



A green university library based on hybrid PV/wind/battery system

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Abstract

This paper presents a techno-economic analysis of hybrid renewable energy systems (HRES) to supply the electrical load requirements of the Central Library of Kırklareli University located in Kavaklı Campus, Kırklareli, Turkey. The standalone and grid connected HRES (Grid/PV/battery, wind/battery and PV/wind/battery etc.) considered in the analysis were comprised of different combinations of PV modules and wind turbines supplemented with battery storage. Meanwhile, wind and solar energy potential in Kırklareli is fairly appropriate for supplying energy requirements of some places with no high electricity load like libraries. In this study, the HOMER software is used as the assessment tool to determine the optimal configuration of HRES taking total net present cost (NPC) and cost of energy (CoE) into consideration. As a result, it is determined that the optimal system configuration of standalone hybrid system with the lowest total NPC consists of 40kW PV array, 10kW Wind turbine, 20kW power converter and 72 batteries and also that total NPC and CoE of the optimal configuration are estimated to be \$228,330, \$0.334/kWh, respectively. Similarly, it is determined that the optimal system configuration of grid connected hybrid system with the lowest total NPC consists of 30kW Wind turbine, 100kW Grid and also that total NPC and CoE of the optimal configuration are estimated to be \$137,979, \$0.185/kWh, respectively. When these configurations are compared considering CoE and total NPC it is clearly shown that Grid connected hybrid systems is more economical than standalone hybrid system. But some environmental effects (CO₂, CO NO_x and carbon tax etc.) are taken into consideration the standalone hybrid system must be preferred.

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Keywords: Library; Solar energy; Wind energy; Hybrid renewable energy systems.

1. Introduction

Recently, efficient utilization of domestic wind and solar energy potential in some places like schools, libraries, universities, etc. has been more popular. Therefore, a remarkable energy saving in these places is fulfilled since the required electricity demand is provided from regional indigenous renewable energy resources instead of the grid. Furthermore, there is a considerable amount of renewable energy potential such as wind and solar energy in the Thrace region of Turkey. So far they have been slightly utilized for generating electricity and they are usually used for the following primitive purposes: heating water and mechanical energy obtained from the kinetic energy inside wind. But, they can be utilized for electricity

generation by using the hybrid renewable energy systems (HRES) technologies that consider renewable energy sources as main power suppliers during electricity generation [1]. HRES are fairly useful method for the following reasons: assessment of the regional renewable energy potential, reduction in energy dependency and also green energy generation. They contain renewable based power suppliers such as wind and solar energy to meet the great variety of electricity demands, small or large demand. Furthermore, they are considered as reasonable solution ways for the power supply problems of remote areas with no grid connection. But, all the renewable energy systems do not always generate sufficient electricity energy to supply the demand depending on climate and weather conditions. Hence, the standalone PV or wind system is completely useful to keep the energy balance of the system for the time periods when there are sufficient amount of solar or wind energy. Therefore, if renewable energy resources are used, usually, a backup energy source and/or an energy storage system is needed. In case the renewable energy is unavailable, the backup energy source supplies energy. Conversely, power supply from Diesel generators is independent of climate and weather and is predictable. Even so, the use of Diesel generators has major drawbacks such as high operation and maintenance costs and air pollution by CO₂ emission [2-7].

In the last couple of decades, HRES technologies and their applications have been heavily investigated. Some of the recent studies handled this issue considering economic and environmental parameters. In the following sentences, a brief literature review is presented to summarize the recent studies in the field of HRES technologies and their applications. In [8] with the purpose of showing the use of a hybrid photovoltaic/wind system with energy storage banks is to reliably deliver power to remote locations [8]. Diaf et al. assessed the potential of solar and wind energy in a group of regions in Corsica Island, France. They realized the techno-economical optimization and sizing of a standalone hybrid photovoltaic/wind system with a battery storage system to determine the optimal size of the proposed system which satisfies the energy requirements of a given load distribution [9]. Similarly, Bhandari *et al.* proposed different hybridization methods for standalone, small-sized power systems which consist of PV/Wind/micro-hydro sources for Kolkhop and Thingan villages in Makawanpur, Nepal [10]. Besides the design-related issues of HRES technologies, another important issue in the use of renewable energy sources is the cost analysis. With this purpose, Celik studied hybrid PV/wind energy generation systems and analyzed the total system cost and the unit cost of the generated electricity as reported by the annual system performance [11-13]. In addition, it was shown in [12] that an optimal combination of the hybrid PV/Wind energy generation system can provide better performance than the considered single renewable energy systems for every battery storage capacity and for the same system cost. Abodwair et al., proposed a standalone hybrid renewable energy system (HRES) design for Al-Faowar village in Libya. They evaluated the most optimal hybrid system combinations for Al-Faowar village was PV/Wind/Diesel/Battery system. Additionally, this study showed promising results that capable to meet the load demand via renewable energy generations with minimal diesel generator running time [7]. Finally, Yang *et al.* proposed an iterative optimization procedure and obtained several different combinations of solar/wind generation capacities from the proposed iterative procedure [2].

In this study, wind and solar energy potentials of the nearest region to Kırklareli University library are presented. Then, in the HOMER software program [14, 15], number or amount of the components in both the standalone and grid connected HRES are assigned in a range to determine the best configuration. After evaluating all the possible configurations depending on the total NPC and CoE, the best configuration for the HRES is determined. Eventually all the results obtained from the calculations in the HOMER software are analyzed economically and environmentally.

2. Load profile

The Central Library of Kırklareli University is located in Kayalı Campus of Kırklareli University, Kırklareli, Turkey. It has an exhibition hall, a reading hall for students, a high-speed Internet access center, and a section for rare books and collections. The load of the central library was identified accurately and it is expected that the HRES designed in this study will meet the maximum load of 9.5 kW and 110 kWh consumed for the artificial lighting systems, the outdoor garden, the main system room, computers, and some auxiliary electronic equipment. As the daily energy consumption of the central library is shown in Figure 1, night-time energy consumption is solely for the lighting of the garden. The HOMER software can synthesize the 8760 hourly electrical loads values for a whole year, use this hourly loads profile and add random variability factors, namely time-step-to-time-step variability and day-to-day variability. For the evaluation purposes, the time-step-to-time-step variability and day-to-day variability values were set to 12% and 8% respectively.

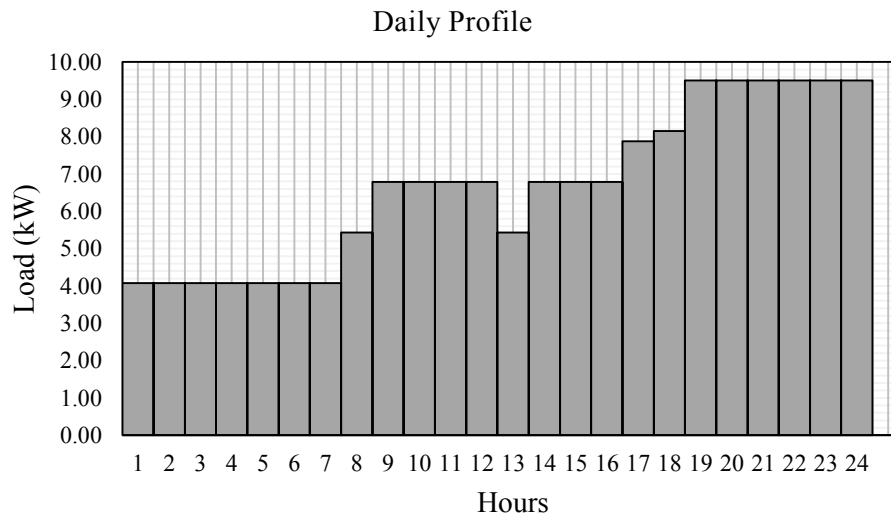


Figure 1. Load demand of the Central Library of Kırklareli University.

3. Wind and solar energy resources

The average monthly solar radiation data in central library of Kırklareli University, Turkey which is located at $41^{\circ} 40' 5''N$ of latitude and $26^{\circ} 34' 32''E$ of longitude was obtained from the Atmospheric science Data Center of NASA [16, 17]. In HOMER Software, the hourly solar radiation data was generated using the monthly solar data by means of the Graham algorithm. An annual average solar radiation value of central library of Kırklareli University is $3.91 \text{ kWh/m}^2/\text{day}$. Figure 2 shows the average monthly solar radiation data and the solar radiation's clearness index values according to the months.

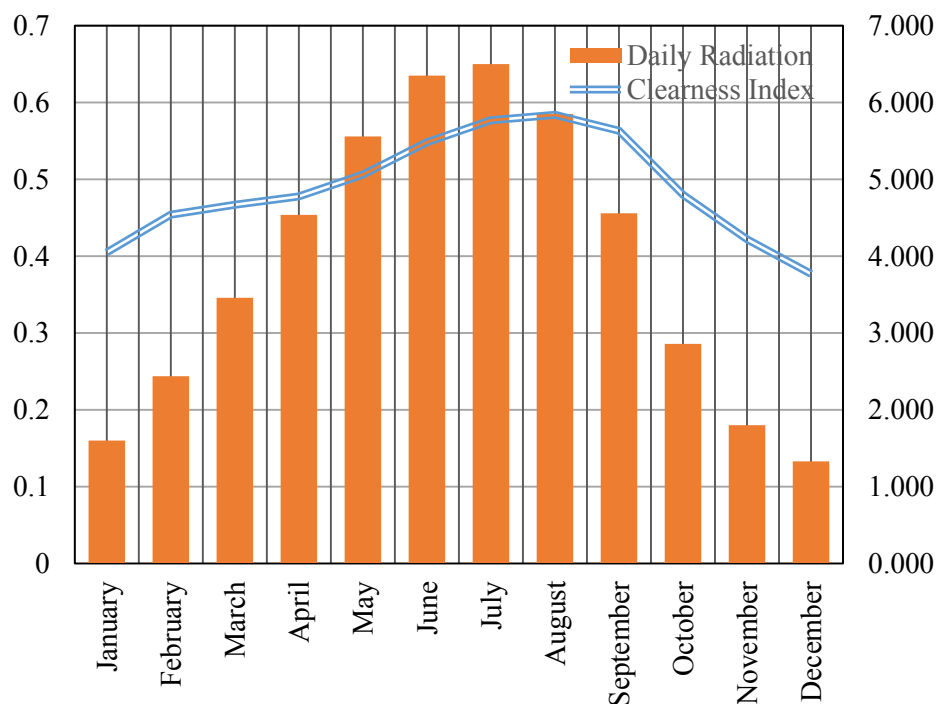


Figure 2. The average monthly solar radiation data and clearness index values of central library of Kırklareli University.

The clearness index gives information about the clearness of the atmosphere and also expresses the amount of the solar radiation that is able to reach to the earth surface. It is a dimensionless number varying between 0 and 1 [15]. The hourly wind speed data of Kırklareli province is measured at the height of 50m and is provided by General Directorate of Renewable Energy [18]. Annual wind speed distribution profile of

Kırklareli province is shown in Figure 3. Considering the wind speed data, it can be emphasized that wind speed distribution ranges between 4.3m/s and 5.5m/s whereas the regional average wind speed is around 5m/s. Furthermore, it can easily be seen that the lowest and the highest wind speed values occur in October and June, respectively. The surface roughness of the site is 0.001 as a result of the calculations depending on the wind speeds at different heights.

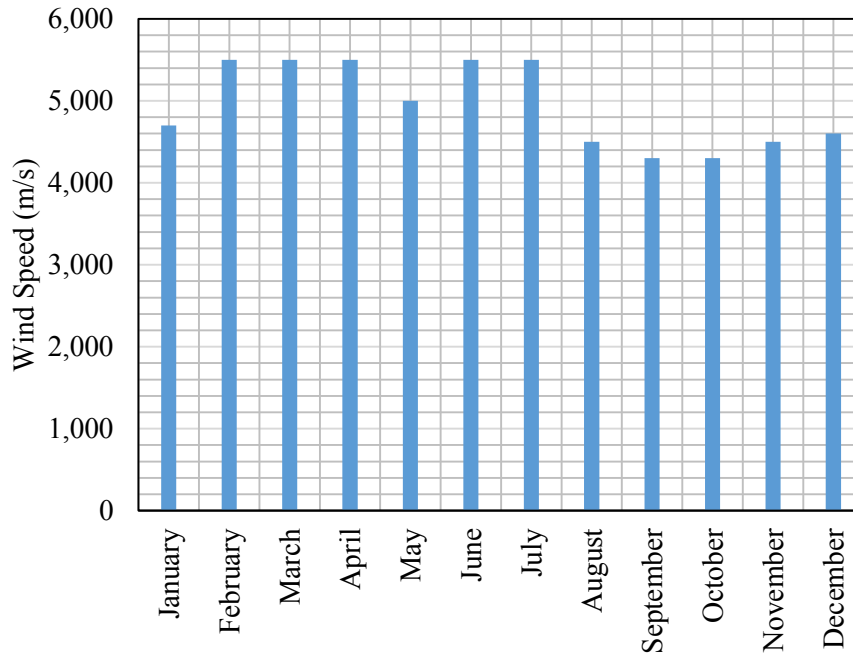


Figure 3. Annually wind speed distribution profile of Kırklareli province.

4. Costs and technical details

4.1 Calculation of the annual real interest rate for Turkey

One of the inputs of the HOMER software is the annual real interest rate. The annual real interest rate is related to the nominal interest rate by Equation (1):

$$i = \frac{i_0 - f}{1 + f} \quad (1)$$

Where, i is the real interest rate, i_0 is the nominal interest rate (the rate at which you could get a loan), and f is the annual inflation rate.

For Turkey, $i_0 = 9.25\%$ (12.02.2018) and $f = 8.5\%$ (annual inflation rate in 2017) are used. With these values, using Equation (2), the real interest rate is found 0.69% [1, 19-21].

$$i = \frac{i_0 - f}{1 + f} = 0.0069 \rightarrow i = 0.69\% \quad (2)$$

In the simulations, the real interest rate was set to 0.69%.

4.2 Levelized cost of energy

The HOMER software defines the levelized CoE as the average cost/kWh of useful electrical energy produced by the system. The CoE can be calculated using Equation (3).

$$CoE = \frac{C_{a,t}}{E_{p,AC} + E_{p,DC} + E_{g,s}} \quad (3)$$

Where, $C_{a,t}$ is total annualized cost [\$/year], $E_{p,AC}$ is AC primary load served [kWh/year], $E_{p,DC}$ is DC primary load served [kWh/year], $E_{g,s}$ is total grid sales [kWh/year]. The total annualized cost is the sum of the annualized costs of each system component, plus the other annualized cost. Since the HOMER software uses it in the calculation of both the levelized CoE and the total NPC, it is an important value [1, 3, 19,20].

4.3 Net present cost (NPC)

The present value of the cost of installing and operating a power system over the lifetime of a project is NPC and is also known as lifecycle cost. The expected lifetime of the project analysed in this study is considered as 20 years. The total NPC is the main economic output of the HOMER software. Based on NPC, all the systems are ranked and with the purpose of finding the NPC all other economic outputs are calculated. Equation (4) can be used to calculate the NPC [1, 19, 20]:

$$C_{NPC} = \frac{C_{a,t}}{CRF(i, R_p)} \quad (4)$$

where, CRF is capital recovery factor, R_p is project lifetime [year]. The CRF is a ratio used in the calculation of the present value of an annuity. The CRF is given by Equation (5).

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (5)$$

where N is number of years.

Information about the cost and the technical detail of the main components of HRES is given below. Additionally, the project lifetime is 20 years. The annual real interest rate was set to 9.25% for Turkey. It should be noted that no cost subsidy is available from the government of Turkey.

5. Components of hybrid renewable systems

5.1 PV Panel

In Turkey, solar energy is one of the most abundant renewable energy sources. Hence, it is selected as one of the basic load suppliers of the proposed system. Each PV module is rated at 1000W, with a nominal voltage of 12V. Model name of the PV modules is generic flat plate with a derating factor of 80% and slope of 21%. Efficiency of PV module is 13% and lifetime of PV module is 20 years. It should be mentioned that the PV array can efficiently generate power during the daytime, from 6 am to 6 pm. Hence, during the night-time, from 6 pm to 6 am, the output power of the solar energy system is almost 0W. To balance this gap, during the night-time, energy will be supplied by either or a combination of the wind turbines, the generators, or the battery. The costs of the capital, replacement, and operating and maintenance of the PV panel are \$3000, \$2250 and \$10/year, respectively [22]. In the HOMER software, PV panel powers change with increment of 20kW from 0kW to 80kW and the most feasible configuration of the hybrid power system is determined by the economy analysis.

5.2 Wind turbine

In Turkey, wind energy is another abundant renewable energy source. Hence, it is also selected as one of the basic load suppliers of the proposed system. Basically, wind turbines convert wind energy into usable forms of energy. The model name of the wind turbine is BWC XLS [23]. Rated power of the wind turbine is about 10kW and its hub height is 50m. Its lifetime is 20 years. The costs of the capital, replacement, and an annual operating and maintenance of the wind turbine are \$29000, \$25000 and \$400, respectively. In the HOMER software, the number of the wind turbines ranges from 0 to 4 and the most feasible configuration of the hybrid power system is determined by the economy analysis.

5.3 Power converter

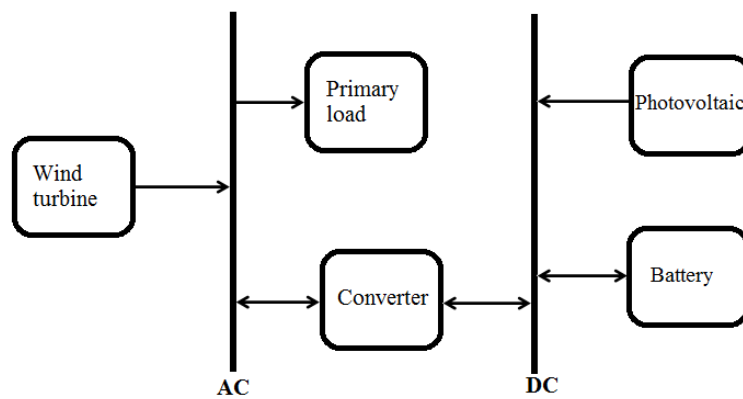
Output power of the power converter is 20 kW. It will entirely supply both the PV power and the excess power of the wind turbine that will remain after the load demand is met. Moreover, the power converter has a conversion efficiency of 90%. Hence, the supplied power will be less than 20 kW. The initial and replacement cost of the inverter are \$800 and \$600, respectively. In addition, operating and maintenance cost and lifetime are about \$5/year and 15 years [24].

5.4 Battery bank

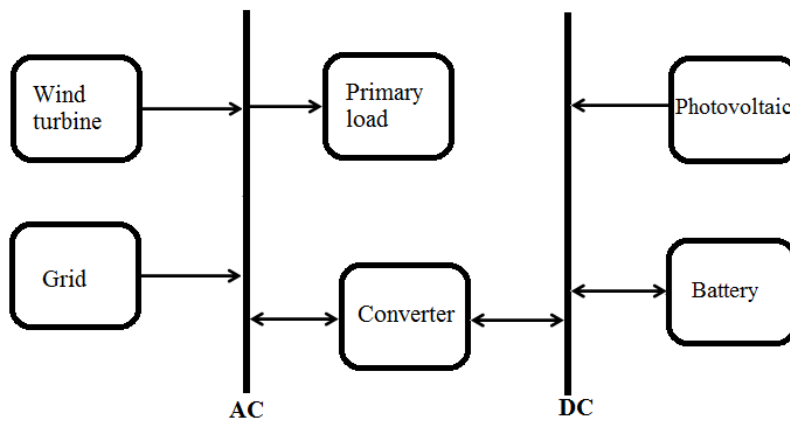
In the HOMER software, the number of batteries varies between 12 and 144 (12 battery banks) with an increment of 12 batteries. The model name of the battery used in the proposed system is Surrrette 6CS25P with a nominal capacity of 1156Ah and nominal voltage of 6V. A single battery can store 6.94kWh of energy. The battery bank is configured to be a total of 6 strings and there are two batteries in each string. Consequently, with a bus nominal voltage of 12 V, the battery bank includes 12 units of battery. As given in the datasheet provided by the HOMER software, the round trip efficiency of the battery is 80% and the minimum state of charge of the battery is 40%. The capital, replacement and operating and maintenance costs of the battery are considered to be \$400, \$300 and \$0.25/hour, respectively [25].

6. HRES modelling and operating characteristics

HRES provides the best conditions for the system operating characteristics by combining two or more renewable power generating technologies. They also offer the advantage of dealing with the diurnal and seasonal characteristics of the available renewable energy sources. The standalone and grid connected PV/wind/battery HRES designed by means of the HOMER software is demonstrated in Figure 4.



(a) Standalone PV/wind/battery HRES.



(b) Grid connected PV/wind/battery HRES.

Figure 4. The configuration of the proposed standalone and grid connected hybrid PV/wind/battery HRES.

The HOMER software takes the following inputs into consideration for the techno-economic analysis: the loads, costs and technical details of components, renewable energy resources availability. Moreover it simply makes simulation of the operating system providing that energy balance is kept during all the time steps. For each step, the energy flows in the system components are calculated by comparing the electric load demand to the generated energy. Added to them, a decision on how to operate the power generators and whether to charge or discharge the batteries is made in each step. Then, the most feasible system configuration and whether the electric load demand could be supplied under the available conditions are

determined. Furthermore, it calculates the different type of costs including capital, replacement, operation and maintenance costs to determine the total cost of the considered HRES [15].

The operation principles of the HRES are mentioned below in details.

- ❖ PV array and wind turbine are the main load suppliers. After supplying the load demand, if there is remaining excess power, they are going to charge the batteries.
- ❖ As output power of PV arrays is in DC mode, by using a power converter, it must be converted to the AC power in order to utilize it to meet the AC load demand.
- ❖ If the PV module and wind turbines cannot meet the existing demand, the battery bank will be discharged to supply the demand. As a result, in this case, the battery bank will not be charged.
- ❖ If the PV module and wind turbines cannot meet the existing demand and the battery bank is empty the existing demand will meet from the Grid.
- ❖ The operating reserve of hourly load is 10% and the operating reserves of renewable output are 40% for wind output power and 25% for solar output power. Note that the operating reserve can be described as safety margin which enables the reliable power supply in spite of the variances in the solar power supply, wind power supply and electricity load.

7. Results and discussions

The aim of the optimization process is to assess and determine the optimal value of a set of decision variables including the capacity of wind turbines, PV arrays and power converters as well as battery numbers. Thanks to the HOMER software, in the optimization process, several different system configurations can be simulated, the infeasible configurations can be discarded, the feasible configurations can be ranked based on the total NPC, and finally the most feasible one with the lowest total NPC and CoE as the optimal system configuration can be viewed.

7.1 Standalone HRES

In this study, three different standalone HRES (PV/battery, wind/battery and PV/wind/battery) are considered and analyzed using the HOMER software to determine the optimal hybrid power systems for the Central Library of Kırklareli University. The best configurations obtained for these hybrid power systems are given in Table 1 in detail.

Table 1. Some optimal system configurations obtained (by the HOMER software) for the different values of the sensitivity variables.

Solar (kWh/m ² /d)	Wind (m/s)	PV (kW)	WT	Battery	Converter (kW)	Initial capital	Operating cost (\$/yr)	Total NPC	COE (\$/kWh)	Renewable fraction
3.910	4.000	40	1	72	20	\$ 193,800	1,856	\$ 228,330	0.334	1.00
3.910	3.000	60		72	20	\$ 224,800	1,656	\$ 255,609	0.374	1.00
3.910	5.000	20	2	48	20	\$ 153,200	1,806	\$ 186,804	0.273	1.00
3.910	6.000	20	1	72	20	\$ 133,800	1,656	\$ 164,609	0.240	1.00
3.910	7.000		2	72	20	\$ 102,800	1,856	\$ 137,330	0.197	1.00
3.500	4.000	40	2	48	20	\$ 213,200	2,006	\$ 250,525	0.367	1.00
3.500	3.000	60		96	20	\$ 234,400	1,906	\$ 269,855	0.397	1.00
3.500	5.000	20	2	72	20	\$ 162,800	2,056	\$ 201,050	0.292	1.00
3.500	6.000		3	72	20	\$ 131,800	2,256	\$ 173,771	0.251	1.00
3.500	7.000		2	72	20	\$ 102,800	1,856	\$ 137,330	0.197	1.00
4.500	4.000	40	1	48	20	\$ 184,200	1,606	\$ 214,084	0.314	1.00
4.500	3.000	40		120	20	\$ 184,000	1,956	\$ 220,381	0.325	1.00
4.500	5.000	20	2	48	20	\$ 153,200	1,806	\$ 186,804	0.269	1.00
4.500	6.000	20	1	48	20	\$ 124,200	1,406	\$ 150,363	0.219	1.00
4.500	7.000		2	72	20	\$ 102,800	1,856	\$ 137,330	0.197	1.00
5.500	4.000	40		72	20	\$ 164,800	1,456	\$ 191,889	0.279	1.00
5.500	3.000	40		72	20	\$ 164,800	1,456	\$ 191,889	0.279	1.00
5.500	5.000	20	1	72	20	\$ 133,800	1,656	\$ 164,609	0.242	1.00
5.500	6.000	20	1	48	20	\$ 124,200	1,406	\$ 150,363	0.215	1.00
5.500	7.000	20	1	24	20	\$ 114,600	1,157	\$ 136,117	0.198	1.00
6.500	4.000	40		48	20	\$ 155,200	1,206	\$ 177,643	0.263	1.00
6.500	3.000	40		48	20	\$ 155,200	1,206	\$ 177,643	0.263	1.00
6.500	5.000	20	1	48	20	\$ 124,200	1,406	\$ 150,363	0.222	1.00
6.500	6.000	20	1	48	20	\$ 124,200	1,406	\$ 150,363	0.213	1.00
6.500	7.000	20	1	24	20	\$ 114,600	1,157	\$ 136,117	0.196	1.00

In the current case where average solar irradiance and average wind speed are almost 3.91 kWh/m²/d and 4m/s, respectively;

The optimal system configuration with the lowest total NPC consists of 20kW Wind turbine, 20kW power converter 20kW PV array and 48 batteries. It is easily noticed from Figure 5 that total NPC of the optimal HRES configuration is anticipated to be \$186,804 and CoE is about \$0.271/kWh. Besides, the share of the wind turbine in the total cost is the highest with 39% followed by PV panel with 34%, battery with 15%, and power converter with 11%.

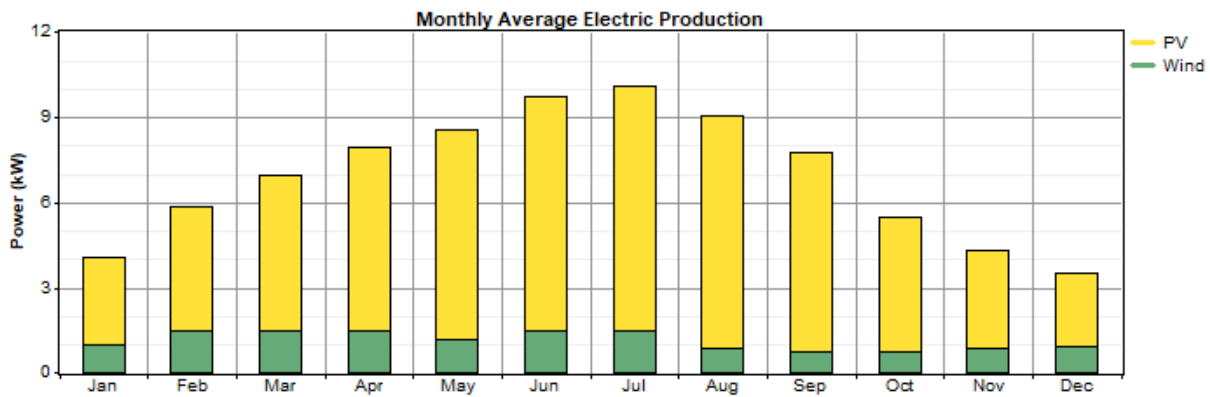


Figure 5. Monthly average electricity production by sources.

The total annual electricity production is about 60,788kWh consisting of 84% of PV array and 16% of wind turbines. Figure 5 shows the monthly average electricity production from different system components in the optimal HRES. In addition, the capacity shortage of the optimal system is only 0.07% and the excess electricity is 8,909 kWh/year (10.1%). Generally, the excess electricity produced by hybrid power systems always exists and it can be used for different purposes including improving the system reliability [25, 26]. Furthermore, renewable fraction in the hybrid power system with optimal configuration is 100. Therefore, electricity generated through this hybrid system is completely clear and no harmful emission gases in this hybrid system are generated and there is no contribution of the HRES to the pollution of environment.

7.2 Grid connected HRES

In this study, three different grid connected HRES (Grid/PV/battery, Grid/Wind/PV, Grid/Wind and Grid/PV) are considered and analyzed using the HOMER software to determine the optimal hybrid power systems for the Central Library of Kırklareli University. The best configurations obtained for these hybrid power systems are given in Table 2 in detail.

In the current case where average solar irradiance and average wind speed are almost 3.91 kWh/m²/d and 4m/s, respectively;

The optimal system configuration with the lowest total NPC consists of 30kW Wind turbine, and 100kW Grid. It is easily noticed from Figure 6 that total NPC of the optimal HRES configuration is anticipated to be \$137,979 and CoE is about \$0.185/kWh. Besides, the share of the wind turbine in the total cost is the highest with 56% and grid purchased 44%. Renewable fraction is 56%.

The total annual electricity production is about 53,404kWh consisting of 56% of Wind turbine and 44% of purchased from grid. Figure 7 shows the monthly average electricity production from different system components in the optimal grid connected HRES. In addition, the capacity shortage of the optimal system and the excess electricity are about zero. Moreover, renewable fraction in the grid connected HRES with optimal configuration is 56%. Electricity generated from this hybrid system has caused some greenhouse emissions (CO₂, CO, NO_x etc.) Moreover, it causes the pollution of environment.

8. Sensitivity analysis of HRES

Sensitivity analysis aids in assessing the effects of changes or uncertainty in the variables over which a designer has no control such as average solar irradiance and average wind speed. A sensitivity analysis basically reveals how sensitive the outputs are to change in the inputs. In this study, while doing the sensitivity analysis for the HRES, two different sensitivity variables such as average solar global irradiance

and average wind speed are taken into consideration. In the sensitivity analysis, the sensitivity variables are considered to be in a proper range which can cover the probable changes in the model inputs in future:

- ❖ Average wind speed values vary between 3m/s and 7m/s, that is, five different values are specified.
- ❖ Average solar global irradiance values vary in the range of 3.5–6.5 kWh/m²/d, with an increment of 1 kWh/m²/d, that is, five different average solar global irradiance values are specified.
- ❖ The total number of sensitivity cases is 25, which is calculated by multiplying of wind speed (5) and solar global irradiance (5) multipliers.

Table 2. Optimal system configurations obtained (by the HOMER software) for the different values of the sensitivity variables.

Solar (kWh/m ² /d)	Wind (m/s)	PV (kW)	WT	Battery	Converter (kW)	Grid (kW)	Initial capital	Operating cost (\$/yr)	Total NPC	COE (\$/kWh)	Renewable fraction
3.910	4.000		3			100	\$ 87,000	2,74	\$ 137,979	0.185	0.56
3.910	3.000	20		24	20	100	\$ 85,600	3,763	\$ 155,606	0.208	0.52
3.910	5.000		2			100	\$ 58,000	1,882	\$ 93,004	0.125	0.63
3.910	6.000		2			100	\$ 58,000	696	\$ 70,947	0.095	0.76
3.910	7.000		2			100	\$ 58,000	-125	\$ 55,668	0.075	0.84
3.500	4.000		3			100	\$ 87,000	2,74	\$ 137,979	0.185	0.56
3.500	3.000	20	1		20	100	\$ 105,000	3,02	\$ 161,174	0.216	0.52
3.500	5.000		2			100	\$ 58,000	1,882	\$ 93,004	0.125	0.63
3.500	6.000		2			100	\$ 58,000	696	\$ 70,947	0.095	0.76
3.500	7.000		2			100	\$ 58,000	-125	\$ 55,668	0.075	0.84
4.500	4.000	20			20	100	\$ 76,000	2,407	\$ 120,784	0.162	0.53
4.500	3.000	20			20	100	\$ 76,000	2,407	\$ 120,784	0.162	0.53
4.500	5.000		2			100	\$ 58,000	1,882	\$ 93,004	0.125	0.63
4.500	6.000		2			100	\$ 58,000	696	\$ 70,947	0.095	0.76
4.500	7.000		2			100	\$ 58,000	-125	\$ 55,668	0.075	0.84
5.500	4.000	20			20	100	\$ 76,000	2,115	\$ 115,352	0.154	0.56
5.500	3.000	20			20	100	\$ 76,000	2,115	\$ 115,352	0.154	0.56
5.500	5.000		2			100	\$ 58,000	1,882	\$ 93,004	0.125	0.63
5.500	6.000		2			100	\$ 58,000	696	\$ 70,947	0.095	0.76
5.500	7.000		2			100	\$ 58,000	-125	\$ 55,668	0.075	0.84
6.500	4.000	20			20	100	\$ 76,000	1,987	\$ 112,955	0.151	0.57
6.500	3.000	20			20	100	\$ 76,000	1,987	\$ 112,955	0.151	0.57
6.500	5.000		2			100	\$ 58,000	1,882	\$ 93,004	0.125	0.63
6.500	6.000		2			100	\$ 58,000	696	\$ 70,947	0.095	0.76
6.500	7.000		2			100	\$ 58,000	-125	\$ 55,668	0.075	0.84

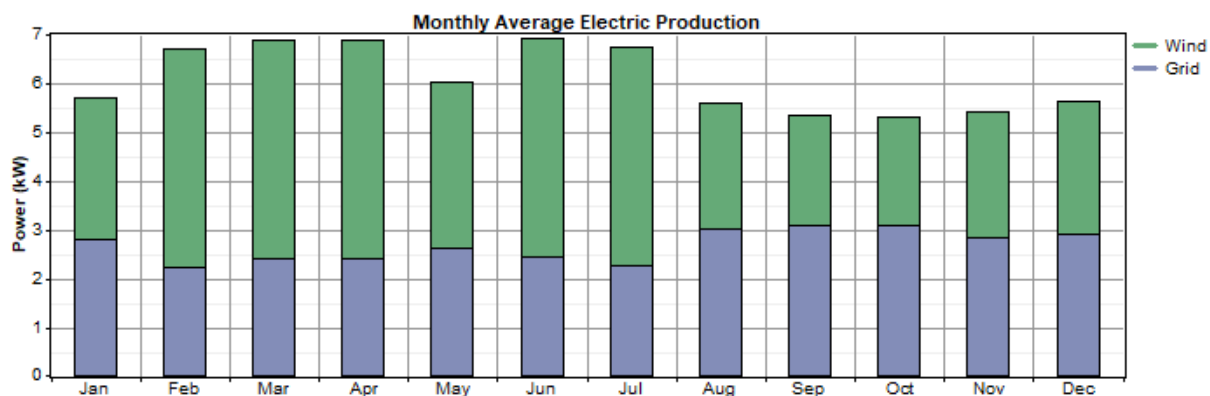


Figure 6. The monthly average electricity production in the optimal grid connected HRES.

8.1 Sensitivity analysis of standalone HRES

- It is easily understood from Figure 7 that increasing the evaluation range of wind speed and solar radiation value for the sensitivity analysis (they do not only contain the current value of these two sensitivity variables), the Wind/PV/Battery renewable hybrid system among all the systems are more efficiently applicable because it occupies the bigger blue area in this figure. It is followed by PV/Battery hybrid system marked with yellow and also the Wind/Battery hybrid system marked with green. Rest of them is Wind/PV/Battery hybrid system marked with blue.

- Analyzing Figure 7 more detail, while both the solar radiation value is upper than 3.5kWh/m²/day and also the wind speed is lower than 4.1m/s, the optimum hybrid system is PV/Battery renewable hybrid system but under and it is shown in this figure as a yellow area. Table 3 shows the mathematical modeling of the sensitivity analysis in standalone HRES.
- Under the conditions that are described like the followings: Both wind speed are between 5.7m/s and 7m/s and also solar radiation value is below the value of 5.4kWh/m²/day, the region is completely green, that is, the Wind/Battery hybrid system is the most suitable power supplying system.

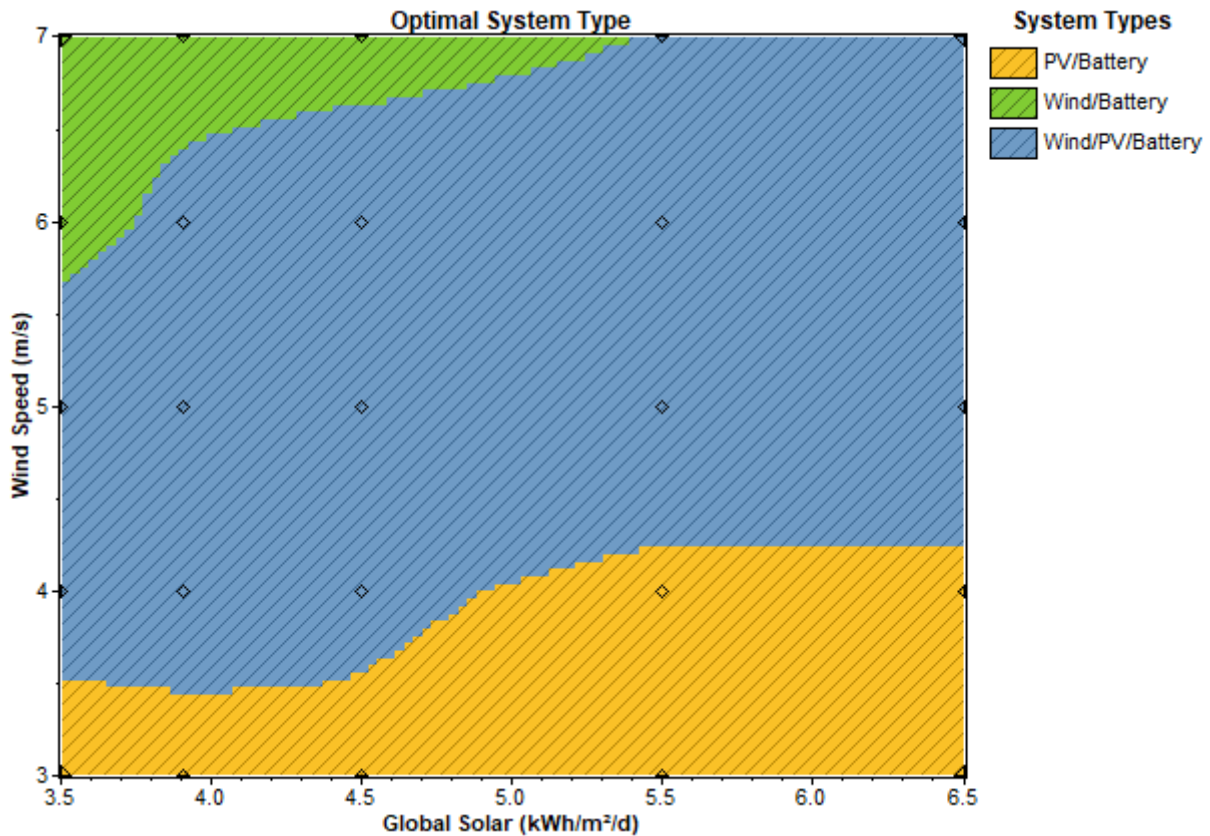


Figure 7. Situation of the standalone HRES for all possible wind speed and solar irradiation values.

Table 3. Mathematical modeling of the sensitivity analysis in standalone HRES.

Wind speed (m/s)	Solar Radiation	Equation	Color of the area	Type of HRES
$3 \leq w_s \leq 3.5$	$3 \leq s_r \leq 4.5$	$y = 0.6x - 13.5$		
$3 \leq w_s \leq 4.1$	$4.5 \leq s_r \leq 5.5$	$y = 0.6x + 0.9$	Yellow	Standalone PV/Battery
$3 \leq w_s \leq 4.2$	$5.5 \leq s_r \leq 6.5$	$y = 0.6x - 0.9$		
$6.4 \leq w_s \leq 7$	$3.9 \leq s_r \leq 5.4$	$y = 0.41x + 4.78$		
$6.4 \leq w_s \leq 7$	$3.5 \leq s_r \leq 3.9$	$y = 1.5x + 1.15$	Green	Standalone Wind/Battery
$5.7 \leq w_s \leq 6.4$	$3.5 \leq s_r \leq 3.9$	$y = 1.75x - 0.425$		
$5.7 \leq w_s \leq 7$	$3.5 \leq s_r \leq 5.4$	$y = 1.46x - 4.83$		
$5.7 \leq w_s \leq 7$	$5.4 \leq s_r \leq 6.5$	$y = 1.44x - 2.10$		
$4.2 \leq w_s \leq 5.7$	$3.5 \leq s_r \leq 6.5$	$y = 0.5x + 2.45$	Blue	Standalone Wind/PV/battery
$3.5 \leq w_s \leq 4.2$	$3.5 \leq s_r \leq 4.5$	$y = 0.7x + 1.45$		
$3.5 \leq w_s \leq 4.2$	$4.5 \leq s_r \leq 5.4$	$y = 0.78x$		

In all the line equations in the analysis results of the figure indicating all the probable renewable hybrid systems according to the wind speed and solar irradiation values, the variables y and x represent wind speed and solar irradiation, respectively.

8.2 Sensitivity analysis of Grid connected HRES

It is easily understood from Figure 8 that increasing the evaluation range of wind speed and solar radiation value for the sensitivity analysis, the Grid/Wind HRES among all the systems are more efficiently applicable because it occupies the bigger green area in Figure 8. It is followed by Grid/PV/ HRES marked with yellow and also the Grid/Wind/PV hybrid system marked with blue. Lastly, it is followed by Grid/PV/Battery hybrid system at the least area marked with yellow line in Figure 8.

- Both wind speed are between 3m/s and 4m/s and also solar radiation value is below the value of 3.94kWh/m²/day, the region is completely blue, that is, the Grid/Wind/PV hybrid system is the most suitable power supplying system.
- Both wind speed value varies from 3m/s to 4 m/s and also solar radiation value varies from 3.5kWh/m²/day to 3.9 kWh/m²/day, the most feasible hybrid system is Grid/Wind/PV hybrid systems. Similarly, when the solar radiation value is above the value of 4. 5kWh/m²/day and the wind speed value varies from 4m/s to 4.5m/s the most feasible system is Grid/PV hybrid system. The region is marked with yellow in the Figure 9.
- For wind speed values that are greater than 4.5m/s, and the solar irradiation value varies above 4.5kWh/m²/day, the optimum system configuration is Grid/Wind hybrid system which is marked with green. Moreover, the solar irradiation values varying between 4.1 kWh/m²/day and 4.5 kWh/m²/day, and wind speed value varying from 4m/s to 4.5 m/s the most appropriate system configuration is Grid/PV hybrid system.
- When both the solar irradiation values varying between 3.5 kWh/m²/day and 4.2 kWh/m²/day, and wind speed value varying from 3.6m/s to 4.4 m/s the most appropriate system configuration is Grid/Wind/PV hybrid system. Its region is marked with blue in the Figure 9.
- The most appropriate system configuration is Grid/PV/Battery hybrid system for the rest of area marked with yellow line in the Figure 9. The installation of the Grid/PV/Battery hybrid system can be realized conveniently.

In all the line equations in the analysis results of the figure indicating all the probable Grid/Wind/PV/Battery hybrid systems according to the wind speed and solar irradiation values, the variables y and x represent wind speed and solar irradiation, respectively. Mathematical modeling of the sensitivity analysis in grid connected HRES is demonstrated in Table 4. Specific wind speed and solar radiation values are given in Table 4. It is obtained some linear equations for corresponding to these values to determine the optimal hybrid system configuration among the four different hybrid systems (Grid/Wind, Grid/PV, Grid/ Wind/PV, Grid/PV/Battery).

Table 4. Mathematical modeling of the sensitivity analysis in standalone HRES.

Wind speed (m/s)	Solar Radiation	Equation	Colour of the area	Type of HRES
$4.4 \leq w_s \leq 7$	$3.5 \leq s_r \leq 6.5$	$y = 0.86x + 1,36$		
$4 \leq w_s \leq 4.4$	$3.5 \leq s_r \leq 4.3$	$y = 0.5x + 2.57$	Green	Grid/Wind
$4 \leq w_s \leq 4.4$	$4.3 \leq s_r \leq 4.5$	$y = 2x - 4.6$		
$4 \leq w_s \leq 4.4$	$4.3 \leq s_r \leq 4.5$	$y = 2x - 4.6$		
$4 \leq w_s \leq 4.4$	$4.5 \leq s_r \leq 6.5$	$y = 0.2x + 3.1$	Yellow	Grid/PV
$3 \leq w_s \leq 4$	$4.1 \leq s_r \leq 6.5$	$y = 0.42x + 1.29$		
$3 \leq w_s \leq 4$	$4 \leq s_r \leq 4.1$	$y = 10x - 37$		
$3 \leq w_s \leq 3.2$	$3.5 \leq s_r \leq 3.9$	$y = 0.5x + 1.25$		
$3.2 \leq w_s \leq 4$	$4 \leq s_r \leq 4.1$	$y = 8x - 27.8$		
$3.2 \leq w_s \leq 4$	$4 \leq s_r \leq 4.5$	$y = 1.6x - 3.2$	Blue	Grid/ Wind/PV
$3 \leq w_s \leq 3.2$	$3.9 \leq s_r \leq 4$	$y = 2x - 4.8$		
$3 \leq w_s \leq 3.2$	$3.9 \leq s_r \leq 4$	$y = 2x - 4.8$	Yellow line	Grid/PV/Battery

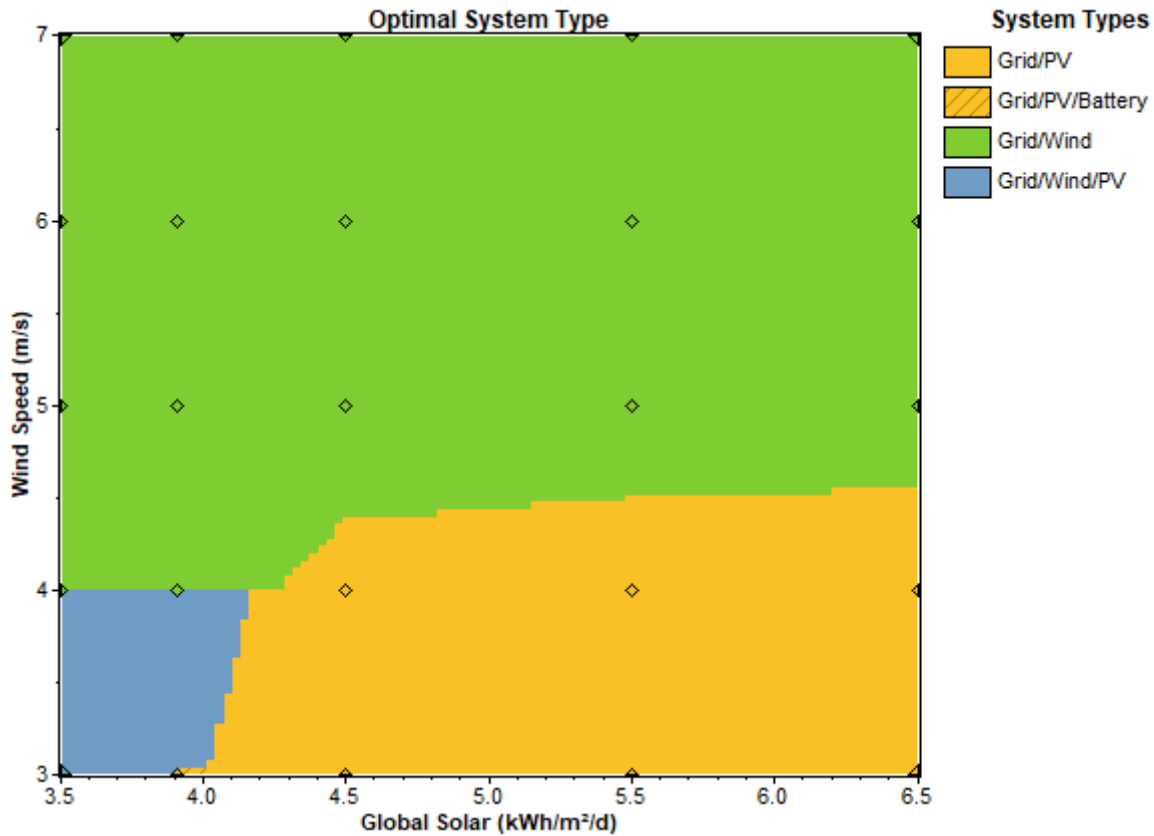


Figure 8. Situation of the grid connected HRES for all possible wind speed and solar irradiation values.

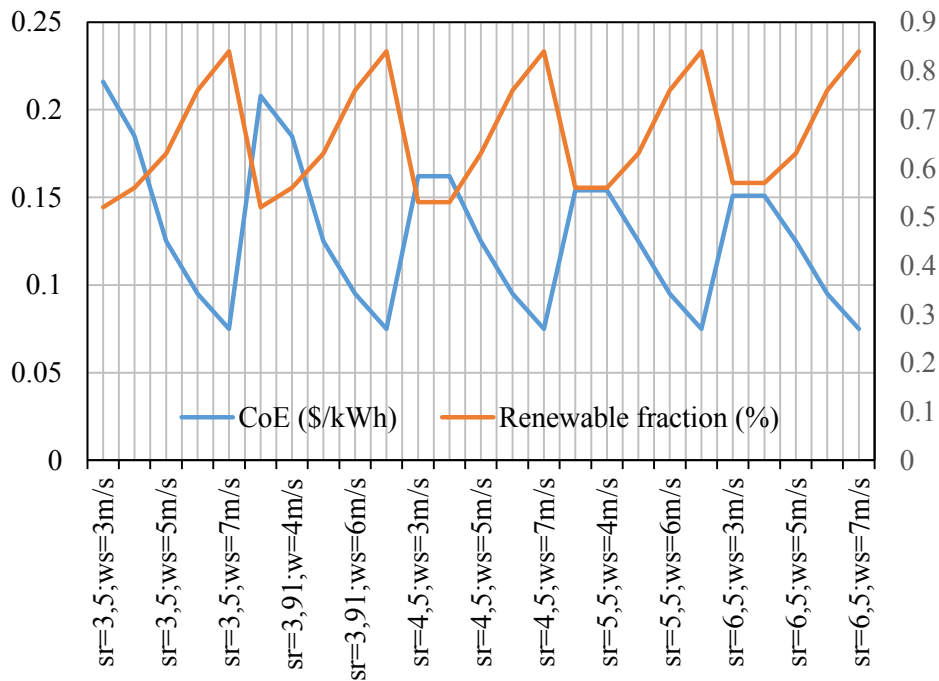


Figure 9. Relation between CoE and Renewable Fraction for all sensitivity variables.

Relation between CoE and Renewable Fraction for all sensitivity variables are demonstrated in Fig. 9. In case of 3.91kWh/m²/day of solar radiation value and of 4m/s of wind speed, the CoE and renewable fraction values of the optimal configuration of standalone Wind/PV/Battery are 0.185 and 56%, respectively. Similarly, in the case of 7m/s of wind speed and all the solar radiation (sr=3.5, 3.91, 4.5, 5.5 and 6.5kWh/m²/d) values, when the lowest CoE is 0.075\$/kWh the highest renewable fraction value is 84%.

9. Conclusions

All possible standalone and grid connected HRES that can be applied in the Central Library of Kırklareli University are investigated in this study.

Considering the results obtained in the simulations performed using the HOMER software, for standalone PV/Wind/Battery hybrid systems the following important outputs can be highlighted.

- Renewable fraction in the hybrid power system with optimal configuration is 100. Therefore, electricity generated through this hybrid system is completely clear and no harmful emission gases in this hybrid system are generated and there is no contribution of the hybrid system to the pollution of environment.
- The optimal system configuration with the lowest total NPC contains 10kW Wind turbine, 20kW power converter, 60kW PV array, and 120 batteries.
- Total NPC of the optimal HRES configuration is estimated to be \$291,499 and COE is about \$0.674/kWh.
- Share of the PV array in the total cost is the highest with 65% followed by batteries with 17%, wind turbine with 12%, and power converter with 5%.
- Total electricity generation of the hybrid power system is 86,009kWh/year; shares of wind turbine and PV array in the total cost are almost 89% and 11%, respectively.

The sensitivity analysis was realized to investigate how the economic parameters of the interested HRES show a change in the case of the strongly probable small or large change in the sensitivity variables in future (solar irradiance value and wind speed). A summary of the results obtained in the sensitivity analysis is given below;

- It can be seen from the results of the sensitivity analysis that the Wind/PV/Battery renewable hybrid power system among all the systems are more efficiently applicable and this hybrid power system is more suitable for the majority of all possible combinations of wind speed and solar irradiance values.
- Figure 7 including the sensitivity analysis results shows the most suitable HRES under the various conditions.

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Abbreviations

$C_{a,t}$	total annualized cost [\$ /year]	f	the annual inflation rate
C_{NPC}	net present cost	HRES	hybrid renewable energy system
CoE	cost of energy	i	the real interest rate,
CRF	capital recovery factor	i_0	the nominal interest rate
$E_{p,AC}$	AC primary load served [kWh/year]	NPC	net present cost [\$]
$E_{p,DC}$	DC primary load served [kWh/year]	R_p	project lifetime [year]
$E_{g,s}$	total grid sales [kWh/year]		

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