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Optimal Selection and Economical Ranking of Isolated Renewable-based CHP Microgrid in Cold Climate, A Case Study for a Rural Healthcare Center

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Abstract

Rural Health Centers (RHCs) are nationally crucial points of interests, requiring electricity to continue storing drugs, offering health services, performing minor and outpatient surgeries, and other health services under any circumstances. With outbreaks such as COVID-19, constant power supply has become a challenging endeavor in Iran craving more attention. Accordingly, this research aimed at finding an optimum combined heat and power (CHP) system using renewable energies (wind, solar, and animal biomass) for the first time in a RHC in Iran. Different hybrid scenarios were evaluated and ranked in HOMER v2.81. The techno-economic-environment-energy performance of vortex turbines were assessed, for the first time, and were then added to the software database. The results showed that the top three scenarios are solar cell-battery (first scenario), solar cell-biomass-battery (second scenario), and solar cell-wind turbine-battery (third scenario) with levelized cost of energy (LCOE) of 0.393, 0.406, and 0.468 $/kWh, respectively. In the top economic scenario, 25% of the required energy was generated by solar cells and the rest by gas boiler that producing 7,050 kg of CO_2 annually. In the third scenario, the most environmentally friendly one, CO_2 was reduced by about 60 kg compared to the first scenario. Another important point is the important role of dump load in converting excess electricity into heat, contributing to 20% of the generated heat in the first scenario. Based on the results, the authors suggest focusing on solar energy in the studied region given its higher economic potential than wind and biomass energies.

Keywords: Rural healthcare; CHP; HOMER software; Vortex bladeless; Excess electricity

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1. Introduction

In order to achieve better results in the health sector in developing countries, most policies focus on direct factors such as expanding the network of health institutions, training health care staff, and financing [1]. However, one of the main goals of the

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United Nations Sustainable Development Goal and "Global Strategy for Women's, Children's and Adolescents' Health (2016–2030)" is that achieving adequate health goals in an environment requires the provision of basic infrastructure required by the health sector, the most important of which is electricity [2, 3] (Figure 1). In fact, the World Health Organization emphasizes that electricity is "a significant factor" in global access to health care and without electricity, many life-saving measures would not be easily done [4].

It is increasingly argued that increased access to electricity along with reliability, including supply hours and required voltage, can have much greater well-being effects on health [5-12] (Figure 2). Many rural communities in developing countries face frequent and prevalent electricity shortages. As a result, many RHCs do not have access to enough power supply for some essential daily tasks [13]. Most clinics are equipped with diesel or gasoline generators that can only operate for a short time due to operating costs. Moreover, greenhouse gas emissions can also pose health risks and climate change. Many people have lost their lives due to lack of adequate food supply because rural doctors often refer many patients to urban clinics and many of them die during transportation. In order to address this issue, an alternative power supply is essential for effective functioning in rural communities.

Rural health services are an important national and international priority. However, there is insufficient availability of electricity to support adequate rural health services in many countries.

In recent years, the development of energy systems at reasonable and reliable prices has made it possible to develop vaccines and other basic health services in remote areas. Some international, national, and local institutions, NGOs, and private companies are now developing renewable energy systems in developing rural communities that have put health care in rural areas on their agenda as a national priority [14]. The successful development of reliable energy systems requires precise evaluation of all aspects of the energy needs in medical centers, including electrical and thermal energy needs [15].

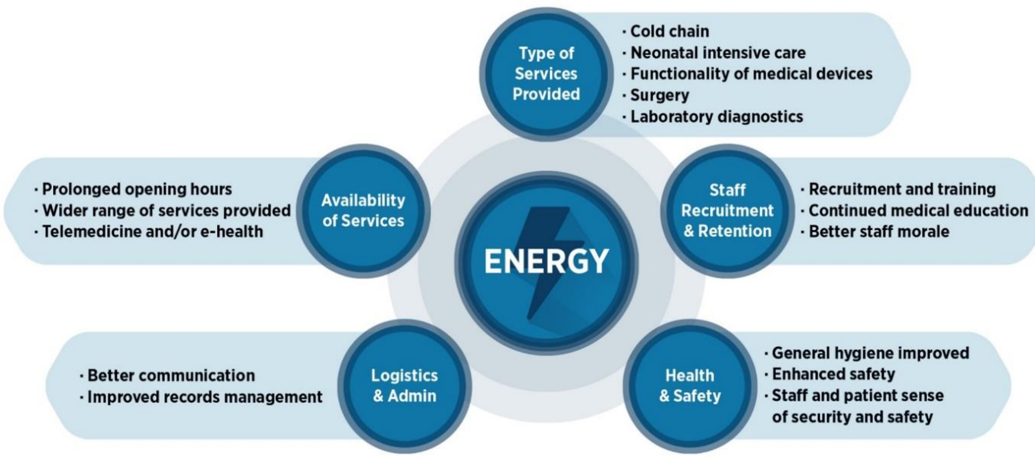


Figure 1. Energy for health services [5].

After assessing daily energy demand, the next step is to evaluate potential technical solutions to provide sustainable energy services. In areas where access to the national grid electricity infrastructure is available and reliable, it is the main source of energy, and wherever it is not, off-grid energy systems and on-site power generation solutions should be considered. Off-grid energy systems include generators, renewable energy systems (solar energy, wind energy, hydroelectric micro), batteries, or a combination of two or more of the above technologies. The best alternative for a given plan depends on several factors, and in some cases, a combination of power supply options may be the best solution (Figure 3). Due to the fact that about 17% of the world's population does not have access to electricity, a remote power supply is an essential development program for many developing countries [16]. Even in villages with electricity located in remote areas, the electricity is low and irregular in terms of quality and availability [17].

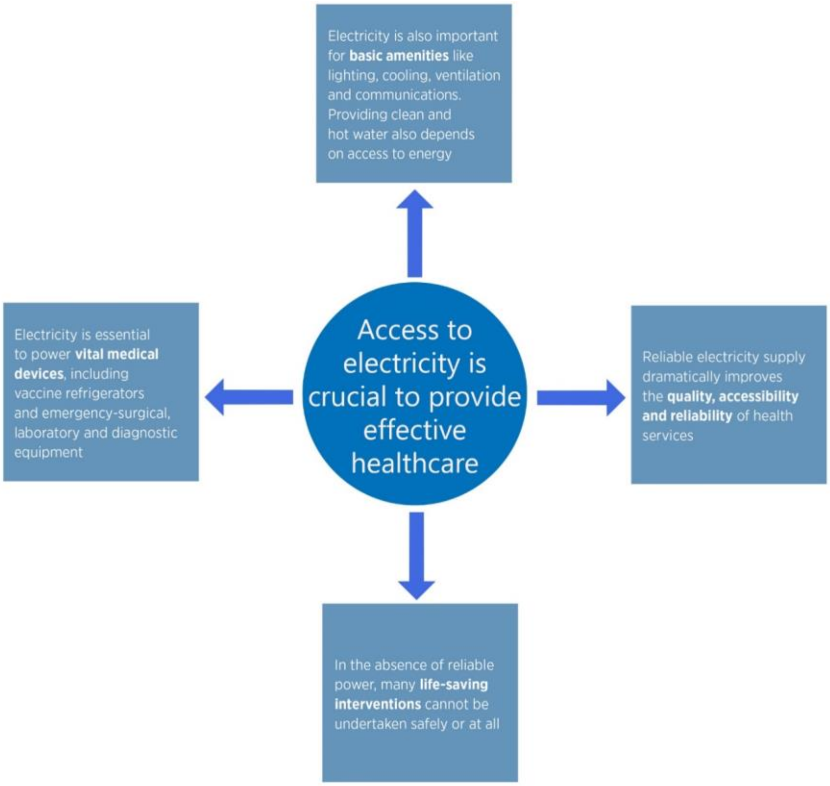


Figure 2. The importance of access to electricity to provide effective health care [5].

Due to fossil fuel shortages, environmental pollution, and high transportation costs, the intrusion of local renewable has attracted widespread worldwide attention for access to electricity in remote areas [18], particularly the use of hybrid renewable energy systems such as solar and wind energies as the most popular sources of renewable energy in the world, and based on a lot of research in this field, they are very effective in both connected and disconnected to grid modes [19-24]. Table 1 presents a number of recent studies on rural electrification, including their purpose, method of analysis, and results.

Figure 3. Schematic representation of a rural health care center equipped with renewable electricity supply systems

Table 1. Literature review for electrifying the RHC

Source, Year	Purpose of study	Analysis and method used	Results
[13], 2019	Presenting an off-grid hybrid renewable energy system model including PV, wind, diesel generator, and battery systems at selected rural health centers in 6 regions of Nigeria.	HOMER software	The results showed that in all the considered locations, the PV/diesel/battery system is the most cost-efficient option.
[25], 2018	Investigation of safe environmental conditions and the availability of standard precautions for the prevention and treatment of infections in health care centers in order to achieve the goals of sustainable development in low- and middle-income countries	Logistic regression model	It is estimated that approximately 60% of health care centers in 46 low- and middle-income countries lack reliable electricity.
[26], 2018	Evaluation of an independent solar photovoltaic (PV) power supply system for rural primary health centers located in Abadam local government in Northwest Nigeria	HOMER software	The proposed PV system prevents CO_2 emissions of 8357-8956 kg/year.
[27], 2018	Analysis of independent hybrid renewable energy systems for health centers located in rural areas.	HOMER software	The abundance of wind and solar resources in a country creates an ideal environment for the inclusion of renewable energy systems to improve rural health care services.

The above-mentioned issues highlight the necessity of conducting a feasibility study on energy supply of an RHC in Iran. To this end, this research evaluates a CHP system using renewable energies (wind, solar, and animal biomass) for the first time in an RHC in Chaharmahal and Bakhtiari Province, Iran. HOMER was used to conducted technical, energy, economic, and environmental analyses. The cases receiving either very little or no attention in the literature include vortex bladeless wind turbines, effect of ambient temperature on solar cell performance, conversion of excess electricity into heat using dump load, recovering heat in biomass generator, accurate identification of pollutants generated by auxiliary gas boiler and biomass generator, and imposing fines for pollutants.

2. Study location

Shamsabad Village is a suburb of Shahrekord County in Chaharmahal and Bakhtiari Province, Iran, with a population of 2,609 by 2016. Figure 4 shows its location on map of Iran. The tourist attractions of this tourism village include Vaght Va Saat Spring (Fig. 4a), Yousef Khan Amir Mojahed Castle (Fig. 4b), and Gorz-e Rostam Cave (Fig. 4c). A view of the studied RHC is shown in Fig. 5. The approximate building area and the openings area are 100 and 26 m^2, respectively, and the RHC has 4 employees. The study site is one of the target villages for tourism in Chaharmahal and Bakhtiari province. This village is very busy due to its location on the near of the road (passing travelers) and patients from many neighboring villages go to its medical center. Therefore, according to the above and access to energy consumption data, this medical center has been selected for the study.

Figure 4. Location of Shams Abad on map of Iran and its tourist attractions

Figure 5. Studied building

3. Methodology

HOMER software is capable of evaluating and designing an optimum micro-power to achieve the objectives of the intended practical plans [28]. Selecting of the best system can be a complicated decision-making process due the high number of technologies deployed, changes in the cost of these technologies, and accessibility of energy sources [29]. The sensitivity analysis and optimization algorithms provided in this software facilitate evaluation of many feasible systems [30]. Figure 6 shows a schematic of the working procedure in this software [31].

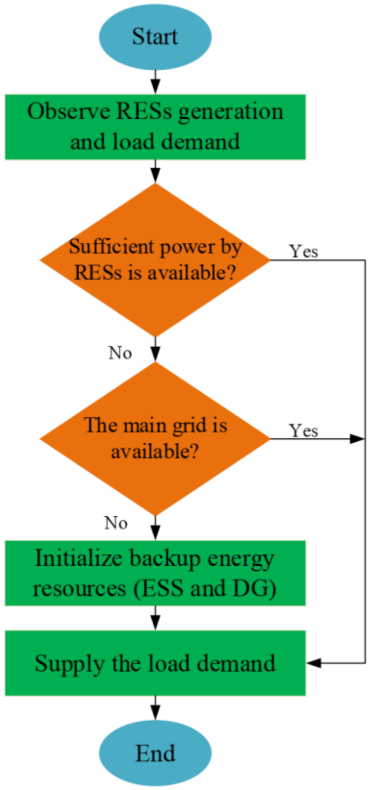


Figure 6. The operational flowchart of HOMER [31]

The present work used solar cell, wind turbine, biogas generator, and battery to design a hybrid system. Equations governing the function of these devices are presented in Eqs.1 to 4, respectively [32-35].

$$P_{pv} = Y_{pv} \times f_{pv} \times \frac{\overline{H_T}}{\overline{H_{T,STC}}} \quad (1)$$

$$P_{WTG} = \frac{\rho}{\rho_0} \times P_{WTG,STP} \quad (2)$$

$$\eta_{Biog.gen.} = \frac{3.6\, P_{Biog.gen.}}{\dot{m}_{Biog.}\, LHV_{Biog.}} \quad (3)$$

$$P_{batt.cmax} = \frac{Min\,(P_{batt.cmax.kbm}, P_{batt.cmax.mcr}, P_{batt.cmax.mcc})}{\eta_{batt.c}} \quad (4)$$

In the optimization phase of this software, the planned designs are fully examined for a maximum energy and cost reduction [36]. Economic calculations are carried out based on total NPC and

LCOE parameters [37, 38], with the most optimum system having the least total NPC.

$$NPC = \frac{C_{ann,total}}{\frac{i\,(1+i)^N}{(1+i)^N - 1}} \quad (5)$$

$$LCOE = \frac{C_{ann,total}}{E_{Load\ served}} \quad (6)$$

4. Required data

The studied building is an RHC in Shamsabad Village with coordinates of 32° 17’ N and 50° 59’ E and an altitude of 2,061 m above sea level. Table 2 presents monthly data of wind speed, solar radiation, and air temperature (extracted from NASA website) averaged over 20 years [39].

Natural gas price is 0.03 $/m^3 [40], animal-waste biomass price is 192 $/ton, annual interest rate is 18% [41], project lifetime is 25 years [42], and approximate amount of available animal-waste biomass is 500 kg/d per month. Regarding the cost of each ton of animal biomass, it should be mentioned that the cost of animal waste has been calculated along with the cost of transportation and manual worker. Table 3 provides the specifications of the used biomass, amount of pollutants from utilization of natural gas and biomass, and rate of fines for pollutants.

Table 2. Climatic parameters of the studied station

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Wind speed (m/s)	3.7	3.9	4.2	4.4	4.6	4.9	5.0	4.7	4.3	4.0	3.6	3.1
Solar radiation (kWh/m^2-day)	2.7	3.5	4.3	5.5	6.7	7.7	7.3	6.8	6.0	4.5	3.2	2.4
Air temperature (°C)	0.9	2.2	6.0	12.8	18.8	23.9	26.9	26.1	21.6	15.4	8.2	4.0

Table 3. Information on the fuels used and the fines for pollutants

Item	Properties	Emission factor
Natural gas [40]	Lower heating value: 45 MJ/kg Density: 0.79 kg/m^3 Carbon content: 67% Sulfur content: 0.33% Boiler efficiency: 85%	Carbon monoxide: 4.4 g/m^3 Unburned hydrocarbons: 0.87 g/m^3 Particulate matter: 0.04 g/m^3 Fuel sulfur converted to PM: 0.002 % Nitrogen oxide: 12 g/m^3
Biomass [43]	Lower heating value: 5.5 MJ/kg Carbon content: 5% Gasification ratio: 0.7 kg/kg	Carbon monoxide: 16.5 g/m^3 Unburned hydrocarbons: 0.72 g/m^3 Particulate matter: 0.1 g/m^3 Fuel sulfur converted to PM: 2.2 % Nitrogen oxide: 15.5 g/m^3
Emission penalty [44]	Carbon dioxide: 3.1 $/t Carbon monoxide: 57 $/t Sulfur dioxide: 560 $/t Nitrogen oxides: 184 $/t	-

Regarding the amount of heat required for the space, it should be mentioned that the required heat of the space during a working day is calculated based on natural gas fuel consumption. Then HOMER software using random variability parameters, i.e. day-to -day and time step-to-time step estimates the amount of heat required in 365 days of the year. The average required monthly heat profiles for the RHC space are presented in Fig. 7, which takes into account the space heating and sanitary water. As shown in figures, from May to September, no space heating is required, and the heat is only used for the consumed sanitary water. The studied building operates from 8 a.m. to 4 p.m., requiring an average 103 kWh/d heat over a year.

Electricity consumption for one day (24 hours) was read from the electricity meter. HOMER software then estimates the amount of electricity consumed in 365 days of the year using random variability parameters, i.e. day-to-day and time step-to-time step. Figure 8 shows data related to hourly power consumption over one year. The average electricity demand over one year is 8.5 kWh/d, and with a peak of 1.33 kWh in August.

Information on equipment price, size, and other design specifications of the renewable hybrid system is indicated in Table 4. The wind turbine used is a new generation of wind turbines that has very little noise and takes up little space and is therefore suitable for the study site. Schematic of the simulated system is also shown in Fig. 9.

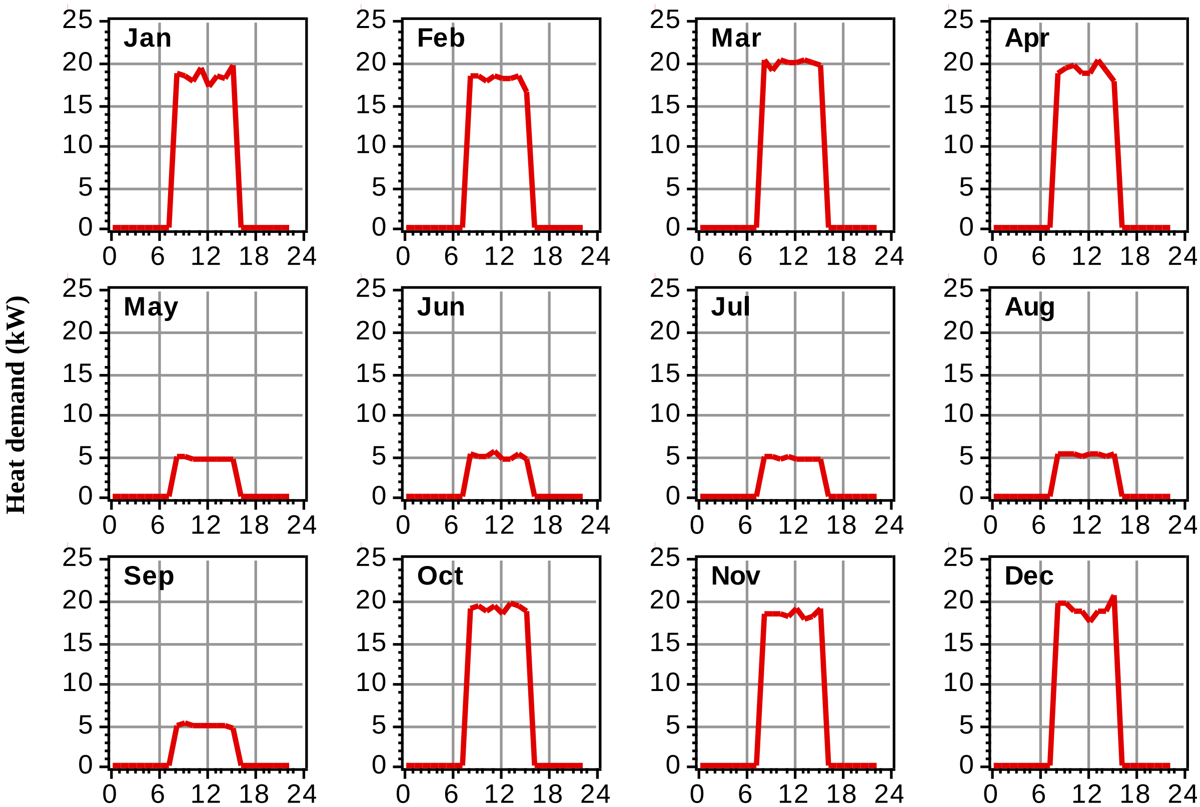


Figure 7. Heat required for the RHC building during different months

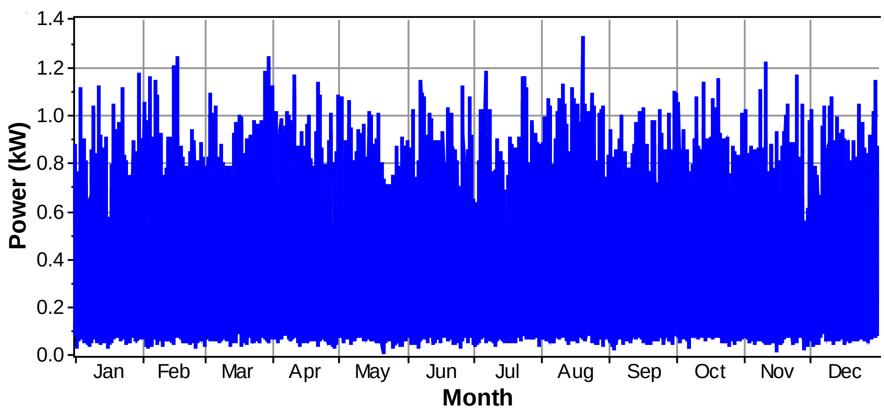


Figure 8. Electricity required for the RHC building over one year

Table 4. Information on the studied system

Equipment	Cost ($)			Size (kW)	Other information
	Capital	Replacement	O&M		
Converter [31]	138	138	10	0-5	Lifetime: 15 y Inverter Efficiency: 95% Rectifier Efficiency: 95%
PV [31]	350	350	10	0-5	Lifetime: 25 y Derating factor: 85 % Temp. Coeffic. of power: -0.38 %/ºC Nominal operating cell temp.: 45 ºC Efficiency at std. test condition: 16.25 %
Battery Trojan T-105 [45]	174	174	5	0-5	Lifetime: 845 kWh Nominal specs: 6V, 225 Ah
Biogas generator [45]	800	700	0.001	0-5	Lifetime: 15000 h Max. efficiency: 30% Intercept coefficient: 2.66 kg/hr/kW rated Slope: 1.52 kg/hr/kW output
Vortex bladeless [46]	242	242	12	0-2	Lifetime: 25 y Hub height: 2.75 m Rated power: 0.1 kW DC

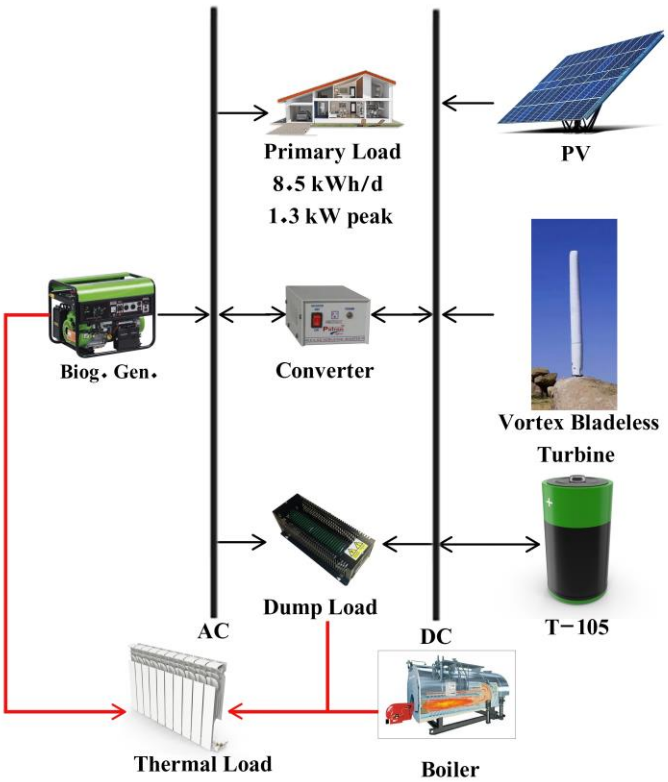


Figure 9. Schematic of the simulated system

5. Results

Simulation results of different scenarios are presented in Table 5. It can be seen that the first scenario, with 7 kW of solar cell and 15 batteries, is the most economic, signifying the superiority of solar energy potential over wind and biomass energies at the studied location. Cycle charging is the dispatch strategy of this scenario, and its operating expense is 426 $/yr, which is minimum among all considered scenarios. The total NPC and LCOE costs are, respectively, 7,667 and 0.393 $/kWh in this scenario, resulting from 25%

deduction of renewable energies. Natural gas consumption in this scenario is 3,650 m^3/yr. Average monthly power and heat generation rates for the first scenario are presented in Figs. 10a and 10b. According to the software results, 11,021 kWh/yr of electricity is produced by solar cells, of which 68.6% is surplus. As shown in Fig. 10a, the maximum and minimum solar power generations occur in warm and cold months of the year, respectively. Fig. 10b indicates that about 20% of the required heat is produced by dump load and the rest by gas boiler. According to the results, the amount of electricity converted into heat is 7,557 kWh/yr, and 597 kWh/yr out of the total 38,192 kWh/yr produced heat can be considered as excess heat. As seen in Fig.10b, a large part of the heat required in warm months of the year (to supply sanitary water) is supplied by the dump load.

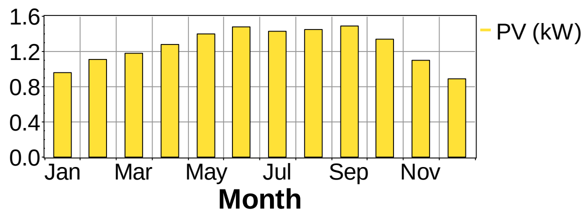
Table 6 presents pollutant release rate in the first scenario, resulting from boiler's natural gas consumption. As shown, more than 7 Ton of CO_2 is released annually.

Figure 11 shows the cost summary chart for the first scenario. The largest share in the total project cost was 5,336 $, which pertains to purchasing the equipment, followed by operating expense as 1,129 $, replacement cost as 626 $, and fossil fuel cost as 599 $. Batteries account for the largest share in purchasing, replacing, and maintenance costs. By selling second-handed equipment, 22 $ of salvage value is obtained. Adding all costs together yields a total NPC of 7,667 $.

Figure 12 shows the cash flow chart of the first scenario. It can be seen that the major costs are imposed at the zeroth year (project's starting point), 10^{th} year, and 20^{th} year. The expenses of the starting point relate to purchase of equipment, and those at the 10^{th} and 20^{th} years to replacing batteries after their lifetime has ended. There are also operating expenses (for solar cells, batteries, and transformers) and natural gas fuel expenses (for boilers) throughout the 25-year lifetime of the project.

Table 5. Simulation results

PV (kW)	Wind turbine	Biogas generator (kW)	Battery	Converter (kW)	Dispatch strategy	Initial capital ($)	Operating cost ($/year)	Total cost ($)	COE ($/kWh)	Renewable fraction	Natural gas (m^3)	Biomass (t)	Biogas generator (Hour)
7	0	0	15	2	CC	5336	426	7667	0.393	0.25	3650	0	0
5	0	1	11	2	LF	4740	577	7893	0.406	0.18	3973	1	15
7	5	0	14	2	CC	6372	471	8950	0.468	0.25	3619	0	0



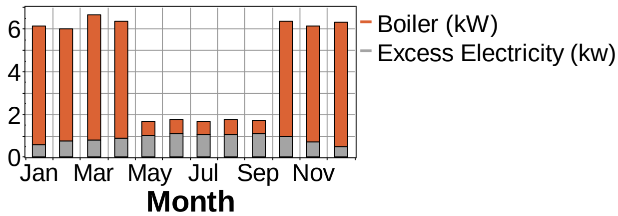


Figure 10. Monthly average production of a) Electricity b) Thermal

Table 6. The results of pollutant in scenario 1

Pollutant	Emissions (kg/yr)
Carbon dioxide	7,050
Carbon monoxide	16.1
Unburned hydrocarbons	3.18
Particulate matter	0.146
Sulfur dioxide	19
Nitrogen oxides	43.8

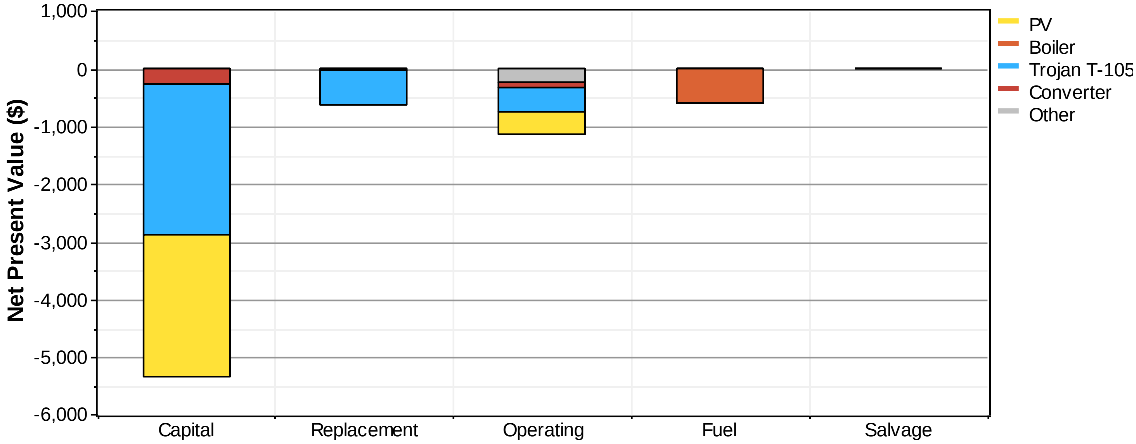


Figure 11. Net present value versus cost type

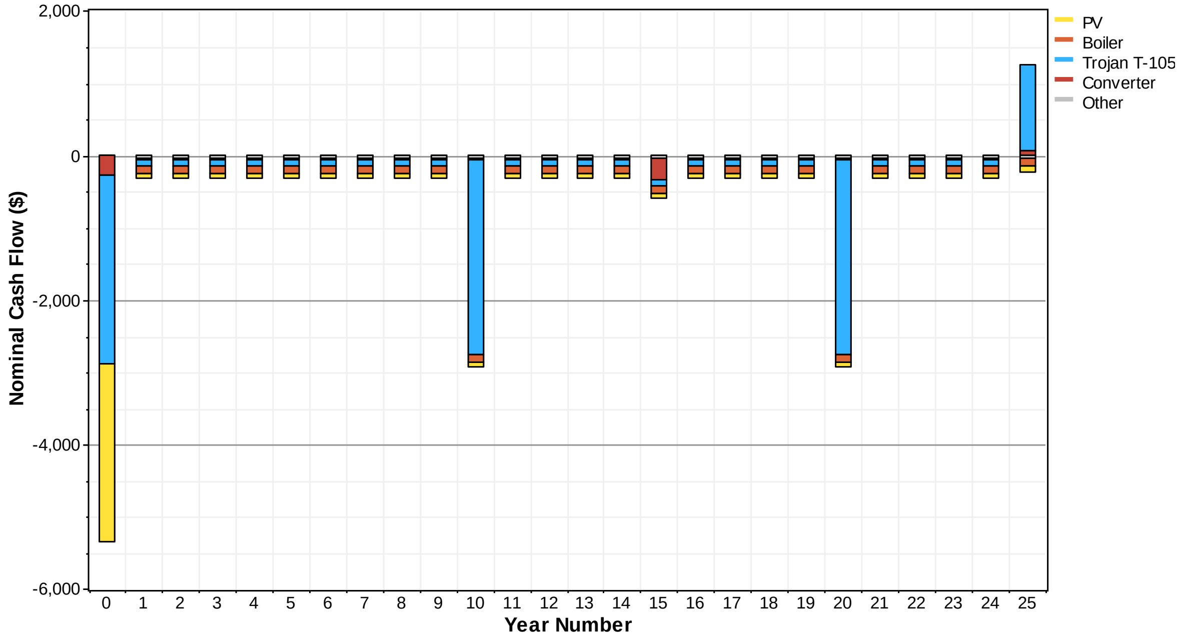


Figure 12. Nominal cash flow during the project lifetime

Figures 13 and 14 show economic comparison between the first and second scenarios and between the first and third scenarios, respectively, throughout the 25-year lifetime of the project. Figure 13 demonstrates that time interval for return on capital in the first scenario, in comparison to the second scenario, is 5.4 years, and the internal rate of return is 25.5%. Moreover, at the end of the project lifetime, the first scenario reduces costs by 2,474 $ compared to the second scenario. Figure 14 illustrates that the first scenario economically outperforms the third one within the entire project lifetime, and saves 1,069 $ after 25 years.

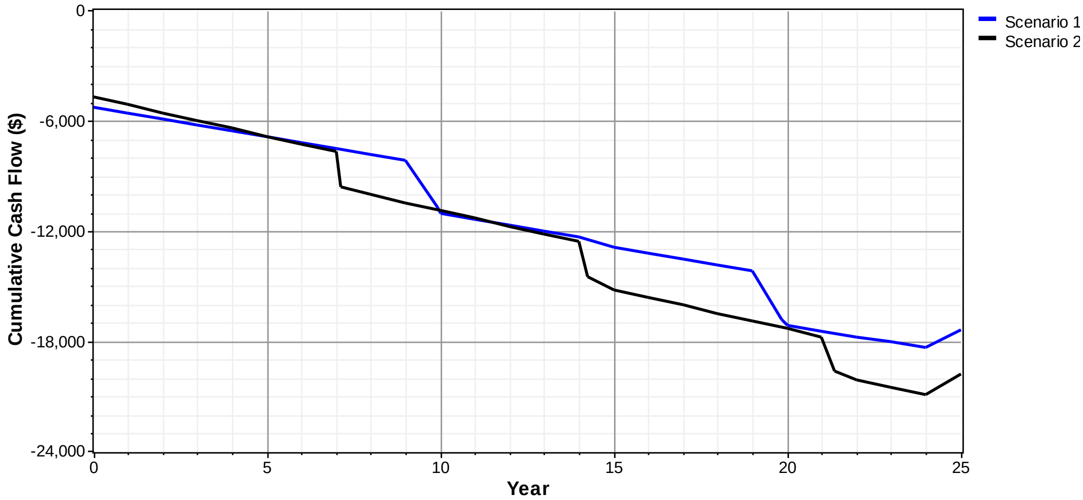


Figure 13. Financial comparison of scenarios 1 and 2

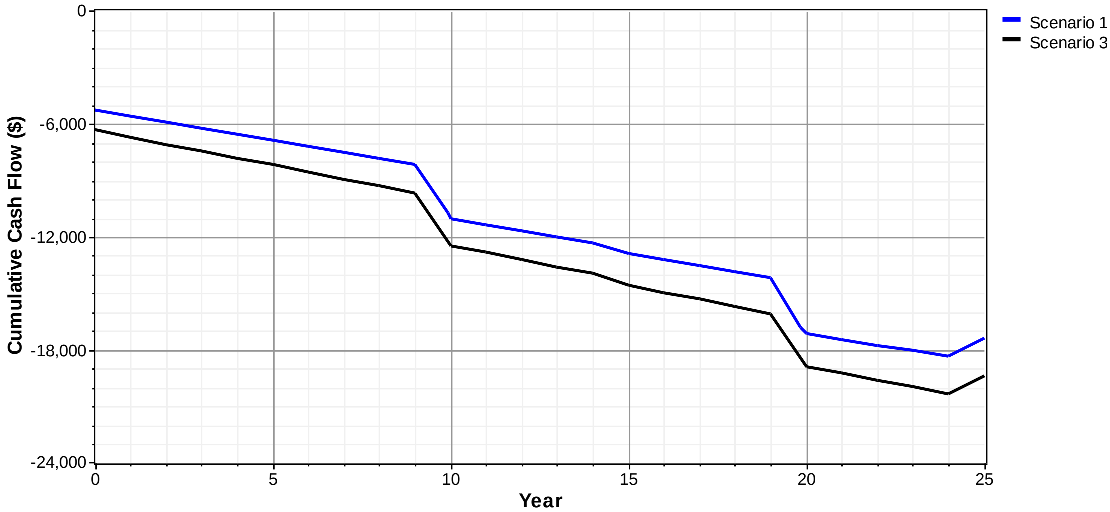


Figure 14. Financial comparison of scenarios 1 and 3

In Figures 15 and 16, indicating 24 hours of the system function on January 31st for the first scenario, electric charges and thermal loads are evaluated respectively. Figure 15 shows that solar cells start to generate energy from 7 a.m. to about 7 p.m., producing a maximum amount of roughly 4.2 kW at 10:30 a.m. Batteries are also charged from 7 a.m. to about 3:30 p.m., and start to discharge and supply power since 3:30 p.m. up to 7 a.m. of the next day. Excess electricity profile, very similar to generation electiciy profile of solar cells, indicates that excess electricity is produced from 7 a.m. to 3:30 p.m. Figure 16 shows that the excess electricity explained in Fig. 15 is obtained from gas boiler heat used to meet thermal requirements. As observed, in the last working hour of the studied building, i.e. 3:30 to 4:30 p.m., the entire amount of heat is produced by the boiler.

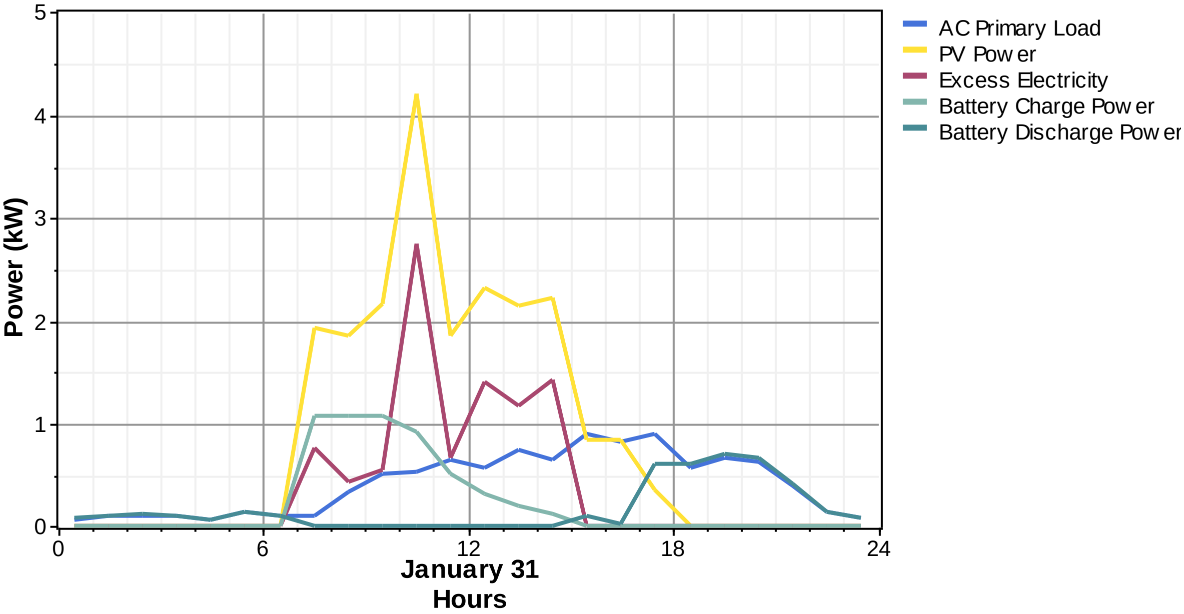


Figure 15. Electrical performance of the scenario 1 in one day

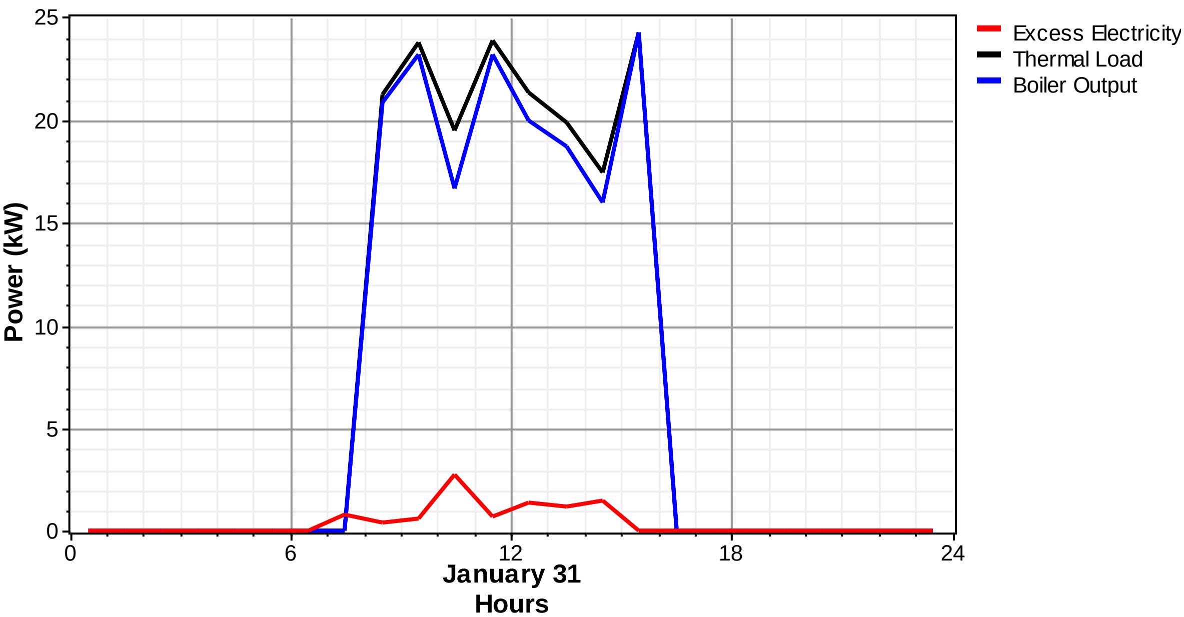


Figure 16. Thermal performance of the scenario 1 in one day

The second scenario, a hybrid of solar cell and biomass, uses 5 solar cells, 1 biogas generator, and 11 batteries. Load following is used as the dispatch strategy of this scenario. Its renewable energy supply deduction is 18%, and 3,973 m^3 of natural gas is consumed annually. Compared to the top economic scenario (the first one), total NPC and LCOE parameters are increased by 226 $ (2.95%) and 0.013 $/ kWh (3.3%), respectively. In this scenario, 1 ton of biomass is consumed, and the biomass generator produces 154 h/yr of electricity and heat.

The third scenario, a hybrid of wind and solar energies, uses solar arrays with a capacity of 7 kW, 5 wind turbines, and 14 batteries, with cycle charging as the dispatch strategy. Renewable energies account for 25% of the energy in this scenario, and the total NPC and LCOE are 8,950 and 0.468 \$/kWh, respectively. A total of 3,619 m^3 of natural gas is consumed in this scenario, which is the least amount among all scenarios. Figures 16a and 16b illustrate the average monthly generation of electricity and heat in this scenario. Solar cells produce 97% of power, and the rest is produced by wind turbines. In sum, 11,367 kWh of power is produced annually, of which 69.7% is surplus. Twenty-one percent of the required heat is supplied by dump load and the rest by gas boiler, and the produced excess heat is less than 2% per year. Table 7 presents pollutant release rate in the third scenario, indicating that with an amount of 6990 kg/yr, CO_2 ranks first among the produced pollutants. Therefore, the third scenario is the most environmentally friendly one.

Table 7. The results of pollutant in scenario 3

Pollutant	Emissions (kg/yr)
Carbon dioxide	6,990
Carbon monoxide	15.9
Unburned hydrocarbons	3.15
Particulate matter	0.145
Sulfur dioxide	18.8
Nitrogen oxides	43.4

6. Conclusion

Reliable access to electricity and heat is the prerequisite of improving socioeconomic life of rural people, whose absence in RHCs leads to fatalities. Therefore, this research aims at supplying electricity and heat to an RHC in Iran using solar, wind, and biomass energies for the first time. Technical, economic, environmental, and energy simulations were carried out by HOMER, and the studied location was Shamsabad Village in Chaharmahal and Bakhtiari Province, Iran. The advantages and innovations of this research include use of vortex bladeless wind turbines for the first time, imposing fines for pollutants for the first time in Iran, examining the effect of temperature on solar cell performance, and conducting a feasibility study on simultaneous production of electricity and heat by a hybrid renewable energy system for an RHC. The main results are as follows:

- Solar cell-battery scenario with a total NPC of 7,667 \$ is the top economic scenario.
- The minimum LCOE is 0.393 \$/kWh, pertaining to the solar cell-battery scenario.
- The highest percentage of energy supply using renewable energies among all considered scenarios is 25%.
- In the top economic scenario, 68.6% excess electricity and 1.59% excess heat are produced.
- In the top economic scenario, about 7 ton of CO_2 is produced annually.
- In all considered scenarios, dump load plays an important role in supplying the required heat.
- Compared to the second and third scenarios, the first scenario cuts the costs by 2,474 and 1,069 \$, respectively, after 25 years.

Nomenclature

i	Annual interest rate (%)
ρ	Real air density (kg/m^3)
ρ_0	Air density under standard temperature and pressure conditions (1.225 kg/m^3)
Y_{PV}	Output power of solar cell under standard conditions (kW)
P_{PV}	Output power of PV cells (kW)
$\overline{H_T}$	Incident radiation on the cell's surface on a monthly basis (kW/m^2)
$\overline{H_{T,STC}}$	Incident radiation on the cell's surface under standard conditions (1 kW/m^2)
$C_{ann,total}$	Total annual cost (\$)
f_{PV}	Derating factor (%)
$P_{batt, Cmax}$	Maximum battery charge power (kWh)
$\eta_{batt, c}$	Batteries charge efficiency (%)
P_{WTG}	Wind turbine output power (kW)
$P_{WTG, STP}$	Wind turbine output power under standard conditions (kW)
$E_{load\ served}$	Real electrical load by system (kWh/year)
N	Useful life-time (year)
$P_{batt, cmax, kbm}$	Maximum battery charge power base on kinetic battery model (kWh)
$P_{batt, cmax, mcc}$	Maximum battery charge power base on maximum charge current (kWh)

$P_{batt,\ cmax,\ mcr}$	Maximum battery charge power base on maximum charge rate (kWh)
O & M	Operating and maintenance (-)
$LHV_{Biog.}$	Lower heating value of the biogas (MJ/kg)
$H_{Biog.\ gen.}$	Electrical efficiency of biogas generator (%)
$P_{Biog.\ gen.}$	Electricity produced by biogas generators (kW)
$\dot{m}_{Biog.}$	Fuel consumption of generator (units/hr)
PV	Photovoltaic (-)
NPC	Net present cost ($)
LCOE	Levelized cost of electricity ($/kWh)
RHC	Rural health center (-)
CHP	Combined heat and power (-)
NASA	
yr	Year(-)

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