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RESEARCH ARTICLE

On-Grid and Off-Grid Hybrid Renewable Energy System Designs with HOMER: A Case Study of Rural Electrification in Turkey

Mikail Pürlü, Sezen Beyarslan, Belgin Emre Türkay

Department of Electrical Engineering, İstanbul Technical University, İstanbul, Turkey

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ABSTRACT

In this study, hybrid renewable energy systems were designed to minimize the cost of electrical energy and harmful gas emissions in line with environmental and economic concerns. While the on-grid hybrid renewable energy systems were designed by providing optimum power dispatching between solar panels, wind turbines, a small hydroelectric power plant, and the main grid, off-grid systems were designed by completely disconnecting from the grid and adding a battery energy storage system. Therefore, data such as power demand, peak load, solar irradiation, wind speed, and river flow rate of a rural area in Turkey have been collected to realize the analyses of optimal hybrid energy systems in Hybrid Optimization Models for Energy Resources program. While on-grid systems provide very economical solutions, off-grid systems have become more environmentally friendly. By introducing grid usage restriction, carbon emissions in on-grid systems have also been reduced. Also, more feasible systems have been achieved by including various constraints such as sell-back capacity, shortage capacity, and the maximum number of wind turbines to fit in the area. Finally, the effects of the increase in the renewable energy capacities were examined by performing sensitivity analyses and positive economic and environmental contributions have been observed.

Index Terms—HOMER, hybrid energy systems, grid-connected, standalone, renewable energy

I. INTRODUCTION

The rapid increase in population and technological developments in recent years has increased the electrical energy demand all over the world [1]. On the other hand, the United Nations Environment Program reports that an estimated 2.0 billion people around the world, mostly living in underdeveloped countries or rural areas, are deprived of a reliable electricity grid service [2]. It is a challenge to provide reliable, efficient, and economical electrical energy to these remote and underpopulated areas [3]. Off-grid microgrids including distributed energy sources in small-scale are more cost-effective than stretching transmission and distribution lines to these rural regions [4].

The use of electrical energy has become a basic need for people living in both urban areas and villages/islands, and the demand is increasing day by day [5]. The enormous increase in fossil fuel prices [6] and the decrease in fossil fuel reserves led to an energy crisis. Alternative renewable energy sources are proposed to cope with this energy crisis and reduce harmful gas emissions. Alternative renewable energy sources (RESs) are proposed to cope with this energy crisis and reduce harmful gas emissions. However, a single RES cannot meet the energy demand due to the generation uncertainties of RESs. Therefore, hybrid renewable energy systems (HRESs) including various RESs such as solar, wind, biomass, hydro energy, and energy storage systems are recommended [7]. Hybrid energy systems (HESs) can be designed to operate as off-grid (stand-alone and grid-isolated) or on-grid (grid-connected) systems and can utilize energy storage systems (ESSs) [8].

There are a lot of studies for off-grid and on-grid HESs using various optimization algorithms and tools. The authors in [1] proposed a stand-alone hybrid hydro/wind/solar/diesel/battery energy system to power the Persian Gulf Islands by using Hybrid Optimization Models for Energy Resources (HOMER). In [2], a grid-isolated hybrid solar/wind/diesel/battery energy system was studied on HOMER for a village named Perumal Kovilpathy, Tamil Nadu, in India. An off-grid hybrid solar/wind/hydro/battery energy system design on HOMER to electrify remote and hard-to-reach villages in the Indian Himalayan Region was proposed by [3]. In [4], a comparison of grid-isolated and grid-connected solar/battery systems for a rural community in Rwanda was examined by using HOMER.

Corresponding author: Mikail Pürlü, purlu@itu.edu.tr

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The feasible HES designs of solar/wind/biomass/diesel/battery/non-battery on Sbessi Island, South Lampung Regency, Indonesia, were conducted by the authors in [5]. In [6], two HOMER models for off-grid and on-grid HES consisting of solar/wind/diesel/battery were studied without sensitivity analyses for Statesboro.

A grid-connected hybrid solar/wind/biomass energy system without battery was designed considering the effect of sensitivity variables for a university campus utilizing HOMER [7]. Hybrid combinations of wind turbines (WTs), photovoltaic panels (PVs), and battery energy storage system (BESS) were optimized for an 80 m^2 residential building in Durban by using genetic algorithm and particle swarm optimization methods [8].

The authors in [9] proposed a numerical algorithm to determine the optimal size of wind, solar, and wind/solar hybrid energy system with batteries for a typical residential load in a remote area in Montana. Three recent optimization algorithms, bat optimization, equilibrium optimizer, and black hole, were used to optimize the grid-connected HES consisting of PV/BESS/hydrogen storage systems (HSS) for Dobaa Region in Egypt [10].

In [11], renewable and nonrenewable energy sources with BESS and HSS were used to design stand-alone HES for Newfoundland by using HOMER. HOMER-MATLAB combined tool was used to optimize on-grid PVs with BESS for a large commercial load in Makkah, Arabia [12].

The authors in [13] proposed the generalized reduced gradient method to design both optimal off-grid and on-grid HRES including WT, PV, and BESS for a remote rural area. In [14], a moth-flame optimization algorithm was presented to determine the optimal size of wind/solar HES with hybrid ESS including BESS and supercapacitor. HOMER and MATLAB/Simulink models for a residential area in Pakistan were introduced to design grid-isolated wind/solar/battery HESs [15].

HESs such as off-grid PV/HSS for an area in Brazil [16], on-grid PV/BESS at University of Campinas (UNICAMP) campus [17], various combinations of diesel/PV/WT/HPP/BESS for a remote region in Nigeria [18], stand-alone PV/diesel/BESS for a remote area in South Africa [19], and grid-isolated and grid-connected PV/WT/HPP/HSS HES for a rural area in Turkey were designed using HOMER software.

Main Points

- Both off-grid and on-grid scenarios were examined.
- A reliable and robust hybrid energy system was designed using various renewable energy sources.
- Feasible case studies by using the constraints.
- Economic and environmental contributions.
- As future work, another renewable energy source such as biomass can be integrated into the proposed hybrid energy system.

This paper proposes the optimal solution scenarios to both on-grid and off-grid hybrid energy systems consisting of RESs, such as WT, PV, HPP, and BESS, and also examines sensitivity analyses for a rural area by using HOMER software under the various constraints based on power system operation, used components, and feasibility.

The remaining of this paper is organized as follows. In section II, the introduction of the HOMER software and its mathematical modeling are given. The data of the rural area about consumption and renewable generation are presented in section III. The results of the performed analyses for on-grid and off-grid systems are included in section IV. The results are discussed in section V. Finally, the conclusion of this paper is located in section VI.

II. METHODOLOGY

In this study, the HOMERsoftware was used to design RHESs. HOMER is a microgrid optimization tool developed by National Renewable Energy Laboratory [2, 3]. The basic functions of HOMER are imitation, optimization, and sensitivity analysis. Power balance, load profile, location-specific tools, and system components are all considered by HOMER. The schematic summary of the HOMER software is shown in Fig. 1 [4].

In HOMER, the electrical power generated by the HPP is calculated with the following equation [18]:

$$P_{hyd} = \frac{\eta_{hyd} \cdot h_{net} \cdot \rho_{water} \cdot Q_T \cdot g}{1000\left(W / kW\right)} \tag{1}$$

where η_{hyd} is the total efficiency of the hydro plant (%), h_{net} refers to the effective head (m), ρ_{water} is the water density (1000 kg/m^3), Q_T denotes the flow rate of the hydro turbine (m^3/s), and g is the gravitational acceleration (9.81 m/s^2).

The effective electrical power output generated by the WTs is calculated as follows [1, 13].

$$P_{e,wt} = \eta_{wt} \cdot A_{wt} \cdot P_{wt} \tag{2}$$

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

where η_{wt} is the wind turbine efficiency, A_{wt} is the swept area of the turbine, N_{wt} is the number of the WTs, P_r is the rated power of each WT (kW), v is the wind speed (m/s), v_{ci}, cut-in wind speed, is the threshold value of the wind speed, and v_{co}, cut-out wind speed, is the threshold value of the wind speed.

The output power of the PV system can be defined by (4) [1, 8 ,10, 18]:

$$P_{pv}(t) = N_{pv} \cdot P_{pv_r} \cdot f_{pv} \cdot \frac{G(t)}{G_n}\left[1 + \alpha_p\left(T_C(t) - T_{C_n}\right)\right] \tag{4}$$

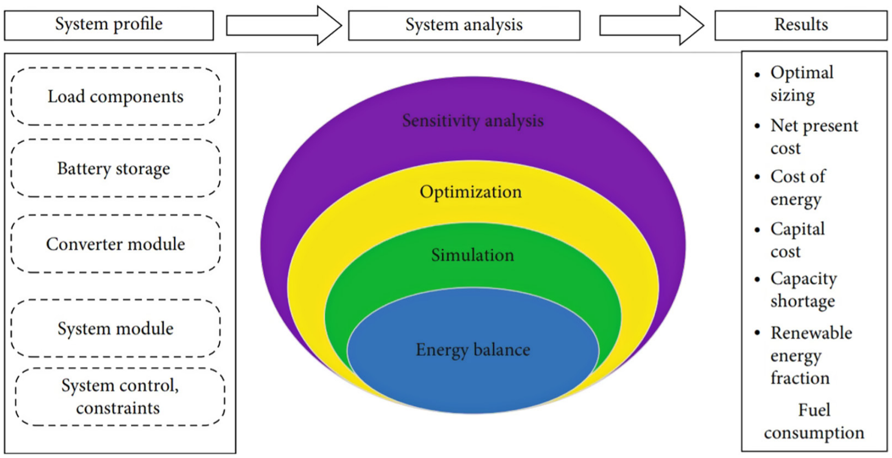

Fig. 1. Schematic representation of HOMER program [4].

where N_{pv} is the number of the PV modules, P_{pvr} is the rated power of each PV module (kW), f_{pv} is the PV derating factor (%), $G(t)$ is the irradiation at the operating temperature (kW/m^2), G_n is the irradiation at the standard test condition ($1kW/m^2$), α_p is the temperature coefficient ($\%/^{\circ}C$), $T_c(t)$ is the cell temperature (°C), and T_{c-n} is the nominal operating (test condition) temperature of the PV module (25°C).

In HOMER, performance indicators are cost of unit energy (CoE), net present cost (NPC), operational cost (OC), and initial cost (IC).

CoE is the most critical metric and it represents the cost of producing 1 kWh of electrical energy. It is calculated as follows [21]:

$$CoE(\$/kWh) = \frac{TAC(\$/yr)}{TAEC(kWh/yr)} \tag{5}$$

where *TAC* is the total annual cost and *TAEC* is the total annual energy consumption.

NPC is the total of all expenses including capital, replacement, operation and maintenance, and fuel expenditures minus the salvage cost at the end of the project's lifetime. It is calculated as follows [1]

$$NPC(\$/yr) = \frac{TAC(\$/yr)}{CRF} \tag{6}$$

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{7}$$

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

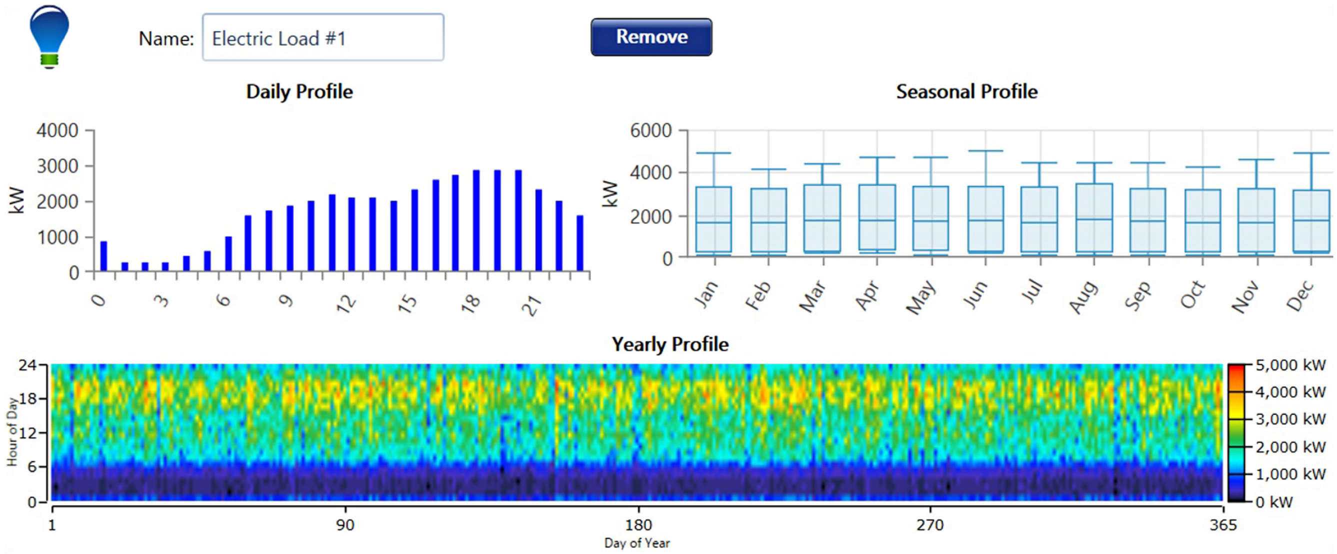

Fig. 2. Load profile.

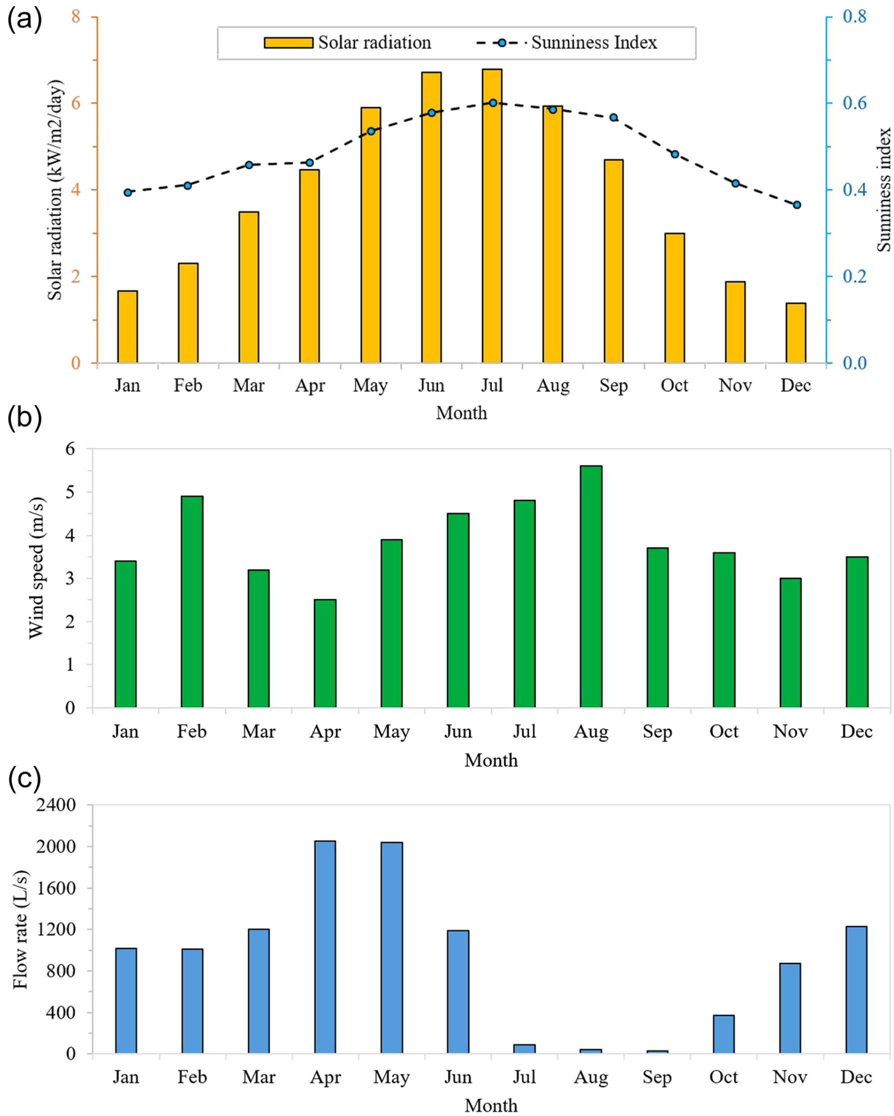

Fig. 3. Renewable sources' data of the region for: a) irradiance; b) wind speed; c) flow rate.

OC is calculated by subtracting the total annual cost from the capital investment and is formulated as follows [1, 21]:

$$OC(\$/yr) = TAC(\$/yr) - ACC(\$/yr) \tag{8}$$

where *ACC* is the annual capital cost.

III. TEST SYSTEM DATA

In this study, a grid-connected village in Bursa, Turkey, was examined. The village is located at 40°08′55.27" north latitude 29°16′06.73" east longitude. The population of this village, located near the Delicay river, was 390 in 2021. The daily, seasonal, and yearly load profiles of the region are given in Fig. 2.

The meteorological data for the village was obtained from the NASA Prediction of Worldwide Energy Resource (NASA POWER) database [22]. Solar radiation data come from NASA POWER by HOMER software. The average sunniness index was recorded as 0.515 and the average daily radiation was recorded as 4.028 kWh/m²/day. The average wind speed for this village, which is located at an altitude of 611 m, is 3.88 m/s. The average flow of Delicay river is 928 L/s. All renewable resources' data used in this study is shown in Fig. 3. Capacity and turbine cost of three types of WT are listed in Table I and the power characteristics of WTs are shown in Fig. 4 [23].

IV. RESULTS OF THE ANALYSES

The analyses were performed for both off-grid and on-grid systems. Village daily energy demand is 29 MWh/day and daily peak load is 3500 kW. Because of the availability of wind and solar energy potential in most areas [8], they were chosen as the major RESs in this study.

TABLE I.
CAPACITY AND TURBINE COST

Type of WT	Abbreviation	Capacity (kW)	Turbine cost ($)
Enercon E33	E33	330	429 000
Leitwind90 LT90	LT90	1500	1 800 000
Enercon E82	E82	3000	3 300 000

WT, wind turbine.

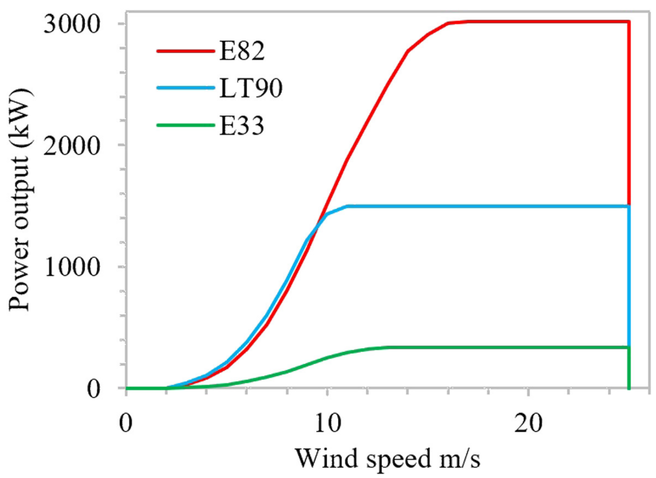

Fig. 4. Power characteristics of wind turbines.

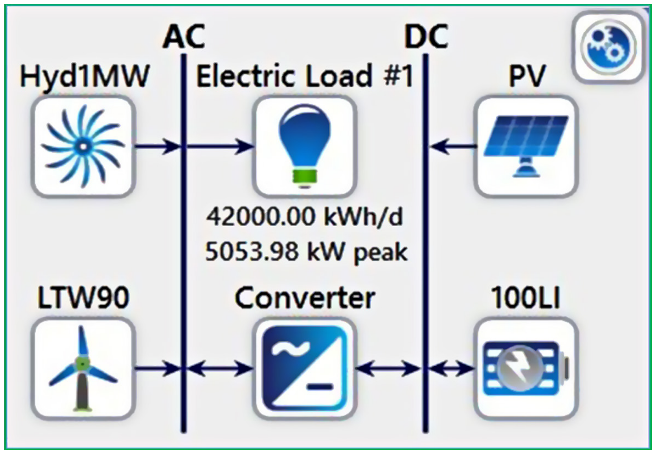

Fig. 5. Off-grid HRES design.

A. Off-grid System Analyses

Off-grid system in Fig. 5 has been designed with renewable energy such as PV, WT, HPP, and ESS such as Li-ion battery.

Analyses were made with 1%, 5%, and 10% shortage capacity to select the most proper one among the three types of WT such as E33, LTW90, and E82. HOMER program analyzes the system economically [24]. In this study, the area of the village is insufficient, the number of WTs is limited to three in terms of feasibility. Due to its low capacity of 330 kW, E33 WT was not used in the limited analyses. The results of the analyses are listed in Table II. According to the

TABLE II.
OFF-GRID ANALYSES RESULTS

SC (%)	WT Type	PV (kW)	WT (kW)	HPP (kW)	Li-ion (100 kWh)	Converter (kW)	NPC (M$)	CoE ($)	OC (M$/Year)	IC (M$)
	E33	12 263	11 550	212	357	4051	73.0	0.371	1.87	48.8
1	LT90	9469	9000	212	338	4156	62.3	0.317	1.65	41.0
	E82	11 673	15 000	212	355	4571	73.6	0.374	1.82	50.1
	E33	9469	9000	212	239	3674	57.6	0.300	1.50	38.2
5	LT90	7293	7500	212	224	3157	47.9	0.249	1.30	31.1
	E82	9841	12 000	212	256	3500	58.8	0.306	1.49	39.6
	E33	8592	8250	212	190	3458	49.9	0.267	1.32	32.8
10	LT90	5677	7500	212	160	3657	41.7	0.224	1.13	27.0
	E82	8623	9000	212	218	3494	50.4	0.270	1.32	33.3
5*	LT90	11 131	4500	212	266	3621	51.7	0.269	1.40	33.6
	E82	11 841	9000	212	272	4811	59.6	0.310	1.51	40.1

*for the case of maximum three WTs limitations.
SC, shortage capacity; WT, wind turbine; PV, photovoltaic; HPP, hydro power plant; NPC, net present cost; CoE, cost of unit energy; OC, operating cost; IC, initial cost.

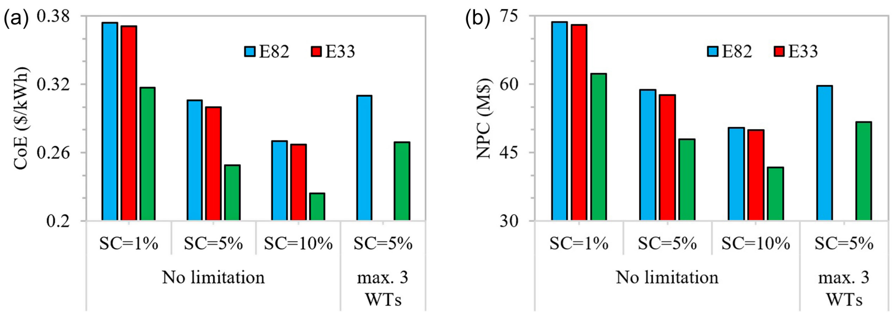

Fig. 6. Comparison of the off-grid designs for a) CoE; b) NPC.

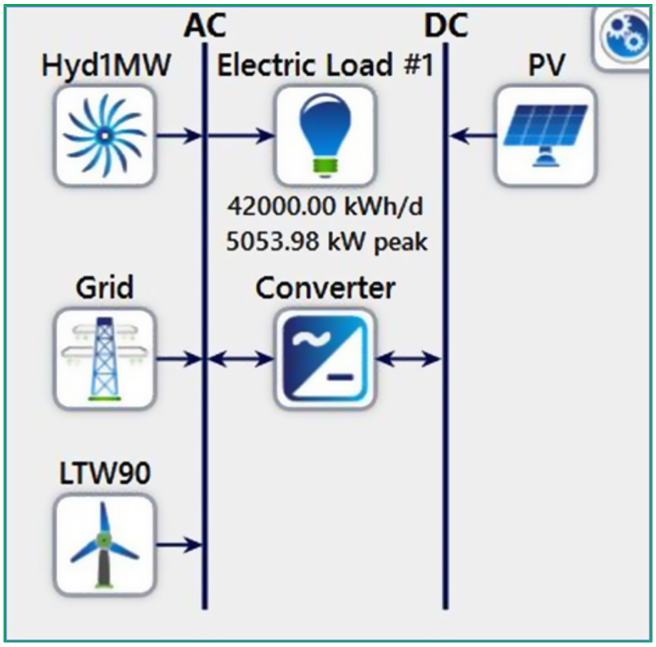

Fig. 7. Grid-connected HRES design.

results, LTW90 is the best option and 10% cheaper than E82. The economical comparison of off-grid designs is shown in Fig. 6.

B. On-grid System Analyses

On-grid system has been designed with PV, WT, and HPP without using any ESS. While designing the on-grid system, HOMER economically prefers grid usage instead of RES. In order to design on-grid with RES and decrease carbon emission level, the grid usage was limited. Since LTW90 was chosen for off-grid, it was also used for on-grid. The on-grid design is shown in Fig. 7.

Grid usage cost of unit energy is defined as 0.1$/kWh and sell-back prices is defined as 0.05$/kWh [25]. Grid usage was separately limited to 4000 kW and 5000 kW for choosing the best option. Sell-back option from renewable energy to grid was defined as 0 kW, 500 kW, 750 kW, and 1000 kW. Since there is no storage system, sellback should be defined for not to waste rest energy generation. Also, for feasible case study, the number of WTs was limited to maximum three. The results of on-grid designs are listed in Table III.

The comparison of on-grid designs is shown in Fig. 8. Although RES usage had no differences, the costs were changed by each sell-back capacity. In case the grid usage is limited to 5000 kW, it is seen that PV and converter are not used.

TABLE III.
ON-GRID ANALYSES RESULTS

GU (kW)	SBC (kW)	PV (kW)	N_{WT}	HPP (kW)	Converter (kW)	NPC (M$)	CoE ($/kWh)	OC (M$/Year)	IC (M$)	GER (%)	CE (kg/Year)
4000	0	1625	7	212	584	31.6	0.16	1.15	16.7	74.1	2 508 538
	500	1615	7	212	723	30.2	0.132	1.03	16.8	77.9	2 471 529
	750	1615	7	212	723	29.5	0.122	0.977	16.8	79.2	2 471 529
	1000	1615	7	212	723	28.8	0.113	0.927	16.8	80.2	2 471 529
5000	0	-	2	212	-	22.8	0.115	1.33	5.60	47.4	5 097 380
	500	-	2	212	-	22.2	0.106	1.29	5.60	50.3	5 097 380
	750	-	2	212	-	22.0	0.103	1.27	5.60	51.2	5 097 380
	1000	-	3	212	-	21.9	0.0953	1.12	7.40	61.9	4 277 795

(*Continued*)

TABLE III.
ON-GRID ANALYSES RESULTS (*CONTINUED*)

GU (kW)	SBC (kW)	PV (kW)	N_{WT}	HPP (kW)	Converter (kW)	NPC (M$)	CoE ($/kWh)	OC (M$/Year)	IC (M$)	GER (%)	CE (kg/Year)
4000*	0	17932	3	212	2274	44.2	0.223	1.31	27.3	76.8	2 246 013
	500	18804	3	212	1171	43.2	0.195	1.29	26.5	74.7	2 749 088
	750	18084	3	212	1171	42.7	0.184	1.25	26.5	75.7	2 749 088
	1000	17812	3	212	1964	41.4	0.167	1.12	26.9	80.9	2 312 578

*For the case of maximum three LT90 WT limitations.
GU, grid usage; SBC, sell-back capacity; N_{WT}, number of wind turbine; HPP, hydro power plant; NPC, net present cost; CoE, cost of unit energy; OC, operating cost; IC, initial cost; GER, green energy usage rate; CE, carbon emission.

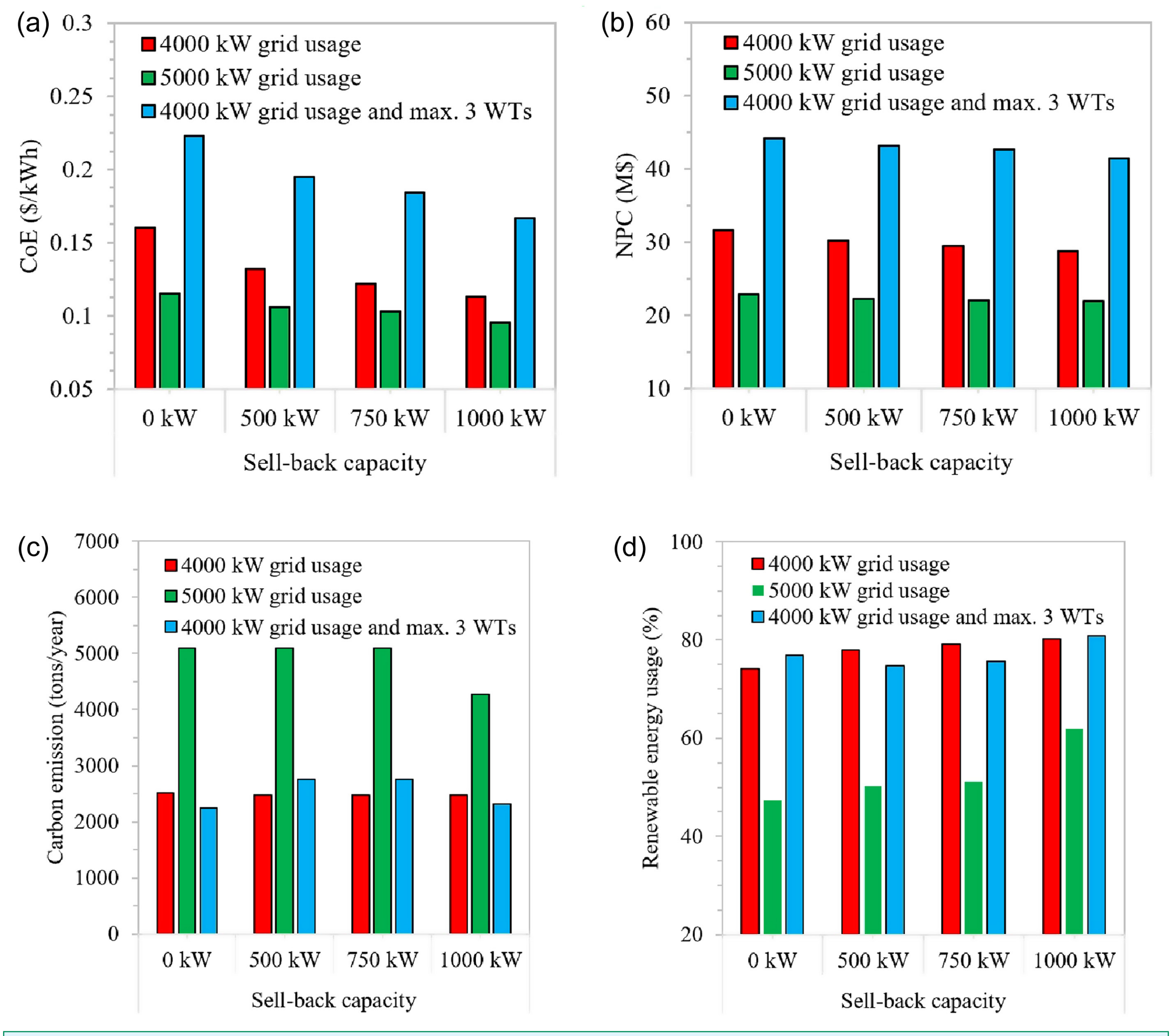

Fig. 8. Comparison of on-grid designs for a) CoE; b) NPC; c) carbon emission; d) renewable energy usage.

Despite the systems with limited grid usage not having cost benefit, they have contributed to the environment by reducing carbon emissions, thanks to the increasing use of RES.

If the grid usage is limited to 4000 kW, the use of renewable energy increases by 25% compared to the case limited to 5000 kW, while carbon emissions decrease by 50%. Considering environmental concerns, limitation of grid usage to 4000 kW is more appropriate than limitation to 5000 kW.

In this case, the best on-grid option is chosen as the system with 4000 kW grid limitation, 3 LTW90 WTs, and 1000 kW sell-back capacity.

C. Sensitivity Analyses

Sensitivity analyses were designed for the off-grid system by increasing renewable energy sources' potential such as wind speed, solar radiation rate, and stream flow speed. In order to catch on-grid system prices, renewable energy potential was increased by 25% and all sensitivity analyses were compared with the base case.

In sensitivity analyses, off-grid systems were designed by three LT90 WTs of 4500 kW and only BESS. The sensitivity analyses results are listed in Table IV and the cost comparisons of all sensitivity analyses are shown in Fig. 9.

While the 25% increase in all renewable energy potential has a positive economic effect, the best result has been obtained for increasing the wind speed.

V. DISCUSSION

The results of on-grid and off-grid system analyses are given in Table V. In the systems limited to three WTs for feasible design, it is seen that the costs of the off-grid system are on average 5 times the on-grid system.

In this study, hybrid energy systems including renewable energy sources and energy storage systems were designed for both on-grid and off-grid by using HOMER. The systems were optimized with economic and environmental concern to be feasible.

TABLE IV.
THE RESULTS OF THE SENSITIVITY ANALYSES

Sensitivty	PV (kW)	WT (kW)	HPP (kW)	Li-ion (100 kWh)	Converter (kW)	NPC (M$)	CoE ($/kWh)	OC (M$/Year)	IC (M$)
Base case	11 131	4500	212	266	3621	51.7	0.269	14 611	33.6
Solar radiation	7284	4500	212	241	3795	45.2	0.235	1.27	28.8
Stream flow	10 347	4500	212	265	3495	50.5	0.263	1.38	32.7
Wind speed	6067	4500	212	210	4771	42.3	0.220	1.18	27.0

PV, photovoltaic; WT, wind turbine; HPP, hydro power plant; NPC, net present cost; CoE, cost of unit energy; OC, operating cost; IC, initial cost.

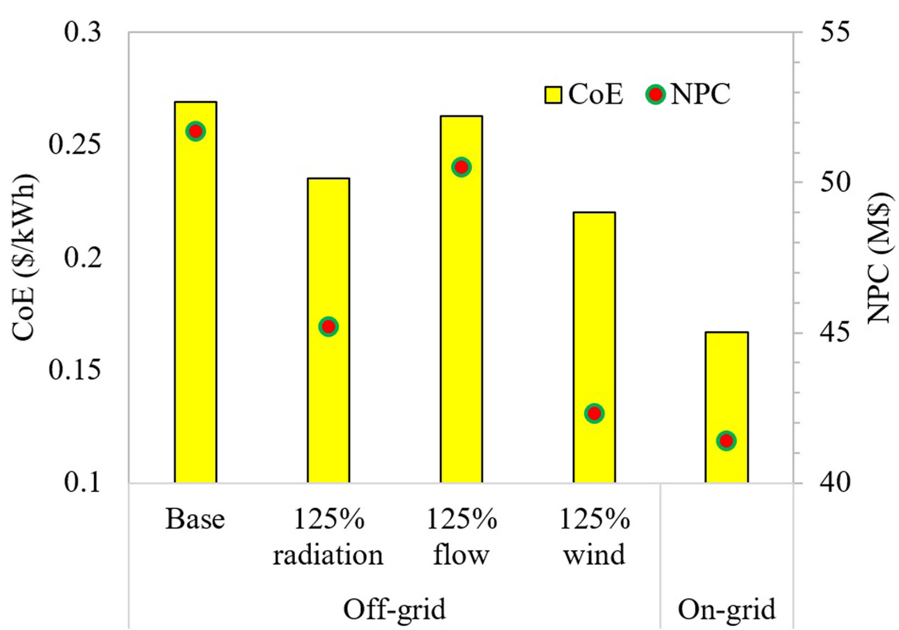

Fig. 9. Comparison of the sensitivity analyses.

TABLE V.
RESULTS OF OFF-GRID AND ON-GRID SYSTEM ANALYSES

Grid Type	NPC (M$)	CoE ($/kWh)	OC (M$/Year)	IC (M$)
Off-grid with 3 WT limitation	41.4	0.167	1.12	26.9
On-grid with 3 WT limitation	51.7	0.269	1.40	33.6

NPC, net present cost; CoE, cost of unit energy; OC, operating cost; IC, initial cost.

According to the results, while on-grid designs are more economical solutions, off-grid systems are the more environmentally friendly solution. Sensitivity analyses show that increasing the renewable energy potential increases both economic and environmental contribution. Although increasing the potential by 25% cannot keep up with on-grid prices, more affordable costs are expected, thanks to developing renewable energy generation technology.

The operating times of PV, WT and HPP are 4400, 6951 and 6552 hours per year (h/yr), respectively. While the increase in stream flow speed and solar radiation rate don't change the operating times in the sensitivity analyzes, it is observed that only the operating time of WT increased by 583 hours to 7534 h/yr when the wind speed increased.

As a result, the on-grid system limited to three wind turbines with 1000 kW sell-back capacity and 4000 kW grid usage has been proposed because it is feasible, economical, and environmentally friendly.

VI. CONCLUSION

In this study, renewable hybrid energy systems have been designed with renewable energy sources and battery energy storage systems. These systems were designed by HOMER with both economic and environmental concerns.

The off-grid system, which has the optimum solution in terms of feasibility, environmental friendliness, and economy, was designed by PVs with a total capacity of 11 131 kW, 3 LT90 WTs with a total capacity of 4500 kW, HPP with a capacity of 212 kW, 266 Li-ion batteries with a capacity of 100 kWh, and the converter with a capacity of 3621 kW.

While the on-grid systems in this study generally provide much more economical solutions, they require some environmental limitations. For this reason, it is aimed to increase the rate of renewable energy usage by limiting the use of fuel-based grids. In designed optimal on-grid system, grid limitation is 4000 kW and the total capacities of sell-back, PV, WT, hydro, and converter are 1000 kW, 17 812 kW, 4500 kW, 212 kW, and 1964 kW, respectively.

In the sensitivity analysis of the stand-alone system, 25% increase in renewable energy potential has increased both economic and environmental contributions, but it is still not as economical as the grid-connected system.

According to all analyses results, while on-grid systems offer more economical solutions, off-grid systems offer more environmental solutions. It is hoped that systems with higher use of clean energy will be more economical with the further development of renewable energy technologies and the decrease in component prices.

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