The Viability and Cost-Effectiveness of Hybrid Renewable Energy Systems in Rural Areas

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***Abstract*— This research aims to develop a computer model of a hybrid renewable energy system that can operate independently for a faculty of engineering of Karabuk university, located in Turkey. The hybrid system consists of several components, such as Photovoltaic (PV) panels, wind turbines, diesel generator, and battery storage system as a backup. The primary purpose of this system is to meet the energy needs of a university building . Different combinations of the hybrid system were examined using HOMER software to determine the most cost-efficient solution based on the net present cost. Following the analysis of multiple combinations, the optimal hybrid system was determined, which consists of a 500kW PV system, wind turbines with a total capacity of 7.5MW, and a 327Ah, 15.7kw/h battery storage system, diesel generator of 2000 kw. The overall cost of the system $693,000,000, the project lifespan is 25 years.**

Keywords*— *Hybrid energy system, HOMER, PV-Wind-Battery, diesel generator.

I. Introduction

Hybrid power systems that combine conventional and renewable energy sources are becoming increasingly popular, particularly in remote areas where traditional energy sources may not be available. These systems utilize renewable sources like solar and wind power to reduce dependence on fossil fuels and promote sustainable development while ensuring a reliable electricity supply[1]. Battery storage systems play an important role in these hybrid systems, helping to provide electricity to consumers when renewable sources are unable to meet the load demand due to intermittent resources. In a hybrid system, PV, wind turbines, and diesel generator systems work together to meet the load demand. To address the energy issues, researchers are exploring the potential of hybrid energy systems to provide reliable electricity supply. In a study focused on Karabuk university, faculty of engineering building located in Karabuk,Turkey, researchers assessed the feasibility of using PV and wind turbines as the main power sources, with a backup system from diesel generator, and battery storage. They used HOMER software to determine the optimal hybrid system configuration based on several crucial parameters, such as the availability of renewable resources and the project cost.[2]. HOMER analyzed the specific arrangement of the system components in terms of component sizing and operating scheme over a particular project lifecycle, and then ranked the system configuration output based on its total net present cost. The results of the study could serve as a benchmark for other sites looking to implement alternative energy sources[3]. The system is comprised of a PV array, wind turbine, power converter, diesel generator, and batteries with different capacities.

II. Literature Review

In order to build hybrid renewable energy systems (HRES) that take into account the possible resources that may be available at a particular place, software called HOMER is commonly used. Numerous research have been done in relation to the techno-economic analysis and design of HRES [4]. The design of the Hybrid Renewable Energy System (HRES) will be based on a comprehensive evaluation of both technical and economic performance criteria to determine the optimal solution. [5]. In terms of technical performance, The best possible renewable fraction should be applied to the ideal HRES design, which is the ratio of renewable energy sources to the total energy generated, and the lowest proportion of yearly unmet load. The annual unmet load percentage represents the amount of energy demand that is not met by the HRES. These technical performance criteria ensure that the HRES can meet the energy demand of remote areas without access to grid sources[6]. On the economic front, the HRES with the least levelized cost of electricity (COE), which is the total cost of electricity generation over the lifetime of the HRES, and minimum net present cost (NPC) is preferred. The economic performance criteria ensure that the HRES is affordable and sustainable for remote areas. If the HRES design satisfies both the technical and economic performance criteria, then this optimized hybrid system is well-suited for providing electricity to rural areas that are located beyond the reach of traditional grid sources, making it an ideal solution for remote electrification efforts. It is recommended for implementation in such areas. [7]. The use of HOMER software and related research can help inform policymakers and energy planners in making informed decisions for rural electrification projects. Additionally, numerous research studies have been undertaken To study the technological economic design of hybrid clean energy systems[8]. For example, in one study cited as Reference [9], a hybrid system which consists of battery storage, solar energy, and biogas, and a power converter was The implemented system aimed to provide electricity and cooking solutions in rural region of Bangladesh. The study revealed that an optimal hybrid system could be achieved with 0.2 kW-PV, The hybrid system consisted of a 250 W solar panell, a 0.3 kW electrical power converters and a 0.6 kW biogas engine ,three 360 Ah batteries, demonstrating its ability to provide electricity to households in isolated regions, and making sure that 73% of the system's generated biogas had been used for cooking..

Such research studies provide valuable insights into the design and optimization of hybrid renewable energy systems for rural electrification projects[10]. By using the knowledge gained from these studies, policymakers and energy planners can make informed decisions on the deployment of HRES to ensure sustainable and affordable electricity access in remote areas. An HRES with a COE of 0.384 $/kWh has been found to be the most cost-effective option for fulfilling the energy needs of rural communities in Bangladesh, based on a study detailed in Reference[11]. In Reference [12], A research team conducted an investigation into the viability and deployment of hybrid grid-interactive energy produced from renewable sources system techno-economic aspects (HGIRES) in a rural area of Egypt[12]. The study evaluated multiple system configurations, HOMER Pro software was utilized to assess various parameters, for a load demand of 48 kW, taking into account COE, NPC, the proportion of renewable energy, the percentage of unmet load, and emission levels. The findings demonstrated that the PV/DG/converter arrangement offered the best technical performance, cost-effectiveness, and environmental sustainability for the given location. This system boasted the lowest COE of 0.139 $/kWh, a significant improvement over a DG-only system. Reference [2] the study analyzed a range of system configurations for a hybrid renewable energy system that included PV panels, wind turbines, fuel cells, a diesel generator, converters, and batteries for storage. Seasonal variations in load demand were taken into account, and the research was carried out with the aid of HOMER software. According to the research. The most practical and efficient alternative to other system concepts was the combination of the solar/Wind/Fuel cell/Diesel-generator/Converter system [13]. A novel hybrid power system has been proposed for meeting the daily energy demands of households in the coastal regions of Turkey[14]. This innovative system effectively balances the need for reliable power supply with cost-effectiveness and environmental sustainability, achieving a remarkable 95% renewable energy fraction while minimizing the levelized (COE) to $0.282/kWh and the (NPC) to $253,590. Furthermore, to address future energy challenges, the study suggests the implementation of a 15 MW Saudi Arabia wind energy system [9]. This strategic move would not only reduce the COE but also enable the country to tap into its immense wind energy potential, thereby ensuring a sustainable energy future for the region. By adopting such innovative and sustainable approaches, we can pave the way for a greener and more equitable world. According to the estimates, the cost of generating power through wind turbines for the Khamis-Mushayt region is $0.1016 per kWh, whereas it is $0.0612 per kWh for the Badanah region [15]. The research is based on the ability of wind energy to meet the total annual load demand of 33.37 kWh/d in these regions. Wind energy has the potential to be a cost-effective and sustainable solution for meeting the energy needs of these areas. By harnessing the power of wind, we can create a cleaner and more sustainable future while simultaneously meeting the growing energy demands of our communities[11]. In Reference [8]. In their research published , In order to develop and plan hybrid energy systems that combine a systematic framework combining wind, solar power, biomass, fossil fuels, and battery systems., with the aim of achieving low carbon emissions. These systems have been specifically designed for urban electrification in Canada. The study highlights that the cost of energy (COE) for the The cost of a PV/wind/biomass system is three times lower than that of a solar/wind hybrid system. Given the variability and uncertainty in input variables, the authors have employed three sensitivity parameters, which include the discount rate, PV panel capital cost, and storage capital cost, to accurately calculate the COE for these models. The study offers valuable insights for policymakers to create effective urban hybrid system policies and procedures. Additionally, the research also indicates that incorporating low-carbon natural gas generators into the design of the PV/wind/biomass system can reduce the cost of electricity by nearly 30%, making it a viable alternative to traditional natural gas power plants. These findings are crucial in enabling policymakers to make informed decisions about designing and implementing hybrid energy systems that are both cost-effective and environmentally sustainable. In Reference[16], the authors have proposed a model predictive control method aimed to improve energy demand management by balancing power between both generation and consumption and lowering the system's total operating costs. To achieve this, they utilized an autoregressive average model to estimate the values of wind power production, load demand, and tariffs for electricity. The researchers also examined the unpredictability of electricity prices using a method called conditional value at risk. From the reviewed literature, it was noted that utilizing hybrid renewable energy systems, the difficulties of providing uninterrupted electricity to rural areas are unable to be resolved by a single power source, but a combination of sources, such as those utilizing biomass, solar, and wind energy technology, can be more dependable. One of the most effective hybrid systems for remote rural areas with abundant solar irradiation is the PV/diesel generator/battery/converter model, while the wind energy/diesel generator/battery/converter model is ideal for areas with high wind potential availability. The HOMER software was used to design optimal hybrid systems, with a COE ranging from $0.054 to $0.588 per kWh. The most suitable system Future electrification should aim for the lowest COE, lowest NPC, the most significant proportion of renewable energy, lowest carbon emission, and absolutely no unmet load. Many ongoing research studies are focused on developing optimal hybrid renewable energy systems, including both renewable and conventional energy sources, for both grid-connected and standalone systems.

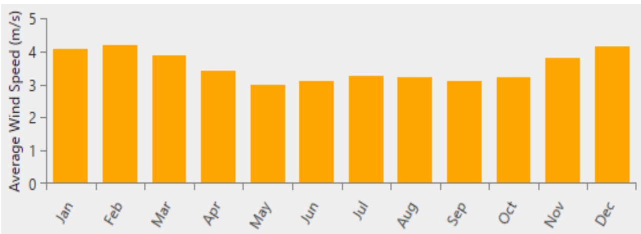


Fig. 1. Monthly wind speed

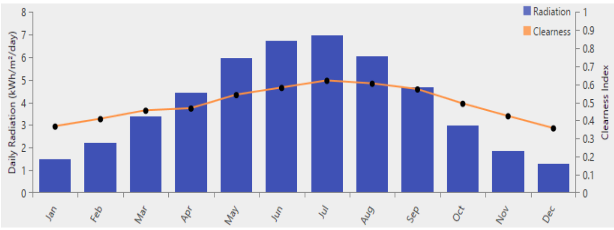


Fig. 2. Monthly solar radiation

III. . Research Method

A. Simulation

The research conducted a simulation using HOMER software to optimize a hybrid system consisting of a photovoltaic (PV) array, wind turbine, diesel generator, and Battery bank for Karabuk university, faculty of engineering in Turkey. During the simulation process, input data, such as solar radiation, wind speed, and load demand, were used to establish the system configuration, which was ranked by net present cost (NPC). The building is located in Karabuk city in Turkey at 41º12'70 latitude and 32º 39'14 longitude. Using HOMER software, the researchers simulated a hybrid system composed of PV, wind, diesel generator, and battery storage. To optimize the system configuration based on net present cost (NPC), the software considered various inputs, including solar radiation, wind speed, and load demand, which were estimated from the system's location [13].

B. Wind speed

According to data gathered from NASA Surface Meteorology and Solar Energy between 1984 to 2013, the average monthly wind speed at a height of 50 meters is 3.54 m/s. December has the highest wind speed with a maximum of 4.13 m/s, while May has the lowest with a minimum of 3.0 m/s. Figure 1 provides a graphical representation of these wind speed variations throughout the year. [17][9].

C. Solar radiation

Based on the information displayed in Figure 2, the village has an average daily solar radiation of 3.99 kWh/m2 from 1983 to 2005. The highest solar radiation levels are observed in July, reaching 6.9 kWh/m2/day, while the lowest levels are recorded in December with only 1.28 kWh/m2/day[18].

D. Load demand

The estimation of the load demand for the faculty of engineering building was carried out by analyzing the customary energy consumption patterns of individual offices and laboratory inside the building, revealing that the highest demand of 1576.62 kW transpires in January, and the average load is 1089.5 kW. Figure 3 illustrates the monthly load profile for the building, which exhibits the highest demand during the year. HOMER, the software utilized for this analysis, generates a load profile with a normal distribution of a mean of 1 and a standard deviation of 20% to simulate the actual load profile[11].

IV. Hybrid System Design

The recommended system design involves the combination of a photovoltaic (PV) array and a wind turbine system as the main sources of renewable energy for generating electricity. A diesel generator, and battery storage system is also integrated to serve as a backup power source, ensuring a reliable supply of electricity[19]. Figure 4 displays the configuration of the hybrid system as modeled in HOMER software[20].

A. Bulding site detail

This study focuses on a site situated in Turkey ,faculty of engineering, Karabuk university, the building is located at 41º 12'49 latitude and 32º 39'14 longitude, as depicted in Figure 5. Although grid power is available, it is inadequate to meet the rising demand, especially during the winter months. Therefore, it is necessary to construct a hybrid power system at this location to cater to the escalating to ensure a reliable electricity supply that meets the required load demand [20].

B. Wind system

To simulate the hybrid power system, the Enercon [7.5MW] wind turbine was chosen with a rated power of 7580 kW, an asynchronous generator.The wind turbine illustrated in Figure 6 has a rotor diameter of 127 meters, and it is installed at a hub height of 135 meters. Table 1 outlines the economic and technical specifications of the turbine. [6]. The estimated capital cost for a single wind turbine is $187,000/kW [12], and it is projected to decrease by 17% from 2022 to 2030, resulting in a replacement cost of $156,000 [12]. The annual cost of operation and maintenance for a wind turbine is $12,500/kW [13].

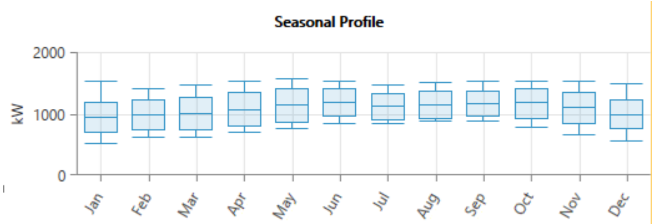


Fig. 3. Load profile

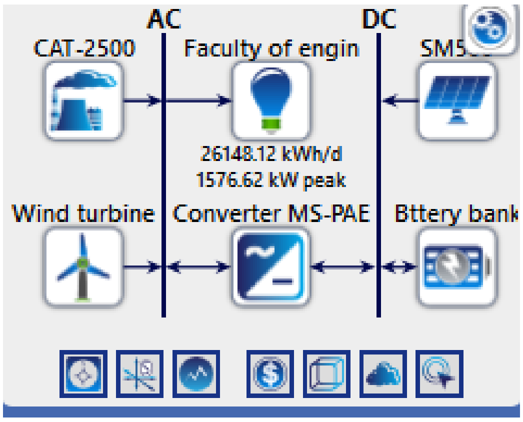


Fig. 4. Hybrid system configuration using HOMER

Fig. 5. Geographic map of the study area

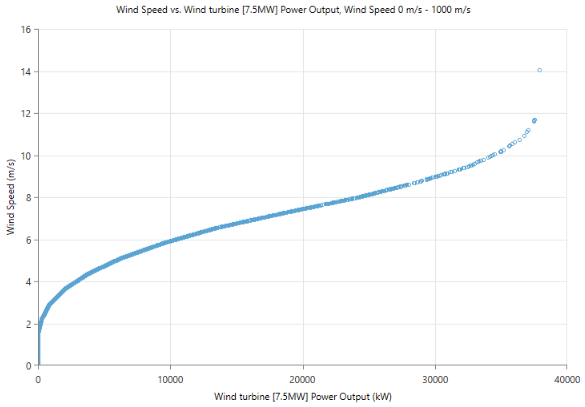
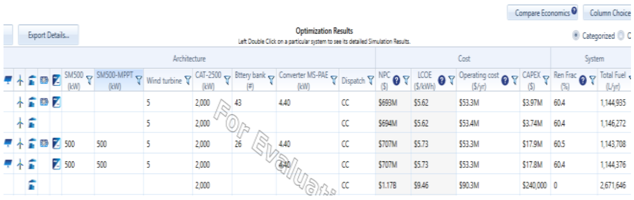


Fig. 6. Wind turbine power curve

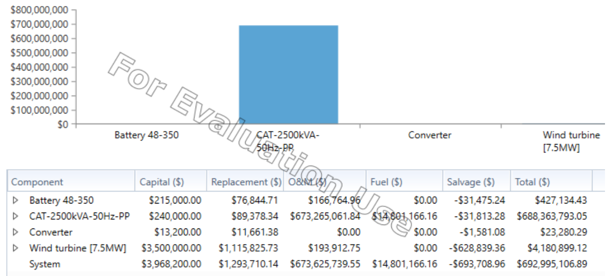


Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

SM500 (kW)	SM500-MPPT (kW)	Wind turbine	CAT-2500 (kW)	Bttery bank (#)	Converter MS-PAE (kW)	Dispatch	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)	Ren Frac (%)	Total Fuel (L/yr)
		5	2,000	43	4.40	CC	$693M	$5.62	$53.3M	$3.97M	60.4	1,144,935
		5	2,000			CC	$694M	$5.62	$53.4M	$3.74M	60.4	1,146,272
500	500	5	2,000	26	4.40	CC	$707M	$5.73	$53.3M	$17.9M	60.5	1,143,708
500	500	5	2,000		4.40	CC	$707M	$5.73	$53.3M	$17.8M	60.4	1,144,376
			2,000			CC	$1.17B	$9.46	$90.3M	$240,000	0	2,671,646

Fig. 7. Categorized optimization results for diesel price of 0.1 $/L



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Battery 48-350	$215,000.00	$76,844.71	$166,764.96	$0.00	-$31,475.24	$427,134.43
CAT-2500kVA-50Hz-PP	$240,000.00	$89,378.34	$673,265,061.84	$14,801,166.16	-$31,813.28	$688,363,793.05
Converter	$13,200.00	$11,661.38	$0.00	$0.00	-$1,581.08	$23,280.29
Wind turbine [7.5MW]	$3,500,000.00	$1,115,825.73	$193,912.75	$0.00	-$628,839.36	$4,180,899.12
System	$3,968,200.00	$1,293,710.14	$673,625,739.55	$14,801,166.16	-$693,708.96	$692,995,106.89

Fig. 8. Hybrid system NPC

TABLE I. TECHNICAL AND ECONOMIC DETAILS OF THE WIND TURBINE

Description	Specification
Producer	Enercon
Rotor diameter	127 M
Hub height	135 M
Lifecycle	20 years
Nominal voltage	230/400 V (AC)
Cut out wind speed	28-34 M/sec
Capital Cost	$700000
Replacement Cost	$700000
O&M Cost	3000 $/year
Rated power	7580 kW

A. Diesel generator

The selected diesel generator CAT-2000kw-50Hz,with capital cost of $240,000, operation cost $/yr 673.000, considering that the fuel price is1 $/L.

B. Pv system

As per the Q1 2022 report by the National Renewable Energy Laboratory (NREL), the capital cost for installing and replacing a PV system is $56/kW. The operation and maintenance costs for the PV system are $10/year[21, 22]. The PV system used in this study has a capacity of 500 kW and a lifetime of 20 years, with no tracking system. Table 2 displays the technical specifications of the PV modules.

C. Battery

For the proposed hybrid system, the selected storage battery is the Kinetic 15.7kwh battery, which has a rated capacity of 327 Ah and a rated voltage of 48 V. The battery can store up to 1 kWh of energy. The initial cost for one unit of this battery is $5000, with a replacement cost of $5000 as well. The annual cost for operation and maintenance is estimated to be $300, according to[5] [20].

D. Power converter

The selected converter for the proposed hybrid system is the converter SM-PAE 120/240V, which has a step range size of 1,000 kW and a maximum capacity of 17.6 kW. The converter has an efficiency of 94%, an initial cost of $3000/kW, and a lifespan of 10 years.

V. RESULTS AND DISCUSSION

The HOMER software runs simulations for all the systems to determine the most cost-effective option that can meet the electricity load demand.

A. Optimization results

The HOMER software generated the top ten optimized outcomes for cost efficiency, as depicted in Figure 7. The selected hybrid system that satisfies the economic feasibility criteria consists five units of 7580 kW wind turbine, a 17.6 kW power converter, diesel generator with 2000kw capacity, and a 43 battery with a 327 Ah capacity[14].

B. Cash flow summary results

According to the results generated by HOMER software, a hybrid system that integrates 5 units of wind turbines, a power converter, and a 43 batteries storage system would have a total Net Present Cost (NPC) of $693.000.000. The operating and maintenance cost would be approximately $674,000,000. As a result, the cost of energy produced by this system is estimated to be 5.62 $/kWh. The wind turbine system is the most expensive component of the hybrid system, costing $3.500.000, which is attributed to the high price and capacity of the wind turbines. The second most expensive component is the diesel generator, with a cost of $240.000. Figure 8, and table 3 explains the NPC of the proposed hybrid system.

TABLE II. SPECIFICATION OF SOLAR PV ARRAY

Description	Specification
Manufacturer	Generic
Solar Cells	Flat plate
Module Number	SM500
Nominal Power	500kW
Average Panel Efficiency	17.3%
Max. System Voltage	600 V
Capital Cost	56 $/kW
Replacement Cost	10 $/kW

TABLE III. SPECIFICATION OF SOLAR PV ARRAY

Net Present Value	$474M
Capital Investment	$3.73M
Annualized Savings	$37.0M

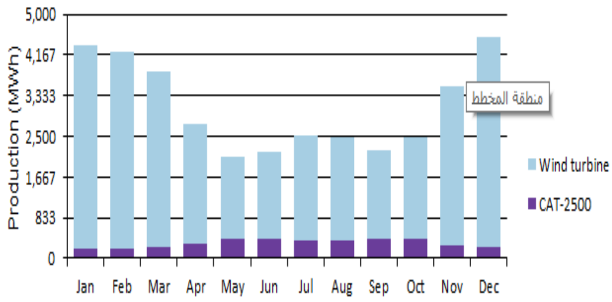


Fig. 9. Monthly average electric production

C. *Finding of Energy production*

Figure 9 illustrates the monthly average electric production of a hybrid system that generates a total of 37,130,595 kWh/year. The results indicate that the PV system contributes zero kWh/yr, , while the wind turbines generate 33,351,963 kWh/yr, representing 89.8% of power generation. While the diesel generation produced electricity of 3,778,632 kWh/yr, which representing of 10.2% of total energy production. The excess electricity generated by the hybrid system is 27,586,531 kWh/yr, indicating that the system produces more electricity than the total demand. Additionally, the unmeet load capacity is estimated to be 0.0 kWh/yr. [23].The total renewable production representing of 89.8% of the proposed hybrid system electricity production.

CONCLUSION

The present study employed the HOMER software for simulating a hybrid system that integrates photovoltaic (PV) panels, wind turbines,diesel generator, and battery storage. By optimizing the analysis, the study identified the top ten optimal combinations of system components based on their net present cost (NPC). The most cost-effective system configuration was found to consist of a 33.351.963kW Enercon E-126 wind turbine, Generic 1MWh of 43 batteries, and MS-PAE 17.6 kW power converter, diesel generation produced electricity of 2000kw . The study has shown that there is no benefit in using solar panels as the first two options for the hybrid system, while It is possible to use the solar system in the third proposed option according to HOMER software simulation results by installing 500 solar panels, but this will increase the initial cost of the project see Figure 7. This hybrid system was designed to provide electricity to the faculty of engineering building in Karabuk university in Turkey with the least cost possible. The study demonstrates the potential of alternative energy sources to generate electricity in Turkey.

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CONTRUBITION OF THE AUTHORS

The contributions of the authors to the article are equal.

CONFLICT OF INTEREST

There is no conflict of interest between the authors.

STATEMENT OF RESEARCH AND PUBLICATION ETHICS

Research and publication ethics were observed in this study.

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