Hindawi
Journal of Engineering
Volume 2022, Article ID 6280334, 6 pages
https://doi.org/10.1155/2022/6280334

Research Article

Modeling and Thermodynamic Analysis of Solar Collector Cogeneration for Residential Building Energy Supply

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Received 15 May 2022; Accepted 24 June 2022; Published 7 July 2022

Academic Editor: Francesco Colangelo

Concerns about limited energy resources and environmental problems are growing. One of the solutions to increase energy efficiency is to produce it sparsely. In this regard, cogeneration systems are of particular importance. The home sector is one of the most consumed sectors due to the potential of solar radiation in this country, a system of simultaneous generation of electricity and heat for the home sector has been proposed, and modeling operations have been performed on the proposed system. The results show that the proposed system is capable of supplying more than 85% of hot water demand and annual production of 316.36 kWh of electricity.

1. Introduction

Energy is considered to be the main factor in the socio-economic development of human societies. But the process of production, transmission, distribution, and consumption has always been considered a cause of environmental pollution on a local, regional, and global scale along with other factors. Human societies have a variety of energy needs in their daily lives or industrial products [1–3]. On the other hand, traditional power plants are very large and concentrated energy production. The new approach to energy production is moving towards distributed generation, which means that energy conversion units are close to their consumers. As a result, transfer losses are minimized.

A distributed generation system is a reliable and environmentally friendly alternative to conventional energy systems. The most important issue addressed in recent studies is the development of technology solutions in the field of energy conversion, fuel support, storage, and integration of energy systems. Integration of distributed energy generation systems reduces transportation costs, reduces the damage caused by load shedding, and also includes environmental benefits. A better understanding of the relationship between distributed energy production systems and sustainable development requires extensive political, economic, social, and technological considerations [4–6].

In many countries that are suppliers of fossil fuels, in recent years, with falling oil prices and economic and political crises, it can be noticed the increasing attention of the government, researchers, and industrialists to strategic activities in the field of energy [7, 8].

The per capita final energy consumption in the agricultural, household-commercial-public, transportation, and industrial sectors is 2, 3, 8, 1, 6, 1, and 5, 1 times the global average, respectively. A comparison of Iran's per capita final energy consumption by energy carriers on a global scale shows that the per capita consumption of natural gas and crude oil and oil products is 9، 5 and 6 ،1 times the global average per capita consumption, respectively [9]. The per capita consumption of other carriers is lower than the global average. This is due to low efficiency in operation, high energy consumption, as well as the use of energy for goods and services. Given the importance of distributed energy generation and environmental problems in the world, it seems that decentralized electricity generation in small and scattered dimensions can minimize these losses.

On the other hand, considering the high potential in renewable energy, especially the high interest in solar energy, it seems that this small-scale renewable energy can be used to meet the demand of the domestic sector [10, 11].

There have been many studies in the field of distributed generation systems as well as distributed generation systems using solar energy and ORC technology in the world. Pedro Mago et al. in 2009 used the Organic Rankine Cycle (ORC) in the CHP system in small commercial buildings. In this study, the waste energy of exhaust is used to generate electricity, as a result of which the primary energy (PEC) reduces the amount of carbon dioxide emissions (CDE). The purpose of this research is the energy, environmental, and economic analysis of the CHP-ORC combined system [12, 13].

In [14], they performed a thermal-economic optimization on the recovery of waste heat using the organic Rankine cycle. The optimization process is performed under constant conditions for the heat source. The ORC investment's thermal efficiency and net cost in single-stage and two-stage recovery modes are optimized using a genetic algorithm [15]. The authors have shown in their study that dry and isotropic fluids are preferred for use in the ORC cycle. This is because dry and isotropic fluids become superheated after expansion [16]. In [17], they conducted a study on the cogeneration system of solar cooling, heating, and electricity. Their proposed system is a combination of the Brighton cycle and the transient refrigeration cycle of the critical state of CO_2 with the ejector. We have conducted a study on the energy, environmental and, economic analysis of a parabolic trough concentrating the photovoltaic or thermal system [18].

In [19], they performed a multivariate optimization on the solar, heating, and solar cogeneration systems. In this study, a flat plate collector was used to collect solar thermal energy. On an organic Rankine cycle, the solar power system was used to provide heating and power to the home sector. Calculations on the performance of small-scale solar heating and power generation systems have been performed to estimate the potential of this technology to meet heating and power demand [20]. In [21], they conducted a study on the numerical investigation of the energy performance of a solar micro-CHP unit. In [22], they conducted a study on the innovative geothermal-based power and cooling cogeneration system, thermodynamic analysis, and optimization.

In this research, the aim is to investigate the cogeneration of electricity and heat with the solar collector system, in which the amount of thermal and electrical energy required for residential buildings has been determined. In this research, thermal modeling of a solar collector with fluid relationships has been done, which is considered as a support system for the heater in the absence of solar heat. In the studied system, the output of the solar collector is considered as the input of the steam turbine in order to evaluate the potential of generating electric energy from this system.

2. Materials and Methods

2.1. Explanation of the System. The combined heat and power generation system proposed by this research consists of a solar cycle consisting of a solar collector, a pump, and a heat storage tank. The solar cycle is connected to the power generation cycle by a steam generator. The cogeneration system proposed in this research transfers the energy collected from the sun by the solar collector to a steam generator to be converted into electricity in the organic Rankine power generation cycle. Since this system is proposed for the home sector, we will have an area limit for installing solar panels. Due to the area of roofs in Tehran, an area of 15 m^2 has been considered for the installation of solar collectors. In this research, solar vacuum tube collectors have been used. This is because they are a common type in the market and have a higher efficiency than flat plate collectors. The heated water inside the solar collector enters the heat storage tank after the heat transfer with the organic fluid in the steam generator. In this research, R245fa organic fluid has been used due to its suitable thermophysical characteristics and environmental compatibility. The configuration of the studied system can be seen in Figure 1.

2.2. Modeling Method. Coproduction system modeling consists of three general parts:

Input radiation.

Solar Cycle Section.

Organic Rankine Cycle Section.

System modeling is done by MATLAB software. Due to the time-dependent nature of solar energy, the performance of the complex should be evaluated at reasonable intervals. The minimum time interval developed to calculate the amount of input radiation as well as experimental measurements is one hour [12]. The total received radiation of a surface consists of three direct radiations, diffused radiation, and reflective radiation.

$$I_T = I_{T,b} + I_{T,d} + I_{T,\text{refl}}. \quad (1)$$

The amount of radiation between hours ω_1 and ω_2 for a plate outside the atmosphere is calculated from the following equation [23, 24].

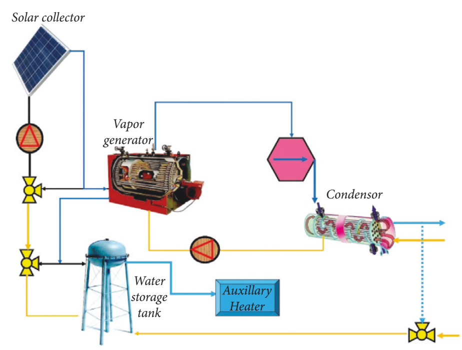

Figure 1: Configuration of the system for simultaneous generation of electricity and solar heat.

$$I_0 = \frac{12 \times 3600 \times G_{sc}}{\pi} \times \left(1 + 0.0033 \cos \frac{360n}{365}\right) \times \left(\cos \phi \times (\sin \omega_2 - \sin \omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180} \times \sin \phi \times \sin \delta\right)\left[\frac{J}{m^2}\right], \quad (2)$$

where the value of n is the number of days, the value of G_{SC} is the solar constant, and the angles of φ and δ are the latitude of the angle of the mounting position relative to the reference coordinates (equator) and the angle of solar deflection, respectively. The radiation received on the ground is calculated using

$$I_T = I_b R_b + I_d \left(\frac{1 + \cos \beta}{2}\right) + I_{\rho g}\left(\frac{1 - \cos \beta}{2}\right), \quad (3)$$

where R_b defines the ratio of the received radiation of an angled plate to a flat plate at any time. The received radiation is collected in a solar collector. As shown in the figure, a three-way valve is seen in the design to determine the return path to the solar collector. The circulating fluid in the solar collector circulates in a closed circuit until it reaches a certain temperature (T_{sp}), and as soon as the temperature of the circulating water in the solar collector reaches the set temperature, The three-way valve is closed and the water flow is stopped. It enters the steam generator to exchange heat with the organic fluid. The solar collector efficiency of the vacuum tube in this research can be calculated from the following equation.

$$\eta_{SC} = C_0 - C_1 \frac{(T_{sc} - T_{ext})}{I_{sol}} - C_1 \frac{(T_{sc} - T_{ext})^2}{I_{sol}}. \quad (4)$$

Therefore, the thermal energy absorbed by the fluid inside the solar collector is obtained from

$$Q_{sol} = \eta_{SC} I_{sol} A_{SC}. \quad (5)$$

When we do not have solar radiation, the flow rate of the fluid pump in the solar cycle is also zero.

$$\dot{m}_{sc} \begin{cases} 0 & \text{if } I_{sol} \\ \dot{m}_{sc} & \text{otherwise} \end{cases} = 0. \quad (6)$$

The steam generator in this study is considered to be of the vane and plate type, and the pinch temperature difference ($\Delta T_{pich} = 5$) between the fluid entering from the hot heat source and the organic cycle fluid at the exit of the steam generator (turbine inlet) is assumed. Therefore, the temperature of the organic agent fluid at the exit of the steam generator is calculated according to the following equation.

$$T_{evp} = T_3 = T_{hs,in} = \Delta T_{pin}. \quad (7)$$

Until the water temperature inside the solar collector cycle reaches the set temperature (T_{sp}), the water in this cycle is heated by the sun. When the water temperature reaches the set value, water enters the steam generator to start the organic Rankin cycle. Therefore, the flow of organic fluid $\dot{m}_{wf}$ is zero until it reaches the specified value.

$$\dot{m}_{wf} \begin{cases} 0, & \text{if } T_{sc,out} < T_{sp}, \\ \dot{m}_{wf}, & \text{otherwise.} \end{cases} \quad (8)$$

After transferring heat with organic fluid, water enters the heat storage tank, the tank temperature can be calculated for each hour according to the following equation.

$$T_s^+ = T_s + \frac{\Delta t}{(mc_p)_s}\left[Q_u - L_s - (UA_s)(T_s - T_a')\right]. \quad (9)$$

In this regard, Q_u is the heat input to the heat storage tank, L_s is the heat load taken from the tank, and (UA_s) is the heat loss coefficient of the storage tank in its area. The work generated by the turbine in the organic Rankine cycle can be calculated according to the thermodynamic equations of

$$W_{e,ORC} = \eta_g \dot{m}_{wf}(h_3 - h_4), \quad (10)$$

where η_g=90 is considered. The net output work of the organic Rankine cycle is obtained based on the following equation.

$$W_{net} = W_{e,ORC} - W_{pump,ORC} - W_{pump,sc}. \quad (11)$$

3. Results

The mass flow rate of the working fluid in the solar cycle has a direct effect on the water temperature at the outlet of the solar collector. If the mass flow of the fluid is high, the temperature during the solar collector will be low, but the efficiency will be high. On the other hand, with the increase of water mass flow according to the second law of thermodynamics, the number of losses due to irreversible processes will increase, and the efficiency will decrease. In Figure 2, it can be seen that the output temperature of the solar collector is shown based on changes in mass flow.

The amount of steam generator pressure has a direct effect on the output of the organic Rankine cycle. Output work changes in terms of steam generator pressure are shown in the diagram. In Figure 3, it can be seen that the results show that the maximum amount of output work is obtained at saturation pressure.

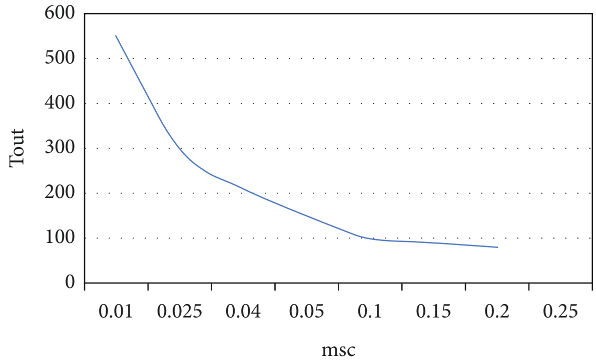

Figure 2: Fluid temperature changes in the solar cycle based on mass flow.

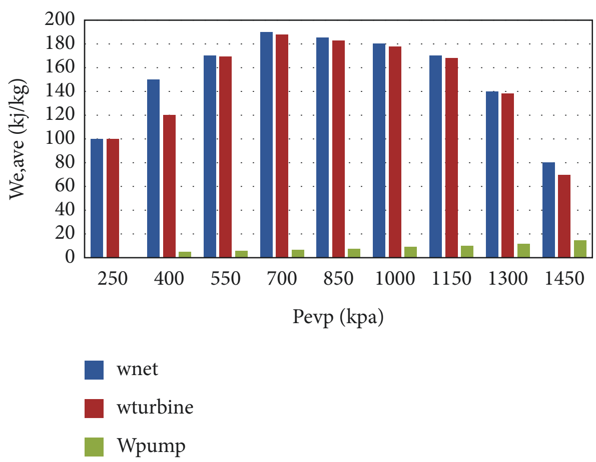

Figure 3: Changes in electricity generated by the organic Rankine cycle based on steam generator pressure.

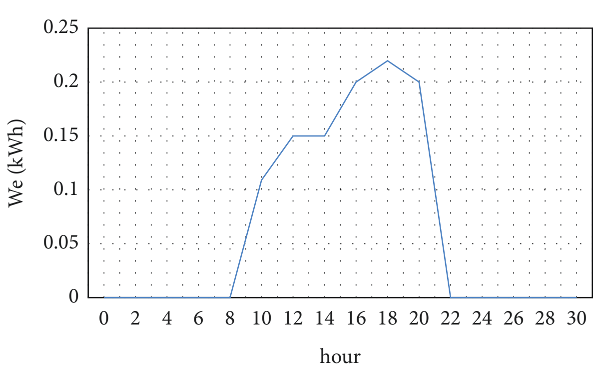

Figure 4: Electricity from the organic Rankin cycle for an index day in June.

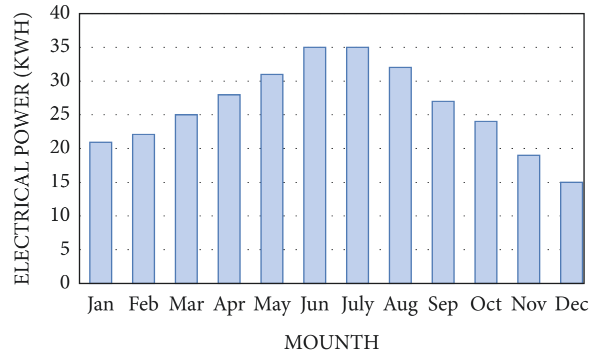

Figure 5: Total electricity generated by the organic Rankin cycle per month.

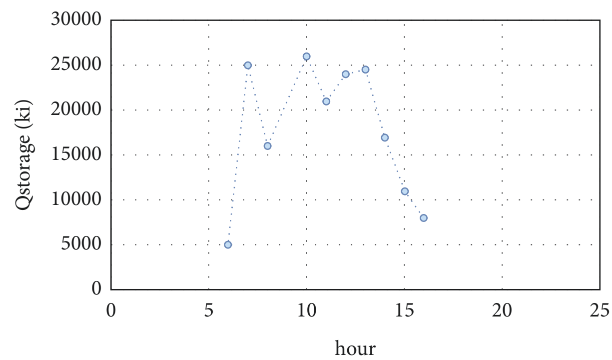

Figure 6: Heat storage tank water temperature changes for each hour of an index day in June.

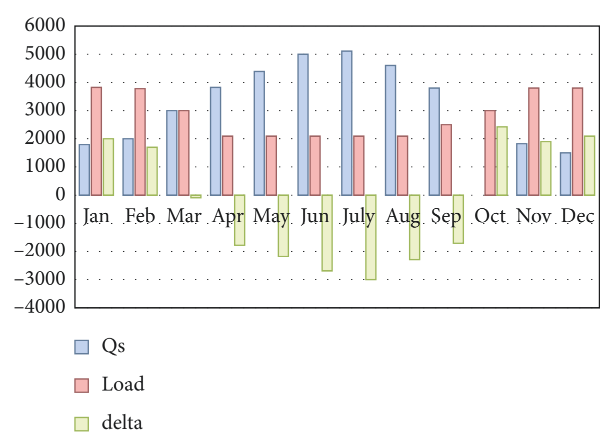

Figure 7: Changes in heat load in the heat storage tank according to the load consumed per month.

The model developed in this research can calculate the amount of electricity generated on each day of the year on an hourly basis. In Figures 4 and 5, it can be seen that changes in the amount of electricity produced per hour for June show that the intensity of solar radiation is at its maximum.

The temperature of the heat storage tank is calculated on an hourly basis based on a load of hot water consumption, which is calculated according to the ASHRE standard. Changes in water temperature inside the tank in terms of hours for one day in June are shown in Figure 6.

The amount of heat load stored in the heat storage tank and the amount of hot water load are cumulatively shown in the diagram. The difference between the hot water load and the heat load stored by the heat storage tank is also plotted for each month. According to Figure 7, from April to September, the heat load of the tank is more than the load of hot water during the day and night.

4. Conclusion

Today, the production of energy required by societies from other energy sources is very important, among which solar energy is more popular due to its availability in all parts of the world. Another advantage of solar energy is the production of energy such as electrical energy and thermal energy in a system. Therefore, in this study, the cogeneration of electricity and heat from the solar collector system that is connected to the steam turbine has been performed. In the studied system, the heater is considered as a support for the heating system, so that when solar heat is not available, this system can act as a source of heat and electrical energy. According to the obtained results, it can be said that the higher the flow rate of the collector inlet, the lower the temperature absorbed by the fluid, which will reduce the thermal and electrical energy produced. Also, the studied system has the ability to supply all the required energy of the studied building, including thermal and electrical energy.

Data Availability

All data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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