300
September	4545.09	119.850
October	4573.21	105.246
November	4574.41	109.038
December	4575.99	112.848

technical specifications and assumptions that were used to model and simulate the hybrid energy systems.

Further technical details of each component are summarized as follows:

- Photovoltaic panels (flat plate): Each panel has a nominal capacity of 1 kWh, with a conversion efficiency of ~17%, and a projected operational lifespan of 25 years. The capital cost per unit was set at $2500, with no replacement cost due to the alignment with the project lifetime.
- Wind turbine (G-10kW): Each turbine has a rated power of 10 kW and an estimated capacity factor of 36.5%, consistent with regional wind conditions. The capital cost per turbine is $50 000, and the replacement cost was factored in after 20 years.
- Battery (UAE sundepot 6.26 kWh): The battery has a usable depth of discharge of 80%, an expected lifetime of 8.7 years, and an initial cost of $1420 per unit. Battery degradation and cycling efficiency were also modeled using HOMER's internal algorithms.
- Diesel generator (CAT-1000): Used only in the off-grid scenario, with a nominal capacity of 800 kWh, a fixed generation cost of $1.11/hour, and a marginal cost of $0.286/kWh. The generator's operation was constrained to backup use only.
- Converter: Bidirectional converters (inverter/rectifier) were set with an efficiency of 90%, a capital cost of $300, and a lifetime matching the system's operation.

These inputs were derived from manufacturer datasheets and validated literature to ensure technical accuracy.

C. Simulating Results

To address the energy needs of Çanakkale, simulations of the proposed scenarios were conducted, considering the region's location and land values, using the HOMER Pro program.

1) Scenario-1: On-Grid System:

The grid-connected system is designed with PV flat-plate solar panels having a capacity of 1 kWh, combined with wind turbines offering a capacity of 10 kWh. The direct current (DC) energy produced by the PV panels is converted for use via a system converter. Additionally, the system includes batteries with a storage capacity of 6.26 kWh, enabling energy storage. Figure 9 presents the HOMER Pro schematic for the on-grid hybrid system, showing the energy flow from PV and wind sources through the DC–AC converter, connected to both storage (battery) and the utility grid. The graphic clearly distinguishes between generation, storage, and grid interaction.

2) Scenario-2: Off-Grid System:

For the off-grid system, diesel generators were integrated to support the system independently of the grid while utilizing the same PV panels and wind turbines as in scenario-1. Figure 10 illustrates the standalone off-grid configuration. In this setup, solar and wind

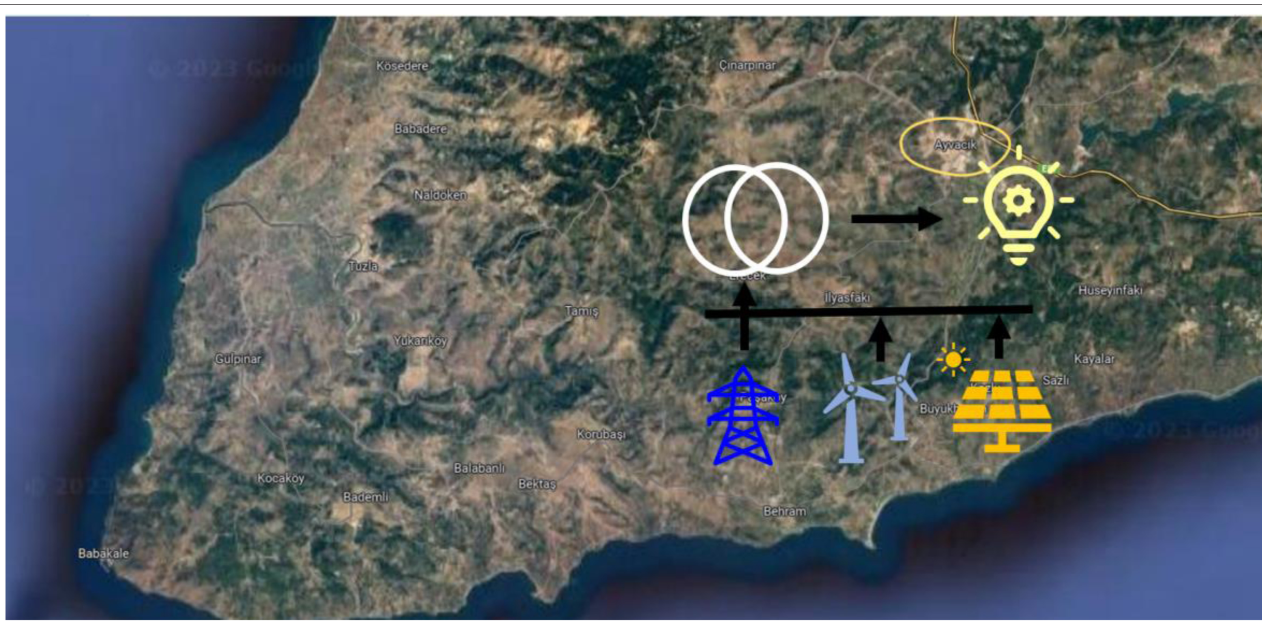


Fig. 7. On-grid and off-grid system representation on the map (scenario-1 and scenario-2).

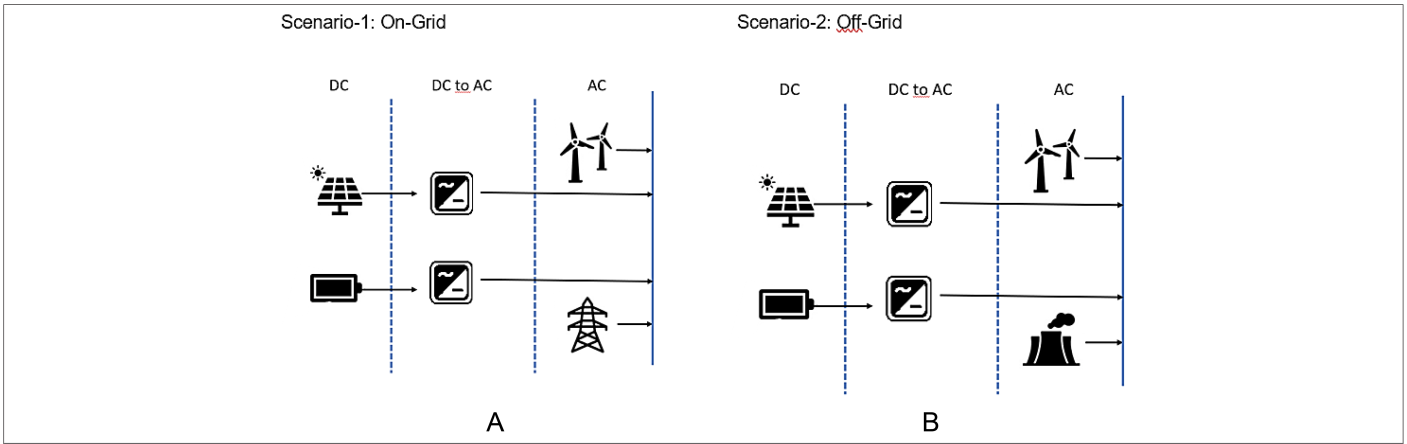


Fig. 8. On-grid and off-grid system scenarios.

TABLE III. FEATURES OF COMPONENTS USED IN THE SYSTEM

Components	Model	Capacity (kWh)	Quantity	Capital Cost ($)
PV panel	Flat plate	1	20	2.500
Wind turbine	G-10kW	10	13	50.000
Converter	System converter	1	5	300
Generator	CAT-1000kVA	800	1	100.000
Battery	UAE sundepot	6.26	1	1.420

sources feed into the converter, with energy stored in batteries. A diesel generator is incorporated as a secondary backup to ensure reliability during low renewable output periods.

Global solar irradiance and wind speed data for the selected region were obtained from the NASA Prediction of Worldwide Energy Resource database. These data were incorporated into the HOMER Pro simulation and optimization process. The components and constraints of the designed scenarios were entered into the program to create simulations. The simulation results provided outputs in the form of graphs and tables, accessible in the "Results" section of the program. These outputs included key data such as: costs, emissions, and electrical energy generation.

By analyzing these results, the system's efficiency, sustainability, and cost-effectiveness were evaluated. The processes were repeated across different scenarios, and the resulting data were compared to identify the most suitable scenario for Çanakkale. Figure 11 shows the complete simulation workflow in six steps—from data input to final scenario selection, providing transparency for model replication.

VI. RESULTS AND DISCUSSION

A hybrid renewable energy plant is planned for installation in the Çanakkale region to meet its electrical energy needs using renewable resources. Monthly radiation and wind speed graphs, sourced from the NASA Prediction of Worldwide Energy Resources database, are shown in Figs. 12 and 13. These graphs were utilized to develop two distinct scenarios for HESs through simulation.

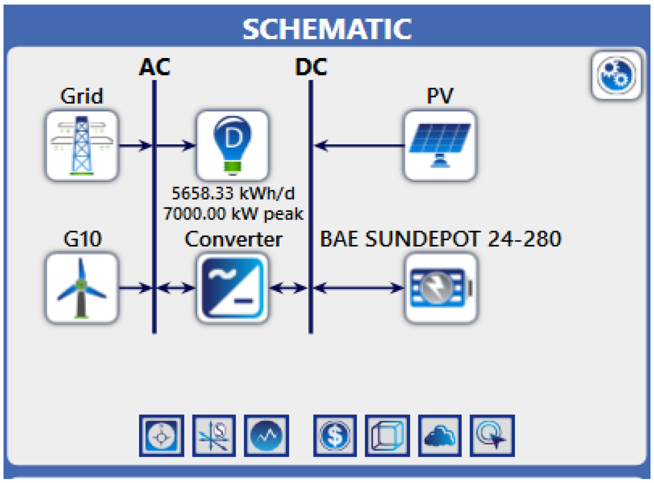


Fig. 9. On-grid system schematic in HOMER Pro.

The average annual Global Horizontal Irradiance (GHI) rate in the region is 4.20 kWh/m^2/day, with the highest GHI observed between June and July (6.98–6.87 kWh/m^2/day). This high radiation level indicates that the region is highly productive for solar energy generation.

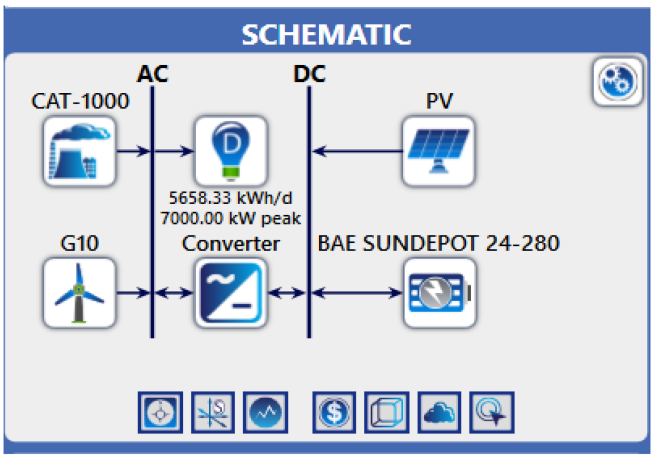


Fig. 10. Off-grid system schematic in HOMER Pro.

Similarly, the annual average wind speed in the region is 6.83 m/s, with the highest wind speeds occurring in December, January, and February (7.94–7.76 m/s). This wind speed level highlights the region's efficiency for wind energy generation, making it possible to meet a significant portion of its electrical energy needs through wind power.

The most suitable scenarios were developed by creating different combinations for the system. To select the optimal scenario, the NPC and COE values from the HOMER Pro simulations were compared. Additionally, carbon emissions were assessed to evaluate the scenarios' environmental impacts, focusing on minimizing emissions of

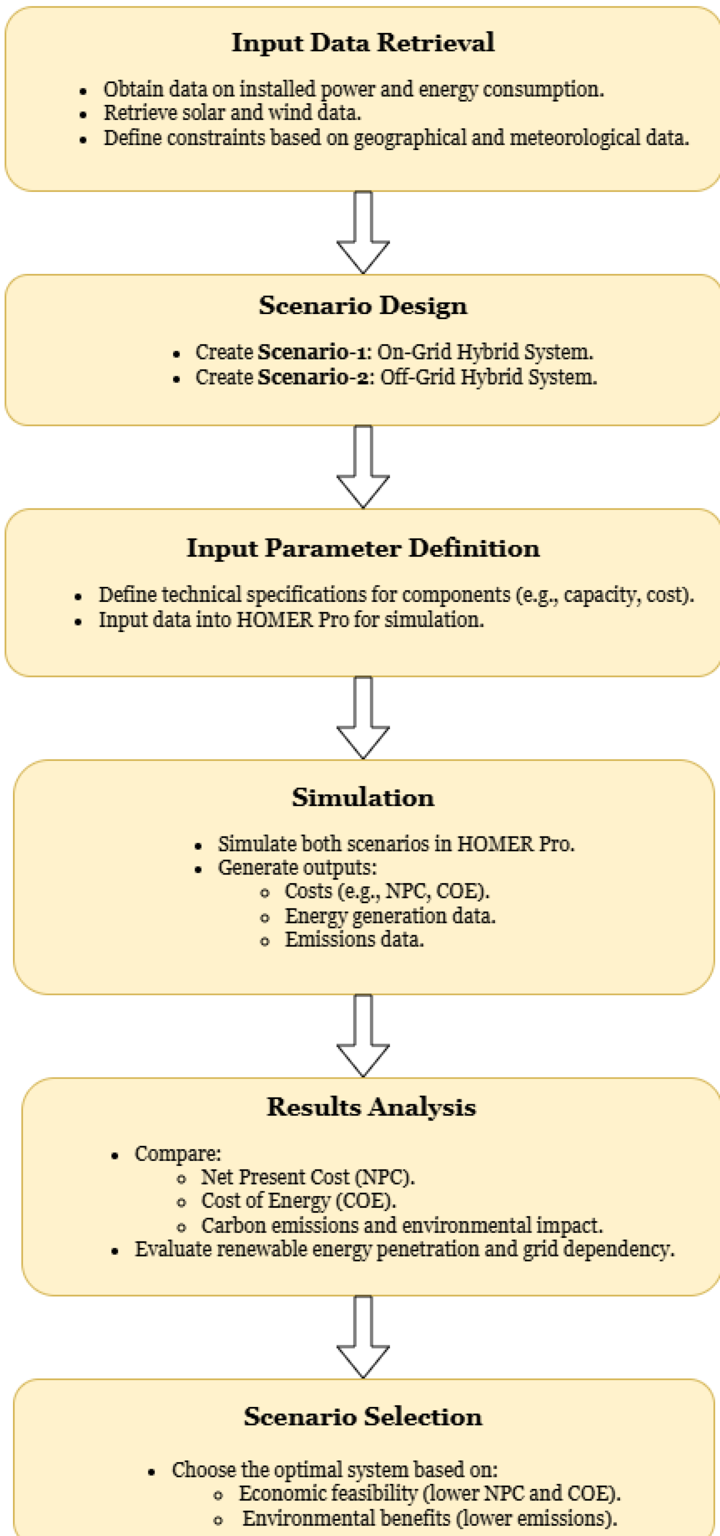


Fig. 11. Flow diagram of optimization and simulation in HOMER Pro

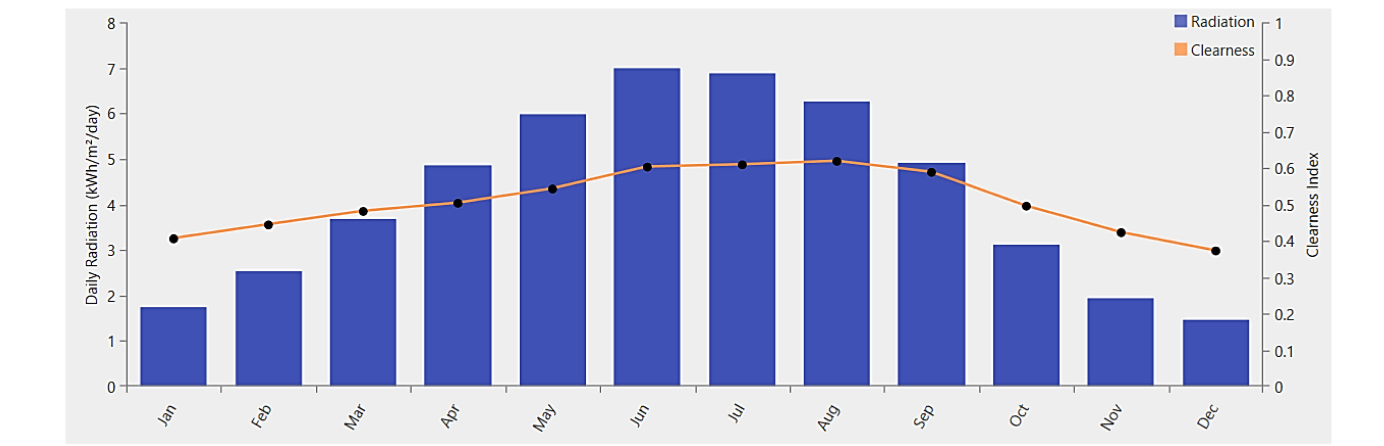


Fig. 12. Monthly average global horizontal irradiance in Çanakkale.

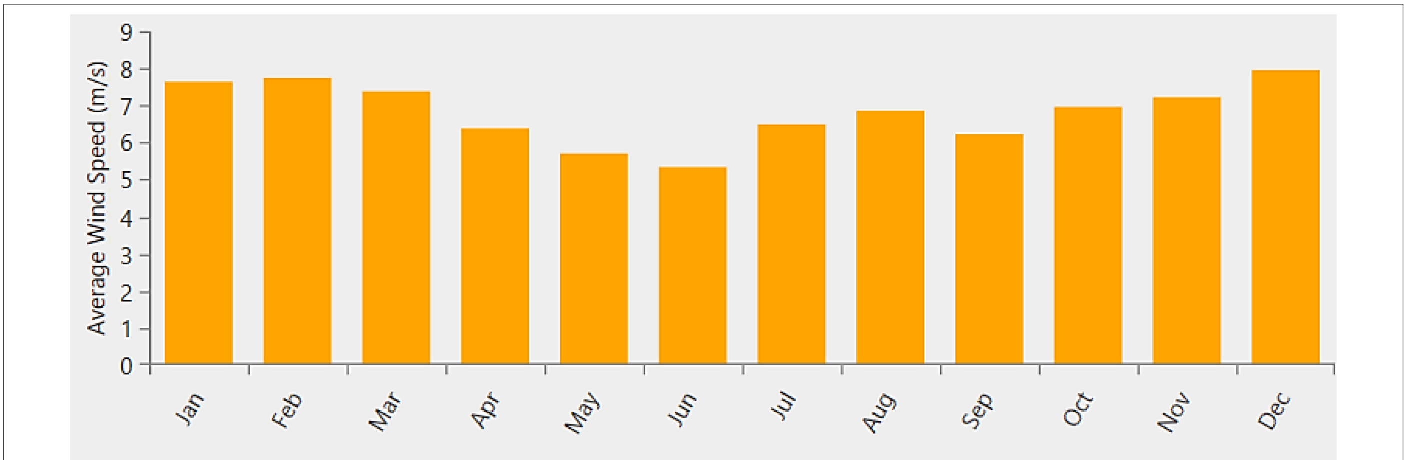


Fig. 13. Monthly average wind speed in Çanakkale.

carbon, sulfur, and nitrogen into the ecosystem. The data for the on-grid and off-grid scenarios are provided in Table IV and V.

The total net present cost represents the present value of all expenses incurred for the installation and operation of equipment over the project's lifespan, minus the present value of all revenues generated during the same period [27]. A positive NPC value indicates that operation and maintenance (O&M) costs exceed the revenues. Conversely, a negative NPC value suggests that revenues surpass the installation and operational costs.

The analysis of carbon emissions revealed that the off-grid system significantly reduces environmental impact by cutting carbon emissions by 99.3% compared to the on-grid system. This reduction underscores its environmental suitability and demonstrates the system's potential to contribute to a cleaner, more sustainable energy future. However, the economic evaluation presents a different outcome. Despite the off-grid system's impressive environmental performance, its profitability falls short when compared to the on-grid system. The NPC comparison highlights that the on-grid system is more cost-effective, offering a better balance between installation, operational expenses, and revenue generation. Additionally, a detailed cost analysis of the wind turbines and PV panels used in the scenarios is presented in Table VI. This evaluation further supports the conclusion that scenario-1, representing the on-grid system, stands out as an efficient and well-balanced option. It effectively

TABLE IV. SUMMARY OF OUTPUTS FROM ON-GRID SYSTEM

On-Grid						
Load	NPC ($)	COE ($)	OC ($)	Carbon Dioxide (kg/yr)	Sulfur Dioxide (kg/yr)	Nitrogen Oxide (kg/yr)
Base	25.1M	0.0257	3.33M	388.6	1.685	824

TABLE V. SUMMARY OF OUTPUTS FROM OFF-GRID SYSTEM

Off-Grid						
Load	NPC ($)	COE ($)	1OC ($)	Carbon Dioxide (kg/yr)	Sulfur Dioxide (kg/yr)	Nitrogen Oxide (kg/yr)
Base	9.88M	0.371	106.1M	2,696	6,61	23.2

TABLE VI. COST ANALYSIS OF RENEWABLE ENERGY SYSTEMS

Component	Capital ($)	Replacement ($)	O&M ($)	Total ($)
G-10 kW	10.612.500	3.383.343	1.371.932	13.641.044
Flat plate PV	4.244.250	0	219.470	4.463.720
System	17.922.248	4.683.953	45.537.662	25.082.979

TABLE VII. SIMULATION RESULTS FOR SYSTEM COMPONENTS IN ON-GRID AND OFF-GRID SCENARIOS

	Scenario-1			Scenario-2	
	Flat Plate PV		**Flat Plate PV**		
Rated power	16.977 kW		Rated power	4430 kW	
Mean output	2619 kW		Mean output	683 kW	
Capacity factor	15.4%		Capacity factor	15.4 %	
Total production	22.942.199 kWh/yr		Total production	5.986.783 kWh/yr	
G-10 Kw			**G-10 kW**		
Total rated power	16.98 kW		Total rated power	570 kW	
Mean output	6202 kW		Mean output	208 kW	
Capacity factor	36.5%		Capacity factor	36.5 %	
Total production	54.329.884 kWh/yr		Total production	1.823.795 kWh/yr	
System Converter			**System Converter**		
Capacity	Inverter	Rectifier	Capacity	Inverter	Rectifier
	10.218 kW	10.218		5607 kW	5609 kW
Mean output	2357 kW	0 kW	Mean output	226 kW	60.9 kW
Maximum output	10.218 kW	0 kW	Maximum output	5609 kW	542 kW
Capacity factor	23.1%	0%	Capacity factor	4.02%	1.09%
Losses (kWh/yr)	1.086.867	0	Losses (kWh/yr)	104.024	28.064
Storage			**Storage**		
Batteries	3294 quantity		Batteries	2853 quantity	
String size	100 batteries		String size	100 batteries	
Strings in parallel	3294 strings		Strings in parallel	2853 strings	
Bus voltage	24.0 V		Bus voltage	24.0 V	
Grid			**Diesel Generator**		
Energy purchased	614.882 kWh		Hours of operation	309 hours/yr	
Energy sold	73.539.968 kWh		Number off starts	305 starts/yr	
			Operation life	48.5 years	
			Capacity factor	3.53%	
			Fixed generation cost	1.11 $/hr	
			Marginal generation cost	0.286 $/kWh	

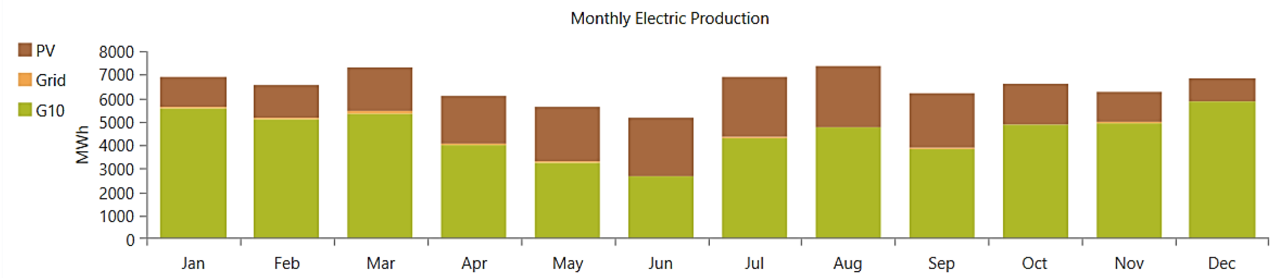


Fig. 14. Monthly electricity production for on-grid system.

TABLE VIII. ANNUAL ELECTRICITY GENERATION OVER COMPONENTS FOR THE ON-GRID SYSTEM

Components	Production (kWh/yr)	% (year)
Flat plate PV	22.942.199	29.5
G-10 kW	54.329.884	69.8
Grid	614.882	0.789
Total	77.886.964	100

meets the region's energy needs while maintaining a strong economic foundation.

The elevated NPC and COE in the off-grid scenario are primarily attributed to three interrelated factors. First, the reliance on a large-scale battery bank to ensure 24/7 energy availability, especially during low solar or wind periods, drastically increases upfront and replacement costs. Second, diesel generator integration, while necessary for reliability, incurs significant operational and maintenance expenses despite low usage frequency. Third, the lack of grid backup forces the oversizing of generation and storage capacities to prevent energy shortfalls, leading to inefficiencies in asset utilization and investment payback. These constraints are common in off-grid architectures without regulatory support or grid interaction flexibility.

To address the economic limitations of off-grid systems, several cost-reduction strategies can be considered. First, dynamic load management and the inclusion of smart controllers can optimize energy use and battery cycles, extending battery life. Second, modular system scaling, matching generation more closely to demand profiles, can reduce oversizing. Third, hybridization with low-cost backup options (e.g., biomass microgenerators or community storage hubs) may reduce diesel dependency. Lastly, policy interventions, such as targeted subsidies for battery systems or capital grants for rural energy independence, could significantly enhance the economic viability of off-grid projects in Turkey, aligning with national sustainability goals.

A. Component Properties of Scenarios

In the HOMER Pro simulation, two distinct scenarios were created by incorporating different components. These scenarios utilized configurations of photovoltaic (PV) solar panels, wind turbines, batteries, and generators, designed as either grid-connected or off-grid systems. The simulation results for the components in both scenarios are summarized in Table VII.

In scenario-1, it was observed that wind turbines played a more significant role in electrical energy production. The turbines generated 54.329.884 kWh of electrical energy annually, satisfying a large portion of the system load. Additionally, PV panels contributed by producing 22.942.199 kWh of electrical energy annually.

This combination substantially reduced the system's reliance on the grid, requiring only 614.882 kWh of electrical energy to be purchased from the grid annually.

It is essential to interpret the simulation results within the context of Turkey's evolving energy policy. The Turkish government has adopted several national strategies, such as the National Energy and Mining Policy (2017) and the Green Deal Action Plan (2021),

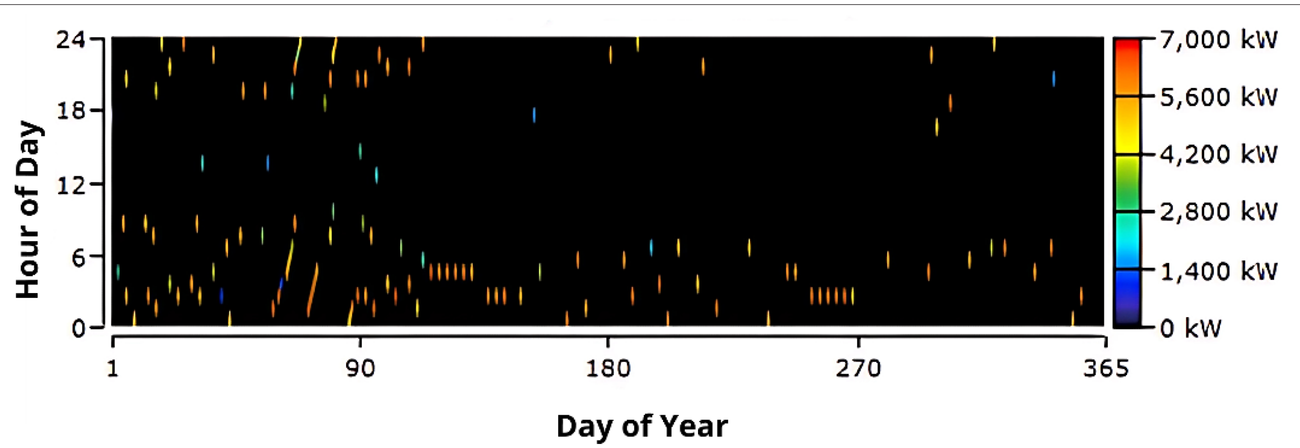


Fig. 15. Energy purchased from the grid.

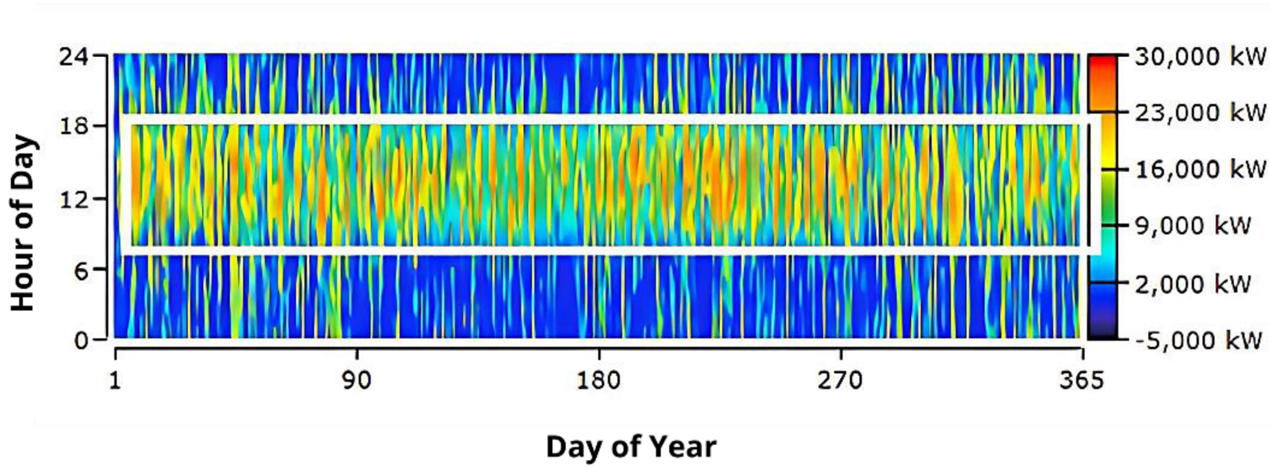


Fig. 16. Energy sold to the grid.

which promote decentralized renewable energy and energy independence. However, regulatory and infrastructural limitations still pose challenges, particularly for off-grid deployments in semi-urban regions like Çanakkale. Net metering regulations currently favor on-grid systems, offering financial incentives for energy sold back to the grid, while off-grid setups lack access to such benefits. Additionally, the absence of regional storage subsidies or feed-in premiums increases the capital burden on isolated systems, partially explaining their higher lifecycle costs despite superior environmental performance.

B. Productivity Analysis

1) Scenario-1: On-Grid System:
The simulations demonstrated that the components used in the on-grid system contributed significantly to electrical energy production. The monthly distribution of electrical energy generated by the system components is illustrated in Fig. 14.

Based on the values in Table VIII, 69.8% of the electrical energy produced was supplied by wind turbines (WT), reducing grid dependency to 0.789%. The system achieved a remarkable 99.3% efficiency in terms of renewable energy utilization. Furthermore, carbon emissions were reduced by up to 388 kg per year in this scenario, enhancing environmental benefits.

The simulation also revealed that the payback period for the on-grid system was approximately 4.9 years. The results for energy purchased and sold relative to the maximum load for the designed on-grid system are summarized in the accompanying table.

The penetration rate, as determined through simulation, is detailed in Figs. 15 and 16. According to the network purchasing intensity data in Fig. 15 and the monthly distribution in Table IX, the penetration rate was highest during July and August.

When the sales intensity to the network, as shown in Fig. 16, is analyzed, it is evident that the system achieved high sales levels during the 6–10 AM timeframe.

Figure 17 further reveal that: the intensity of purchases from the grid peaked in March and April. The intensity of sales to the grid was highest in July and August. Additionally, the designed on-grid system demonstrated a renewable fraction rate of 99.2%, underscoring its high sustainability and efficiency.

2) Scenario-2: Off-Grid System:
Figure 18 shows the monthly distribution of electrical energy produced in the off-grid system according to the components used. Based on the data in Table X, it was observed that 76.6% of electrical energy production was supplied by PV panels. Electrical energy production reached its highest levels in July and August. The designed off-grid system successfully reduced CO_2 emissions to 2696 kg per year, which is a significant contribution to the ecosystem.

In simulation-2, the monthly distribution of annual electrical energy generated from solar energy and wind speed, as simulated using

TABLE IX. MONTHLY ELECTRICITY TRANSACTIONS (PURCHASE AND SALE) FROM THE NETWORK

Monthly	Energy Purchased (kWh)	Energy Sold (kWh)	Peak Load (kW)
January	81.461	6.525.810	6150
February	56.784	6.179.163	6067
March	113.735	6.748.344	6381
April	102.197	5.699.041	6300
May	50.846	5.283.547	6012
June	22.883	4.823.094	6125
July	41.146	6.542.202	6150
August	26.956	6.935.012	5953
September	45.486	5.767.788	6012
October	22.015	6.356.041	6125
November	26.237	5.994.172	6150
December	25.135	6.685.757	6017
Annual	614.882	73.539.971	6381

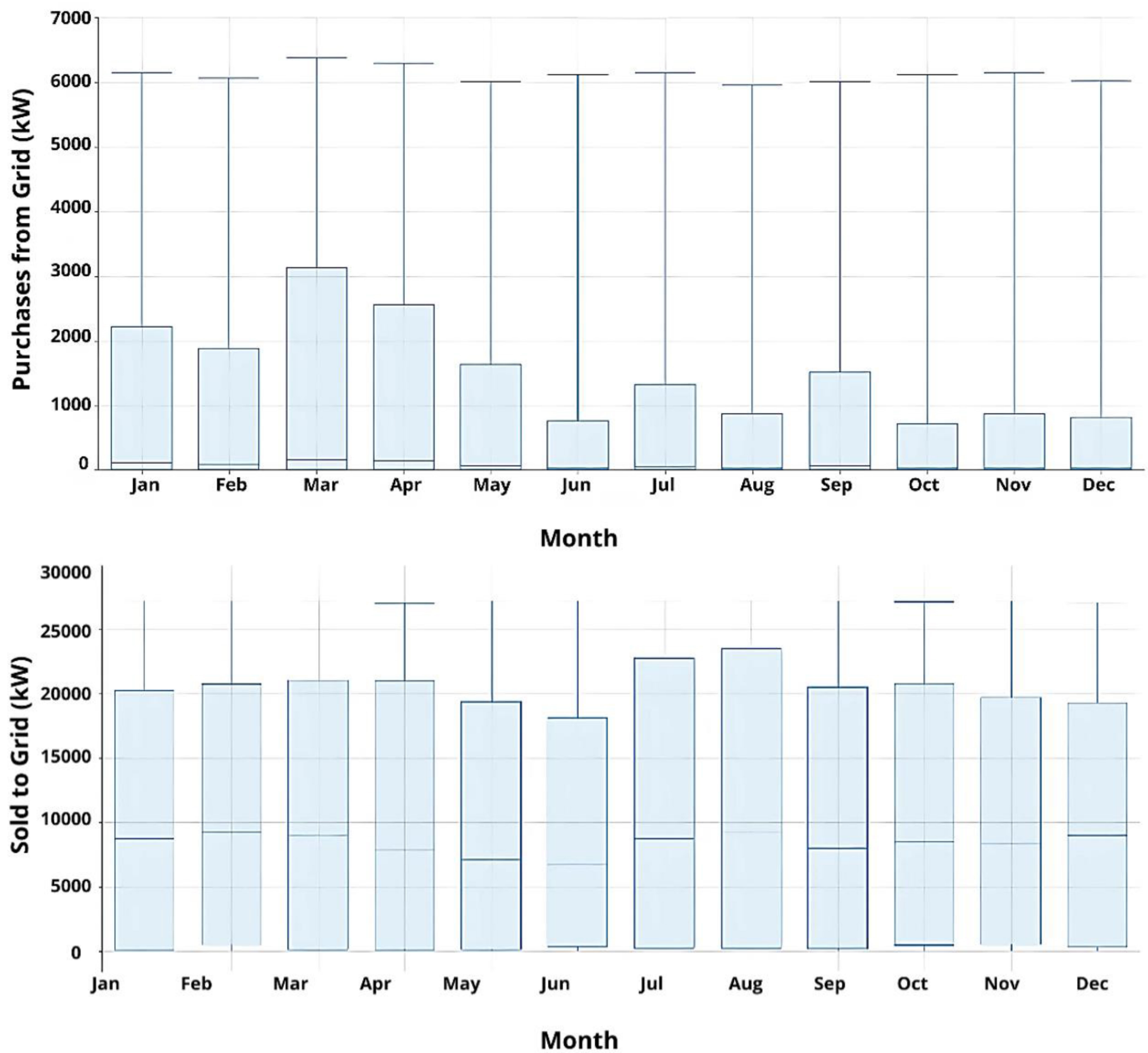


Fig. 17. Average monthly energy purchased from the grid and sold to the grid.

HOMER Pro, is illustrated in Fig. 19. According to the data, electrical energy production from solar energy peaked in June and July. Wind energy production was highest during February and December.

The system analysis indicates that the electrical energy demand of the region is largely met by wind energy, with solar energy making a substantial contribution to the system's energy needs. These

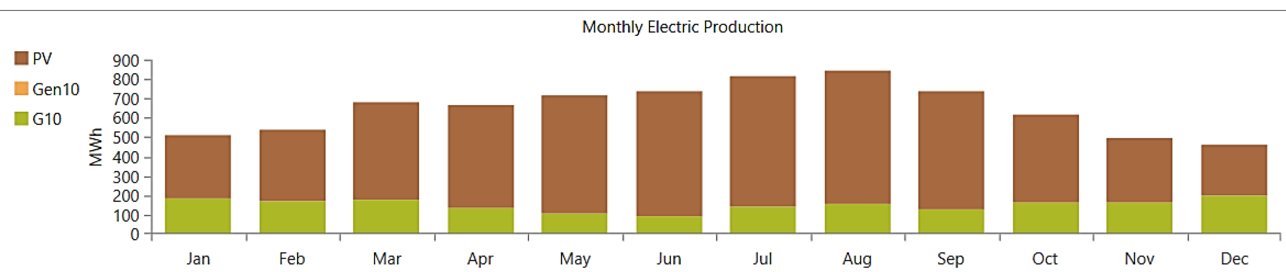


Fig. 18. Monthly electricity production for off-grid system.

TABLE X. ANNUAL ELECTRICITY GENERATION OVER COMPONENTS FOR THE OFF-GRID SYSTEM

Components	Production (kWh/yr)	% (year)
Flat plate PV	5.986.738	76.6
G-10 kW	1.823.795	23.3
Diesel generator	3.089	0.0395
Total	7.813.622	100

findings, presented in Table XI, are supported by the monthly average Global Solar and Wind Speed graphs in Fig. 19, generated using HOMER Pro.

According to HOMER Pro standards, the rate of renewable energy divided by load is 77.5%. The rate of renewable energy divided by total generation is 100%. Additionally, the annual renewable penetration rates are shown in Fig. 20 and Fig. 21. The high penetration rates ensure the system's independence, while the significant renewable fraction enhances its efficiency.

As a result of the simulation conducted in HOMER Pro, the battery system used in scenario 2 has an expected lifetime of 8.77 years, storing 1 916 864 kWh of energy annually. The charge status of the batteries, showing daily and monthly distribution rates, is illustrated in Figs. 22 and 23. Figure 22 reveals that the designed system significantly meets the electrical energy demands of the load. The batteries remain fully charged for most of the year, demonstrating the system's efficiency and reliability.

C. Emissions

The quantities of emissions were derived from the simulation results of the HOMER Pro software and were used to determine the annual amounts of each pollutant, measured in kg/year, produced by the

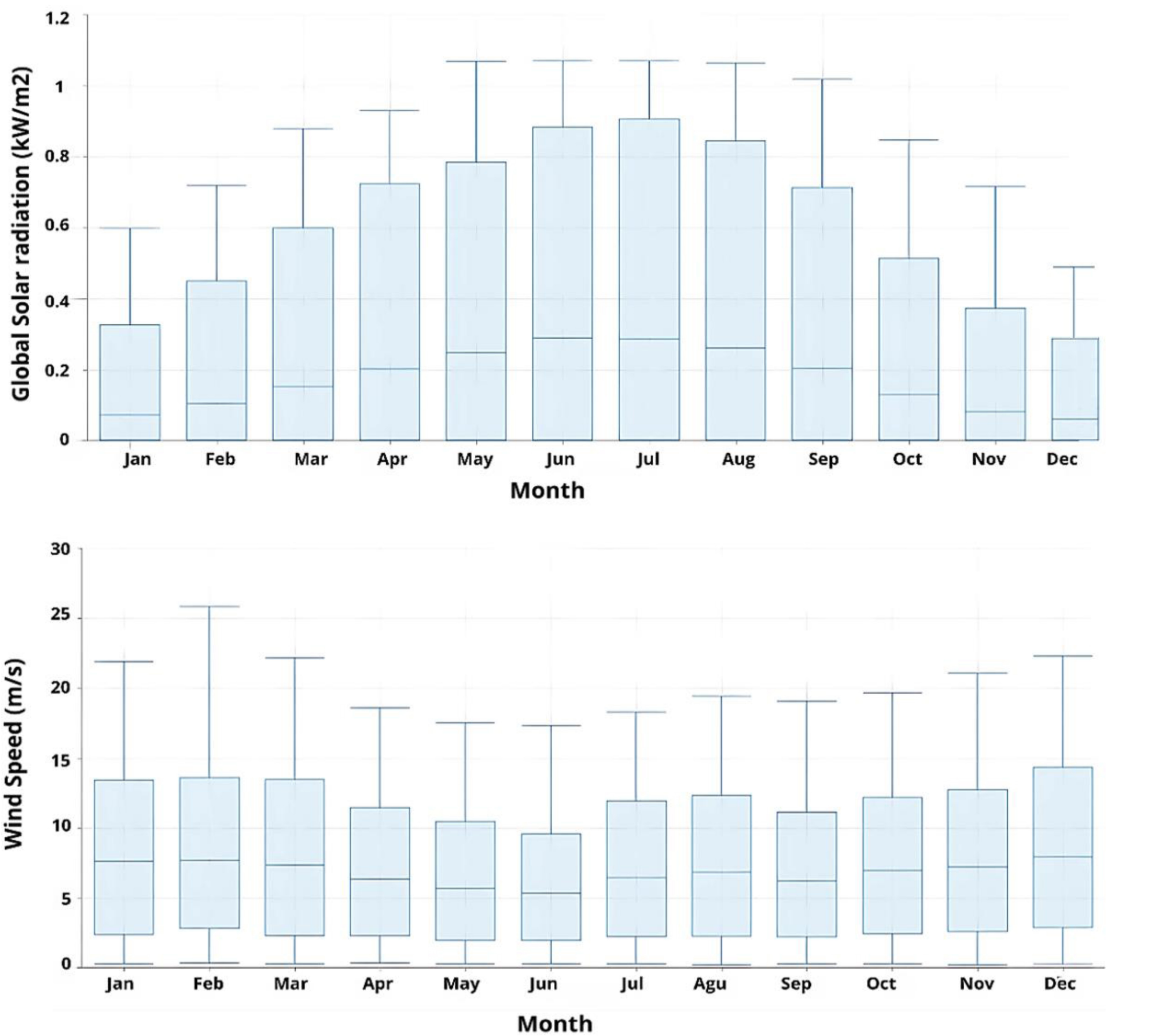


Fig. 19. Monthly global solar radiation and wind speed data.

TABLE XI. MONTHLY DISTRIBUTION OF ELECTRICAL ENERGY GENERATED BY THE SUN AND WIND

Monthly	Global Solar (kW)	Wind Speed (kW)
January	9.9	403.2
February	13.5	408.3
March	18	405
April	21.6	343.2
May	23.4	313.2
June	26.4	285.9
July	27	359.1
August	25.5	370.8
September	21.3	335.1
October	15.3	365.1
November	11.1	374.1
December	8.7	429.3
Annual	221.7	4492.3

power system [28]. While focusing on renewable energy sources, it is important to note that significant greenhouse gas (GHG) emissions can also originate from sources other than power plants.

In the scenario selection process, emissions were a critical factor. A lower GHG emission rate highlights the efficiency and sustainability of the designed system for the ecosystem. Fig. 24 presents the annual carbon (CO_2), sulfur (SO_2), and nitrogen (NO_x) emissions for both scenario-1 (on-grid) and scenario-2 (off-grid).

As shown in Fig. 24, the off-grid system in scenario-2 emits significantly less carbon (CO_2) and nitrogen (NO_x) into the ecosystem compared to the on-grid system in scenario-1. Specifically: in scenario-1, 388 605 kg of CO_2 is released annually. In scenario-2, carbon emissions are reduced by 99.3%, making it a more sustainable option for ecosystem protection.

This reduction demonstrates that the off-grid system designed in scenario 2 is better suited for maintaining ecological sustainability and reducing the environmental impact of energy production.

VII. CONCLUSIONS

This study performed a comprehensive techno-economic assessment of hybrid renewable energy systems to determine the most cost-effective and environmentally sustainable scenario for Çanakkale Province. This evaluation involved simulating off-grid and grid-connected systems using the HOMER Pro program.

Analysis of the study region revealed that wind energy accounted for a significant portion of the load demand. Moreover, the integration of photovoltaic (PV) panels into the hybrid configuration significantly improved overall system reliability. With an average daily load demand of 5.6 MWh in Çanakkale Province, the proposed scenarios successfully met this requirement.

- In the grid-connected scenario, the system imported 614.882 kWh from the grid while exporting 73.539.971 kWh, highlighting its capacity to generate a substantial energy surplus.
- In the off-grid system, the system was supported by a diesel generator, as annual electricity generation from renewable sources

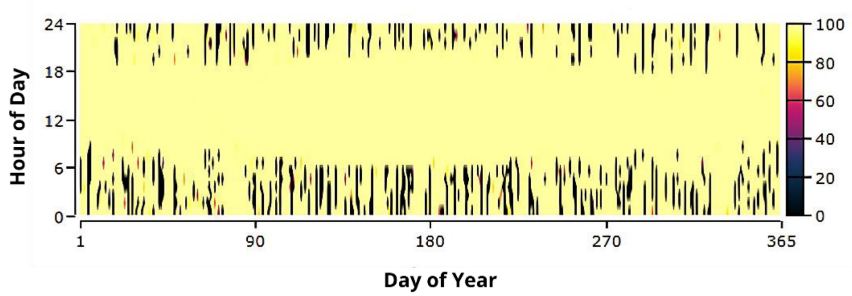


Fig. 20. Hourly contribution of renewable energy to annual energy generation.

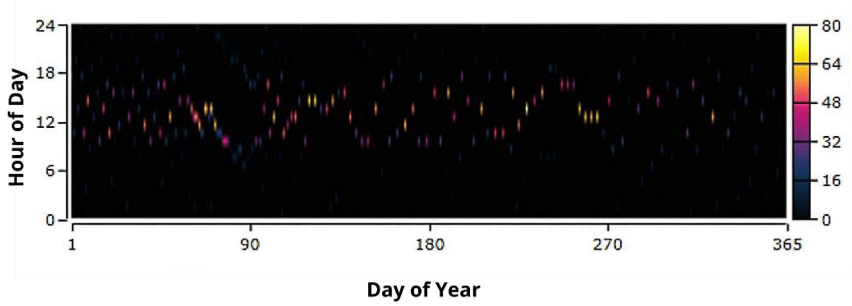


Fig. 21. Hourly contribution of renewable energy to annual energy consumed by the load.

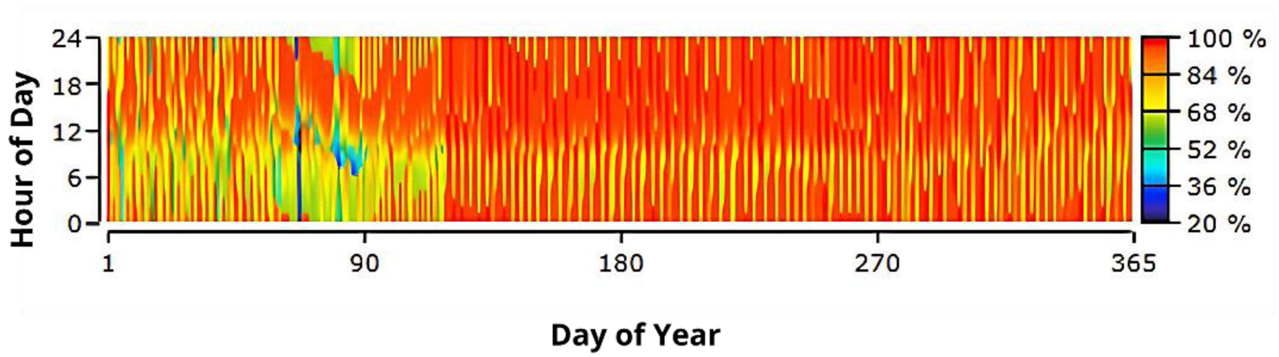


Fig. 22. Batteries' state of charge.

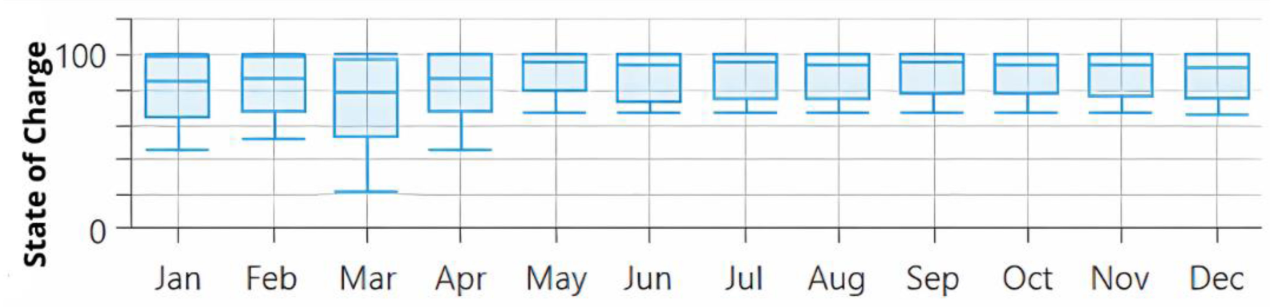


Fig. 23. Monthly charge state for battery system.

totaled 4714 MW. The diesel generator contributed merely 0.0395% of the total energy, reflecting minimal dependence on nonrenewable resources.

In terms of carbon emissions, the grid-connected system released 388 kg of CO_2 annually, whereas the off-grid system achieved a substantial reduction to 2.7 kg, underscoring the systems' environmental compatibility and sustainability.

When comparing the NPC and COE values:

- The grid-connected system exhibited lower NPC ($25.1M) and COE ($0.0257/kWh) values, positioning it as the more cost-effective alternative.
- The off-grid system, with NPC ($9.88M) and COE ($0.371/kWh) values, proved advantageous in reducing environmental impacts.

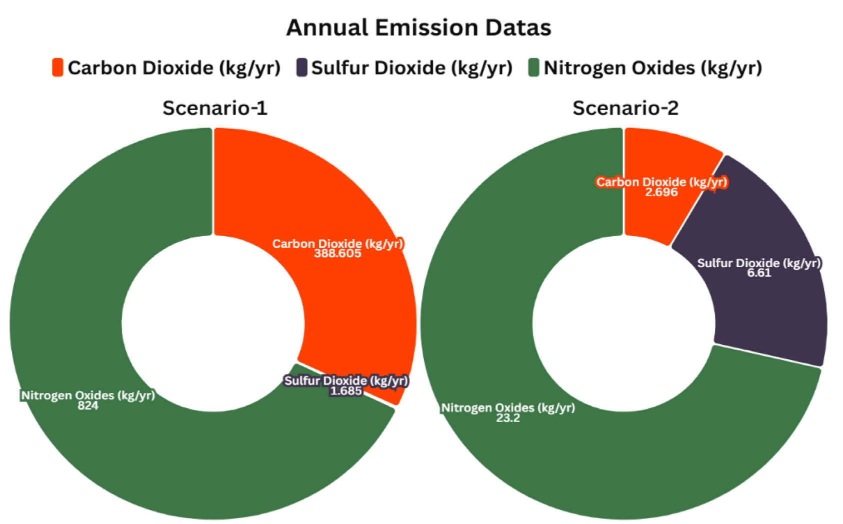


Fig. 24. Annual emissions for on-grid and off-grid scenarios.

With a payback period of 4.9 years, the grid-connected system proved to be the most economically viable solution for the Çanakkale region.

In summary, the simulation-based analysis conducted for Çanakkale province revealed a clear trade-off between economic feasibility and environmental sustainability in hybrid renewable systems. The on-grid system demonstrated superior economic performance, with an NPC of $25.1M and COE of $0.0257/kWh, bolstered by grid interaction and energy sales. In contrast, the off-grid system, while reducing carbon emissions by 99.3%, incurred significantly higher operational costs, primarily due to extensive battery storage and the absence of grid support.

This study provides critical insights into regional renewable energy planning, highlighting the importance of policy-aligned hybrid designs. It also emphasizes the need for holistic evaluation frameworks that integrate environmental benefits, technical feasibility, and economic return. Future studies should explore the integration of predictive control systems, peer-to-peer energy trading models, and policy-based financial simulations to evaluate off-grid systems under varied support schemes. Moreover, multi-objective optimization techniques could be employed to balance environmental and economic trade-offs more effectively.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – N.P.; Design – N.P., F.A.O.; Supervision – N.P.; Resources – F.A.O.; Materials – F.A.O.; Data Collection and/or Processing – N.P., F.A.O.; Analysis and/or Interpretation – N.P.; Literature Search – F.A.O.; Writing – N.P., F.A.O.; Critical Review – N.P.

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