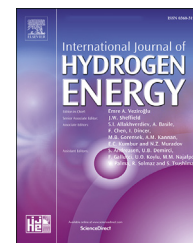


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Performance analysis of a stand-alone integrated solar hydrogen energy system for zero energy buildings

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HIGHLIGHTS

- A stand-alone hybrid solar-hydrogen energy system is designed and investigated.
- The system is proposed for a zero-energy building with no connection to the grid.
- The hybrid system has PV panels, electrolyzer, and fuel cell.
- The selection of the components is dictated by the actual solar and weather data at the site.
- The consumption profile at the house is based on actual data.

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ABSTRACT

This study analyzes the optimal sizing design of a stand-alone solar hydrogen hybrid energy system for a house in Afyon, Turkey. The house is not connected to the grid, and the proposed hybrid system meets all its energy demands; therefore, it is considered a zero-energy building. The designed system guarantees uninterrupted and reliable power throughout the year. Since the reliability of the power supply is crucial for the house, optimal sizing of the components, photovoltaic (PV) panels, electrolyzer, storage tank, and fuel cell stack is critical. Determining the sufficient number of PV panels, suitable electrolyzer model and size, number of fuel cell stacks, and the minimum storage tank volume to use in the proposed system can guarantee an uninterrupted energy supply to the house. In this study, a stand-alone hybrid energy system is proposed. The system consists of PV panels, a proton exchange membrane (PEM) electrolyzer, a storage tank, and a PEM fuel cell stack. It can meet the continuous energy demand of the house is sized by using 10 min of averaged solar irradiation and temperature data of the site and consumption data of the house. Present results show that the size of each component in a solar hydrogen hybrid energy system in terms of power depends on the size of each other components to meet the efficiency requirement of the whole system. Choosing the nominal electrolyzer power is critical in such energy systems.

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Introduction

With the introduction of the Paris Agreement and the seventh Sustainable Development Goal, “Affordable and Clean Energy,” solar energy is becoming increasingly used in many applications. Solar electricity prices are falling, and it is known that solar energy has the potential to meet a considerable portion of the global energy demand. However, solar energy is intermittent and not continuous. Also, the available power from PV is highly dependent on environmental conditions, such as temperature and irradiance. Therefore, effective energy storage is needed to supply the uninterrupted energy demand during nighttime and cloudy days. In the literature, integrated electrolyzer-hydrogen storage-fuel cell systems are considered as clean, fast, and reliable backup solutions to tackle this challenge.

In the literature, there are numerous studies focusing on solar-based hydrogen energy systems in stand-alone applications and zero-energy buildings. For instance, Javadpoor et al. [1] have focused on a hybrid PV-hydrogen/fuel cell system which includes an alkaline water electrolyzer and a hydrogen gas tank. The authors have verified the self sufficiency of the system for stand-alone applications. Khalid et al. [2] have proposed an integrated PV-fuel cell system for zero energy buildings and conducted comprehensive thermodynamic and economic analyses. The authors have calculated the overall energy and exergy efficiencies as 20.7% and 21.0% and the levelized cost of electricity as 0.387 \$/kWh.

Yunez-Cano et al. [3] have presented an analytical model to size, analyze, and assess the feasibility of a hybrid PV-hydrogen energy system using real weather data in Mexico City. Even though the authors have used real time irradiation values, the temperature is not considered while evaluating the PV's electricity generation. The authors have concluded that the proposed system works with 65% efficiency. Elgammal and Ali [4] have presented presents a low-cost DC and AC active power filters to enhance the power quality of hybrid hydrogen PV-fuel cell systems for stand-alone applications. The authors have aimed reducing the complexity of design and control of active harmonic filters that effectively mitigate power system harmonics.

Ozden and Tari [5] have investigated the effect of PEM fuel cell degradation on the overall performance of a stand-alone PV-fuel cell system. The authors have concluded that the system cannot operate continuously if the PEM fuel cell degradation is not avoided. Their 25-year economic analysis shows that degradation increases the levelized cost of electricity by 0.08 \$/kWh. Singh et al. [6] have conducted a techno-economic investigation of a hydrogen fuel cell-PV hybrid renewable energy system for stand-alone applications in India. Their results have shown that the hydrogen storage tank-electrolyzer-fuel cell can meet the energy demand of the selected building (university) when solar electricity is not available or sufficient.

Tiar et al. [7] have investigated the performance of a small scale stand-alone PV-fuel cell hybrid system and introduced a fuzzy logic controller to allow extracting the maximum available PV power with less oscillation around

the optimum, regardless the load changing. Assaf and Shabani [8] have investigated a solar hydrogen system sized to meet 100% of the power demand of a house. The results have showed that the system can meet more than 90% of the hot water demand, 83% of the heating demand and 100% of the power demand. Therefore, the system is concluded to be effectively used in remote households and stand-alone applications for their heating, cooling, hot water, and power demands.

Khosravi et al. [9] have investigated the thermodynamic performance of a hybrid PV-fuel cell system for stand-alone applications. The authors have found that the system's energy and exergy efficiencies to be 12% and 16%, respectively and the maximum exergy destruction to be 65%. Their economic analysis shows that energy storage makes up 50% of the total initial investment. Ramesh et al. [10] have investigated the performance of a hybrid PV-fuel cell system for a stand-alone application. The authors have obtained continuous supply to the load by implementing a control strategy. With this control strategy, the PV and the fuel cell supply the voltage to the load by getting constant supply from the DC link during day and night. The authors have modeled the entire system and investigated its performance in MATLAB/Simulink environment.

Sorgulu and Dincer [11] have proposed a solar based hydrogen energy system that can provide 1381.5 MWh electricity annually with overall efficiency between 33% and 45%. Budak and Devrim [12] have investigated the performance of a PV-fuel cell hybrid system with water and methanol electrolysis based on the actual solar irradiance data of İzmir, Turkey. According to their analysis the levelized cost of energy of the hybrid system based on water and methanol electrolyzer are 0.912 and 0.54 \$/kWh, respectively. Jafari et al. [13] have conducted a comprehensive thermoeconomic analysis of an integrated solar hydrogen energy system with PV/T, fuel cell, and a battery to meet the power and domestic hot water over a year for a stand-alone application. The authors have concluded that the overall electrical efficiency of the system is 9% and the levelized cost of electricity is 0.286 \$/kWh.

Natarajan et al. [14] have integrated PV and fuel cell for efficient and continuous power generation. The authors have simulated the PV and fuel cell separately first and then conducted a combined analysis by using MATLAB Simulink. Based on the models, the authors have concluded that the hybrid systems are very much useful in remote areas where there is difficulty to get electricity. Samy et al. [15] have conducted the techno-economic feasibility study of off-grid PV-fuel cell hybrid systems in isolated urban regions of Egypt. The authors have proposed a model to estimate the optimum number of PV panels and fuel cell/electrolyzer/storage tank size. The optimum system configuration is concluded to have 27 PV panels and levelized cost of energy of 0.334 \$/kWh.

Ghenai et al. [16] have conducted technical and economic investigation of a hybrid PV/fuel cell system. The stand-alone system is aimed to meet the electricity demand of an off-grid residential community. The authors have also investigated the effects of temperature and dust accumulation on the performance of PV. Their results show that the distributed power generation using PV and fuel cell integrated with an electrolyzer and hydrogen storage system can meet the daily

energy demand of 4500 kWh/day. The system is also considered to be economically viable with a levelized cost of energy of 145 \$/MWh and is environmentally friendly (zero CO₂ emissions during operation).

Temiz and Javani [17] have designed a hybrid floating PV-fuel cell system to meet the electrical energy demand of a small community in Aegean Region of Turkey. The authors have concluded that floating PV decreases the loss of water via evaporation from water resources by providing a 3010 m² shading area. The integrated system provides 99.43% of the electricity demand without any grid connection or fossil fuel usage. And the levelized cost of electricity is 0.6124 \$/kWh.

These studies focus on many aspects, including detailed energy and exergy analyses, cost and emissions calculations, and system optimization. However, most of the studies in the literature use average power consumption as the base in their calculations and lack providing more accurate data for the feasibility of the real-life applications. With this motivation in mind, this study investigates the performance of a stand-alone PV/electrolyzer/fuel cell system which can provide uninterrupted continuous power to meet the demand of a house. The data that used in this system is quite large and comprehensive such that solar irradiation, temperature and household energy consumption is collected in practical locations. The data are collected once every 10 min for an entire year.

Several hybrid systems with different number of PV panels, electrolyzer sizes, hydrogen storage tank volumes and fuel cell stacks are considered. Every integrated PV/electrolyzer/fuel cell system is tested based on its capacity to meet the demand of the house at every 10 min time-frame throughout the year. For every 10 min time-frame, the power generated by PV at current irradiation and temperature, the amount of hydrogen generated by the electrolyzer together with the power consumed by the electrolyzer, the amount of hydrogen in the storage tank, the amount of power generated by the fuel cell stack together with the amount of hydrogen consumed by the fuel cells are calculated, and overall, the system's self-sufficiency is tested to meet the demand of the house for the same 10 min time-frame.

In a similar study, Ertis et al. [18] have examined the feasibility and optimal sizing design of a stand-alone wind/hydrogen hybrid power system for a house in Catalca, Istanbul, Turkey. In that study, the selected location (Catalca) was more suitable for wind than solar. The location of the current study (Afyon) is more suitable for a solar hydrogen-based stand-alone system because it has sufficient irradiance for a stand-alone application. One advantage of solar-based hydrogen energy systems is they provide a more predictable energy output than wind-based hydrogen energy systems. Another advantage is unlike wind turbines, solar panels don't require particular space for installation as they can be installed on the roofs of houses or offices. For this reason, the present study is more applicable for urban zero energy building applications.

With the use of more reliable data and including the temperature of the PV's effect on electricity generation, the outputs of this study might be considered as a useful guide before the field test of the integrated PV/electrolyzer/fuel cell systems in practice.

System configuration and modelling

Site information

In this study we consider a remote house away from the national power grid lines in Afyon city, Turkey. Close to this house, there is a 12 m meteorological solar/wind measurement tower and the data used in the present study is collected from this measurement system. The meteorological measurement system collects 10 min of averaged solar irradiance, solar duration, wind speed and direction, air temperature and pressure and also relative humidity data. It is desired to construct a solar hydrogen hybrid energy system that will ensure uninterrupted power to the house at any time of the year. The schematic of the solar hydrogen hybrid energy system for the house are given in Fig. 1.

System components

Photovoltaic (PV) solar panels

A monocrystalline module (GCL-M3/60H [19]) is used for the hybrid system after reviewing several photovoltaic solar panels and their specifications. The manufacturer's product sheet which includes the electrical specifications is shown in Table 1. Standard Test Conditions (STC) denotes the measurements at 1000 W/m² irradiance, 25 °C module temperature and air mass 1.5 spectra where as the Nominal Operating Cell Temperature (NOCT) denotes the measurements at 800 W/m² irradiance, 20 °C ambient temperature and 1 m/s wind in Table 1.

During operation, the solar irradiance and the module cell temperature change all the time, and these parameters affect the instantaneous output of the solar panel. The effect of the instantaneous solar irradiance and the cell temperature should be taken into consideration to create the actual operating conditions [20]. The cell temperature is calculated using the following equation [21].

$$T_{\text{cell}} = T_{\text{air}} + (\text{NOCT} - 20) \frac{G}{800 \frac{\text{W}}{\text{m}^2}} \quad (1)$$

here G is the instantaneous solar irradiance [W/m²] measured by pyranometer in the meteorological measurement system and the temperatures are in Celsius degrees [°C].

Fig. 2 shows the changes in the I–V curve of the considered solar panel according to the solar irradiance and module cell temperature.

Fig. 2a shows the effect of cell temperature on the I–V curve. The cell temperature affects open circuit voltage significantly and the relationship between cell temperature and open circuit voltage is linear. The effect of cell temperature on the short circuit current is negligible. Thus the cell temperature is considered to affect the open circuit voltage only. The relationship between the cell temperature and the open circuit voltage is given by the manufacturer as a percentage change (Temperature Coefficient of V_{OC} ($\text{TC}_{\text{Coef}V_{\text{OC}}}$)) in Table 1. The open circuit voltage is calculated as follows

$$V_{\text{OC}}(T_{\text{cell}}) = V_{\text{OC}}(25^\circ\text{C}) + V_{\text{OC}}(25^\circ\text{C}) \times \text{TC}_{\text{Coef}V_{\text{OC}}} \times (T_{\text{cell}} - 25) \quad (2)$$

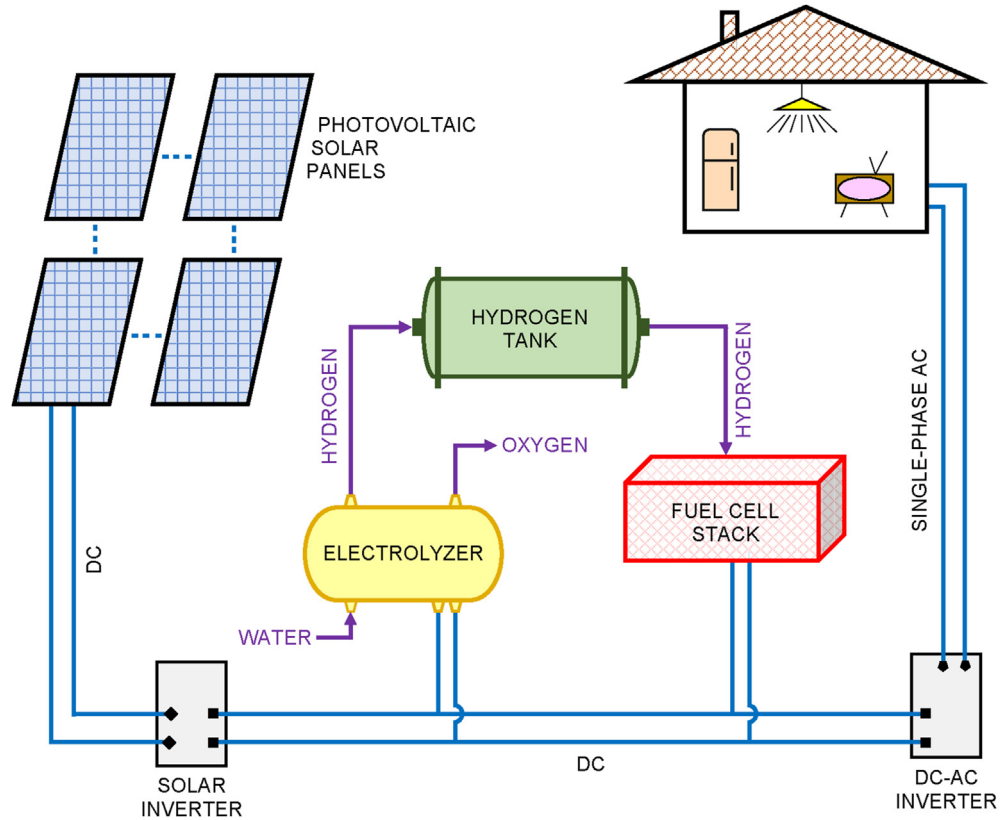


Fig. 1 – Schematic of the considered solar hydrogen hybrid energy system.

Table 1 – Solar panel specifications [19].

Electrical Specifications STC	
Maximum Power P_{max}	325 W
Maximum Power Voltage V_{MP}	34.2 V
Maximum Power Current I_{MP}	9.51 A
Open Circuit Voltage V_{OC}	41.1 V
Short Circuit Current I_{SC}	9.88 A
Module Efficiency	19.3%
Electrical Specifications NOCT	
Maximum Power P_{max}	241.39 W
Maximum Power Voltage V_{MP}	32.1 V
Maximum Power Current I_{MP}	7.52 A
Open Circuit Voltage V_{OC}	38.2 V
Short Circuit Current I_{SC}	7.99 A
Temperature Ratings	
Nominal Operating Cell Temperature NOCT	44 °C
Temperature Coefficient of V_{OC} ($TC_{CoefV_{OC}}$)	−0.3%/°C

Similarly, Fig. 2b shows the effect of solar irradiance on the I–V curve. The solar irradiance affects short circuit current significantly and the relationship between solar irradiance and short circuit current is linear. The effect of solar irradiance on the open circuit voltage is negligible. Thus the solar irradiance is considered to affect the short circuit current only. Short circuit current is calculated as follows [22].

$$I_{sc}(G) = I_{sc} \left(1000 \frac{W}{m^2} \right) \frac{G}{1000 \frac{W}{m^2}} \quad (3)$$

Solar controllers always operate with the Maximum Power Point Tracking (MPPT) algorithm to maximize the efficiency and therefore the output of the solar panels. The instantaneous maximum power (P_{MP}) by using the Fill Factor is calculated from the following equation

$$FF = \frac{P_{MP}}{V_{OC} I_{SC}} \quad (4)$$

Polymer electrolyte membrane (PEM) electrolyzer

In the electrolyzer, water decomposes into hydrogen and oxygen by applying electrical energy. Four different polymer electrolyte membrane (PEM) electrolyzer models which have nominal powers of 3, 5, 7, and 9 kW are used for the hybrid system [23]. Their specifications are given in Table 2. The electrolyzers can work within a load range between the minimum and the maximum load and the corresponding hydrogen production range at nominal, minimum, and maximum loads are given in Table 2. Three points (nominal, minimum, and maximum) are shown on the power vs. hydrogen production rate graph in Fig. 3. The operating curve of the electrolyzer is formed by using these points which show the hydrogen generation of the electrolyzer at any power generation.

It is stated in the specification sheet that the electrolyzers can produce hydrogen up to 30 bar pressure. In some cases, compressors are integrated into hybrid systems to store more hydrogen in relatively smaller tanks to reduce the storage tank volume. Adding a compressor to such a system will decrease the storage tank volume; however, it will

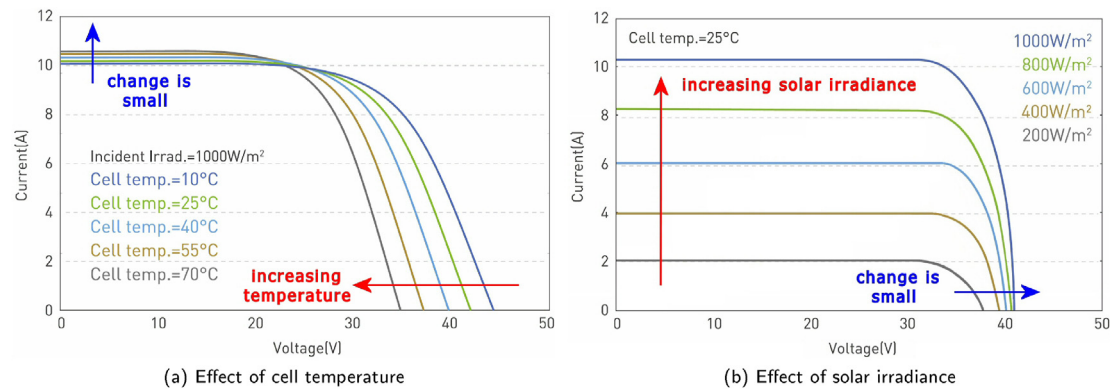


Fig. 2 – Effect of the solar irradiance and cell temperature on the considered solar panel performance [19]. (a) Effect of cell temperature (b) Effect of solar irradiance.

Table 2 – Manufacturer's specifications of the considered electrolyzer models [23].

Parameter	Electrolyzer			
Nominal Load	3 kW	5 kW	7 kW	9 kW
Load Range	0.77–5.63 kW	1.28–9.38 kW	1.79–13.13 kW	2.30–16.88 kW
Load Change	Partial Load - Nominal Load = 5 s Nominal Load - Peak Load = 5 s			
Nominal Efficiency	75%			
H ₂ Nominal Production	0.66 Nm ³ /h	1.10 Nm ³ /h	1.54 Nm ³ /h	1.98 Nm ³ /h
H ₂ Production Range	0.19–0.94 Nm ³ /h	0.31–1.57 Nm ³ /h	0.43–2.20 Nm ³ /h	0.56–2.83 Nm ³ /h
Water Consumption	0.16–0.80 kg/h	0.27–1.33 kg/h	0.38–1.86 kg/h	0.49–2.39 kg/h
Cooling Water Flow Rate	9–199 kg/h	14–330 kg/h	20–463 kg/h	25–594 kg/h
Operating Temperature	30–70 °C			
H ₂ O Purity	DIN ISO 3696 type 1			

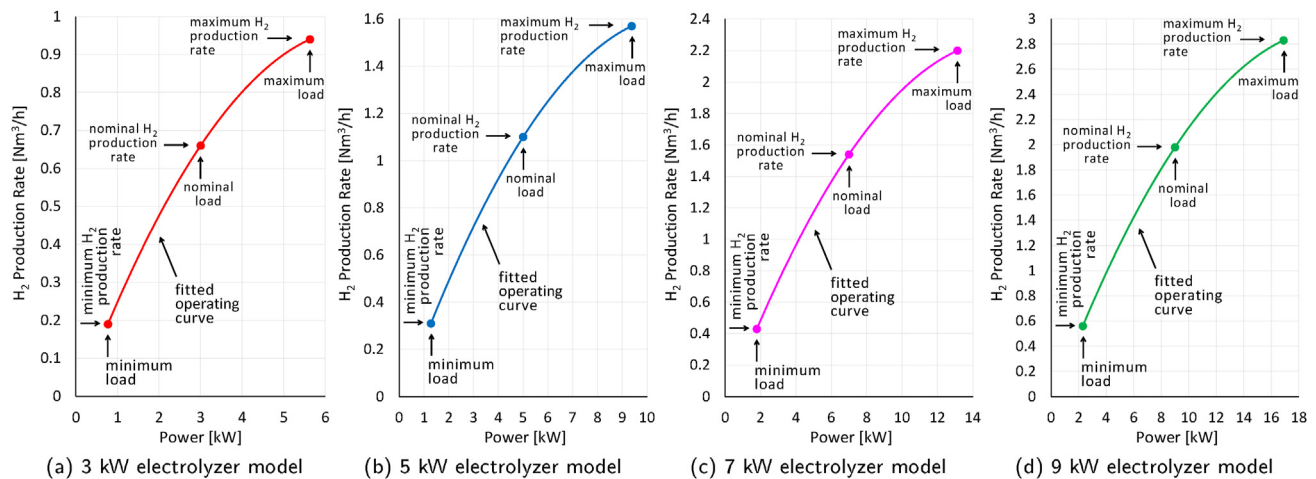


Fig. 3 – Operating curves of the considered electrolyzers (power vs hydrogen production rate). (a) 3 kW electrolyzer model (b) 5 kW electrolyzer model (c) 7 kW electrolyzer model (d) 9 kW electrolyzer model.

undoubtedly increase the complexity of the system since the compressor itself would consume power during operation. As shown in system schematics (Fig. 1), the considered solar hydrogen hybrid system does not contain a compressor. For this reason, it is assumed that the pressure in the storage tank could increase up to a maximum of 30 bar since the electrolyzers can generate hydrogen up to 30 bar. When the pressure in the tank reaches 30 bar, the tank is assumed full and the

hydrogen generation is stopped since the hydrogen generated by the electrolyzer cannot be compressed into the storage tank any longer. Any energy generated in the system when the tank is full is assumed to be wasted.

Hydrogen storage tank

The hydrogen generated by the electrolyzer is stored in the tank. The stored hydrogen is used in the fuel cell stack for

power generation whenever is needed. As explained above, it is assumed that the pressure of the hydrogen in the tank could be at a maximum of 30 bar (3000 kPa). When the hydrogen exists under a critical pressure (<1.3 MPa) condition, it behaves like an ideal gas, and ideal gas law can be applied. Otherwise, the hydrogen acts like a real gas (>1.3 MPa), and the inconsistency between the volume of real gas and ideal gas will be high. This inconsistency is generally determined by using the concept of compressibility factor (Z) and Boyle Charles's equation is given as follows

$$PV = ZnRT \quad (5)$$

where P , V , n , R and T are the pressure, volume, mol number of the hydrogen, gas constant, and temperature, respectively. Following [18], equation (5) is used to calculate the amount of hydrogen in the tank. If the pressure of the hydrogen tank is below the critical pressure of hydrogen, the compressibility factor (Z) will be taken 1. However, if the pressure of the hydrogen tank exceeds 1.3 MPa, the value of the compressibility factor (Z) should be calculated using equation (6). The compressibility factor (Z) depends on both pressure and temperature and the approximate equation is given as follows [24].

$$Z = 1 + P(A + BT^{-1} + CT^{-2} + DT^{-3} + ET^{-4}) \quad (6)$$

where P is pressure, T is temperature, and the constants are

$$\begin{aligned} A &= 4.93482 \times 10^{-5} \\ B &= 2.04036 \\ C &= 8.15334 \times 10 \\ D &= -6.5561 \times 10^4 \\ E &= 4.56516 \times 10^6 \end{aligned} \quad (7)$$

According to equation (6), if the temperature of the hydrogen decreases and the pressure of the hydrogen increases, the impact of the compressibility factor will increase.

The volume of the hydrogen tank is related to the maximum amount of hydrogen that can be stored in the tank. The maximum amount of hydrogen ($m_{H_2,max}$) in the tank (in terms of kg) is calculated by the following equation

$$m_{H_2,max} = \frac{P_{H_2,max} V_{tank}}{ZRT} \quad (8)$$

where Z is the compressibility factor, R is gas constant for hydrogen (4.124 kJ/kg.K), T is the temperature of hydrogen in the tank, $P_{H_2,max}$ is the maximum allowable pressure in the tank (3000 kPa) and V_{tank} is the tank volume. The maximum amount of hydrogen ($m_{H_2,max}$) can be converted to $N_{H_2,max}$ by using the molar mass of H_2 which is 2 kg/kmol. In this study, it is assumed that the temperature of the hydrogen in the tank, which is located outside, is equal to the ambient air temperature.

Polymer electrolyte membrane (PEM) fuel cell stack

A PEM fuel cell generates electricity by combining hydrogen with oxygen like the opposite of an electrolyzer. A PEM fuel cell with 100 W nominal rated power is used for the hybrid system [25] and the specification sheet is given in Table 3. In the hybrid system, there will be 100 W PEM fuel cell stacks to supply the power demand of the house.

The voltage-current ($V-I$) and power-current ($P-I$), and the hydrogen consumption-power curves for the PEM fuel cell

Table 3 – Manufacturer's specifications of the considered fuel-cell model [25].

Type of fuel-cell	PEM
Number of cells	20
Rated Power	100 W
Performance	12 V @ 8.3 A
H ₂ Supply valve voltage	12 V
Purging valve voltage	12 V
Blower voltage	12 V
Reactants	Hydrogen and air
External temperature	5–30 °C
Max. Stack temperature	65 °C
H ₂ Pressure	0.45–0.55 bar
Hydrogen purity	$\geq 99.995\%$ dry H ₂
Humidification	self-humidified
Cooling	Air (integrated cooling fan)
Stack weight	1290 g (± 50 g)
Controller weight	400 g (± 30 g)
Dimension	11.8 cm $\times$ 10.4 cm $\times$ 9.4 cm
Flow rate at max output	1.3 L/min
Startup time	≤ 30 s at ambient temperature
Efficiency of stack	40% @ 12 V
Low voltage shut down	10 V
Over-current shut down	12A
Over-temperature shut down	65 °C

from the product brochure are given in Fig. 4a, b and c respectively.

The output voltage and power of fuel cell change when the current changes as seen in Fig. 4a and b. In the study, all of the calculations depend on power; therefore, the operating curve of the fuel cell gives the hydrogen consumption rate of the PEM fuel cell at any power output in Fig. 4c. The hydrogen consumption of the fuel cell increases almost linearly as the power output of the PEM fuel cell increases at low power outputs. However, towards the rated power (100 W) of the fuel cell, the curve becomes steeper which means that the hydrogen consumption of the fuel cell increases higher than linear behavior. Thus, when the fuel cell is operated close to its rated power, the fuel cell consumes increasingly more hydrogen. This fact will affect the hydrogen amount in the storage tank.

Power consumption of the house

The instantaneous power consumption of the considered house in Afyon is needed for the simulation of the hybrid system. However, the continuous yearly consumption measurement data doesn't exist, and there are only several readings of the consumption power taken at different daily and seasonally times. These measurements show that the power consumption of the house has a daily and seasonal variation. For example, the consumption increases compared to the consumption in the daytime as the households gather in the evening, in which fewer households are at home. Besides, the consumption decreases since the households are at sleep towards midnight and after. In terms of seasonal variation, the power consumption is higher in the winter time than it is in the summer time since households stay indoors.

In the United Kingdom, The Department of Energy & Climate Change carried out the Household Electricity Survey

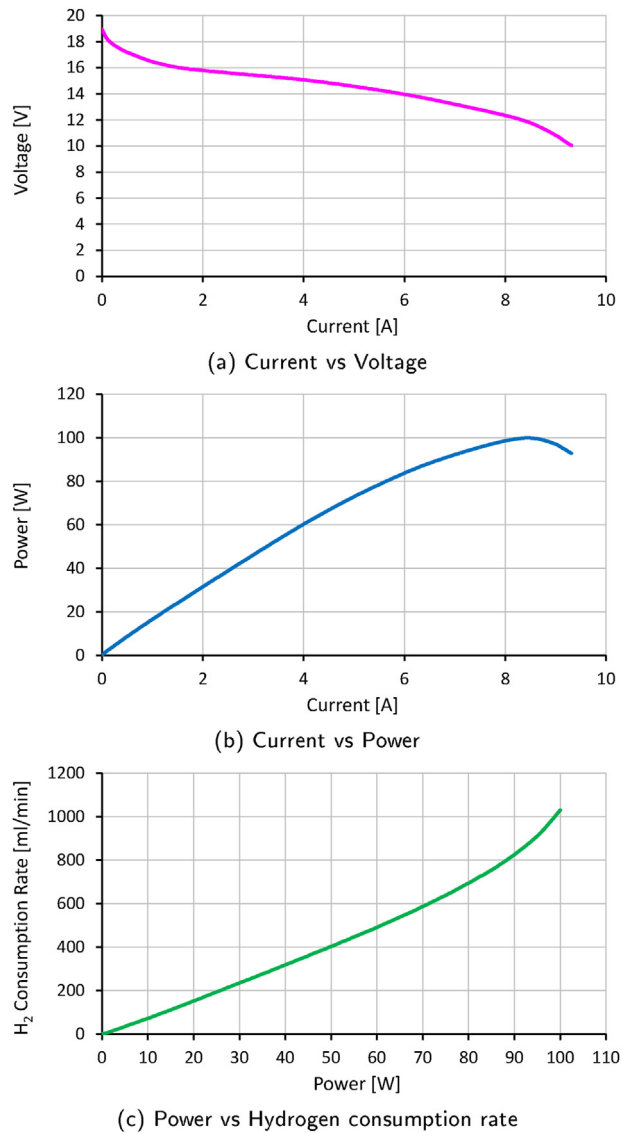


Fig. 4 – Manufacturer's technical figures of the considered fuel-cell model [25].(a) Current vs Voltage, (b) Current vs Power, (c) Power vs Hydrogen consumption rate.

(HES) study in order to examine the scope for reducing peak electricity demand. In this study, the electricity consumption of 250 households across England was monitored at an appliance level. The details of the Household Electricity Survey (HES) study can be found in Ref. [26]. The measured data is publicly available together with many extensive analyses and reports [26]. The data is in 10 min measurements which match in terms of sampling interval with the 10 min measurements of our meteorological measurement system.

Fig. 5 shows the daily consumption of the Household Electricity Survey (HES) data (average of the 250 households) for each month. The consumption increases in the Fall and Winter months compared to the Spring and Summer months. Besides, when everybody is at sleep after midnight, consumption decreases. Conversely, the consumption increases a bit in the mornings but increases more in the evenings since the households are at home. The published Household Electricity Survey (HES) data in Ref. [26] represents the power

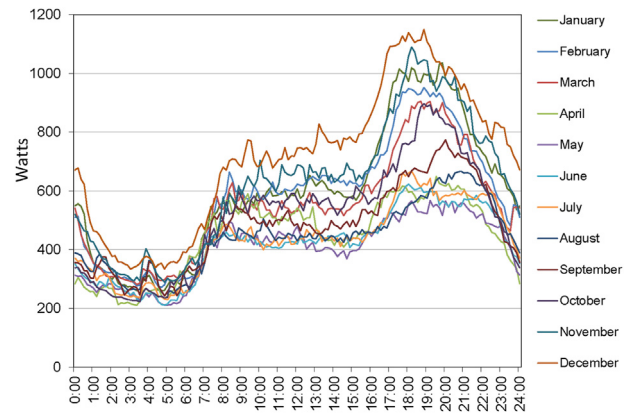


Fig. 5 – Daily average power consumption of the Household Electricity Survey (HES) data in different months of the year.

consumption of the considered house in Afyon, Turkey which is used in the study within some error that would be $\leq \pm 5\%$ on average according to several readings and both daily and seasonal variations (Fig. 5). The daily power consumption profiles repeat every day in the corresponding month that is assumed in a particular month shown in Fig. 5.

Methodology and calculations

The algorithm in the present simulation is given in Fig. 6. For the considered house, the primary power source is the photovoltaic solar panels. The PEM electrolyzer model, the number of photovoltaic solar panels in the solar panel array, and the number of PEM fuel cell stack are decided at the beginning of the simulation. After that, the storage tank volume is set and the simulation is started. The system is simulated based on 10-min intervals, and the power is balanced between the hybrid system components, solar panel array, PEM electrolyzer model, hydrogen storage tank, PEM fuel cell stack, and the house in each 10-min interval. In the daytime, if the power generated by the solar panel array is equal to or above the house's consumption power of the house, then this generated power feeds the consumption power. The electrolyzer uses any excess power above the consumption amount to generate hydrogen.

For the electrolyzer, there are two constraints for hydrogen generation; i) the power coming to the electrolyzer must be above the minimum load of the electrolyzer, ii) it must be below the maximum load since the electrolyzer can only operate between these minimum and maximum loads. When the power coming to the electrolyzer is below the minimum load or above the maximum load, it is considered as 'non-utilizable' and does not contribute to the hybrid system. At any time, if the power coming to the electrolyzer is between the minimum and the maximum load of the electrolyzer, then the operating curve of the electrolyzer is used to determine the amount of hydrogen generated according to the input power given in Fig. 3.

The amount of hydrogen generated by the electrolyzer is stored in the hydrogen storage tank. To maintain a hydrogen flow from the storage tank to the fuel cell, the pressure in the

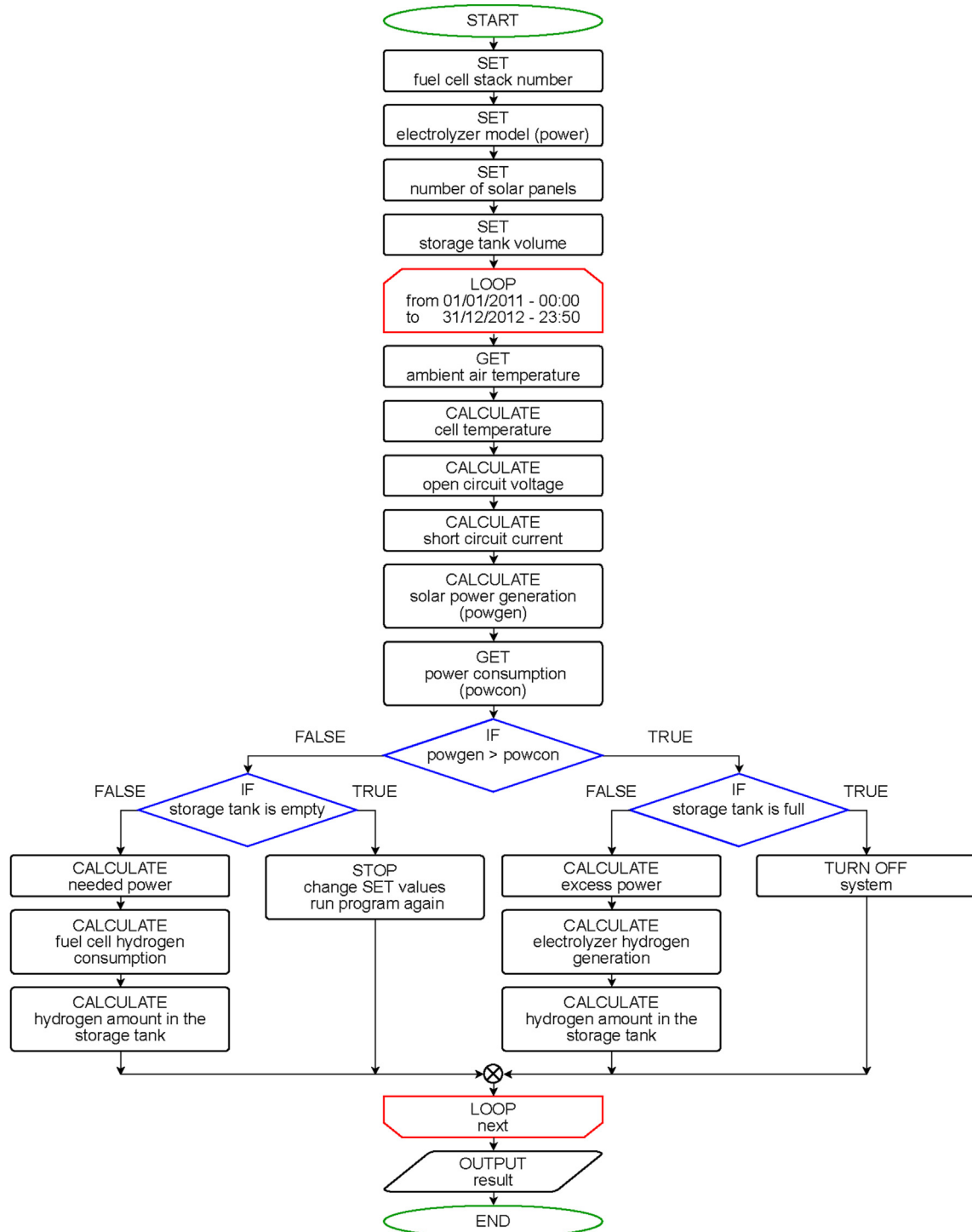


Fig. 6 – Flowchart of the algorithm used in the simulations.

storage tank must be greater than the ambient pressure. During the simulation, at any time when the pressure in the storage tank falls below the ambient pressure, the simulation stops since there is not enough hydrogen left in the storage tank such that the storage tank volume is not enough for the hybrid system. Then, the storage tank volume is changed and the simulation is restarted with the new value. Based on the above criteria, the aim of the study is trying to find the

minimum storage tank volume, which is enough to support the system to operate without any interruption of power all around the year. Any storage tank volume which is above the minimum volume will work in practice. However the aim in the present simulation is to obtain the minimum possible parameters for the hybrid system.

Any amount of hydrogen generated by the electrolyzer is added to the storage tank, and the pressure in the storage tank

is updated, corresponding to the new amount of hydrogen in the tank. As mentioned above earlier, the electrolyzer model can have a discharge hydrogen pressure of 30 bar. For this reason, the pressure in the storage tank can be at a maximum of 30 bar at the full capacity. When the pressure in the storage tank reaches 30 bar, it is assumed that the electrolyzer stops producing hydrogen. In the cases when the storage tank is at full capacity, and there is excess power above the consumption of the house, this power is considered as 'non-utilizable.' In the simulation, the amount of energy not utilized by the electrolyzer is calculated cumulatively due to the full storage tank. This indicates that a hybrid energy system with the chosen solar panel number, PEM electrolyzer model, storage tank volume, and PEM fuel cell stack can support the house; however, the full capacity of the whole system is not used efficiently.

During the simulation, at any time, if the power generated by the solar panel array is not sufficient to support the house itself, then the needed amount of power is generated by the fuel cell stack. The number of fuel cell stacks is set at the beginning of the simulation. The hydrogen consumed by the fuel cell is obtained for any amount of needed power by using the operating curve given in Fig. 4c. The amount of hydrogen decreases from the storage tank, and therefore the amount of hydrogen and the pressure is updated.

A solar inverter and a DC/AC inverter are also considered in the system as shown in the schematics in Fig. 1. The electrolyzer requires a DC input, and the fuel cell stack discharges a DC output. The solar inverter is used to regulate the DC bus. The DC/AC inverter is used to supply AC electricity with 220 V with 50 Hz frequency which is the grid voltage and frequency in Turkey. Solar and AC/DC inverters have 95% and 90% efficiency, respectively, which are average efficiencies among many models.

Results and discussions

Solar energy is one of the most popular renewable energy sources all around the world. There is no mechanical moving part in solar energy systems, which makes the system free from mechanical maintenance. The solar panels remain outside during operation, and dirt can accumulate on the surface of the panels, which can block the solar light. Cleaning the surface of the panels from time to time can help to increase the efficiency of a solar system. The solar panels generate electricity when subjected to sunlight, and the temperature of the panels can increase to high values, which will decrease the solar panel efficiency. The local climate affects the solar system efficiency significantly. Fig. 7 shows the solar irradiance, the ambient temperature, the calculated power generation of a single solar module, and the calculated solar panel cell temperature in a couple of typical summer days. Likewise, Fig. 8 shows the same for a couple of typical winter days. For example, the solar irradiance has a smooth profile showing that there are no clouds in the day on June 10, 2012, in Fig. 7a. On this day, at noon, even though the ambient temperature reaches 25 °C, the solar cell temperature reaches almost 56 °C, which will significantly reduce the solar panel efficiency. Solar panel power generation is also greatly

affected by the clouds, which is a significant problem for solar energy. At times when the clouds block the sunlight, the power production of the solar panel decreases significantly, and the solar panels begin to cool off slightly; thus, the cell temperature decreases as seen in Fig. 7b and c.

In the winter time, even though the ambient temperature is below 0 °C, around noon, the panel cell temperature can reach 16 °C on December 08, 2012, in Fig. 8a. Rainy and cloudy days can also affect solar power generation very significantly as seen in Fig. 8b and c. For these reasons, in such a hybrid system design, using local climatic conditions is essential for system efficiency and simulation accuracy.

Fig. 9 shows some of the yearly measured and calculated parameters such as measured solar irradiance, calculated solar power generation of one solar module, calculated solar panel cell temperature, measured ambient air temperature, and measured power consumption of the house. The location of the considered house, which is in Afyon city in Turkey, is known to be a good place for solar energy systems. From Fig. 9a, the measured average solar irradiation and maximum solar irradiations are 209.1 W/m² and 1196.7 W/m², respectively. The calculated power generation of one solar panel module is given in Fig. 9b according to the irradiance given in Fig. 9a. The solar panel module is rated with a maximum power of 325 W (STC) as given in Table 1. From Fig. 9b, the solar panel module has an average and maximum power generation of 64.2 W and 346.5 W, respectively. The measured air temperature at the site is given in Fig. 9c. The average ambient air temperature in Afyon city is 13.2 °C which is very suitable for a solar system investment with high irradiance and low temperature. Fig. 9d shows the calculated cell temperature of the solar panels. The yearly average cell temperature is 19.5 °C; however, the maximum cell temperature reaches as high as 65.6 °C in the summer. Fig. 9e shows the yearly power consumption of the house. The average power consumption of the house is 517.5 W, and the yearly average wind speed is 4.1 m/s with an average relative humidity of 55% in Afyon city.

The highest power consumption in the house occurs in December as seen in Fig. 9a. During operation of the hybrid energy system, if the fuel cell stack is only the supplying source when there is no solar power, the minimum number of fuel cell stacks (each of 100 W) that must be used in the system by taking the efficiency of the inverter into account is 14 which makes a total power of 1400 W. When 14 fuel stack number is used in the system, for example, in December, the fuel cells work almost at the full capacity. As mentioned earlier, when the fuel cells operate near their full capacity, they consume comparatively more hydrogen, as shown in Fig. 4c. For this reason, different hybrid systems with fuel cell stack numbers are considered higher than 14 in the study (with electrolyzer capacity > 1400 W).

During the daytime, the available power sources for the house are the solar power coming from the solar panel array and the power coming from the fuel cell stack, which consumes the hydrogen in the storage tank during the operation. However, after the sun sets during the night, the fuel cell stack is the only available power source in the hybrid system. The World Meteorological Organization (WMO) defines sunshine duration as the time during which the direct solar radiation

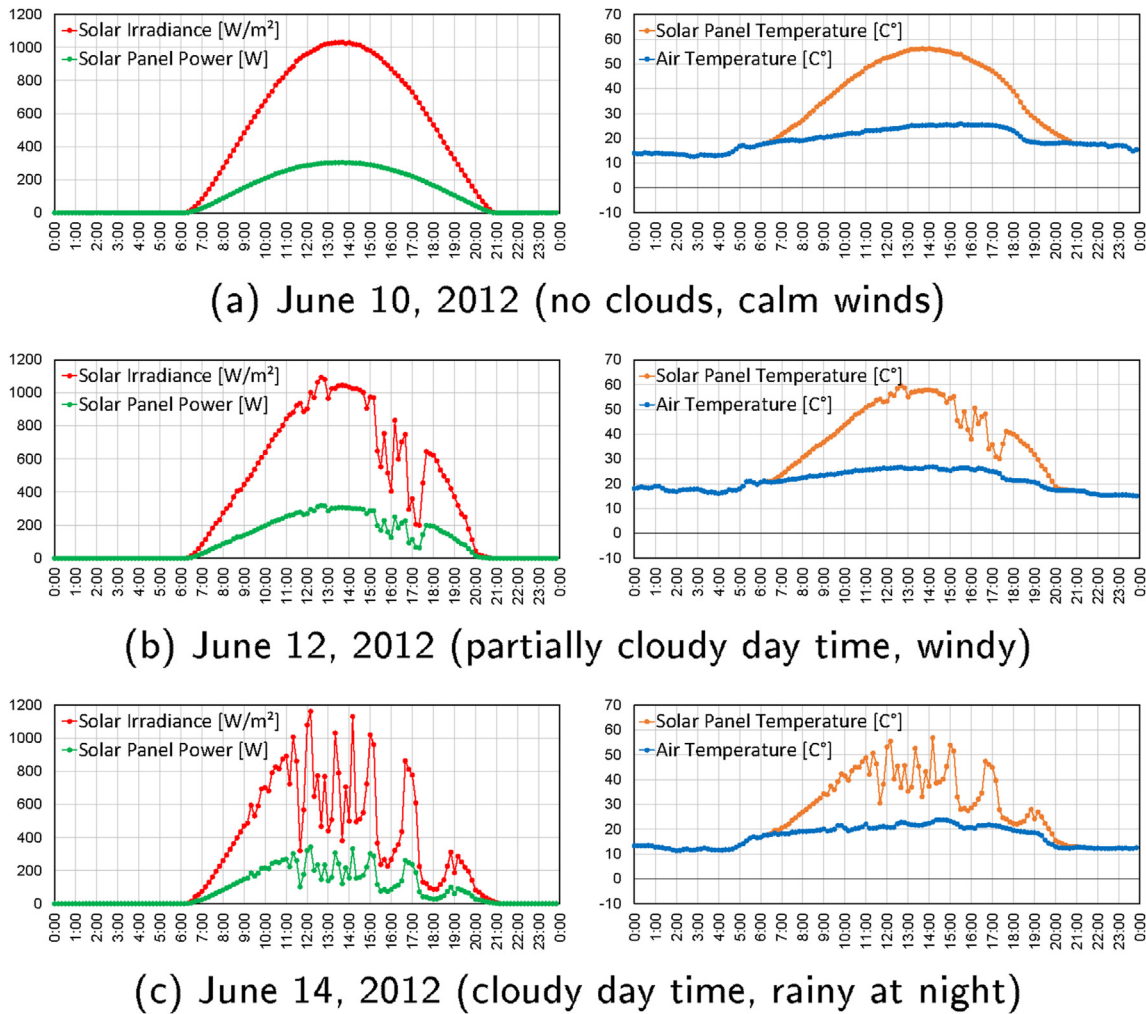


Fig. 7 – Solar irradiance, power generation of 1 solar panel, air temperature and solar panel cell temperature in typical summer days at the site.

exceeds the level of 120 W/m^2 [27]. The sunshine duration increases in summers and decreases in winters, nevertheless at the site, in Afyon Turkey, the yearly averaged sunshine duration is 9.4 h per day. Therefore, the electrolyzer must be able to generate enough hydrogen to be stored in the hydrogen tank for power consumption at night as well as the solar panel array must be large enough to deliver enough power to the electrolyzer in the solar hydrogen hybrid energy system.

At the beginning of the simulation, the storage tank is assumed as full of hydrogen, and the simulation is started on January 1. Several different hybrid systems are obtained from the algorithm given in Fig. 6. They have different solar panel numbers, electrolyzer models, fuel cell stack numbers, and storage tank volume that could supply uninterrupted continuous power to the considered house at any time in a year. These different hybrid systems are tabulated in Table 4 to Table 7.

In Table 4 to Table 7, each row denotes a different suitable hybrid system for the house with given solar panel numbers, electrolyzer models, storage tank volume, and fuel cell stack

numbers. In all of the hybrid systems are listed in Table 4, assuming that the consumption of the house and the meteorological data repeats the same every year, the hybrid system starts to have a repeating yearly hydrogen cycle in the storage tank after the second year. The yearly hydrogen cycle of the system is different for every different hybrid system given in Table 4. The hydrogen amount in the storage tank is given throughout the first and second years for the hybrid systems with 20 fuel cell stacks and a 5 kW electrolyzer model in Fig. 10.

In the third year, the hydrogen cycle is the same as the second year. For example, the hydrogen amount in the storage tank decreases from November to February and then starts to increase from March to May by looking at the repeating hydrogen cycles (second-year cycles) with the 25 solar panels and 12.2 m^3 storage tank given in Fig. 10a. Between June and October, the hydrogen amount is almost full in the storage tank with very little oscillations around the full capacity. The reason for this behavior lies in the consumption cycle of the house given in Fig. 9e.

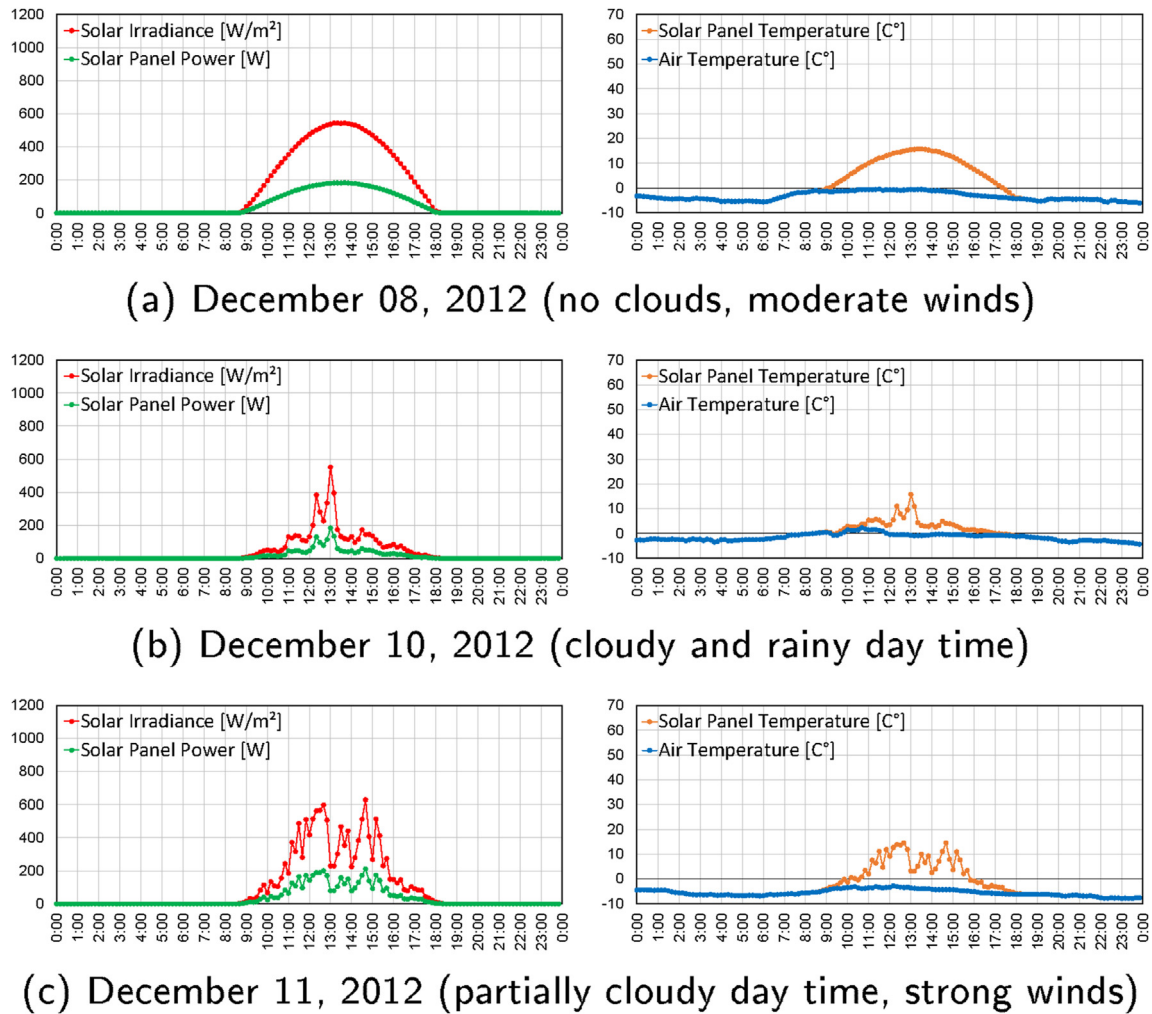


Fig. 8 – Solar irradiance, power generation of 1 solar panel, air temperature and solar panel cell temperature in typical winter days at the site.

In Fig. 9e, the consumption of the house increases in the Fall and Winter seasons and decreases in the Spring and Summer seasons. In the Fall and Winter seasons, the power from the solar panel array is not enough to support the house and the electrolyzer to fill the storage tank since the solar irradiance is relatively low. Therefore, the consumption of the house is mainly supplied by the fuel cell stack mainly day and night in the Fall and Winter seasons since the solar panel array cannot generate enough power. However, the solar array starts to supply the house most of the daytime and the electrolyzer to keep the storage tank full with increasing solar irradiance and solar duration in Spring and Summer seasons. In Spring and Summer seasons, the fuel cell stack kicks in to generate power only at nights when there is no sunlight. The size of the hydrogen storage tank becomes essential, especially in Fall and Winter seasons, such that there should be enough hydrogen stored in the tank to support the house.

There are 25 and 35 solar panels in the different hybrid systems in Fig. 10a and b, respectively. When the number of solar panels is increased in a hybrid system, this will help to generate more solar power in Fall and Winter seasons, which

eventually will increase hydrogen generation. For this reason, when the number of solar panels is increased in the hybrid system, a smaller storage tank can be used in system. A storage tank with a 12.2 m³ capacity is needed when 25 solar panels are used in Fig. 10a whereas a storage tank with 5.1 m³ volume is enough for the system when 35 solar panels are used in Fig. 10b. The hydrogen amount in the tank with 25 solar panels starts to decrease from the full capacity in November and then again increases back to almost full capacity in June (Fig. 10a).

The hydrogen in the storage tank first starts to decrease then increases between November and June (7 months). The tank stays almost full between June and November. However, the hydrogen amount in the storage tank with 35 solar panels starts to decrease from full capacity in December and then increases back to full capacity again in April (4 months) in Fig. 10b. In the system, when there are a large number of solar panels, the decreasing and increasing of the hydrogen in the storage tank occurs less time of the year, and the hydrogen storage tank stays almost full capacity in more time of the year. In Fig. 10c and d, as the number of solar panels is

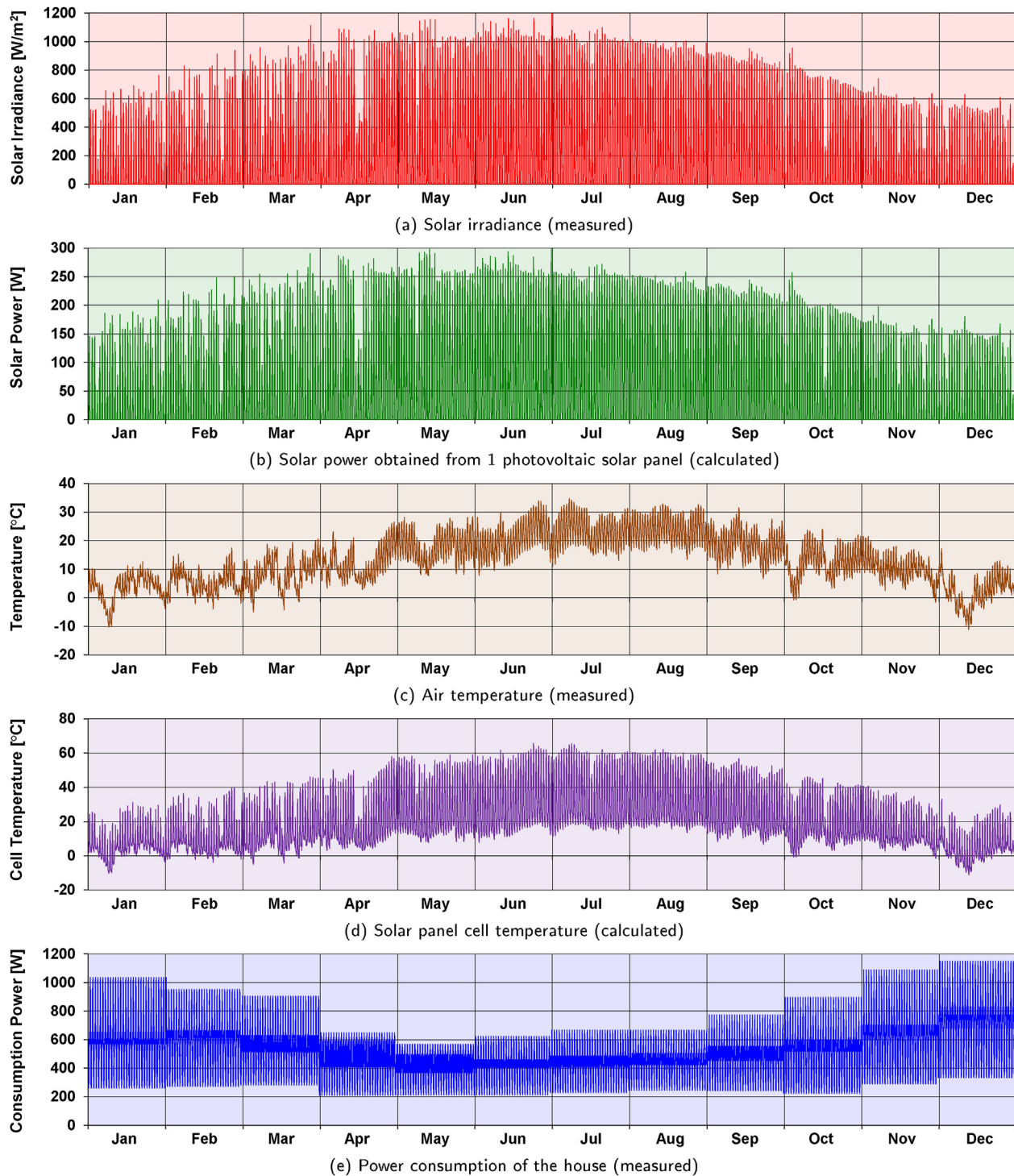


Fig. 9 – Measured and calculated yearly data.

increased to 45 and 55, smaller storage tank can be used, and the hydrogen storage tank stays almost full increased time of the year. Even though 55 solar panel numbers can be considered as many for a single house, these solar panels can able to support the house and the electrolyzer such that the tank is almost full all around the year at any season. A storage tank with 0.7 m^3 volume is enough for the hybrid system when 55 solar panels are used (Fig. 10d).

The storage tank volumes are different such that the y-axis of the figures has different scales in the hybrid systems given in Fig. 10. The storage tank volume is fixed to 12.2 m^3 in all of the hybrid systems to pinpoint the effect of increasing the solar panel number solely, and the simulations are run again. The resultant hydrogen amount in the storage tank cycles is given in Fig. 11. Every component in the hybrid systems is the same except the number of solar panels. When the number of

Table 4 – Designed hybrid systems with 3 kW electrolyzer.

Electrolyzer Capacity [kW]	Number of PV panels	Number of Fuel Cell Stack	Storage Tank Volume [m ³]	Nonutilizable Energy (above) [kWh]	Nonutilizable Energy (below) [kWh]	Nonutilizable Energy (full tank) [kWh]
3	25	14	13.8			4731.5
		16	13.0	412.8	208.6	4824.5
		18	12.5			4886.7
		20	12.3			4936.4
	30	14	10.6			6184.3
		16	9.8	1495.6	182.3	6277.3
		18	9.3			6338.7
		20	9.1			6388.4
	35	14	8.0			7230.3
		16	7.2	2992.2	163.2	7325.9
		18	6.8			7389.7
		20	6.5			7438.7
	40	14	6.0			8043.0
		16	5.2	4785.5	146.6	8154.3
		18	4.9			8224.5
		20	4.7			8283.5
	45	14	4.7			8725.5
		16	4.0	6802.9	133.3	8836.3
		18	3.8			8909.5
		20	3.6			8966.6
	50	14	3.8			9289.5
		16	3.2	8965.0	122.3	9411.1
		18	2.9			9485.8
		20	2.7			9538.3
	55	14	3.0			9780.4
		16	2.4	11228.6	116.1	9883.0
		18	2.2			9952.3
		20	2.0			10003.8
	60	14	2.4			10189.9
		16	1.9	13566.9	109.0	10294.5
		18	1.7			10358.0
		20	1.5			10402.9
	65	14	1.9			10550.6
		16	1.5	15966.6	102.6	10641.5
		18	1.3			10702.6
		20	1.1			10734.9
	70	14	1.6			10864.9
		16	1.2	18415.9	99.3	10946.3
		18	1.0			10992.3
		20	0.8			11014.9
	75	14	1.3			11130.1
		16	0.9	20907.3	95.5	11189.9
		18	0.7			11225.1
		20	0.6			11260.5
	80	14	1.1			11365.8
		16	0.7	23433.1	91.0	11412.5
		18	0.6			11476.2
		20	0.6			11545.9

solar panels increases in Fig. 11a–e, a smaller decrease is observed in the amount of hydrogen in Fall and Winter seasons, and there is almost no decrease in the hydrogen amount with 55 solar panels where the hydrogen amount oscillates around the full capacity in Fig. 11e.

It is stated that the only difference between the hybrid systems given in Figs. 10d and 11e is the storage tank volume; however, the hydrogen cycle is not the same when the zoomed view of Fig. 11e is examined in Fig. 12. The reason for this behavior is that the pressure in the storage tank follows a different cycle when the volume of the storage tank changes,

and this affects the compressibility of the hydrogen accordingly. For example, if there are 2 kg of hydrogen in a smaller tank at full capacity and the fuel cell stack consumes 1 kg of it, the pressure change will be different than 1 kg of hydrogen used from a bigger tank as 30 kg of hydrogen at full capacity. Therefore, when the storage tank volume is changed, the hydrogen cycle in the storage tank changes even though every other system components are the same.

Then, the effect of increasing the fuel cell stack number is examined. As mentioned earlier, 14 fuel cell stacks with a total of 1400 W are enough to support the house even in the highest

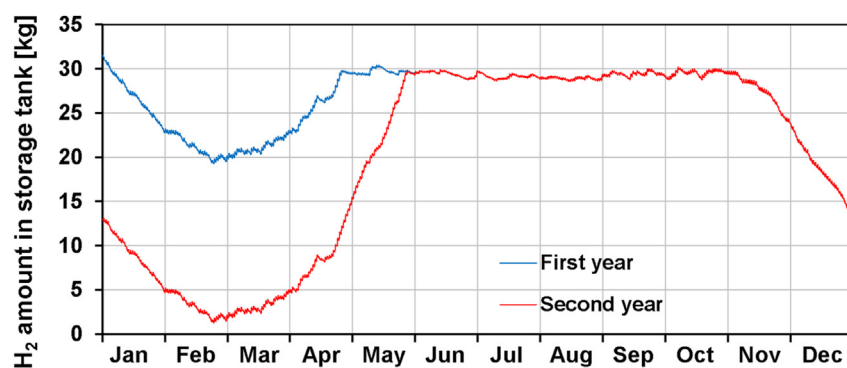
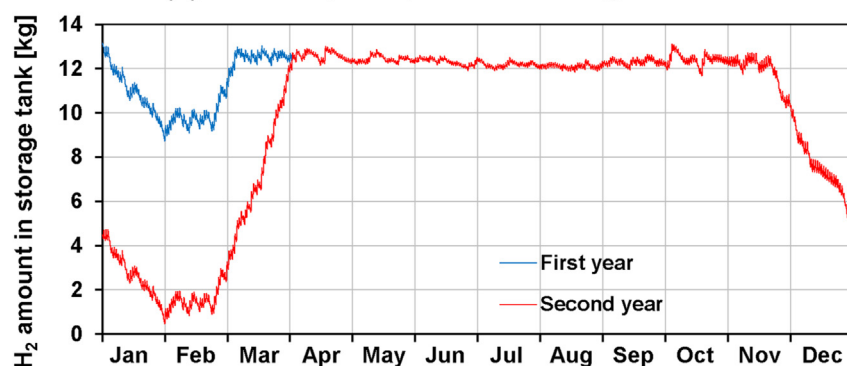
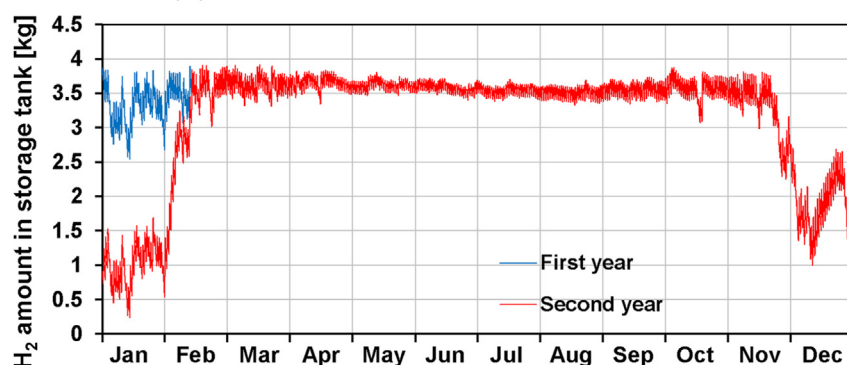
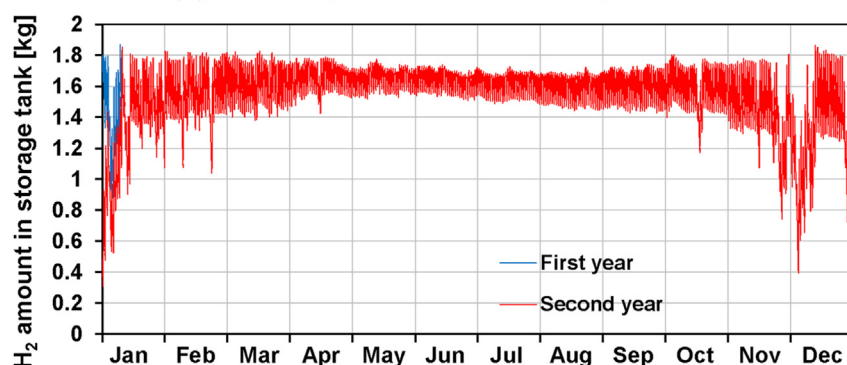
(a) 25 solar panels, 12.2 m³ storage tank(b) 35 solar panels, 5.1 m³ storage tank(c) 45 solar panels, 1.5 m³ storage tank(d) 55 solar panels, 0.7 m³ storage tank

Fig. 10 – Hydrogen amount variation in storage tank, 5 kW electrolyzer model and 20 fuel cell stack.

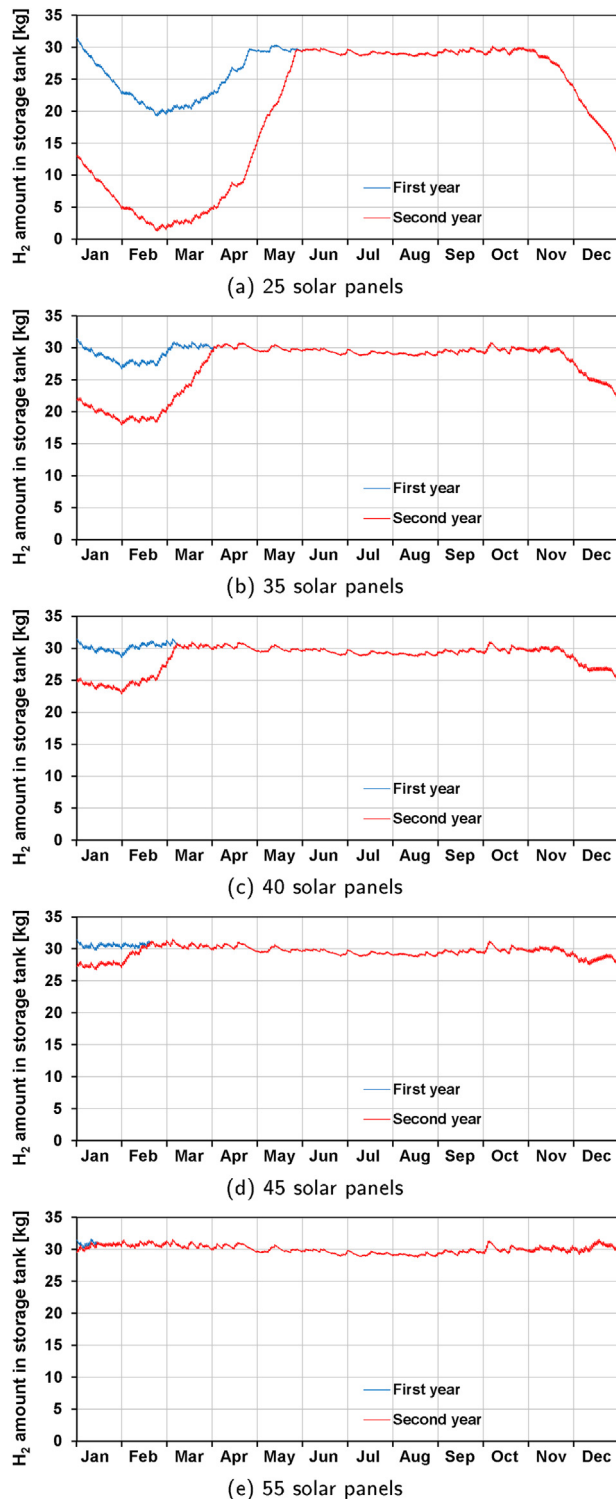


Fig. 11 – Hydrogen amount variation in storage tank, 12.2 m^3 storage tank, 5 kW electrolyzer model and 20 fuel cell stack.

consumption of the house in the case when there is no sun at night. However, when 14 fuel cell stacks are used at high consumption times, the fuel cells operate close to their maximum capacity. In Fig. 13 the hydrogen cycles for hybrid systems with the same solar panel number, electrolyzer

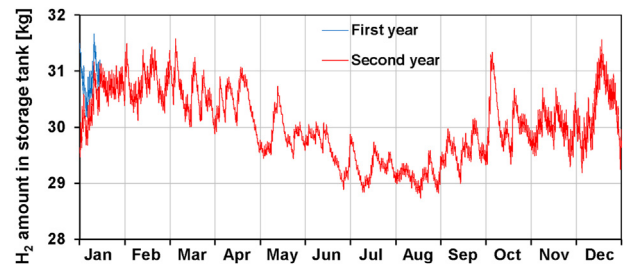


Fig. 12 – Zoomed view of hydrogen amount variation in storage tank, 55 solar panels, 12.2 m^3 storage tank, 5 kW electrolyzer model and 20 fuel cell stack.

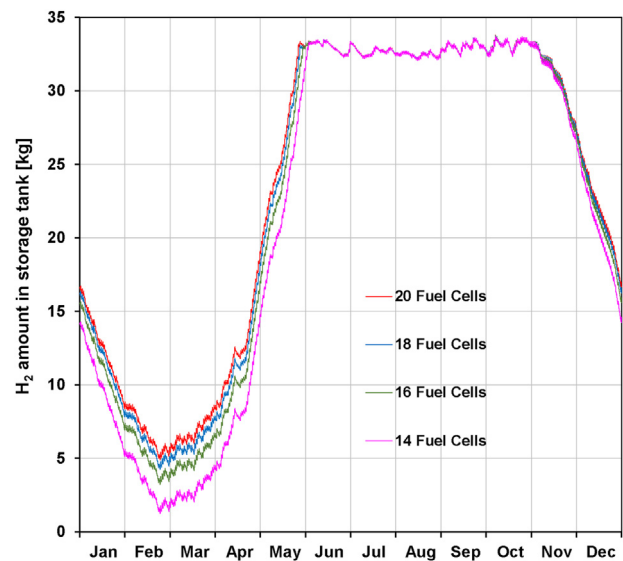


Fig. 13 – Effect of changing fuel cell stack number on hydrogen amount variation in storage tank, 25 solar panels, 13.7 m^3 storage tank, 5 kW electrolyzer model.

model, and storage tank volume but with different fuel cell stack numbers are plotted. When the fuel cell stack number is increased, the hydrogen consumption decreases gradually which increases the hydrogen amount left in the storage tank. There is more hydrogen in the storage tank, especially in the Fall and Winter seasons where the fuel cell stack is the primary source for the house and supplies power to the house most of the time as seen in Fig. 13.

When the hydrogen consumption of the fuel cell increases almost linearly at minor powers as seen in Fig. 4, the hydrogen consumption increases more rapidly towards the full capacity of the fuel cell (100 W). For example, operating one fuel cell stack at 100 W (full capacity) consumes more hydrogen than operating two fuel cell stacks at 50 W each. Even though the same power is used for both, the hydrogen consumption is less by operating two stacks than one, and practically when more fuel cell stacks are used in a hybrid system, it is possible to use smaller storage tanks in the system.

Figs. 14–17 shows the storage tank volume w.r.t. the number of solar panels when different fuel cell stack number is used for the systems with 3, 5, 7, and 9 kW electrolyzer models. The storage tank becomes almost constant with 45 solar panels for 7

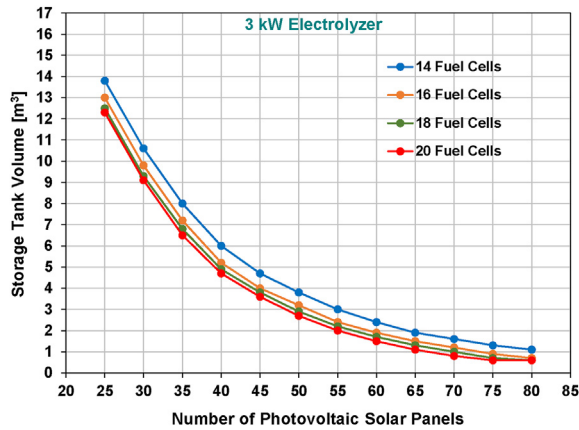


Fig. 14 – Effect of changing fuel cell stack number on the hybrid systems with 3 kW electrolyzer model.

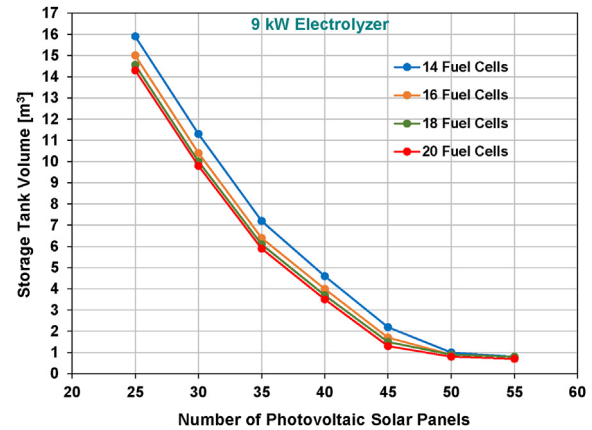


Fig. 17 – Effect of changing fuel cell stack number on the hybrid systems with 9 kW electrolyzer model.

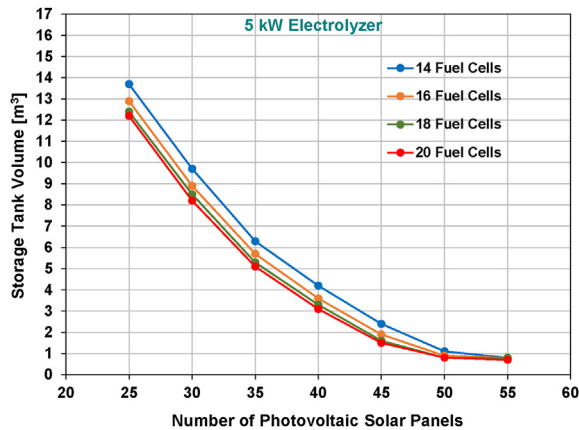


Fig. 15 – Effect of changing fuel cell stack number on the hybrid systems with 5 kW electrolyzer model.

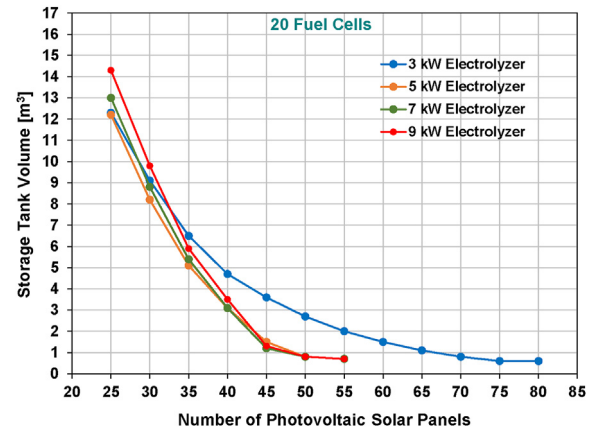


Fig. 18 – Comparison of 3-5-7-9 kW electrolyzer models, hybrid systems with 20 fuel cell stack number.

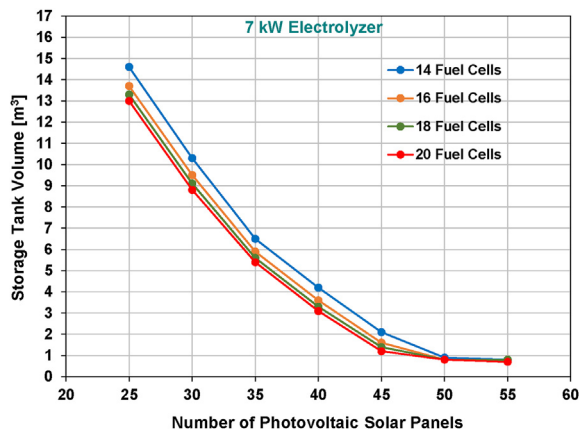


Fig. 16 – Effect of changing fuel cell stack number on the hybrid systems with 7 kW electrolyzer model.

and 9 kW electrolyzer models in Figs. 14 and 15 which means that increasing solar panels more and more does not help to decrease the minimum required storage tank volume. The constant storage tank volume for 5 kW and 3 kW electrolyzer

models is achieved by 50 and 75 solar panels, respectively, as seen in Figs. 16 and 17. Increasing the fuel cell stack number help to decrease the volume of the storage tank with any of the electrolyzer models since more fuel cell stacks consume less hydrogen for a particular demand power (from Figs. 14–17). In practice, the fuel cell stack number is selected based on the maximum consumption power without considering its effect on the storage tank volume. Based on present results, it is suggested to use more fuel cell stacks in solar hydrogen hybrid energy systems than the minimum necessary.

The decrease in the storage tank for 3, 5, 7, and 9 kW electrolyzers with 20 fuel cell stacks are compared in Fig. 18. The storage tank volume is decreased fastly with 5, 7, and 9 kW electrolyzers whereas the decrease is slight for the 3 kW electrolyzer model when the solar panel number is increased. It is clear that when the number of solar panels increases, the total power obtained from the solar panel array increases. During operation, there is a possibility that the power from the solar panel array can exceed the maximum load of the electrolyzer used in the system. When this happens, the exceeding amount of the power can not be utilized by the hybrid system as mentioned above. This problem occurs when an electrolyzer with relatively small nominal power is used together with

rather a large number of solar panels. When this happens, increasing the solar panel number will increase the amount of the non-utilizable power due to exceeding the maximum load even more. On the other hand, when this happens increasing the solar panel number can help the electrolyzer to start to operate at times when there is less solar irradiation, and also it will increase the amount of total time in which the electrolyzer operates at the maximum load.

In Fig. 18, it is interesting to see that the hybrid systems with 25 solar panels need smaller storage tank volume with 3 and 5 kW electrolyzer than 7 and 9 kW. When the nominal power of the electrolyzer increases, its minimum operating load also increases, and thus, the power obtained from the solar panel array stays below the minimum load of the electrolyzer as a possibility. When it happens, the power which is below the minimum load can not be utilized by the hybrid system. This problem occurs when an electrolyzer with a larger nominal power is used together with a relatively small number of solar panels. To overcome this problem, the solar panel number must be increased. When the solar panel number increases, the storage tank volume for 7 and 9 kW electrolyzer decreases quickly in Fig. 18. In a hybrid energy system, any non-utilizable power is related to the efficiency of the whole system. For this reason, comparing their total non-utilizable energy is the best option to understand the efficiencies of different hybrid systems.

In the considered solar hydrogen hybrid system the power generated by the solar panels is not utilized by the system on following three conditions.

1. If the power generated by the solar panels are higher than the consumption power and excess power (the power above the consumption) is lower than the electrolyzer minimum load. This happens when the solar irradiance is low.
2. If the power generated by the solar panels are higher than the consumption power and excess power (the power above the consumption) is higher than the electrolyzer maximum load. This happens when the solar irradiance is high.
3. If the power generated by the solar panels are higher than the consumption power when the hydrogen storage tank is full. This can happen at any solar irradiance values.

At any of these three conditions, the excess power is not utilized by the system. We cumulatively obtain the total non-utilizable energy in a year for each of three conditions. These values are tabulated in Tables 4–7 for different hybrid systems. We name the yearly total energy that corresponds to condition 1, condition 2 and condition 3 as ‘Nonutilizable Energy (below)’, ‘Nonutilizable Energy (above)’ and ‘Nonutilizable Energy (full tank)’ respectively. The amount of total nonutilizable energy in a system gives an indication of efficiency of the system.

We note that ‘Nonutilizable Energy (below)’ and ‘Nonutilizable Energy (above)’ is only affected by the choice of the electrolyzer nominal power. Any of the other hybrid system components such as the number of solar panels, storage tank volume or the fuel stack number do not affect the ‘Nonutilizable Energy (below)’ and ‘Nonutilizable Energy (above)’. However, ‘Nonutilizable Energy (full tank)’ changes as the

Table 5 – Designed hybrid systems with 5 kW electrolyzer.

Electrolyzer Capacity [kW]	Number of PV panels	Number of Fuel Cell Stack	Storage Tank Volume [m ³]	Nonutilizable Energy (above) [kWh]	Nonutilizable Energy (below) [kWh]	Nonutilizable Energy (full tank) [kWh]
5	25	14	13.7	0.0	524.0	5493.6
		16	12.9			5570.1
		18	12.4			5620.0
		20	12.2			5662.3
	30	14	9.7	0.5	472.0	8067.0
		16	8.9			8147.4
		18	8.5			8198.7
		20	8.2			8239.8
	35	14	6.3	75.2	428.0	10574.6
		16	5.7			10669.9
		18	5.3			10730.0
		20	5.1			10778.2
	40	14	4.2	624.3	385.3	12687.4
		16	3.6			12790.2
		18	3.3			12852.8
		20	3.1			12898.6
	45	14	2.4	1606.3	360.8	14324.1
		16	1.9			14404.5
		18	1.6			14450.5
		20	1.5			14492.3
	50	14	1.1	2889.2	325.9	15579.4
		16	0.9			15675.3
		18	0.8			15751.8
		20	0.8			15816.5
	55	14	0.8	4410.8	302.2	16710.9
		16	0.8			16871.0
		18	0.8			16965.3
		20	0.7			17014.9

Table 6 – Designed hybrid systems with 7 kW electrolyzer.

Electrolyzer Capacity [kW]	Number of PV panels	Number of Fuel Cell Stack	Storage Tank Volume [m ³]	Nonutilizable Energy (above) [kWh]	Nonutilizable Energy (below) [kWh]	Nonutilizable Energy (full tank) [kWh]
7	25	14	14.6	0.0	965.1	5286.9
		16	13.7			5356.5
		18	13.3			5405.0
		20	13.0			5442.3
	30	14	10.3	0.0	860.4	7952.5
		16	9.5			8024.3
		18	9.1			8072.4
		20	8.8			8110.2
	35	14	6.5	0.0	781.0	10598.3
		16	5.9			10682.9
		18	5.6			10737.4
		20	5.4			10779.9
	40	14	4.2	0.1	718.6	13295.5
		16	3.6			13385.0
		18	3.3			13440.7
		20	3.1			13483.0
	45	14	2.1	11.5	666.1	15950.8
		16	1.6			16025.7
		18	1.4			16076.7
		20	1.2			16112.8
	50	14	0.9	223.7	606.7	18400.2
		16	0.8			18529.4
		18	0.8			18611.1
		20	0.8			18670.5
	55	14	0.8	836.3	576.8	20565.7
		16	0.8			20705.7
		18	0.8			20787.0
		20	0.7			20838.5

Table 7 – Designed hybrid systems with 9 kW electrolyzer.

Electrolyzer Capacity [kW]	Number of PV panels	Number of Fuel Cell Stack	Storage Tank Volume [m ³]	Nonutilizable Energy (above) [kWh]	Nonutilizable Energy (below) [kWh]	Nonutilizable Energy (full tank) [kWh]
9	25	14	15.9	0.0	1495.2	4936.0
		16	15.0			5003.3
		18	14.6			5050.1
		20	14.3			5086.8
	30	14	11.3	0.0	1350.6	7637.7
		16	10.4			7707.0
		18	10.0			7753.6
		20	9.8			7790.7
	35	14	7.2	0.0	1220.8	10343.7
		16	6.4			10421.8
		18	6.1			10474.0
		20	5.9			10513.7
	40	14	4.6	0.0	1120.0	13081.9
		16	4.0			13167.1
		18	3.7			13221.6
		20	3.5			13262.9
	45	14	2.2	0.0	1029.7	15808.0
		16	1.7			15883.7
		18	1.5			15934.4
		20	1.3			15971.6
	50	14	1.0	0.0	976.0	18502.0
		16	0.9			18628.2
		18	0.9			18705.3
		20	0.8			18756.8
	55	14	0.8	0.0	912.9	21334.0
		16	0.8			21464.5
		18	0.8			21542.8
		20	0.7			21592.4

number of fuel cell stacks changes. This is because, the hydrogen amount in the storage tank decreases rather slowly since the hydrogen consumption decreases when the fuel cell stack number increases for any given hybrid system. When the fuel cell stack number increases since the hydrogen consumption decreases, the storage tank stays full with hydrogen longer times which eventually increases the ‘Nonutilizable Energy (full tank).’ Therefore, when the fuel cell stack number increases, ‘Non-utilizable Energy (full tank)’ also increases for any given hybrid system in Table 4 to Table 7. Thus, the electrolyzer is the critical component in a solar hydrogen hybrid energy system which directly affects the efficiency of the whole system. The amount of total non-utilizable energy in a way reflects whether the choice of the electrolyzer is suitable for the hybrid system or not. Besides, increasing the number of solar panels in the system increases ‘Nonutilizable Energy (above)’ and ‘Nonutilizable Energy (full tank)’ but decreases ‘Nonutilizable Energy (below).’ This is because of increase in the solar panel number causes an increase in total power obtained from the sun at any given solar irradiance. This will not only increase the amount of power exceeding the maximum load of the electrolyzer which eventually increase ‘Nonutilizable Energy (above)’ but it will also increase the total time at which the electrolyzer works at the maximum load. The latter will directly increase the hydrogen amount in the storage tank and therefore increase the ‘Nonutilizable Energy (full tank)’.

In order to illustrate how the electrolyzer model affects the operation of the hybrid system, when a comparatively small nominal power electrolyzer is selected, the minimum load of this electrolyzer would also be comparatively smaller. This electrolyzer would be able to start generating hydrogen at lower solar irradiance which might happen during sun rise and down. However for this electrolyzer the maximum load would be also comparatively smaller, therefore the electrolyzer will not able to generate hydrogen at high solar irradiance for example at noon times. The maximum solar power at noon times can exceed the maximum load of the electrolyzer which cannot utilize all the power allocated.

On the other hand when a large nominal power electrolyzer is selected, since the minimum load of this electrolyzer would be comparatively larger than the previous example, the electrolyzer would not be able to generate hydrogen until the solar power exceeds the minimum load of the electrolyzer. Thus, the electrolyzer cannot utilize solar power at low solar irradiance. However, since the maximum load of the electrolyzer is comparatively higher than the previous example, all the solar power will be utilized when the solar irradiance is high. To the extreme point, if a very high nominal power electrolyzer is selected then the electrolyzer cannot generate hydrogen most of the time due to the fact that the solar power is less than the minimum load.

In Figs. 19 and 20 we plot the ‘Nonutilizable Energy (above)’ and ‘Nonutilizable Energy (below)’ respectively which are directly affected by the solar panel number. The maximum load of 3 kW electrolyzer is so low that the power from 25 solar panels exceeds it from time to time, therefore it has ‘Nonutilizable Energy (above)’ even at the lowest solar panel number considered which is 25, as seen in Fig. 19. The same issue occurs for 5 kW and 7 kW electrolyzers with 35 and 45 panels, respectively. The total power from the solar panel

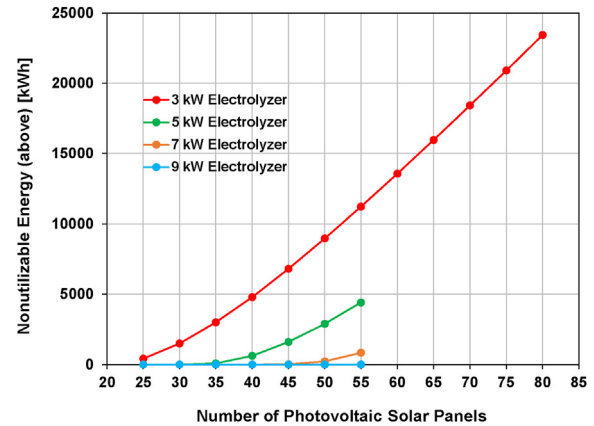


Fig. 19 – Change of Nonutilizable Energy (above) w.r.t. Solar panel number for different electrolyzers.

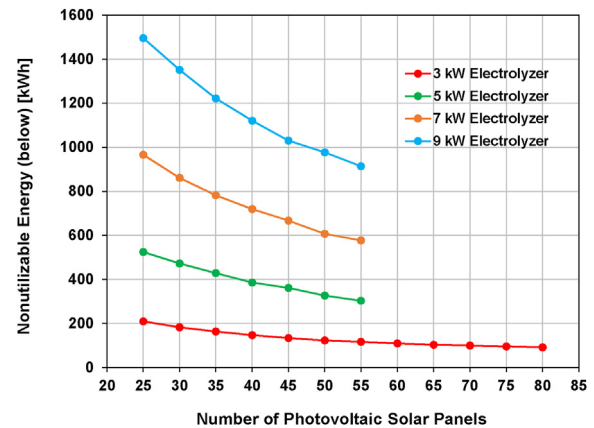


Fig. 20 – Change of Nonutilizable Energy (below) w.r.t. Solar panel number for different electrolyzers.

array never exceeds the 9 kW electrolyzer maximum operating load even with 55 solar panels.

3 kW and 9 kW electrolyzers have the minimum and the maximum ‘Nonutilizable Energy (below)’ at any particular solar panel number, respectively as seen in Fig. 20. As the solar panel number increases ‘Nonutilizable Energy (below)’ decreases for all the electrolyzer models. This is because, the total power coming from the solar panel array increases at any time when the number of solar panels increases such that the electrolyzer should start to operate at lower solar irradiance, making more use from the sun.

The storage tank volume as a function of fuel cell stack number for different solar panel numbers and electrolyzer models is plotted in Fig. 21 which includes all the hybrid systems (given in Table 4 to Table 7). Increasing the fuel cell stack number decreases the storage tank volume comparatively more at small solar panel numbers for any electrolyzer model. The decrease in storage tank volume gets comparatively less at large solar panel numbers such that the profiles start to get more flat in Fig. 21. The 5, 7 and 9 kW electrolyzer model profiles start to get closer to each other while overlapping at 55 solar panel numbers, except for the 3 kW electrolyzer model.

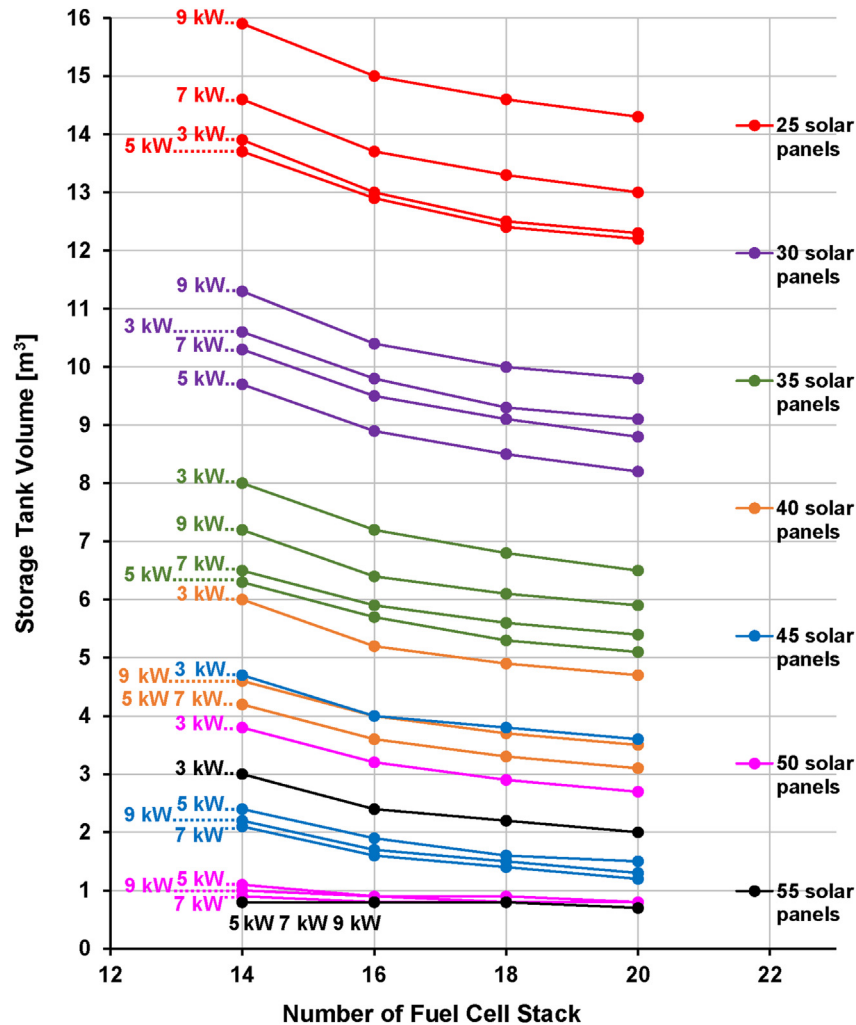


Fig. 21 – Effect of changing fuel cell stack number on the minimum required hydrogen storage tank volume.

Conclusions

In the present study, the simulation of a solar hydrogen hybrid energy system for a stand-alone zero energy house is located in Afyon, Turkey. Meteorological and consumption data are used for a small-time interval (10 min averaged) in the simulation. Different hybrid system combinations with different sized components are considered. In the simulation, the manufacturers specified operating curves are used. After extensive analysis and considering many different combinations, the comments according to the results are given in the following:

- For every different combination of system components, there is a minimum required hydrogen storage tank volume that could supply the demand with uninterrupted continuous power. It is essential to find the storage tank volume. Otherwise, power losses due to a small hydrogen storage tank will be inevitable, or in other words, there will be no power due to the lack of enough hydrogen in the storage tank.
- For sizing the number of the fuel cell stack, consumption data is essential. The total power of the fuel cell must be larger than the maximum instantaneous power consumption, including the system losses. Increasing the fuel cell stack number will help to decrease the hydrogen storage tank volume and use more fuel cell stacks to result in the possibility of using smaller storage tank volumes. The judgment on the number of fuel cell stacks can be made considering the price increase of additional fuel cells with the decrease in the price of the smaller storage tank.
- When analyzing a solar hydrogen hybrid system, the effect of the solar irradiance and the ambient air temperature must be taken into account in calculating the power from the solar panel array. For reliable, uninterrupted power, the number of solar panels used in the system is critical. The number of solar panels used in the system affects the electrolyzer size and also the storage tank volume.
- In the hybrid system, the nominal electrolyzer power is critical for efficiency. Proper sizing of the electrolyzer will reduce the non-utilizable energy and thus, increase efficiency. The nominal power of the electrolyzer affects the number of solar panels and the storage tank volume.

- If uninterrupted power supply is an essential requirement for a solar hydrogen hybrid energy system, such an analysis based on short time intervals is crucial to construct the properly sized components in the system. Otherwise, there will be interruptions in the power inevitably from time to time with undersized hybrid system components.

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.

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