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Evaluation of Off-grid Hybrid Renewable Systems in the Four Climate Regions of Iran

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ABSTRACT

Renewable systems influence the process of supplying domestic electricity demands. It will be useful to replace the conventional energy generation system by renewable energy sources since the uncontrolled use of fossil fuels is accompanied by global warming and environmental hazards, in addition to the danger of their depletion, and because most of the energy derived from these fuels are used in buildings. Economical renewable energy systems have not yet been studied in each climate of Iran. Considering the historical background and the potential biomass of Iran, the potential of using a hybrid solar cell/wind turbine/biomass system for supplying the electricity demands of a residential building in each of the four climate regions of Iran has been studied by using HOMER software in this paper. HOMER software has been determined the most cost-efficient system for each region by using the solar radiation and wind speed data, which are acquired over 20 years. By considering economic issues, results indicate that usage of solar cells is the ideal option for the cold, hot dry and warm humid climates (Total net present cost (NPC) and cost of electricity (COE) are $11639 and 1.808 $/kWh, respectively). Also, usage of systems based on biomass is the best choice for the moderate and humid climates (total NPC and COE are $13211 and 2.052 $/kWh, respectively for Babol and $13075 and 2.031 $/kWh, respectively for Chalous).

1. INTRODUCTION

About 85% of global energy consumption is provided by fossil fuels [1] and domestic energy use accounts for 20.1% of global energy consumption [2]. It is predicted that the average of annual growth rate of global energy consumption will be 1.5% by the year until 2040 [2]. Using hybrid renewable energies and considering climatic factors in designing of buildings can reduce the fossil fuels demands to generate the required domestic energy. There are many advantages of using renewable energies, such as these sources don't contribute in the environmental pollution, they are free of cost, unlimited and accessible and the equipment has a relatively long useful life. [3-19].

Furthermore, these energy sources are comprehensively environment-friendly and they supply about 13.8% of global energy demands in 2016 [1]. The global renewable energy reports of 2016 indicate that many countries have accepted that renewable energy sources are the main energy source that can compete with fossil fuels. The highest possible growth rate of renewable electricity generation was observed in 2015 that had increased by147 GW. Also, the capacity for renewable heat and energies in the transportation sector was increased in 2015 [20].

The amount of energy from renewable sources in the Organization for Economic Co-operation and Development (OECD) member countries was equivalent to 271 million tons of the total primary energy consumption in 1990, which is increased to 510 million tons of the total primary energy consumption in 2015. This represents an average annual growth rate of 2.6%, while the average annual growth rate of energy generated from non-renewable sources is 0.4% in the same period [1]. As shown in Fig. 1, the highest annual growth rates of renewable energy in the OECD countries was 56.3%, 50.6% and 22.1% for biomass (solid, liquid, gas), solar energy (electricity and heat) and wind energy, respectively in 1990-2015.

Gross production of electricity from renewable sources reached to 2471.1 TWh in 2015, which was its highest growth rate since 1990 and it was exhibited a 3.8% increase compared to 2014 [1]. Fig. 2 indicates that the highest annual growth rate of electricity generation from renewable sources is related to the solar cells, wind, and biomass (biogas, solid waste, etc.) by 44.1, 22.1, and

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21.3% growth rates, respectively at the OECD countries in 1990-2014. Moreover, electricity generation from hydropower by 0.6% has the lowest annual growth rate in 1990-2014. The reason is that hydropower consumption had reached its maximum capacity in OECD countries and the share of electricity generation from hydropower has declined from 15.4% in 1990 to 12.8% in 2015 by increasing other types of renewable energy.

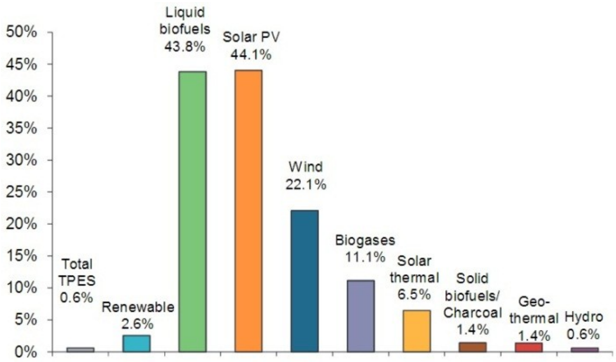


Figure 1. Annual growth rates of energy supplied by renewable sources in OECD Countries in 1990-2015 [1].

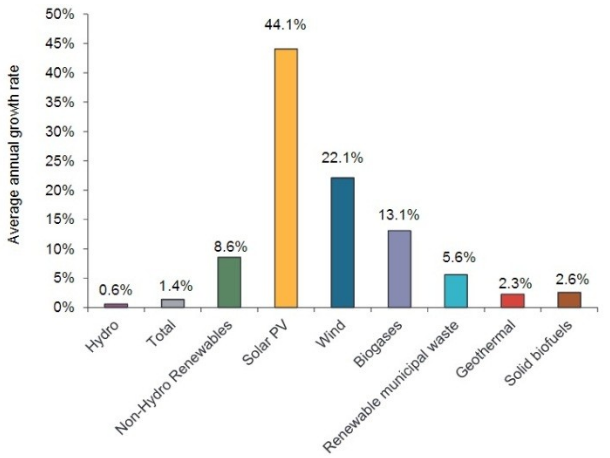


Figure 2. Annual growth rate of electricity generation from renewable sources for OECD countries in the period 1990-2015 [1].

Recent researches on the using of renewable energies for supplying the domestic demands are as follows:

Das et al. (2017) used the HOMER software to assess the feasibility of using a hybrid solar cell/battery/fuel cell system in East Malaysia to supply the electricity demands of 50 village household.

They studied the parameters of the total net present costs and the energy costs. Also, they found that the solar cell-battery system with the net present costs and energy costs of $335,297 and $0.323, respectively, was the most economical and environment-friendly system. It was included 62 solar cells, a battery of 72 kW and a converter of 17 kW. Its price was almost half the price of the fossil-fuel-based one. Despite the advantages of the fuel cell, HOMER did not recommend it due to its high costs [21].

Yilmaz and Dincer (2017) designed an optimized hybrid solar cell/diesel generator/ battery system in off-grid regions which was located in Kilis Province of Turkey. Simulation results by using the HOMER software indicated that about 79% of the required electricity could be supplied by the hybrid system contained a solar cell of 3 kW, a diesel generator of 1 kW, a converter of 2 kW and 6 batteries by the cost of 12,400 Turkish liras.. About 4,248 kW of the annual total electricity (5,021 kW) by this system were supplied by the solar cell and the rest of it was supplied by the diesel generator. [22].

Shezan et al. (2017) studied the techno-economic aspects of a renewable energy system in Brisbane of Australia. They intended to generate 34 kW per day by using HOMER software for simulating its provision. Results showed that the net present cost decreased about 29.65% compared to fossil fuel power plants (together with a 1,600 ton per year reduction in CO_2 emission) and the price of every kW was $0.209 [23].

Al-Sharafi et al. (2017) performed a techno-economic analysis of wind energy and solar systems for power generation and hydrogen production at five different stations under various climate conditions in Saudi Arabia. Six different hybrid systems were simulated by using the HOMER software that contained various combinations of solar cells, wind turbines, batteries, converters, electrolyzers, fuel cells and hydrogen tanks. Daily electricity consumption was 14 kW with a peak of 1.4 kW. Results indicated that the lowest costs of the generated electrical energy were 0.702, 0.612, 0.616, 0.614 and 0.609 ($per kW) at Dhahram, Riyadh, Jeddah, Abha, and Yanbo stations [24].

Kim et al. (2017) used the HOMER software and studied the simultaneous production cycle of electricity, heating and cooling in office buildings. Three types of buildings (small, medium-sized and large) were studied in the Atlanta region of the United States. Improvement of energy efficiency was determined and analysis of economic sensitivity on investments costs of the Combined Cooling Heat and Power (CCHP) systems was performed [25].

Rajbongshi et al. (2017) optimized a grid-connected energy system that included solar cells, biomass and diesel generators. They intended to supply the electricity demands of a village and they studied three types of load profiles (one for the present and two expected for the future). The analysis was performed by using the HOMER software. For the peak load of 19 kW, the off-grid system and the average daily load of 178 kWh, the calculated price of each generated kWh of electricity was $0.145. The general conclusion was that the system based on biomass was superior to the photovoltaic system in the studied region [26].

Tiwari and Bhargava (2017) studied the techno-economic feasibility of an energy system that included biomass and solar cells for an off-grid village in India by using the HOMER software. The optimum proposed system included a biomass generator of 8 kW and a solar cell of 16 kW with the total net present cost of $61,494 (the price of each generated kWh was $0.117) [27].

Shahzad et al. (2017) used the HOMER software to supply electricity of an off-grid village in Pakistan. The studied system was a biomass-solar one. Sensitivity analysis was performed on the input data and the total NPC and COE costs were calculated. The lowest calculated price for each kW was 5.51 PKR and the payback period was 9.5 years. The optimum system included a solar cell of 10 kW, a biomass generator of 8 kW, 32 batteries and a converter of 12 kW [28].

Bukar et al. (2017) evaluated an economic solar cell/diesel generator/battery energy system. The studied region was an off-grid village in Nigeria with a population of 270. Obtained results by using the HOMER software showed that the average radiation, the daily electricity demands, the peak load and the lowest cost of generated electricity were 5.51 kWh/m^2-day, 266 kWh, 17 kW and $0.495 (produced by 20 kW diesel generator using 38289 liters of diesel), respectively in the region.

Another noteworthy point of the results was that the renewable energies (solar cells) were able to supply about 21% of the required electricity in the best case scenario [29].

Hosseinalizadeh et al. (2017) employed the HOMER software to evaluate economical use of small wind turbines in residential areas in Iran. They assessed 88 stations and studied the effects of grid electricity price and FIT on economic efficiency. Results indicated that the use of small wind turbines was cost-effective in about 30% of the studied areas (where wind speed exceeded 5 m/s) [30].

Jahangiri et al. (2015) evaluated the technical and economic performance of standalone renewable energy systems in Khorramabad of Iran by using HOMER software [3]. They studied two scenarios of wind-solar-diesel generator and wind-solar-fuel cell. They also carried out sensitivity analysis on wind speed and diesel price. The results indicated that the fuel cell-based on the scenario with a cost of $7.367/kWh is not cost-efficient due to the high primary price of the fuel cell in Iran.

Mostafaeipor et al. (2016), studied the possibility of installing a solar power plant in 14 cities of Khuzestan province of Iran [31]. They used HOMER software for analysis and evaluated total NPC, COE, electricity produced by each component and … The results showed that the cost of constructing solar power plant was $551433, the lowest annual income was $103896.2 and the profit of the construction of the plant over the course of 25 years was $1870131.6.

Jahangiri et al. (2017) studied solar/diesel generator electrification of three villages in Chaharmahal and Bakhtiari province of Iran by using HOMER software [32]. The results showed that the cost per kilowatt hour of electricity generation was $0.81, $1.35 and $0.79, respectively and due to the use of the diesel generator, 87.1 kg, 3059 kg and 125 kg of CO_2 was produced annually in Cham-e Zin, Cham-e Ali, and Chelvan villages. Furthermore, the usage percentage of renewable energy was 97%, 57% and 96%, respectively in the three studied villages.

As shown in Figs. 1 and 2, use of the wind and solar renewable energies is necessary and justifiable. It must be mentioned that the sun does not shine at night; therefore, solar cells cannot be used at night. Moreover, if the wind speed declines below the cut-in level in wind turbines, they will not generate any electrical power. This problem can be somewhat resolved by combining the wind and solar renewable energy sources [10, 33]. However, the use of energy storage (batteries) is essential.

Previous studies have showed that no research had been conducted on comparing the application of hybrid renewable energy systems for generating electricity to meet the energy requirements of a residential building in each of the four different climate regions of Iran. Therefore, the present article used the HOMER software and selected two cities in each four climate regions of Iran to carry out the technical-economical-environmental study and determined the optimum results for each climate.

2. BACKGROUND INFORMATION CONCERNING STUDIED REGIONS

Tables 1 and 2 present the geographic information, conditions of climate, energy demands of the selected cities and a diagram of solar radiation intensities and wind speeds (the most important parameters of climate), respectively. Fig. 3 shows the locations of the studied cities on the map of Iran. Data of the Iran Meteorological Organization and NASA were used in the calculation process of wind and solar energy consumption.

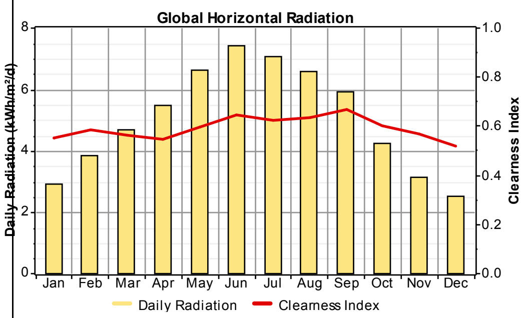
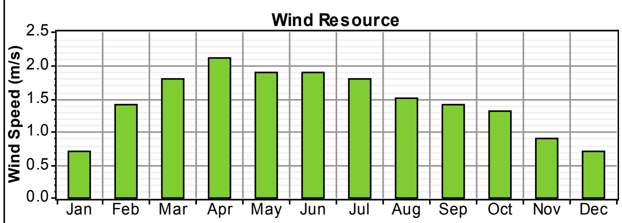
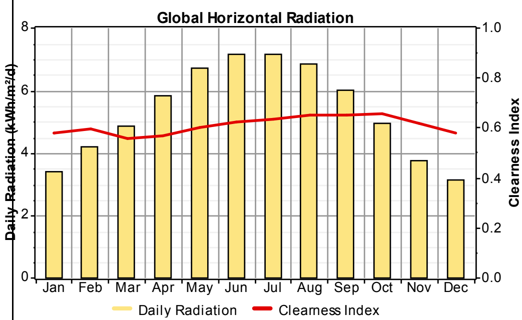
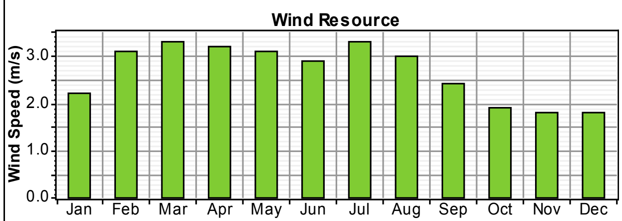
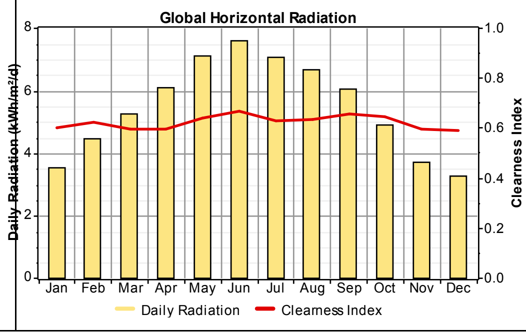
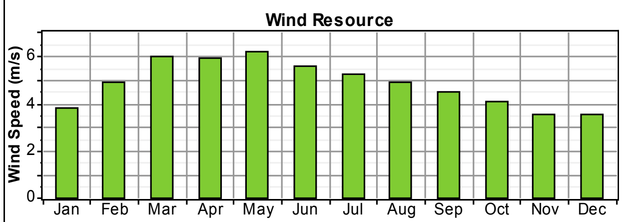
The studied hybrid system included a biomass generator, a solar cell, a wind turbine and a battery. This system was supposed to generate 1.4 kWh of electricity per day. The peak demand of electricity was 211 watts. Data of electricity consumption related to each residential building was extracted from electricity bills. Fig. 4 presents these data for all 12 months of the year.

Electricity consumption of all four regions of climates was similar to calculating electrical energy demands of studied cities. Information of price and size of each component of the employed equipment's, which was entered into the HOMER software, is presented in Tables 3 and Fig. 5.

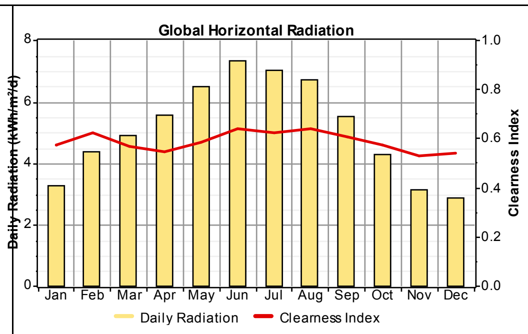
TABLE 1. Geographic and features of climate

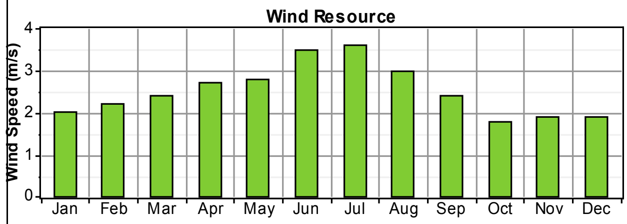
City	Area	Coordinates	Altitude (m)	Dominant demand	Climate
Arak	70 km^2	34.8 N 49.7 E	1743	Heating	Cold
Kerman	185 km^2	30.29 N 57.6 E	1756	Heating	Cold
Shiraz	240 km^2	29.59 N 52.54 E	1480	Heating	Hot Dry
Ahvaz	185 km^2	31.20 N 48.40 E	12	Cooling	Hot Dry
Babol	32 km^2	36.34 N 52.44 E	-2	Heating	Moderate Humidity
Chalous	187 km^2	36.41 N 51.27 E	0	Heating	Moderate Humidity
Bandar Lengeh	13 km^2	26.59 N 54.59 E	11	Cooling	Warm Humid
Bushehr	984.5 km^2	28.59 N 50.59 E	18	Cooling	Warm Humid

TABLE 2. Diagram of Solar Radiation Intensity and Wind Speed during the Different Months of the Year

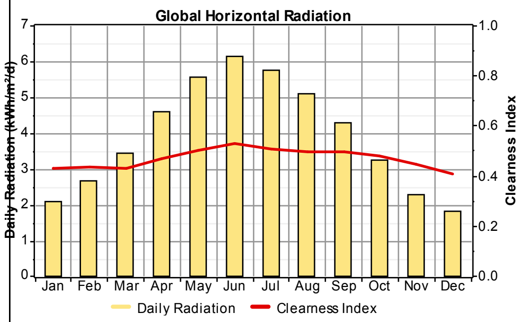
City	solar radiation intensity	wind speed
Arak		
Kerman		
Shiraz		

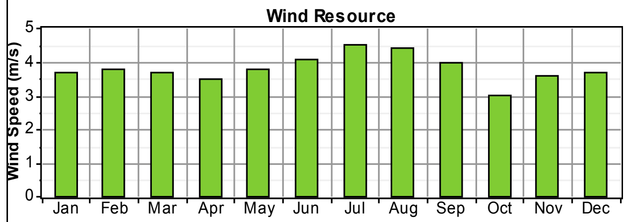
Ahvaz



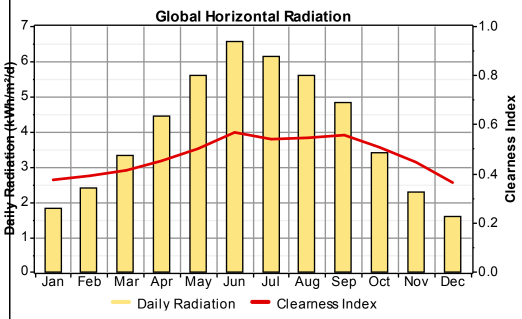


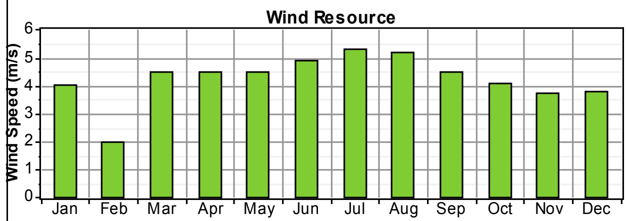
Babol



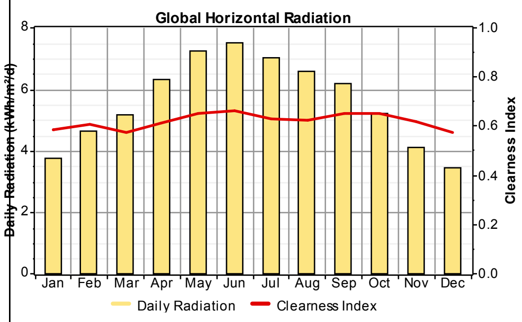


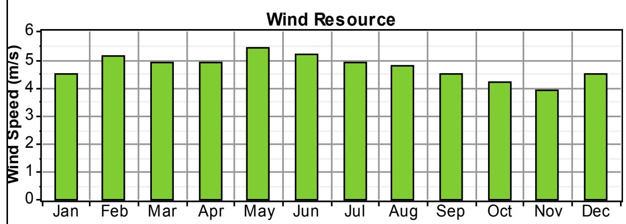
Chalous



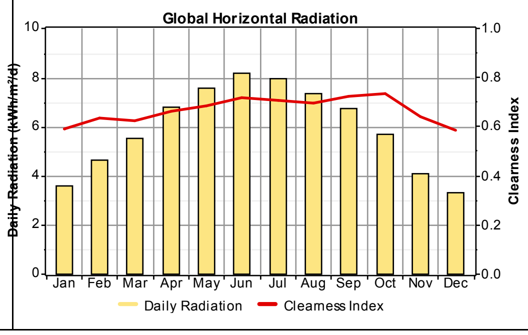


Bandar Lengeh





Bushehr



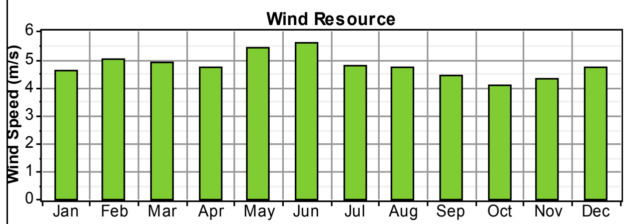


Figure 3. Locations of the studied stations on the map of Iran

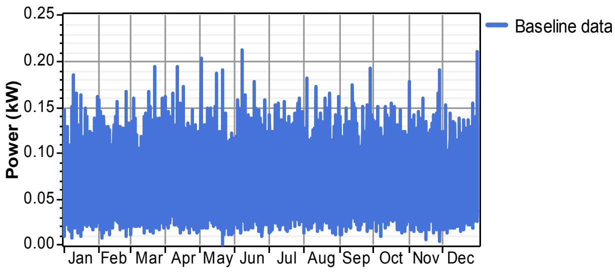


Figure 4. Profile of electricity consumption during one year

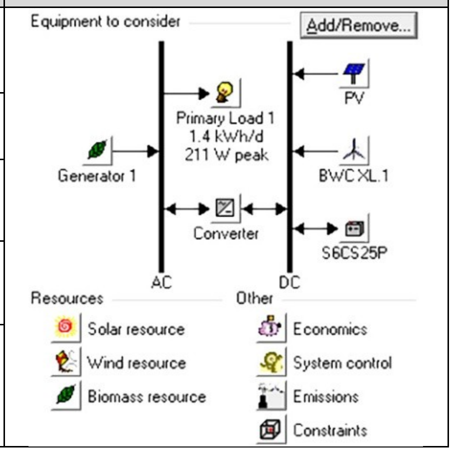
3. HOMER SOFTWARE

HOMER is used to design an optimum micro power system in two scenarios, connected to the grid and disconnected from it, to reach our pre-defined goals. As a power system is designed, many decisions have to be made about its infrastructure, for example essential components of the system such as the panel, wind turbine, diesel generator and hydro, the number of components and their size. Conditions such as cost changes and other available energy sources make it difficult to have a decision. Sensitivity analysis and optimization algorithms of HOMER have made the decision process as a practical task. One can name some capability of HOMER as electrical charges modeling, thermal and hydrogen, solar cell modeling, wind turbines, water turbines, hydrogen production, fossil generators, modeling the connection of a system to the grid, pollution production analysis of different technologies and … [32].
The total NPC is calculated as follows [34]:

$$NPC = \frac{C_{ann,total}}{CRF(i, R_{proj})} \qquad (1)$$

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.

TABLE 3. Information of the studied hybrid systems [3]

Equipment	Cost ($)			Size (Kw)	Other information	
	Capital	Replacement	O & M			
PV	6,900	6,900	0	1	Life time: 20 years Derating factor: 90%	
Converter	800	700	100	1	Lifetime: 15 years Efficiency: 90%	
Wind Turbine BWC XL.1	3,900	3,900	100	1	Lifetime: 25 years Hub height: 10 m	
Biomass Generator	3,500	3,000	0.023	1	Biomass: 250 t/day Biomass price:119.58 $/t	
Battery Surrette 6CS25P	1,200	1,100	50	1	Nominal specs: 6V, 1156 Ah	

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 [34]:

$$CRF = \frac{i\,(1+i)^N}{(1+i)^N - 1} \qquad (2)$$

Software is able to calculate the annual interest rate through the following equation [34].

$$i = \frac{i' - f}{1+f} \qquad (3)$$

Also, the cost of per kWh of energy during the lifetime of the project is obtained by software from the following equation [34]:

$$COE = \frac{C_{ann,total}}{E_{Load\ Served}} \quad (4)$$

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

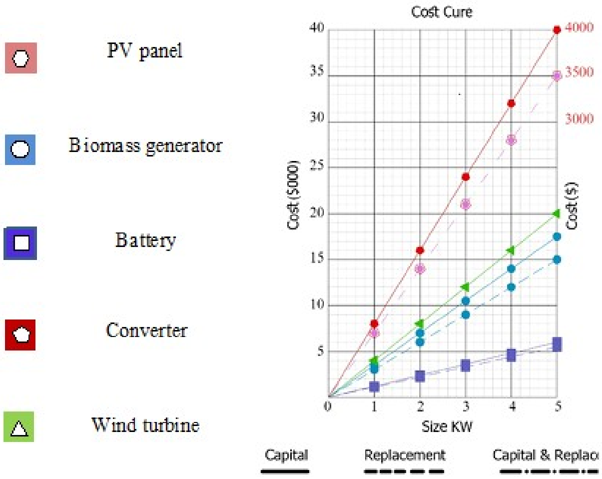


Figure 5. Diagram of the studied hybrid systems

4. RESULTS

Table 4 indicates the obtained results of simulation of the hybrid system in all the studied cities. It is noteworthy to mention that the most cost-effective option, which was considered the top scenario in the simulation processes, carried out for each city. Moreover, the other scenarios were identified and ranked next based on their cost-effectiveness. Table 5 presents the ideal options for each studied city. It should be noted that the same conditions (one solar cell, one battery and one converter) were considered for each studied city.

Results indicated that the optimal scenario in Arak, Kerman, Shiraz, Ahvaz, Bandar Lengeh, and Bushehr was the usage of the solar cell without using the biomass generator, whereas the biomass system and the combined wind turbine/biomass generator system were ranked in Babol and Chalous, respectively. This variation in prioritization among the cities is due to differences of solar radiation intensity, wind speed in different months of the year and other geographic-climatic characteristics. In these scenarios, the biomass generators worked for 1236 and 197 hours in Babol and Chalous, respectively.

If solar cells were not employed in Arak, Kerman, Ahvaz and Chalous, the biomass system could apply for the demand of the electricity and it was identified as the second scenario, whereas the wind turbine-biomass generator system in Shiraz and Babol, and the wind turbine system in Bandar Lengeh and Bushehr were recommended as the second best scenarios. In Arak, Kerman, Ahvaz, and Chalous, the biomass generator worked for 1236 hours. Also, it worked for 131 and 313 hours, in Shiraz and in Babol, respectively and it worked for zero hours in the second best scenario in the other cities. The third best scenario for Kerman, Ahvaz, Bandar Lengeh and Bushehr was the wind turbine-biomass system, whereas it was the solar cell-wind turbine system for Arak and the solar cell system for Babol and Chalous. Finally, it was the biomass system for Shiraz. In the systems proposed for this scenario, the biomass generator worked for 1491, 1538, 104, 91, and 1236 hours in Kerman, Ahvaz, Bandar Lengeh, Bushehr, and Shiraz, respectively. Results indicate that the cost-effective scenarios were similar for Kerman and Ahvaz and the wind system used alone would not be the superior scenario for any of the cities. This indicates that solar radiation and biomass energies have greater potential than wind power in the cities. Furthermore, due to high prices of solar and wind power equipment, simultaneous use of solar cells and wind turbines is not recommended at all. Although researchers have stated that combined solar and wind energy sources enable us to overcome problems that occur when one of these two systems stops.

5. CONCLUSIONS

Developing renewable energy sources is required due to the rapid depletion of fossil fuels, environmental problems that are caused by using fossil fuels, population growth and the ever-increasing demand for energy. Moreover, the large amount of waste produced is one of the major problems in the developed urban. Waste can be used in producing biomass energy since it is known as one of the generating biogas sources. Also, environmental problems caused by this waste are reduced by using them. The HOMER software is used to assess the feasibility of supplying the electricity is required by a residential building in each of the four climates of Iran in this research. Results (based on the three potential optimal scenarios for each city) suggest that using of the solar system is superior in cities by the cold, hot dry and warm humid climates regarding cost-effectiveness. In addition, the solar cell system is recommended because it does not produce any pollution. However, the system based on biomass energy is the best option for the moderate and humid climate in generating the required electricity due to the lower radiation intensity level and lower wind speed in this climate. The main results can be expressed as follows:- Using solar cell system is cost-effective in cities with cold, hot dry and warm humid climates (Arak, Kerman, Shiraz, Ahvaz, Bandar Lengeh and Bushehr).

The biomass-based energy system is the best option for supplying electricity in a moderate and humid climate, due to reduced solar radiation. Therefore, biomass

system and wind/biomass turbine system are recommended in Babol and Chalous, respectively.
The wind turbine system alone is not one of the three top scenarios of any climate, which indicates more radiation and biomass potential compared to the wind.
The simultaneous use of solar cells and wind turbines in any climate is not recommended, due to the high price of solar and wind equipment.

TABLE 4. Results of simulations

Station	system	Total NPC ($)	COE ($/kWh)	Time (hrs)	Electrical Production (%)
Arak	PV	11,639	1.808	0	100
	Wind	-	-	-	-
	Biomass	13,211	2.052	1,236	100
	PV-Biomass	27,354	4.248	5,035	55-45
	PV-Wind	16,817	2.612	0	100-0
	Wind-Biomass	18,335	2.848	1,221	1-99
	PV-Wind-Biomass	32,526	5.051	5,033	55-0-45
Kerman	PV	11,639	1.808	0	100
	Wind	-	-	-	-
	Biomass	13,211	2.052	1,236	100
	PV-Biomass	27,243	4.231	5,001	56-44
	PV-Wind	16,817	2.612	0	90-10
	Wind-Biomass	16,628	2.582	1491	30-70
	PV-Wind-Biomass	31,614	4.910	4,756	54-6-40
Shiraz	PV	11,639	1.808	0	100
	Wind	17,518	2.721	0	100
	Biomass	13,211	2.052	1,236	100
	PV-Biomass	27,054	4.202	4,944	57-43
	PV-Wind	16,817	2.612	0	57-43
	Wind-Biomass	12,955	2.012	131	98-2
	PV-Wind-Biomass	26,835	4.168	3,282	44-34-22
Ahvaz	PV	11,639	1.808	0	100
	Wind	-	-	-	-
	Biomass	13,211	2.052	1,236	100
	PV-Biomass	27,367	4.250	5039	55-45
	PV-Wind	16,817	2.612	0	90-10
	Wind-Biomass	16,778	2.606	1,538	29-71
	PV-Wind-Biomass	31,870	4.950	4,835	53-6-41
Babol	PV	14,061	2.184	0	100
	Wind	19,607	3.045	0	100
	Biomass	13,211	2.052	1,236	100
	PV-Biomass	14,628	2.272	104	98-2
	PV-Wind	16,817	2.612	0	61-39
	Wind-Biomass	13,286	2.063	313	90-10
	PV-Wind-Biomass	29,613	4.599	4,141	40-25-35
Chalous	PV	14,061	2.184	0	100
	Wind	-	-	-	-
	Biomass	13,211	2.052	1236	100
	PV-Biomass	14,679	2.280	132	97-3
	PV-Wind	16,817	2.612	0	53-47
	Wind-Biomass	13,075	2.031	197	95-5
	PV-Wind-Biomass	28,379	4.407	3,759	37-33-30
Bandar Lengeh	PV	11,639	1.808	0	100
	Wind	12,340	1.916	0	100
	Biomass	13,211	2.052	1,236	100
	PV-Biomass	27,101	4.209	4,958	57-43
	PV-Wind	16,817	2.612	0	54-46
	Wind-Biomass	12,906	2.004	0	98-2
	PV-Wind-Biomass	26,711	4.148	3,244	43-36-21
Bushehr	PV	11,639	1.808	0	100
	Wind	12,340	1.916	0	100
	Biomass	13,211	2.052	1,236	100
	PV-Biomass	26,775	4.158	4,860	59-41
	PV-Wind	16,817	2.612	0	56-44
	Wind-Biomass	12,883	2.001	91	98-2
	PV-Wind-Biomass	26,550	4.123	3,195	44-36-20

TABLE 5. The top scenarios of each city

Scenario	System	City
1	PV	Bushehr, Bandar lengeh, Shiraz, Ahvaz, Kerman, Arak
	Biomass	Babol
	Wind-Biomass	Chalous
2	Biomass	Chalous, Ahvaz, Kerman, Arak
	Wind-Biomass	Babol, Shiraz
	Wind	Bushehr, Bandar lengeh
3	Wind-Biomass	Ahvaz, Kerman, Bandar lengeh, Bushehr
	Biomass	Shiraz
	PV	Chalous, Babol
	Wind-PV	Arak

6. CONFLICTS OF INTEREST STATEMENT

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

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