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Renewable Energy-Based Systems on a Residential Scale in Southern Coastal Areas of Iran: Trigeneration of Heat, Power, and Hydrogen

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ABSTRACT

The use of small-scale Combined Heat and Power (CHP) to meet the electrical and thermal needs of buildings has grown exponentially and plans have been made in Iran to expand these systems. In view of the above, in the present work, for the first time, sensitivity analysis has been performed on the parameters of natural gas price, annual interest rate, and the price of pollutant penalties. The CHP system studied included fuel cell, biomass generator, solar cell, wind turbine, and gas boiler. The techno-econo-enviro simulations were performed by HOMER software and the study area was Abadan. The use of a dump load to convert excess electricity into heat and heat recovery in a biomass generator and fuel cell are other advantages presented by the present work. The minimum Cost of Energy (COE) is 1.16 $/kWh. The results also showed that the use of biomass generators was economical when the annual interest rate was 30 %. The significant effect of using dump load on the required heat supply and the lowest price per kg of hydrogen produced equal to $ 35.440 are other results of the present work. In general, the results point to the superiority of solar radiation potential over wind energy potential of the study area and the prominent role of dump load in providing heat on a residential scale is clearly seen. Also, for the current situation, using biomass is not cost-effective.

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1. INTRODUCTION

All around the globe, humans consume much energy to generate heat and electricity in such sectors as industry, construction, and agriculture [1, 2]. To ensure a sustainable future, especially in the wake of global warming and lack of fossil resources, further research and development works are essential to creating more efficient and environmentally friendly energy production systems [3, 4]. In response to this, being one of the best methods of energy efficiency [5], CHP can be a viable solution because it is usually useful to generate heat and electricity at the same time and is obtained in a single process and also, from a single energy source [6, 7]. The CHP system can be defined as a set of components: heat converter (or heat engine), generator, heat recovery system, and electric converter [8].

CHP systems improve the efficiency of the whole system and cause heat recovery in the power generation process [9]. Centralized power generation systems cause heat loss in generation and transportation [10]. For example, only one-third of the primary energy derived from a nuclear power plant is converted into electricity. Thus, the total efficiency of classical energy production (electricity and heat) is about 60 %, while the total efficiency of CHP can reach 90 % (Figure 1) [11, 12]. Thus, CHP systems improve the use of primary energy and in addition, can help diversify the country's energy mix with local electricity and heat generation.

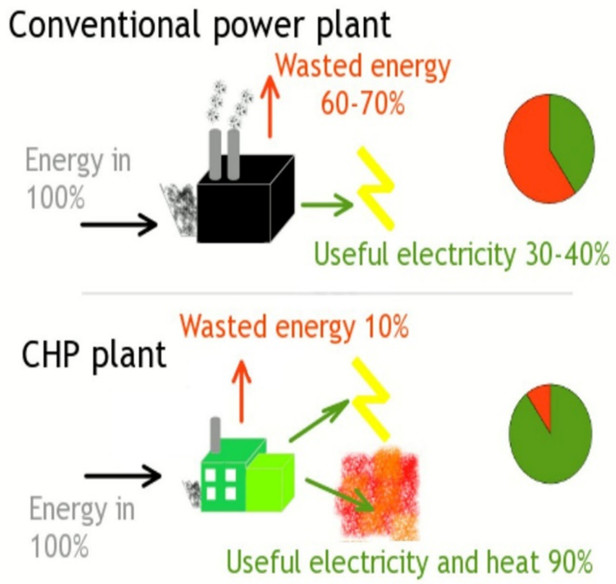

Figure 1. The energy efficiency schematic of a conventional system and CHP [13]

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Population growth in Iran has created a significant demand for electricity generation [14]. The population has doubled in the last 35 years, from 40.2 million in 1981 to 80.2 million in 2016 [15]. CO_2 emissions per capita increased from 2.8 tons in 1981 to 8.28 tons in 2014 [15]. Some of the challenges of Iran's electricity industry are increased electricity demand, low efficiency of centralized thermal power plants, and electrical losses in transmission and distribution lines [16, 17]. Centralized thermal power plants generate about 95 % of Iran's electricity [16]. The residential sector in Iran consumes about 33 % of electricity [16]. The average efficiency of Iran's thermal power plants is 37 %, and electricity losses in the transmission and distribution network are about 12.6 % [15, 16]. This statistic shows that there is an urgent need to upgrade Iran's electricity system using new technologies such as distributed generation systems and CHP. The type of CHP in each case study is determined by the availability of technology and fuel. In Iran, CHP technology is related to internal combustion engines. The price of natural gas is low and is widely available in most parts of the country. Therefore, gas-fired CHP systems are the most suitable technology options in Iran.

So far, few works have been done in the field of simultaneous generation of electricity and heat in the distributed generation scenario by HOMER software. Here are some of them.

Waqar et al. in 2017 [18] evaluated a CHP-based microgrid in the grid connection mode in 6 cities in Pakistan using HOMER software. The reason for the investigation was the frequent disturbances in natural gas and forced use of electricity to provide the required heat. The components used were solar cells, batteries, and diesel generators. The researchers' objectives were to reduce environmental pollution and minimize the cost of energy production. The results showed that Gilgit station had the lowest COE amount of 0.049 $/kWh, Lahore station had the lowest GHG emission amount about 1000 tons/y, Quetta station had the maximum waste heat recovery with an amount of 2040282 MWh/y, and Quetta station had the most electricity sales to the grid with a rate of 8322268 MWh/y.

Yuan et al. in 2017 [19] examined the use of a combined renewable energy system consisting of Photovoltaic Arrays (PV), wood-syngas CHP, and backup batteries in a typical semi-detached house in China. It was to meet home energy demand and reduce greenhouse gas emissions from fossil fuels. HOMER was used to simulate all operational configurations and to evaluate the system technically and economically. The results showed that the proposed optimum consisted of PV, wood gas generator, and the battery with the COE and NPC equal to 0.351 $/kWh and 3572 $, respectively.

Jahangiri et al. (2018) [20] in Zarrinshahr investigated the use of wind, solar, and biomass for simultaneous production of electricity and heat. The results showed that if the distance to the national grid in the study area was less than 2.58 km, receiving electricity from the national grid would be better than using biomass. Also, assuming a 15 % increase in electricity and gas prices annually and if 100 % of the energy required is provided by renewable energy sources over 25 years, the profit will be $ 20,310.

Jahangiri et al. in 2018 [21], for the first time, evaluated the effect of heat recovery factor on the simultaneous production of electricity and heat evaluated in distributed generation by solar cells. HOMER software was used for simulation and the place of study was Isfahan. Three different scenarios were considered for the fuel used by the generator and boiler, which were the diesel consumed by the generator and boiler, natural gas consumed by the generator and boiler, and the diesel consumed by the generator, and the natural gas consumed by the boiler. The results showed that by increasing the heat recovery factor, the consumption amount of fossil fuel reduced and as a result, the amount of CO_2 emissions and the cost per KWh hour of energy decreased. The results also indicated that the cheapest scenario was the natural gas use for both the generator and the boiler. Also, the scenario of using diesel for the generator and natural gas for the boiler was the most expensive scenario. The cheapest electricity produced was priced at 0.167 $/kWh.

Khormali and Niknam in 2019 [22] employed Homer software to minimize the cost of operating a grid-connected home-scale microgrid under usage time pricing. The study site was Gonbadkavoos Industrial Park in Iran and the evaluation criterion was Total NPC. The cost of diesel consumed was 0.16 $/L and the cost of consumed gas was 0.04 $\$/m^3$. The results of studies of two different scenarios of electricity exchange price with the network showed that during the year, in the first scenario 94.7 % and in the second scenario 35.2 % of electricity were purchased from the network. The results also showed a much better potential of solar energy than the potential of wind energy in the study area.

Kalamaras et al. in 2019 [23] conducted a feasibility study on the CHP system of an island separate from the national electricity grid in Greece. HOMER software was used for the studies and their system included solar cell, wind turbine, fuel cell, battery, electrolyzer, and hydrogen tank. The results illustrated that the selected system with a COE of 1.2 €/kWh could meet the thermal and electrical needs throughout the year.

Gbadamosi et al. in 2020 [24] evaluated the optimal power and reliability analysis of the CHP-wind-solar hybrid system for agricultural applications. They used solver CPLEX to solve and their place of study was South Africa. The results showed that the CHP-wind-solar hybrid system would reduce costs by 48 % compared to the CHP system.

Masrur et al. in 2020 [25] conducted an energy-economic evaluation of a CHP-solar PV system for a camp in the United States using HOMER software. They chose two different scenarios to consider: one based on fossil fuels and one combined with solar PVs. The results showed that the solar PV-based system with 25,609 kWh/year energies generated by solar PVs had less LCOE (as much as 0.04 $/kWh).

Pelaez et al. in 2021 [26] conducted a feasibility study for a solar cell-fuel cell-based CHP system using hydrogen as the fuel source. HOMER software was used for the simulation and the study site was an off-grid station in Spain. The results showed that the optimal system had a net present cost of $ 1006293 and a cost per kWh of energy produced was $ 0.8399. They also stated that although the system under consideration was not currently economically viable, it was technically feasible.

Elkadeem et al. in 2021 [27] analyzed the feasibility and optimization of a renewable energy-based desalination system (wind turbine-solar cell-diesel generator-battery) for an airport in Egypt. They used HOMER software for simulation and considered heat supply. For the optimal system, the results showed that the LCOE was equal to 0.08 $/kWh and the payback time was 1.2 years. Also, compared to the traditional system of using a diesel generator, the optimal system produced 59.5% fewer pollutants.

According to studies, the effects of dump load and the use of heat recovery in a CHP system have not been studied so far. Also, due to the variability of the studied parameters, sensitivity analysis has rarely been done in the performed works. Therefore, in the present work, using a 20-year average climatic data and HOMER software, a technical-economic-environmental study has been performed. Finding the optimal system, the amount of electricity, heat, and hydrogen production for each scenario, assessing the number of pollutants produced, as well as assessing the amount of electricity and excess heat are among the items done in the present work. It should also be noted that although the results of the present work are specific to this station, the proposed method can be used to implement a biomass-based CHP system anywhere in the world. Also, performing sensitivity analysis for different parameters makes it possible to evaluate the behavior of the system for wider applications in an area.

2. THE LOCATION UNDER STUDY

In today's world, the protection of coastal areas and their habitats is very important. Coastal environmental management seeks to adapt human uses and activities to the potential of the region [28]. For this reason, the city of Abadan was selected on the coastline of 5000 km south of Iran for the present work, and its wind speed and solar radiation data, including 20-year average data [29], were extracted from the NASA site. The required climatic data are given in Table 1. The location of the study station is also shown in Figure 2.

Table 1. The climatic data for Abadan

Data	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Solar radition (kWh/m^2-day)	3.305	4.432	5.255	5.925	6.846	7.409	7.087	6.913	6.196	4.922	3.775	2.976
Wind speed (m/s)	2.100	2.800	3.000	3.300	3.400	4.500	4.400	3.600	3.300	2.200	2.200	2.100

Figure 2. The location of Abadan on the Iran map

3. METHODOLOGY

For the present studies, HOMER software was used, which performed technical-economic-environmental studies together [20, 30]. This software had the ability to supply electricity, heat, and hydrogen and was used for analysis connected to the grid and standalone [31, 32]. Software optimizations are economical and the selected system has the lowest current net total price [33]. HOMER simulates the performance of the system under study over a year in time steps from one minute to one hour [34]. A very important feature of HOMER software that distinguishes it from other software is the sensitivity analysis that considers the impact of variables that are beyond the user's control such as wind speed, fuel costs, etc. and helps determine how the optimal system changes because of the mentioned parametric variations [35, 36]. Table 2 presents the general advantages and limitations of HOMER software. Figure 3 also shows the flowchart of software performance to better understand the performed process.

Table 2. Advantages and disadvantages of HOMER software [37]

Advantages	Disadvantages
Providing a list of real technologies simulated based on available equipment.	Being time-consuming and slow for some solutions.
Quite accurate simulation results for analysis and evaluation.	Requiring for accurate input data.
Providing a list of possible configurations based on different technologies and different equipment sizes.	Requiring experience-based criteria to achieve a good solution.
Solving many configurations quickly.	High quality of input data (resources).
Utility of results in learning to optimize systems with different combinations.	Software's inability to guess key values or sizes in case of their absence.

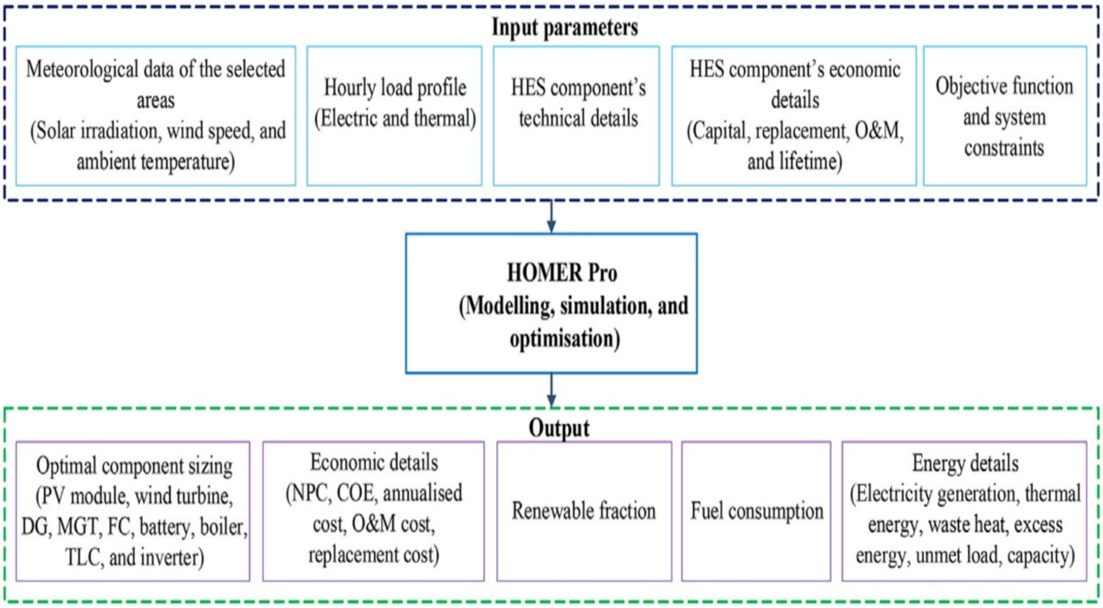


Figure 3. Flowchart of HOMER software performance [38]

By entering the average monthly radiation data, HOMER software calculates the air clearness index through the following equation [21, 39]:

$$k_t = \frac{H_{ave}}{H_{o,ave}} \tag{1}$$

where H_{ave} and $H_{o,ave}$ are the radiation that reaches the surface of the earth and above the atmosphere, respectively.

The power produced by solar cells (P_{PV}) in HOMER software is calculated using the following equation [40]:

$$P_{PV} = Y_{PV}\, f_{PV}\, \frac{\overline{G_T}}{\overline{G_{T,STC}}} \tag{2}$$

where Y_{pv} is the output power of the solar cell under standard conditions (kW), f_{PV} is the derating factor, $\overline{G_T}$ is the solar radiation to the collector surface (kW/m^2), and $\overline{G_{T,STC}}$ is the value of G under standard conditions (1 kW/m^2).

The angle of the solar cells is equal to the latitude of the studied station [41].

The output power of a wind turbine in real conditions depends on its location or, in other words, altitude [42, 43]. In HOMER software, the output power of wind turbines is calculated using the following equation [44]:

$$P_{WTG} = \frac{\rho}{\rho_0}\, P_{WTG,STP} \tag{3}$$

where ρ is the density of air in real conditions, ρ_0 is the density of air in standard conditions, and $P_{WTG,\ STP}$ is the output power of the turbine, which is obtained from the diagram of the turbine power curve.

The efficiency of the fuel cell and gas boiler in the present work is calculated by the following equation [45]:

$$\eta_{gen} = \frac{3.6\, P_{gen}}{\dot{m}_{fuel}\, LHV_{fuel}} \tag{4}$$

where P_{gen} is the total annual electricity produced (kWh/y) and $\dot{m}_{fuel}$ is the total annual fuel consumption (kg/y) and LHV_{fuel} is the low heating value of the fuel (MJ/kg).

HOMER displays a list of classified systems based on the total NPC as the main output which is given by [46]:

$$NPC = \frac{C_{ann,total}}{CRF(i, R_{proj})} \tag{5}$$

where $C_{ann,total}$ is the total annual cost ($), CRF is the factor of capital recovery, i is the real interest rate, and R_{proj} is the lifetime of the project. The CRF that represents the capital return in N years is calculated by [47]:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{6}$$

$$i = \frac{í - f}{1 + f} \tag{7}$$

The COE in kWh during the project useful lifetime is also calculated as follows [48]:

$$COE = \frac{C_{ann,total}}{E_{Load\ Served}} \tag{8}$$

where $E_{Load\ Served}$ is the actual electrical charge by the hybrid systems in kWh/y that is priced in dollars.

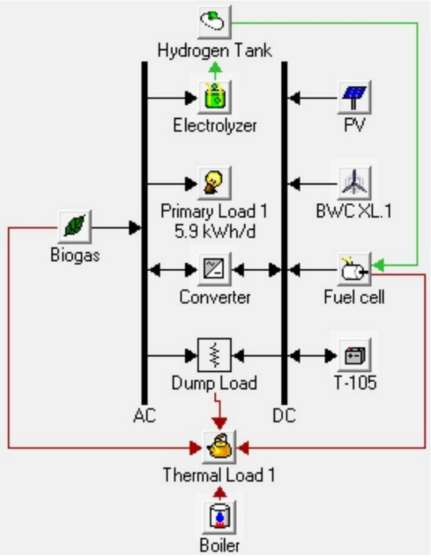
4. REQUIRED DATA

To use the solar cell, information on the average monthly radiation intensity (Table 1), geographical location (30° 40' N, 48° 30' E), and time zone of the studied station (GMT+03:30) is required. Also, the average wind speed (Table 1) and altitude (6 m) are the information required for wind turbines. Table 3 lists other information required for the simulation, including equipment price, equipment lifetime information, the available number of each equipment, etc.

The data used are natural gas price 0.015 and 0.03 $/m^3, average monthly biomass available for the study station equal to 0.788 ton/day, average animal biomass price in Iran 18 $/ton, biomass carbon content 5 %, gasification ratio 0.7 %, biomass low heating value 5.5 MJ/kg, annual interest rates 20 % and 30 %, project useful lifetime 20 years, grid extension cost 7600.6 $/km, grid maintenance cost 160 $/y-km, average price of grid electricity 0.01392 $/kWh, carbon dioxide emission penalty 0 and 150 $/ton, the efficiency of gas boiler 85 %, the content of carbon monoxide and unburned hydrocarbons in natural gas 4.4 g/m^3 and 0.87 g/m^3, respectively.

The required power and heat diagrams are shown in Figures 4 and 5, in which the average annual power and heat requirements are 5.92 kWh/day and 15.6 kWh/day, respectively.

Table 3. The system information

Equipment	Cost ($)			Size to consider	Other information	Schematic
	Capital	Replacement	O & M			
PV [49]	1000	1000	5	1-5	Lifetime: 25 years Derating factor: 90 %	
Biogas generator [20]	800	700	0.001	1	Lifetime: 15000 h Heat recovery ratio: 25 %	
Converter [50]	200	200	10	1-3	Lifetime: 10 years Efficiency: 90 %	
BWC XL.1 wind turbine [51]	5725	3650	100	1	Lifetime: 20 years Hub height: 25 m	
Fuel cell [52]	400	400	0.01	1	Lifetime: 50000 h Heat recovery ratio: 25 %	
Electrolyzer [52]	100	100	5	1-5	Lifetime: 25 years Efficiency: 85 %	
Hydrogen tank [49]	200	150	10	1-6	Lifetime: 25 years	
Battery T-105 [36]	174	174	5	1-10	Lifetime: 845 kWh Nominal specs: 6V, 225 Ah	

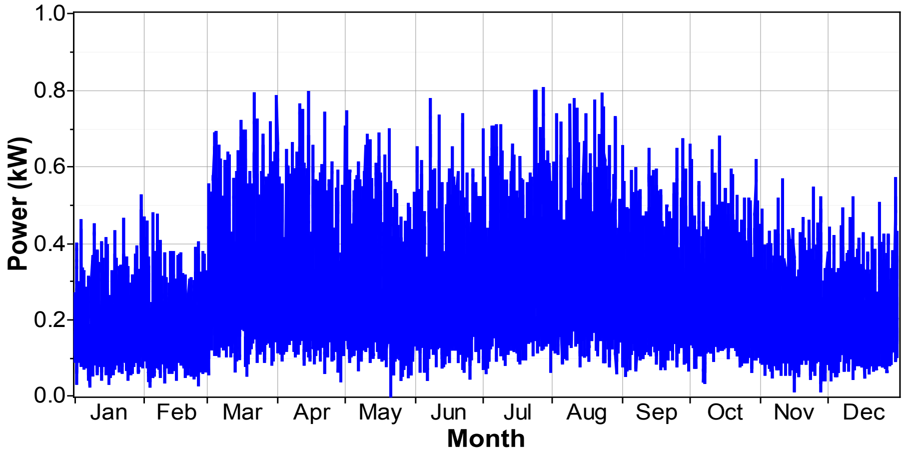


Figure 4. Daily electricity profile

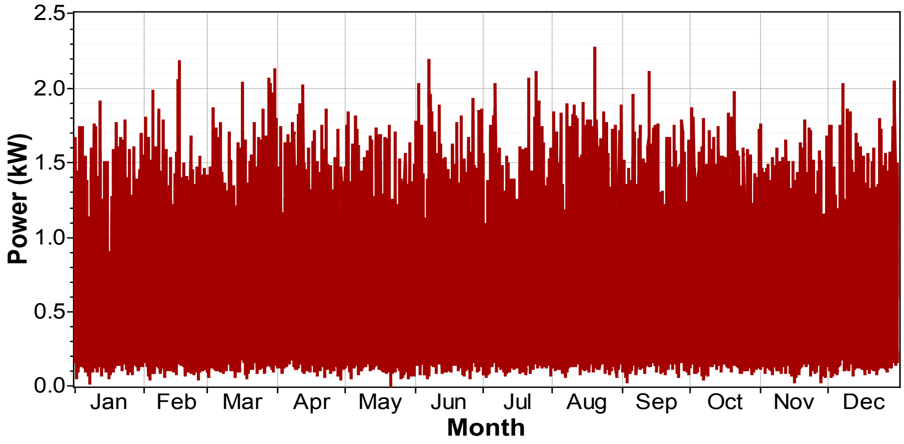


Figure 5. Daily thermal profile

5. RESULTS AND DISCUSSION

The results of the sensitivity analysis performed by the software for the system under consideration shown in Table 3, which includes an evaluation of 1419264 possible configurations, are given in Table 4.

From the results of Table 4, it can be seen that the optimal system under study includes 3 kW solar cells, 1 kW wind turbine, 1 kW biomass generator, 1 kW fuel cell, one battery, 2 kW electrolysis, and 2 kW electric converter. This system also includes a hydrogen storage tank. For the annual interest rates of 20 % and 30 %, 3 and 2 hydrogen storage tanks are used, respectively. The lowest total NPC with 12046 $ is for the second scenario, but the lowest COE with 1.160 $/kWh is for the seventh scenario. Due to the constant solar radiation and wind speed and the amount of biomass available, in all scenarios, 47 % of the required energy is provided by renewable energy. The minimum and maximum gas consumptions for gas boiler and required heat supply are 493 m^3 (second scenario) and 500 m^3 (third and seventh scenarios), respectively.

Table 4. Simulations results

Scenario	Natural gas price (\$/m^3)	Interest rate (%)	CO_2 penalty (\$/ton)	Optimal configuration	Electricity production (kWh/y)	Thermal production (kWh/y)
1	0.015	20	0	3 PV, 1 WT, 1 Biog.,1 FC, 2 Conv., 1 Batt., 2 Elec., 3 H_2 tank	PV: 5888 WT: 681 Biog.: 0 FC: 1307	Biog.:0 FC: 282 Boiler: 4169 Exc. Elec.: 1728
2	0.015	30	0	3 PV, 1 WT, 1 Biog.,1 FC, 2 Conv., 1 Batt., 2 Elec., 2 H_2 tank	PV: 5888 WT: 681 Biog.: 2 FC: 1303	Biog.:3 FC: 281 Boiler: 4142 Exc. Elec.: 1779
3	0.015	20	150	3 PV, 1 WT, 1 Biog.,1 FC, 2 Conv., 1 Batt., 2 Elec., 3 H_2 tank	PV: 5888 WT: 681 Biog.: 0 FC: 1339	Biog.:0 FC: 291 Boiler: 4199 Exc. Elec.: 1661
4	0.015	30	150	3 PV, 1 WT, 1 Biog.,1 FC, 2 Conv., 1 Batt., 2 Elec., 2 H_2 tank	PV: 5888 WT: 681 Biog.: 2 FC: 1336	Biog.:3 FC: 290 Boiler: 4170 Exc. Elec.: 1712
5	0.030	20	0	3 PV, 1 WT, 1 Biog.,1 FC, 2 Conv., 1 Batt., 2 Elec., 3 H_2 tank	PV: 5888 WT: 681 Biog.: 0 FC: 1308	Biog.:0 FC: 283 Boiler: 4171 Exc. Elec.: 1725
6	0.030	30	0	3 PV, 1 WT, 1 Biog.,1 FC, 2 Conv., 1 Batt., 2 Elec., 2 H_2 tank	PV: 5888 WT: 681 Biog.: 2 FC: 1305	Biog.:3 FC: 282 Boiler: 4143 Exc. Elec.: 1776
7	0.030	20	150	3 PV, 1 WT, 1 Biog.,1 FC, 2 Conv., 1 Batt., 2 Elec., 3 H_2 tank	PV: 5888 WT: 681 Biog.: 0 FC: 1340	Biog.:0 FC: 291 Boiler: 4199 Exc. Elec.: 1660
8	0.030	30	150	3 PV, 1 WT, 1 Biog.,1 FC, 2 Conv., 1 Batt., 2 Elec., 2 H_2 tank	PV: 5888 WT: 681 Biog.: 2 FC: 1337	Biog.:3 FC: 290 Boiler: 4170 Exc. Elec.: 1711

Table 4 (Continued)

Scenario	Total NPC (\$)	COE (\$/kWh)	Ren. fraction (%)	Nat. gas (m^3)	Biomass (t)	Excess electricity (kWh/y)	Excess thermal (kWh/y)	Breakeven grid extension distance (km)	LCOH (\$/kg)	CO_2 emission (kh/y)
1	12507	1.184	47	497	0	1728	486	1.48	35.390	960
2	12046	1.667	47	493	3	1779	511	1.47	50.774	946
3	13223	1.161	47	500	0	1661	457	1.56	36.425	966
4	12554	1.657	47	497	3	1712	481	1.53	51.483	951
5	12544	1.183	47	497	0	1725	485	1.48	35.440	960
6	12100	1.679	47	494	3	1776	510	1.48	50.922	945
7	13260	1.160	47	500	0	1660	456	1.56	36.509	966
8	12579	1.655	47	497	3	1711	480	1.53	51.559	951

PV: Photovoltaic, WT: Wind turbine, Biog.: Biogas generator, FC: Fuel cell, Batt.: Battery, Elec.: Eletrolyzer, Exc. elec.: Excess electricity, Nat. gas: Natural gas, Ren. fraction: Renewable fraction

According to the results, another noteworthy point is that for every price of natural gas and every penalty for pollutants, the use of biomass generators is economically justified when the annual interest rate is 30 %. According to the results, solar cells with a production of 5888 kWh/y and wind turbine with a production of 681 kWh/y have a significant role in supplying the required electricity. Of course, after solar cells, the fuel cell is in the second place with the highest amount of electricity production. According to the results, the highest electricity generation by the fuel cell in the seventh scenario is 1340 kWh/y.

Given that dump load is used to convert excess electricity into heat in the present work, according to Table 3, the results show that much of the surplus electricity generated, which according to the results is completely cheaper than the heat generated by fossil fuels, with a value of 1779 kWh/y is in the second scenario.

According to the results, to provide the required heat in all the scenarios studied, the gas boiler had the largest share, followed by the excess electricity converted by the dump load and the fuel cell. It can also be seen that in all scenarios, some excess heat is generated that has no use, and if the system is connected to a district heating network, selling it can reduce costs slightly. The maximum excess heat with the amount of 511 kWh/y is in the second scenario, and the reason is that the dump load has generated more heat in this scenario.

To compare the standalone mode with the grid-connected mode, it can be seen that the minimum and maximum distances from the national power grid should be 1470 m and 1560 m, respectively, in order to use this system economically. Another important point is about the effect of interest rates on the cost per kg of hydrogen produced so that by increasing the interest rate from 20 % to 30 %, the cost per kilogram of hydrogen produced will be about $ 15 more. The lowest and highest costs per kilogram of hydrogen produced with amounts of 35.39 $ and 51.559 $ are for the first and eighth scenarios, respectively.

Due to the use of natural gas fuel in all scenarios, about 1 ton of CO_2 emissions are emitted each year in each scenario. Based on the results, as a general result, it can be said that with the increase of the annual interest rate, the price per kWh of energy increases, the consumption of natural gas decreases, the use of biomass increases, the emission of pollutants decreases, the price each kg of hydrogen produced increases sharply, and excess electricity increases. Also, according to the results, with the increase in the price of penalty for pollutants produced, the amount of COE decreases, the amount of natural gas consumption increases, biomass consumption remains unchanged, the amount of excess electricity decreases, pollutant emissions increase, and the price of each Kg of hydrogen produced also increases. In general, the effect of increasing interest rates is the opposite of the effect of increasing the penalty price of pollutants.

Given that the most economically appropriate system is the system that has the lowest total NPC value, the second scenario is selected as the most appropriate one. Figure 6 shows the monthly average electricity production for Scenario 2. It is observed that much of the electricity (about 75 %) is generated by solar cells; in May to October, the share of solar cells is higher than that in other months. This indicates a very high radiation potential of the study station. The fuel cell is also the second-largest producer of electricity, supplying 17 % of the electricity generated, mainly in the months of March and October to December. Wind energy is the third-largest producer of electricity, supplying about 9 % of the electricity generated, with the share of wind energy in June and July being more significant. The biomass generator also plays a negiligible role in the electricity generated in January.

Figure 7 shows the average monthly heat generation for the second scenario. It can be seen that gas boilers with the production of about 67 % of the thermal need, especially in the cold months of the year (October to April), have the largest share in the required heat production. The important point is the large share of surplus electricity in heat production, which is about 29 % and is more significant in the months of May to September. According to the results of Figure 7, the share of fuel cells in heat production in all months of the year is almost constant and is about 5 %. Also, the share of biomass generators in heat production is very low and is in January.

6. LIMITATIONS

As the number of sensitivity analysis modes or parameters involved in sensitivity analysis increases, the computation time increases exponentially, requiring very powerful computers. Also, due to the use of 20-year average data instead of one-year data, the results may be slightly different from the actual situation. Also, the cheap electricity of the national grid and fossil fuels and the absence of penalties for pollutants in Iran make the scenarios under study uneconomical in the current situation.

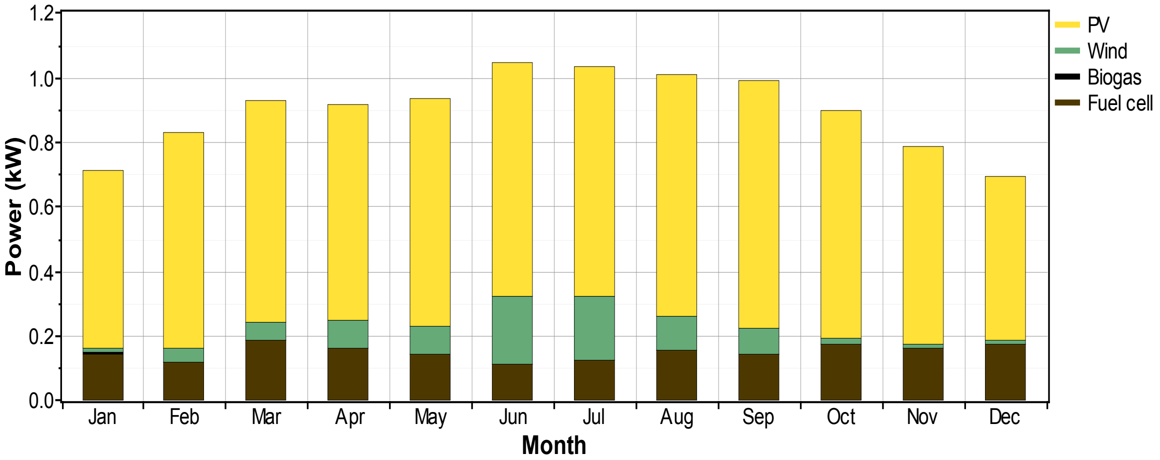


Figure 6. Monthly average electricity production

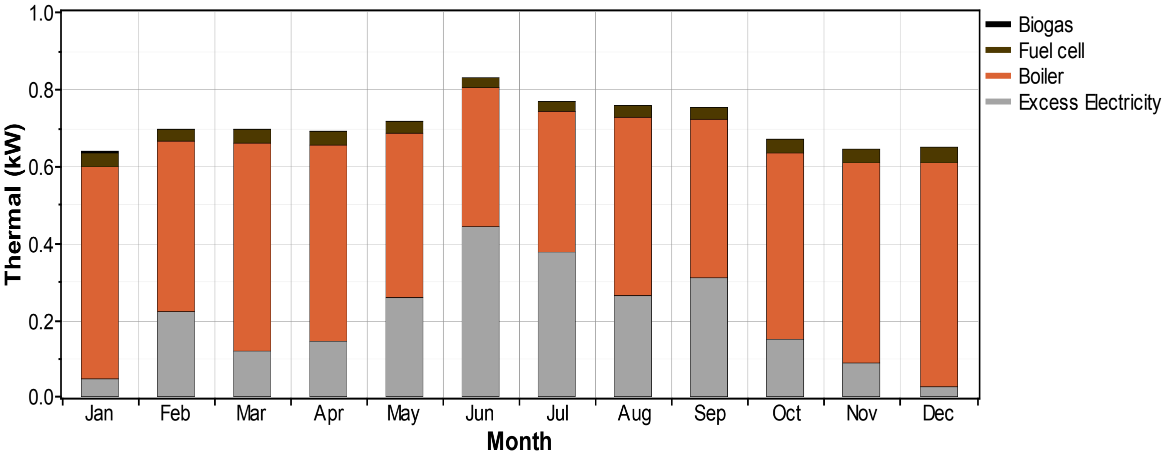


Figure 7. Monthly average thermal production

7. CONCLUSIONS

Despite the many advantages of CHP power plants, compared to other power and heat generation systems separately, including higher efficiency, reliability, stability and financial savings, environment, etc., these power plants have received slight attention in Iran. Therefore, in the present work, a CHP system on a residential scale including wind-solar-biomass-fuel cell-gas boiler-dump load components was investigated using HOMER software. Heat recovery was also performed in biomass generators and fuel cells. To look into the effect of variable parameters on the results, sensitivity analyses were performed on natural gas prices, annual interest rates, and emission penalties. Novelties and benefits of the present work included use of up-to-date prices for equipment used, annual interest rate and fossil fuel prices, use of heat recovery in the fuel cell and biogas generator, sensitivity analysis on the effective parameters, as well as investigating the role of dump load in the required heat supply. The important results of the present work are:

- The lowest COE price in the studied scenarios is 1.160 $/kWh.
- The supply of energy required by renewable energy is equal to 47 %.
- The use of biomass for an interest rate of 20 % is not economically justified.
- Much electricity is generated by solar cells, fuel cells, and wind turbines, in order.
- The highest heat produced by gas boiler, dump load, and fuel cell, in order.
- The minimum distance from the national electricity grid in order to be economical to use the standalone system is 1.47 km.
- The lowest cost per kilogram of hydrogen produced is 35.390 $/kg.
- The maximum annual surplus electricity production is equal to 1779 kWh.
- The maximum annual surplus heat production is equal to 511 kWh.
- About 1 ton of CO_2 emissions are emitted each year in each scenario.

To continue the present work, the following suggestions are provided along with the reason for reviewing them.

- For stations with different climates, the studied hybrid system should be implemented so that the effect of climate on system performance can be seen more clearly.
- Given that, the use of biomass is not economical in the current situation (20 % annual interest rate), other technologies for the use of biomass should be evaluated.
- Due to the surplus electricity generated, the system should also be evaluated when connected to the grid to see the effect of electricity exchange with the grid on the price of each kWh of electricity generated.
- The scale of the present work is domestic. The current renewable hybrid system can be used on a commercial or industrial scale to further determine the impact of such parameters as "dump load" and "heat recovery ratio".
- It is recommended to use other methods of hydrogen production, for example, using a reformer, because the price of hydrogen produced in the present work is very high.

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NOMENCLATURE

i	Annual interest rate (%)
f	Annual inflation rate (%)
i'	Nominal interest rate (%)
CRF	Capacity Recovery Factor
R_{proj}	Lifetime of project (year)
k_t	Clearness index
$H_{o,ave}$	Radiation on the horizontal surface above the atmosphere (kWh/m^2-day)
Y_{PV}	Output power of solar cell under standard conditions (kW)
f_{PV}	Derating factor (%)
$\overline{G_T}$	Incident radiation on the cell's surface on a monthly basis (kW/m^2)
H_{ave}	Monthly average radiation that reaches the surface of the earth (kWh/m^2-day)
$\overline{G_{T,STC}}$	Incident radiation on the cell's surface under standard conditions (1 kW/m^2)
P_{PV}	Output power of PV cells (kW)
$C_{ann,total}$	Total annual cost ($)
$E_{load\ served}$	Real electrical load by system (kWh/yr)
P_{gen}	Electricity produced by diesel generators (kW)
$\dot{m}_{fuel}$	Fuel consumption of generator (units/hr)
P_{WTG}	Power output of wind turbine (kW)
$P_{WTG,\ STP}$	Power output of wind turbine at standard pressure and temperature (kW)
y	Year
GMT	Greenwich Mean Time
O & M	Operations and Maintenance ($)
N	Useful life-time (year)
CHP	Combined Heat and Power
LCOH	Levelized Cost of Hydrogen ($/kg)
NPC	Net Present Cost ($)

COE	Levelized Cost of Energy ($/kWh)
LHV_{fuel}	Lower Heating Value of the fuel (MJ/kg)
Greek letters	
ρ_0	Air density at standard pressure and temperature equal to 1.225 kg/m^3
ρ	Actual air density (kg/m^3)
η_{gen}	Electrical efficiency of generator (%)

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