Technical and environmental analysis of photovoltaic and solar water heater cogeneration system: a case study of Saveh City

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Abstract

The overwhelming growth in energy consumption in Iran is to the extent that in the coming years, it will turn Iran from an energy-exporting country into an energy-importing country. The use of renewable energy is essential to address this threat. In this research, the energy and economic analysis of solar energy-based cogeneration system for a building in Saveh City has been studied. The main purpose of this study is to determine the optimal size of photovoltaic cell and solar water heater by considering environmental parameters and fuel saving. In this regard, the amount of solar radiation intensity and the required loads of the building under study were determined. Then, using the SAM and TSOL relationships and software, results such as the supply of electric and thermal loads of six panels of 327 W and 3.2 m², respectively, are needed. This system will save more than 75% energy.

Keywords: photovoltaic cell; solar water heater; environmental pollutant; electric and thermal demand

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1 INTRODUCTION

Energy resources are one of the most important factors for sustainable development [1–3]. Also, energy is an essential requirement for sustaining economic development, social welfare, improving the quality of life and security of society. In the present era, energy is one of the primary needs of mankind and human dependence on fossil fuels has grown much more than before, as more than 90% of world energy consumption comes from fossil fuels [4,5]. But, because of the limited resources of fossil energy and the problems associated with greenhouse gas emissions, attention to other forms of renewable energy has become increasingly necessary. Therefore, with the reduction of fossil fuels in the world, the use of renewable energies that do not follow the same environmental pollution has played a very important role in the energy basket of different countries in the world [6–8]. Solar energy systems are the most important renewable energies that have made significant progress. Iran is one of the countries with high energy consumption, especially in the construction sector, and also has high potential for solar energy. So, given the positive points in the country, the rational development of these valuable and godly resources seems justified, because this can be done...
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Figure 1. The electrical and thermal energy consumption in different sectors of Iran [2].

to achieve the goals of sustainable development, reduce fossil fuel consumption and thus reduce environmental pollution as showed in the figure 1 [2]. Solar power has advantages, including easier access and huge capacity [9–12]. The amount of solar energy received by the Earth is several thousand times the electricity consumed in the world. Solar power is pollution-free and widely available throughout the world, especially in hot areas and in areas off the grid, for use in electricity generation, heating and economic cooling. Iran is also geographically located in the warm and dry region. With more than 280 sunny days per year, its annual solar radiation is estimated to be 1800–2200 kwh/m$^2$, which is above the global average. Losses in the generation, transmission and distribution of electricity and the scattering of the country’s population make the use of solar energy economically justifiable. One of the most important energy optimization solutions in industrialized countries with the aim of increasing energy production is the use of heat and power cogeneration systems. This is called combined heat and power (CHP) systems. Generally, any combination of thermal and electrical energy from a single energy source with an integrated system and from a single fuel stream is referred to as cogeneration systems [13,14].

Some of the works done in this area are in the References are correct only and need no modifications further. The investigators of this study focuses on the thorough literature survey as detailed below. Raj et al. [15] conducted a study on renewable energy-based cogeneration technologies. In 2016, Rodriguez et al. [16] conducted an analysis on the economic feasibility and reduction of a building's energy consumption and emissions when integrating hybrid solar thermal/photovoltaics (PV)/micro-CHP systems. In 2018, Salmeron Lissén et al. [17] published an article titled ‘An economy, energy, and environmental analysis of PV/micro-CHP hybrid systems: a case study of a tertiary building’. In 2019, Rad et al. [18] conducted a research on designing and optimizing a novel cogeneration system for an office building based on thermo-economic and environmental analyses; Ramadhani et al. [19] published a comprehensive review on optimal design and operations of fuel cell-based cogeneration systems; and Barbu et al. [20] published a technical and economic analysis of the implementation of hybrid solar energy systems in small energy prosumer applications.

In this research, to provide the building consumable hot water, solar water heater is used. Solar water heaters are one of the most effective and easy-to-use solar energy designs for supplying domestic and industrial hot water, as the surface temperature of the solar absorber collectors rises to about 100$^\circ$C and the hot water produced in high efficiency models reaches the boiling point. Solar water heaters operate by absorbing solar energy from their collector plates, and their heating efficiency varies by type of collector. The hot water is maintained at all times of the day in a double-walled tank and a thermal insulator that keeps the water temperature unchanged for up to 3 days. Maintenance costs of these systems are very low and sometimes at zero, because it has no moving parts and has a high technical life of up to 20 years. Solar water heater reduces energy costs because it uses free solar energy. Since it reduces the consumption of fossil fuels, it contributes to a cleaner environment due to its direct impact on reducing greenhouse gas emissions. Figure 2 shows a schematic of a solar water heater.

Therefore, in this present study, the researchers trying to use the solar micro-CHP system to simultaneously generate electricity and heat in order to meet the electrical and thermal requirements of a residential building located in Saveh (Central Province). The electrical charge in this building is also supplied by the solar photovoltaic system and the thermal charge through the solar collectors. Therefore, given that Iran and especially its central cities are susceptible to solar energy, the expansion of cogeneration systems along with solar systems can, in the long run, be a major step toward sustainable development, reducing fossil fuel consumption and thus reducing greenhouse gas emissions. Also, by applying sensitivity analysis, different parameters affecting the performance of solar micro CHP system are discussed. By investigating the economic analysis of the project, hence it is
Table 1. Geographical characteristics of the Markazi (Saveh).

| Parameter     | Quantity | Unit |
|---------------|----------|------|
| Location      | Markazi(Saveh) | -    |
| Latitude      | +35.63° |      |
| Longitude     | +36.15° |      |

designed using the optimization algorithm to optimize the output of the micro CHP system. In this paper, TSOL, SAM and Homer software programs have been used for the design and analysis.

2 MATERIALS AND METHODS

2.1 The area study
The selected location for this study is a residential building located in Saveh, Markazi, Iran. The Geographical characteristics of the case study are shown in Table 1.

2.2 Photovoltaic cells
The photovoltaic array is formed by the assembly of photovoltaic panels that are made of photovoltaic modules. Photovoltaic modules are also composed of PVs that convert solar energy into electricity. PVs are crystals that are made of semiconductor thin films (silicon or gallium arsenic). The cells that are made of silicon have a theoretical maximum efficiency of ~22% and their practical efficiency is ~15–18% [21, 22]. The solar panel used in this study is of the SPR-327NE-WHT-D type manufactured by LG Plant, as detailed in Table 2.

2.3 Inverter
A converter is a device that extracts DC power from photovoltaic arrays and converts it into standard AC current used at home. As the photovoltaic units are divided into two separate grid-connected units, the converters used in each case must also have their own characteristics. In converter selection, advantages such as small volume, high efficiency and high operating speed should be noted [23, 24]. The converter used in this research is the SMA Solar Technology converter type, manufactured in Australia and the model is Sunny 5000TL-20. The details are given in Table 3.

2.4 Electric energy storage
The photovoltaic system’s storage is usually battery type. The battery system includes a battery compartment and a battery charge controller. The battery is used in both separate and grid-connected systems and store surplus energy when the photovoltaic system output is overloaded. In the grid-independent photovoltaic system battery charging control devices are used to prevent batteries from being fully discharged or overcharged, so that their use can be maximized [25–27]. The battery used in this research is the Surrette 4KS25P, manufactured by Surrette/Roll, which has a 4-V and 1900-amp battery. The details are given in Table 4.

2.5 Solar water heater
Solar water heaters can be used to heat the building’s water, which is one of the main goals of this research. Table 5 shows the specifications for the solar water heater system used in the research.

Table 2. Solar panel specifications used in the research.

| Parameter                  | Value                  |
|---------------------------|------------------------|
| Material                  | Silicone mono crystal  |
| Max power (P_{Max})       | W 327                  |
| Cell efficiency           | %5/22                  |
| Panel efficiency          | %1/20                  |
| Calculated voltage (V_{mpp}) | V 7/54                |
| Calculated current (I_{mpp}) | A 98/5                |
| Open-circuit voltage (V_{OC}) | V 9/64                |
| Short-circuit current (I_{SC}) | A 46/6               |

Table 3. Specifications of the converter used in the research.

| Parameter(AC) | Value |
|---------------|-------|
| Calculated power | W 5000 |
| Maximum AC output power | VA 5000 |
| AC rated voltage | V 400/230,PE/N/3 |
| AC network frequency | Hz 50 |
| Calculated power frequency | V 230/Hz 50 |
| Maximum output current | A 3/7 |
| Power factor | 1 |
| Maximum efficiency | %98 |
Table 4. Specifications of the battery used in the research.

| Parameter             | Value          | Parameter             | Value          |
|-----------------------|----------------|-----------------------|----------------|
| Nominal capacity      | Ah 1900        | Maximum charging current | A 5/67         |
| Rated voltage         | V 4            | Lifetime efficiency   | kWh 10569      |
| Efficiency            | %80            | Suggested value       | kWh 10494      |
| Minimum charging mode | %40            | Maximum calculated capacity | Ah 1887      |
| Life span             | 12 year        | Capacity ratio (c)    | 254/0          |
| Maximum charging rate | A/Ah 1         | Constant rate (k)     | 1/hr 528/0     |
| Nominal capacity      | Ah 1900        | Maximum charging current | A 5/67         |
| Rated voltage         | V 4            | Lifetime efficiency   | kWh 10569      |

Table 5. Specifications of the solar collector.

| Parameter             | Value                          | Parameter             | Value                          |
|-----------------------|--------------------------------|-----------------------|--------------------------------|
| Collector type        | Standard flat panel            | The volume of the tank | 300 l                          |
| Collector orientation | 180                            | Tank height           | 1.8 m                          |
| Tilt angle of collector | 30                             | Thickness of the tank insulation | 100 mm                        |
| Azimuth collector angle | 0                             | Backup heat           | Standard gas-fired boiler       |
| Surface area of each collector | 1 m                             | Boiler type           | Modulating boiler               |
| Type of storage tank  | Standard indirect double wall  | Boiler efficiency     | 85%                            |
|                       |                                | The volume of the tank | 300 liters                      |
|                       |                                | Tank height           | 1.8 m                          |

Table 6. The amount of electrical load consumed by the building under study.

| Period | Number of days | Shortcut (KWh) | Peak times (KWh) | Low load (KWh) | Total (KWh) |
|--------|----------------|----------------|------------------|----------------|-------------|
| 1      | 47             | 86             | 47               | 48             | 181         |
| 2      | 64             | 238            | 102              | 199            | 539         |
| 3      | 59             | 258            | 111              | 193            | 562         |
| 4      | 64             | 174            | 109              | 140            | 423         |
| 5      | 58             | 140            | 90               | 110            | 340         |
| 6      | 48             | 106            | 70               | 84             | 260         |
| 7      | 25             | 48             | 26               | 31             | 105         |
| Total  | 365            | 1050           | 555              | 805            | 2410        |

Average daily consumption = 6.6KWh/d

Table 7. Desired data to calculate the amount of heat for hot water supply.

| Parameter                          | Value          | Parameter                          | Value          |
|------------------------------------|----------------|------------------------------------|----------------|
| Specific gravity of water at constant pressure | 4.18 kJ/kg.K | Inlet water temperature to solar water heater | 18.5°C          |
| The actual amount of hot water a day | 240 l         | Outlet water temperature from solar water heater | 50°C            |

2.6 Weather conditions of the study area
The amount of solar energy received at different locations varies depending on latitude, altitude, atmospheric phenomena, etc. Therefore, in order to obtain radiation information, the latitude and longitude of that location must be determined, so that the monthly and yearly averages of sunlight can be determined at the horizon level and at all levels with different directions and slopes. Since the central cities of Iran have high solar radiation intensity, and the use of solar systems is better justified, this study has been investigated as a case study in Saveh City, Markazi.

2.7 Requirements of under study building
By checking the residential bills for electricity in Saveh City in 2016, the average daily consumption of this building is about 6.61 kWh, which is equal to 198.3 kWh per month as revealed from the Table 6.

According to the existing standards for hot water consumption in Iran, 60 l of hot water is consumed per person per day, which for a family of four is ~240 l per day as illustrated in the Table 7.

Therefore, according to the data in the table above, it can be said that a daily heat equivalent to 31.6 MJ or 8.78 KWh is needed to
supply the hot water consumed in this residential building, which would equal the annual thermal energy requirement of 3.2 MWh.

3 RESULTS

The main purpose of calculating the solar photovoltaic system is to determine the size of the required solar panels by the amount of required electrical charge. Figure 3 and 4 illustrates the graphical representation of Annual Solar radiation intensity and number of solar panels needed per month for Saveh city.

As it can be seen, in some months of the year the number of solar panels needed is more than six, so it is advisable to use grid electricity as a backup power source during this time of year, or more than six solar panels. The thermal energy required to supply the consumable hot water is supplied by solar energy through a gas-fired boiler. Figure 5 depicts the collector output temperature and hot-water temperature produced by the system. In fact, it can be said that this arrangement uses as much as 2.38 MWh of solar energy and 795 kWh of a 180-W gas boiler. The simulation results are presented in Table 8.

Figure 6 also shows the monthly contribution of solar energy and heat source to the building’s hot water supply. The share of auxiliary heat sources is negligible in the months of June–September, when the intensity of solar radiation is high. The savings in natural gas consumption as well as the efficiency of the solar water heater system are shown in Figure 7. As can be

Table 8. Results related to simulation of solar water heater system.

| Parameter                          | Value    | Parameter                          | Value    |
|------------------------------------|----------|------------------------------------|----------|
| Collector area installed           | 3.2m²    | Natural gas saving                 | 413.5m³  |
| Collector power installed          | 2.4KW    | Reduce CO2 emissions               | 874.13 kg|
| Collector delivery energy          | 3.151MWh | SF                                 | 76.7%    |
| Share of solar energy in DHW       | 2.61MWh  | Energy saving                      | 78.8%    |
| Auxiliary heat share               | 0.795MWh | System Efficiency                  | 39.5%    |

Figure 3. Annual solar radiation intensity graph for Saveh City.

Figure 4. The number of solar panels needed per month.

Figure 5. The collector output temperature and the hot water temperature produced by the system.

Figure 6. Share of solar energy and auxiliary heat source supply of building consumables.
Finally, the solar fraction of the system are also shown in Figure 9. Regarding the figure, it can be said that by reducing the percentage of solar energy usage, the solar fraction system decreases but the efficiency of the system increases.

4 CONCLUSION

Since a lot of energy is consumed daily in the heating and electricity of residential buildings, design and implementation of buildings that can make the most out of solar energy is very important and useful. But the main reason that different groups of people do not use solar energy at home is the cheapness of energy carriers in Iran. However, with the current state of energy and its high consumption in the country, the necessity to implement solar projects is inevitable. But, in terms of building climatic design, it is essential to note that using solar energy will save money and save additional costs. Therefore, in this research, a system called solar micro-CHP system was used, which can simultaneously generate electricity and heat to meet the heating and electricity needs of a residential building in climatic conditions of Saveh City, Markazi. The electrical charge in this building is also supplied by the solar PV system, and the thermal charge through the solar collectors. Therefore, given that Iran and especially its central cities are susceptible to solar energy, the development of heating and electricity cogeneration systems along with solar systems can in the long run be a major step toward sustainable development, reducing fossil fuel consumption and thus reducing greenhouse gas emissions.

The system modeled in this paper is capable of supplying the hot water of the building under study and its electricity needs. The building needs at least six solar panels with 327 W to supply its required electricity. Also, for the hours that there is no sunlight, and for cloudy days, electricity must either be used from the grid or at least three 4-V and 1900-amp batteries must be used. The solar water heater was also used to supply the thermal energy needed to supply the building's hot water, which was analyzed for different modes of combining the use of solar and gas boilers as backup heat. The results showed that if we were to supply all the thermal energy needed to supply the building's hot power with solar energy, we need an area of $\sim 7 \, m^2$ of flat panel collectors. This will save 345 m$^3$ of natural gas consumption and also reduce CO2 emissions by 1154 kg. But in this case, the efficiency of the system is much reduced and will be 25.4%.

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