Assessment of PV-Based CHP System: The Effect of Heat Recovery Factor and Fuel Type

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It seems that studying the effect of heat recovery factor in combined heat and power (CHP) generation can present new solution for preventing energy loss in various supply and demand sectors and for recovering the dissipated energy in order to enhance energy efficiency. This will certainly have desirable social and economic consequences. This study is the first attempt to investigate the effect of heat recovery factor on CHP generation in distributed generation by solar cells. HOMER is used for simulations and the studied location is Isfahan city. Three different scenarios for the fuel of generator and boiler are studied which include diesel for both generator and boiler (scenario 1), natural gas for both (scenario 2), and diesel for generator and natural gas for boiler (scenario 3). Results indicate that increasing the heat recovery factor reduces the fossil fuel consumption, which in turn lessens the CO_2 emissions and price per kWh of energy. In addition, in all three scenarios, using solar cells combined with generator and boiler will have a higher cost but will reduce the fuel consumption and CO_2 emissions. It can also be concluded from the results that the cheapest scenario is scenario 2. Additionally, the scenario 3 is the most expensive one. The cheapest electricity generated is priced at 0.167 \$/kWh. According to the results, the third scenario and hybrid photovoltaics (PV)-generator microgrid outperform in terms of producing environmental pollutants with emitting 3604 kg/y CO_2 at their best.

Keywords: *Electricity profile, Thermal load, Fuel price, Cost of electricity, Efficiency curve.*

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1. Introduction

Given the growth in the world's energy demand, more important concerns are raised about energy security issues like availability and dependence on fossil fuels, greenhouse gases (GHG) emission and environmental effects of producing energy by fossil fuels and discussions about future effectiveness of fossil fuels [1, 2]. Also, it is forecasted that global energy demand will grow by 37% by 2040 [3].

An increasing number of developing countries have raised their renewable energy capacity in 2016 and some of them are turning into important markets. Utilizing low-cost and more efficient renewable technologies and more reliable prediction of sources, emerging economies are altering their energy industries, which makes such countries as Argentina, Chile, China, India, and Mexico as interesting markets for investors [4].

The increasing global demand in addition to the inefficiencies of conventional power generation systems made the practitioners to turn to using more reliable and efficient CHP technologies with some advantages over the conventional systems such as more fuel efficiency and reduced GHG emissions [5]. The pollutant gases emission is decreased around 13%-18% by using CHP units to generate power and heat, simultaneously [6]. CHP, also known as cogeneration, is the concurrent production of electricity and useful thermal energy from a single source of energy [7]. CHP is an energy-efficient technology used to generate electricity and useful thermal energy for producing steam and hot water to be utilized in space heating, domestic hot water, and industrial processes. CHP is usually used in places where both thermal and electric energy are required. Almost two thirds of the energy consumed for producing conventional electricity is changed into heat. The excess energy is dissipated during power distribution for customers while, avoiding losses, overall CHP efficiencies can reach 80% [8]. It is also noted that considering the recovery of wasted heat during conversion of fossil fuels to electrical energy and such conversions, the energy efficiency of CHP systems achieved is as much as 90% [9]. This will lead to a typical 10-40% savings of generation cost by utilizing CHP units comparing with conventional thermal units and heat-only boilers [10].

In recent years, Iran's energy demand has primarily been supplied through fossil fuels, and given the increasing trend of energy use in the country, Iran's fossil sources are being depleted which highlights the necessity of using CHP in Iran. From July 2009 to the end of April 2018, 2000 million kWh of energy has been produced from renewable sources in Iran, 73 million kWh of which being generated in April this year. According to the reports, this has led to 1,380,000 tons reduction in GHGs emissions, 50,000 tons of which being achieved in April of the current year. This has also caused 568-million m^3 reduction in the consumption of fossil fuels, which are the main causes of air pollution in the country. Furthermore, 440 million liters of water has been saved through producing new energies in recent years, the share of April alone being 16 million liters. The highest installed capacity of new energies of Iran is associated with wind power plants. According to this report, at the present, renewable power plants with a capacity of 566 MW are being constructed in the country while the installed capacity of new energies is reached to 559 MW. In addition, the renewable energy sector employed 47729 people, directly and indirectly, in the country. Evaluation of figures in this sector indicates that of the country's renewable power plants 47% are wind type, 33% are solar, 16% are small hydropower, 2% are heat recovery, and 2% use biomass [11].

So far, few efforts have been made for studying the cogeneration of electricity and heat in the distributed generation scenario using HOMER. Some of them are mentioned in the following:

In a study in Zarin Shahr City, Isfahan, Jahangiri et al., (2018) studied the exploitation of wind, solar, and biomass energies for cogeneration of electricity and heat [9]. Results indicated that if the distance to the access point of the main grid in the studied area is less than 2.58 km, using the main grid is superior to biomass. Also, assuming a 15% increase in gas and electricity prices, and in case of producing 100% of the required energy by renewable sources during 25 years, it would lead to a profit of $20310. Fernando et al., (2018) studied the hybrid energy system at Abertay University, Scotland, using HOMER [10]. They investigated various scenarios including solar cells, wind turbines, and CHP. They were looking for sustainable hybrid solutions based on sensitivity analysis. The studied parameters were cost of electricity (COE) and NPC. Results suggested that the lowest value was related to the scenario including main grid, 70 kW solar cell, 45 kW convertor, and 500 kW CHP. Waqar et al. (2017) evaluated a CHP-based grid-connected micro-grid in 6 cities of Pakistan using HOMER [14]. These authors were motivated by frequent disruptions in natural gas supply, which forced the use of electricity for heating. The arrays they utilized were solar cell, battery, and diesel generator. Their aim was to reduce environmental pollutants and minimizing the costs of energy production. Results indicated that Gilgit, Lahore, Quetta, and Quetta stations had the lowest rate of COE, lowest GHG emission (1000 tons/y), highest recovery of dissipated heat (2040282 MWh/y), and highest rate of selling electricity to the grid (8322268 MWh/y), respectively. Kim et al. (2017) used HOMER to study the applicability of combined cooling, heating and power systems (CCHP) for a building using solar cells [12]. The studied area was Atlanta, Canada. The parameters evaluated were energy consumption, production costs of electricity and heat, pollutants reduction, and reducing water usage. Results showed that, for a residential building, using this system led to a reduction in energy consumption (48.8%), costs (5.6%), and water consumption (48.6%). Yuan et al., (2017) conducted a techno-economic study on solar cell-based hybrid renewable energy DG systems for supplying the required power and heating energy of a village in China [16]. HOMER used annual data on consumed electricity, solar radiation, air temperature, etc. for simulation. Besides, dump load is used to convert excess electricity into thermal energy. Results indicated that the lowest NPC and COE are obtained by using 0.5 kW solar cells, 0.65 kW generator, 3 batteries, and 0.5 kW convertor. Moreover, 6490 kg/y of CO_2 is produced optimally, which is due to the generator. Application of power and heat cogeneration system in domestic sector is widely developing which is due to its capability of producing thermal and electrical energy from one single source and reducing total costs of energy. For these reasons, an optimal CHP system is simulated in this study using HOMER software for a residential apartment with a total area of 130 m^2 located in Isfahan. Given the economic capabilities including higher efficiency and reduction of fuel consumption, the effect of heat recovery factor on combined heat and power generation in distributed generation by solar cells using natural gas and diesel as the fuel was studied for the first time and the best option was suggested.

Below is the HOMER software and the required data for simulation. The under-study location has been introduced and investigated followed by a section on the results of simulation. In the conclusion, the highlights in relation to the present study are explained.

2. Homer software

HOMER is a climate-based software for designing of zero-energy buildings according to the selected climate. The software functions to evaluate and design an optimal microgrid in two modes of grid-connected and off-grid in order to achieve the goals of the related application. HOMER calls the hourly electrical and heating demands to be supplied by the system and calculated the delivered energy current according to the system elements. In addition, for systems including batteries or fuel-based generators, HOMER decides at what times running the generator would be economic or at what times it should charge or discharge the battery and then it concludes about the plausible configurations. HOMER calculates the installation and operation costs of system during its lifetime and after simulating the possible configurations of the system, it outputs a list of configurations arranged according to the net present cost, which enables the comparison of various system options [17]. Some capabilities of this system include: modeling connection to the main grid in various states, modeling and analyzing different scenarios by software, the economic analysis of various technologies, modeling solar cells, power generation, wind turbine, and fossil fuel-based generators, modeling electric, heating, and hydrogen load [17], etc.

Power meter has been read to measure electricity usage consumed over a year in a residential apartment. Figures 1(a) and 1(b) show the average profile of daily electricity usage over a month and a year, respectively. The average daily electricity usage is 5.92 kW over a year. When divided by 24 hours, the average required electricity is 0.247 kW per hour. Moreover, according to the real data shown in Figure 1(b), maximum consumption in January for the under-study location is 0.729 kW. Considering weather conditions during summer, ceiling fan is used in the under study residential apartments, which does not impose much load on the system. Besides, since parents often rest at home in the afternoon, electricity usage is low between 12 and 4 pm. The natural gas and diesel prices have been considered based on domestic gas tariffs in 2018 and as non-subsidized prices, respectively, as in Table 1. Before simulating the power system, HOMER determines the emissions factor (kg of pollutant emitted per unit of fuel consumed) for each pollutant. After the simulation, it calculates the annual emissions of that pollutant by multiplying the emissions factor by the total annual fuel consumption. The price and size of all the required equipment are determined in HOMER according to Table 2.

An annual real interest rate of 18% [25], useful project lifetime of 25 years, and cycle charging strategy for generator have been considered. In this strategy, generators are run in their full capacity and the excess energy is stored in batteries. Using this strategy is only optimal with no or few renewable energy sources. Boiler efficiency of 80% is also taken into account and the required heat is considered as in figure 2. According to figure 2 it is apparent that from 1 A.M. to 8 A.M., the heating load is nearly 2 times the other hours because considering the fact that the weather is not very cold in studied location during daytime compared to nighttime, maximum consumption and peak demand occur at night, that this is in line with [12]. The average consumption and annual average are 1.34 kW and 32.1 kWh/d, respectively. The tilt angle of solar cells is equal to the latitude of the studied location and the solar system is not equipped to tracker. Generator fuel curve describes the amount of fuel that generator consumed to produce electricity. HOMER assumes a straight line for fuel curve [26]. The following relation expresses the generator fuel consumption in units/hr as a function of its electrical output [17]:

$$F = F_0 Y_{gen} + F_1 P_{gen} \quad \textbf{(1)}$$

where F_0 is Coefficient of fuel curve interception (unit/hr/kW), F_1 is the fuel curve slope (unit/hr/kW), Y_{gen} is the rated capacity of generator (kW), and P_{gen} is the electrical output of the generator (kW).

HOMER defines the generator's electrical efficiency as the electrical energy coming out divided by the chemical energy of the fuel going in. The following equation gives this relationship [17]:

$$\eta_{gen} = \frac{3.6 p_{gen}}{\dot{m}_{fuel} \cdot LHV_{Fuel}} \quad \textbf{(2)}$$

If the fuel units are kg, then $\dot{m}_{fuel}$ is equal to F. If the fuel units are L, then we have:

$$m_{fuel} = \rho_{fuel}\left(\frac{F}{1000}\right) \quad \textbf{(3)}$$

Moreover, if the fuel units are m^3, the efficiency equation becomes:

$$m_{fuel} = \rho_{fuel} \cdot F \quad \textbf{(4)}$$

In the present work, F_0 and F_1 are considered to be 0.08 and 0.25, respectively. Considering the efficiency of the generator equal to 30%, the number of used coefficients has been selected.

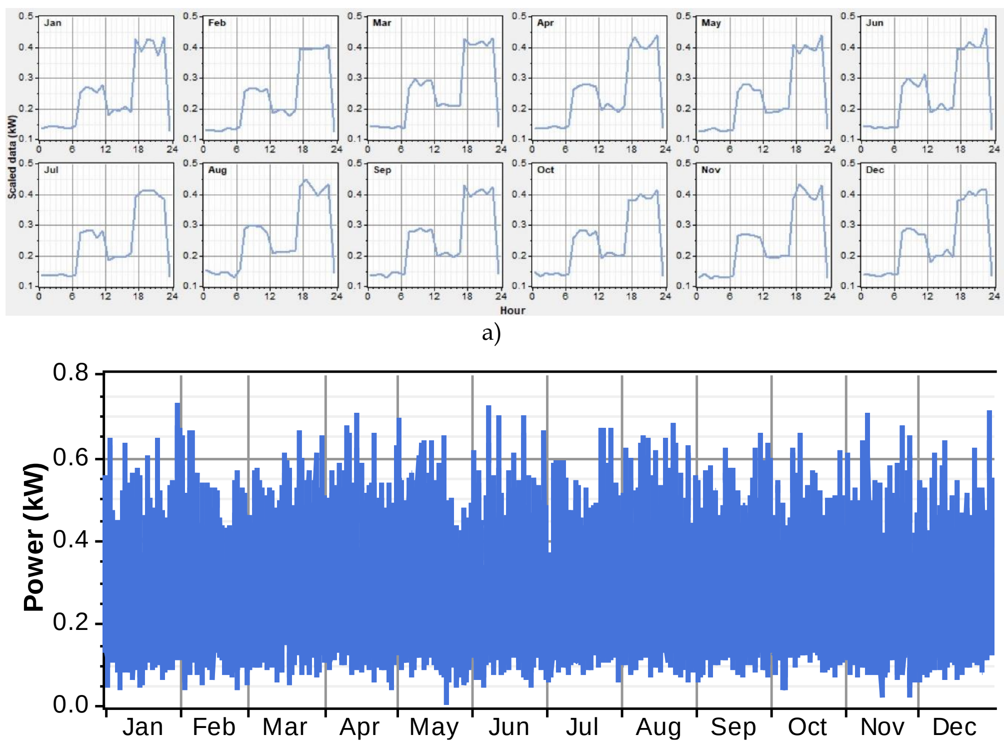

Fig. 1. Average profile of daily electricity usage over a a) month b) year.

Table 1. Fuel properties.

Pollutants [20, 21]	Fuel type	Price ($)
Carbon monoxide 6.5 g/L Unburned hydrocarbons 0.72 g/L Particulate matter 0.49 g/L Proportion of fuel sulfur converted to PM 2.2% Nitrogen oxides 58 g/L	Diesel	0.09 [18]
Carbon monoxide 4.4 g/L Unburned hydrocarbons 0.87 g/L Particulate matter 0.04 g/L Proportion of fuel sulfur converted to PM 0.002% Nitrogen oxides 12 g/L	Natural gas	0.03 [19]

Table 2. The price and size of the equipment used in simulations.

Component	Size/Type	Lifetime	Cost			Size to consider
			Capital ($)	O&M ($/years or h)	Replacement ($)	
PV [22]	1 kW	25 year	640	10	640	0-5
Converter [22]	1 kW	25 year	375	10	375	0-5
Generator [23]	3.5 kW	1500 h	2100	0.01	1300	0-5
Battery [24]	Vision 6FM	10 year	200	10	160	0-5

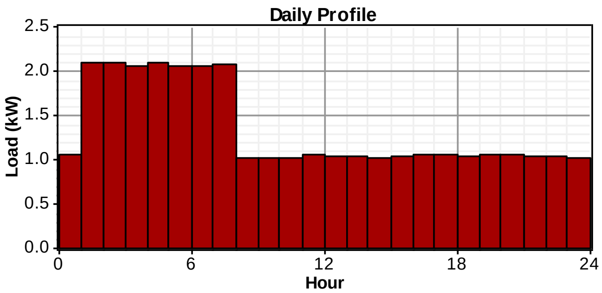

Fig. 2. Daily Profile of heating load

CHP systems use the excess heat of generator to provide all or part of the required heating load. HOMER assumes that the generator converts all energy of fuel into electricity and heat. The generator's fuel curve shows the amount of electricity produced based on the fuel input and then HOMER assumes that the rest of the fuel energy is changed into heat. Heat recovery ratio is the percentage of the heat that can be recovered to serve the thermal load. Various scenarios for CHP generation are depicted in Fig. 3. From this figure it is obvious that increasing the heat recovery percentage will rise the total efficiency, so that for percentages of 0, 10, 20, 30, 40, 50, the total efficiencies of 30.8, 37.7, 44.6, 51.6, 58.5, 65.4, respectively.

Since solar cells are also used in the studied hybrid system, it is required to input the monthly average radiation for the studied area. These data, which are shown in Fig.4, are extracted from NASA website. As it can be observed in Fig.4, the highest radiation ($7.5\frac{KWh}{m^2-day}$) occurs in June and the annual average radiation is 5.337 $\frac{KWh}{m^2-day}$. The clearness index is calculated by feeding the monthly average radiation data in HOMER and through the following relation given the latitude of the studied area [27]:

$$K_T = \frac{H_{ave}}{H_{o.ave}} \quad \textbf{(5)}$$

Clearness index is a number between 0 and 1 defined as the ratio of horizontal global irradiance (H_{ave}) to the corresponding irradiance available out of atmosphere ($H_{o.ave}$). It is clear in Fig.6 that the mean clearness index for Isfahan is 0.626.

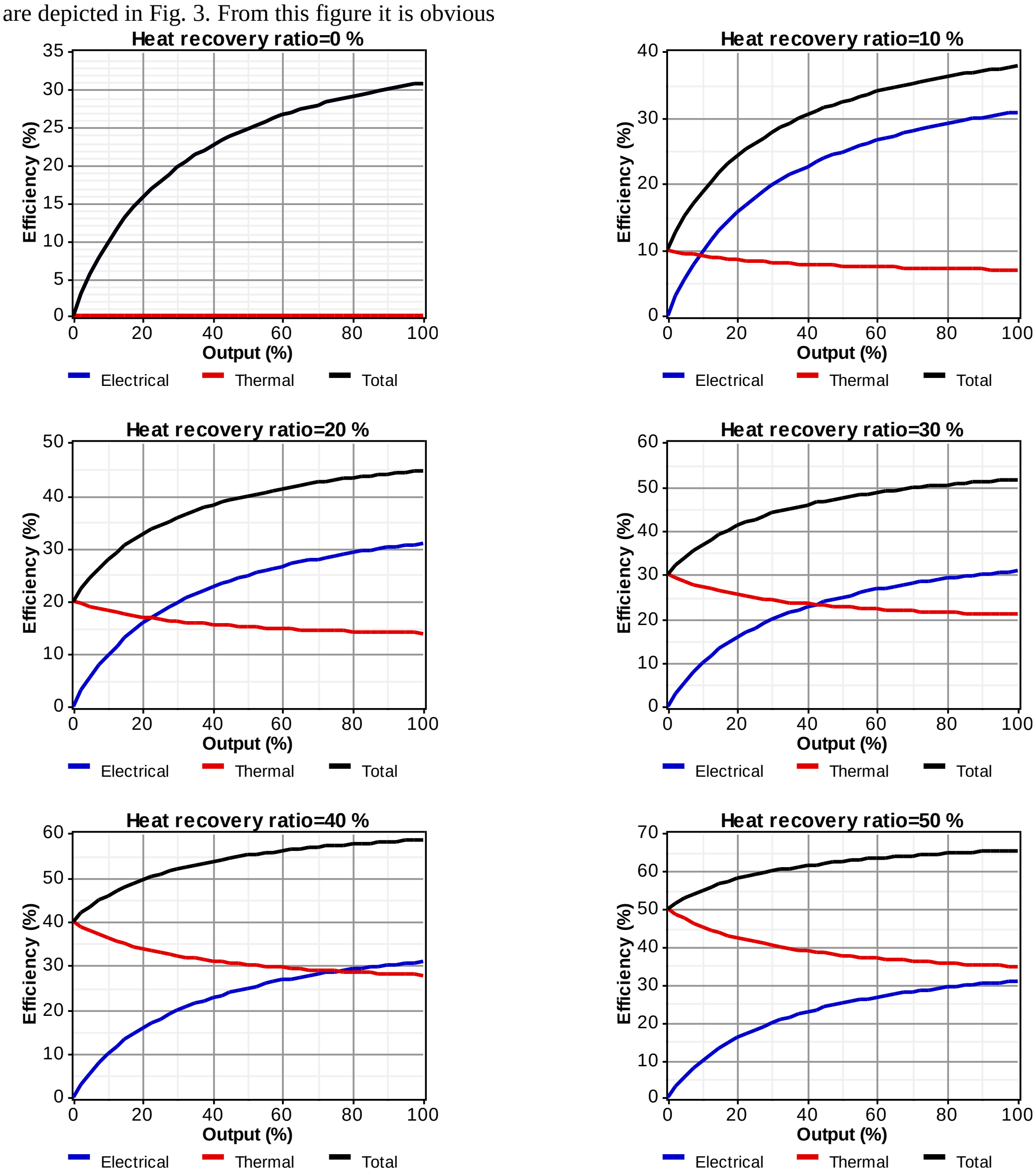

Fig. 3. Efficiency Curve for different heat recovery scenario.

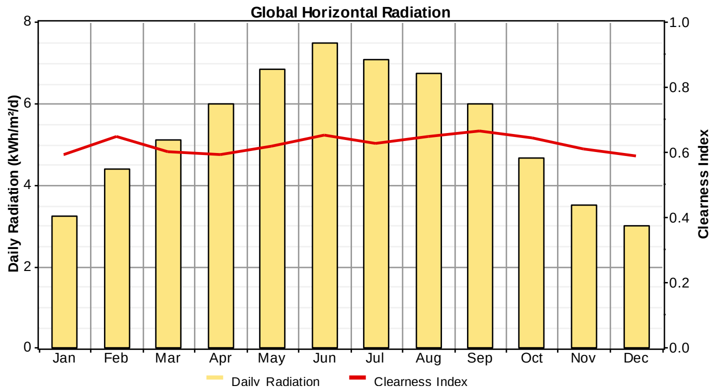

Fig. 4. Monthly global horizontal radiation.

The equations of the method of optimal system measuring, which has the minimum amount of total net present cost, are as follows [28]:

$$NPC = \frac{C_{ann.total}}{CRF\ (i.R_{proj})} \quad \textbf{(6)}$$

In the above equation, $C_{ann,total}$, CRF, i and R_{proj} are the total annual cost, cost recovery factor, real interest rate and lifetime of the project, respectively. All costs and incomes are evaluated at a constant interest rate over the year. The actual interest rate resulting from inflation is calculated and the effect of the change in interest rate on final NPC is applied to purpose of influencing inflation in calculations. The cost recovery factor, which indicates the cost recovery over the N years, is calculated as follows [28]:

$$CRF = \frac{i\ (1+i)^N}{(1+i)^N - 1} \quad \textbf{(7)}$$

Software is able to calculate the annual interest rate through the following equation [28].

$$i = \frac{i' - f}{1 + f} \quad \textbf{(8)}$$

Also, the cost of per kWh of energy during the lifetime of the project is obtained by software from the following equation [28]:

$$COE = \frac{C_{ann.\ total}}{E_{Load\ Served}} \quad \textbf{(9)}$$

In the above equation, $E_{Load\ Served}$ is the real electric load in the hybrid system by unit kWh/yr.

3. THE STUDIED CASE

The studied apartment is located in a residential four-story building with a total area of 130 m^2, Isfahan (Fig.5). An optimal CHP system is provided for this apartment based on real electricity and heat load data using HOMER.

Isfahan is located 424 km south of Tehran. To the east, the province of Yazd and South Khorasan borderd it, to its north stand the Markazi, Qom, and Semnan Provinces, to the west it is bordered by the provinces of Lurestan and Chahar Mahal and Bakhtiyari, and to its south it is bordered by Fars and Kohgiluyeh and Boyer-Ahmad provinces. Having a GPS coordinates of 51˚ 39' 40'' E and 32˚ 38' 30'' N, Isfahan as the third most populous metropolitan area in Iran after Tehran and Mashhad covers an area of approximately 213 km^2 with an altitude of 1570 m. The city consists of 13 municipal districts and the studied apartment is located in the 12th district, Negarestan Ave.

Fig. 5. A view of the studied residential building in Isfahan.

4. RESULTS

Three different scenarios have been investigated for generator and boiler consumed fuel. In the first scenario, generator and boiler use diesel as their fuel, in the second, natural gas and in the third, diesel is used for generator and natural gas for boiler. It is noteworthy that the third scenario is more conventional in Iran. The flowchart of HOMER calculations to find the optimum values of the minimum total net present cost (TNPC) and cost of energy (COE), the highest waste heat recovery (WHR), and the highest grid sales (gs) is shown in Fig.6. The results for the first to third scenarios are summarized in Table 3-5.

Table 3. Scenario 1, diesel fuel for both generator and boiler.

Heat Recovery ratio (%)	Scenario	Diesel consumption (L)	Cost of energy ($/kWh)	CO_2 emission (kg/y)
0	Generator	2829	0.216	7450
	PV-Generator	1909	0.245	5028
10	Generator	2696	0.210	7099
	PV-Generator	1865	0.243	4912
20	Generator	2563	0.205	6749
	PV-Generator	1821	0.241	4796
30	Generator	2430	0.199	6398
	PV-Generator	1779	0.238	4685
40	Generator	2297	0.194	6050
	PV-Generator	2097	0.234	5522
50	Generator	2167	0.188	5707
	PV-Generator	2006	0.230	5282

Table 4. Scenario 2, natural gas for both generator and boiler.

Heat Recovery ratio	Scenario	Natural gas consumption	Cost of energy	CO_2 emission

(%)		(m^3)	(\$/kWh)	(kg/y)
0	Generator	2824	0.176	5456
	PV-Generator	2524	0.220	4876
10	Generator	2691	0.174	5198
	PV-Generator	2426	0.219	4686
20	Generator	2558	0.172	4941
	PV-Generator	2327	0.217	4494
30	Generator	2424	0.171	4683
	PV-Generator	2226	0.216	4300
40	Generator	2292	0.169	4427
	PV-Generator	2125	0.214	4105
50	Generator	2162	0.167	4176
	PV-Generator	2025	0.213	3911

Table 5. Scenario 3, diesel fuel for generator and natural gas for boiler.

Heat Recovery ratio (%)	Scenario	Diesel consumption (L)	Natural gas consumption (m^3)	Cost of energy (\$/kWh)	CO_2 emission (kg/y)
0	Generator	1428	1396	0.216	6458
	PV-Generator	509	1396	0.245	4035
10	Generator	1428	1263	0.214	6201
	PV-Generator	508	1351	0.245	3948
20	Generator	1428	1130	0.212	5945
	PV-Generator	509	1305	0.244	3863
30	Generator	1428	998	0.210	5689
	PV-Generator	510	1260	0.243	3776
40	Generator	1428	866	0.208	5434
	PV-Generator	510	1214	0.242	3689
50	Generator	1428	736	0.207	5183
	PV-Generator	510	1170	0.241	3604

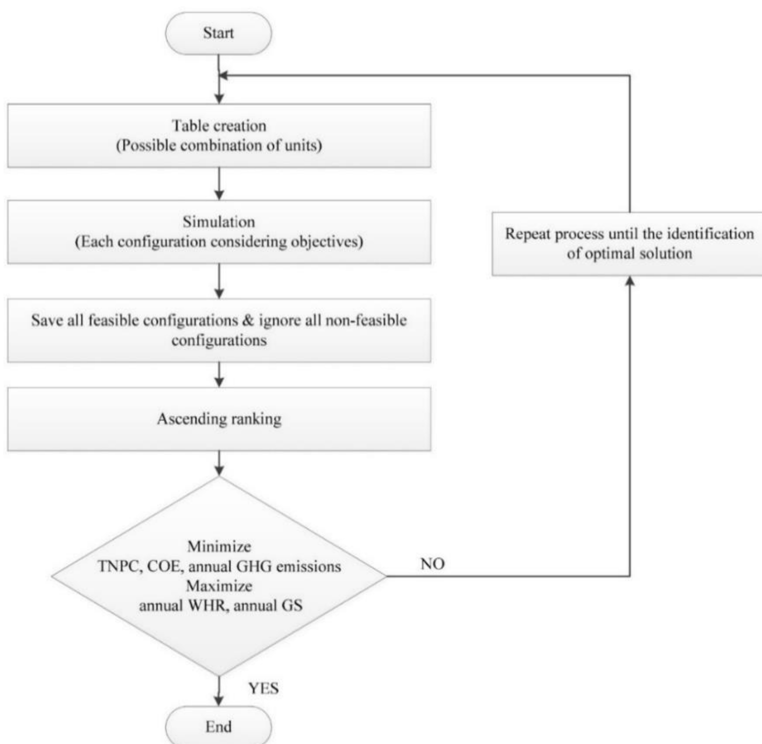

Fig. 6. Homer flow chart.

According to the results of all three scenarios, it is obvious that by increasing the heat recovery factor, a reduction occurs in the fossil fuel consumption and, consequently, the CO_2 emissions and price per kWh of energy. Furthermore, for all three scenarios, solar cells in hybrid mode with generator and boiler have a higher cost but much lower CO_2 emission and fuel consumption.

In the first scenario, the lowest fuel consumption (2006 L/y), which produces 5282 kg/y of CO_2 and is obtained by 50% heat recovery factor is associated with PV-Generator hybrid microgrid. Although the lowest cost of energy (0.188 $/kWh) is related to 50% heat recovery factor and using the generator alone.

In the second scenario, the lowest consumption of natural gas (2025 m^3/y) is related to PV-Generator hybrid microgrid and 50% heat recovery factor, which produces 3911 kg/y CO_2 emissions. however, it is noteworthy that the lowest price per kWh of electricity generated in this scenario, which is related to the generator alone, is $ 0.167.

For the third scenario, the least CO_2 emissions (3604 kg/y) are produced by consuming 510 L/y diesel and 1170 m^3/y natural gas and are related to PV-Generator hybrid microgrid. The lowest cost of energy for this scenario is equal to 0.207 $/kWh which is related to using the generator alone. In the third scenario, the important point is that by increasing the heat recovery factor, diesel consumption remains constant but a reduction occurs in gas consumption. This is because more thermal energy is passed to the boiler, which reduces the required thermal energy of the boiler and natural gas consumption. Moreover, as in the first and second scenarios, in the third scenario, the diesel consumption in PV-Generator mode is lower than Generator alone but the reverse is true about natural gas. In other words, due to lower diesel consumption in PV-Generator mode compared to the Generator alone, the boiler has to consume more natural gas to supply its heat requirements.

According to the results of all three scenarios, it is obvious that increasing the heat recovery factor will reduce the fossil fuel consumption, subsequently, the CO2 emissions, and the cost per kWh of energy. Also, in all three scenarios, using hybrid solar cell-generator-boiler system entails a higher cost but outperforms in terms of reduced fuel consumption and less CO_2 emissions.

5. Conclusion

The CHP generation is one of the most important applications of distributed generation. The more efficient use of heat released during combustion of the fuel, leads to higher energy efficiency, reduced fuel consumption and, eventually, the relevant costs of primary energy supply. The recovered waste heat can be utilized for heating, cooling, and many industrial processes. In addition to increased efficiency and reduced fuel consumption, heat and power cogeneration leads to lower pollutant emissions [29, 30]. This study is the first attempt to investigate the effect of heat recovery factor in three different scenarios of CHP in distributed generation using HOMER in a residential apartment located at Isfahan, Iran. In the first scenario, generator and boiler consume diesel. In the second scenario, they use natural gas as their fuel, and in the third one, the generator consumes diesel and the boiler consumes natural gas. As a general conclusion, it can be said that the cheapest scenario is used natural gas for both generator and boiler. Also, the scenario including diesel for generator and natural gas for boiler is the most expensive one. In addition, the cheapest electricity generated is priced at 0.167 $/kWh. From the results, it can be observed that in terms of producing environmental pollutants, the third scenario and hybrid microgrid (by producing at best 3604 kg/y CO_2) outperform other scenarios.

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