

Research Article

Effect of Emission Penalty and Annual Interest Rate on Cogeneration of Electricity, Heat, and Hydrogen in Karachi: 3E Assessment and Sensitivity Analysis

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Pakistan is the world's sixth-most populous country with a semi-industrialized economy. It has been always an energy importer and dependent on fossil fuels. Great pressure is imposed on Pakistan's national grid from the rise in fossil fuel costs, variations in the annual interest rate, and increased costs of greenhouse emissions. To meet the ever-increasing energy demand, the Government of Pakistan has decided to further harness wind and solar energies currently having a negligible share in Pakistan's energy portfolio. Despite the importance of this issue, no study has been conducted so far on the cogeneration of power, heat, and hydrogen in Pakistan. Accordingly, this study is aimed at technical-economic-environmental sensitivity analysis of supplying electric and thermal loads of a residential building in Karachi by an off-grid wind-solar-fuel cell system. To this end, 4500000 possible cases were analyzed, simulated, and optimized with the HOMER software using 20-year average meteorological data from the NASA website. A sensitivity analysis was performed on this system for the first time in Pakistan. The other novelties are the use of dump loads for converting the surplus electricity into heat and also heat recovering in the fuel cells. The results showed the great potential of the station understudy for supplying the required power and heat by renewable energies. Hydrogen production was also affordable at every emission penalty price with an interest rate of less than 9%. Moreover, dump loads play a key role in supplying the thermal demand. Comparison of the wind turbine-solar cell-fuel cell-battery system with the wind turbine-solar cell-battery and solar cell-battery systems indicated that the internal rate of return and the payback period were, respectively, 9.39% and 11.4 years and 11.7% and 11 years. According to these results, it is recommend that Pakistani authorities promote the use of renewable energies through incentives and investment subsidies.

1. Introduction

Energy has been turned into a necessity for improving the quality of life and income in developing countries such as Pakistan [1] leading to a growing demand for the electric power

[2]. It is noteworthy that sustainable power supply is a prerequisite for sustainable economic growth [3–5]. Renewable energies, in particular wind and solar energies, are used for this purpose [6].

Despite a very high potential for renewable energies [7–9], Pakistan has failed to utilize them effectively due to

inefficient strategies. As shown in Figure 1, Pakistan has failed to compensate over the 500 MW deficit [10] and inaccessibility of about 144 million Pakistanis to the electric power [11] in recent years.

As clearly shown in Figure 2, the share of renewable energies in Pakistan's energy portfolio is only 3%, which is negligible in comparison with fossil fuels [12, 13].

According to the reports, Pakistan's estimated wind energy potential is 346 GW [2]. Of this, 308 MW is currently in operation and 1140 MW is under construction [4]. As shown in Figure 3 [14], the Sindh coastal line and Baluchistan are the most susceptible areas for the use of wind energy in Pakistan. Of 43 GW wind energy capacity in these regions, only 11 GW can be commercially utilized [15, 16].

The high investment cost is the main factor preventing the development of wind energy in Pakistan [2]. The high noise of large wind turbines and damages to birds are other negative features in this regard [17]. Accordingly, it is recommended to use home-scale wind turbines not having these problems.

Geographically, Pakistan is located in a region with a high solar radiation potential so that 95% of its territory receives an average daily solar radiation of 5–7 kWh/m² [18]. According to Figure 4 [19], most desert regions in Baluchistan, Sindh, and Punjab have the highest solar energy potential in Pakistan [20]. Of the estimated solar energy potential of 2.9 TW in Pakistan [21, 22], 100 MW is currently in operation and 856 MW is under construction [4].

Given the great public interest in solar cells, particularly for partial loads [23], it is recommended to use a hybrid solar cell–small wind turbine system to generate more sustainable energy by eliminating the drawbacks of solar cells and wind turbines [24].

Hydrogen can play a key role in improving energy security and reducing greenhouse emissions in Pakistan [25, 26]. Hydrogen generated from a renewable resource could be a clean sustainable fuel [27, 28]; wind and solar energies are the most reliable renewable resources in this field in Pakistan [25, 29]. Despite the considerable growth of global hydrogen generation, unfortunately, hydrogen has no share in Pakistan's energy portfolio [25]. Given few studies on hydrogen generation from renewable energies in Pakistan, it is recommended to consider hydrogen production from wind and solar energies. Table 1 summarizes recent technical-economic-environmental feasibility studies on renewable energies in Pakistan.

Figure 5 shows electric power consumption in different sectors in Pakistan [8]. As seen, the domestic sector is the major consumer of electric power in Pakistan [4]; thus the electric power supply for a residential building was considered in this study. Moreover, Pakistan is largely dependent on thermal energy so 35% of the electric power is consumed for heat generation [6]. According to the literature, there is no technical-economic-environmental feasibility study on the cogeneration of power, heat, and hydrogen in Pakistan. For the first time in this study, the effect of emission penalties and the annual interest rate was studied on the performance of a renewable hybrid system for cogeneration of power, heat, and hydrogen using NASA's 20-year average meteoroidal data

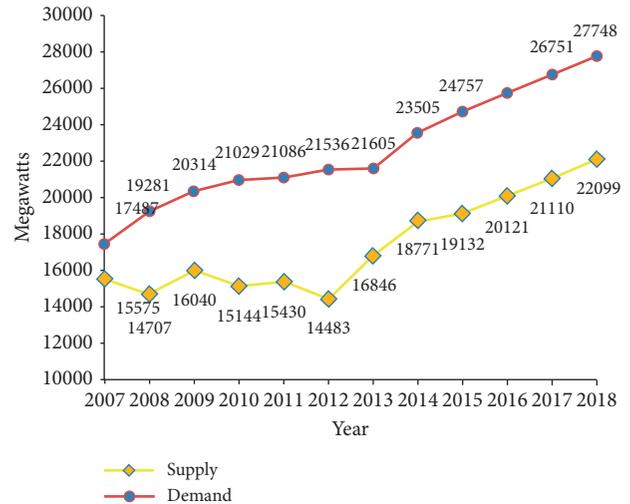


FIGURE 1: Electric power demand and supply in Pakistan [10].

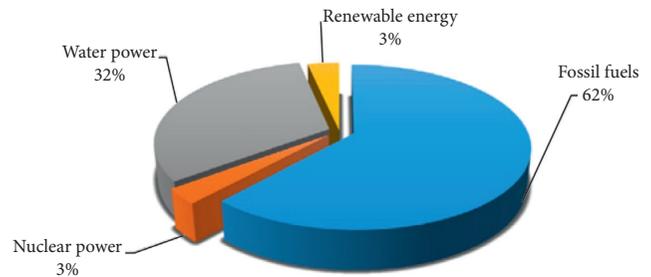


FIGURE 2: The production capacity per energy source [12, 13].

[41] with the HOMER software. The results of this study will be not only helpful for the utilization of hybrid renewable energies in Pakistan but also useful for other countries with the same climate aiming at implementing similar projects in the future.

2. Study Area

Pakistan with the capital city Islamabad is located in South Asia. Pakistan has a 1000 km maritime boundary with the Oman Sea in the south and is neighbor to Iran from the west, Afghanistan from the north, India from the east, and China from the northeast. With a land area of 796096 km², Pakistan is located on the global solar belt [4]. About 95% of Pakistan's land is exposed to solar radiation in over 300 days for 8–10 h per day [42]. Moreover, 1100 km of Pakistan's coastal line with a wind speed of 7–8 m/s provides a high potential for utilization of wind energy [43, 44].

Karachi, the largest city in Pakistan, is the capital city of Sindh Province. As shown in Figures 6 and 7, Karachi is located in the southeast of Pakistan along the Arabian Sea and the northwest of the Sindh Delta. According to the statistics published in 2017, Karachi's population was 14910352. In this regard, Karachi is the most populous city in Pakistan and the sixth-most populous city in the World. Figures 6 and 7, respectively, display the wind speed at an elevation of 100 m and power generation by solar cells (in

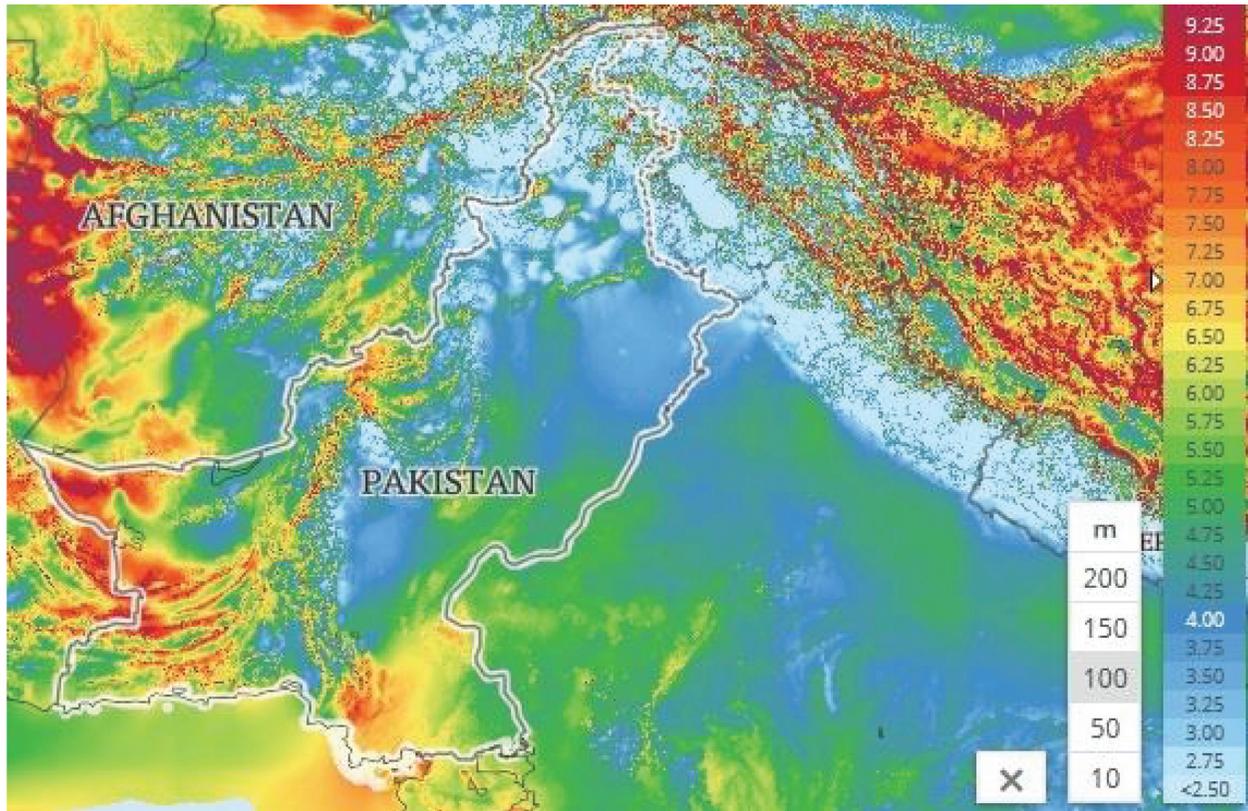


FIGURE 3: Atlas of wind speed at an elevation of 100 m [14].

terms of kWh). The geographical locations of large wind and solar power plants are also shown in these figures.

The share of renewable energies (except for large hydro) in Pakistan is expected to reach 9700 MW by 2030, seeming achievable considering available potentials and financial and political commitments of the Government of Pakistani in this regard [46].

The above discussion reveals the high solar and wind energy potentials in Karachi and also the ever-increasing need of this megacity for a sustainable energy resource. Accordingly, Karachi was selected as the station investigated in this study.

Although the present work is a case study for Karachi, the new trigeneration system (electricity, heat, and hydrogen) with heat recovery and dump load, as well as the proposed method for analysis and calculation and how to compare the performance of different configurations, in any place of the world can be used.

3. Difficulties of Wind-Solar System Operation

One of the problems that producers and consumers of renewable energy face when installing solar cells or wind turbines is finding the right place [47, 48]. In the case of solar cells, the holder base must be such that it is not damaged by wind. Also, finding the optimal installation angle and cleaning dust from the panels are things that, if properly done, will lead to better solar cell performance [49]. Also, the installation of solar cells should be such that the ventilation

behind them is well done [49]. The issue of land prices is also an important issue for the installation site of the solar power plant [50]. Regarding the installation and operation of wind turbines, how to install wind turbines at height is one of the problems. In addition, maintenance is difficult due to the lack of easy access to rotating equipment of wind turbine. Noise pollution and bird damage are also problems that wind turbine users face [51]. Finding the dominant direction of the wind is another problem and exploitation problems [52, 53].

4. Simulation

4.1. HOMER Software. HOMER developed by the US National Renewable Energy Laboratory (NREL) facilitates the design of off-grid and on-grid systems. The software can be used for simulation, optimization, and sensitivity analysis of energy systems. The result of the analysis is the economic ranking from the minimum to the maximum total net present cost (NPC). HOMER is also used for technical and environmental analysis of systems [54].

The following equation is used in the software to calculate the output power of photovoltaic cells [55]:

$$P_{pv} = Y_{pv} f_{pv} \left(\frac{\overline{G_T}}{\overline{G_{T,STC}}} \right), \quad (1)$$

where Y_{pv} represents the output power of the solar cells under standard conditions in terms of kW, f_{pv} is the derating factor, $\overline{G_T}$ is the monthly solar irradiation incident on the

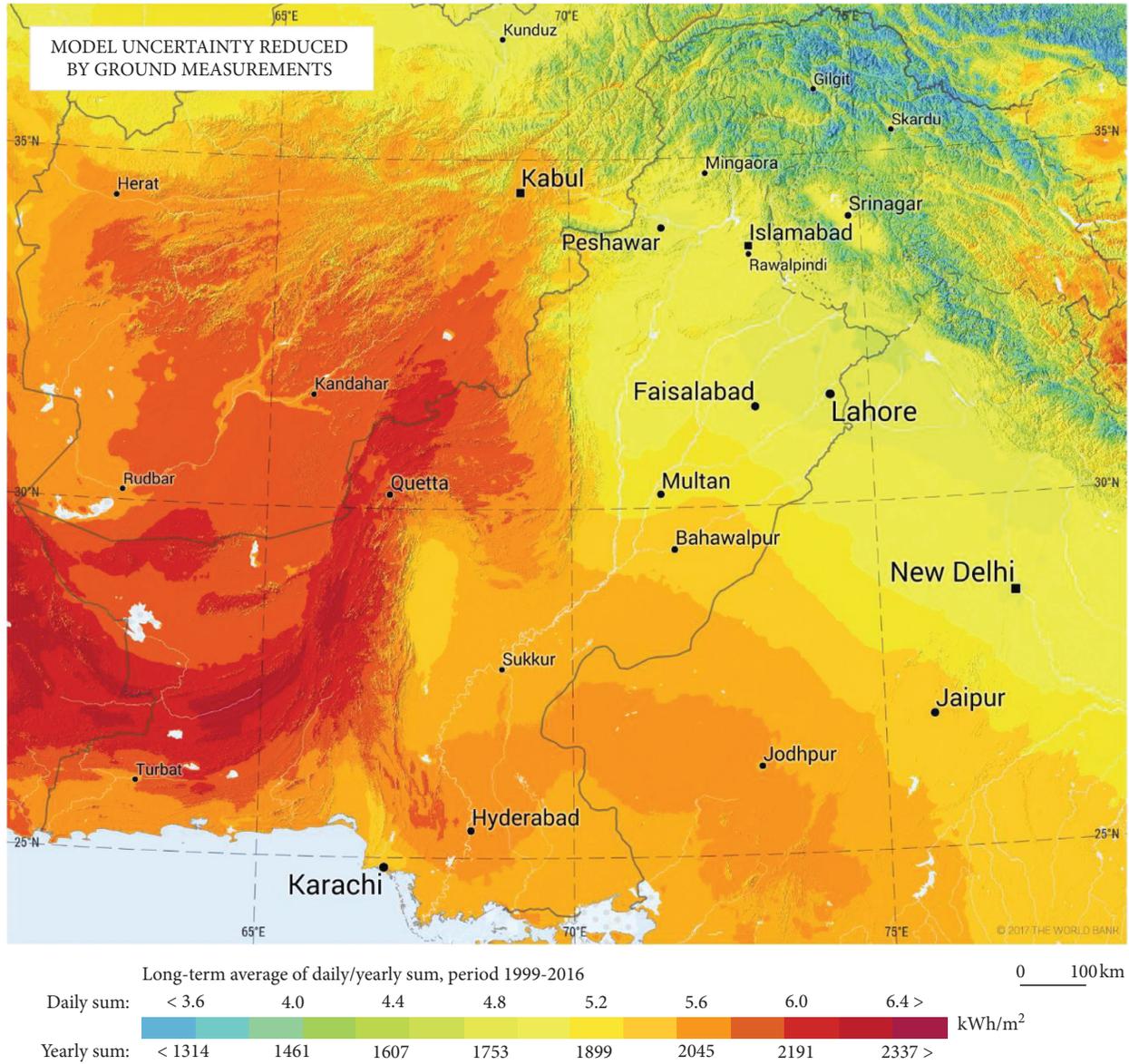


FIGURE 4: Atlas of solar radiation in Pakistan [19].

cell surface in terms of kW/m^2 , and $\overline{G_{T,STC}}$ is the solar irradiation incident on the cell surface under standard conditions in terms of 1 kW/m^2 .

Using the power curve and the wind speed at the hub elevation, the output power of wind turbines is calculated as follows [56]:

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

where ρ represents the actual density of air in terms of kg/m^3 , ρ_0 is the air density at standard temperature, and pressure ($\rho_0 = 1.225$) and $P_{WTG,STP}$ are the output power of wind turbines at standard temperature and pressure.

In each time step, the software calculates the maximum power received by the battery. The maximum power in each time step differs depending on the current state of charge of

the battery, discharge history, etc. The software applies three constraints on the maximum charging power of the battery. $P_{\text{batt.cmax.kbm}}$ represents the kinetic battery model, $P_{\text{batt.cmax.mcr}}$ is the maximum charge rate of the battery, and $P_{\text{batt.cmax.mcc}}$ is the maximum charge current. According to (3), the maximum power is considered the minimum of these values [57].

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

where $\eta_{\text{batt.c}}$ is the charging efficiency of the battery.

By entering the fuel curve for the fuel cell, the software plots the corresponding efficiency curve. Equation (4) represents the electrical efficiency of the fuel cell [58].

TABLE 1: Recent studies on renewable energies in Pakistan.

Ref., year	Station	Load type	Method	Studied parameter	Connection type	Optimum configuration	Sensitivity analysis	Dump load	Emission penalty
[30], 2017	Layyah	Electricity	HOMER	Total NPC	Off-grid	PV cell-biogas generator-battery	No	No	No
[31], 2018	Gujranwala	Electricity	HOMER	Total NPC	Off-grid	PV cell-fuel cell-diesel generator-battery	No	No	No
[32], 2018	Chakwal	Electricity	HOMER	Total NPC	On-grid	PV cell-wind turbine-biogas generator	No	No	No
[33], 2018	Four selected sites	Electricity	Analytical	Hydrogen cost	Off-grid	Wind turbine	No	No	No
[34], 2018	Punjab	Electricity	HOMER	Total NPC	Off-grid	Hydroturbine-PV cell-wind turbine-diesel generator	No	No	No
[1], 2019	Bhimber	Electricity	HOMER	Total NPC	On-grid off-grid	PV cell-diesel generator PV-Battery	No	No	No
[35], 2019	Mohmand	Electricity	HOMER	Total NPC	Off-grid	PV cell-wind turbine	No	No	No
[36], 2019	Quetta	Electricity	HOMER-MATLAB	Total NPC	Off-grid	Wind turbine-battery	No	No	No
[37], 2019	Faisalabad	Electricity	HOMER	Total NPC	Off-grid	PV cell-battery	No	No	No
[38], 2019	Larkana	Electricity	HOMER	Total NPC-Emission analysis	On-grid	PV cell-battery	No	No	No
[39], 2020	Faisalabad	Electricity, heat	HOMER	Total NPC-Emission analysis	Off-grid	PV cell-wind turbine-biogas generator-diesel generator	Yes	No	No
[40], 2020	Sindh	Electricity	HOMER	Total NPC	On-grid off-grid	PV cell-wind turbine-grid	No	No	No
Present work	Karachi	Electricity, heat and hydrogen	HOMER	Hydrogen cost, total NPC-emission analysis	Off-grid	PV cell-wind turbine-fuel cell-battery	Yes	Yes	Yes

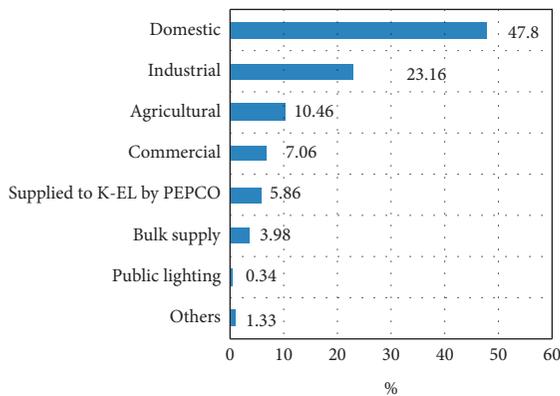


FIGURE 5: Electric power consumption in different sectors in Pakistan from 2017 to 2018 [8].

$$\eta_{FC} = \frac{3.6 P_{FC}}{\dot{m}_{fuel} LHV_{fuel}}, \quad (4)$$

where P_{FC} represents the output power in terms of kW, LHV_{fuel} is the lower heating value of the fuel in terms of MJ/kg, and \dot{m}_{fuel} is the hourly fuel consumption by the fuel cell.

The inverter efficiency is the percentage of the DC power converted to the AC power by the inverter. The rectifier efficiency is defined as the percentage of the AC power converted to the DC power. Note that HOMER assumes constant inverter and rectifier efficiencies [59].

For modeling a system generating its required hydrogen through electrolysis of the surplus electricity, a hydrogen storage tank should be available to store the hydrogen consumed by the fuel cell. The autonomy of the hydrogen storage tank is defined as the ratio of the energy capacity of hydrogen in the tank to the electric charge [60]:

$$A_{htank} = \frac{Y_{htank} LHV_{H_2} (24 \text{ (h/d)})}{L_{prim.ave} (3.6 \text{ (MJ/kWh)})}, \quad (5)$$

where Y_{htank} represents the nominal capacity (rated capacity) of the hydrogen tank in terms of kg, LHV_{H_2} is the

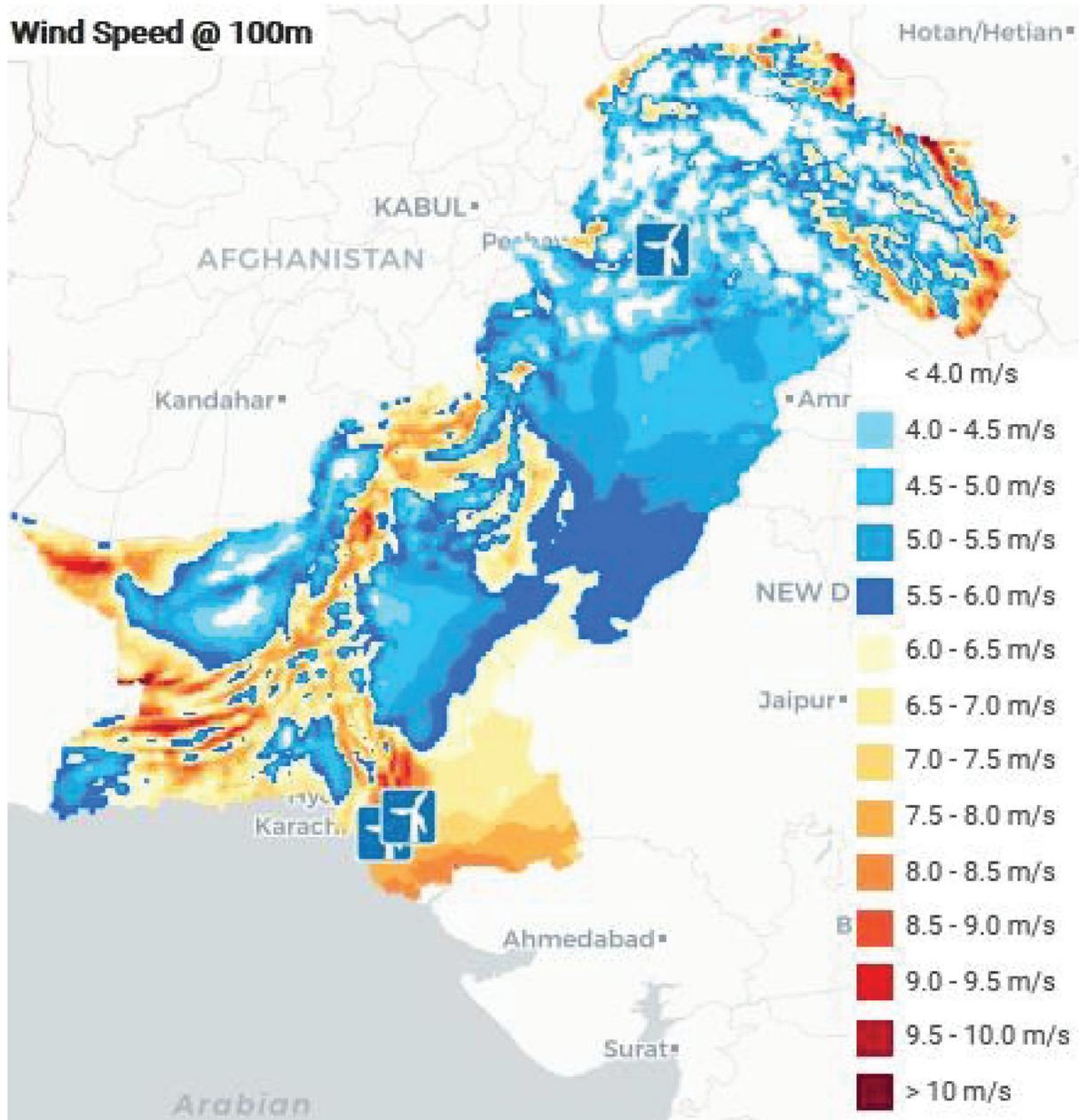


FIGURE 6: Location of large wind power plants in Pakistan [45].

lower heating value of hydrogen (120 MJ/kg), and $L_{\text{prim,ave}}$ is the average primary load in terms of kWh/day.

The electrolysis efficiency is defined as the rate of converting electricity into hydrogen, i.e., the energy content of hydrogen based on the higher heating value (HHV) divided by power consumption [61].

The following equation is used in HOMER to calculate the actual annual interest rate (i) from the nominal interest rate (i') [62]:

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

where f is the annual inflation rate. The software assumes an identical inflation rate for all costs. The total NPC is obtained

by dividing the total annual cost by the payback period factor, where the payback period factor is calculated as follows [63]:

$$\text{CRF} = \frac{i(1+i)^N}{(1+i)^N - 1}. \quad (7)$$

The levelized cost of energy (LCOE) per kWh of the generated power is obtained by dividing the total annual cost by the actual cost of the generated power [64]. The internal rate of return (IRR) is a criterion used in capital budgeting to evaluate the profitability of probable investments. The IRR is a discount rate leading to a zero net present value (NPV) for all cash flows obtained from a particular project and is calculated as follows [65]:

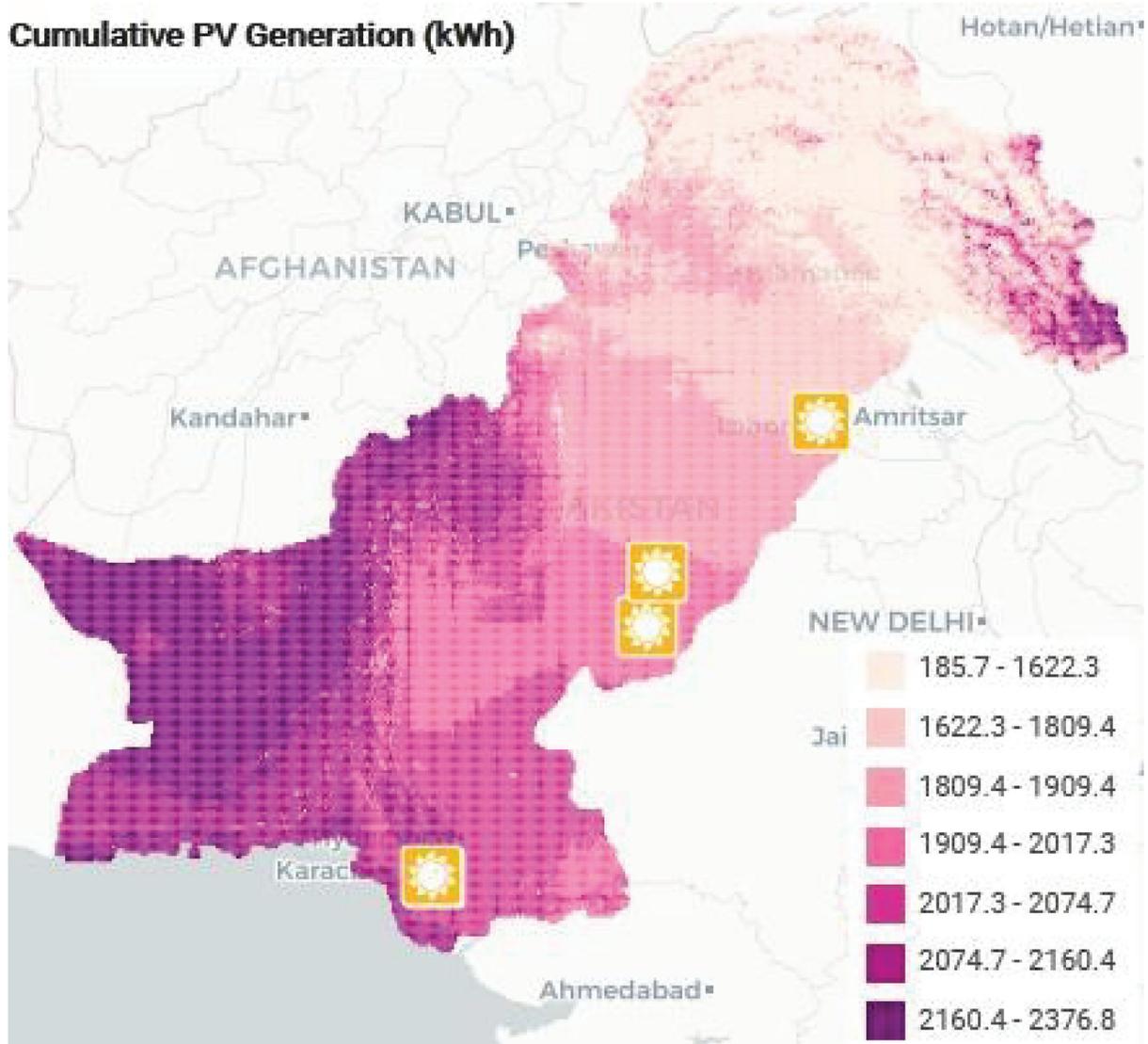


FIGURE 7: Location of large solar power plants in Pakistan [45].

$$C_0 = \sum_{t=1}^T \frac{C_t}{(1 + \text{IRR})^t} \quad (8)$$

where C_t is the net inflow in the study period, C_0 is the total initial investment costs, IRR is the internal rate of return, and t is the number of time steps. A project with a higher IRR is more profitable, and this parameter allows managers to rank projects based on the IRR rather than the NPV.

4.2. Required Data. Figure 8 schematically shows the understudy system. As seen, the most important input data to the software include required power and heat during a 24 h period as shown in Figures 9(a) [38] and 10(a) [66]. Random variables are used in the software to convert the daily data into annual data. These variables are expressed as hour-to-hour and time step-to-time step ones and were, respectively, considered 15% and 20% in this study. Applying the random

variables, Figures 9(b) and 10(b), respectively, show the electricity and heat required throughout the year.

As shown in Figure 8, a dump load is used in this study to convert the surplus electricity into heat. The dump load or the electric boiler is in fact a resistive heater capable of converting the surplus electricity into heat that cannot be stored in the battery.

The data on solar radiation and wind speed recorded at the understudy station should be used given the use of solar cells and the wind turbine. The average 20-year data were obtained from the NASA website [67] and, respectively, displayed in Figures 11(a) and 11(b). According to Figure 11, the average solar radiation and wind speed at the Karachi Station are 5.34 kWh/m²-day and 3.51 m/s, respectively.

Given the use of diesel in the boiler, a cost per liter of \$ 0.83 was considered in calculations [68]. To investigate the effect of CO₂ emission penalties on the total costs of the system, an emission penalty per ton of \$0, 50, 100, and 150 was considered in this study. Furthermore, an actual annual

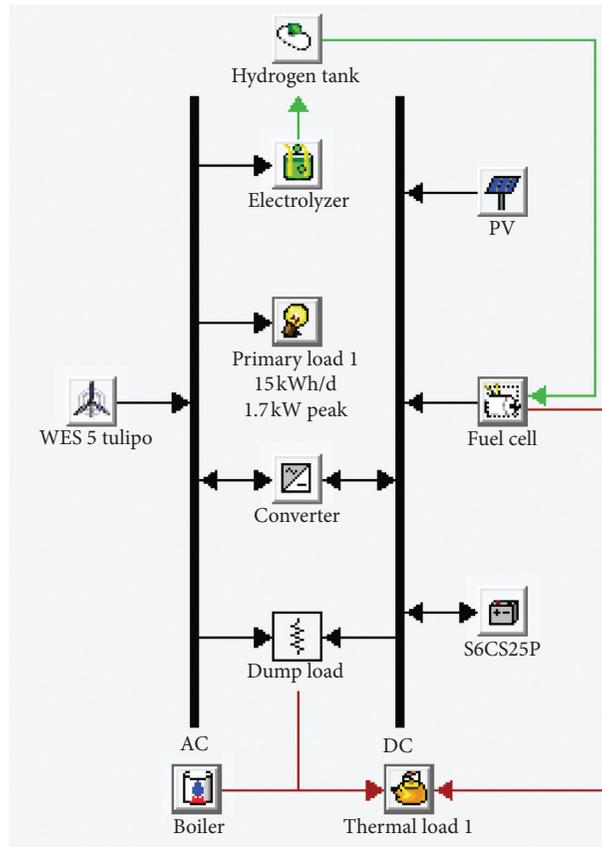


FIGURE 8: Schematic of understudy system.

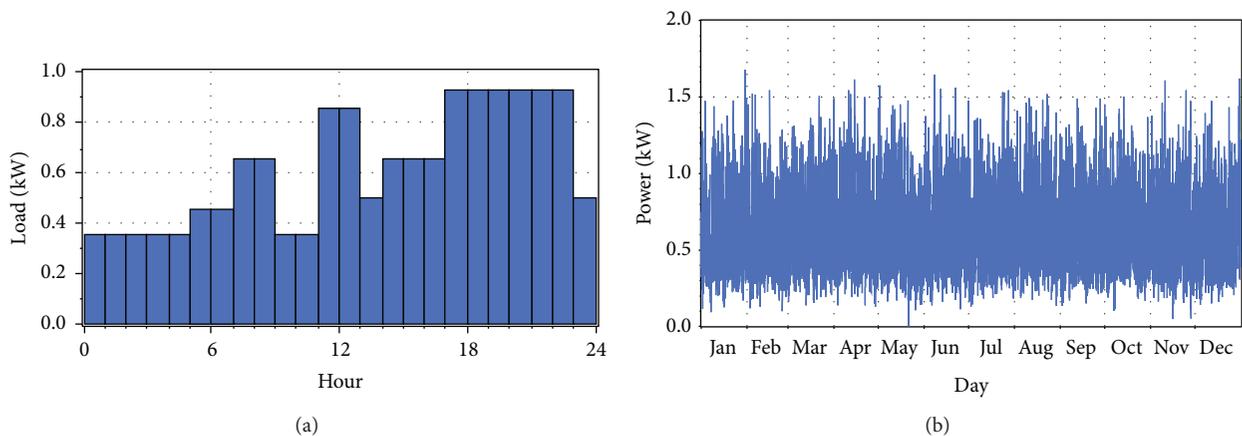


FIGURE 9: Electrical load. (a) Daily profile. (b) Yearly profile.

interest rate of 5, 10, 15, and 20% was considered. Table 2 summarizes the specifications and price of equipment used in the system.

5. Results

Table 3 presents the simulation results. As seen, with increasing the annual interest rate, the total NPC decreases whereas the LCOE increases. With increasing the emission penalties, the LCOE decreases, and the performance of the fuel cell and thus the diesel fuel consumption increase.

Moreover, at interest rates of 0 and 5%, the solar cells outperform the wind turbine in terms of energy production and the opposite is true at interest rates of 10 and 15%. With increasing the emission penalties, the fuel cell is further used and energy production by the fuel cell increases due to the use of the clean hydrogen fuel.

According to the results, the dump load converting the surplus electricity into heat plays a key role in supplying the required thermal energy. An increase in the annual interest rate causes an increase in the LCOE of the generated energy. Consequently, the surplus electricity is infeasible to be

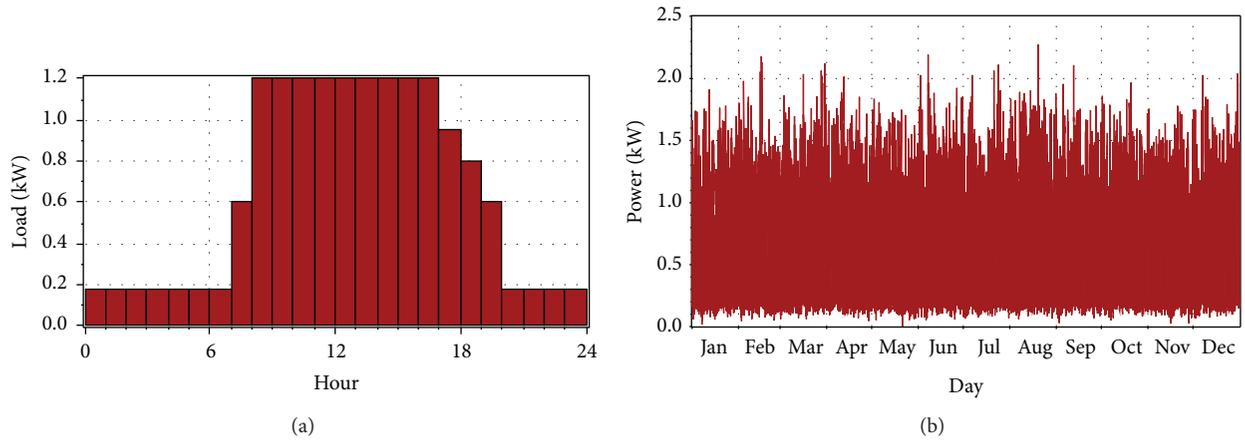


FIGURE 10: Thermal load. (a) Daily profile. (b) Yearly profile.

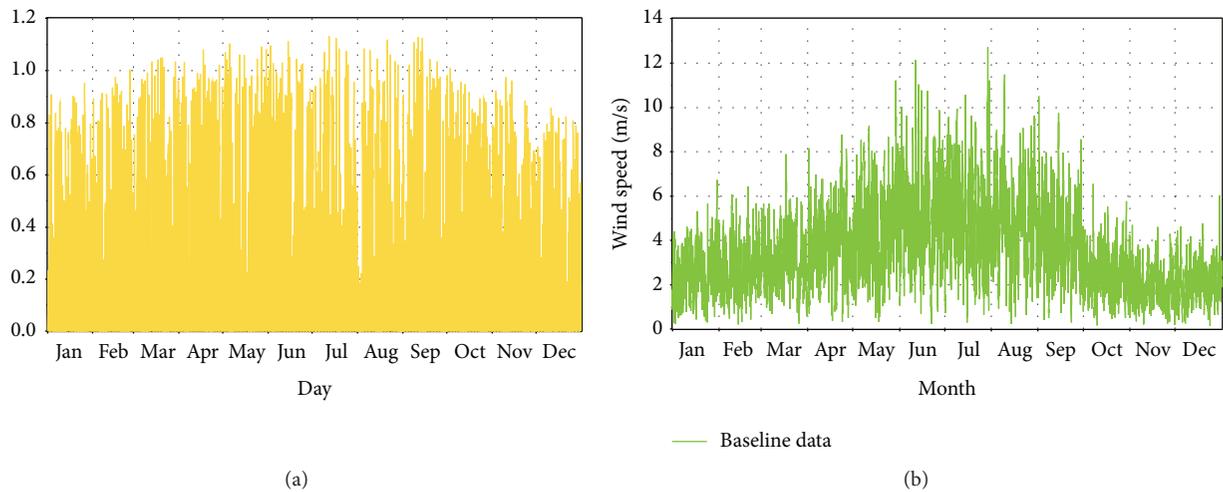


FIGURE 11: Yearly resources. (a) Global horizontal radiation. (b) Wind speed.

converted into heat by the dump load leading to a lower conversion rate of electricity to heat with increasing the annual interest rate.

The results indicate a negligible hydrogen production rate in different scenarios due to the high costs of electrolysis equipment and the hydrogen storage tank. The low energy production rate by the fuel cell is attributed to the high cost of the fuel cell. Given the negligible CO_2 emissions, the understudy region has a great potential to supply the required power and heat from renewable energies. Less energy is produced with an increase in the annual interest rate and thereby an increase in the cost of renewable energy equipment leading to more utilization of the boiler and further diesel fuel consumption. This in turn causes an increase in the CO_2 emissions.

It should also be mentioned that, with the increase in penalties for fossil fuel pollutants, the use of these fuels loses its priority. Therefore, the use of fuel cells and, consequently, hydrogen production will be preferred and more widespread. With rising inflation rate, the use of equipment to produce, store, and consume renewable electricity will be

less economical. The use of fossil fuels will be more cost-effective and, therefore, results in more pollution.

Figure 12 shows the results of the sensitivity analysis of the studied parameters regarding the most economically optimal system. As seen, the solar cell-wind turbine-fuel cell is cost-effective up to an annual interest rate of 8.5–9% for all emission penalties. The solar cell-wind turbine is, however, more cost-effective at higher interest rates. In a very small range in which the annual interest rate is about 20% and the emission penalties are close to 0, the solar cell-based system was identified by the software as the optimal system. It is also seen in Figure 12 that a greater priority is given to hydrogen production at annual interest rates less than 8.5–9%, and higher interest rates rank hydrogen production in the next places in terms of significance.

Figure 13 shows the total NPC for various annual interest rates and emission penalties. The results are consistent with those in Table 3. In other words, the total NPC increases with decreasing the annual interest rate and increasing emission penalties. Figure 13 is also helpful in calculating the LCOE of the generated energy and the total NPC at different

TABLE 2: Specifications and price of equipment.

Component	Cost (\$)			Specifications
	Capital	Replacement	Operation and maintenance	
PV [69]	2000	2000	10	Lifetime: 25 years Derating factor: 80% Slope: 24.15° Type: WES 5 Tulipo
Wind turbine [70]	5000	4000	50	Rated power: 2.5 kW AC Lifetime: 25 years Hub height: 25 m Cut-in speed: 2 m/s
Battery [70]	1200	1100	50	Type: Surrrette 6CS25P Lifetime: 9645 kWh
Converter [69]	300	300	0	Lifetime: 20 years Inverter efficiency: 95% Rectifier efficiency: 95%
Fuel cell [71]	3000	2500	0.02	Lifetime: 40000 h Min. load ratio: 25% Efficiency: 90%
Electrolyzer [71]	500	250	10	Heat recovery ratio: 25% Lifetime: 20 years Min. load ratio: 0%
Hydrogen tank [69]	574	574	10	Efficiency: 85% Lifetime: 25 years Initial tank level: 20%
Boiler [72]	—	—	—	Efficiency: 85% Carbon monoxide 6.5 g/L Unburned hydrocarbons 0.72 g/L Particulate matter 0.49 g/L Fuel sulfur converted to PM 2.2% Nitrogen oxides 58 g/L

TABLE 3: Technological-economic-environmental results of sensitivity analysis.

Interest rate (%)	CO ₂ penalty (\$/t)	Total NPC (\$)	LCOE (\$/kWh)	FC (hr)	Diesel (L)	Electrical production (kWh/y)			Excess electricity (%)	Thermal production (kWh/y)		Excess heat (%)	H ₂ production (kg/y)	CO ₂ emission (kg/y)
						PV	Wind turbine	FC		PV	Boiler			
5	0	44459	0.483	844	236	10121	8258	502	11729	104	1972	8148	27.9	621
	50	44892	0.473	840	236	10121	8258	504	11733	103	1974	8152	27.9	621
	100	45328	0.462	835	236	10121	8258	510	11735	103	1979	8159	28.1	623
	150	45761	0.451	830	237	10121	8258	512	11739	102	1982	8166	28	624
10	0	40233	0.722	844	236	10121	8258	502	11729	104	1972	8148	27.9	621
	50	40513	0.711	840	236	10121	8258	504	11733	103	1974	8152	27.9	621
	100	40378	0.691	988	338	6747	8258	600	8237	124	2827	5530	32.6	890
	150	40785	0.683	987	338	6747	8258	603	8239	123	2827	5533	32.6	890
15	0	37420	0.974	262	313	6747	8258	193	8849	29	2609	5830	9.99	821
	50	37691	0.965	269	313	6747	8258	203	8846	30	2611	5829	10.3	822
	100	37469	0.942	988	338	6747	8258	600	8237	124	2827	5530	32.6	890
	150	37758	0.934	987	338	6747	8258	603	8239	123	2827	5533	32.6	890
20	0	35738	1.242	262	313	6747	8258	193	8849	29	2609	5830	9.99	821
	50	35945	1.233	269	313	6747	8258	203	8846	30	2611	5829	10.3	822
	100	35795	1.211	998	338	6747	8258	600	8237	124	2827	5530	32.6	890
	150	36017	1.202	987	338	6747	8258	603	8239	123	2827	5533	32.6	890

annual interest rates of 5 to 20% and emission penalties of \$0 to 150 per ton of emissions. The same is true for Figure 12.

Given the actual annual interest rate of about 15% in Pakistan [73] and considering a reasonable price of \$50 per ton of carbon emissions [74], this scenario is studied in detail below.

Figure 14 shows the approximate current situation of Pakistan. As seen, the wind-solar hybrid system with an LCOE of \$0.923 is the most optimal system in which 86% of the generated power is supplied by renewable energies. The second optimal system only includes solar cells and shows a slight increase of about 1.2% in the LCOE, but the use of

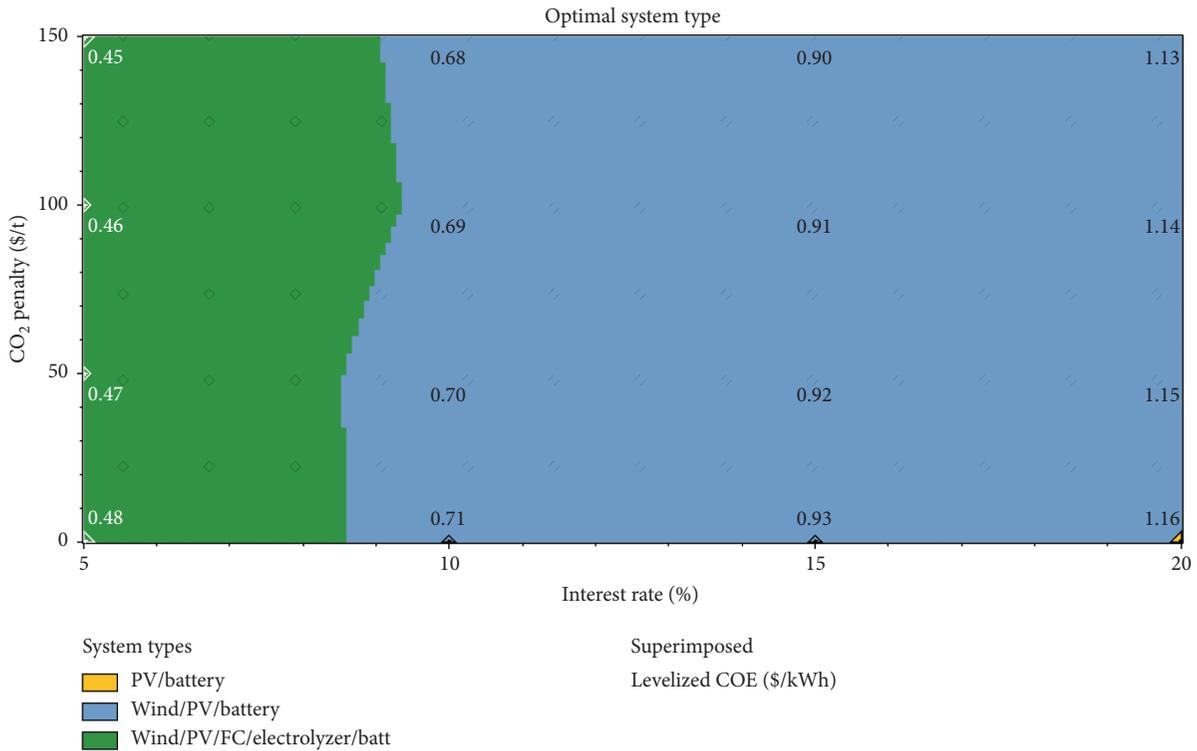


FIGURE 12: Graph of optimal system type.

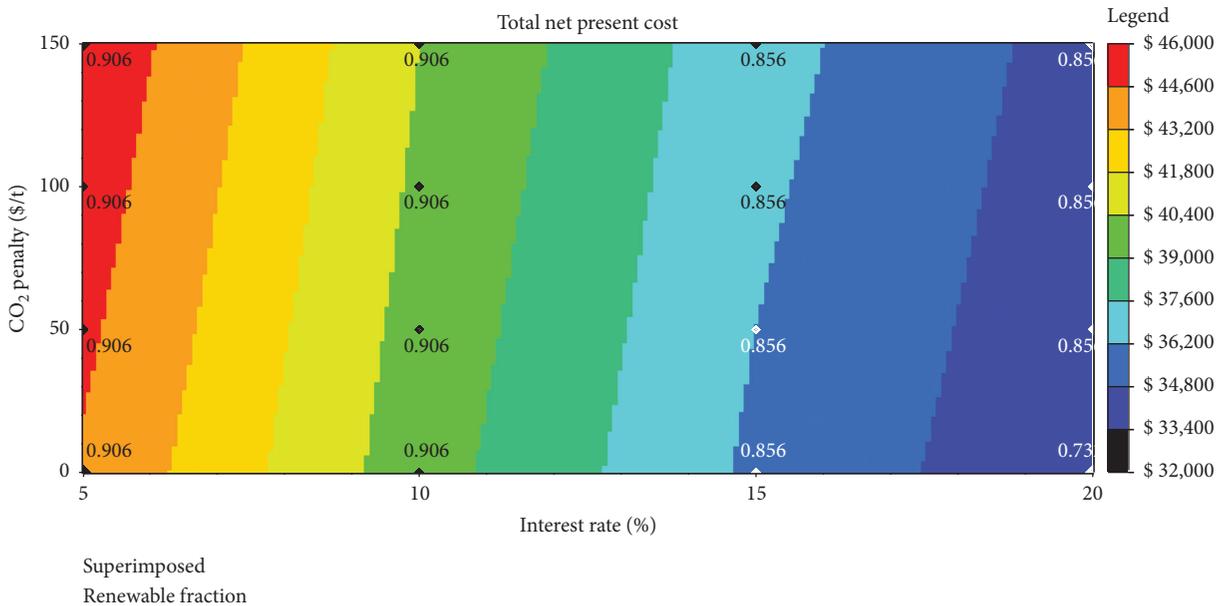


FIGURE 13: Surface plot of total NPC.

renewable energies is decreased by 13% in this system. As shown in Figure 14, hydrogen production by the fuel cell ranks third, and the results are consistent with those in Figure 12. Hydrogen production will increase the LCOE by 4.55% as compared to the most optimal system (the wind-solar hybrid system). The fourth system lacking batteries is not approved by renewable energy experts. The only advantage of the fourth system over the third one is the

production of more hydrogen leading to a 13.37% increase in the LCOE in comparison with the system in which the battery is used.

Since this study is aimed at cogenerating power, heat, and hydrogen, the third system in Figure 14 was further analyzed. Figure 15 shows the monthly power, heat, and hydrogen generation profiles for the solar cell-wind turbine-fuel cell-battery system.

Interest Rate (%) 15 CO2 Penalty (\$/t) 50

Double click on a system below for simulation results.

	PV (kW)	WES5	FC (kW)	S6CS25P	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Disp. Strgy	Initial Capital	Operating Cost (\$/yr)	Total NPC	COE (\$/kWh)	Ren. Frac.	Diesel (L)	FC (hrs)
	4	2		8	2			CC	\$ 28,200	1,237	\$ 36,194	0.923	0.86	301	
	6			12	2			CC	\$ 27,000	1,486	\$ 36,609	0.934	0.73	444	
	4	2	2	4	2	2	2	LF	\$ 31,548	950	\$ 37,691	0.965	0.85	313	269
	6	2	2		4	4	6	CC	\$ 34,644	1,158	\$ 42,133	1.094	0.89	333	4,254

FIGURE 14: Results of simulation for 15% real interest rate and \$50/t emission penalty.

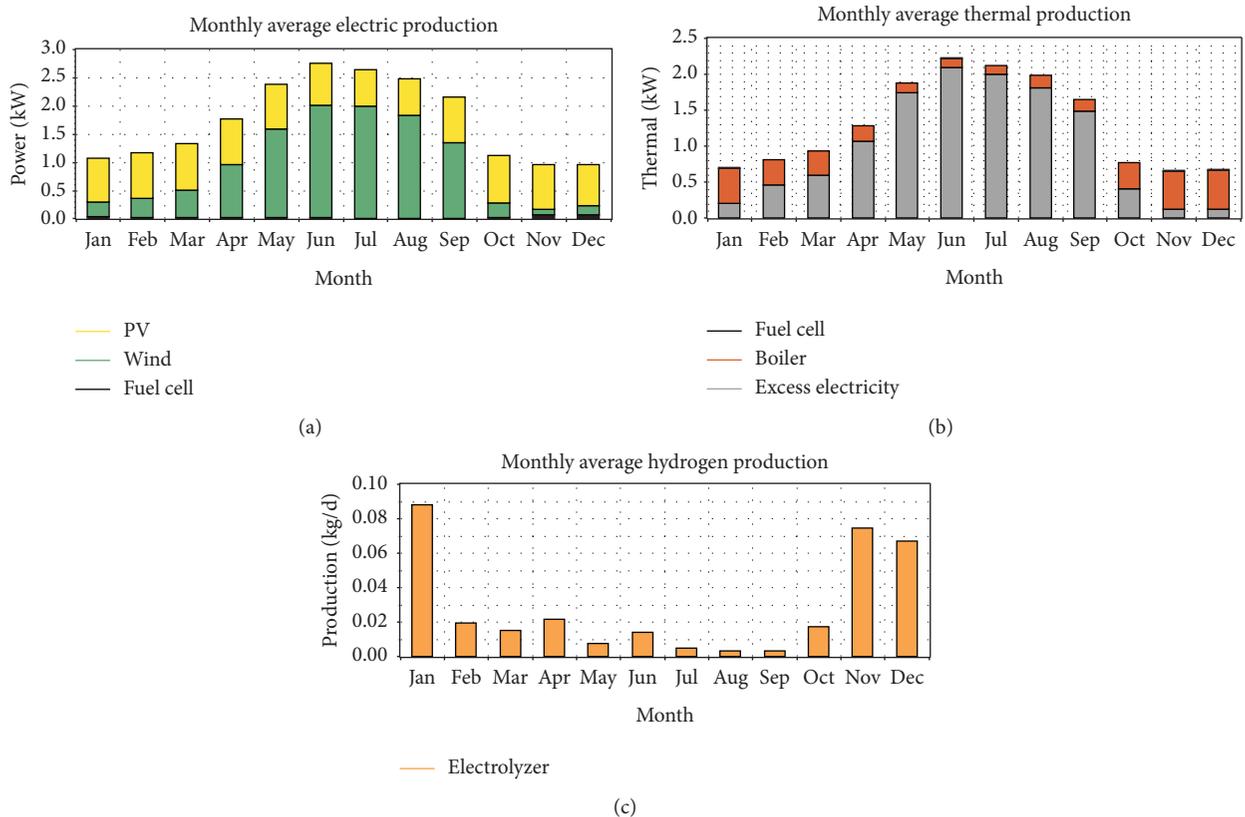


FIGURE 15: Monthly average production. (a) Electricity. (b) Thermal energy. (c) Hydrogen.

According to the electric power profile, the wind turbine, and solar cells each play a dominant role in power generation in six months. The electric power generation by fuel cell is visible in January, November, and December. As seen in the heat profile, the boiler plays a major role in heat supply in January, November, and December when the electric power generation is low, whereas the dump load plays a major role in this regard in other months by converting the surplus electricity into heat. According to the hydrogen generation profile, a maximum hydrogen generation of about 0.09 kg/day is observed in January, and the minimum hydrogen generation is seen in August and September.

The notable point implicitly drawn from the results in Figure 15 is that about 8846 kWh surplus electricity is generated annually, which is 58.2% higher than the required electric power. Moreover, 5829 kWh surplus heat is generated, 103% more than the required thermal energy. The costs can be significantly reduced by selling the surplus electricity and heat to the national grid or neighbors.

According to Figure 14, despite the higher total NPC, the operating cost of the solar cell–wind turbine–fuel cell–battery system is lower than other systems. To evaluate the payback period, the fuel cell–battery-based system was considered as the base system and compared with other systems during the project lifetime (25 years). The results are presented in Figure 16.

Comparing the base system with the wind turbine-solar cell system, the internal rate of return (IRR) equals 9.39% with a payback period of 11.4 years. In other words, after 11.4 years, the base system will economically outperform the wind turbine-solar cell system. The internal rate of return and the payback period for the base system in comparison with the solar cell only system are 11.7% and 11 years, respectively. The difference in payback period for an optimal system (base system) compared to solar cell only and wind turbine-solar cell system systems is due to the different prices of equipment purchase, operating and maintenance, and operation of these systems.

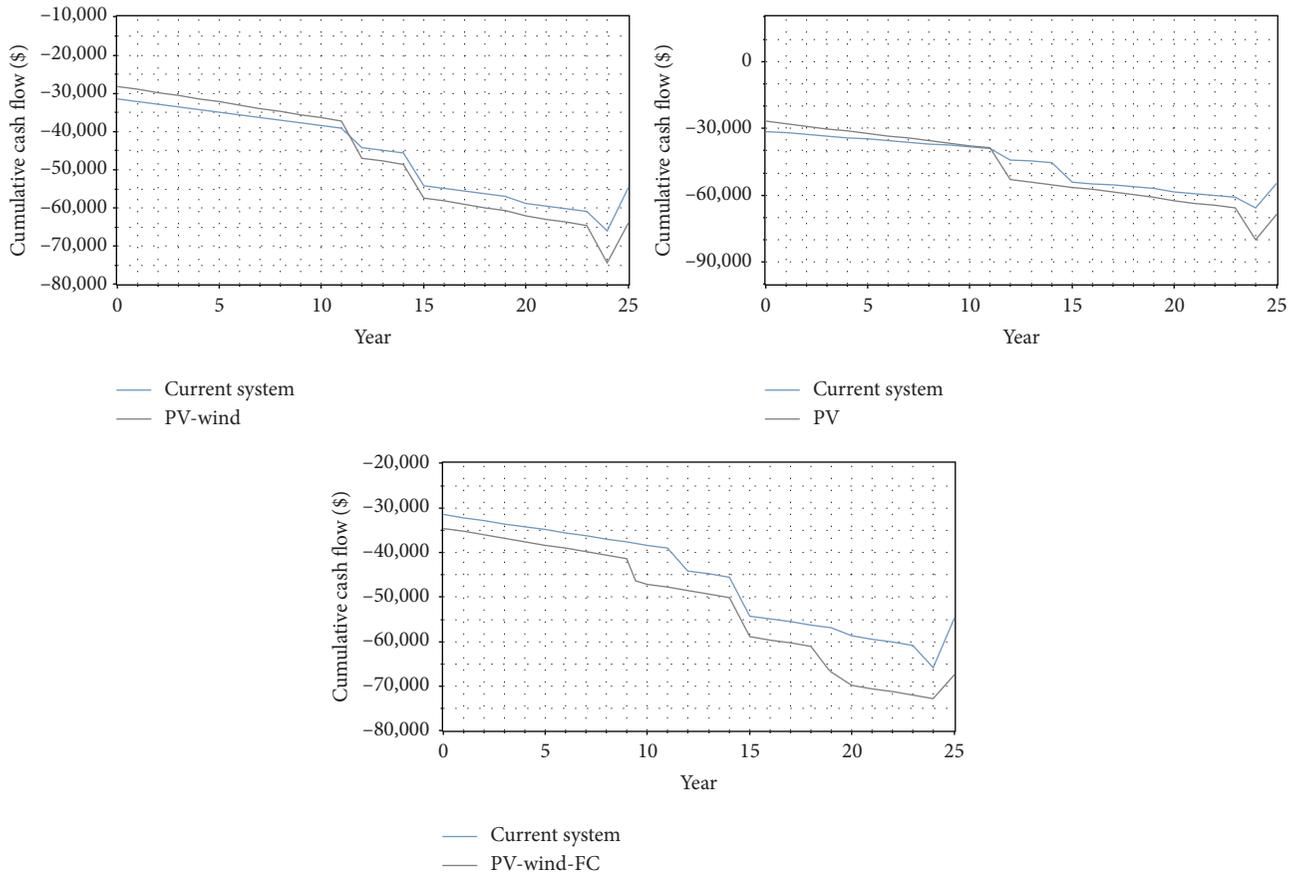


FIGURE 16: Current system compared to base case.

Comparing the base system with the system including the fuel cell without a battery, it can be seen that there are no payback period and internal rate of return and the base system outperforms other systems throughout the 25-year lifetime of the project. This highlights the need for the use of a battery as a backup.

6. Conclusion

About 51 million Pakistanis do not have access to Pakistan's national grid, and more than 144 million people do have unreliable access to the national grid [75]. Therefore, the Government of Pakistan is aware of the necessity for improving the current energy situation through policies and renewable energy projects. Considering undeveloped renewable energies in Pakistan, there is a serious need for the use of distributed generation systems based on renewable energies. Accordingly, for the first time in this study, cogeneration of power, heat, and hydrogen in a residential building in Karachi was investigated using the average 20-year data on wind speed and solar radiation extracted from the NASA website and updated costs of renewable energy equipment and fossil fuels. Given the variable annual interest rate and to study the effect of emission penalties on the LCOE of the generated energy and hydrogen, a sensitivity analysis was performed on these parameters. For the first

time, the surplus renewable electric power was converted into heat. The main results are summarized below:

- (i) The total NPC decreased but the LCOE increased with increasing the annual interest rate
- (ii) The LCOE and utilization of fuel cells increased with increasing the emission penalties
- (iii) Solar energy outperformed wind energy at interest rates less than 10%
- (iv) The dump load plays a significant role in supplying the required heat
- (v) There is a low potential for generating renewable hydrogen in Karachi
- (vi) There is a high potential for cogeneration of renewable power and heat in Karachi
- (vii) Hydrogen generation ranked first economically at interest rates less than 9%
- (viii) The solar cell-battery system ranked first at interest rates above 20% and emission penalties of zero
- (ix) The surplus renewable electricity and renewable heat in Karachi were, respectively, 85.2% and 103%
- (x) The most optimal system for hydrogen generation relative to the wind-solar and solar-only systems, respectively, showed a payback period of 11.4 and 11 years

Data Availability

All data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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