Technical and Economic and Exergy Feasibility of Combined Production of Electricity and Hydrogen using Photovoltaic Energy

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Abstract –In the study of a villa residential unit with an area of 100(m2), first, the energies required for hot water consumption and power consumption of public equipment used are calculated. The cooling and heating load was then calculated using carrier software, and the required electrical power is calculated with the COP coefficient. The maximum cooling load required on February 6 at 16 hours is equal to 6250 (W), and the electrical power required by Photovoltaic panels are calculated according to the amount of radiation and consumption during operation and according to the service period of one year, which is equal to 7545 (W). PEM fuel cells are used as a source of energy storage, and the maximum energy stored for 4 hours is equal to 52.9 (kWh), and the maximum of 1.59 (kg) of hydrogen gas is produced during one day. According to the electricity cost, the global average of 0.14 (kW/h) will be achieved after 9.5 years.

Keywords: Photovoltaic system, Fuel cell, Hydrogen, Eexergy, Energy

1. Introduction

By reducing fossil energy resources, environmental pollution, climate change, and increasing dependence on exporting countries' fossil fuels are reduced. Researchers are trying to find clean fuels. To assess the weaknesses, items such as fewer emissions, suitability for mobile and fixed applications, and cost-effective range have been defined. This leads to more attention to renewable energy [1]. Electricity consumption due to population growth and high Per capita going, development of domestic, industrial, agricultural, etc. sectors are constantly increasing, and the supply of electricity needed by consumers requires the development of the electricity network. [2]

Iran is one of the most suitable countries in the world in terms of solar radiation energy so that according to estimates, Iran has an average of more than 2900 hours of sunshine per year. In most parts of the country, we have more than 280 sunny days, and the amount of solar radiation in Iran is 1800 to 2200 (kWh⁄m2) per year [3]. This high potential of clean energy production can be used to generate electricity in urban communities. Also, to increase efficiency, it is necessary to use solar energy in integration with other systems to be used as intelligent energy. Be vectorized [4]. The methods used by solar energy to generate electricity can be divided into two general methods [5]: solar thermal technology and solar cell technology.

Solar cells (PVs) convert sunlight energy directly into electrical energy. In this phenomenon, when a quantum of light energy, a photon, penetrates a substance, it is likely to be absorbed by the electron and the electron transfer. Finds and generates electricity. [6]

According to a study by Mohammad Hossein Mohammad Nezami et al., The cost is in the building, and the cost of generating electricity at the same time is equal to 0.62 \$/kWh, which is 78% cheaper than the cost of wind turbine electricity and 34% of the solar cell alone.

Shaygan et al. [8] examined the exergy and energy of a power and hydrogen production system for use in fuel cells and concluded that the price of electricity generated is 0.127 \$/kWh competitive with the price of offshore and solar thermal wind turbine electricity Is.

Majid Haroufiani and Reza Kandahar in [9] have determined the optimal distance between solar arrays as one of the most important issues in designing solar power plants. The large distance increases the land price and reduces the production of the power plant per unit area, and its small size leads to mutual shadows between the arrays and reduces their production capacity. However, the tendency to produce more on a certain land area in limited urban areas

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needs to be reconsidered in the distances between arrays.

Hossein Yousefi et al. In 2017 [10] Main and practical criteria for feasibility and determining the optimal location of solar energy for Iran to use to evaluate the best places to install equipment, facilities, and solar power plants to have more profit and reduce environmental pollution Participate in sunny hours, cloudy hours, dust, relative humidity, altitude, solar potential map, land use and land cover, power transmission lines, and access roads.

Mr. Jules Voisin et al. In 2020 [11], Using the method of measuring genetic algorithm and assessing the building's thermal requirement, the amount of local radiation. And the different climatic conditions for a particular independent building, a comparative study has been done for Moscow, Cairo, Paris, Hanoi, and Montreal around the world. The results measured between different neighborhoods show that local climate has a great impact on the system's final price. The model also states that the heat demand during the winter has a major share in the cost of the system for cold weather. In such cases, proper insulation of the house is important for a building to be efficient.

A study by Yang Zhang et al. In 2016 [12] for a residential building in Sweden to compare cost performance between battery storage and hydrogen shows that battery storage has improved compared to hydrogen storage in the case study. Hydrogen ions indicate that the cost of electrolysis is the most critical factor for improvement.

According to a 2019 study by Hasan Mehrjerdi et al. [13], For a zero-energy building with combined solar, fuel cell, and hydropower systems, it was shown that the hydrogen storage system provides additional energy during the day when solar energy is available. It converts the sun into hydrogen. During the summer, when the hydropower is low, the energy shortage is supplied by the solar system, and during the winter, when the solar energy is low, the energy is compensated by the hydropower.

With studies by F. Gutierrez-Martín et al. In 2020 [14] on the combination of hydrogen and solar energy technologies for locations away from the grid with climate data and electrical variables of components to perform energy balance and system evaluation In terms of load, stored energy level and costs with two electrolytic systems, ethanol was determined to reduce electrolysis energy requirements and current intensity. The integration of hydrogen and solar energy technologies is a viable option with capital and energy. Suitable for meeting energy needs in places isolated from the mains.

Benedetto Nastasi and Umberto Di Matteo's study in 2017 [15] for historic buildings protected from the environmental benefits of adding hydrogen to natural gas for heating purposes using combustion in boilers with cogeneration plants give. The addition of hydrogen increases electrical efficiency to natural gas.

According to the research of A. Herrmann et al. In 2019 [16] on hydrogen-based houses to calculate and compare the amount of carbon and energy production with electricity and heat generation methods integrated with hydrogen-fueled hydrogen fuel cell systems, Green hydrogen fuel cell with natural gas, natural gas hot water boiler, geothermal heat pump and natural gas hot water boiler integrated with solar heating, which have the highest efficiency of electricity and heat generation system with a hydrogen fuel cell with electric efficiency. And it is available at a low investment cost.

According to research by R. Greenoug, P.J. Boait in 2019 [17], with a performance comparison of a small power plant and simultaneous generation of heat (micro CHP) and the model with the fuel cell (PEMFC), which has been replaced, we have in the warm season of 2017-2018 in the United Kingdom. Fuel cell CHP technology is more useful than micro CHP in terms of its ability to deliver power generation, and the results of the experimental model show that the micro fuel cell CHP achieves a much higher annual power generation capacity over a year.

In this paper, based on the required energy of the building, the amount of electricity consumed for a residential unit of 100 (m2) in which four people live in the city of Karaj is calculated and based on electricity consumption based on one-year operation, the amount of photovoltaic cells required is calculated. The fuel cell is used to store energy during non-sunny hours, and the required hydrogen gas is supplied by electrolysis. After calculating the solar cells, the economic analysis of the return on investment is calculated using the present value method.

This study aims to consider global warming and the effect of greenhouse gas emissions by increasing the consumption of electricity produced by fossil fuel power plants. The existing urban space should be used to reduce greenhouse gases with renewable energies, so examining the factors affecting the technical feasibility due to changes in the output power of photovoltaic cells in Karaj and reducing network losses due to installation is independent. Innovations of this research:

• Utilizing the urban space of Karaj to generate electricity

• Production of hydrogen gas in Karaj using renewable energy

• Operation of fuel cell in residential space

2. Materials and methods:

Geographical and climatic characteristics of Karaj city:

The city of Karaj is located in the south of the Central Alborz Mountains in 35.8 degrees latitude and 50.9 degrees longitude. The elevations and heights around the city area have an altitude difference of about 1360 above sea level. [18]The plan and isometric images of the building are shown in Figure 1. The intended building has an area of 100 m2. The graph of electricity consumption trends for August and January is shown in Figures 2 and 3. To calculate the heat and cold loads, Carrier software has been used, based on which the heat and cold loads in each month have been calculated as the average monthly amount and the hourly heat and cold load. The cooling and heating loads of the building are shown in Table 1.

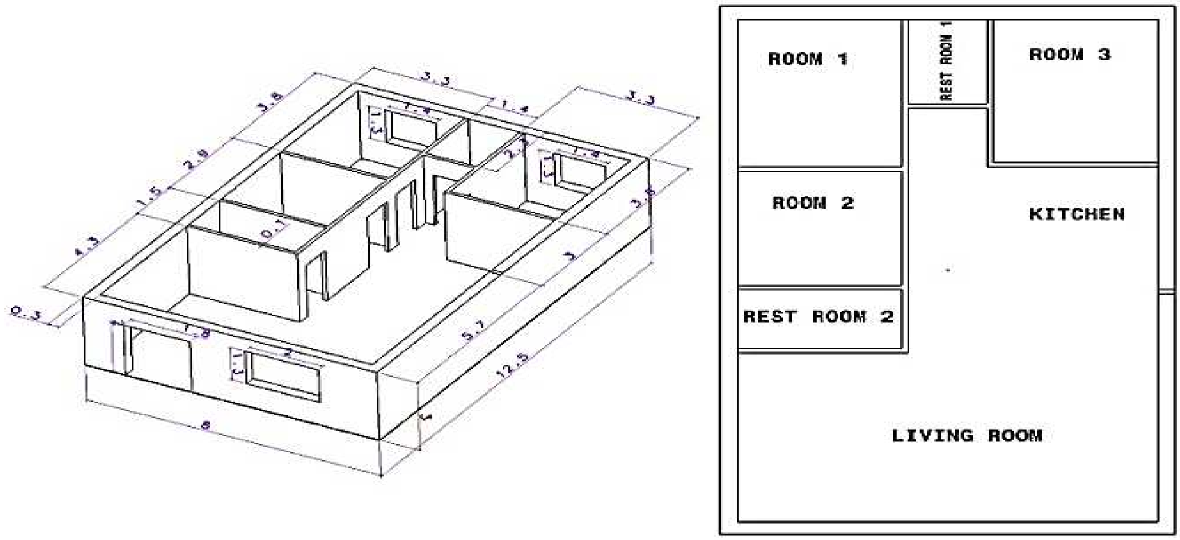

Figure 1. Plan and isometric images of the building (m)

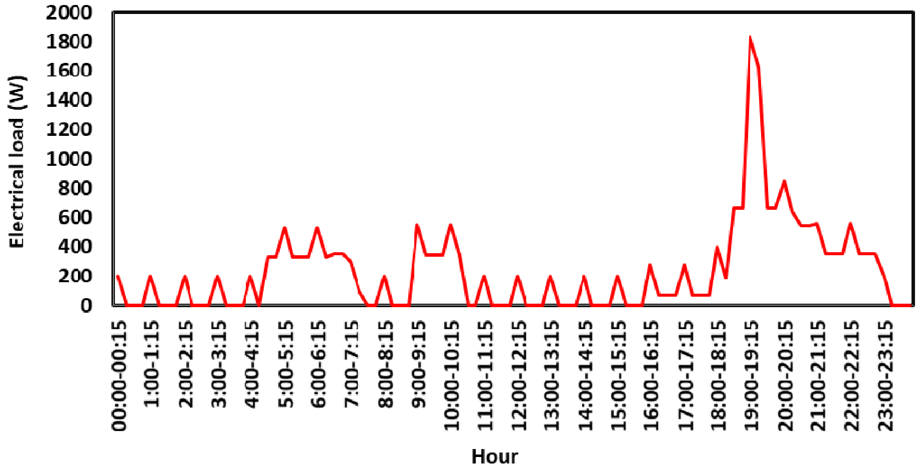

Figure 2. The total rate of electricity consumption in watts per hour (Wh) in August

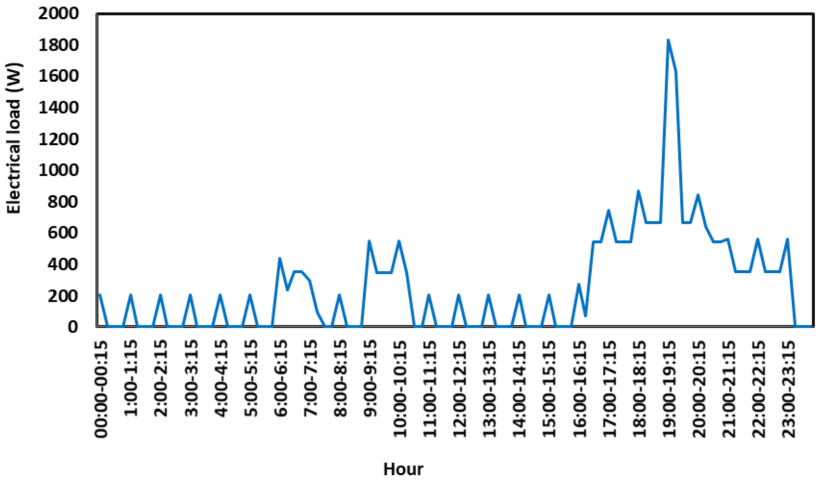

Figure 3. The total rate of electricity consumption in watts per hour (Wh) in January

Table 1. Cooling and heating load of a residential house for different months of the year

Load/hour	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
1	2700	3564	648	453.6	302.4	1512	3888	3456	2916	648	1620	2916
2	2808	3672	648	453.6	280.8	1404	3888	3240	2916	756	1836	3348
3	3132	3996	648	453.6	259.2	1296	3348	2916	2268	756	2052	3564
4	3348	4320	756	529.2	172.8	864	2916	2592	1944	756	2376	3780
5	3564	4536	864	604.8	151.2	756	2700	2376	1512	648	2430	3870
6	3735	4644	1080	756	108	540	2376	2160	1404	585	2484	3996
7	3996	4977	1125	787.5	93.6	468	2295	1980	1170	531	2448	3978
8	3888	4968	1188	831.6	86.4	432	2268	1944	972	468	2376	3942
9	3825	4860	1188	831.6	86.4	432	2484	1890	1080	432	2268	3888
10	3780	4860	1080	756	108	540	2592	1944	1188	216	2268	3996
11	3564	4644	864	604.8	194.4	972	3456	2268	1404	108	2160	3996
12	3240	4428	648	0	259.2	1296	3672	2484	1404	0	1836	3564
13	2979	3780	0	0	388.8	1944	4104	3132	2070	0	1188	3015
14	2808	3564	0	0	410.4	2052	4536	3240	2376	0	972	2592
15	2484	2916	0	0	496.8	2484	5580	3456	3024	0	864	2376
16	2160	2808	0	0	626.4	3132	5625	4104	3672	0	756	2160
17	2016	2520	216	0	777.6	3888	5562	4725	4428	0	486	2070
18	2052	2340	306	214.2	799.2	3996	5490	4815	4536	0	432	2052
19	1836	2376	324	226.8	810	4050	5445	4770	4500	0	324	1944
20	1944	2376	337.5	236.25	819	4095	5229	4752	4455	108	432	1944
21	1944	2484	432	302.4	813.6	4068	5184	4698	4428	117	540	2052
22	1980	2520	459	321.3	810	4050	4644	4680	4365	153	612	2070
23	2484	2808	648	453.6	756	3780	4365	4644	4212	324	756	2484
24	2700	3456	648	453.6	712.8	3564	4050	4212	3564	432	864	2592

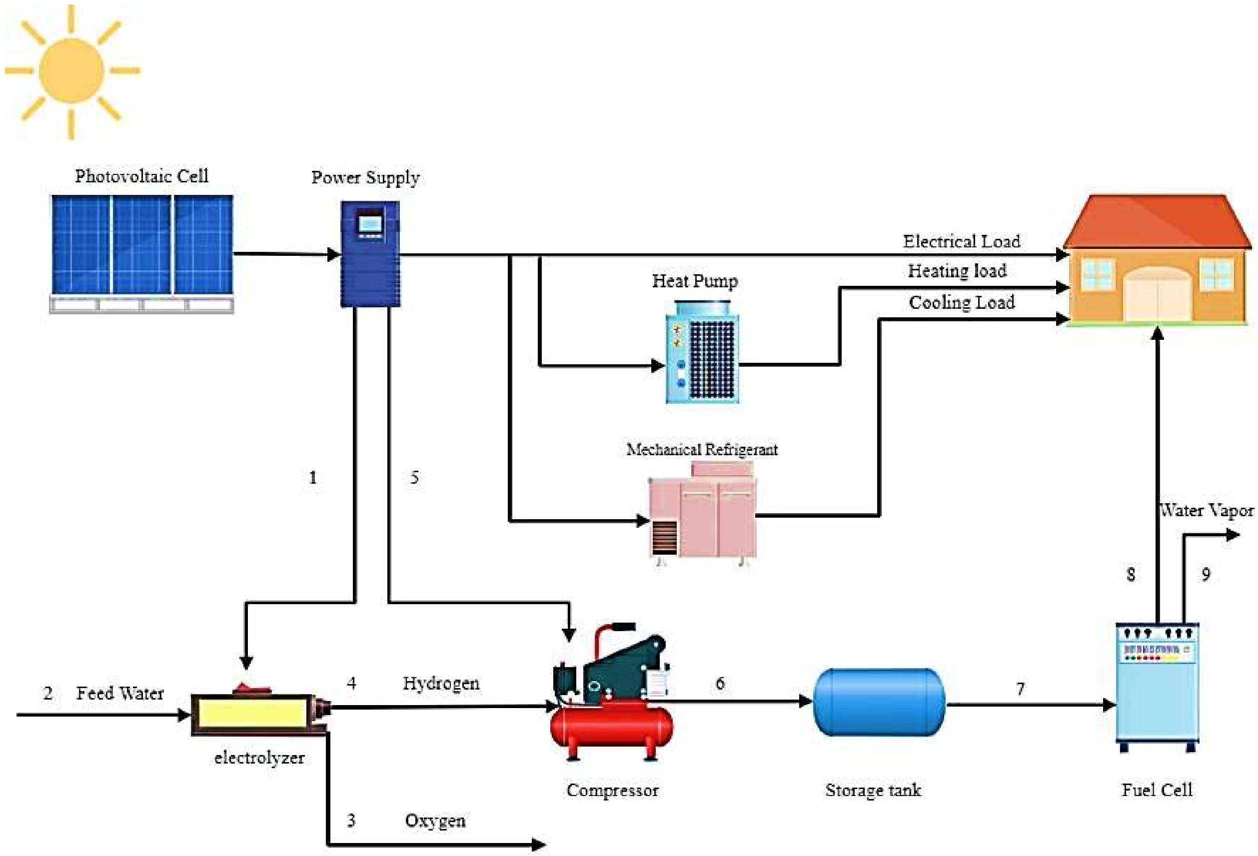

Figure 5. Schematic of the proposed system to meet the needs of electricity, heat, and cold

3. Energy, exergy, and economic modeling of the system

To calculate the solar cell's electricity, the amount of solar radiation intensity at different hours and months must be calculated. For a solar cell, the deflection angle δ is calculated according to equation (1). [19]

$$\delta = 23.45 \sin\left(360 \frac{284+n}{365}\right) \quad (1)$$

δ is the angle of deviation, n is the number of days from 365 days. The angle of sunlight is calculated according to Equation (2) [19]

$$\cos\theta_z = \cos\varphi . \cos\delta . \cos\omega + \sin\varphi . \sin\delta \quad (2)$$

θ_z is the angle of sunlight, δ is the angle of deviation, φ is latitude, ω is longitude. The following equations are used to calculate the amount of solar radiation per unit area [20]:

$$I_b = S \sin\left(\frac{\pi}{2} - \theta_z\right) \quad (3)$$

$$S = G_{sc}\left(\frac{\bar{d}}{d}\right)^2 \quad (4)$$

$$\left(\frac{\bar{d}}{d}\right) = \frac{1}{1-0.01673\cos\left(\frac{2n\pi}{365}\right)} \quad (5)$$

G_{sc} is the amount of sunlight. The average amount of energy output from solar cells is equal to equation (6) [21]

$$\dot{E}_{array} = I_b . A_{array} . \eta_{pv} . f_{man} . f_{temp} . f_{dirt} . H_{tilt} . N \quad (6)$$

E_{array} is average amount of solar energy received from the solar cell (W), A_{array} is solar cell surface area (m^2), η_{pv} is solar cell efficiency, f_{man} is solar cell error rate with approximately 5% ∓ at 25C temperature (W), f_{temp} is the coefficient of performance of temperature decreases with increasing temperature, f_{dirt} is the coefficient of air pollution, H_tilt is the installation angle of the solar cell, and N is the number of solar cells. The rate of performance decrease with increasing temperature can be calculated from equation (7) [8].

$$f_{temp} = 1 - \left(\gamma(T_{cell.eff} - 25)\right) \quad (7)$$

The current generated in photovoltaic cells is direct current (DC) so that a converter or inverter must be used to convert it to alternating current (AC). Converter output can be obtained from the product catalog. According to the first law of thermodynamics, we have:

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}h = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}h \quad (8)$$

Q˙ and W are the heat transfer rates and work between the control volume and its surroundings. H is the net enthalpy (J/kgK), m˙ is the flow rate (kg/s) of the subtitles "in," "out" Refers to the input and output values to the control volume.

The overall reaction in the fuel cell is [22]

$$2H^+ + \frac{1}{2}O_2 \rightarrow H_2O + \text{power} + \text{heat} \quad (9)$$

The energy stability equation in the fuel cell is [22]

$$\Delta H_{total} = H_{product} - H_{reactant} \quad (10)$$

ΔH_{total} is the maximum heat output from the fuel cell obtained by the difference between the enthalpy of the product $H_{product}$ and the enthalpy of the reactant $H_{reactant}$ (kJ/kmol). The net energy is calculated as follows: changes in volume, pressures, and another irreversibility in the fuel cell.

$$\Delta G = \Delta H_{total} - T\Delta S \quad (11)$$

In this regard, ΔG is the maximum efficiency of the fuel cell reaction (movement of electrons in an external circuit), known as the Gibbs free energy change (kJ/kmol), ΔS is the amount of entropy change (kJ/kmol), and T is the temperature. The reaction is (K). The direction of the fuel cell is calculated as follows.

$$\Delta \bar{g}_f = \bar{g}_f(\text{proudcts}) - \bar{g}_f(\text{reactans}) \quad (12)$$

$$\Delta \bar{g}_f = (\bar{g}_f)_{H2O} - (\bar{g}_f)_{H2} - \frac{1}{2}(\bar{g}_f)_{O2} \quad (13)$$

Gibbs energy is standard at 25 □ at a pressure of 1 atm at zero. If we consider the fuel cell voltage equal to E, we will have [23]:

$$\Delta \bar{g}_f = -2FV_{rev} \quad (14)$$

V_{rev} is the value of the fuel cell's reversible voltage (V), and F is the constant value of Faraday. We have a fuel cell to calculate the enthalpy. [23]

$$\Delta \bar{h}_f = -2FV_{theoretical} \quad (15)$$

$V_{theoretical}$ is the nominal voltage (V) of the fuel cell. The amount of output voltage from the fuel cell is calculated as follows. [23]

$$V_{FC} = V_{nernst} - V_{ohmic} - V_{activation} - V_{concentration} \quad (16)$$

V_{FC} fuel cell output voltage (V), V_{nernst} is cell open-circuit voltage in resistor mode, V_{ohmic} is the value of voltage drop across the resistor (V), $V_{activation}$ is the amount of voltage (V) reduced by the activation of the electrode between the anode and cathode, $V_{concentration}$ is the voltage drop (V) due to the concentration of catalyst to calculate V_{nernst} [23].

$$V_{nernst} = \frac{\Delta G}{2F} + \frac{\Delta S}{2F} + (T - T_{ref}) + \frac{RT}{2F}\left[\ln(P_{H_2}) + \frac{1}{2}\ln(P_{O_2})\right] \quad (17)$$

ΔG represents the amount of Gibbs energy changes (J/mol), ΔS represents the entropy changes (J/molK), $P_{(H2)}$ partial pressure of hydrogen and $P_{(O2)}$ partial pressure of oxygen, R is the constant amount of gases, T is Fuel cell temperature (K), T_{ref} is the reference temperature (K). ΔG and ΔS are calculated relative to the standard temperature and pressure. V_{ohm} indicates the voltage drop (V) of the resistance drop and is obtained from the relation (18) [23].

$$V_{ohm} = i_{FC}(R_M + R_C) \quad (18)$$

R_C is the resistance of the electrodes against the passage of electrons (Ω/cm), R_M is the resistance of the electrolyte against the displacement of ions (Ω/cm), and is calculated from the following equation [23].

$$R_M = \rho_M \frac{L}{A} \quad (19)$$

$$\rho_M = \frac{181\left[1+0.03\left(\frac{i_{FC}}{A}\right)+0.062\left(\frac{i_{FC}}{A}\right)^{2.5}\left(\frac{T}{303}\right)^2\right]}{\left[23-0.634-3\left(\frac{i_{FC}}{A}\right)\right]*\exp\left(4.18\left(\frac{T-303}{T}\right)\right)} \quad (20)$$

ρ_M is membrane resistivity in a fuel cell (Ω.cm), A is the effective area of the fuel cell compared to 2100 cm, L is the membrane thickness in the fuel cell (cm), i_{FC} is the fuel cell density value A (A/cm^2). V_{act} is showing the value of the reduced voltage (V) from the activation of the electrode between the anode and the cathode, and from equation 34 is obtained [23]

$$V_{act} = -\left[\xi_1 + \xi_2 + \xi_3 T\ln(C_{O_2}) + \xi_4 T\ln(i_{FC})\right] \quad (21)$$

ξ Geometric parameters based on which the theoretical thermodynamic equations of electrochemical reactions are obtained. $C_{(O2)}$ is the oxygen concentration at the catalyst surface (mol/cm^3) and is calculated as equation (22).

$$C_{O_2} = \frac{P_{O_2}}{5.08*10^{-6}\exp\left(-\frac{498}{T}\right)} \quad (22)$$

To reduce the voltage due to concentration [23]:

$$V_{concentration} = -\frac{RT}{2F}\ln\left(1 - \frac{J}{J_{max}}\right) \quad (23)$$

J is the density value (mA/cm^2), and J_{max} is the maximum density value (mA/cm^2). Consumed oxygen is supplied from the air. And the amount of hydrogen consumed is obtained from the following [23]:

$$M_{H2} = \frac{\dot{W}_{FC}}{2*V_{FC}*\eta_{FC}*F} \quad (24)$$

$$\dot{W}_{FC} = I_{FC}.V_{FC}.N_{FC} \quad (25)$$

V_{FC} Output Voltage (V), η_{FC} Fuel Cell Efficiency W_{FC} Fuel Cell Output Power (W), N_{FC} The number of elements forming the fuel cell for mathematical modeling of the fuel cell is initially calculated by V_{nernst} from Equation (17). Then the voltage drops V_{ohmic} from equation (18), $V_{activation}$ from equation (21), and finally, $V_{concentration}$ equation (23) is the actual value of the output voltage equal to equation (16) and the amount of output power from the fuel cell is equal to equation (25). The total reaction in water electrolysis is equal to [23]:

$$H_2O + \text{Electricity} \rightarrow H_2 + \frac{1}{2}O_2 \quad (26)$$

The following equation determines the voltage efficiency of the electrolyzer [23]:

$$\eta_V = \frac{1.25}{V_{ELZ}} \quad (27)$$

The hydrogen produced in the electrification process is equal to [23]:

$$M_{H2} = \frac{\dot{W}_{ELZ}}{2.V_{ELZ}.F} \quad (28)$$

M_{H2} indicates the amount of moles of hydrogen production in electrolysis (mole/s). The amount of power consumed by the compressor is equal to [24]

$$\dot{W}_C = C_P.\frac{T_1}{\eta_C}\left(\left(\frac{P_6}{P_4}\right)^{\frac{K-1}{K}} - 1\right).\dot{m}_c \quad (29)$$

C_P is the specific heat capacity of hydrogen at constant pressure, T_1 is Hydrogen gas temperature, P_4 is Inlet gas pressure, P_6 is Outlet gas pressure (Pa) to the compressor, k is the coefficient of specific heat ratio in the isotropic state for hydrogen gas, η_C is Mechanical efficiency of the compressor, m_c is current flow through the compressor (kg/s). W_C is the power required for the compressor supplied by photovoltaic panels. The volume of the hydrogen storage tank is calculated from equation (30) [8].

$$V_{tank} = \frac{M_{tank}.T_{tank}.R}{P_{tank}} \quad (30)$$

M_{tank} Weight (kg) The amount of hydrogen needed to store in the tank and V_{tank} Volume (Lit) The amount of hydrogen needed to store in the tank, P_{tank} is the storage tank pressure, T_{tank} is the storage tank temperature, R is the constant gas.

The current generated by the fuel cell is DC, which usually uses a DC to AC converter that, in addition to converting the current, also controls the frequency, voltage, and output amps. The efficiency of the converter is between 94-98%. The flow of exergy is in the form of equation (33) [25]:

$$\sum_{in}\left(1-\frac{T_0}{T_i}\right)\dot{Q}_i + \dot{W}_{in} + \sum_{in}\dot{m}_i ex = \sum_{out}\left(1-\frac{T_0}{T_i}\right)\dot{Q}_i + \dot{W}_{out} + \sum_{out}\dot{m}_i ex + \dot{E}x_D \quad (31)$$

Ex_D is the amount of exergy destruction (W), $\sum_{in} m_i ex$ is the amount of exergy entering the system, and $\sum_{out} m_i ex$ is the exergy amount leaving the system. T_0/T_i is the ratio of the ambient temperature to the flow temperature. The exergy equilibrium equation for different units is shown in Table 4. Index D indicates the loss of PV of photovoltaic cells, FC of fuel cells, compressor C, and exergy. [26]

Table 4. Exergy equilibrium equation for different process units

Component	*Exergy balance*	*Exergy efficiency*
Electrolyzer	$\dot{E}x_1 + \dot{E}x_2 = \dot{E}x_4 + \dot{E}x_3 + \dot{E}x_{D,electrolyzer}$	$\eta_{ex,electrolyzer} = \frac{\dot{E}x_4}{\dot{E}x_1 + \dot{E}x_2}$
Compressor	$\dot{W}_C + \dot{E}x_4 = \dot{E}x_6 + \dot{E}x_{D,C}$	$\eta_{ex,C} = \frac{\dot{E}x_6}{\dot{W}_C + \dot{E}x_4}$
Fuel Cell	$\dot{E}x_7 = \dot{W}_{FC} + \dot{E}x_9 + \dot{E}x_{D,FC}$	$\eta_{ex,FC} = \frac{\dot{W}_{FC}}{\dot{E}x_7}$
Photovoltaic cell	$\dot{E}x_{10,SOLAR} = \dot{W}_{PV} + \dot{E}x_{D,PV}$	$\eta_{ex,PV} = \frac{\dot{W}_{PV}}{\dot{E}x_{10}}$

Table 5. The initial investment cost amount

Component	*unit*	*number*	*cost*	*Ref.*
Photovoltaic cell	m^2	119.5	11950$	[30]
Electrolyzer	W	11,612	21,598$	[8]
Compressor	W	390	741$	[31]
Hydrogen tank	m^3	1.78	89$	[31]
Fuel cell	W	11,612	51,092$	[32]

The amount of energy entering the solar cell is denoted by $EX_{(10, SOLAR)}$ (W) and is calculated as equation (32) [27]:

$$\dot{E}X_{10,SOLAR} = A_{PV} I\left[1 - 1.33\left(\frac{T_0}{T_S}\right) + 0.33\left(\frac{T_0}{T_S}\right)^4\right] \quad (32)$$

A_{PV} is the surface area of the solar cell (m^2), I is the amount of radiation received by the solar cell (W/m^2), T_0 is the ambient temperature (K), T_S is the surface temperature of the sun. The amount of energy efficiency and exergy is equal to:

$$\eta_{en,sys} = \frac{\dot{W}_{FC} - \dot{W}_C}{I b A_{PV} + \dot{m}_2 h_2} \quad (33)$$

$$\eta_{ex,sys} = \frac{\dot{W}_{FC} - \dot{W}_C}{\dot{Ex}_{10} + \dot{Ex}_2} \quad (34)$$

3.1 Economic calculations

The production price of the studied system is calculated as follows. [28]

$$CF = Y_{PH} k_E \quad (35)$$

CF Annual Cogeneration Income ($), Y_{ph} Annual Production Capacity, and k_E Electricity Consumption Cost 0.14 ($/kWh) [29], C_0 is Initial Investment Cost ($) Total, C_{PH} is solar Cell Cost ($), C_{El} is electrolysis Cost ($), C_C is compressor cost ($), C_V is hydrogen tank cost ($) and C_{FC} is fuel cell cost ($). O&M indicates maintenance costs ($) and equal to 3% of initial costs which are shown in Table 5.

The investment cost is calculated using equation (36) [33]:

$$C_n = C_0(1+i)^n \quad (36)$$

C_n system investment costs in a particular year considering inflation rate ($), C_0 initial investment cost ($), I is the bank interest rate (%), and n is the number of years of operation (25 years), IRR is the equal rate of internal return with 9.3 and a simple refund period of 9.78.

4. Results and Discussion:

The average monthly amount of solar radiation (W/m^2) for the city of Karaj is shown in Figure 5. Figure 6 shows the average and maximum amount of heating and cooling load of the building in different months of the year.

By considering a heat pump for cooling and heating the building, the building's thermal energy is converted into electrical energy. Consumption is obtained by the average production of each photovoltaic cell surface area required by photovoltaic cells. The maximum area of the solar cell is 60.6 (m^2) for the average electrical load of the building and 119.5 (m^2) for the maximum load, which is the maximum required solar cell area.

With 119.5 (m^2) of solar cell area and 4 hours for hydrogen storage, the amount of hydrogen production is equal to Figure 7. To supply this amount of electrolyzed hydrogen with a capacity of 11,612(W) is required.

The solar cell's efficiency and the whole system in different months of the year are shown in Figure 8. The efficiency of the whole system is always less than the efficiency of photovoltaic panels alone.

The efficiency of the solar cell is directly related to the ambient temperature and decreases with increasing temperature. The maximum efficiency of the solar cell in January is equal to 13.24%, and the minimum value in summer and July is equal to 11.18%, and for the whole system, and July is equal to 12.6% and is 11.3%.

The amount of exergy of the solar cell and the whole system in one year is equal to Figure 10. The maximum efficiency of exergy in January for the solar cell is equal to 14.18% and the minimum value in summer and July is equal to 12.7% and for the whole system is equal to 13.5% and 12.1%.

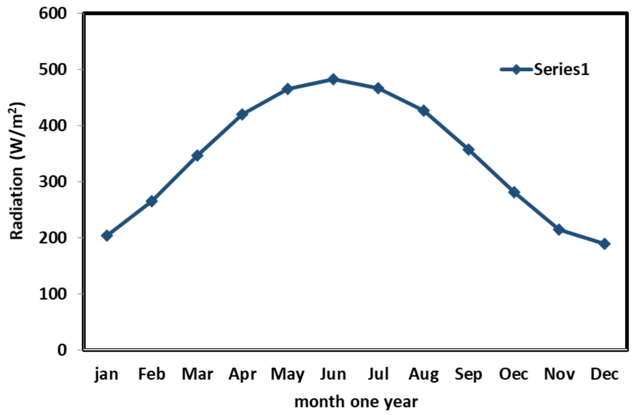

Figure 5. The average monthly amount of solar radiation for the city of Karaj

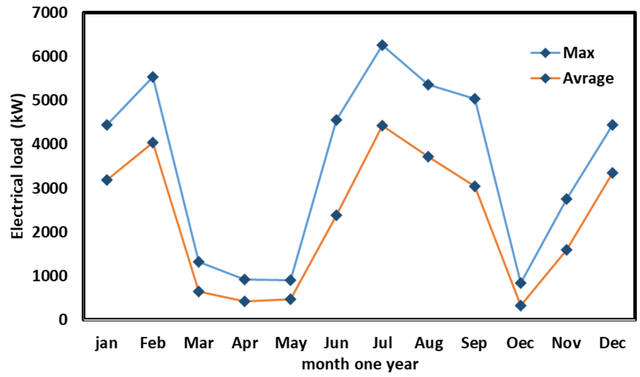

Figure 6. The average and maximum amount of heating and building load in different months of the year

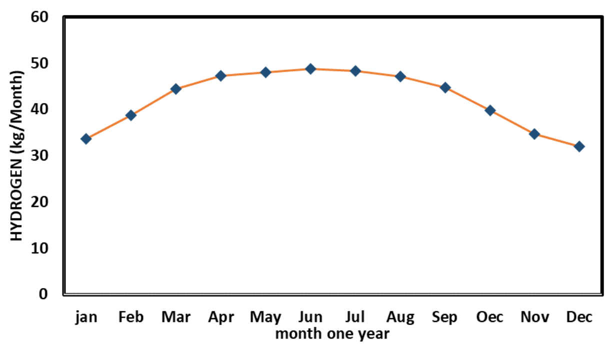

Figure 7. Amount of hydrogen gas production in different months of the year

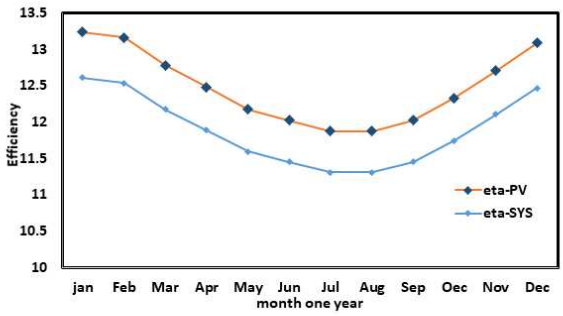

Figure 8. The amount of efficiency of the solar cell and the whole system in different months of the year

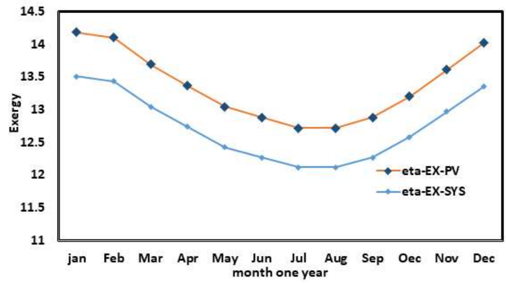

Figure 9. The amount of exergy of the solar cell and the whole system in different months of the year

5. Conclusion:

In the study of a villa residential unit with an area of 100 m^2, first, the energies required for hot water consumption and the power consumption of public equipment used are calculated. Carrer software is used to calculate the cooling and heating load, and the required electrical power is calculated with the COP coefficient. The maximum cooling load required is on February 4, at 4 pm (6250 W). The required electrical power by photovoltaic panels is calculated according to the amount of radiation and consumption during operation and according to one year's operating period, equal to 7545 (W). PEM fuel cells are used as a source of energy storage, and the maximum energy stored for 4 hours is equal to 52.9 (kW.h), and a maximum of 1.59 kg of hydrogen gas is produced during one day. According to the global average electricity cost (0.14 kW/h), the system will be efficient after 9.5 years. The hydrogen production system of solar panels has the following features compared to the ones presented:

1- Generation of electrical energy for building electricity consumption and cooling and heating loads

2- Production of hydrogen as an inter-system energy carrier for use in buildings and vehicles

3- Storing the required electrical energy without using the battery by using the conversion of hydrogen to the required electricity

4- Reducing pollution in electricity generation and helping to preserve the environment by eliminating the conversion of fossil fuels into electricity

5- It has small scales and dimensions that can be used in residential houses

6- Can be used in non-urban areas and isolated from the national electricity

7- Possibility of use for different cities and geographical locations according to the efficiency of solar panels in the region

References:

[1]. Romagnoli, F., D. Blumberga, and I. Pilicka, Life cycle assessment of biohydrogen production in photosynthetic processes. international journal of hydrogen energy, **36**(13): p. 7866-7871, 2011.

[2]. Integration of low-pressure hydrogen storage cylinder andautomatic controller for carbon deposit removal in car engine. international journa l o f hydrogen energy, **41**(46),2016.

[3]. Renewable Energy and Energy Efficiency Organization. 2021; Available from: http://www.satba.gov.ir/en/iranresourceassesment/atlas/map.

[4]. Dincer, I. and C. Acar, Smart energy systems for a sustainable future. Applied energy, 2017. **194**: p. 225-235.

[5]. Zhang, H., et al., Concentrated solar power plants: Review and design methodology. Renewable and sustainable energy reviews, 2013. **22** :p. 466-481.

[6]. Alaaeddin, M., et al., Photovoltaic applications: Status and manufacturing prospects. Renewable and Sustainable Energy Reviews, 2019. **102**: p. 318-332.

[7]. Mohammadnezami, M.H., et al., Meeting the electrical energy needs of a residential building with a wind-photovoltaic hybrid system. Sustainability, 2015. **7**(3): p. 2554-2569.

[8]. Shaygan, M., et al., energy, exergy, advanced exergy and economic analyses of hybrid polymer electrolyte membrane (PEM) fuel cell and photovoltaic cells to produce hydrogen and electricity. Journal of Cleaner Production, 2019. **234**: p. 1082-1093.

[9]. Horoufiany, M. and R. Ghandhari, A new photovoltaic arrays fixed reconfiguration method for reducing effects of one-and two-sided mutual shading. Journal of Solar Energy Engineering, 2019. **141**(3.(

[10]. Yousefi, H., et al., A review of the criteria for locating of solar power plants in Iran. Geospatial Engineering Journal, 2017. **8**(2): p. 25-38.

[11]. Voisin, J., et al., Climate impact analysis on the optimal sizing of a stand-alone hybrid building. Energy and Buildings, 2020. **210**: p. 109676.

[12]. Zhang, Y., et al., Comparative study of battery storage and hydrogen storage to increase photovoltaic self-sufficiency in a residential building of Sweden. Energy Procedia, 2016. **10** :۳ p. 268-273.

[13]. Mehrjerdi, H., et al., Daily-seasonal operation in net-zero energy building powered by hybrid renewable energies and hydrogen storage systems. Energy Conversion and Management, 2019. **201**: p. 112156.

[14]. Gutierrez-Martin, F., et al., Hydrogen storage for off-grid power supply based on solar PV and electrochemical reforming of ethanol-water solutions. Renewable Energy, 2020. **147**: p. 639-649.

[15]. Nastasi, B. and U. Di Matteo, Innovative use of hydrogen in energy retrofitting of listed buildings. Energy Procedia, 2017. **111**: p. 435-441.

[16]. Herrmann, A., A. Mädlow, and H. Krause, Key performance indicators evaluation of a domestic hydrogen fuel cell CHP. International Journal of Hydrogen Energy, 2019. **44**(35): p. 19061-19066.

[17]. Boait, P.J .and R. Greenough, Can fuel cell micro-CHP justify the hydrogen gas grid? Operating experience from a UK domestic retrofit. Energy and Buildings, 2019. **194**: p. 75-84.

[18]. Plan and Budget Organization of the Islamic Republic of Iran. 2021; Available from: https://www.mporg.ir/en.

[19]. John A. Duffie, W.A.B., Nathan Blair, Solar Engineering of Thermal Processes, Photovoltaics and Wind, 5th Edition. 2013.

[20]. Duffie, J.A., W.A. Beckman, and N. Blair, Solar engineering of thermal processes, photovoltaics and wind. 2020: John Wiley & Sons.

[21]. Bakelli, Y., A.H. Arab, and B. Azoui, Optimal sizing of photovoltaic pumping system with water tank storage using LPSP concept. Solar energy, 2011. **85**(2): p. 288-294.

[22]. Lamy, C. and P. Millet, A critical review on the definitions used to calculate the energy efficiency coefficients of water electrolysis cells working under near ambient temperature conditions. Journal of Power Sources, 2020. **447**: p. 227350.

[23]. Barbir, F. and T. Gomez, Efficiency and economics of proton exchange membrane (PEM) fuel cells. international journal of hydrogen energy, 1997. **22**(10-11): p. 1027-1037.

[24]. Li, Y., et al., Analysis of air compression, progress of compressor and control for optimal energy efficiency in proton exchange membrane fuelcell. Renewable and Sustainable Energy Reviews, 2020. **133**: p. 110304.

[25]. Dincer, I. and M.A. Rosen, Exergy: energy, environment and sustainable development. 2012: Newnes.

[26]. Ghorbani, B., et al., A comprehensive approach toward utilizing mixed refrigerant and absorption refrigeration systems in an integrated cryogenic refrigeration process. Journal of Cleaner Production, 2018. **179**: p. 495-514.

[27]. Kelly, S., G. Tsatsaronis, and T. Morosuk, Advanced exergetic analysis: Approaches for splitting the exergydestruction into endogenous and exogenous parts. Energy, 2009. **34**(3): p. 384-391.

[28]. Batman, A., et al., A feasibility study of grid-connected photovoltaic systems in Istanbul, Turkey. Renewable and Sustainable Energy Reviews, 2012. **16**(8): p. 5678-5686.

[29]. Prices, G.P., Global Petrol Prices. 2016.

[30]. fam, s.p. Cost Of Solar Panels Per Square Meter – Bank Breaking Beauty. 2020; Available from: https://www.solarpowerfam.com/cost-of-solar-panels-per-square-meter./

[31]. Gutiérrez-Martín, F., L. Amodio, andM. Pagano, Hydrogen production by water electrolysis and off-grid solar PV. International Journal of Hydrogen Energy, 2020.

[32]. store, f.c. 2020; Available from: https://www.fuelcellstore.com/fuel-cell-stacks/high-power-fuel-cell-stacks.

[33]. Park, C.S. and G.P. Sharp-Bette, Advanced engineering economics. 1990: Wiley.