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Utilization of Livestock Waste Biomass in Off-Grid Energy Systems: A Roadmap for Decision Makers and Investors in the Renewable Energies Sector in Iran

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Abstract

Iran possesses strong animal biomass resources, which are readily accessible and can contribute to local energy production, reduce dependence on fossil fuels, create local jobs, and enhance economic sustainability. Given Iran's diverse climates and the availability of different renewable energy sources in each climate, a knowledge gap exists regarding the potential for renewable electricity generation based on biomass in each region. Therefore, this study evaluates the energy, economic, and environmental performance of a wind-solar-biomass hybrid system supported by batteries in eight different climate zones of Iran. Key questions addressed include: What is the optimal system configuration for each climate? What is the levelized cost of electricity (LCOE) for the optimal system in each climate? And which climate is the most suitable? These considerations highlight the necessity of this work. Simulations were conducted using HOMER V2.81 software. The results indicate that the Jask station, located in a very hot and humid climate, has the lowest electricity production cost at $0.615 per kWh. To meet a daily electricity demand of 1488 kWh with a peak load of 168 kW, 226,270 different configurations were analyzed. The system, consisting of 550 kW solar panels, a 500 kW biomass generator, a 150 kW converter, and 500 batteries, was selected as the economically optimal configuration.

Keywords: Net present cost (NPC); Energy cost; Renewable fraction; Excess electricity; CO_2 emissions.

Introduction

Biomass, a carbon-neutral source, has become a thriving global market and is now one of the largest sectors of renewable energy worldwide. One of its greatest advantages is its environmental compatibility, and it can contribute to socio-economic sustainability through stable electricity production [1].

Figure 1 shows the top ten countries in the field of biomass energy. As seen, China ranks first with approximately 34.1 GW, followed by Brazil and the United States [2].

As of June 2023, biomass accounted for only 1.3% of Iran's total renewable energy capacity of 1058.48 MW, a figure that is quite insignificant given Iran's biomass potential [3].

Figure 2 presents a map of Iran's biomass potential, with the results indicating very limited usage in the southern, southeastern, and eastern regions of the country [4].

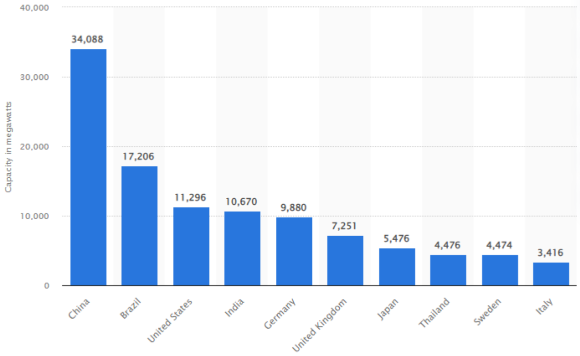


Figure 1. Leading countries in the field of biomass energy

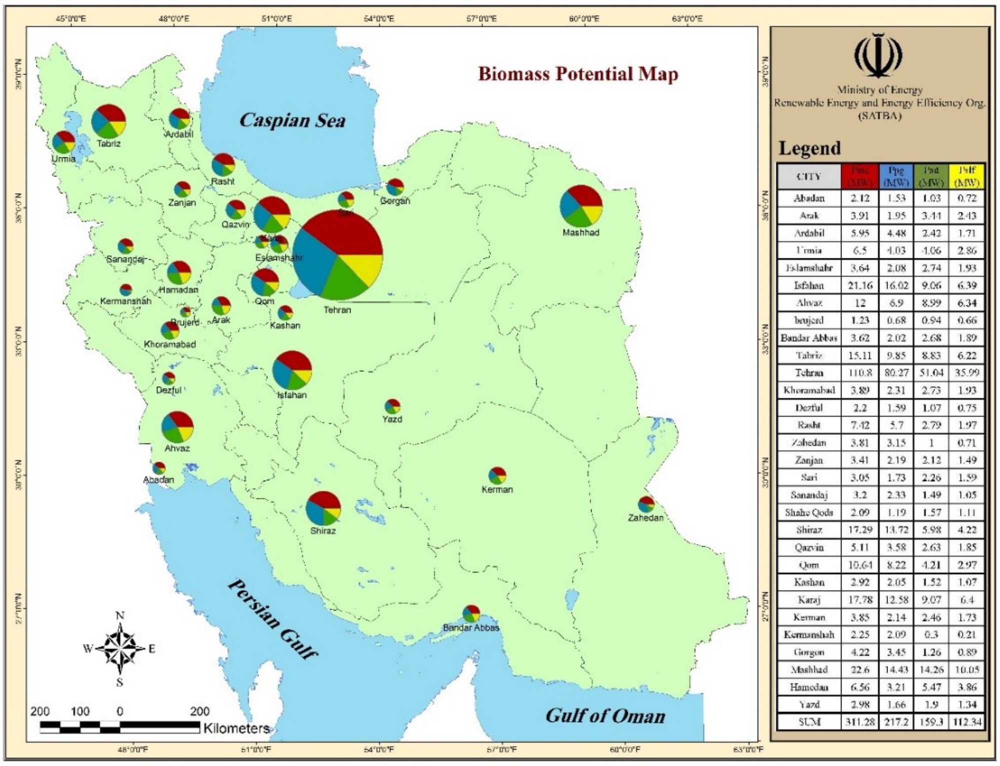


Figure 2. Biomes potential map of Iran

Below are recent studies conducted worldwide on the use of biomass. The presentation of the details is such that it highlights the specifics of each study and how they differ from the present work.

Vahdatpour et al. (2017) [5] analyzed hybrid energy systems in four different climates of Iran using HOMER software. The systems studied were not connected to the national power grid and utilized available wind, solar, and biomass energy. Their findings showed that solar energy was the ideal option in cold, hot, and hot-dry climates, while biomass energy was the best option in temperate and humid climate.

Jahangiri et al. (2021) [6] focused on the simultaneous production of electricity, heat, and hydrogen in the coastal regions of southern Iran. Their study was conducted on a domestic scale and used HOMER software for a 25-year energy-economic-environmental analysis. The available energy sources included solar, wind, and biomass, with hydrogen produced via an electrolyzer and fuel cells. Their results indicated that the lowest production cost per kWh of energy and per kg of hydrogen was $1.16 and $35.44, respectively.

Dehkordi et al. (2022) [7] used HOMER outputs and GIS maps to evaluate the energy-economic-environmental performance of wind-solar-biomass systems in Iran. Their goal was to identify suitable locations for the hybrid system under study and assess the effect of grid connection. Their findings showed that Bardarabbas and Jask were the most suitable stations for wind and solar energy combined with biomass, respectively. Grid connection reduced costs by 65-80%.

Mohseni et al. (2022) [8] evaluated a solar-biomass system for electrifying remote areas, using various economic parameters. The study focused on a village in Kohgiluyeh and Boyer-Ahmad Province, Iran, and employed HOMER PRO software for the assessments. Results showed that, under current conditions (40% inflation rate and 18% discount rate), the optimal system consisted of a 3 kW biomass generator, a 4.74 kW solar panel, a battery with a 10 kWh capacity, and a 2.07 kW converter. The cost per kWh of electricity for the optimal system was $0.093, with annual CO_2 emissions of 2.95 kg.

Yimen et al. (2022) [9] used a solar-wind-biomass-battery system for rural electrification in northern Cameroon. The optimal design and sensitivity analysis were conducted using HOMER software. Simulation results showed that for anaerobic digestion and gasification, the minimum cost per kWh of electricity was $0.347 and $0.319, respectively. Additionally, incorporating biomass into a wind-solar-battery system reduced electricity production costs by 29%.

Kumar and Channi (2022) [10] studied an off-grid solar-biomass system for rural electrification in India. They used HOMER PRO software for the assessments and ranked five top scenarios using the TOPSIS method. Simulation results revealed that in the optimal case, biomass supplied 64.4% of the energy, and solar supplied 35.6%. The payback period for the optimal system was calculated at 1.58 years.

Shah et al. (2022) [11] aimed to minimize energy costs in a small town in India by evaluating an off-grid system based on solar panels, wind turbines, biomass, and fuel cells. HOMER PRO software was used for the simulations, and batteries were employed for electricity storage. Their findings showed that for a 101.1 kW load, the optimal system had an electricity cost of $0.138 per kW and a total NPC of $1.58 million.

Tehrani et al. (2023) [12] aimed for sustainable development in deprived areas of northern and southern Iran by evaluating a renewable hybrid system based on biomass. The system included wind turbines, solar panels, diesel generators, biogas, and batteries. The available biomass was from animal and agricultural sources, and HOMER software and the MCDM method were used for evaluations. Results showed that the lowest cost per kWh of electricity in northern and southern Iran was $0.251 and $0.219, respectively.

Mohammadi and Gezegin (2023) [13] conducted a feasibility and economic analysis of rural electrification in Afghanistan using a photovoltaic-wind turbine-biomass generator system. They studied three scenarios: solar-biomass-battery, solar-diesel generator-battery, and solar-wind turbine-battery. Their results showed that the system with the biomass generator had the lowest cost at $0.29 per kWh, which was still higher than the national grid price for households in major cities.

Akinte et al. (2023) [14] assessed the electrification and heating of a remote area in Thailand using HOMER PRO software. They managed power using several distribution strategies, including hybrid, load-following, and cycle-charging. The system under study included solar panels and biomass as energy sources. Their findings indicated that if the distance from the study location to the national grid was more than 87.22 km, using the renewable energy system would be cost-effective.

Aykut et al. (2023) [15] conducted a comprehensive technical-economic-environmental evaluation of a solar-biomass system for a university campus in Turkey. They used biomass from an on-campus animal farm and simulated the system using HOMER software. Results showed that wind energy potential was unsuitable, and thus, a solar-biomass system was studied. Their findings indicated that the grid-connected optimal system had a total NPC of $18.8 million and an LCOE of $0.107 per kWh.

Youssef et al. (2023) [16] analyzed an off-grid system consisting of solar panels, wind turbines, a biomass generator, and batteries at a school in Egypt. Eight different models based on biomass, wind energy, and solar energy were simulated using HOMER software. Their results showed that the optimal system had a production cost of

$0.382 per kWh and included solar panels, wind turbines, a biomass generator, and lithium-ion batteries. The excess electricity generated was calculated at 26.8%.

EL-Maaroufi et al. (2024) [17] used HOMER PRO software for rural electrification in northern Morocco. The renewable energy sources available were wind, solar, and biomass with battery storage. The total NPC of the optimal system was $8.29 million, and the LCOE was $0.125 per kWh. The system generated 11.1 GWh annually, leading to a reduction of 5,900 tons of CO_2 emissions.

Kassem et al. (2024) [18] simulated a real rural electrification project using solar and biomass energy in Egypt. HOMER PRO software was used, and the simulations were validated with Simulink/MATLAB. Results indicated a total NPC of $11,026 and an LCOE of $0.184 per kWh. The study of annual carbon emissions revealed that the solar-biomass system performed significantly better than grid or solar-diesel generator systems.

Nadeem et al. (2024) [19] optimized a solar-biomass generator system for electrifying an off-grid rural community in Pakistan. The results from HOMER PRO software showed that the optimal system included a 15 kW biomass generator, an 11.5 kW solar panel, 16 lithium-ion batteries, and a 10.8 kW converter. The system produced 71,280 kWh of electricity annually, with a production cost of $0.104 per kWh and a payback period of 7.7 years.

Baghel et al. (2024) [20] aimed to decarbonize and transition to sustainable energy for a university building in India using a solar-biomass hybrid system. HOMER software was used to assess the feasibility of supplying daily electricity consumption of 588 kWh with a peak load of 65 kW. The optimal system generated 376,780 kWh annually at a cost of $0.207 per kWh. Biomass provided 23.4% of the electricity, and solar panels provided 76.6%, avoiding 161 tons of CO2 emissions annually.

Ennemiri et al. (2024) [21] optimized an off-grid solar-biomass-battery hybrid system for a commercial sector in Morocco. Their goal was to achieve the most cost-effective electricity, reduce greenhouse gas emissions, and use locally available renewable energy resources. HOMER software was used for the simulations. Results showed that the solar-biomass-battery system was more efficient than using a single energy source. The optimal system included 231 kW of solar panels, a 170 kW biomass generator, a 140 kW converter, and 201 kWh of lithium-ion batteries, with a cost of $0.28 per kWh. The system emitted 40% fewer pollutants compared to the biomass-only system.

Based on the above studies and others conducted by the authors, it can be seen that none have compared the different climates of a country, or they were focused on other geographical locations. Furthermore, some studies did not account for emissions penalties, or they lacked the comprehensive analysis seen in the current work. Therefore, this study is the first to conduct a 25-year energy-economic-environmental analysis of a wind-solar hybrid system combined with a biomass generator across eight different climates in Iran. Simulations were carried out using HOMER software, and the most economically suitable station was selected.

Location under study

Table 1 summarizes the stations studied across various climates and provides geographical, demographic, climatic, and biomass information [22]. The stations are distributed across eight different climate types in Iran:

- Tabas (Hot & Dry)
- Dezful (Very Hot & Dry)
- Gonbad (Semi Moderate & Rainy)
- Jask (Very Hot & Humid)
- Marand (Very Cold)
- Ramsar (Moderate & Rainy)
- Shahrekord (Cold)
- Yazd (Semi-Arid)

The geographical location of each station significantly affects its solar radiation, wind speed, and cloud cover. For example, Jask has the highest solar radiation but the lowest biomass availability, while Ramsar has the lowest solar radiation yet possesses substantial biomass resources. These differences highlight the importance of thorough analysis, as no single station outperforms the others in every aspect. The simulations will determine the potential of each station when utilizing a mix of energy resources and the configuration costs for the most optimized system in each climate.

Table 1. Surveyed stations in each climate and their information [22]

Station	Location	Population	Annually average solar radiation (kWh/m^2-day)	Annually average wind speed (m/s)	Height above sea-level (m)	Average biomass (tonnes/day)
Tabas	Y=33.6, X=56.9	39676	5.17	4.7	961	30.4
Dezful	Y=32.4, X=48.5	370498	5.13	4.2	503	78.8
Gonbad	Y=34.4, X=58.7	151910	5.07	4.6	1195	115.6
Jask	Y=25.8, X=57.5	16860	6.18	4.1	24	17.9
Marand	Y=38.4, X=45.8	130825	4.71	4.3	1406	86.8
Ramsar	Y=36.9, X=50.7	35997	4.34	2.0	-20	77.6
Shahrekord	Y=32.3, X=50.9	190441	5.07	4.2	2430	34.1
Yazd	Y=31.9, X=54.4	529673	5.15	5.2	1230	24.5

Methodology

In this study, the energy, economic, and environmental simulations were conducted using HOMER software to identify the optimal configuration for each station. The process involves several stages [23]:

Problem Definition: This includes identifying the electricity demand and consumption patterns in the location and defining optimization goals.

Data Collection: Gathering hourly load data and monthly averages for energy resources such as wind speed, solar radiation, and available biomass.

System Modeling: Creating a system model within the software and defining the components of the system.

Scenario Analysis: Running simulations to evaluate system performance, costs, energy production, and more.

Conclusions and Recommendations: Summarizing the findings, their implications for energy decision-making, and recommendations for improving the model.

The governing equations for the performance of various system components are presented in Equations 1 to 3. Equation (1) [24] calculates the electricity produced by solar panels, Equation (2) [25] calculates the electricity generated by wind turbines, and Equation (3) [26] determines the efficiency of the Biomass generator. Additionally, Equation (4) [27] calculates the cost per kWh of electricity generated by the system under study.

$$P_{PV} = Y_{PV} \times f_{PV} \times \frac{\overline{H}_T}{\overline{H}_{T,STC}} \quad (1)$$

$$P_{WT} = \frac{\rho}{\rho_0} \times P_{WT,STC} \quad (2)$$

$$\eta_{gen} = \frac{3.6 \times P_{gen}}{\dot{m}_{fuel} \times LHV_{fuel}} \quad (3)$$

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

Required data

In Figure 3, the electricity demand profiles over 24 hours and 12 months of the year are presented. The goal is to supply a daily electricity requirement of 1,488 kWh throughout the year, with a maximum electricity demand of 168 kW.

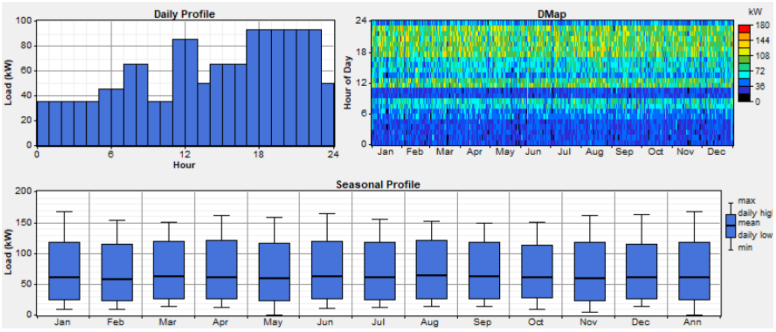
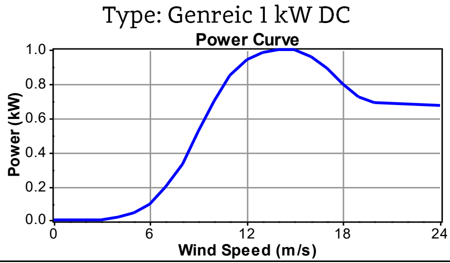


Figure 3. Required power consumption profile

Biomass data, solar radiation, and wind speed for the examined stations are also provided in Table 1. An annual interest rate of 18% [28] and a 25-year lifetime [29] have been considered for the renewable systems. The biomass generator's operational strategy for battery charging is set to cycle-charging. The penalty fees for emissions of pollutants are as follows: \$3.1 per ton of CO_2, \$57 per ton of CO, \$560 per ton of SO_2, and \$184 per ton of NO_x [30]. Pricing and equipment details are presented in Table 2. Additionally, the schematic of the system under study is shown in Figure 4.

Table 2. Required data for simulation with HOMER software

Equipment	Cost (\$)			Size (kW)	Other technical information
	Capital	Replacement	Operating & Maintenance		
PV [31]	350	350	10	0-700	Lifetime: 25 years, Derating factor: 80%
Wind turbine [32]	2000	2000	20	0-500	Lifetime: 20 years, Hub height: 25 m Type: Genreic 1 kW DC 
Battery [31]	174	174	5	0-500	Type: Trojan T-105, Lifetime: 845 kWh
Converter [31]	138	138	10	0-160	Lifetime: 15 years, Efficiency: 95%
Biomass generator [33]	800	700	0.001	0-5000	Lifetime: 15000 hr, Efficiency: 16% Destination of fuel Carbon: CO_2 = 100%

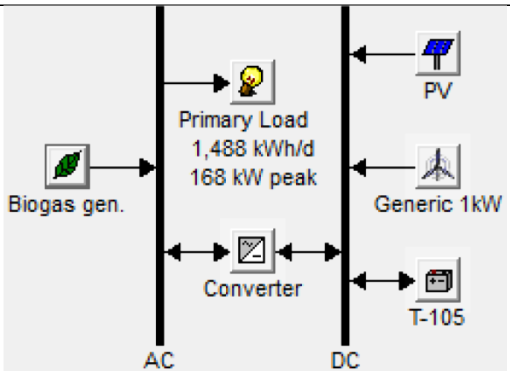


Figure 4. Schematic of the investigated system

Results

Based on the data in Table 3, which presents the simulation results, Jask has the lowest LCOE of electricity produced among the eight cities studied. Out of the 226,270 simulation scenarios, the software identified two optimal configurations for each station that can meet the required energy demand.
The results show that in Jask, solar energy is more economically advantageous than wind energy. A key observation from the results is that the use of biomass energy is economically mandatory in both scenarios. The optimal system configuration includes 550 kW of solar panels, 500 kW of biomass generators, 500 batteries, and a 150 kW electrical converter.

Table 3. The results of the performed simulations

Station/Scenario no.	Optimal configuration	LCOE ($/kWh)	Pollutions (Tonnes/year)	PV capacity factor	Battery losses (kWh/year)	Converter losses (kWh/year)		Biomass consumption (Tonnes)	Biomass performance (Hour)
						Inverter	Rectifier		
Tabas/1	500 kW PV, 500 kW BG, 400 Battery, 150 kW Converter	0.637	1.35	19.3	23067	17739	4386	7366	3307
Tabas/2	400 kW PV, 50 kW WT, 500 kW BG, 400 Battery, 160 kW Converter	0.652	1.32	19.3	22326	18166	3763	7224	3244
Dezful/1	400 kW PV, 500 kW BG, 450 Battery, 150 kW Converter	0.648	1.41	18.7	25312	18002	5104	7676	3446
Dezful/2	350 kW PV, 50 kW WT, 500 kW BG, 450 Battery, 160 kW Converter	0.673	1.39	18.7	24832	18216	4589	7588	3407
Gonbad/1	350 kW PV, 500 kW BG, 450 Battery, 160 kW Converter	0.634	1.38	18.9	25022	17731	5125	7539	3384
Gonbad/2	400 kW PV, 50 kW WT, 500 kW BG, 400 Battery, 160 kW Converter	0.653	1.33	18.9	22337	17892	3792	7253	3257
Jask/1	550 kW PV, 500 kW BG, 500 Battery, 150 kW Converter	0.615	1.20	22.1	27141	19995	5067	6529	2930
Jask/2	400 kW PV, 50 kW WT, 500 kW BG, 500 Battery, 160 kW Converter	0.630	1.20	22.1	26602	20002	4632	6525	2929
Marand/1	350 kW PV, 500 kW BG, 500 Battery, 160 kW Converter	0.658	1.43	18.0	27527	18166	5829	7815	3508
Marand/2	350 kW PV, 50 kW WT, 500 kW BG, 450 Battery, 160 kW Converter	0.683	1.42	18.0	25060	17974	4719	7762	3485
Ramsar/1	400 kW PV, 500 kW BG, 450 Battery, 160 kW Converter	0.660	1.45	16.0	25311	17347	5273	7888	3541
Ramsar/2	400 kW PV, 50 kW WT, 500 kW BG, 450 Battery, 160 kW Converter	0.700	1.46	16.0	25107	17315	5258	7948	3568
Shahrekord/1	350 kW PV, 500 kW BG, 450 Battery, 160 kW Converter	0.652	1.44	18.3	25230	17604	5260	7852	3525
Shahrekord/2	400 kW PV, 50 kW WT, 500 kW BG, 450 Battery, 160 kW Converter	0.681	1.40	18.3	24811	18265	4687	7621	3422
Yazd/1	300 kW PV, 100 kW WT, 500 kW BG, 500 Battery, 120 kW Converter	0.636	1.17	18.7	23460	18256	3080	6406	2876
Yazd/2	400 kW PV, 500 kW BG, 450 Battery, 160 kW Converter	0.647	1.40	18.7	24880	17947	5166	3435	3435

Due to the high initial costs of wind turbines, as the number of turbines increases, the total initial costs also rise. This increase in initial costs leads to a higher NPC, making each kWh of energy more expensive. According to the results, the cheapest electricity cost is $0.615 per kWh, achieved by consuming 6,529 tons of biomass annually and 2,930 hours of generator operation. This cost is for the Jask station.
The second most economical option has a 44.2% higher cost per kWh. Considering that, based on reference [34], the price of each kWh of electricity in Iran is $0.002, it is evident that the optimized scenario's electricity cost is 307.5 times higher than the grid electricity cost in Iran, meaning this system is not currently cost-effective in Iran. However, according to reference [34], the designed system in its most optimal state would be feasible for countries like Denmark, Belgium, Austria, and Italy.
Since Jask is the most suitable station, a more detailed examination of its renewable energy system follows. The results from Jask reveal the following key points.
In Figure 5, the difference between the most economical scenario and the second scenario (which involves wind turbines) is shown. The results indicate that over the 25-year lifetime of the system, the second scenario will never economically outperform the first scenario. By the end of the project, there will be a financial gap of $46,299 between the two scenarios.

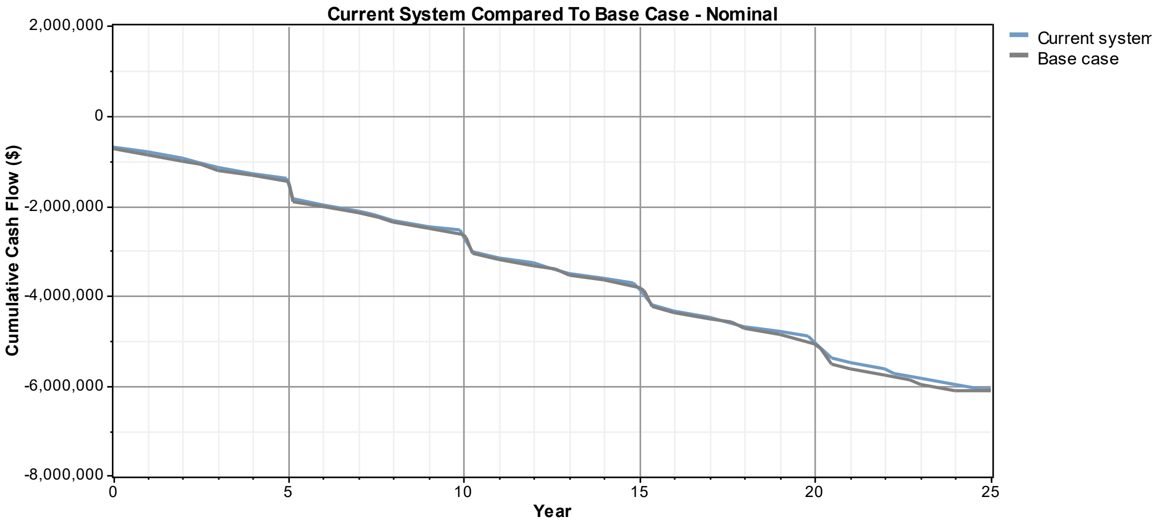


Figure 5. Comparison of different scenarios during the 25-year useful life of the project

In Figure 6, the detailed costs of the system are shown. The results indicate that the highest cost is associated with the biomass generator, while the lowest cost is related to the electric converter. The largest portion of the expenses is the purchase of equipment, which amounts to $700,200. The second largest expense is the fuel cost for the biomass generator, totaling $642,497.
Following that, the costs related to equipment replacement and maintenance are next in line. An interesting observation from the second part of the figure is that the battery replacement costs exceed the initial battery purchase cost.
Based on Figures 7(a) and 7(b), it can be observed that in years 6, 11, 16, and 21, there are significant replacement costs associated with the biomass generator. These costs contribute substantially to the overall system expenses during these years.
Based on Figure 8, it is observed that 71% of the electricity is generated by solar panels, while 29% comes from the biomass generator. Over the year, a total of 1,509,602 kWh of electricity was produced. Of this, 542,775 kWh was consumed, and 914,336

kWh was surplus, amounting to 60.6% of the total production. If this surplus electricity is exported at the global average price [34], it would generate $165,494 in revenue, which would make the system more cost-effective.

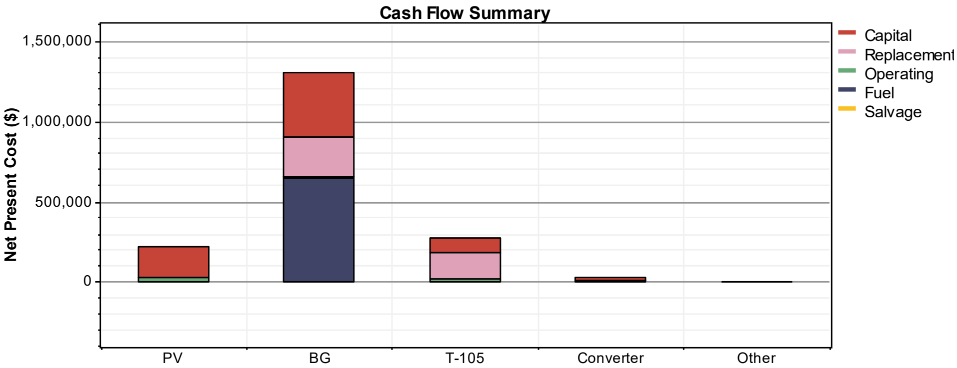
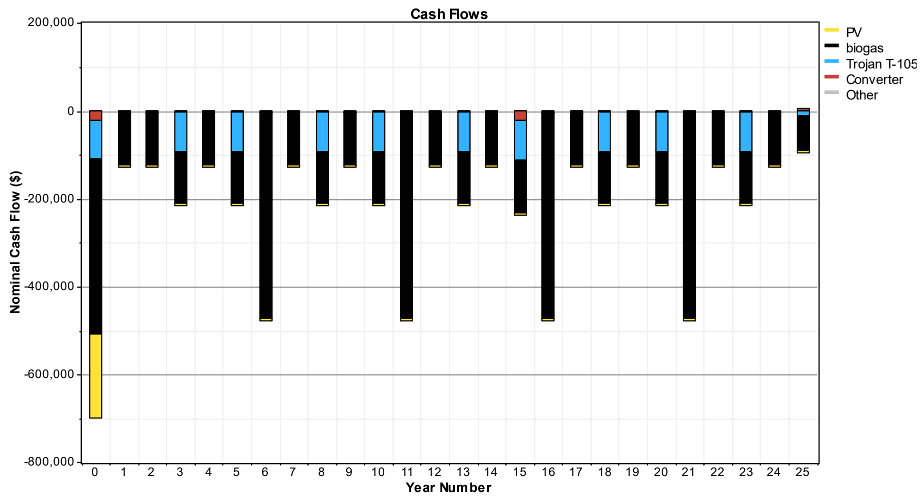
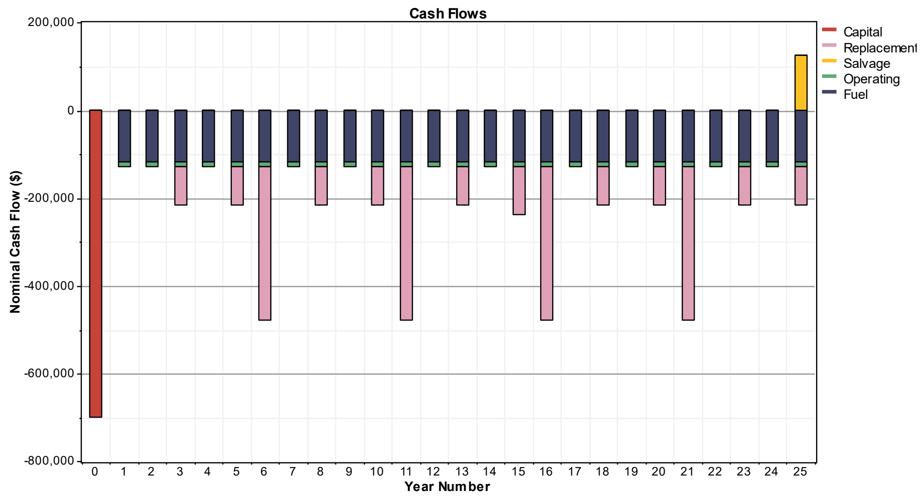


Figure 6. Summary of the cost of the system in the best economic mode



(a)



(b)

Figure 7. Costs of the best economic scenario during the 25 years of the lifetime of the project a) by equipment b) by type of cost

Given that Jask is near the borders of Qatar, Bahrain, Oman, and Kuwait, and considering the reference prices [34], the revenue from exporting electricity to these countries would be:

- $29,258 from Qatar
- $39,316 from Bahrain
- $23,772 from Oman
- $26,515 from Kuwait

This revenue would reduce the overall cost of the system. Furthermore, Figure 8 demonstrates that solar electricity generation surpasses biomass electricity production in all months in terms of quantity.

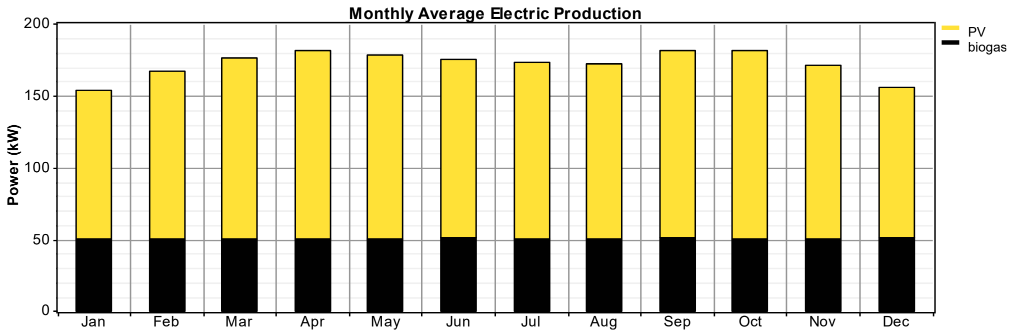


Figure 8. Average monthly electricity production

In Figure 9, the daily electricity production by solar panels throughout the year is presented. It is observed that all the electricity is produced during sunlight hours, from 7 AM to 5 PM. The maximum production is 540 kW, while the average output is 122 kW. The capacity factor of the solar panels is 22.1%, and there are 4,383 sunny hours throughout the year during which the solar panels generate electricity.

In Figure 10, which illustrates the power production by the biomass generator, it is evident that the majority of electricity is produced during the nighttime hours. During sunlight hours (from 7 AM to 5 PM), the solar panels predominantly meet the energy needs. Over the year, the biomass generators operated for 2,930 hours, resulting in a capacity factor of 10.1%. Consequently, the useful life of the biomass generator is approximately 5.12 years, with a maximum operational capacity of 210 kW.

In Figure 11, it is observed that the minimum battery charge level is 30%. The battery reaches 100% charge approximately 19% of the time, which predominantly occurs in the months of April, May, June, July, and August and mainly during peak sunlight hours from 12 PM to 5 PM. An important observation is that the battery experiences a loss of 27,141 kWh annually and has a useful life of approximately 2.5 years.

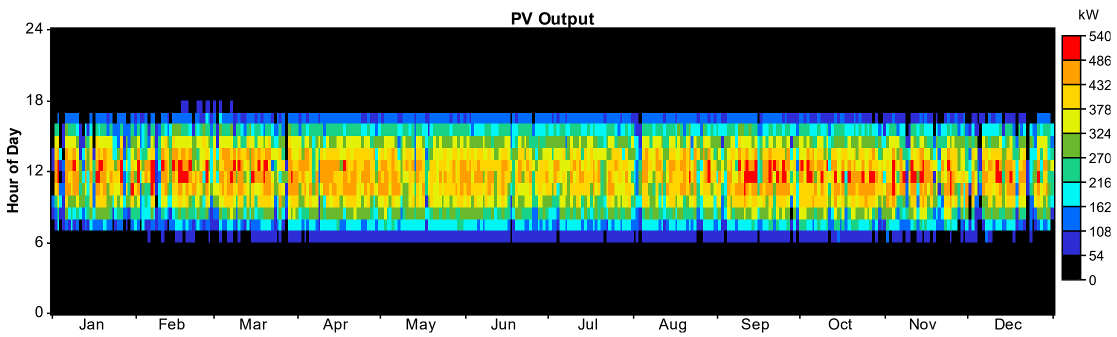


Figure 9. Output power of solar cells during the year

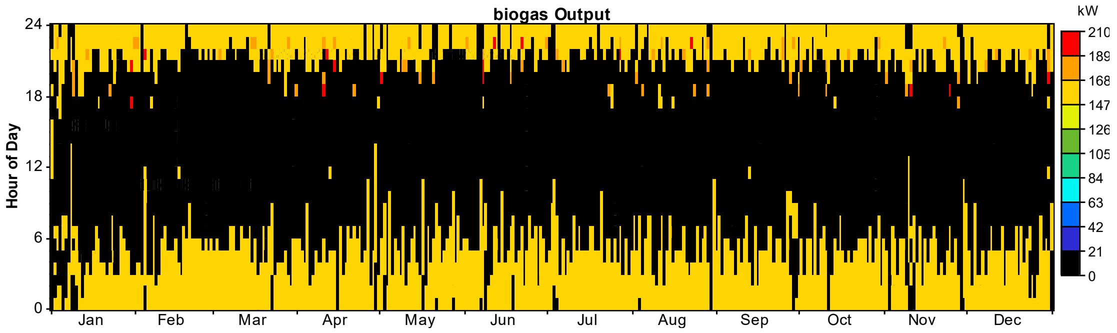


Figure 10. Biomass generator output power during the year

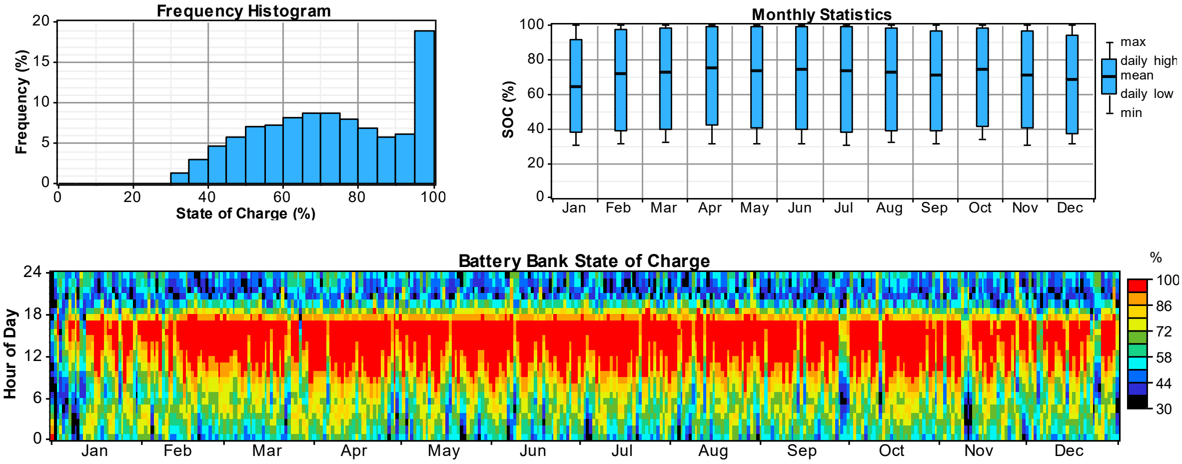


Figure 11. How the battery works over the year

In Figure 12, it is observed that the converter has operated in both inverter and rectifier modes, with the inverter performing more than four times better than the rectifier. The inverter operates primarily during daylight hours, while the rectifier functions during nighttime. The capacity factor for the inverter is 28.9%, and for the rectifier, it is 7.3%. The annual losses for the inverter are 19,995 kWh, while the rectifier experiences losses of 5,067 kWh.

Based on Table 2 and Table 4, since all the carbon in the biomass is converted into CO_2, the use of the biomass generator will produce 1,197 tons of CO_2 annually. Given the penalties for CO_2 emissions, this level of pollutant production will negatively impact the system's performance.

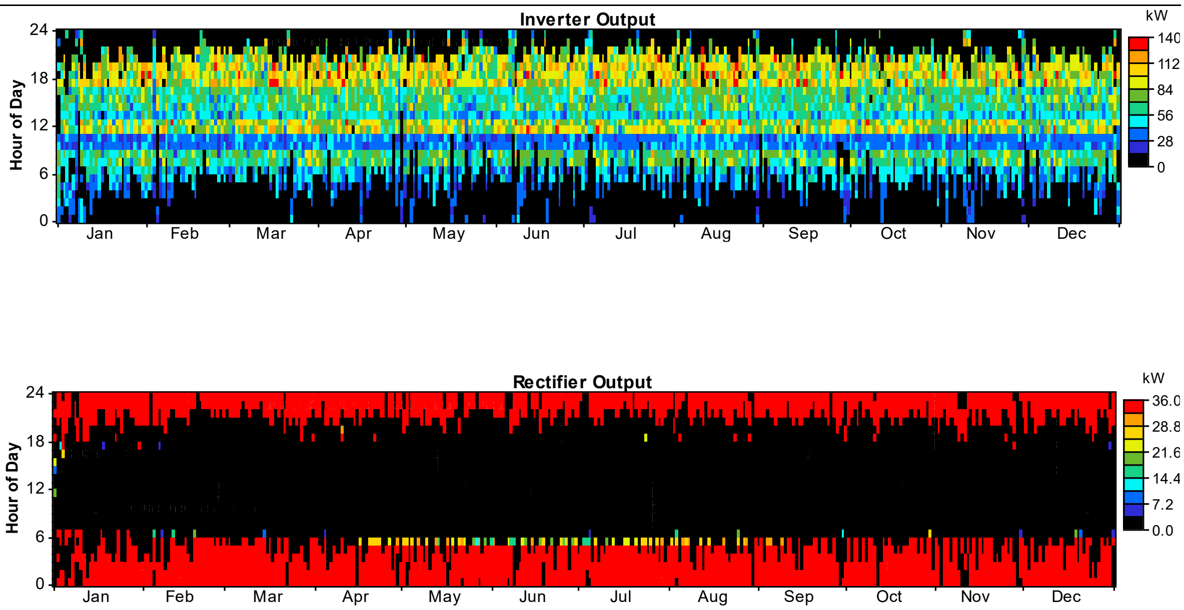


Figure 12. Inverter and rectifier power contour during the year

Table 4. Diffuse pollutants in the economic optimal system

Pollutant	Emissions (kg/yr)
Carbon dioxide	1,197
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	0
Nitrogen oxides	0

Conclusion

The study shows that the use of a wind-solar-biomass renewable energy system for residential electricity supply not only offers economic savings but also promotes sustainable development and improves quality of life in various climatic regions of Iran. This study, conducted for the first time using HOMER V2.81, evaluates the performance of the wind-solar-biomass system across eight different climates in Iran. It addresses the scientific gap regarding optimal configurations, the cost per kWh of electricity produced, and the electricity generation capacity for each climate. The 25-year energy-economic-environmental analysis reveals the following:

- Economic Priorities: Except for Yazd, wind energy is not a priority economically in the other studied stations.
- Cheapest Electricity: The lowest cost of electricity, at $0.615/kWh, is found at the Jask station.
- Most Expensive Electricity: The highest cost of electricity, at $0.660/kWh, is found at the Ramsar station.
- Energy Mix: At the top-performing station (Jask) and in the most economically favorable scenario, 71% of the electricity is generated by solar cells, with the remainder produced by biomass generators.
- Excess Electricity: In the top-performing station (Jask) and scenario, there is an excess of 60.6% of electricity.
- Annual Losses: At the top-performing station (Jask) and in the best economic scenario, the annual losses are 27,141 kWh for batteries, 19,995 kWh for inverters, and 5,067 kWh for rectifiers.
- CO_2 Emissions: At the top-performing station (Jask) and in the best economic scenario, approximately 1.2 tons of CO_2 pollutants are produced annually.

This analysis highlights the potential for integrating renewable energy sources effectively, considering both economic and environmental factors, to enhance energy sustainability and efficiency in different climates.

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