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RESEARCH ARTICLE

Optimal Design of Hybrid Renewable Energy System for a Region in Turkey Using HOMER

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ABSTRACT

In recent years, increasing the rate of green energy use in order to meet the increasing energy demand and combat global warming has become one of the important goals of the countries. For this reason, the integration of renewable energy sources as distributed generation has become increasingly popular. In this study, hybrid renewable energy systems were designed for the electrification of a 100-household area in the Sarayköy district of Denizli province, Turkey, and the Hybrid Optimization Model for Electric Renewables program was used to optimize the required component outputs to to achieve the best economic and environmental results. A total of six hybrid renewable energy system designs, three grid-connected and three stand-alone, were created with different combinations of components such as photovoltaic panel, wind turbine, diesel generator, battery energy storage system, and converter. The most economical design was the grid-connected system with only solar energy with a unit energy cost of 0.0362 $/kWh, while the most cost-effective was the stand-alone system containing solar energy, wind energy, and batteries with 1.61 $/kWh. In terms of the environment, on the contrary, off-grid systems emit less carbon dioxide, while on-grid systems emit more carbon dioxide.

Index Terms—Energy storage systems, grid-connected, HOMER, hybrid energy systems, renewable energy sources

I. INTRODUCTION

Energy demand is increasing all over the world in parallel with the increasing population and developing technologies. To overcome the climate crisis brought about by conventional energy generation techniques and to meet the increasing energy demand, the integration of renewable energy resources (RESs) into existing grids and providing a high renewable fraction (RF) have gained importance. Hybrid renewable energy systems (HRESs), which include RESs, energy storage systems (ESSs) and conventional generation systems, offer environmentally friendly and sustainable solutions. They are highly useful and efficient systems, especially in rural areas that are far from the grid or have no grid connection. There are off-grid HRESs containing diesel generators (DG) and/or battery energy storage systems (BESSs), and on-grid HRESs that can deliver excess energy of the system to the main grid and take energy from the grid when energy generation is insufficient. On-grid systems are referred to as grid-connected, while off-grid systems are referred to as stand-alone, islanded, and grid-isolated in the literature [1].

While making the optimum design of HRESs, it includes objectives or constraints such as maximum utilization of the renewable potential in the region, minimum energy cost, and minimum emission. In the literature, HRES designs have been provided through various optimization techniques, tools, and computer simulation software. Some simulation programs are listed in Table I and compared according to the features they support [2, 3].

In [4], to separate Kuhin village of Qazvin region from the Iranian national grid, to provide cleaner energy generation and a high-resilient power system, an HRES including wind turbine (WT), electrolyzer, hydrogen storage, and proton-exchange membrane fuel cell (FC) was designed and optimized in the MATLAB environment. In [5], three off-grid HERSs including different combination of WT, photovoltaic panel (PV), DG, and BESSs were designed to meet the energy demand of Farafra region in Egypt by using the methods such as Archimedes Optimization Algorithm (AOA), Improved AOA, Artificial Electric Field Algorithm, Equilibrium Point Optimizer, Grey Wolf Optimizer (GWO), and Harris Hawks Optimization Algorithm.

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TABLE I.
SIMULATION PROGRAMS FOR THE DESIGN OF HYBRID RENEWABLE ENERGY SYSTEM

Software	Wind	Solar	Free Trial	Technical	Economic	Optimization
RETScreen	✓	✓	✓	✓	✓	×
Hybrid2	✓	✓	✓	✓	×	×
SolSim	×	✓	×	✓	✓	✓
HYBRIDS	✓	✓	×	✓	×	✓
HYDROGEMS	✓	✓	×	✓	✓	✓
TRNsys	✓	✓	✓	✓	×	×
Ihoga	✓	✓	×	✓	✓	✓
pvSYSST	×	✓	✓	✓	×	✓
SAM	✓	✓	✓	✓	✓	×
HOMER	✓	✓	✓	✓	✓	✓

In [6], a stand-alone HRES including PV, WT, DG, and BESS was designed using Moth Flam Optimization Algorithm, Genetic Algorithm (GA), and Particle Swarm Optimization (PSO) to electrify a hilly and rural area of Uttarakhand in India. In [7], to provide the electricity demand of a data center in South Korea in a green and reliable manner, off-grid HRES design including WT, PV, and ESS was carried out using the Hybrid Optimization Model for Electric Renewables (HOMER) program, and the steady-state and transient responses of the network were analyzed in the DIgSILENT power factory program. The authors at [8] designed an off-grid HRES with PV, WT, and DG for Riphah international University Faisalabad Campus in Pakistan using HOMER Pro. In [9], to meet the energy demand of a remote area in the Sahara Desert of Niger, off-grid and on-grid HRESs including PV, BESS, and DG were designed using the Mixed-Integer Linear Programming optimization algorithm. In [10], various-scale off-grid PV systems with various sun-tracking systems at 37 locations in Northern Cyprus were designed using mathematical modeling methods and RETScreen Expert software. In [11], to meet the energy demand of Basra city in Iraq, Hybrid Grey Wolf with Cuckoo Search Optimization was proposed to design an off-grid HRES consisting of PV, WT, BESS, biogasifier, and DG, and its performance was compared to other optimization algorithms such as PSO, GA, GWO, Cuckoo Search Optimization, and Antlion Optimization algorithms. In [12], PSO and Fuzzy Logic are proposed for the design of an off-grid HRES consisting of PV, WT, DG, and BESS to enable electrification of rural area called Olooji in Nigeria. The authors in [13] designed a grid-connected HRES with PV and biogas generator and superconducting magnetic energy storage or pumped hydro energy storage as an ESS to meet the energy demand of Debre Markos University, Debre Markos Ethiopia. In this design, a fractional order (FO) calculus for proportion-al-integral-derivative (PID) controllers and fuzzy controllers with an opposition-based whale optimization algorithm was proposed to minimize power and frequency oscillations and various metaheuristic algorithms were used to compare the performance of the proposed algorithm. In [14], HOMER Pro was used to design seven different islanded microgrids consisting of different combinations of PV, WT, FC, BESS, and converter to provide affordable and clean energy to a remote village in Assam, India. A prospect-theory-based TOmada de Decisao Interativa Multicriterio approach was proposed to evaluate the performance of the scenarios and choose the best one. On-grid and off-grid HRESs with PV/WT/Small Hydro Power Plant (SHPP)/Li-ion battery [1] and PV/WT/SHPP/electrolyser/FC/hydrogen tank [15] were designed using HOMER for a rural electrification in Turkey. In [16], on-grid and off-grid HRES designs including DG, PV, WT, and BESS were carried out using HOMER to provide uninterrupted power to the security systems of Samsun and Antalya seaports located in the north and south of Turkey, respectively. The economic and environmental evaluation of the grid-connected rooftop solar system for a building in Çerkezköy, Tekirdağ, Turkey, was examined using HOMER [3].

Main Points

- Six different hybrid renewable energy system designs, both on-grid and off-grid, were realized with Hybrid Optimization Model for Electric Renewables program.
- A reliable and robust hybrid energy system was designed using various renewable energy sources.
- Dependency on the grid was reduced by using diesel generators and batteries.
- By increasing the renewable fraction, clean energy has been increased and minimum carbon emission has been achieved.

In this comprehensive study, we present the design of 6 distinct HRESs to electrify a community of 100 households located in the Sarayköy district of Denizli province, a strategic location in the southwest of Turkey. This undertaking not only underscores the viability of using mixed renewable energy sources but also showcases the adaptability and scalability of HRES solutions in diverse geographical and infrastructural conditions. The designs include three off-grid and three on-grid systems, each comprising different combinations of PV, WT, DG, and BESS. Through meticulous simulations conducted in the HOMER program, we determined the optimal sizing for each component, ensuring maximum efficiency and sustainability. Furthermore, this study serves as a crucial guide for formulating energy policies and addressing local energy demands through the integration of HRESs into the grid, thereby advancing the global push for clean energy distribution.

The remaining of this paper is organized as follows. Section II presents the mathematical modeling of the HRES and economic equations. The material and methodology are described in Section III. Section IV discusses the simulation and optimization result. Finally, the study is concluded in Section V.

II. HYBRID RENEWABLE ENERGY SYSTEM MATHEMATICAL MODELING

A. Photovoltaic Power Model

The PV output power can be calculated as follows [1, 3, 14]:

$$P_{pv}(t) = N_{pv} \cdot P_{pv}^{r} \cdot f_{pv} \cdot \frac{G(t)}{G_n}\left[1 + \alpha_p\left(T_C(t) - T_{C_n}\right)\right] \quad (1)$$

where $P_{pv}(t)$ represents the instantaneous output power of the PV system (kW), N_{pv} is the number of the PV modules, P_{pv}^{r} reflects the rated power of each PV module (kW), f_{pv} is the PV derating factor (%), $G(t)$ is the real-time irradiation at the operating temperature (kW/m^2), G_n is the irradiation at the standard test condition (1 kW/m^2), α_p is the temperature coefficient (%/°C), T_c(t) is the real-time cell temperature (°C), and T_{cn} is the nominal operating (test condition) temperature of the PV module (25°C).

B. Wind Turbine Power Model

The effective output of the WTs is calculated as follows [3, 14].

$$P_{e,wt}(t) = \eta_{wt} \cdot A_{wt} \cdot P_{wt}(t) \quad (2)$$

$$P_{wt}(t) = N_{wt} \times \begin{cases} 0, & v(t) \le v_{ci} \; or \; v > v_{co} \\ P_{wt}^{r}\left(\dfrac{\{v(t)\}^3 - v_{ci}^3}{v_r^3 - v_{ci}^3}\right), & v_{ci} < v(t) \le v_r \\ P_r, & v_r < v(t) \le v_{co} \end{cases} \quad (3)$$

where $P_{e,wt}(t)$ reflects the effective electrical power output of WT as real time (kW), η_{wt} is the efficiency of the WT, A_{wt} represents the WT swept area, N_{wt} is the WT number in the system, P_{wt}^{r} is the rated power of each WT (kW), $v(t)$ is the real-time wind speed (m/s), v_{ci}, cut-in wind speed (*m/s*), is the threshold value of the wind speed, and v_{co}, cut-out wind speed (*m/s*), is the threshold value of the wind speed.

C. Diesel Modeling

The DGs convert the mechanical energy obtained from the heat generated by the combustion of fuel into electrical energy through an alternator [5]. In HRESs, DG is activated as a backup power supply when renewable generation and battery banks do not meet the load demand [11]. For optimum efficiency, a generator should run between 70% and 89% of its rated capacity [17]. Hourly fuel consumption in DG is calculated as in (4) and generator-rated power can be calculated as in (5) [5].

$$FC_{DG}(t) = a_{DG} \cdot P_{DG}(t) + b_{DG} \cdot P_{DG}^{r} \quad (4)$$

$$P_{DG}^{r} = \frac{FC_{DG}(t) - a_{DG} \cdot P_{DG}(t)}{b_{DG}} \quad (5)$$

where $FC_{DG}(t)$ represents the hourly fuel consumption of the DG in L/h, $P_{DG}(t)$ represents the real-time output power of the DG in kW, P_{DG}^{r} represents the rated power of the DG in kW and α_{DG} represents the slope coefficient of the fuel curve, and b_{DG} is the intercept coefficient.

The values of α_{DG} and b_{DG} are taken as 0.2461 L/kWh and 0.08415 L/kWh, respectively [11, 12].

The DG efficiency (η_{DG}), which measures the performance of DG, is calculated as follows [6, 9].

$$\eta_{DG} = \frac{3600 \cdot P_{DG}}{\rho_{f,DG} \cdot FC_{DG} \cdot LHV_{DG}} \quad (6)$$

where $\rho_{f,DG}$ and LHV_{DG} denote the lower calorific value in kj/kg and the density in L/kg of the fuel used in the DG, respectively.

D. Battery Energy Storage System Modeling

ESS serves as a reservoir for surplus energy generated during periods of renewable energy production exceeding the immediate demand, subsequently facilitating its utilization during periods of insufficient renewable energy generation. The capacity of the BESS is calculated as follows [5, 9].

$$C_{BESS} = N_{bat} \cdot \frac{AD \cdot P_L}{\eta_{inv} \cdot \eta_{bat} \cdot DOD} \quad (7)$$

where C_{BESS} represents the battery capacity (kWh), N_{bat} is the number of batteries, AD is the battery autonomy daily, P_L is the load quantity required (kW), *DOD* is the depth of discharge (%), and η_{inv} and η_{bat} are the efficiencies of the inverter device and battery system (%), respectively.

E. Convertor Modeling

There are two types of converters: inverters, which convert from DC to AC, and rectifiers, which convert from AC to DC [3]. The inverter power rating is calculated as follows [11]:

$$P_{inv} = \frac{P_L^{max}}{\eta_{inv}} \quad (8)$$

where P_{inv} is the inverter rating power, and P_L^{max} represents the peak load demand.

F. Grid Modeling

In grid-connected HRES, the power supplied to or absorbed from the grid is calculated as follows [9]. If the calculated value is positive, it is absorbed power from the grid and if it is negative, it is supplied power to the grid.

$$P_{grid}(t) = P_L(t) - \sum\left(P_{pv}(t) + P_{wt}(t) + P_{DG}(t) + P_{BESS}(t)\right) \quad (9)$$

G. Economic Equations

Cost of unit energy (COE), net present cost (NPC), operational cost (OC), and initial cost (IC) must be calculated to construct the economic objective function in HRES [1, 3].

The most important index, COE, is the unit energy (1 kWh) generation cost and is calculated as follows:

$$COE(\$/kWh) = \frac{TAC(\$/yr)}{TAEC(kWh/yr)} \quad (10)$$

where the total annual cost is represented by TAC, and the annual total energy consumption is represented by TAEC.

The NPC is calculated as follows:

$$NPC(\$/yr) = \frac{TAC(\$/yr)}{CRF} \quad (11)$$

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (12)$$

where CRF is the capital recovery factor, i is the interest rate (%), and n is the lifetime of the components (year).

The OC is calculated as follows:

$$OC(\$/yr) = TAC(\$/yr) - ACC(\$/yr) \quad (13)$$

where ACC is the annual capital cost.

H. Renewable Fraction

The RF refers to the usage rate of renewable energy and it is calculated as a percentage as follows:

$$RF(\%) = \frac{E_{RES}}{E_{RES} + E_{nonRES}} \times 100 \quad (14)$$

where E_{RES} is the amount of renewable generation, and E_{nonRES} is the amount of energy supplied from nonrenewable energy sources and the grid.

III. MATERIAL AND METHODOLOGY

A. Hybrid Optimization Model for Electric Renewables Software

The HOMER software is a tool developed for holistic and integrated analysis of renewable energy technologies. This software enables the technical and economic optimization of hybrid energy systems, thus facilitating the design and evaluation of renewable energy projects. In this study, the HOMER program was used to model the HRESs for a region in Denizli. The main reason for using the program is to determine how to design a system in which various energy sources (PV, WT, and DG) can work together in the most efficient way, both technically and economically. This comprehensive analysis capability provided by HOMER has enabled the design and analysis of the most efficient hybrid energy system, considering local conditions (e.g., meteorological data such as irradiation and wind speed) and load demands for a specific region in Denizli. In this way, the feasibility and cost-effectiveness of site-specific energy solutions can be accurately evaluated.

B. Study Region: Sarayköy

This study was carried out in the Sarayköy district of Denizli province, which is in the Aegean region of Turkey, specifically at the geographical coordinates of 37°55’35.24’’ N and 28°55’35.99’’ E. Fig. 1 shows the geographic area as observed on the Google Earth platform.

Given its geographical location and the absence of nearby settlements and vacant land, the area is highly suitable for the installation of an HRES. In this region, the HRES based on solar and wind energy has been modeled using the HOMER program. The HRES, consisting of PV, WT, DG, converter, and BESS, has been modeled to power 100 households in the Sarayköy region.

Fig. 1. The aerial perspective of Sarayköy, Denizli.

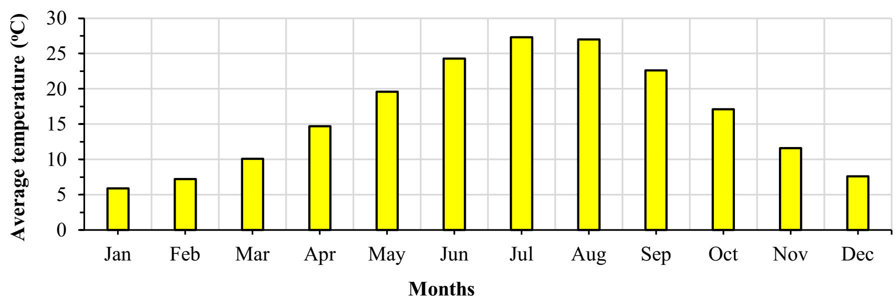


Fig. 2. Monthly average temperature values for the study region.

The monthly average temperature data for Denizli between 1991 and 2020 are shown in Fig. 2. The average temperature over this period is determined as 16.3°C [18].

The daily radiation, clearness index (CI), and wind speed data for the region were obtained from NASA through the HOMER program and are shown in Fig. 3 and Fig. 4, respectively.

The average annual solar radiation in the Sarayköy region is estimated at 2.01 kWh/m²/day. It is seen from Fig. 3 that the maximum amount of solar radiation during this period is about 7.8 kWh/m²/day. The annual average and lowest CI are around 0.593 and 0.485, respectively. The average annual wind speed is around 3.34 m/s and the maximum wind speed is 4.46 m/s.

C. Load Demand of the Region

In this study, the HRES model is designed to meet the electricity demand of 100 households in the region of Sarayköy, Denizli. The RESs and other equipments are sized according to the load value. The daily load curve of 100 houses in the region is shown in Fig. 5.

The daily energy demand of the power system is close to 886.52 kWh and the peak load is 144.45 kW. As the electricity supply strategy within the electric utility industry, supplying energy must exceed the demand. Therefore, it is aimed to maintain electricity output at levels higher than demand in this study.

IV. HYBRID RENEWABLE ENERGY SYSTEM DESIGNS

The HOMER program was used to perform an analysis of the technical feasibility of RES, as well as to investigate the economic costs

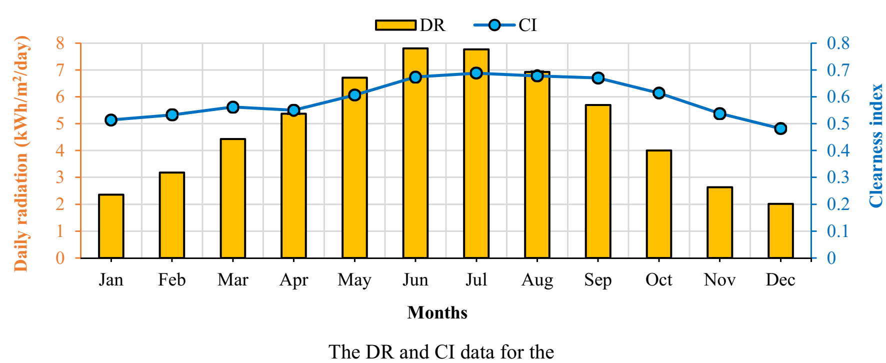


Fig. 3. The daily radiation and clearness index data for the region.

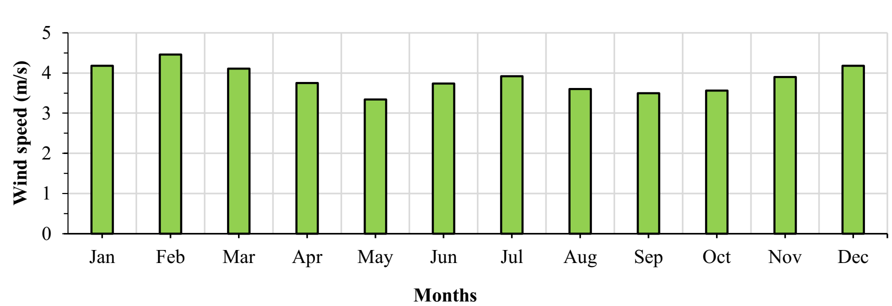


Fig. 4. The average wind speed for the region.

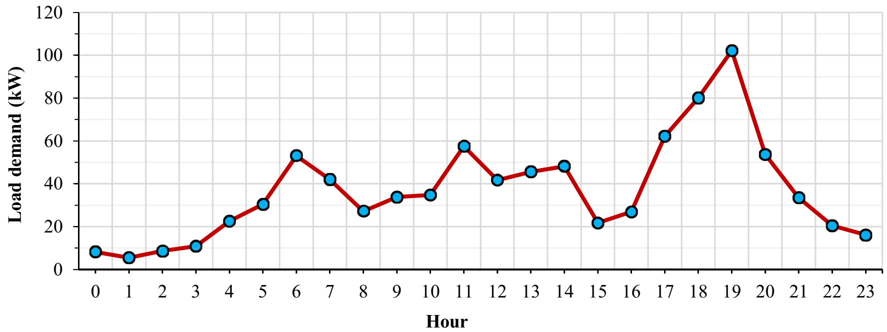


Fig. 5. Daily load curve of residential area in Sarayköy.

associated with operating the system. Both on-grid and off-grid HRES designs were carried out in this study and these models are illustrated in Fig. 6.

According to Fig. 6, an on-grid HRES utilizes PV/WT and a converter. On the other hand, an off-grid HRES, due to the absence of power flow from the grid, employs not only PV/WT and a converter but also includes DG and BESS to meet the energy requirements.

V. SIMULATION AND OPTIMIZATION RESULTS

As a result of the HOMER program running the modeling, combinations based on various scenarios were created for six different HRES. Fig. 7 shows a total of six scenarios, including three on-grid and three off-grid HRES models.

While PV/WT/DG/BESS HRES was used in the first scenario, PV/DG/BESS system was used in the second scenario and PV/WT/BESS system was used in the third scenario. In these first three scenarios, off-grid HRES was simulated. Large-scale lithium-iron phosphate battery banks are needed to store electricity and a DG is needed to meet the electricity demand. While PV/WT/Grid system was used in the fourth scenario, WT/Grid system was used in the fifth scenario and PV/Grid system was used in the sixth scenario. For the last three scenarios, a grid block model has been added to the HOMER program for the simulation of the on-grid HRES.

Table II shows the costs and technical parameters of HRES elements. The grid energy sell price was determined as 0.082 $/kWh, and the grid energy buy price was 0.067 $/kWh.

A. OPTIMIZATION RESULTS

Table III shows the component values used for six different scenarios by examining the architecture column, which shows the architecture of the systems.

Scenario 1 uses five batteries and a 121 kW converter in addition to the WT, PV, and DG. The NPC value represents the comprehensive financial assessment of a scenario, encompassing both the investment and operational costs incurred throughout the project's lifespan, while deducting the total revenues generated over the same period. In short, it means net cost. It is seen that the NPC value for the first scenario is $1.21 M. When all scenarios are compared, the sixth scenario created by the PV/Grid HRES model provides the lowest net cost of $231 192. This is because in Case 6, the PV/Grid HRES model is connected to the grid, which ensures that the generator and battery systems do not impose an additional cost on the model. These systems are an important advantage as they do not have operating costs as well as ICs and the DG does not consume fuel.

The COE value is defined as the average cost per 1 kWh of electrical energy produced by the system. Upon comparison of all scenarios, it is observed that the sixth scenario, an on-grid model, is eight times

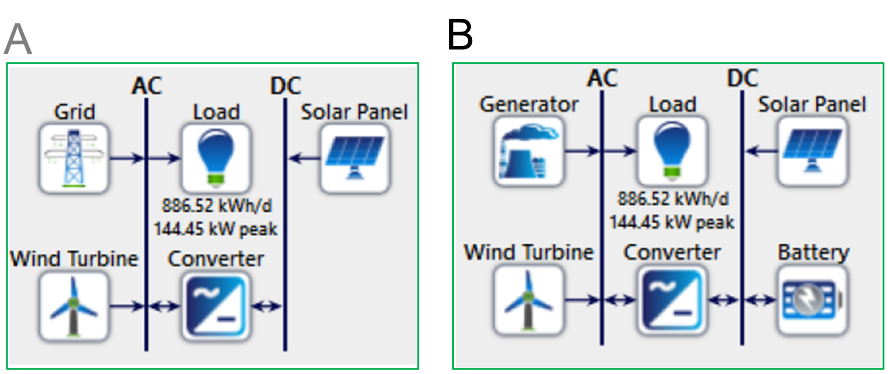
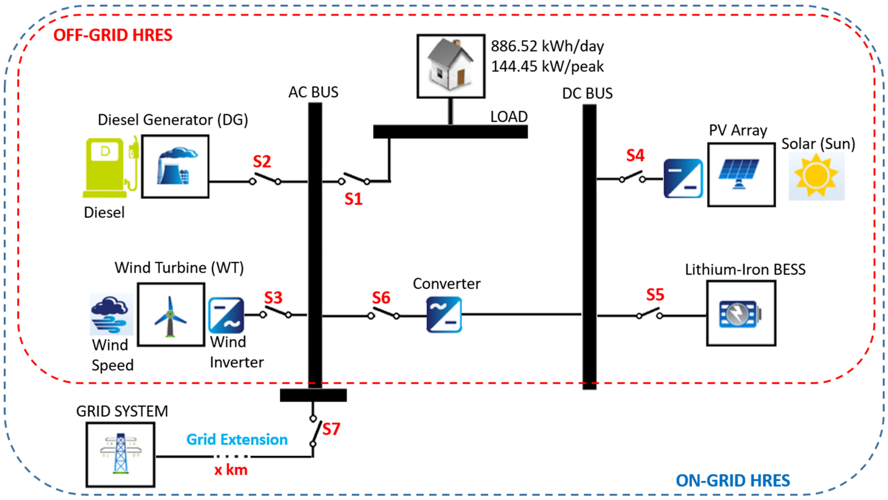


Fig. 6. Hybrid renewable energy system designs as: (a) on-grid and (b) off-grid.



Scenario HRES Models	S1	S2	S3	S4	S5	S6	S7
PV-WT-DG-BESS	√	√	√	√	√	√	
PV-DG-BESS	√	√		√	√	√	
PV-WT-BESS	√		√	√	√	√	
PV-WT-DG-BESS-grid	√	√	√	√	√	√	√
PV-DG-BESS-grid	√	√		√	√	√	√
PV-WT-BESS-grid	√		√	√	√	√	√

Fig. 7. On-grid and off-grid hybrid renewable energy system models.

more cost-effective at $0.0362, in contrast to the first scenario, which holds the lowest energy price at $0.29 in the off-grid HRES model.

The initial capital value refers to the pre-installation capital amount. As demonstrated in Table IV, Case 5's WT results in the lowest initial capital of $110 000, while Case 3, comprising a PV/WT/BESS, necessitates the highest initial capital of $8.42 million. This large IC in Case 3's HRES model is due to the requirement of a substantial quantity of battery modules (85 units) to store the electrical energy. Operating cost embodies all annual expenses and revenues, excluding the initial capital costs, and is calculated by deducting the total annual cost from the annual capital cost. In Table IV, Case 4 presents the minimal operating cost of $2509, whereas Case 3 manifests the maximum operating cost of $130 715. O&M costs are the yearly operational and maintenance expenditures. In Table IV, Case 2 shows the least O&M cost of $702.06, while Case 5 records the highest O&M cost of $24 024. The maximum fuel cost of $29 664 is observed in Case 2. When total costs are considered, Case 5 yields the lowest cost at $158 048, while Case 3 results in the highest cost at $8552 million. The impact of batteries on the installation cost of the HRES model is noticeably substantial. Upon a comprehensive review of the system, it is found that the unit energy cost in the fourth scenario, which employs both renewable energy systems, is higher than in the sixth scenario which solely uses solar energy. This discrepancy is due to the insufficiency of the wind energy required for the chosen region in this system. The system with the lowest average energy cost is the solar energy–grid system in the sixth scenario.

According to Table V, excess electricity production is an important factor for the efficiency and functioning of energy systems. Excess

TABLE II.
THE TECHNICAL PARAMETERS AND COSTS OF HYBRID RENEWABLE ENERGY SYSTEM COMPONENTS

Parameter	Quantity	Model	Capital Cost	Replacement Cost	O&M Cost	Fuel Cost (Diesel)	Lifetime
PV	200 kW	Peimar SG200M5	640 $	512 $	-	-	30 years
WT	25 kW (×1)	SWP25-16TV20	110 000 $	100 000 $	1500 $/yr	-	25 years
DG	150 kW	Generac SD150	200 000 $	140 000 $	4000 $/yr	1.5 $/L	25 years
BESS	134 kW	Iron Edison LFP 2800Ah	95 500 $	95 500 $	-	-	15 years
Converter	100 kW	System Converter	300 $	300 $	-	-	15 years

BESS, battery energy storage system; DG, diesel generator; PV, photovoltaic; WT, wind turbine.

TABLE III.
OPTIMIZATION RESULTS OF HYBRID RENEWABLE ENERGY SYSTEM MODELS.

System	Architecture					Cost	
Case: Configuration	**PV (kW)**	**WT (kW)**	**DG (kW)**	**BESS (x1)**	**Converter (kW)**	**COE ($/kWh)**	**NPC ($)**
Case 1: PV/WT/DG/BESS	200	25	150	5	121	0.2900	1.21 M
Case 2: PV/DG/BESS	200	-	150	5	119	0.2990	1.25 M
Case 3: PV/WT/BESS	200	25	-	85	201	1.6100	6.73 M
Case 4: PV/WT/Grid	200	25	-	-	142	0.0467	313 155
Case 5: WT/Grid	-	25	-	-	-	0.1000	420 570
Case 6: PV/Grid	200	-	-	-	142	0.0362	231 192

COE, cost of unit energy; BESS, battery energy storage system; DG, diesel generator; NPC, net present cost; PV, photovoltaic; WT, wind turbine.

electricity is electricity that is produced in excess of demand and cannot be stored by ESSs. This is often due to fluctuations in demand forecasts as well as energy production from RES. In the first scenario, the highest surplus electricity production was observed with 74 197 kWh/year, while the lowest surplus electricity production was determined as 43 342 kWh/year in the third scenario. This indicates that energy production and storage capacity are important factors that determine the amount of excess electricity production. In the fourth, fifth, and sixth scenarios, excess electricity generation is not specified in any way. This could mean that in these scenarios, power generation fully meets or exceeds demand, being fed back into the power grid. Such systems are more common in energy markets, where energy demand and production are often very closely matched, and excess energy is sold to the power grid or used in other ways. These scenarios provide greater flexibility in energy system design and operations. As a result, excess electricity production can have a significant impact on the efficiency, flexibility, and economic performance of an energy system. It is important to consider this factor in the design and operation of energy systems.

According to Table V, the rate of renewable energy among the first, second, and third scenarios differs according to the energy sources and system components used. In the first scenario, the RF ratio was determined as 88.5% with the use of PV, wind, generator, and battery components together. However, in the second scenario, it is seen that the RF ratio decreases to 82% when the wind energy is removed. This shows that the use of wind energy increases the RF ratio. In the third scenario, it is seen that the RF ratio increases to 100% as a result of the removal of the generator component. This shows that removing generators and using only RES maximizes the RF ratio. The fourth, fifth, and sixth scenarios each use different energy sources and system components. In the fourth scenario, it is seen that PV and wind energy are used and batteries are not used. This reduces the RF rate to 68.8%. In the fifth scenario, only wind energy was used and this caused the RF ratio to drop to 15.1%. In the sixth scenario, only PV energy was used and this caused the RF ratio to decrease to 62.3%. Because the wind energy used cannot meet the electrical energy demanded, electrical energy is taken from the grid and causes a low renewability rate. These results show that the diversity of energy sources has a significant effect on the amount of RF ratio. Also, using a single RES (scenarios five and six) appears to result in lower RF rates compared to using mixed energy sources (scenario four). This shows that the rate of renewable energy in energy systems can be maximized by a combination of energy sources and technologies used.

According to Table V, between the first, second, and third scenarios, CO_2 emissions vary according to the type of energy used and system components. In the first scenario, the CO_2 emission was calculated as 33 186 kg/year with the use of PV, wind, generator, and

TABLE IV.
OPTIMIZATION RESULTS OF COST DETAILS FOR HYBRID RENEWABLE ENERGY SYSTEM MODELS

System	Initial Capital ($)	Operating Cost ($/yr)	O&M ($)	Fuel ($)	Total ($)
Case 1: PV/WT/DG/BESS	781 938	33 251	1954	18 971	836 114
Case 2: PV/DG/BESS	671 275	44 711	702.06	29 664	746 352
Case 3: PV/WT/BESS	8.42 M	130 715	1503	-	8552 M
Case 4: PV/WT/Grid	280 722	2509	1687	-	284 918
Case 5: WT/Grid	110 000	24 024	24 024	-	158 048
Case 6: PV/Grid	170 722	4678	3856	-	179 256

TABLE V.
OPTIMIZATION RESULTS OF HYBRID RENEWABLE ENERGY SYSTEM MODELS

System	Solar Energy (kWh/yr)	Wind Energy (kWh/yr)	Diesel Energy (kWh/yr)	BESS (kWh/yr)	Excess Energy (kWh/yr)	RF (%)	CO_2 (kg/year)
Case 1	332 091	48 804	37 106	144 736	74197	88.5	33 186
Case 2	332 091	-	58 158	152 225	44 561	82	51 892
Case 3	332 091	48 804	-	174 987	43 342	100	-
Case 4	332 091	49 227	-	-	-	68.8	102 443
Case 5	-	49 227	-	-	-	15.1	174 530
Case 6	332 091	-	-	-	-	62.3	118 055

battery components together. However, in the second scenario, it is seen that CO_2 emissions increase to 51 892 kg/year when wind energy is removed. This shows that the use of wind energy reduces CO_2 emissions. In the third scenario, it is seen that CO_2 emissions are completely eliminated as a result of the removal of the generator component. This shows that not using generators plays an important role in reducing environmental impacts. The fourth, fifth, and sixth scenarios each use different energy sources and system components. In the fourth scenario, it is seen that PV and wind energy are used and batteries are not used. This resulted in 102 443 kg/year CO_2 emissions. In the fifth scenario, only wind energy was used, resulting in CO_2 emissions of 174 530 kg/year. In the sixth scenario, only PV energy was used and this resulted in 118 055 kg/year CO_2 emissions. These results show that the diversity of energy sources and technologies has a significant impact on the amount of CO_2 emissions. In addition, using a single RES (fifth and sixth scenarios) appears to cause higher CO_2 emissions compared to using mixed energy sources (scenario four). This shows that the environmental impacts of energy systems can be minimized by a combination of energy sources and technologies used.

VI. CONCLUSION

This study comprehensively addresses the design and effectiveness of an HRES for residential areas in Sarayköy, Denizli. The novelty of the study is the establishment of HRES models that combine PV, WT, and DG and detailed simulation and analysis of this system by using the HOMER program. Thus, a detailed evaluation of various parameters such as cost, carbon footprint, and renewable energy factors between on-grid and off-grid models has been made. In particular, comparisons in CO_2 emissions, energy costs, and renewable energy rates between on-grid and off-grid systems offer innovative perspectives on how energy production and consumption strategies can be optimized for sustainability. In particular, initial capital value and operating costs can vary significantly depending on different scenarios. For example, Case 3, the off-grid scenario, has the highest initial capital ($8.42 million), while Case 5, the on-grid scenario, has the lowest initial capital ($110 000). Thus, it is seen that the integration of BESS into the grid significantly affects the cost. The combination of different energy sources and technologies also has a decisive influence on the rate of RF. The RF rate from 88.5% in Case 1 drops to only 15.1% in Case 5. There are also significant differences in CO_2 emissions between different scenarios; in Case 3, with the removal of the generators, emissions are completely eliminated, while in Case 5, it reaches 174 530 kg/year. With the integration of hybrid energy systems into the grid, the use of RES in electrical energy production increases, the carbon footprint decreases, and thus the demand for hybrid systems increases. In conclusion, this study makes an important contribution to the literature in optimizing energy costs and environmental impacts by providing an in-depth look at the design and grid connection potential of hybrid energy systems to meet residential energy demand. In addition, this study is a valuable guide for establishing energy policies and meeting local energy needs by connecting HRES to the grid, thus promoting clean energy circulation around the world.

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