# GREEN HYDROGEN BASED OFF-GRID AND ON-GRID HYBRID ENERGY SYSTEMS

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**Abstract:** This study aims to evaluate a green hydrogen ($H_2$) based hybrid energy system (HES) from solar and wind renewable energy sources. The proposed HES contains PV panels, wind turbines and a proton exchange membrane water electrolyzer. Meteorology data such as solar radiation, temperature and wind speed were obtained from Atilim University Incek Campus Meteorology Station (Ankara, Turkey). The designed HES has been examined as both grid-connected and off-grid. In the grid-connected system, the electricity requirement of the load is supplied by the sun and wind, and the surplus energy produced is stored by producing $H_2$ using an electrolyzer. In the off-grid HES, the electricity requirement of the load is completely provided by the proton exchange membrane fuel cell (PEMFC). In this system, the electrolyzer produces the $H_2$ needed by the PEMFC with the energy provided by solar and wind energy. According to the results, 20,186 kWh of energy is produced annually in the on-grid and 3,273 $sm^3$ of $H_2$ is stored. The off-grid system is investigated for Design-1 and Design-2 using two different wind turbine (WT) rated power. In Design-1 and Design-2, annually 95,145 kWh and 83,511 kWh of energy are produced annually 17,942 $sm^3$ and 14,370 $sm^3$ $H_2$ are stored, respectively. When the on-grid and off-grid systems are examined; levelized cost of energy (LCOE) was calculated as 0.223 $/kWh for the on-grid system and 0.416 $/kWh and 0.410 $/kWh for Design-1 and Design-2 for off-grid systems, respectively.

**Keywords:** Green Hydrogen, Hybrid Energy System, Photovoltaic, Wind Turbine, Fuel Cell, Hydrogen Production, Hydrogen Storage

## 1. Introduction

With the increasing energy demand, the generation, transmission, distribution and use of energy have become a major problem all over the World. In addition to the benefits of energy use to humanity, it especially harms natural life [1]. Today, there is an increase in the number of greenhouse gases emitted into the atmosphere due to developing technology, the human population, and related energy needs. Increasing greenhouse gases are responsible for the greenhouse effect by increasing the heat in the atmosphere, which ultimately leads to global warming [2]. Increasing greenhouse gas concentrations can have adverse effects on the climate. The frequency and intensity of extreme weather events (including floods, droughts, forest fires and hurricanes), which especially affect millions of people and cause great economic loss, are increasing day by day [3]. The constantly rising energy demand in parallel with the increasing population and industrialization creates new and different clean energy investment needs [4]. Renewable energy sources have a substantial share among these alternative energy production methods. They also cover many energy production methods; they contain solutions that will support the energy supply for each country [5–7].

Although the COVID-19 pandemic crisis has affected societies in every aspect, the renewable energy sector has been one of the sectors least affected by this crisis. Renewable capacity additions are on track for a record expansion of around 10% in 2021, according to the latest report from the International Energy Agency (IEA). Renewable energy will overtake coal as the world's largest source of electricity generation by the near future [8].

Renewable energy sources such as solar, wind, geothermal and hydropower are the most popular sources [9]. Especially the sun and wind, which have endless resources, are the most important renewable energy sources today. One of the most important obstacles to the use of renewable energy sources is the large-scale production and storage of the electricity produced. The major problems with the use of solar and wind energy are their intermittent nature. PV systems have the highest performance on summer days when the days are longer and the sun is abundant [10], while the energy systems formed by the WT have the highest performance in the spring and winter months when the wind is abundant [11,12]. Therefore, solar and wind energy systems should be used together as hybrid energy systems.

Hybrid energy systems (HES) contain two or more distinct types of systems, continuous and discrete states, which interact with each other [13]. Hybrid systems are more advantageous because they have high efficiency and power reliability. The purpose of HES is to increase efficiency by using energy sources together and to ensure that the others meet the energy needs of the system in case one of the sources is absent or reduced. One of the most important problems of hybridizing renewable energy sources is the necessity of storing excess power when the produced power is more than the required power. The most suitable energy storage methods for off-grid applications are electrochemical, chemical, or thermal storage methods. The electrochemical energy storage solutions used are mostly based on rechargeable batteries such as Li-ion or lead-acid. However, these systems, which can be used for short-term storage ranging from days to weeks, are not suitable for long-term seasonal storage due to their self-discharge and limited capacity. Therefore, in recent years, chemical storage methods, which can produce large amounts of energy and store it as a fuel that can be used, when necessary, have been preferred. One of the most promising methods among these methods is the $H_2$ storage method, which can be produced electrochemically from water, stored and, if desired, converted back into electricity with a fuel cell [14].

$H_2$ energy is gaining momentum day by day, especially since it is integrated with renewable energy sources and provides clean and safe energy production [15,16]. $H_2$ energy, known as carbon-free, has no $CO_2$ emission when burned to generate heat, electricity or both. Green hydrogen produced from water using renewable energy sources enables both energy storage and energy production when necessary [17–19]. In addition, the long-term energy storage feature of $H_2$ energy with minimum losses is very useful in renewable energy sources where electricity production is intermittent and increases system efficiency [20]. Therefore, excess electricity generated from renewable energy sources can be used to produce $H_2$ as a clean fuel and reserved to supply it at peak times when demand is high [21]. When used with fuel cells, green $H_2$ storage based on renewable energy is an alternative energy storage technology with the potential to generate power from renewable energy with long-term and high reliability.

Electricity generation systems typically operate either on-grid connected or off-grid connected. In an on-grid connected system, it can use renewable resources to meet its energy demand and the electricity deficit is supplied from the grid. Off-grid systems are often located in remote or isolated locations where connection to the grid is not possible or too expensive [22]. Off-grid systems integrated with renewable electricity are also a viable option to provide clean energy. This can reduce emissions and operating costs while increasing reliability. Numerous on-grid and off-grid connected hybrid energy systems are possible and many have been examined. Nesamalar et al. proposed a techno-economic analysis of an on-grid and off-grid Hybrid Energy System (HES) design installed at Kamaraj College of Engineering and Technology, India. The HES was designed and optimized using HOMER (Hybrid Optimization Model for Electric Renewables) software [23]. Temiz and Javani investigated a floating PV system and integrated $H_2$ production unit to meet the electrical energy demand of a small community in the Aegean Region in Turkey. PV electricity provides the required load and excess electricity to be used in the electrolyzer and to produce $H_2$. Floating

PV and $H_2$ systems provide 99.43% of electricity demand without any grid connection or fossil fuel usage, where 60.30 MWh/year of 211.94 MWh/year produced electricity consumed by the electric load at $0.6124/kWh Levelized cost of electricity [24]. Hassan compared the on-grid and off-grid connected PV systems [25]. They observed the total net present cost increases since batteries are used in off-grid systems. The energy cost of on-grid and off-grid systems are obtained as $0.183/kWh and $0.196/kWh, respectively. Jahannoush and Nowdeh calculated the optimal design and energy management of an off-grid hybrid PV/WT/fuel cell system by minimizing and considering the loss of load interruption probability by using irradiation and wind speed data of the Iran region [26]. The optimal, reliable and economical design combination has been determined with various configurations includes of PV/WT/FC, PV/FC and WT/FC. Zhang et al. designed an on-grid connected hydro/PV/WT hybrid system. The HES design is an important guide for energy saving, reducing emissions and cleaner production by minimizing cumulative fluctuations in electricity [27]. Al-Buraiki and Al-Sharafi proposed the $H_2$ production by using excess electric energy of an off-grid hybrid solar/wind system. They investigated that the electricity demand was fully met with HES using 18 kW PV, 2 wind turbines and 14 batteries and its LCOE were found as $0.593 7kWh. The production and storage of the $H_2$ were sized according to excess electricity [28]. Zhang et al. conducted a study aiming to provide a zero-emissions solution using renewable energy sources in an off-grid connected system. The energy was produced from solar, wind and $H_2$ sources. Li-ion batteries and $H_2$ were used as energy storage. In addition, HES in different configurations was simulated using HOMER software to determine optimum sizes. It had been seen that the best system was PV/wind/battery/PEMFC and the LCOE was found as $0.366/kWh [29]. Izadi et al. investigated a hybrid renewable energy system and its integration into buildings to create zero-energy buildings in four different areas: Tehran, Yazd, Tabriz and Bandar Abbas. The energy system was simulated in TRNSYS, a powerful transient simulation software, and an optimization neural network-genetic algorithm was used. Simulated HES consisted of PV panels, vertical-axis wind turbines and $H_2$ storage. The results of the simulation showed that 35% to 49% of the required electricity of buildings could be generated via PV panels and wind turbines, and 70% to 88% could be covered by a combination of renewable sources and $H_2$. it was also understood from the results, adding $H_2$ storage system to the main system improved the reliability of the HES and reduced the dependency on grid electricity [30].

In this study, solar and wind energy-based green $H_2$ production is investigated as grid-connected and off-grid. Design calculations were conducted using MATLAB/Simulink software to evaluate HES performance. To compensate for the intermittent disadvantage of renewable energy sources, either the system is connected to the grid or the $H_2$ energy production and storage system is integrated into the system. The main novelty of this study is to provide data and compare the operation and management of on-grid and off-grid connected HES. The parameters of the electrolyzer and the fuel cell were obtained from experimental results [31]. The strategies of both systems are reducing electricity costs, supplying uninterrupted energy, increasing system efficiency, and improving operational safety. This study contributes to obtaining more realistic technical, operational and economical results of on-grid and off-grid connected HES. In addition, the evaluation of the economic feasibility and system performance of the green $H_2$-based hybrid energy system proposed in the study will provide significant benefits to academicians and decision-makers in similar systems.

## 2. Methodology

### 2.1. System Configuration

On-grid and off-grid HES designs with PV, WT, electrolyzer, $H_2$ storage and fuel cell are shown in Figure 1 (a) and (b), respectively. Solar and wind energy sources are used as the main power sources to supply the load energy demand for the on-grid system. The energy storage system consists of an electrolyzer and $H_2$ storage tanks. In an on-grid HES system, if the sun is shining and/or the wind is blowing, PV and WT systems produce electricity. The produced electricity is directly fed to the load to supply energy demand. In the case of electricity production being more than consumption, the electrolyzer consumes the excess electricity to produce $H_2$ and $O_2$. In this system, the excess electricity generated from the sun and wind is stored as $H_2$ instead of batteries. In a grid-connected system, when the energy produced by the system is not enough to meet the demand the energy deficit is drawn directly from the grid.

In an off-grid HES, PV and WT systems generate electricity when solar and wind are available. Since the HES is not connected to the grid, the electricity requirement of the load is met by the PEMFC in the system. Therefore, the electricity is sent to the electrolyzer and used in the production of $H_2$ and $O_2$, and the produced gases are stored. The produced $H_2$ and $O_2$ from the electrolyzer were stored in storage tanks and then fed into PEMFC to supply the electrical demand of a load. Wind speed, solar radiation, sunshine duration and temperature in the region where HES has been installed affect system performance [32]. The system design is performed for Atilim University (Ankara, Turkey) which is at 39.8 latitudes and 32.7 longitudes, 1182 m above sea level. The solar radiation, ambient temperature, and wind speed data were obtained from Atilim University Meteorology Station.

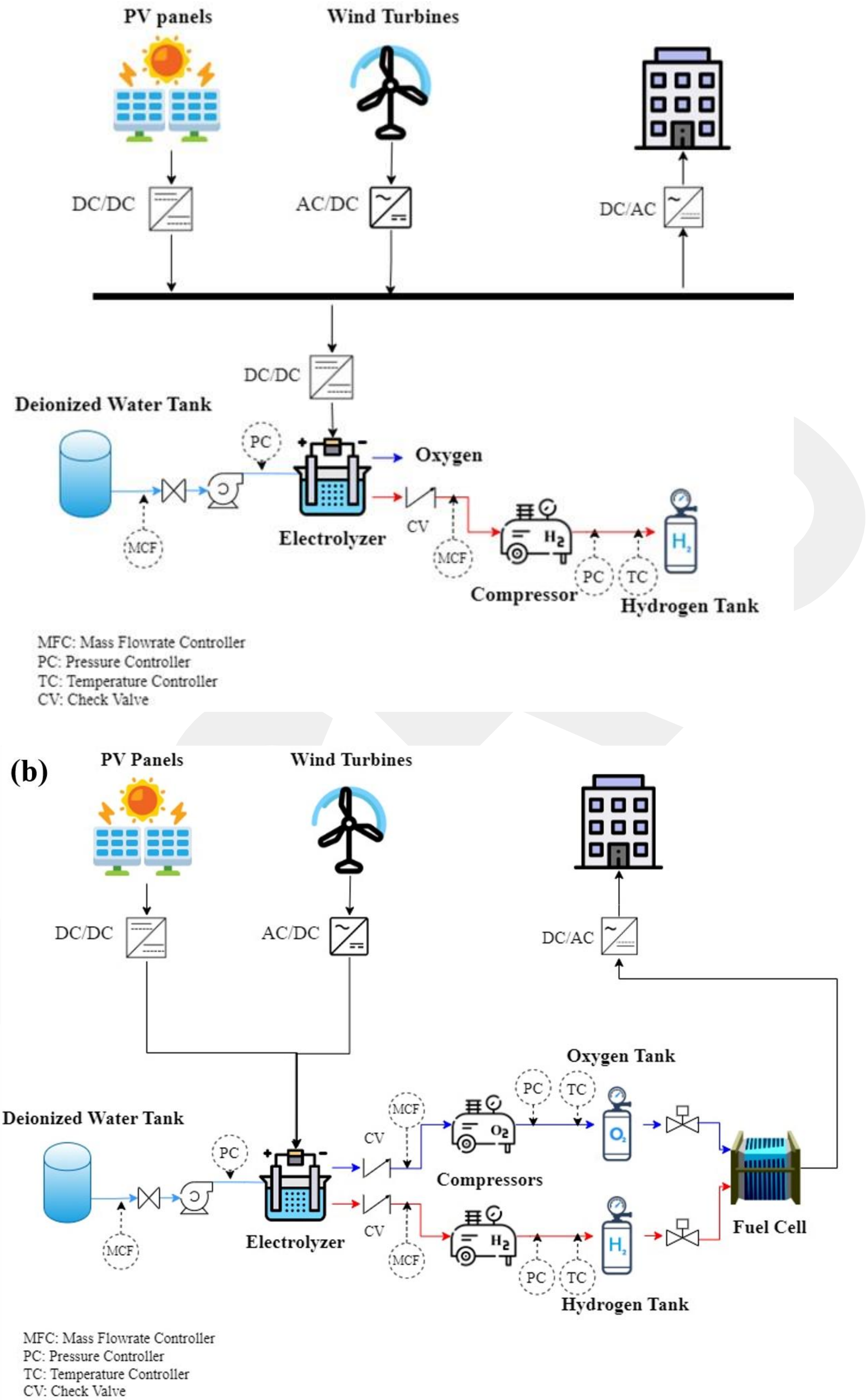

Figure 1. Schematic illustration of the investigated a) on-grid and (b) off-grid HES

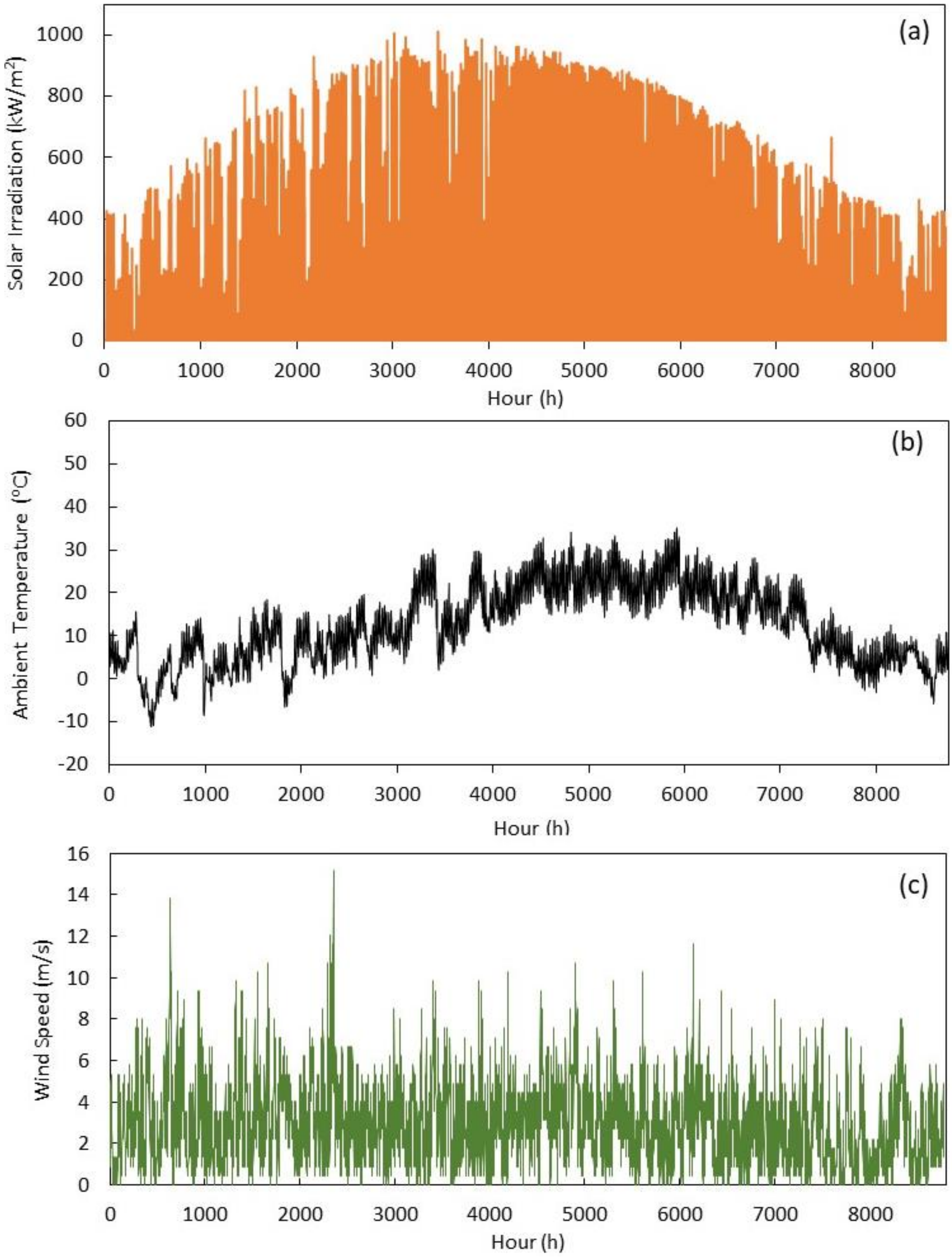

Figure 2. One year hourly a) solar radiation, b) ambient temperature and c) wind speed

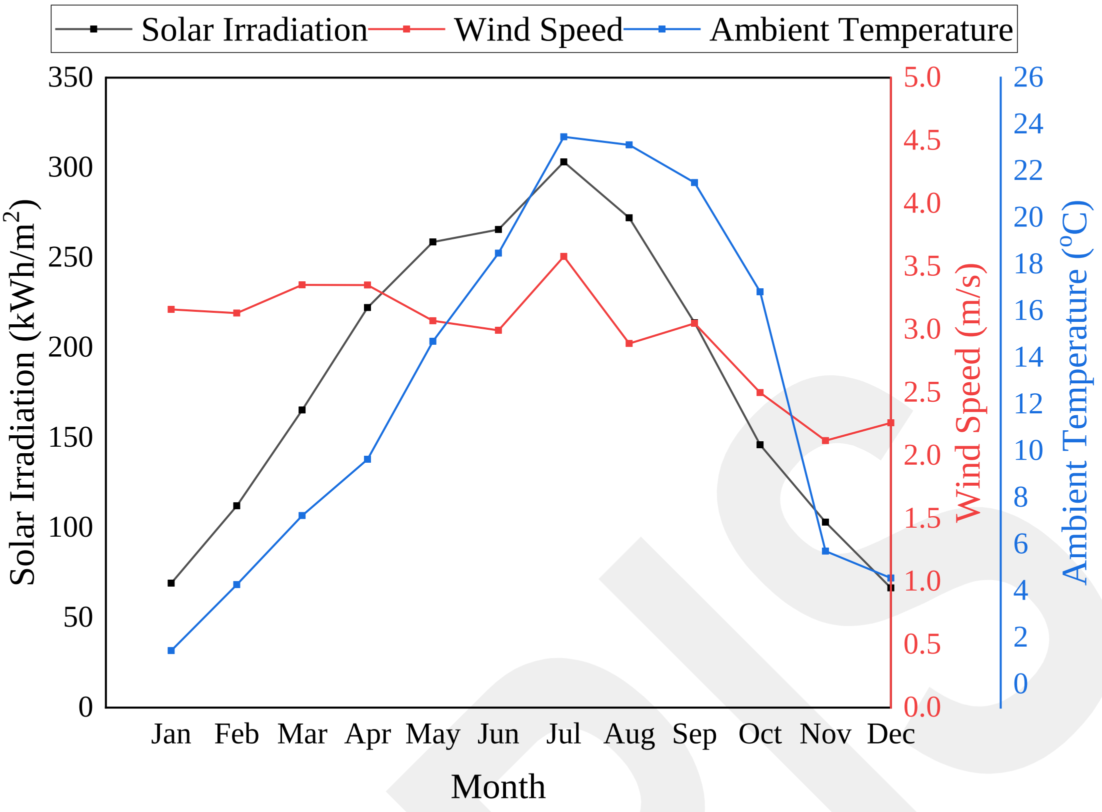

Figure 3. Monthly solar radiation, ambient temperature and wind speed values.

The solar radiation, ambient temperature and wind speed data are shown in Figure 3a, Figure 3b and Figure 3c, respectively. The monthly average solar radiation, ambient temperature and wind speed data are also illustrated in Figure 3.

### 2.2. Design Calculation

#### 2.2.1. PV Calculation

PV design analysis and calculations were performed by using measured global irradiation and ambient temperature data. Solar cell temperature ($T_c$) and power of the PV ($P_{PV}$) are calculated as below Equations (1) and (2) [33];

$$T_c = T_a + G_I \left[\frac{NOCT-20}{800}\right] \quad (1)$$

$$P_{PV} = N_{PV} \frac{G_I}{G_{I,ref}} \left[P_{PV,max} + \mu_p (T_c - T_{c,ref})\right] \quad (2)$$

Where $T_a$ is ambient temperature, $G_I$ and $G_{I,ref}$ refer to solar irradiance and reference solar irradiation of PV, NOCT is the nominal operating cell temperature (45 C$^{o}$). $N_{PV}$ and $P_{PV,max}$ represent the number of PV panels and the maximum power of PV panels.

### 2.2.2. WT Calculation

WT design calculations were executed according to measured wind speed data. The output power of a WT ($\mathrm{P_{WT}}$) can be expressed based on the wind speed as [34].

$$\mathrm{P_{WT}} = \begin{cases} \mathrm{aV^3 + bP_r}, & \text{for } \mathrm{V_{cut,in} \le V < V_{rated}} \\ \mathrm{P_r}, & \text{for } \mathrm{V_{rated} \le V < V_{cut,out}} \\ 0, & \text{for otherwise} \end{cases} \tag{3}$$

Where, $\mathrm{P_r}$ is rated output power of WT, $\mathrm{V}$ is wind speed, $\mathrm{V_{cut,in}}$ and $\mathrm{V_{cut,out}}$ represent cut-in speed and cut-out speed, respectively. $\mathrm{V_{rated}}$ is the rated speed of WT. a and b are constants that can be calculated according to the rated speed and cut-in speed of WT.

$$a = \frac{P_r}{V_{rated}^3 - V_{cut,in}^3} \tag{4}$$

$$b = \frac{V_{cut,in}^3}{V_{rated}^3 - V_{cut,in}^3} \tag{5}$$

### 2.2.3. PEMFC Calculation

According to Barbir [35], the molar flow rates of the $H_2$ ($\dot{n}_{H_2}$), $O_2$ ($\dot{n}_{O_2}$) and air ($\dot{n}_{air}$) are determined as following Equations (6) and (7), respectively.

$$\dot{n}_{H_2} = S_{H_2} \frac{i.A}{2.F} N_{cell} \qquad \text{(anode)} \tag{6}$$

$$\dot{n}_{O_2} = S_{O_2} \frac{i.A}{4.F} N_{cell} \qquad \text{(cathode)} \tag{7}$$

Where $S_{H_2}$ and $S_{O_2}$ are stoichiometric ratios of $H_2$ and $O_2$ , $A$ the area, $i$ the current density and $F$ Faraday constant.

### 2.2.4. Electrolyzer Calculation

The electrolyzer working reaction to produce $H_2$ and $O_2$ from water is expressed in Equation 8 as shown below [36];

$$H_2O_{(l)} + 237.2\left(\frac{kJ}{mol}\right)_{electricity} + 48.6\left(\frac{kJ}{mol}\right)_{heat} \rightarrow H_2 + 0.5O_2 \tag{8}$$

The produced $H_2$ and $O_2$ are stored in special storage tanks. The mass flow rate of produced $H_2$ ($\dot{m}_{H_2}$) is also calculated according to Equation 9 [37].

$$\dot{m}_{H_2} = \frac{\eta_{elec}.P_{elec}}{HHV_{H_2}} \tag{9}$$

Where, $\eta_{elec}$ is the efficiency of the electrolyzer, $P_{elec}$ is the input electrical power consumed by the electrolyzer, the Higher Heating Value (HHV) of $H_2$ is equal to 39.4 kWh/kg [38].

### 2.2.5. Gas Storage

$H_2$ and $O_2$ gases are stored in high pressure storage tank in proposed hybrid system. The volume of $H_2$ tank (V) is determined according to Van der Walls Equation (Equation10) [39].

$$P = \frac{nRT}{V-nb} - \frac{n^2a}{V^2} \tag{10}$$

$$a = \frac{27}{64} \times \frac{R^2T_c^2}{P_c} \tag{11}$$

$$b = \frac{R}{8} \times \frac{T_c}{P_c} \tag{12}$$

Where P is the pressure, n is the number of mole, $R_u$ is the universal gas constant, T is absolute temperature, a is the net intermolecular attractive force, b is the finite volume of the molecules, $T_c$ is critical temperature and $P_c$ is critical.

## 2.3. Economic Model

Levelized cost of energy (LCOE) is defined as the cost of generation, capital investment and operating costs of each electricity produced over the entire lifetime of wind, solar and $H_2$ energy and it is calculated according to Equation 13 [40].

$$LCOE = \frac{CAPEX.CRF+OPEX}{AEP} \tag{13}$$

Where, $CAPEX$ and OPEX are capital and operational expenditures, respectively. AEP is annual electricity production, CRF is capital recovery factor and calculated due to annual real interest rate (i) and period (N) [41]:

$$CRF = \frac{i(1+i)^N}{(1+i)^N-1} \tag{14}$$

The annual interest rate relates to the nominal interest rate ($i_o$) and inflation rate (f). It is used to convert between past cost and annual capital cost and calculated as [42]:

$$i = \frac{i_o-f}{1+f} \tag{15}$$

One of the best and simplest methods used in the system feasibility study is the payback period calculation. The payback period is used to evaluate the short and long-term advantages, if any, of the proposed energy systems. Economically, a viable project should have a short equity payback period [43]. The payback period refers to the time it takes for the project to recoup all funds invested and is usually stated in years [44]. Using the ratio between the initial investment cost and the annual cash inflow, it is calculated how long it will take to repay the system's setup cost as shown in Equation 16.

$$Payback\ Period = \frac{Initial\ investment\ cost}{Annual\ cash\ inflow} \tag{16}$$

# 3. Results

## 3.1. Design Results

This study was conducted to determine the optimal HES component sizes to provide a 25 kWh electrical energy to meet the demand. PV and WT were chosen as the main renewable energy sources based on their availability in the selected location. Different strategies are applied for energy management, including on-grid and off-grid connections. In this study, both grid-connected and off-grid HES based on green $H_2$ were designed and comparatively examined.

The energy management strategy is essential for the safe and continuous operation of the HES to meet the load demand. Thus, according to the energy management strategy, renewable energy sources are effective as a complement to meeting optimum design load by minimizing the HES cost and ensuring reliability [45]. In Figure 4a, the HES operating connected to the grid is given. In the system, the electricity requirement of the load is completely supplied from PV and WT. Firstly, hourly meteorological data (solar radiation, ambient temperature and wind speed) were obtained for one year. If the energy obtained from the PV and WT in the system is more than the load energy demand, the excess energy was used in the $H_2$ production via electrolyzer and the produced $H_2$ was stored in the compressed tank.

The solution flowchart of the proposed green $H_2$-based off-grid electricity generation system is given in Figure 4b. The electrical energy produced from PV panels and WT was determined using meteorological data. The PV and WT numbers required for the uninterrupted operation of the designed off-grid HES in both the summer and winter months have been determined. The generated electricity was transferred to the electrolyzer to produce $H_2$ and $O_2$. The produced $H_2$ and $O_2$ gases were sent to

PEMFC and electricity was produced to meet the energy needs of the load. Excess $H_2$ produced by the system was stored and sold A storage system can increase system reliability when both energy sources are insufficient compared to stand-alone energy systems. The characteristics of the equipment selected for the proposed systems and other relevant technical details are given in Table 1.

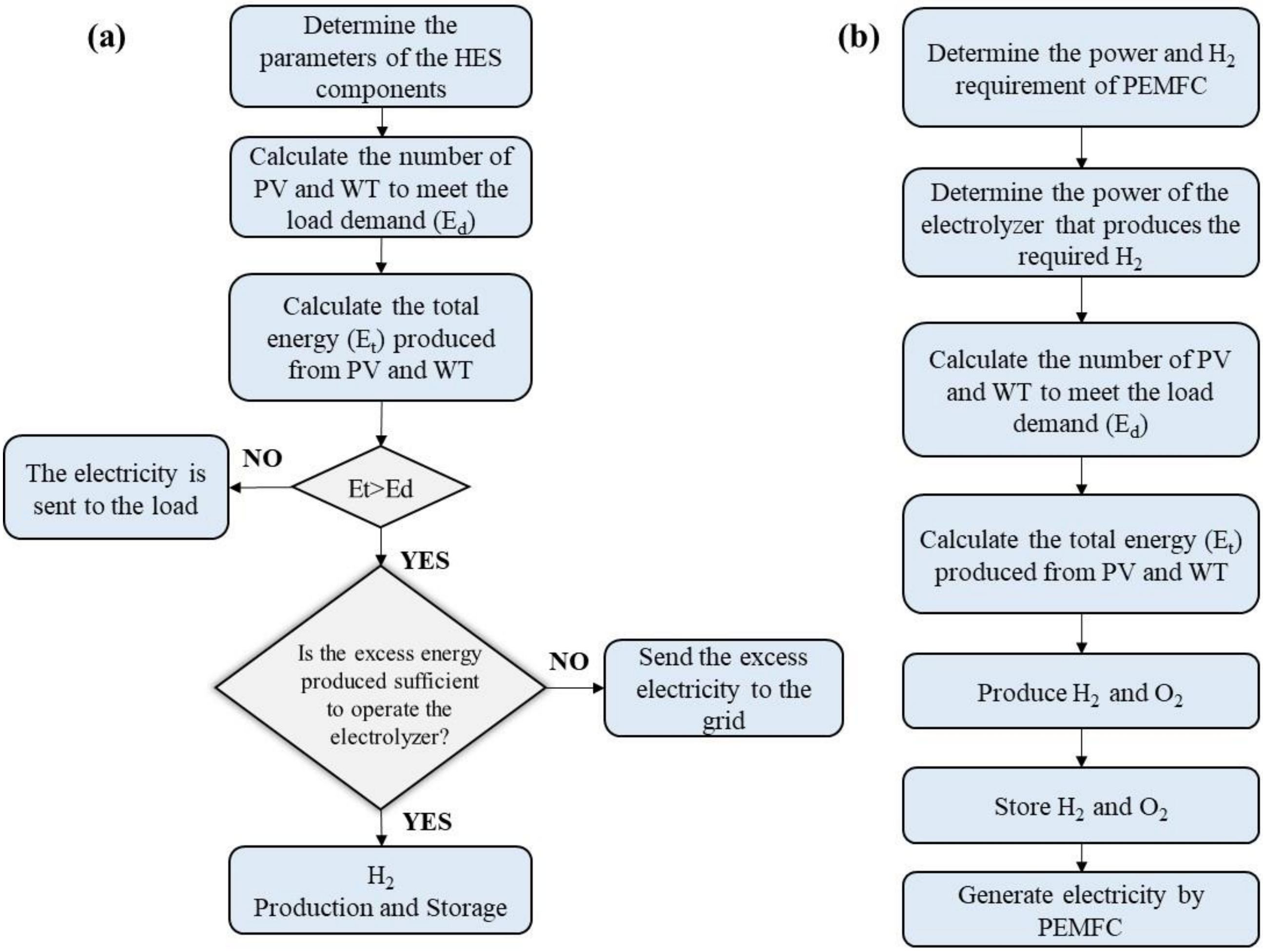

Figure 4. Flowchart of (a) on-grid and (b) off-grid HES systems

Table 1. Technical specification of the main components of HES

| **Component** | **Parameter** | **On-grid/Off-grid** | | |
|---|---|---|---|---|
| **PV** [46] | Efficiency | 22.70% | | |
| | Nominal Power | 370 W | | |
| | Cell type | Monocrystalline | | |
| **Compressed Gas Storage** [47] | Gas Store Pressure | 150 bar | | |
| | Tank Volume | 300 L | | |
| | Critical Temperature of $H_2$ | 33.2 K | | |
| | Critical Pressure of $H_2$ | 12.8 atm | | |
| | Critical Temperature of $O_2$ | 15.4 K | | |
| | Critical Pressure of $O_2$ | 49.8 atm | | |
| **PEM Electrolyzer** [48] | | **On-grid** | **Off-grid** | |
| | Cell Area | 625 $cm^2$ | 150 $cm^2$ | |
| | Cell Number | 19 | 89 | |
| | Current Density | 1 $A/cm^2$ | 1 $A/cm^2$ | |
| | Cell Voltage | 1.55 V/cell | 1.55 V/cell | |
| | Membrane | Perflorosulfonic acid | Perflorosulfonic acid | |
| | Design Power | 7 kW | 20 kW | |
| | Efficiency | 88% | 88% | |
| **PEMFC** [31] | Current Density (0.6V) | NA | 1 $A/cm^2$ | |
| | Membrane | | Nafion 212 | |
| | Active Area | | 150 $cm^2$ | |
| | Design Power | | 6 kW | |
| | Working Temperature | | 70 $^oC$ | |
| | $\lambda_{anode}:\lambda_{cathode}$ | | 1.5:2.5 | |
| **WT** [49] [50] | | **On-grid** | **Off-grid** | |
| | | | **Design-1** | **Design-2** |
| | Hub Height | 15 m | 15 m | 20 m |
| | Swept Area | 14.5 $m^2$ | 14.5 $m^2$ | 75.4 $m^2$ |
| | Rated Power | 4 kW | 4 kW | 10 kW |
| | Cut in Speed | 2 m/s | 2 m/s | 2 m/s |
| | Rated Speed | 11 m/s | 11 m/s | 10 m/s |
| | Cut out Speed | 21 m/s | 21 m/s | 30 m/s |

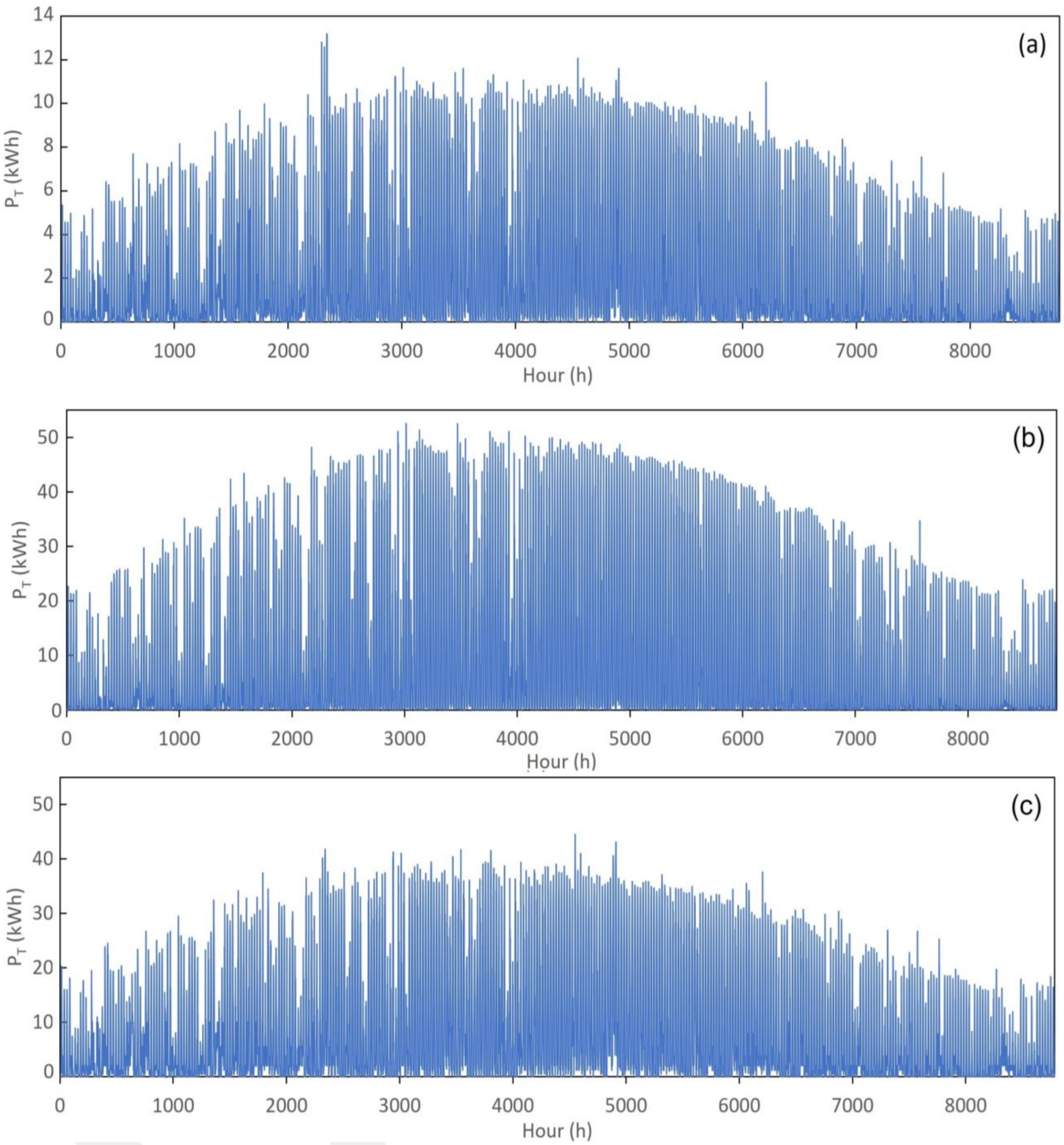

Figure 5. The total power produced from PV and WT for a) on-grid, b) off-grid Design-1 and c) off-grid Design-2.

Figure 5 shows the hourly variation of the total power generated from PV and WT in on-grid and off-grid systems. The main purpose of the grid-connected system is to design a HES that can meet the electricity demand of the load and convert excess electricity to $H_2$ so that it can be used in different applications. When the results are examined, it has been determined that more electricity is produced in the HESs operating independently of the grid than in the system operating connected to the grid.

Table 2. The installed power and number of components, the annual produced energy and the amount of stored $H_2$

| **Components** | | **On-grid** | **Off-grid** | |
|---|---|---|---|---|
| | | | **Design-1** | **Design-2** |
| **PV** | Number of Panels | 30 | 140 | 105 |
| | Installed Power | 11.1 kW | 51.8 kW | 38.85 kW |
| **WT** | Number of Turbines | 1 | 1 | 1 |
| | Installed Power | 4 kW | 4 kW | 10 kW |
| **PEM Electrolyzer** | Number of Electrolyzer | 1 | 1 | 1 |
| | Power of Electrolyzer | 7 kW | 20 kW | 20 kW |
| **PEMFC** | Number of PEMFC | - | 1 | 1 |
| | Power of PEMFC | - | 5 kW | 5 kW |
| **Annual Produced Energy** | | 20,186 kWh | 95,145 kWh | 83,511 kWh |
| **Annual Stored $H_2$ Amount** | | 3,273 $sm^3$ | 17,942 $sm^3$ | 14,370 $sm^3$ |

PEMFC, which operates at 5 kW power and 5 hours a day in off-grid systems, is designed to meet the 25 kWh energy requirement of the load. Two off-grid systems were designed using WT with two different capacities, 4 kW and 10 kW. When the results are examined, it has been determined that in Design 2, where WT is used with higher power capacity in off-grid systems, lower energy production is achieved due to the decrease in the number of solar panels. Since the wind speed was not sufficient in the studied region, the wind speed remained below the WT activation speed for many days throughout the year and could not reach the optimum level. For this reason, more solar panels were used in Design-1 to ensure uninterrupted energy demand of the load, and accordingly higher energy was produced (Table 2).

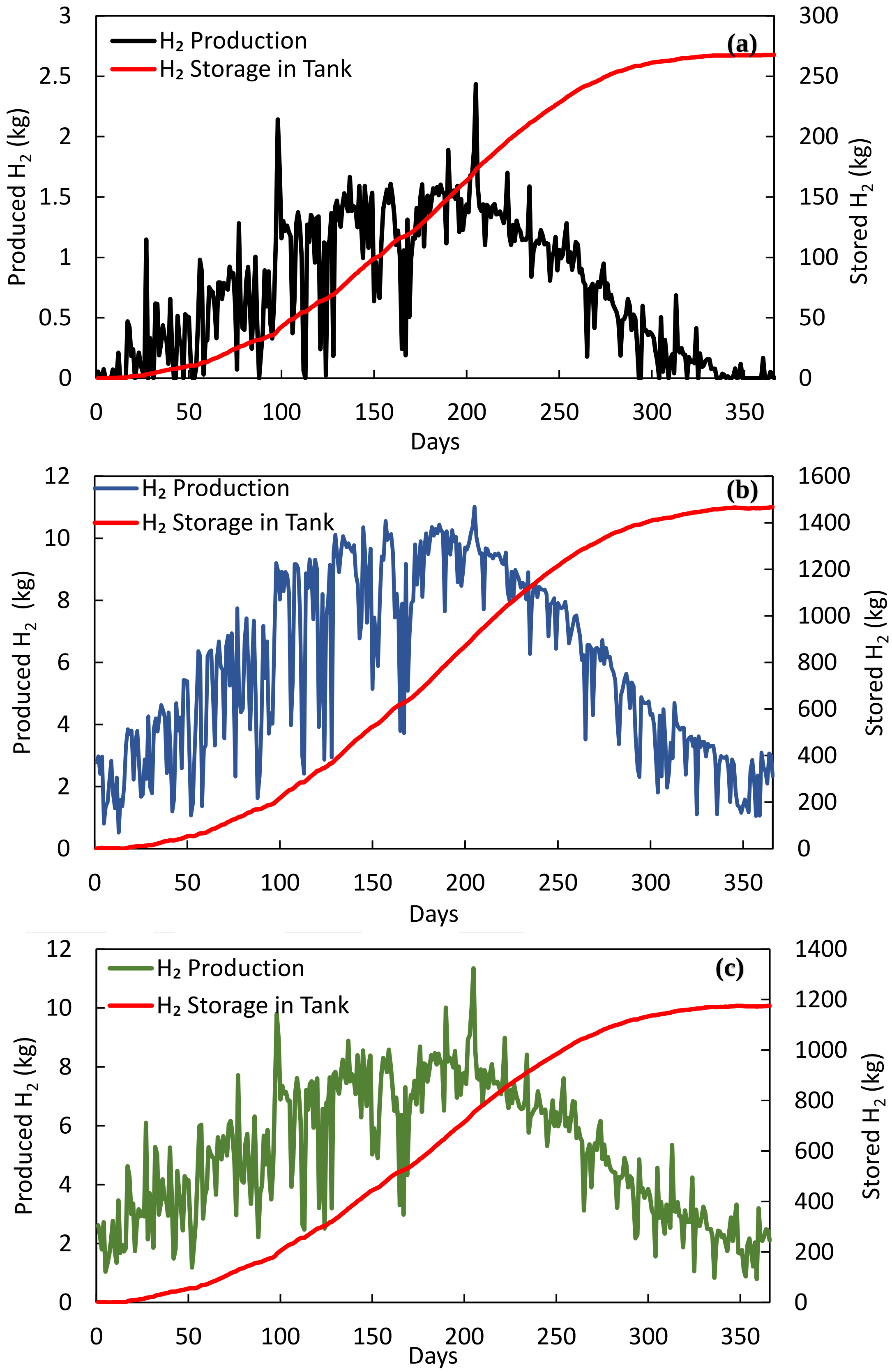

Figure 6. The amount of daily produced and annually stored $H_2$ for (a) on-grid system, (b) off-grid system with Design-1, c) off-grid system with Design-2

Figure 6 shows the total amount of $H_2$ produced during the whole year for grid-connected and off-grid systems. The amount of $H_2$ stored in a year for the grid-independent system and grid-connected Design-1 and Design-2 was determined as 268 kg, 1466 kg and 1175 kg, respectively. Figures 6b and 6c show only excess stored $H_2$ for one year in off-grid systems and the $H_2$ required for the operation of the PEMFC is not considered as it is used for electricity generation. In this study, the capacity of the $H_2$ tank was determined as 300 L. The $H_2$ produced by the electrolyzer is stored in a tank when there is no demand for $H_2$, and the stored $H_2$ is sold for use in different application areas at certain periods. The economic analysis was made according to this strategy.

### 3.2. Economic Result

Acceptable shortage, project lifetime and economic values as the discount rate, and the inflation rate were determined for the feasibility analysis. According to the prices of the components given in Table 3, the LCOE values were obtained using Equations 13-15. Economic analyses were executed for a 20-year life cycle based on the lifetime of the WT system. The following assumptions are made to calculate the LCOE and payback period:

- The lifetime of the system is selected as 20 years.
- The prices of the components are given in Table 3.
- The selling price of compressed green $H_2$ has taken as 15\$/kg [51] and it is expected to increase by 10% annually.
- The selling price of electricity has taken as 0.3\$/kWh and it is expected to increase by 15% annually.

Table 3. Economic parameters of HES components

| **Component** | **Parameter** | **Price** | **Unit** |
|---|---|---|---|
| PV [52] | Investment cost | 630 | \$/kW |
| | Replacement cost | 0 | \$/kW |
| | O&M cost | 13 | \$/kW year |
| | Lifetime | 25 | year |
| WT [53] | Investment cost | 1695 | \$/kW |
| | Replacement cost | 0 | \$/kW |
| | O&M cost | 51 | \$/kW year |
| | Lifetime | 20 | year |
| Converter and Inverter [54,55] | Converter investment cost | 500 | \$/kW |
| | Inverter investment cost | 700 | \$/kW |
| | Converter replacement cost | 500 | \$/kW |
| | Inverter replacement cost | 700 | \$/kW |
| | Converter O&M cost | 3.33 | \$/kW year |
| | Inverter O&M cost | 7 | \$/kW year |
| | Converter lifetime | 15 | year |
| | Inverter lifetime | 10 | year |
| Compressor [56] | Investment cost | 2500 | \$/kW |
| | Replacement cost | 2500 | \$/kW |
| | O&M cost | 50 | \$/kW year |
| | $H_2$ compressor power | 2.20 | kW |
| | $O_2$ compressor power | 1.08 | kW |
| | Lifetime | 10.00 | year |
| Electrolyzer [55] | Investment cost | 1400 | \$/kW |
| | Replacement cost | 0 | \$/kW |
| | O&M cost | 28 | \$/kW year |
| | Lifetime | 20 | year |
| Compressed Storage Tank [57] | $H_2$ tank investment cost | 575 | \$/m$^3$ |
| | $O_2$ tank investment cost | 575 | \$/m$^3$ |
| | Lifetime | 20.00 | year |
| PEMFC [58] | Investment cost | 3000 | \$/kW |
| | Replacement cost | 2700 | \$/kW |
| | O&M cost | 0.02 | \$/kW year |
| | PEMFC power | 5 | kW |
| | Lifetime | 30,000 | hour |

Table 4. The LCOE and payback period results of on-grid and off-grid systems

| | **On-grid System** | **Off-grid Systems** | |
|---|---|---|---|
| | | **Design-1** | **Design-2** |
| **LCOE ($/kWh)** | 0.223 | 0.416 | 0.410 |
| **Payback Period (year)** | 14.25 | 17.74 | 17.9 |

The values of LCOE and payback period are given in Table 4. In an on-grid system, the LCOE and payback period of the system is found as 0.223$/kWh and 14.25 years, respectively. If $H_2$ storage was not used in the system, the system payback period was determined as 4.79. It has been determined that the payback period is longer with the use of the $H_2$ production, compression, and storage system in the system. When the off-grid systems are examined, the LCOE values of Design I and Design II are found as 0.416 $/kWh and 0.410 $/kWh, and their payback period of them are found as 17.74 and 17.9 years, respectively. Although it is important to produce electricity at low cost, especially in meeting the energy needs with the developing technology, it has become extremely important today in environmental concerns. For this reason, even though electricity production from renewable energy sources is higher than traditional sources in terms of cost, they have the advantages of being renewable, sustainable and environmentally friendly.

## 4. Conclusion

In this study, technical and economic analyses of renewable energy-based on-grid and off-grid HES were examined. The HES were modeled using MATLAB for one-year real climatic conditions (solar radiation, ambient temperature, and wind speed). The economic analysis reveals that the minimum and maximum value of LCOE is 0.223 $/kWh and 0.416 $/kWh for the on-grid system and off-grid system with Design-1. The payback period varies from 14.25-17.9 years. As can be seen from the results obtained, the use of renewable HES is quite suitable for providing high-quality clean power and for green $H_2$ production. The results obtained in the study will form the basis for future solar, wind, $H_2$ and fuel cell hybrid energy systems. With future research, it is planned to focus on ways to increase the overall performance of the designed HES, as well as to prepare the designed hybrid energy system prototype and conduct experimental studies.

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