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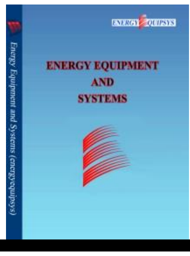

Comprehensive 3E analysis and optimization of off-grid renewable-based microgrids to meet the clinic energy demand, a case study for medical tourism

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ABSTRACT

Technical and executive problems available in the Iranian utility grid inhibit utilizing power at all times. Therefore, considering the importance of the applications of hospitals and medical service centers they should either use auxiliary and backup devices such as diesel generators and UPS, or renewable hybrid power systems. To this end, this paper conducted 3E analysis (energy-economic-environmental analysis) in a medical clinic of Mashhad using HOMER software. The studied renewable hybrid system was an off-grid wind-solar system designed with a peak load of 5.3 kW to produce 19 kWh/day power. Adapting the data of a 20-year history of solar radiation and wind speed and use of the updated price of devices, updated price of fossil fuels and annual interest rate consistent with current economic conditions are other advantages of this work. The investigation of results indicates the superiority of solar potential to wind potential in the studied region. In addition, the configuration of the most economic scenario with minimum pollution emission was as follows: PV cells (4 kW), a diesel generator (4 kW), batteries (n=20) and inverter (4 kW). The minimum price for producing 1 kWh power is 0.721 $ and the minimum emitted CO_2 is 1861 kg/year.

Keywords: HOMER Software; Medical Tourism; Solar Energy; Wind Energy.

1. Introduction

On average, buildings in Iran consume six times as much energy as buildings in European countries. 40% of the electrical energy and nonrenewable energy resources of Iran are consumed in buildings [1]. Although there are no distinct and independent statistics on the of residential, office, and commercial buildings due to the importance of using many pieces of medical equipment [2].

There are many reasons for the growth in the energy consumption of Iranian hospitals. The major reasons are listed as follows: the increased number of hospital beds; the advent of novel energy-consuming devices and tools, especially electrical devices in paraclinical wards; the increased levels of social welfare; changes in hospital hoteling requirements; climate change resulting in the need for electrical cooling and heating systems; low costs and tariffs on energy before the implementation of the Iranian subsidy reform plan; low productivity and efficiency of different electrical appliances across Iran; noncompliance with correct energy consumption patterns on the part of hospital staff and patients; and finally, high loss of

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energy consumption by hospital buildings and their systems [3].

Different devices consume a great deal of power throughout the day at a hospital where the uninterrupted supply of power is a must. Various wards of a hospital consume different amounts of electric energy. For instance, an emergency ward and an operating room are characterized by the highest rates of energy consumption in a hospital. In fact, an emergency ward needs an uninterrupted supply and high consumption of power due to heavy traffic, whereas an operating theater needs such conditions due to the use of advanced devices and tools. After these two wards, an intensive care unit (ICU) and then general wards consume large amounts of electric energy. There are also some wards that need an uninterrupted supply of power, which is provided thanks to UPSs and batteries [4]. According to the latest statistics, the energy consumption of hospitals and healthcare centers in 2008 was more than 410 million barrels of crude oil, which is equal to 35% of the overall energy consumption in Iran (*i.e.* they were the largest energy consumer in the country) [5].

Energetic, economic, exergetic, and environmental analysis and optimization-based studies have recently received a lot of attention from researchers [6-12]. Table 1 presents an overview of recent studies on the supply of power for all or some wards of a hospital or a clinic of healthcare services through renewable energy resources.

Table 1. Recent studies on the supply of power for healthcare centers through renewable energy resources

Reference	Year	Location	Method	System configuration	LCOE	Purpose
[13]	2016	Nigeria	HOMER software	PV/Wind/Diesel/Battery	0.377-0.454 ($/kWh)	Hybrid renewable system for a rural health clinic
[14]	2016	The Democratic Republic of the Congo	Monte Carlo simulation	PV/Diesel/Battery	0.62-0.87 (€/kWh)	Electrical supply for an off-grid hospital
[15]	2017	Libya	Matlab/Simulink & HOMER software	PV/Wind/Diesel/Battery	0.2687 ($/kWh)	Design of renewable energy system for a mobile office/hospital in an isolated rural area
[16]	2017	Nigeria	HOMER software	Grid/PV//Battery	0.096 ($/kWh)	Feasibility analysis of PV/wind options for rural healthcare center
[17]	2018	sub-Saharan Africa	Experimental	PV	-	Electrical and thermal energy demand model for rapid assessment of rural health centers
[18]	2018	India	HOMER software	PV/Diesel/Battery	0.11 ($/kWh)	Hybrid system analysis with renewable energy and thermal energy for a health clinic
[19]	2019	Iran	HOMER software	Scenario 1: Grid/Diesel Scenario 2: Grid/PV/Battery	0.0396 ($/kWh) Scenario1, 0.000003 ($/kWh) Scenario 2	Power resilience enhancement of a local clinic
[20]	2019	Saudi Arabia	HOMER software	Biogas cofire/PV/Battery	0.21 ($/kWh)	Smart energy solution for an optimized sustainable hospital
[21]	2020	Uganda	HOMER software	PV/Diesel/Battery	0.256 ($/kWh)	Optimal sizing and techno-economic analysis for Busitema Health Centre
[22]	2020	Nigeria	HOMER software	PV/Diesel/Biomass gasifier	20.76 (₦/kWh)	Supplying power to a remote hospital
[23]	2021	Saudi Arabia	HOMER software	PV/Diesel/Battery	0.105 ($/kWh)	Evaluation of an off-grid health clinic considering the current

						and future energy challenges
[24]	2021	Iraq	HOMER software	PV/Wind/Battery	0.547 ($/kWh)	Analysis of a Hybrid System for a Health Clinic in a Rural Area

According to Table 1 and other reviews by the authors of the present work, researchers of different countries have focused greatly on the use of renewable electricity for healthcare centers and hospitals. According to studies, so far very few studies have been conducted on the supply of electricity to a clinic in Iran using renewable energy. Due to the need for continuous electricity for medical centers, there is a gap that for a clinic in a medical tourism city such as Mashhad, no feasibility study has been done to produce sustainable electricity. It is not clear to what extent renewable wind and solar energy meet the electricity needs of the clinic, how much pollution has been prevented from being released, etc. Previous works done in the climate were not similar to Mashhad and therefore their results could not be used for Mashhad. Also, energy, economy, and environment (3E) analysis was not performed accurately and completely for all possible scenarios and configurations. Therefore, this is the first study to evaluate the 3E of a hybrid renewable-diesel generator system for Mashhad. Three different scenarios were evaluated for this purpose based on wind and solar energy resources. They were then compared with the conventional power generation scenario (only a diesel generator). For every scenario, the produced amount of pollutants and the generated amount of energy by every energy resource were measured to determine the economically and environmentally optimal scenario. An advantage of this study was to consider the up-to-date prices of the adopted pieces of equipment, the consumed fossil fuel, inflation, and also the 20-year average of solar radiation and wind speed. Finally, it should be mentioned that although this is a case study, the methods of problem-solving and technical analysis used in this research can be applied to other climates by energy researchers.

Nomenclature

CRF	Capacity recovery factor (-)
f	Annual inflation rate (%)
i	Annual interest rate (%)
i'	Nominal interest rate (%)
LCOE	Levelized cost of electricity ($/kWh)
N	Useful lifetime (year)
NPC	Net present cost ($)
O & M	Operating and maintenance (-)
PV	Photovoltaic (-)
RES	Renewable energy sources (-)
3E	Energy, economic, and environmental (-)
$C_{ann,total}$	Total annual cost ($)
$E_{load\ served}$	Real electrical load by the system (kWh/year)
f_{PV}	Derating factor (%)
$\overline{H_T}$	Incident radiation on the cell's surface on a monthly basis (kW/m^2)
$H_{T,STC}$	Incident radiation on the cell's surface under standard conditions (1 kW/m^2)
$P_{batt,\ Cmax}$	Maximum battery charge power (kWh)
$P_{batt,\ Cmax,\ kbm}$	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)
P_{PV}	The output power of PV cells (kW)
P_{WTG}	Wind turbine output power (kW)
$P_{WTG,\ STP}$	Wind turbine output power under standard conditions (kW)
R_{proj}	The lifetime of the project (year)
Y_{PV}	The output power of solar cells under standard conditions (kW)

Greek symbols

ρ	Real air density (kg/m^3)
ρ_0	Air density under standard temperature and pressure conditions (1.225 kg/m^3)
$\eta_{batt,\ c}$	Batteries charge efficiency (%)

2. Background

Located in the northeast of Iran, the metropolis of Mashhad is the capital of Razavi Khorasan Province. With an area of 351 km^2, it is the second-largest city of Iran after Tehran. According to the consensus of population and homes in 2016, Mashhad is Iran's second most populated city with a population of 3,001,184 after Tehran. It is also considered the 101st most populated city worldwide. Since Mashhad is a touristic-religious city, it welcomes more than 27 million domestic pilgrims and two million foreign pilgrims every year. Attracting many pilgrims due to its high-quality medical facilities, Mashhad has long been considered the destination of medical tourism by this group of travelers.

3. Simulation with HOMER

The simulations were performed in HOMER, which was developed by the National Renewable Energy Laboratory (NREL), and is intended for designing hybrid energy systems [26, 27]. Figure 3 illustrates how HOMER works [28]. This well-known, widely-used, and proven program [29] allows for the economic simulation of a system based on the total Net Present Cost (NPC) [30, 31]. Table 2 presents a list of advantages and limitations of HOMER. The optimization performed by HOMER software is such that among all the available configurations for microgrid design, according to the available equipment, it selects the optimal number of each equipment in a way that has the lowest total NPC [32]. As an output, HOMER software gives a list of all the different configurations based on the lowest to highest total NPC [33].

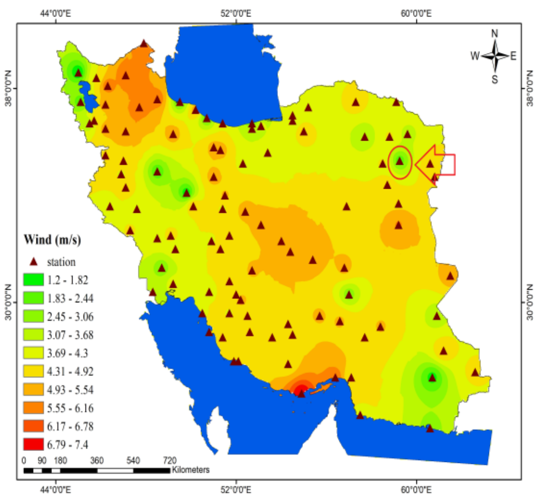

Fig. 1. Wind energy atlas of Iran [25]

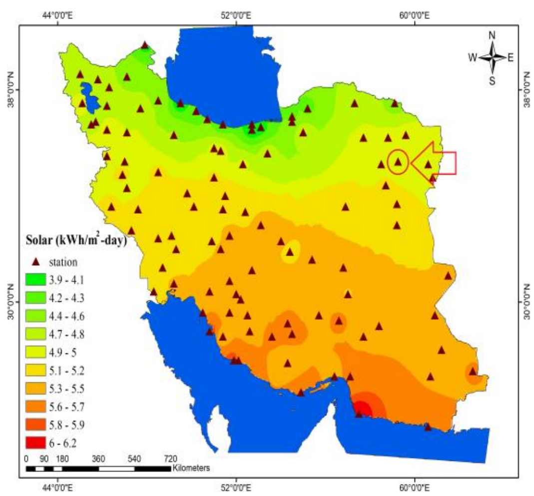

Fig. 2. Solar energy atlas of Iran [25]

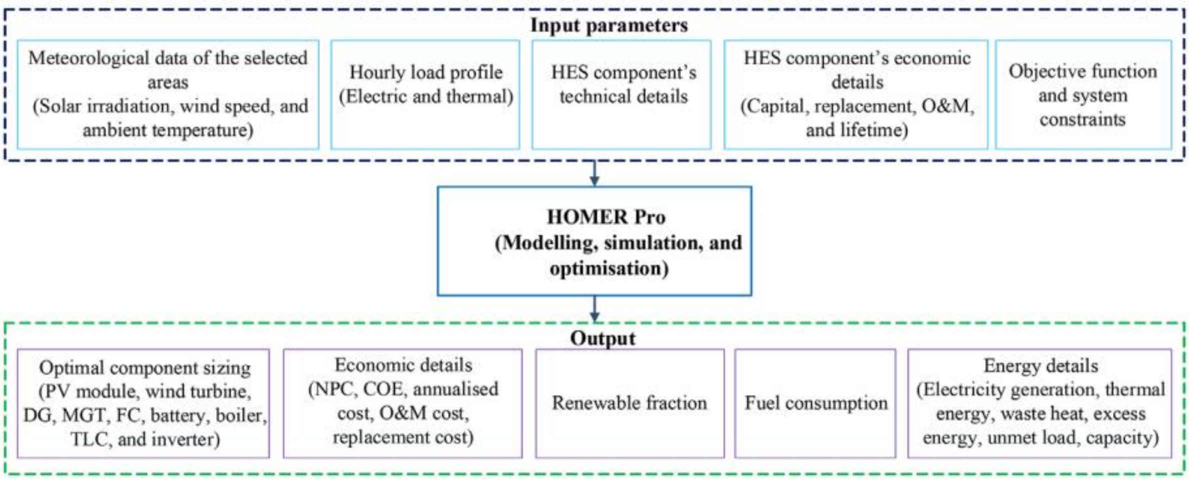

Fig.3: Operational flowchart of HOMER [28]

Table 2. Advantages and disadvantages of HOMER [34]

Advantages	Disadvantages
It presents a list of real technologies simulated based on the existing equipment.	The input data (resources) should be of high quality.
The simulation results are very accurate for analysis and evaluation	It requires accurate input data.
It provides a list of possible configurations based on different technologies and various sizes of equipment.	Experience-based criteria are required to achieve good solutions.
It solves many configurations quickly.	It fails to guess key values or sizes if they do not exist.
The results can help learn optimization of systems with different combinations.	It might be time-consuming and slow for some solutions.

The annual interest rate was considered 18% [35], whereas the fuel price including transportation costs was set at $0.115 per liter [36]. The project's useful life was considered 25 years [37], whereas the penalty rate for pollutants was considered zero [38]. The altitude and daily power consumption rate were considered 2180 m and 19 kWh (with a peak of 5.3 kW). Figures 4, 5, and 6 demonstrate the monthly average radiation, monthly average wind speed, and required power for 24 hours, respectively. Furthermore, the type and quantity of equipment were based on Table 3 in accordance with [39]. Table 4 reports the prices of equipment and their other specifications for the supply of power in a hospital.

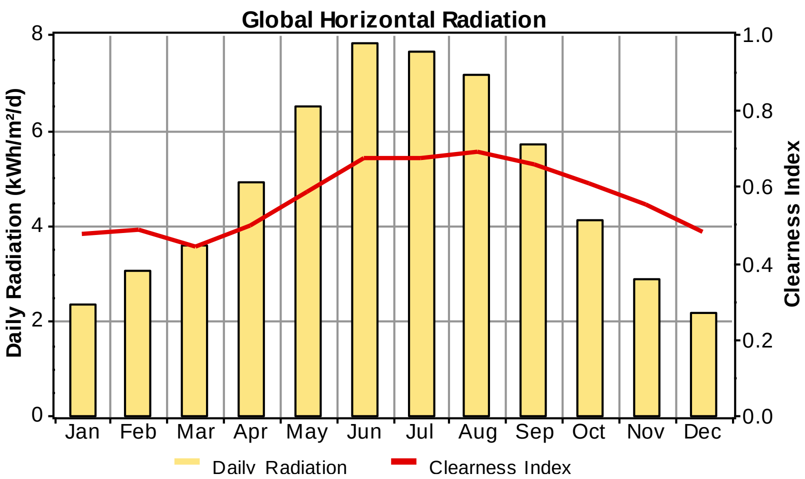

Fig.4. Monthly-average radiation at the studied station

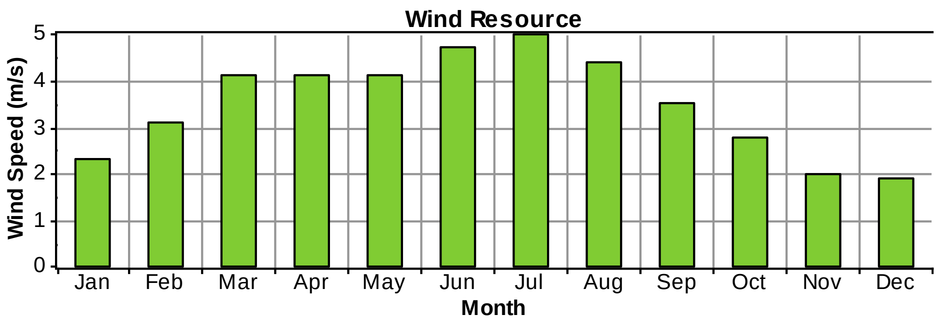

Fig.5. Monthly-average wind speed at the studied station

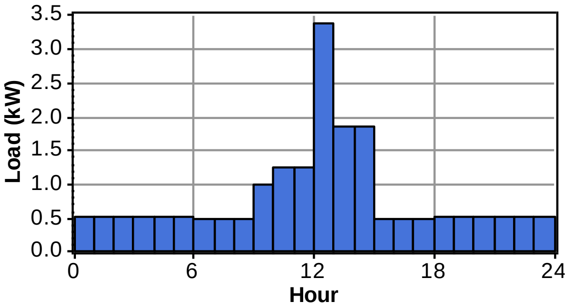

Fig. 6. Daily-average power consumption at the studied station

Table 3. Devices used in a healthcare center [38]

Power consumption	Power (Watts)	Qty	Load (watt × qt)
Vaccine refrigerator/freezer	60	1	60
Small refrigerator (nonmedical use)	300	1	300
Centrifuge	575	1	575
Hematology mixer	28	1	28
Microscope	15	1	15
Security light	10	4	40
Lighting	10	2	20
Sterilizer oven (laboratory autoclave)	1,564	1	1,564
Incubator	400	1	400
Water bath	1,000	1	1,000
Communication via VHF radio		1	
Stand-by	2		2
Transmitting	30		30
Desktop computer	200	2	400
Printer	65	1	65

Table 4. Specifications of the analyzed system

Equipment	Cost ($)			Size (kW)	Other information
	Capital	Replacement	O&M		
Converter [27]	200	200	10	0-10	Lifetime: 10 year Inverter Efficiency: 90% Rectifier Efficiency: 85%
PV [27]	3200	3000	0	0-12	Lifetime: 20 year Derating factor: 90 % Tracking system: No
Battery Trojan T-105 [27]	174	174	5	0-33	Lifetime: 845 kWh Nominal specs: 6V, 225 Ah
Generator [27]	200	200	0.5	0-17	Lifetime: 15000 h Max. efficiency: 31%
Wind turbine (BWC XL.1) [38]	5725	3650	100	0-13	Lifetime: 25 year Hub height: 25 m Rated power: 1 kW DC

4. Governing Equations

Figure 7 depicts a schematic view of the simulated system. Accordingly, Eqs. (1-7) are the equations governing the research problem. The amount of power generated by the solar cell is given as [40]

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

The amount of power generated by the wind turbine is given by [41]

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

The maximum power of the battery is expressed by[42]

$$P_{batt.cmax} = \frac{\mathrm{Min}\,(P_{batt.cmax.kbm}, P_{batt.cmax.mcr}, P_{batt.cmax.mcc})}{\eta_{batt.c}}. \quad (3)$$

Also, the economic calculations by HOMER are carried out using[43-45]

$$NPC = \frac{C_{ann,total}}{CRF\ (i, R_{proj})}, \quad (4)$$

$$CRF = \frac{i\,(1+i)^N}{(1+i)^N - 1}, \quad (5)$$

$$i = \frac{i' - f}{1 + f} \text{ and} \quad (6)$$

$$COE = \frac{C_{ann,total}}{E_{Load\ served}}. \quad (7)$$

For brevity, the parameters used in all equations and their dimensions are presented in the Nomenclature.

5. Results

5.1. Energy Analysis

Table 1 of the Appendix lists top results derived from 1,225,224 possible configurations. According to this table, in all studied scenarios (4 scenarios), wind and solar energies failed to cover 100% of power demand. In other words, the diesel generator was a necessary component in all scenarios. Another important point observed in this table is that solar potential is more economic than wind speed potential.

According to Table 1 of Appendix, scenario 1 supplies power by the following configuration: PV cells (4 kW), a diesel generator (2 kW), batteries (n=20), and an inverter (4 kW). In this scenario, PV cells contribute to 77% of 9111 kWh/year produced power and the remaining amount is supplied by a diesel generator with an excess power of 7.73%. The PV cells produce power by a working time of 4379 hr/year. In addition, the running time of the diesel generator is 1168 hr/year and it consumes 707 liters of diesel fuel. Figure 8 shows mean power production on a monthly basis. This figure shows that the maximum solar power was produced in July and the maximum running time of the diesel generator was in December.

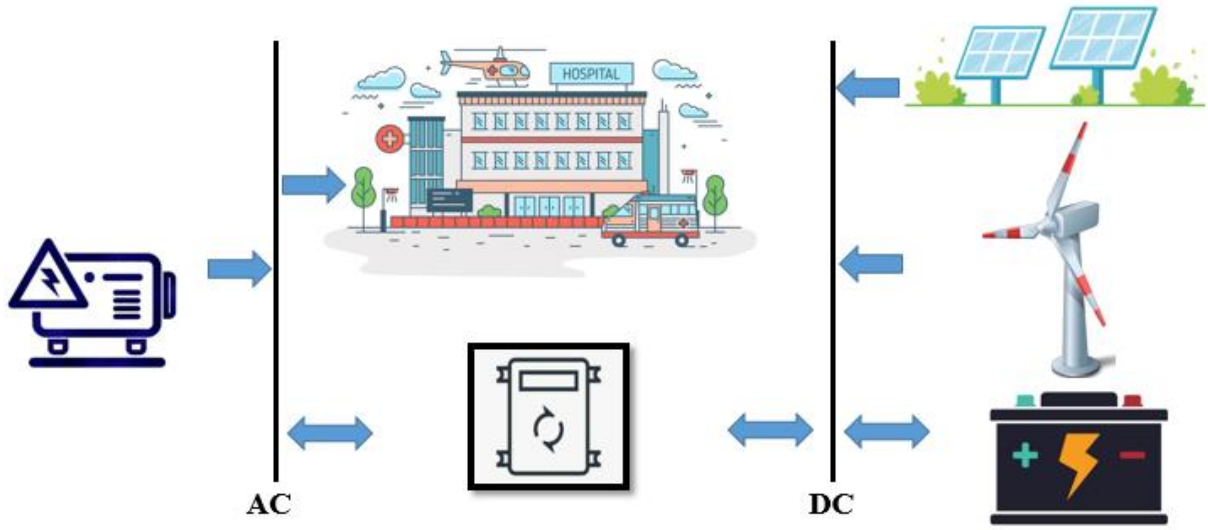

Fig.7. A schematic view of the simulated system

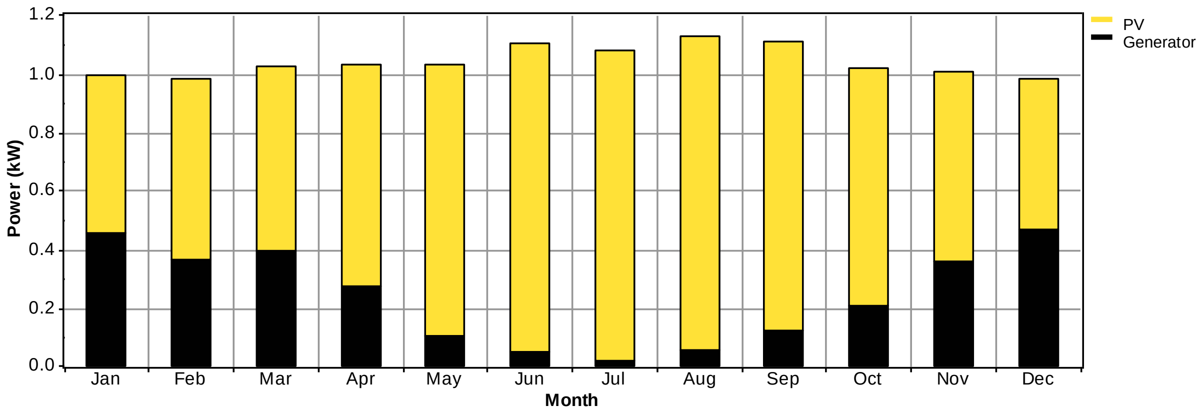

Fig.8. Monthly Average Electric Production (Scenario 1)

The configuration of scenario 2 is as follows: PV cells (3 kW), a wind turbine (1 kW), a diesel generator (2 kW), batteries (n=22), and inverters (n=4). This scenario supplies 5274 kWh/year solar power, 938 kWh/year wind power, and 2464 kWh/year diesel power with 301 kWh/year excess power. According to Fig. 9, maximum and minimum renewable power has been supplied in July and December, respectively. The working time of the PV cells, wind turbine, diesel generator, and inverters and rectifiers is 4379 hr/year, 5418 hr/year, 1344 hr/year, 7745 hr/year, and 1004 hr/year, respectively. The capacity factor of the PV cells, wind turbine, diesel generator, inverter, and rectifier is 20.1%, 10.7%, 14.1%, 16.8%, and 3.1%, respectively. In addition, the electrical losses of the batteries, inverter, and rectifier are 429 kWh/year, 655 kWh/year, and 192 kWh/year, respectively.

The configuration of scenario 3 is as follows: a diesel generator (3 kW), batteries (n=31), and an inverter (3 kW). In this scenario, the diesel generator contributes to 100% of 9180 kWh/year produced power. The running time of this generator is 3067 hr/year and it consumes 3031 liters of diesel fuel. The capacity factor of the diesel generator, inverter, and rectifier is 34.9%, 15%, and 19.5%, respectively.

Scenario 4 uses the same configuration as scenario 3 plus a wind turbine. In this scenario, wind turbine produces 938 kWh/year which corresponds to 10% of total produced power. According to Fig.10, maximum wind power has been supplied in July and it was zero in November and December. The average output of the wind turbine (5418 hr/year) is 0.11 kW with a capacity factor of 10.7%. In this scenario, the running time of the diesel generator is 2735 hr/year corresponding to the capacity factor of 30.6% with 2665 L/year diesel fuel consumption. The electrical losses of the batteries, inverter, and rectifier are 674 kWh/year, 454 kWh/year, and 756 kWh/year, respectively, indicating the severity of converting AC to DC in the rectifier.

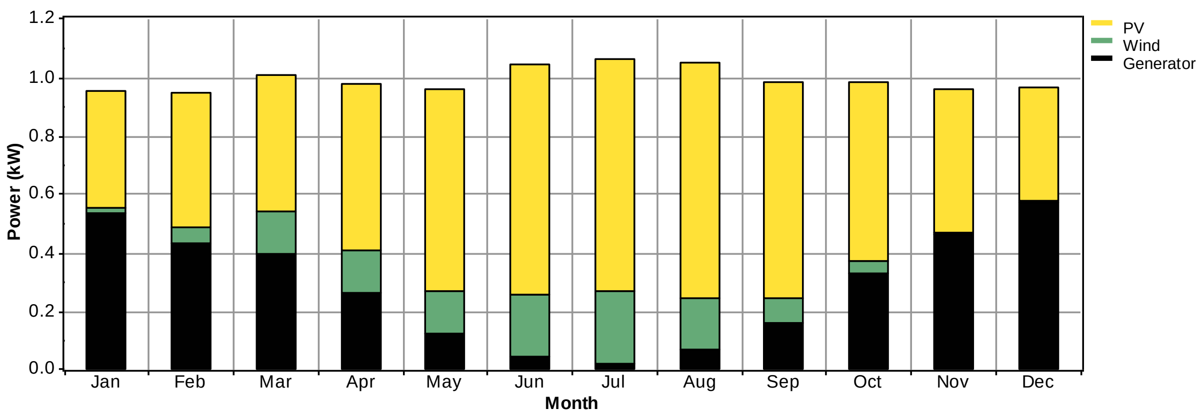

Fig.9. Monthly Average Electric Production (Scenario 2)

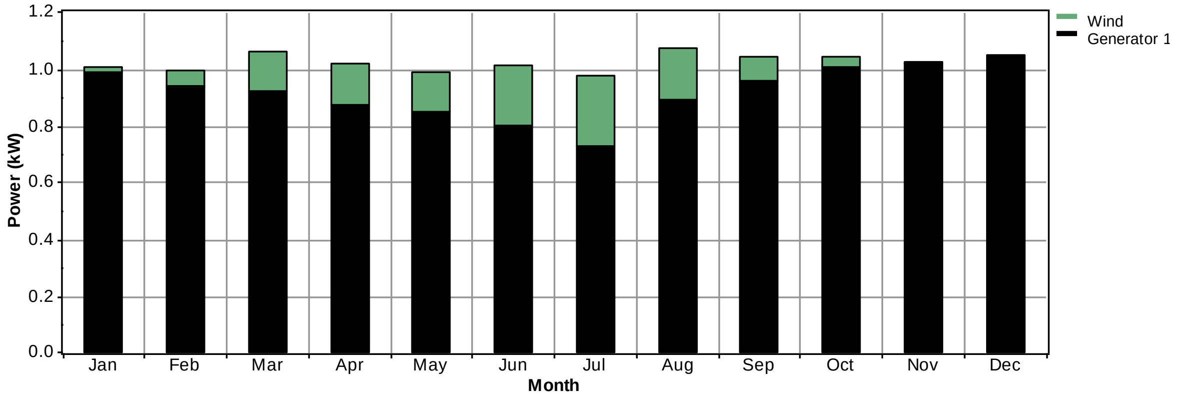

Fig.10. Monthly Average Electric Production (Scenario 4)

5.2. Economic Analysis

According to Table 2 of the Appendix, the total net present cost (NPC) is 27920$ in scenario 1, as the most economic scenario. This means that producing 1 kWh power costs 0.721$. In this scenario, the levelized cost of PV cells is 0.341 $/kWh whereas it is 0.014 $/kWh for batteries. In addition, Fig.11 shows that return on capital is 2.91 years with an annual worth of 1977 $/year, compared to scenario 3 (100% fossil fuel system).

According to Table 2 of Appendix, in the second most economic scenario (scenario 2) where a combination of wind and solar energies is used, total NPC and COE are 31995$ and 0.827 $/kWh, respectively. In addition, levelized cost of PV cells and wind turbines are 0.341 $/kWh and 1.22 $/kWh, respectively with batteries with an average COE of 0.017 $/kWh.

According to Fig.12, return on capital is 3.99 years with an annual worth of 1232 $/year, compared to scenario 3 (100% fossil fuel system).

Scenario 3 is the traditional power production system where only diesel generators are used to produce power. In this scenario, the total NPC is 38728$ i.e. producing 1 kWh power costs 1$. In addition, the average COE of batteries is 0.034 $/kWh.

In scenario 4 where a combination of wind energy and the diesel generator is used, for producing 1 kWh power NPC and COE has been increased by 48.5% compared to scenario 1 (the most economic scenario) according to Table 2 of Appendix. In this scenario, the levelized cost of the wind turbine is 1.22 $/kWh and the average COE of batteries is 0.033 $/kWh.

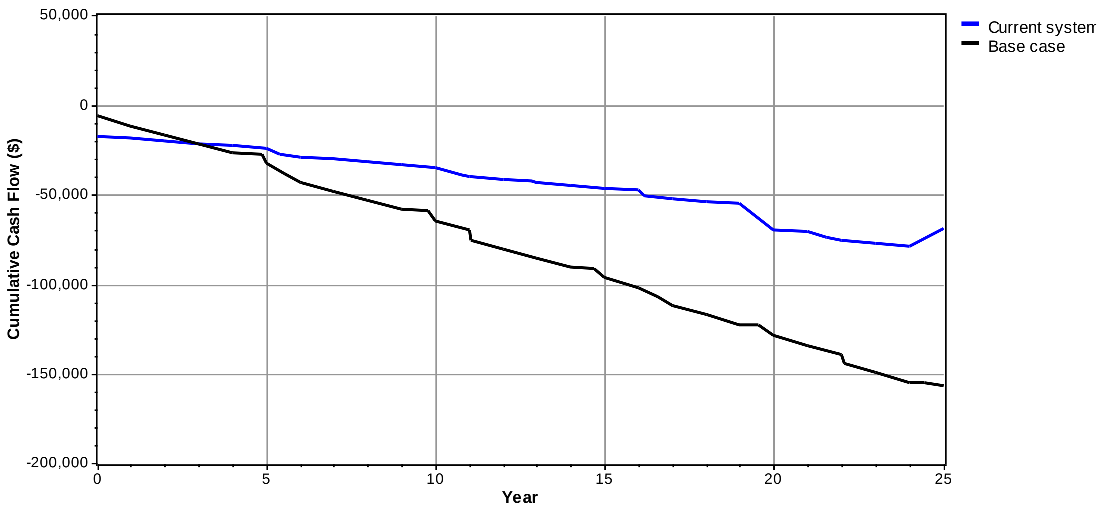

Fig.11. Current System (scenario 1) Compared to Base Case (scenario 3)

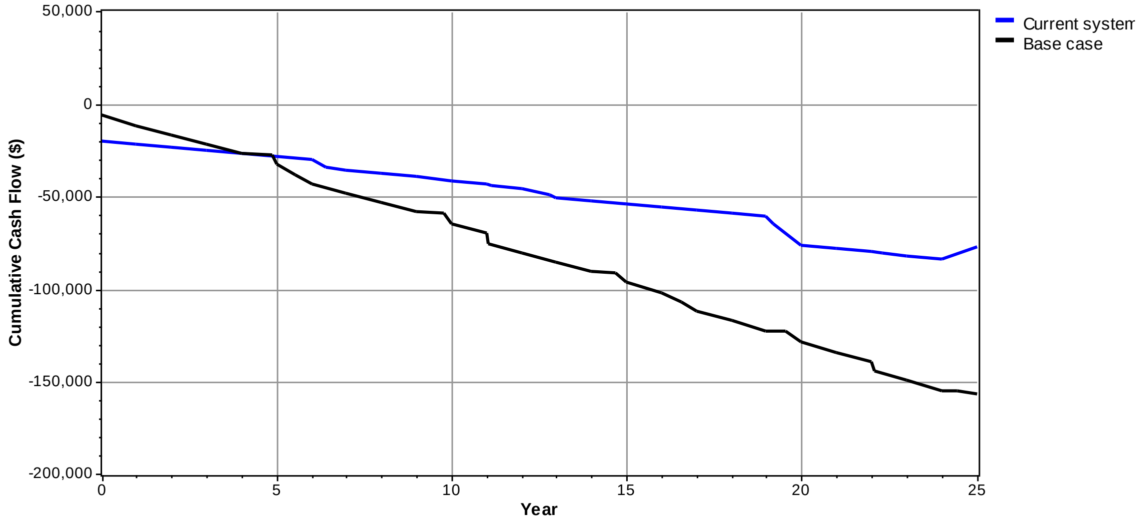

Fig.12. Current System (scenario 2) Compared to Base Case (scenario 3)

5.3. Environmental Analysis

Table 3 of the Appendix shows the pollution emission of the scenarios. According to this table, scenario 1 consumes 707 liters of diesel fuel and emits 1861 kg/year CO_2 and 41 kg/year NO. Scenario 2 consumes 831 liters of diesel fuel and emits 2189 kg/year CO_2 and 48.2 kg/year NO. Scenario 3, which only uses diesel generators, consumes 3031 liters of diesel fuel and emits 7982 kg/year CO_2 and 176 kg/year NO. Scenario 4 consumes 2665 liters of diesel fuel and emits 7019 kg/year CO_2 and 155 kg/year NO. It can be concluded that scenario 1, which is the most economic scenario, is also the most environmentally friendly scenario.

The authors of this paper are hopeful that their analyses and results will be helpful for Iranian decision-makers in the field of energy and medical tourism.

6. Conclusion

Hospitals and medical service centers consume a large amount of energy. Although they account for only 1% of total commercial buildings, they contribute to consuming 4.3% of total supplied power in the commercial sector. In addition, hospitals need backup systems due to their special applications. The supply of electricity to a medical clinic by renewable energy in Iran is an issue that has not been evaluated in a medical tourism target city such as Mashhad. Also, so far the different scenarios of renewable systems have not been compared to the traditional scenario (diesel generator only) in terms of technical, economic, and environmental. Therefore, this study investigated an off-grid wind-solar hybrid system, used to supply the power demand of a medical clinic in Mashhad, using HOMER. 3E analyses were conducted on 4 scenarios and the following important results were derived:

Scenario 1 (PV cells, diesel generator):

- The most economic scenario with a COE of 0.721 $/kWh.
- Solar energy contributes to 77% of total produced power.
- Return on capital is 2.91 years compared to the traditional scenario (diesel generator only).
- CO_2 emission is 1861 kg/year and it is the least environment polluting scenario among the studied scenarios.

Scenario 2 (PV cells, diesel generator, wind turbine):

- The second most economic scenario with a COE of 0.827 $/kWh.
- Renewable energies contribute to 72% of total produced power (61% by PV cells and 11% by wind turbine).
- Return on capital is 3.99 years compared to the traditional scenario (diesel generator only).

Scenario 3 (diesel generator):

- This is the traditional power production scenario with a COE of 1 $/kWh.
- CO_2 emission is 7982 kg/year (The worst environmental scenario).

Scenario 4 (wind turbine, diesel generator):

- Economic costs increased by 48.5% compared to the most economic scenario.

- Wind turbine contributes to about 10% of total produced power.
- Return on capital is 5.51 years compared to the traditional scenario (diesel generator only).

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Appendix

Table 1 of Appendix: Energy analysis of different scenarios

Scenario	Components (kW)					Renewable fraction (%)	Electricity Production (kWh/year)	Excess electricity (%)	Hours of operation	Fuel consumption (Liter)	Capacity factor (%)	Electricity losses (kWh/year)
	PV	WT	DG	Batt.	Conv.							
1	4	0	2	20	4	77	9111	7.73	4379 PV, 1168 DG, 7911 Inv., 828 Rect.	707	20.1 PV, 11.9 DG, 17.3 Inv., 2.6 Rect.	476 Batt., 675 Inv., 161 Rec.
2	3	1	2	22	4	72 (61 PV, 11 WT)	8677	3.46	4379 PV, 5418 WT, 1344 DG, 7745 Inv., 1004 Rect.	831	20.1 PV, 10.7 WT, 14.1 DG, 16.8 Inv., 3.1 Rect.	429 Batt., 655 Inv., 192 Rec.
3	0	0	3	31	3	0	9180	0	3067 DG, 5928 Inv., 2831 Rect.	3031	34.9 DG, 15 Inv., 19.5 Rect.	747 Batt., 437 Inv., 905 Rec.
4	0	1	3	31	3	10	8974	0	5418 WT, 2735 DG, 6260 Inv., 2499 Rect.	2665	10.7 WT, 30.6 DG, 15.5 Inv., 16.3 Rect.	674 Batt., 454 Inv., 756 Rec.

PV: Photovoltaic panel, WT: Wind turbine, DG: Diesel generator, Batt.: Battery, Conv.: Converter, Inv.: Inverter, Rec.: Rectifier.

Table 2 of Appendix: Economic analysis of different scenarios

Scenario	Total NPC ($)	Cost of electricity (COE) ($/kWh)	Annual worth ($/year)
1	27920	0.721	1977
2	31995	0.827	1232
3	39728	1.000	-
4	41448	1.071	No.

Table 3 of Appendix: Environment analysis of different scenarios

Scenario	CO_2 emission (kg/year)	NO emission (kg/year)
1	1861	41
2	2189	48.2
3	7982	176
4	7019	155