Engineering Science and Technology, an International Journal 24 (2021) 397–404

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Full Length Article

Design and optimization of a solely renewable based hybrid energy system for residential electrical load and fuel cell electric vehicle

Sunay Turkdogan

Department of Electrical and Electronics Engineering, Faculty of Engineering, Yalova University, Yalova 77200, Turkey

ARTICLE INFO

Article history:
Received 15 June 2020
Revised 19 August 2020
Accepted 31 August 2020
Available online 26 September 2020

Keywords:
Renewable and sustainable energy
Hybrid energy
Solar photovoltaics
Wind energy
Hydrogen

ABSTRACT

Due to increasing energy demand, limited fossil fuels and increasing greenhouse gasses people is in need for alternative energy sources to have a sustainable world. The objective of this study is to look for alternative solutions and design a hybrid energy system to meet any energy needs of a single family house including both utility and transportation. The system is designed and optimized using HOMER software. According to the optimization studies, levelized cost of electricity and hydrogen production was found to be 0.685$/kWh and 6.85$/kg, respectively and the cost of hydrogen which is half of its market price is very attractive. To project possible future costs in advance, sensitivity analysis was carried out and the results show that when the main components' price decays to the half, both costs of energy will be reduced by 26.4%. This implies that further decrease on the components' cost would bring the cost of energy to the level of energy produced by fossil fuels or even lower. Hydrogen would also be produced with much lower and tempting price. It is important to note that energy used by residential electrical load and fuel cell electric car in this study was generated by sole renewable energies and the system consumes zero fossil fuels, thus emitting no greenhouse gasses. The study considering both utility and transportation simultaneously is believed to be the first on a small scale and to attract the interest of everyone.

1. Introduction

Growing world population and industrialization increase the energy demand and world energy consumption is expected to grow by 50% from 2018 to 2050 [1]. Big portion of this energy demand is met by fossil fuels and therefore causing detrimental effects to the environment. By burning fossil fuels harmful gasses are emitted to the atmosphere and this threatens people health and causes climate change due to the elevated level of greenhouse gasses. Because of the aforementioned reasons it is necessary to meet energy demand utilizing alternative energy resources such as solar, wind, tidal, geothermal and etc. It is known that sun is the primary or secondary source of all renewables with the exception of geothermal energy. Solar energy, among others, is the most promising one as it is capable to capture energy as much as the world's annual need in less than an hour [2,3]. After solar energy, wind energy is the most and last promising one to meet the entire world's energy demand [4]. By hybridizing two energy sources with different storage strategies, we can produce unremitting energy and this way we can eliminate the disadvantageous of intermittent nature of renewable energy resources. In the literature, there are many studies analyzing different energy systems for green and sustainable world [5–12]. Most of the studies in the literature utilize renewable energies to provide energy for only electrical loads. However, feeding electrical loads by renewable energy is not the only solution for sustainable future because around 29% of the greenhouse gasses was released by the vehicles in the world [13,14]. Therefore, besides electrical load we should also provide power for the vehicles from renewable energy sources. In the scope of this paper, hydrogen fuel cell car was used for transportation and the source of hydrogen was obtained from water via a renewable energy powered electrolyzer. It is also important to note that there are several ways of producing hydrogen, but the others involve breakage of fossil fuels and still causing the emission of greenhouse gasses. Those, therefore, might not be the solution for a sustainable and green universe.

According to the study [13,14], 29% of the greenhouse gasses was released from transportation sector while 28% was released from electric sector in the US. If we take a detail look into the transportation sector, it is seen that big portion of this amount (59%) comes from light-duty vehicles and 70.19% of this is due to the passenger vehicles. From 1990 to 2017, the CO_2 emission caused by passenger vehicles was increased by 20.5% and keep increasing with the growing population. In another study [15,16], it is

E-mail address: sunay.turkdogan@yalova.edu.tr

https://doi.org/10.1016/j.jestch.2020.08.017
2215-0986/

Nomenclature

AC	Alternative Current	HOMER	Hybrid Optimization Model for Electric Renewables
AEM	Anion Exchange Membrane	LA	Liquid Alkaline
AnnC	Annualized Cost	NPC	Net Present Cost
CF	Capacity Factor	NREL	National Renewable Energy Laboratory
COE	Cost of Energy	OC	Operating Cost
COH	Cost of Hydrogen	PEM	Polymer Electrolyte Membrane
CRF	Capital Recovery Factor	PV	Photovoltaic
CS	Capacity Shortage	SI	Supporting Information
DC	Direct Current	SOC	State of Charge
DOD	Depth of Discharge	WD	Weekdays
FCEV	Fuel Cell Electric Vehicle	WK	Weekend

revealed that 30% of the EU' s total CO_2 emission comes from the transportation and 60.7% of this is due to the passenger vehicles. Although the CO_2 emission is likely to reduce due to the increasing utilization of renewable energy sources, CO_2 emission in transportation sector keeps increasing. This shows that conventional vehicles should be replaced with more environment friendly types such as hydrogen and electric cars.

As mentioned earlier, greenhouse gasses are produced not only by electric energy generation sector, but also transportation sector. When people do a research, transportation is usually neglected and only electrical energy is considered to be produced by renewable energy sources. For this reason, I thought that it is necessary to conduct such a study and the feasibility of the system was discussed in detail. All the aforesaid facts support the idea of my study and show how critical my research is for a sustainable world. In this study, I build an energy model which analyzes a standalone PV-wind-battery-hydrogen system. This model meets the electrical load demand without connecting to the grid and excess renewable energy power goes to the battery and electrolyzer to store energy for compensation purpose of intermittent renewable energy and to generate hydrogen for storage in the hydrogen tank to be later used to power a fuel cell electric vehicle (FCEV). Besides optimization study, sensitivity analysis of the system was also carried out to see different scenarios with the new advancement in the technology of the constituent components. To the best of our knowledge, this study is one of the first of its kinds where only renewable hybrid energy system is utilized to provide energy for both residential and transportation applications on a single family basis.

2. System description

The system is mainly designed to produce electricity for residential electrical loads and to produce hydrogen as a fuel source for hydrogen car used to commute and for weekend activities. The hybrid system is not connected to the grid and provide enough energy for a single family house with zero emission. As seen in Fig. 1, my dream is to have a green and sustainable life and the energy system designed to realize this includes PV panels, wind turbines, electrolyzer, battery bank and hydrogen tank. Economic and technical analysis studies of the system were carried out using Hybrid Optimization Model for Electric Renewables (HOMER) program designed by National Renewable Energy Laboratory (NREL) [17,18].

As long as wind is blowing and/or sun is shining, the system produces electricity and this is directly feeding the electrical load. If there is any excessive electric energy, it is used to charge batteries and to power the electrolyzer in order to generate hydrogen. In case there is neither of two renewable sources available, stored energy in the battery bank is used to feed the electrical load and the stored hydrogen in hydrogen tank is used to fill the car's fuel tank for enough distance.

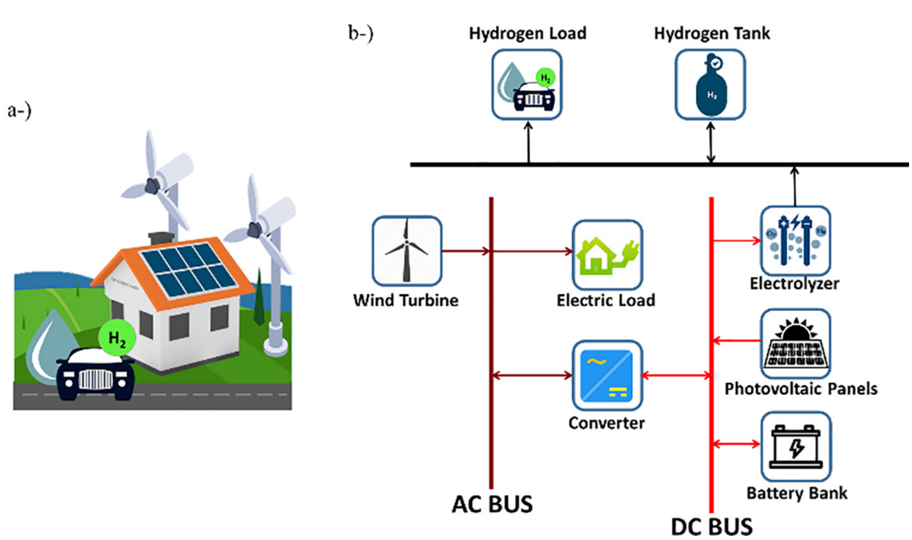

Fig. 1. a-) Representative view of the desired life style with zero emission b-) Schematic layout of the hybrid energy system.

The system is planned to be setup in Ayvalık province of Turkey located at 39.282 N and 26.614E coordinates at sea level. The available sources to produce energy is very important to realize energy systems based on renewables. For the study, average solar irradiance, average wind power and average temperature are so critical to produce more energy. All these information for the given location was gathered from NASA Surface Metrology and Solar Energy Database [28]. Table 1 summarizes all these data based on months. It is clearly seen that solar irradiation and temperature substantially increases in the summer whereas wind speed changes oppositely. This opposition is good for my purpose because those energy carriers act as a complementary to each other. The data shown in Table 1 was collected during a long period of time at 39.5 N and 26.5E coordinates. Solar related data was taken over 22 year period from July 1983 to June 2005 and wind speed was taken over 10 years period from July 1983 to June 1993 at 50 m height. Besides monthly data, Table 1 also shows annual average for each column. According to that, annual average of clearness index, solar irradiation, temperature and wind speed are 0.581, 4.62 kW/m2/day, 16.47 °C, and 5.86 m/s, respectively. Clearness index is a nondimensional number and showing the ratio of surface radiation to extraterrestrial radiation. The number changes from 0 to 1 indicating how good sun is shining. While solar irradiance is directly proportional, temperature is inversely proportional to the produced power by PV and both were taken into account in this study. The energy generated by the wind turbine is proportional to the cube of wind speed shown in the last column [19].

In order to find the best configured energy system, detailed load profiles should be taken into account otherwise a solar PV system could be picked to meet the energy demand only occurring nighttime. In this kind of situation, designed PV system becomes useless. Therefore, I concentrate on the load profiles in the system and arranged as in Fig. 2. Since I design the stand alone system for a single family house, the typical residential load profile was

Table 1
Monthly average clearness index, solar irradiation, temperature and wind speed values obtained from NASA Surface Metrology and Solar Energy Database.

Month	Clearness Index	Average Solar Irradiation (kW/m^2/day)	Average Temperature (°C)	Average Wind Speed (m/s)
January	0.549	2.392	6.41	6.37
February	0.539	3.111	6.71	7.35
March	0.599	4.655	9.50	6.55
April	0.583	5.672	14.70	5.65
May	0.573	6.339	20.34	4.88
June	0.587	6.809	24.93	4.78
July	0.584	6.575	27.32	5.39
August	0.599	6.050	26.95	5.28
September	0.620	5.141	23.15	5.13
October	0.616	3.848	17.95	6.50
November	0.571	2.637	12.04	6.04
December	0.560	2.200	7.66	6.42
Annual Average	0.581	4.620	16.47	5.86

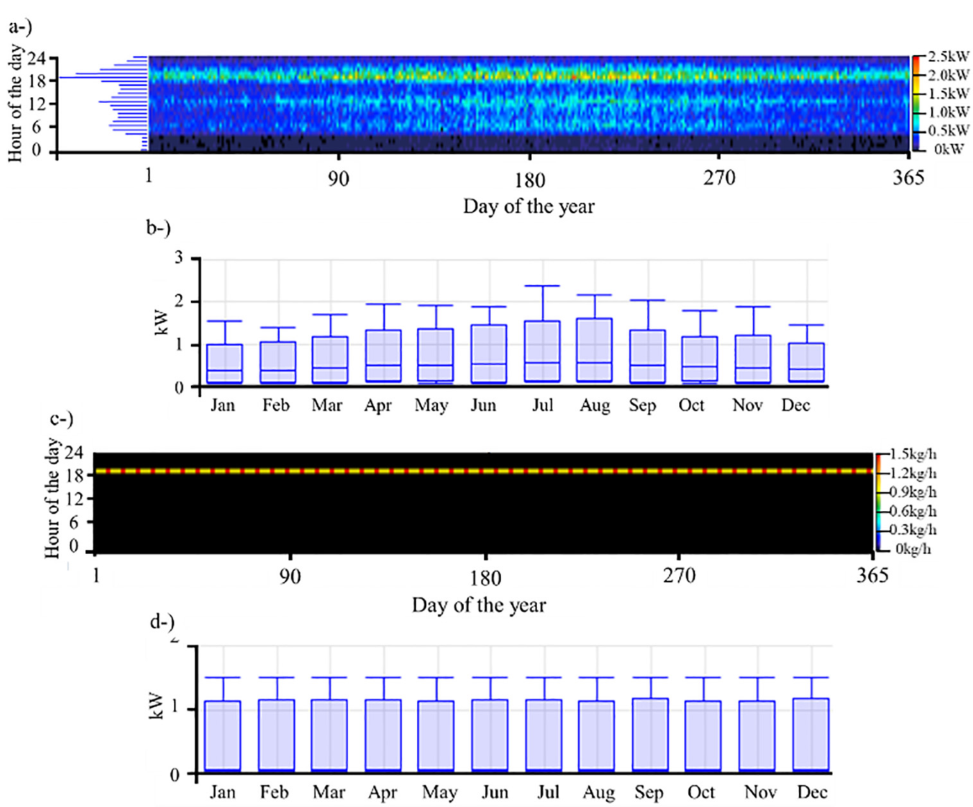

Fig. 2. a-) Yearly (365/24) and b-) seasonal electric load profiles c-) Yearly (365/24) and d-) seasonal hydrogen load profiles. Plot seen on the left hand side of day 1 in (a) shows daily residential load profile.

used with 11.27kWh/d scaled annual average and 2.39 kW peak power. In Turkey, average daily energy consumption is 8.31kWh/d for a single family house [20], but this excludes any energy used for air conditioners. I expect to use air conditioners at such a hot city and therefore load profile has the max power demand in July as seen in Fig. 2b. In addition to the electrical load, a hydrogen load is also included in the system. Unlike electrical load, hydrogen load is needed only at 19:00o'clock everyday, but 1 kg on weekdays and 1.5 kg on weekend with 1.14 kg/d scaled annual average. This load is planned based on the average distance taken for commuting on weekdays and for social activities on weekends. According to the research [21], average one way commute distance is 31.7 km and a typical hydrogen car consumes 0.8 kg per 100 km [22]. By considering round trip commute and doubling it, we can take the travel distance about 120 km to be in safe and this requires 1 kg hydrogen every day. For the weekend, people need more fuel to go somewhere else to socialize with family and therefore hydrogen need for weekends was given 1.5 kg. Unlike electrical load profile, seasonal load profile for hydrogen does not change as seen in Fig. 2d.

In order to evaluate the feasibility of any system, we compare the unit price of the energy with the energy produced by other energy carriers. For this reason, economical inputs are very critical to figure out the real cost of the energy. Since the market price of the components used in the proposed system is in US dollar, energy cost would be also in US dollar currency. Because of that, the economy inputs such as inflation rate and discount rate are taken into account based on the values for US dollars. According to Ref. [23,24], recent inflation rate and discount rate for US dollar are 2.17% and 2.25%, respectively and used as is in the HOMER simulation. In addition to these inputs, annual capacity shortage and project lifetime are also important and affect the economic findings of the system. In the system, maximum annual capacity shortage which is the fraction of capacity shortage (CS) to the total electric load was defined as 2%. Any number higher than this is considered unfeasible. Focus Factor which is a metric to determine the quality of solution in terms of being close to the global optima was chosen default value of 50. The project life time on the other hand was selected as 25 years although some of the components require replacement within the system's lifetime.

2.1. Photovoltaic panels

16.97% efficient 330 W Canadian Solar MaxPower CS6U-330P flat plate panels with 45 °C nominal cell temperature and −0.41%/°C temperature dependent power coefficient were used in the hybrid system [25]. Since temperature at the project site varies by season as seen in Table 1, photo conversion efficiency of the panels also changes based on the given coefficients and more realistic power generated by the PV panels are therefore figured. In the current system, panels are used without any tracking system and fixed at 39.32° slope (corresponding to the location's latitude) throughout the year. Unit price for each kW of PV was taken 1000$, but studies project that this price will substantially drop with new advancements in the PV industry [26]. In addition to those, derating factor which accounts loses due to soling, shading, snow covering, wire losing, aging and so on was taken 88% and lifetime of the PV panels is 25 years.

2.2. Wind turbine

In the project, I intentionally used 1 kW Aeolos brand small sized turbines with 3.2 m rotor diameter and 8.0 m^2 swept area instead of using one larger size. The reason is that any mechanic malfunctioning on the turbine could cause energy cut and the entire system would be ruined. However, if small size turbines are used, probability of problem occurring in all turbines are low and therefore other turbines will be running while one is under maintenance. By this way, meeting the energy demand is always kept high. Cost of the specified turbine is around $2500 [27] and used as is in the HOMER. Although wind speed data was gathered at 50 m height by NASA, 15 m hub height was used in the analyzed system. This indicates that the wind turbines face lower wind speeds at lower hub heights and the details are given in Section 3 [18,19]. Wind speed with the hub height changes logarithmically and this can be seen in Supporting Information (SI) - FigS. 1. In order to find how much energy a wind turbine can generate, we need two sets of data: one is wind turbine power curve representing power output vs. wind speed and the other is Weibull distribution of wind speed. The latter one is taken from NASA surface metrology and solar energy database [28] and the former one was entered into the HOMER based on the data given in the datasheet of the wind turbine [27]. This curve (SI, FigS.2.) shows that the turbine shuts down when the wind speed is too low (<3m/s) for the operation or too fast (>18 m/s) to damage the turbine. Lifetime of the turbines was taken 20 years indicating the requirement for a replacement within the lifetime of the entire project. It is important to note that if this value is somehow extended to 25 years, both cost of energy (COE) and cost of hydrogen (COH) would be much lower.

2.3. Electrolyzer

By applying a small potential, we can split water into hydrogen and oxygen and this process is called electrolysis. The machine does this process is called hydrogen electrolyzer. It generates H_2 and store it in a hydrogen storage tank. It can be later used to fill-up the FCEV tank. It is important to stress that H_2 is a sustainable solution as long as it comes from water. Otherwise there are many methods to generate hydrogen utilizing fossil fuels and those create tremendous amount of greenhouse gasses. For this reason, all the methods with the exception of water splitting to generate hydrogen is not suitable for my purpose. Hydrogen electrolysis from water is usually undertaken with liquid alkaline (LA) or polymer electrolyte membrane (PEM). LA electrolyzer is not very suitable for intermittent renewable energy and produces uncompressed H_2 requiring to use giant hydrogen tanks or additional compressor to store H_2. PEM on the other hand overcomes some of the problems related to LA electrolyzer. Proton exchange membrane in PEM electrolyzer is responsible for separation of protons and electrons. Inconsistent power coming from renewable sources is not an issue for this type and create hydrogen very efficiently. However, its cost usually is very high due to expensive layers (iridium, gold, platinum) in its structure. Anion exchange membrane (AEM) electrolyzer is a revolutionary and take the advantages of both aforesaid electrolyzers. AEM uses a low cost alkaline solid polymeric membrane and produces directly compressed hydrogen over 30 bar. AEM electrolyzer is the solution to create pure and directly compressed hydrogen with a lower cost [29,30]. In this study, AEM electrolyzer with 15 years lifetime and 85% efficiency was utilized and the unit price per kW was specified $2000 in the HOMER software.

2.4. Hydrogen storage tank

In the designed system 3 kg hydrogen tank was used to meet the daily load demand (WD:1kg, WK:1.5 kg) with an extra storage to increase the autonomy time in case hydrogen cannot be generated for a while for some reasons. Hydrogen tank is as durable as the system and therefore does not require any replacement within the project lifetime. Unit price for each kg is defined $1500 as suggested by HOMER.

2.5. Battery

Since the energy generated by renewables is not consistent, any type of storage methods is needed to supply stable energy to the users. Although there are various ways of storing energy, batteries are the most commonly used one; however, they have some disadvantageous such as high cost, difficult disposal and frequent replacement. Among various types of batteries, Lithium ion batteries were preferred in the current system because of longer lifetime, higher throughput and lower minimum state of charge specs. Generic 6 V Li-Ion batteries with 90% roundtrip efficiency and 1kWh capacity were used in the hybrid system. Each battery costs $400 and has 15 years lifetime with 20% minimum state of charge capability. Price of the batteries are expected to drop substantially and in the near future price can be even less than the half according to Ref. [30]. All the batteries were assumed fully charged before the project starts.

2.6. Converter

Converter is used to rectify any excess energy generated by wind turbine to charge the batteries or power the electrolyzer and to invert DC power generated by PV panels or stored in the batteries to energize the electrical loads. Efficiency of the conversion in both ways (AC to DC and vice versa) is 95% and the cost of the converter with 15 years lifetime is $300/kW.

3. Calculation procedures of HOMER

In this section, important equations used in optimization studies will be explained in detail. Since the hybrid system utilizes both solar and wind energies, equations used to calculate power outputs of both are given in Eq.(1) and Eq.(2), respectively.

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) [1 + \alpha_f (T_C - T_{C,STC})] \quad (1)$$

where:

Y_{PV}: the maximum power output of the PV array under standard test condition (STC) (kW)
f_{PV}: the PV derating factor (%)
G_T: the solar irradiation incident on PV array (kWh/m^2)
$G_{T,STC}$: the solar irradiation under STC (1 kWh/m^2)
α_f: the temperature coefficient of PV panel power (% / °C)
T_C: the PV cell temperature (°C)
$T_{C,STC}$: the PV cell temperature under STC (25 °C)

In order to find the wind power output, we first need to find the hub height speed and then the specific wind turbine' s power curve is used to figure out the power output at a specific time. If the wind speed at specific hub height is not in the range of wind turbine's power curve, the system assumes that wind turbine produce no power. Wind speed at a specific hub height is calculated by Eq. (2) using logarithmic law and simulations are run based on the calculated wind speed and a specific wind turbine's power curve.

$$V_{hub} = V_{anem} \frac{\ln(Hhub/Ho)}{\ln(Hanem/Ho)} \quad (2)$$

where:

V_{hub}: the wind speed at the hub height of the wind turbine (m/s)
V_{anem}: the wind speed at anemometer height (m/s)
H_{hub}: the hub height of the wind turbine (m)
H_{anem}: the anemometer height (m)
H_o: the surface roughness height (m)

In terms of economy, it is important to calculate Net Present Cost (NPC), Cost of Energy and operating cost (OC) of the system and following equations are used in the simulation procedure to do so. Net Present Cost is sum of present costs of the system incurs over its lifetime, minus the present value of revenues the system earns. The present costs include capital costs, operation & maintenance costs and replacement cost. The proposed system only earns salvage revenue within its lifetime. Before figuring the cost of energy, annualized cost (AnnC) should first be defined as follows;

$$AnnC = CRF * NPC \quad (3)$$

where CRF stands for capital recovery factor and it is figured by Eq. (4).

$$CRF(i, n) = \left(\frac{i(1+i)^n}{(1+i)^n - 1} \right) \quad (4)$$

where "i" is annual real discount rate and "n" is number of years. Real discount rate (i) is found by Eq. (5).

$$i = \frac{i' - f}{1 + f} \quad (5)$$

where "i'" is nominal discount rate which is the rate we can borrow money and "f" is inflation rate.

After finding "AnnC" and served energy (E_{served}), we can find the cost of energy per kWh produced by the hybrid system using Eq. (6).

$$COE = AnnC \left(\frac{/yr}{Eserved(kWh/yr)} \right) \quad (6)$$

Besides cost of energy and net present cost, operating cost is another important parameter for the energy systems and defined as the annualized value of all costs and revenues with the exception of annualized capital costs which is found by product of initial capital cost and CRF. For the other equations used in HOMER, it is recommended to check HOMER Instruction guide [18].

4. Results and discussion

HOMER simulates all possible combinations for the hybrid energy system with battery backup and sorts them based on the Net Present Cost values. The total number of 766.656 simulations were run and 95.832 optimization cases were evaluated to find the most suitable system configuration. Components of the optimum system with sizes and economic parameters are shown in Table 2. As seen, the best optimized hybrid system is comprised of 4x1kW wind turbine, 11.7 kW PV panel, 7 kW electrolyzer, 6 strings 1kWh Li-Ion battery, 3 kg hydrogen tank and 4.08 kW converter. This system resulted in NPC of $69,221 with $43,776 capital investment. Some of the components mentioned earlier require replacement within 25 years of the project lifetime and therefore we have replacement cost of $27,264. At the end of the project, we get $13,116 from the salvage and the detailed cash flow diagram of the system is seen in FigS. 3.

Although the average and maximum electrical load are only 470 W and 2.39 kW, respectively the optimal PV array size and wind turbine size are 11.7 kW and 4 kW. Since FCEV needs stored hydrogen and couple of inefficient procedures in the system taken place, the size of the energy generators must greatly exceed the electrical load. As a result, the cost of energy becomes very high. As seen in Table 3, COE and COH for the optimum hybrid system are $0.685 and $6.85, respectively. Although the cost of energy is almost 5 times higher, the cost of hydrogen is less than half of the market price [31].

Table 2
Technical and economical parameters of all components used in the hybrid system.

Name	Size	Life Cycle	Capital	Operating	Replacement	Salvage	Total
Wind Turbine Aeolos 1 kW	4 ea.	20 Years	$10,000	$6,929	$9,845	($7,355)	$19,419
Pv Panel CS6U-330P	11.7 kW	25 Years	$11,651	$2,883	$0.000	$0.000	$14,534
Electrolyzer	7 kW	15 Years	$14,000	$0.000	$13,837	($4,576)	$23,260
1kWh Li-Ion Battery	6 Strings	15 Years	$2,400	$1,485	$2,372	($784.500)	$5,472
Hydrogen Tank	3 kg	25 Years	$4,500	$0.000	$0.000	$0.000	$4,500
Converter	4.08 kW	15 Years	$1,225	$0.000	$1,210	($400.330)	$2,035
System		25 Years	$43,776	$11,297	$27,264	($13,116)	$69,221

Table 3
Sensitivity analysis results.

Electrolyzer Cost ($/kW)	PV Cost ($/kW)	Wind Turbine Cost ($/kW)	COE ($)	COH ($)	Electrolyzer Cost ($/kW)	PV Cost ($/kW)	Wind Turbine Cost ($/kW)
1,000	500	1,250	0.504	5.04	1,000	500	1,250
1,000	500	2,500	0.555	5.55	1,000	500	2,500
1,000	1,000	1,250	0.566	5.66	1,000	1,000	1,250
1,000	1,000	2,500	0.616	6.16	1,000	1,000	2,500
2,000	500	1,250	0.574	5.74	2,000	500	1,250
2,000	500	2,500	0.624	6.24	2,000	500	2,500
2,000	1,000	1,250	0.636	6.36	2,000	1,000	1,250

According to the results seen in Table S1, produced yearly energy (27,385kWh) by renewable sources are much more than needed by electrical load (4,083kWh) and surplus energy (23,030kWh) goes to the electrolyzer and batteries. For the situations of overnight and/or insufficient wind energy, the stored energy both in electric form and hydrogen form are utilized to feed the load demands. The results show that 70.2% of the total energy produced by PV panels and the rest was produced by the wind turbines. Fig. 3a shows the monthly production of electrical energy by PV panels and wind turbines. It is clearly seen that energy produced by PV panels increases during the hot seasons (Fig. 3b), while the energy produced by the wind turbines becomes less. This becomes opposite in the cold seasons and the contribution of wind energy becomes much more effective (see Fig. 3c). Complementary nature of these two energy producers is very suitable for hybrid energy systems and solves intermittency problem of renewable energy sources. As seen in Fig. 3b, PV panels produce more power during the noon and middle of the year due to greater solar irradiance and longer equivalent sun hours, respectively. When the sun sets, PV panels are not able to produce any power as indicated in the graphic by black color. Wind turbine in contrary can produce power any time of the year, but more power is generated during the first and last 90 days of a year. Capacity factor (CF) is an important value showing how effective the energy sources are used and it is calculated by the ratio of generated energy over a time period divided by the installed capacity. In this study, CF of the PV panels and wind turbines is found to be 18.8% and 23.3%, respectively. These values are in a good agreement with the literature. In addition to those, the optimum system has only 41.8kWh/y capacity shortage corresponding to 1.02% and this is much lower than the allowed level of capacity shortage.

The optimum system has six 1kWh Li-Ion batteries in parallel with bus voltage of 6 V. Although nominal capacity of the batteries is 6kWh, usable nominal capacity is 4.6kWh due to 80% depth of discharge (DOD) capacity of the batteries. 13,171kWh energy was stored in the lifetime of the battery bank. Fig. 4 shows yearly and seasonal state of charge (SOC) of the battery storage bank. It is clearly seen in Fig. 4a

when the max. PV power produced, battery banks are fully chared, but when the sun goes down, energy stored in the batteries are used to meet the load demands. Fig. 4b shows that SOC of the batteries gets lower during the summer. It is as expected because

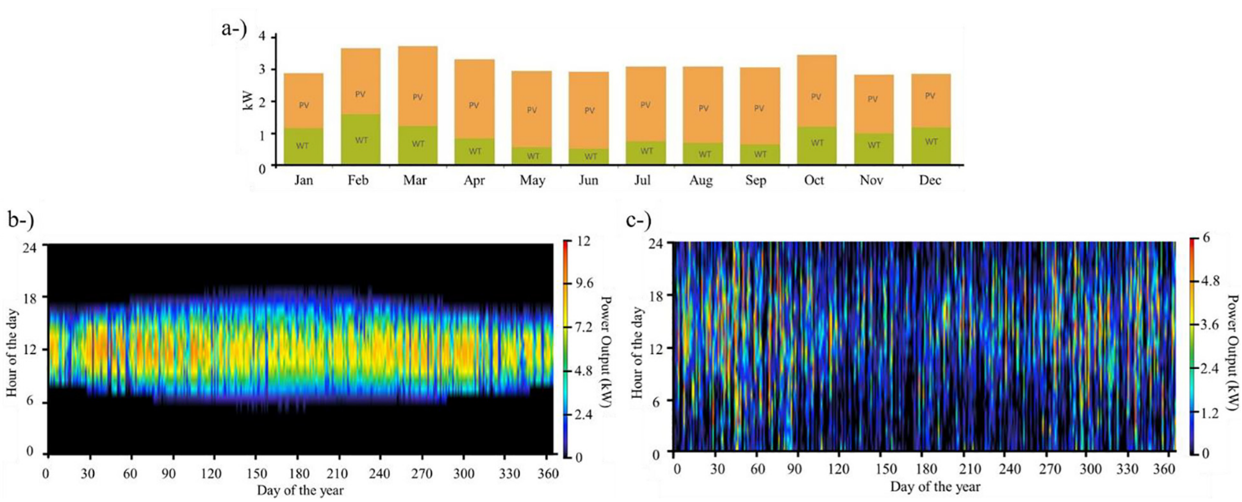

Fig. 3. a-) Monthly average electric production by generation methods. Yearly (365/24) b-) PV and c-) wind turbine power outputs.

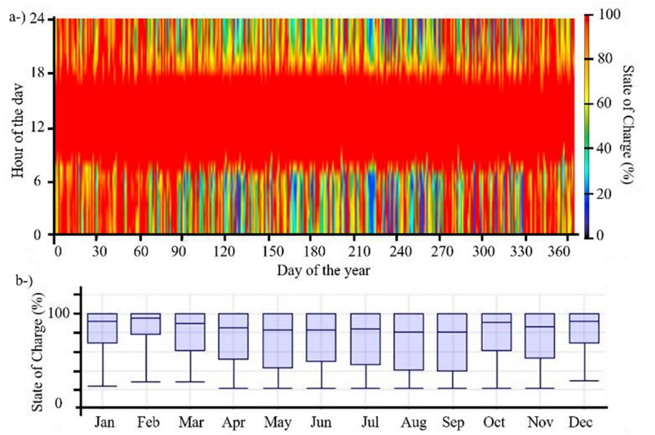

Fig. 4. a-) Yearly state of charge plot of storage batteries b-) Seasonal variation of the battery bank's charge status.

wind turbines cannot generate enough power and electrical load demand due to air conditioners (July is the peak month) becomes higher during the summer season.

The optimum system has 7 kW electrolyzer and this produces 408 kg of hydrogen in a year by consuming 46.4kWh energy per one kg of hydrogen. Mean and maximum output of the electrolyzer are 0.0466 kg/h and 0.151 kg/h, respectively. Although rated capacity and maximum input of the electrolyzer are 7 kW, mean input is found to be 2.16 kW. 18.947kWh energy produced by the renewable sources was consumed by the electrolyzer in a year and CF is figured to be 30.9%. The electrolyzer were in operation during 5,128 h of a year. From all these inputs, we can calculate the average power of the electrolyzer through the year and it becomes 1.15 kW which is in agreement with the seasonal average power plot in Fig. 5b. As in the battery case, electrolyzer was also powered mostly at noon when the power generation occurs at high level due to stronger solar irradiation (see Fig. 5a).

In the proposed system, hydrogen is produced on site via wind and solar energies and this removes a series burden for transportation and distribution stages. In this system, the hydrogen tank starts the year with 0.3 kg hydrogen (10% of its capacity) and ends up the year with 0.3141 kg (10.47%) indicating the system provide enough power from the first year to the second year. Fig. 6 shows yearly hydrogen tank level and it is obvious that when the sun rises the level of tank starts to increase and becomes mostly full till evening.

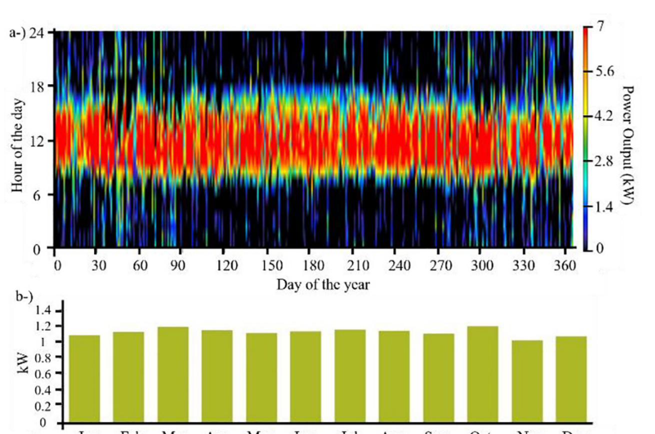

Fig. 5. Electrolyzer a-) yearly input power and b-) seasonal average power.

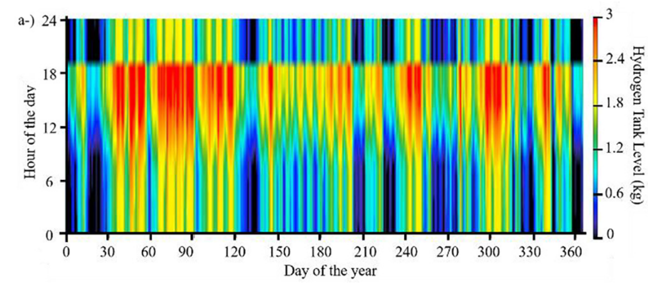

Fig. 6. Yearly hydrogen tank level.

At 7:00 pm, I have a scheduled hydrogen intake by the hydrogen car and therefore hydrogen level of the tanks drop substantially in 1–1.5 h. Later the system prioritize the electrical load demand and any excess power later on used to energize electrolyzer again to generate hydrogen to be stored in the hydrogen tank for later use by the car.

In order to see different scenarios with lower component prices, a sensitivity analysis was also carried out. In the sensitivity analysis process, HOMER performs multiple optimizations with a given possible inputs to gauge the effects of uncertainty or changes in the model inputs. In this analysis, it was assumed that electrolyzer, PV and wind turbine costs fell half of their original price. As seen in Table 3, we have 8 scenarios and it is figured Electrolyzer, PV and Wind turbine have the most effective to least effective costs, respectively. That means any change for electrolyzer has more impact on the cost of energy than change for PV and wind turbine. When all these components' unit price drop to half, COE and COH are dropped by 26.4% and become $0.504 and $5.04, respectively.

It is important to mention that this model can be used not only in Ayvalık, but also in different part of the world. If solar irradiation and average wind speed is higher at those locations, both COE and COH could be even lower than $0.504 and $5.04. This system was designed for a single family house, but when we expand the size of the system for larger applications it is known that the price of the energy would drop substantially [32]. In addition to wind and solar energy, the system can be integrated with biomass and hydrokinetic generators if the resources are available to further drop the energy and hydrogen costs.

5. Conclusions

In this study, technical and economic analysis of a renewable energy based hybrid energy system were carried out. This system is designed to meet the energy demands of both electrical and hydrogen loads of a single family house by 100% renewable energy sources. To achieve this, PV panels and wind turbines with battery backup were synergistically used to construct a hybrid system and therefore addressing the biggest problem of intermittent energy of renewable energy sources. In contrast to the most studies in the literature, this study considers the greenhouse gasses emission not only by residential applications, but also by transportation applications. Therefore the proposed system is very promising for a green and sustainable world. The hybrid system is comprised of PV panels and wind turbines as energy generators and batteries, electrolyzer and hydrogen tank as energy storage units. Optimization studies were done using HOMER, which is based on black box approach and the results can be used for validation. The results show that the hybrid system generates hydrogen and electrical energy for the price of $6.85 and $0.685, respectively with the optimum system. Although the price of electricity is higher compared to the grid parity, cost of the hydrogen is less than the half of its market price. In order to project the effects of any further enhancement occurring in the component technology, a sensitivity analysis was conducted and this shows that COE and COH would be $0.504 and $5.04, respectively when the cost of electrolyzer, PV panels and wind turbines come down to half of their original price. In addition to those, promising methods to bring the cost of electricity and hydrogen down were also discussed. This study with zero emission is believed to be a good reference for creating a sustainable universe by taking care of both residential and transportation loads. If everyone in the world build such energy system to meet their any form of energy needs, the world will be much lovely and healthy.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jestch.2020.08.017.

References

[1] J. Conti, P. Holtberg, J. Diefenderfer, A. LaRose, J.T. Turnure, L. Westfall, International energy outlook 2019 with projections to 2050, USDOE Energy Information Administration (EIA), Washington, DC (United States). Office of Energy Analysis, 2019 Sep 24.
[2] S. Turkdogan, A facile growth of Cu 2 ZnSnS 4 /ZnS materials by sulfurization of stacked Co-electroplated-annealed metallic film(s) for photovoltaic applications, Mater. Res. Express 5 (4) (2018) 045903.
[3] S. Turkdogan, B. Kilic, Metal oxide sandwiched dye-sensitized solar cells with enhanced power conversion efficiency fabricated by a facile and cost effective method, Mater. Sci. Semicond. Process. 71 (2017) 382–388.
[4] O. Ellabban, H. Abu-Rub, F. Blaabjerg, Renewable energy resources: Current status, future prospects and their enabling technology, Renew. Sustain. Energy Rev. 39 (2014) 748–764.
[5] M. Temiz, N. Javani, Design and analysis of a combined floating photovoltaic system for electricity and hydrogen production, Int. J. Hydrogen Energy 45 (5) (2020) 3457–3469.
[6] R.P. Micena, O.R. Llerena-Pizarro, T.M. de Souza, J.L. Silveira, Solar-powered Hydrogen Refueling Stations: A techno-economic analysis, Int. J. Hydrogen Energy 45 (3) (2020) 2308–2318.
[7] M. Gökçek, C. Kale, Techno-economical evaluation of a hydrogen refuelling station powered by Wind-PV hybrid power system: A case study for İzmir-Çeşme, Int. J. Hydrogen Energy 43 (23) (2018) 10615–10625.
[8] M. Fereidooni, A. Mostafaeipour, V. Kalantar, H. Goudarzi, A comprehensive evaluation of hydrogen production from photovoltaic power station, Renew. Sustain. Energy Rev. 82 (2018) 415–423.
[9] L. Kong, J. Yu, G. Cai, Modeling, control and simulation of a photovoltaic / hydrogen/ supercapacitor hybrid power generation system for grid-connected applications, Int. J. Hydrogen Energy 44 (46) (2019) 25129–25144.
[10] M.A.V. Rad, R. Ghasempour, P. Rahdan, S. Mousavi, M. Arastounia, Techno-economic analysis of a hybrid power system based on the cost-effective hydrogen production method for rural electrification, a case study in Iran, Energy 190 (2020) 116421, https://doi.org/10.1016/j.energy.2019.116421.
[11] S. Türkdoğan, S. Dilber, B. Çam, Hibrit Enerji Sistemlerinin Şebekeden Bağımsız Bir Çiftlik Evinde Uygulanabilirliğinin Ekonomik ve Teknik Açıdan İncelenmesi, Sinop Üniversitesi Fen Bilimleri Dergisi. 3 (2) (2018) 52–65.
[12] S. Türkdoğan, M. Mercan, T. Çatal, Şebekeden Bağımsız Hibrit Enerji Sistemleri Kullanılarak 40 Hanelik Bir Topluluğun Elektrik ve Termal Yük İhtiyacının Karşılanması: Teknik ve Ekonomik Analizleri, Avrupa Bilim ve Teknoloji Dergisi. 18 (2020) 476–485.
[13] CO, Carbon Dioxide, and Nitrous Oxide N2O. "Fast facts." Transportation 6, no. 7,000 (2017): 8-000.
[14] US EPA. 2020. Fast Facts On Transportation Greenhouse Gas Emissions | US EPA. [online] Available at: <https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions> [Accessed 12 March 2020].
[15] A. Rau, D. Bongardt, G.D. Schmid, Facts and figures on transport. Technical report, GTZ Transport Policy Advisory Service, 2010.
[16] Transport and Environment, CO2 EMISSIONS FROM CARS: the facts report, April 2019.
[17] P. Lilienthal, L. Flowers, C. Rossmann, HOMER: The Hybrid Optimization Model for Electric Renewable, American Wind Energy Association, Washington, DC (United States), 1995.
[18] The HOMER. Hybrid optimization of multiple energy resources microgrid software. Pro; 2017.
[19] A. Sarkar, D.K. Behera, Wind turbine blade efficiency and power calculation with electrical analogy, Int. J. Sci. Res. Publ. 2 (2) (2012) 1–5.
[20] A. Sayfa, F. Bilgiler, Türkiye'de Hane Başına Düşen Ortalama Elektrik Tüketimi Ne Kadar?. [online] Gazelektrik. Available at: <https://gazelektrik.com/faydali-bilgiler/elektrik-tuketimi> [Accessed 12 March 2020], 2020.
[21] W. Do Lee, C.H. Joh, S. Cho, B. Kochan, Issues in feathers application in the Seoul metropolitan area, in: Intelligent Transportation and Planning: Breakthroughs in Research and Practice, IGI Global, 2018, pp. 979–995.
[22] , Com (2020).
[23] "$1 in 1859 → 1860 | Inflation Calculator." Official Inflation Data, Alioth Finance, 15 Jul. 2020, https://www.officialdata.org/1859-dollars-in-1860?amount=1.
[24] Reserve, Federal. "Selected Interest Rates—H. 15." (2020).
[25] Zerohomebills.com. 2020. CS6U-330P Datasheet. [online] Available at: <https://zerohomebills.com/wp-content/uploads/Canadian-Solar-MaxPower-CS6U-P-325-340W-Series-Data-Sheet-on-zerohomebills.com-by-solaranna.pdf> [Accessed 12 March 2020].
[26] R. Fu, D.J. Feldman, R.M. Margolis, Us Solar Photovoltaic System Cost Benchmark: Q1 2018 (No. Nrel/Tp-6a20-72399), National Renewable Energy Lab.(Nrel), Golden, Co (United States), 2018.
[27] Turbine, A., 2020. Aeolos Aeolos-H 1Kw 1Kw Wind Turbine. [online] renugen. Available at: <https://www.renugen.co.uk/aeolos-aeolos-h-1kw-1kw-wind-turbine/> [Accessed 12 March 2020].
[28] Stackhouse, W. Paul, Surface meteorology and solar energy, 2011.
[29] Bischoff, Jens, Cost-efficient production of hydrogen with AEM electrolyzer, 2016.
[30] L. Goldie-Scot, A behind the scenes take on lithium-ion battery prices. Bloomberg New Energy Finance, 2019 May.
[31] Cafcp.org. 2020. Cost To Refill | California Fuel Cell Partnership. [online] Available at: <https://cafcp.org/content/cost-refill> [Accessed 12 March 2020].
[32] R. Fu, D.J. Feldman, R.M. Margolis, US solar photovoltaic system cost benchmark: Q1 2018, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2018 Nov 21.

Sunay Turkdogan received his B.Sc. degree in Electronic Engineering from Uludag University, Turkey in 2007 and he got both his M.S. and Ph.D. degrees in Electrical Engineering from Arizona State University, US in 2012 and 2015, respectively. Currently, he is an Associate Professor in the Department of Electrical and Electronics Engineering at University of Yalova, Turkey and his research mainly focuses on renewable energy systems, nanotechnology, nanophotonics, nanomaterial growth and characterization, solar cells and photovoltaic systems.