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Effect of PV technology, solar tracker and electrolyzer type on electricity and hydrogen production in provincial centers of Pakistan: Finding the optimal angle and azimuth considering losses

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Abstract

Today, solar hydrogen has been proposed as a viable alternative to current fossil fuels in Pakistan. Therefore, in this work, for the first time, solar hydrogen production has been investigated in 6 centers of Pakistani province. PVGIS 5.2 software was used for simulation and different solar cell technologies were investigated. Considering the solar tracker in 3 modes: horizontal single-axis, vertical single-axis and two-axis, and considering the losses makes the results more comprehensive. The use of 4 different types of electrolyzers to produce hydrogen is another innovation of the present work. By performing sensitivity analysis, the optimal mounting angle and the optimal azimuth angle for the investigated station were found. The results showed that the optimal angle is between 28° to 32°, and the optimal azimuth is between -17o to 4o for the investigated stations. For the Gilgit and Peshawar stations, CIS technology is the most suitable, and CdTe technology is the most suitable for the Quetta, Islamabad, Lahore and Karachi stations. Also, the vertical axis tracker is superior to the horizontal axis only in the Gilgit station, and the horizontal axis tracker is more suitable in the rest of the stations. Out of the 4 investigated electrolyzers, the SOE electrolyzer produces more hydrogen.

Keywords: Electrolyzer; SARAH database; Solar hydrogen; Solar tracker

Introduction

The energy efficiency of solar cells depends on many factors, the most important of which is the amount of radiant energy to the solar panel [1]. Another important parameter affecting the power of a solar cell is its technology type [2].

The three common types of solar cell technology are thin film modules (CIS), thin film modules made from cadmium telluride (CdTe), and crystalline silicon (c-Si) [3]. Considering that each of these types of technologies is related to the geographical location of the place under investigation, if a solar cell is moved from one climate to another climate, it is expected to perform differently [4].

One of the solutions used to increase the output power of solar cells is to use solar trackers [5] which are vertical, inclined, and two axes. Each solar tracker has a different performance according to the effect of the ambient temperature on the performance of the solar cell in each climate [6].

The nominal power of the solar cell is different from its output power, which is the reason for this problem of energy loss. The main losses are thermal losses, reflection losses, wiring losses, losses due to dust and losses due to life span, etc. [7]. In the examination of the accurate estimation of the power produced by solar cells, the number of losses should be taken into account in the calculations.

One of the problems faced by renewable electricity generation systems is the long-term storage of generated electricity [8]. Experts have stated that one of the sure ways of long-term storage of renewable electricity is hydrogen production [9, 10]. The most common renewable hydrogen production technology is water electrolysis [11]. For water electrolysis, an electrolyzer is needed, and the 4 common types of electrolyzers are AE, PEME, SOE, MCE [12].

According to the mentioned cases, the recent studies in the field of solar technology, solar electricity production losses, solar trackers and hydrogen production have been reviewed.

Atsu et al. (2021) [13] analyzed the performance of three different grid-connected solar cell technologies in Hungary. The installed system has a capacity of 9.6 kW and DS2 (a-Si), ASE (pc-Si) and DSI (a-Si) technologies were used. The results of using the PVSyst software showed that the annual production energy of the above technologies is 2468 kWh, 2609 kWh and 3762 kWh, respectively.

Touili et al. (2022) [14] have evaluated the production of hydrogen by electrolysis using three technologies: monocrystalline, polycrystalline, and amorphous. The investigated location was Morocco, and the investigated climate was dry. The results showed that per kW, P-Si technology is more suitable with about 37 kg of hydrogen per year than the other two types. Also, the price of each kg of hydrogen in the cheapest state is $34.89.

Kumar et al. (2021) [15] investigated yield and loss ratios for Bikaner College in India using PVSyst software. The results showed that 98.3% of the required electricity is provided by solar cells, which was 75.48 kWh. Also, the average annual performance factor was 72.8%.

Baqir and Channi (2022) [16] investigated the amount of 670 MW of imported electricity in Afghanistan, the reason for this was that the Afghan government plans to produce 1500 MW of solar electricity by 2032. The place under investigation was Daykundi province. The results showed that 700 kW solar cells in the state connected to the grid produce 1266 MWh of electricity annually. The annual performance coefficient was 0.797.

Nishiyama et al. (2021) [17] investigated solar hydrogen production from water electrolysis on a scale of 100 m^2. The method they investigated was a photocatalyst. The results showed that this method is safe and scalable. However, to be economically viable, reactor optimization, photocatalyst stability, etc. should be done.

Astakhov et al. (2021) [18] investigated the role of batteries as storage for photovoltaic-electrochemical devices for hydrogen production. The reason for using batteries was that photovoltaic cells did not produce electricity continuously. The results showed that the battery plays a very effective role and increases the efficiency of hydrogen production by 5-10%. Especially because there is no sunlight at night.

Jahangiri et al. (2022) [19] used the TOPSIS method to investigate the effect of photovoltaic cell losses and the effect of solar trackers to produce electricity and solar hydrogen. They used PVSyst and Meteonorm software. The results showed that Zahedan has the highest production of hydrogen with an annual production of 671.5 kg of solar hydrogen, which the one-axis and two-axis trackers increase by 30.6% and 34.3%. Of course, the TOPSIS method showed that the Yasuj station is the most suitable.

Mostafaeipour et al. (2022) [20] investigated the effect of solar trackers on hydrogen production in Iran. They used the HOMER software and examined 4 different scenarios without a tracker, with a horizontal axis tracker, with a vertical axis tracker and with a dual axis tracker. In the grid-connected state, the vertical axis tracker is the most appropriate and economic scenario with a price of $0.223 per kWh of electricity and $29.33 per kg of hydrogen produced.

According to the investigations, until now, finding a suitable station in the field of solar hydrogen production connected to the national power grid mode has not been done in Pakistan. Also, finding the optimal installation angles and azimuth, investigating the effect of using different solar trackers, considering the losses in solar electricity production, and also finding the best solar cell technology are some of the tasks that have been done sporadically in previous works. In the present work, a comprehensive survey has been done on the centers of the Pakistani provinces using PVGIS 5.2 commercial software, and the potential of each station has been obtained by considering all the variables mentioned above. The purpose of the present work is to provide a road map to energy decision-makers and investors in Pakistan.

Location under study

The selected locations are the centers of the provinces of Pakistan, their geographic, population, and area characteristics are given in Table 1 [21]. As can be seen from Figure 1 [22], Quetta station has the highest amount of radiation and Gilgit station has the lowest amount of radiation. In other words, by moving from north to south, the radiation potential increases greatly. In this country, the 17-year average radiation shows that the average daily radiation during the year is between 3.6 and 6.4 kWh/m^2.

Table 1: Geographical and population information of the investigated stations

Station	Latitude	Longitude	Elevation	Population
Quetta	30.11 N	67 E	1680	1001205
Gilgit	35.55 N	74.18 E	1463	216000
Islamabad	33.41 N	73.03 E	555	1900000
Peshawar	34 N	71.34 E	331	1970042
Lahore	31.32 N	74.20 E	217	10000000
Karachi	24.51N	67.0 E	8	14910352

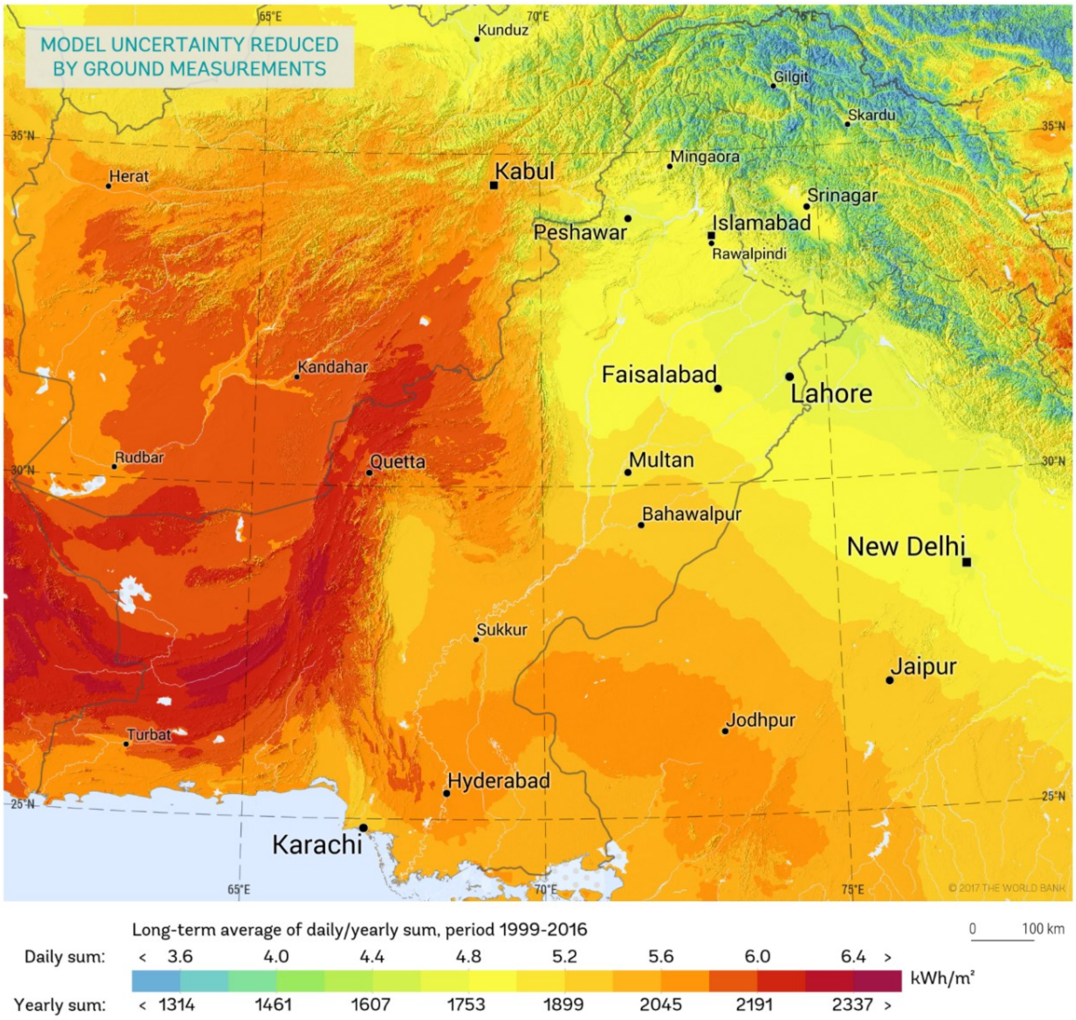

Figure 1: Solar potential map of Pakistan

Governing equation

In the present work, the PVGIS-SARAH database was used for solar radiation data with hourly time scale, which was generated from the CM SAF algorithm, and its time range is 2005-2016 [23].

PVGIS calculates the power of the solar cell by considering the temperature of the module (Tm) and the radiation reaching the surface of the module (G) using the following equations [24]:

$$P = \frac{G}{1000} \times A \times \eta_{(G,T_m)} = \frac{G}{1000} \times A \times \eta_{norm} \times \eta_{rel\,(G,T_m)} \quad (1)$$

$$\eta_{rel\,(\acute{G},\acute{T}_m)} = 1 + k_1 \ln(\acute{G}) + k_2 \ln(\acute{G})^2 + k_3\, \acute{T}_m + k_4\, \acute{T}_m \ln(\acute{G}) + k_5 \acute{T}_m \ln(\acute{G})^2 + k_6\, \acute{T}_m{}^2 \quad (2)$$

$$\acute{G} = \frac{G}{1000}\ , \quad \acute{T}_m = T_m - 25 \quad (3)$$

The coefficients k_1 to k_6 are different for each PV technology and are obtained experimentally and are presented in Table 1 Appendix [25].

Due to the solar radiation on the surface of the PV modules, their temperature increases. In other words, the temperature of the modules depends on both the air temperature and the radiation. Additionally, wind may help cool the modules. Therefore, the temperature of the Tm module is calculated in the PVGIS software using the following equation [26]:

$$T_m = T_a + \frac{G}{U_0 + U_1 W} \quad (4)$$

where T_a is the air temperature and W is the wind speed. U_0 and U_1 coefficients used in PVGIS software are given in Table 2 [27].

Table 2: Coefficients of module surface temperature calculation

Module technology	Installation	u_o W/(°C.m^2)	u_1 W.s/(°C.m^3)
c-Si	Free-standing	26.9	6.2
	BIPV/BAPV	20.0	3.2
CIS	Free-standing	22.64	3.6
	BIPV/BAPV	20.0	2.0
CdTe	Free-standing	23.37	5.44
	BIPV/BAPV	20.0	3.2

Now, with the power produced by the solar cell, the amount of hydrogen produced can be obtained from equation 5 [28].

$$M_{H_2} = \frac{P_{PV} \times \eta_{ele}}{HHV_{H_2}} \quad (5)$$

Based on equation 5, to calculate the amount of hydrogen produced, the parameters of electrolysis efficiency and the high heating value (HHV) of the produced hydrogen are needed, which are given in Table 3 [29] of the specifications of the 4 types of electrolysis used.

Table 3: Various electrolyzer technologies for hydrogen production

Electrolyzer type	Temperature (°C)	Energy consumption (kWh/kg H_2)	Efficiency
AE cell	60-80	53.4-70.1	56-73
PEME cell	50-80	54.2-90.3	48-65
SOE cell	600-900	26.9	90
MCE cell	600-700	37.8	90

It should be noted that the rated power of the investigated solar power plant is 20 kW, the system losses are equal to 15% and the optimal azimuth angle was determined by the PVGIS 5.2 software. Also, the losses included in the calculations include radiation angle losses, spectral effects losses, and temperature losses.

Figure 2 shows the schematic of the investigated system. As it is known, the system is connected to the national electricity grid and the generated electricity after passing through the electrical converter, is decomposed by the electrolyzer into oxygen and hydrogen. The produced hydrogen is also stored in the hydrogen storage tank.

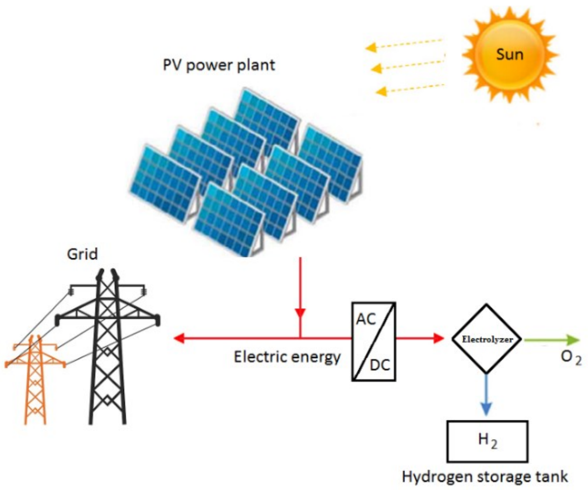

Figure 2: Schematic of system under study

Results

The simulation results are given in Table 4. From the results, the lowest optimal angle is related to Karachi with 28 degrees and the highest is related to Islamabad and Peshawar with 33 degrees. Regarding the optimal azimuth angle, the highest angle of 4 degrees is related to Karachi and the lowest angle of -17 is related to Gilgit. The results of the analysis of the impact of the type of solar cell technology on the amount of electricity production show that the most suitable technology depends on the city under investigation. In the cities of Gilgit and Peshawar, CIS technology produces the most electricity, and in other investigated stations, CdTe technology produces the most electricity. Another point that can be seen in Table 4 is that most electricity produced in the state without using the solar tracker with the amount of 38895.6 kWh/year is related to the Peshawar station. Another important point that can be evaluated is the number of losses of the solar system, which are the lowest related to the Karachi station. In addition, from the results, for each type of technology, the maximum loss is related to one station, which is because the amount of loss is dependent on climatic conditions such as air temperature, wind speed, air humidity, radiation intensity and the angle of the radiation hitting the surface of the solar cell. This issue is also true for the mode of using solar trackers (Table 5). In general, based on the results, it can be said that the Peshawar station ranks first in terms of losses. The statistical analysis of the data shows that comparing the average losses of different solar cell technologies, CdTe has the lowest losses with 23.15%. In total, the most produced electricity with the amount of about 195 MWh/year is related to CdTe technology for the 6 investigated stations.

Table 4: Effect of PV technologies on electricity generation

Station	Optimum azimuth	Optimum angle	PV technologies					
			CdTe		CIS		c-Si	
			Losses (%)	Electricity generation (kWh/year)	Losses (%)	Electricity generation (kWh/year)	Losses (%)	Electricity generation (kWh/year)
Quetta	30	-3	23.7	36330.1	24.9	35747	25.26	35579.6
Gilgit	31	-17	23.3	24382.7	20.49	25278.3	20.75	25195.8
Islamabad	33	1	23.35	32005.8	26.47	30702.9	26.1	30866.5
Peshawar	33	-4	27.4	31011.6	24.2	32385.7	27.16	31109
Lahore	32	0	22.9	32212.9	27.3	30347.8	26.78	30581
Karachi	28	4	18.22	38895.6	20.14	37980.9	18.9	38574.8

Regarding the comparison of the vertical axis tracker with the horizontal axis tracker in Table 5, the results show that only in the Gilgit station, the vertical axis tracker is superior to the horizontal axis tracker. In other investigated stations, the horizontal axis tracker is superior to the vertical axis tracker. Also, as expected, the two-axis tracker produces the most electricity because its rotation is such that the radiation is always perpendicular to its surface. The results point out that the lowest average loss of 21.68% is related to the horizontal axis tracker. The most produced electricity is related to the two-axis tracker, which is 253 MWh/year in the 6 investigated stations.

Table 5: Effect of PV tracking type on electricity generation

Station	PV tracking type					
	Two-axis		Horizontal		Vertical	
	Losses (%)	Electricity generation (kWh/year)	Losses (%)	Electricity generation (kWh/year)	Losses (%)	Electricity generation (kWh/year)
Quetta	22.98	48955.7	22.78	47403	22.8	47166
Gilgit	23.1	27641.7	22.8	27103.3	27.8	27222.8
Islamabad	22.5	41825	22.3	40520	22.41	40442.2
Peshawar	23.16	42442.4	23	41110.7	23.1	41033.3
Lahore	21.9	41117.2	21.8	39881.3	21.9	39833.1
Karachi	17.6	50892.6	17.4	49294.8	17.5	48985.4

Table 6 shows the maximum amount of hydrogen produced for 4 common types of electrolysis for the investigated stations. The maximum amount of hydrogen produced is if a two-axis tracker is used. From the results, SOE has the most hydrogen production due to its high efficiency and low HHV. The lowest hydrogen production is related to the PEME electrolyzer. According to the mentioned cases, the highest hydrogen production with the amount of 1702.7 kg/year was related to the Karachi station and SOE electrolyzer. The total amount of hydrogen produced for MCE, SOE, PEME, and AE electrolysis in the 6 investigated stations is 6, 8.5, about 2, and 2.6 tons/year, respectively.

Table 6: Effect of Electrolyzer type on maximum hydrogen generation

Station	Electrolyzer type			
	MCE	SOE	PEME	AE
Quetta	1165	1637	382	511
Gilgit	658.1	924.8	216.7	288.7
Islamabad	995.8	1399.3	327	436.8
Peshawar	1010.5	1420	331.9	443.3
Lahore	978.9	1375.6	321.5	429.4
Karachi	1211.7	1702.7	397.9	531.5

Conclusions

Hydrogen can help solve Pakistan's energy crisis by replacing fossil fuels considering political, financial and environmental factors. Considering the abundance of solar energy in Pakistan, this energy can be used to produce hydrogen by electrolysis. According to the materials mentioned, in this work, for the first time, 4 different types of electrolyzers, 3 different types of solar trackers and 3 different solar cell technologies have been investigated by PVGIS 5.2 software. Considering all the losses of the solar system and checking the performance of the solar system connected to the grid at the most optimal installation angle and the most optimal azimuth angle will allow the highest solar hydrogen production to be simulated in the most realistic possible state. The main results of the present work are:

- CIS technology is superior in Gilgit and Peshawar stations and CdTe technology is superior in other stations.

- With an annual production of 38895.6 kWh due to the use of CdTe technology, the Karachi station has produced the most electricity in the state without a solar tracker.

- In all the investigated stations, the two-axis tracker is superior to the single-axis tracker. In Gilgit station, the vertical axis tracker is superior and in other stations, the horizontal axis tracker is superior.

- If the two-axis tracker is used, 253 MWh of electricity will be produced annually in the investigated stations.

- SOE, MCE, AE and PEME electrolyzer technologies have produced the most hydrogen with values of 8.5, 6, 2.6 and about 2 tons/year, respectively.

- The Karachi station, using SOE electrolyzer with an annual production of 1702.7 kg of hydrogen, is known as the most appropriate station.

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Appendix

Table 1: Experimental coefficient for power generation of each PV technology

Coefficient	c-Si	CIS	CdTe
k_1	-0.017237	-0.005554	-0.046689
k_2	-0.040465	-0.038724	-0.072844
k_3	-0.004702	-0.003723	-0.002262
k_4	0.000149	-0.000905	0.000276
k_5	0.000170	-0.001256	0.000159
k_6	0.000005	0.000001	-0.000006