Review Article

Comprehensive Investigation of Solar-Based Hydrogen and Electricity Production in Iran

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Hydrogen is a clean and environmentally friendly energy vector that can play an important role in meeting the world's future energy needs. Therefore, a comprehensive study of the potential for hydrogen production from solar energy could greatly facilitate the transition to a hydrogen economy. Because by knowing the exact amount of potential for solar hydrogen production, the cost-effectiveness of its production can be compared with other methods of hydrogen production. Considering the above, it can be seen that so far no comprehensive study has been done on finding the exact potential of solar hydrogen production in different stations of Iran and finding the most suitable station. Therefore, in the present work, for the first time, using the HOMER and ArcGIS softwares, the technical-economic study of solar hydrogen production at home-scale was done. The results showed that Jask station with a levelized cost of energy equal to \$ 0.172 and annual production of 83.8 kg of hydrogen is the best station and Darab station with a levelized cost of energy equal to \$ 0.286 and annual production of 50.4 kg of hydrogen is the worst station. According to the results, other suitable stations were Bushehr and Deyr, and other unsuitable stations were Anzali and Khalkhal. Also, in 102 under study stations, 380 MW of solar electricity equivalent to 70.2 tons of hydrogen was produced annually. Based on the geographic information system map, it is clear that the southern half of Iran, especially the coasts of the Persian Gulf and the sea of Oman, is suitable for hydrogen production, and the northern, northeastern, northwestern, and one region in southern of Iran are unsuitable for hydrogen production. The authors of this article hope that the results of the present work will help the energy policymakers to create strategic frameworks and a roadmap for the production of solar hydrogen in Iran.

1. Introduction

1.1. The Necessity of Using Hydrogen. The continuous growth of the world's population and economy, along with rapid urbanization, has led to a significant increase in energy demand [1–3]. Power supply in the traditional form is based on fossil fuels, which have problems such as not being easy to extract, polluting, and being limited to a specific geographical area [4–6]. Therefore, the use of renewable energy (RE) is essential for the sustainability of future energy and global security [7–9]. Renewable energies, due to the nature of their variability and intermittency, require large energy storage systems to be able to manage supply and demand [10–12]. A good idea,

which is a cost-effective solution for storing, transporting, and exporting large-scale RE, is to store hydrogen-based energy [13–15].

The heat generated by each unit of hydrogen mass is 3 times greater than that of gasoline. In addition, in hydrogen combustion, only water vapor is produced. Therefore, hydrogen energy is a suitable solution for future energy needs due to the environmental problems of fossil fuels [16].

An economic evaluation of renewable hydrogen production is very important for evaluating the durability and feasibility of selecting the type of technology. In this regard, the first step is to examine the potential for renewable hydrogen production at the under study site.

1.2. Perspective of Hydrogen Production. Global hydrogen demand in 2013 was reported to be 255.3 billion m^3 , which in 2020 will reach 342.8 billion m^3 [17]. If the hydrogen economy improves, it should attract about \$ 70 billion in investment by 2030. It is also noted that the cost of producing and distributing hydrogen from renewable sources will be reduced by 50% over the next decade [18]. It is also noted that hydrogen can meet up to 10% of the global warming demand of buildings by 2050 [19].

As shown in Figure 1 for the share of RE capacity in Iran's electricity, in April 2020 with 63 power plants, solar energy with 44% has the largest share among all renewable sources in Iran's electricity production [20]. Therefore, the focus of the present study for investigating the prospect of renewable hydrogen production in Iran is solar energy.

1.3. Different Ways of Producing Hydrogen. Today, most of the hydrogen produced (more than 90%) is from fossil fuels such as coal and natural gas, which is considered gray hydrogen and does nothing to reduce CO_2 emissions [21]. Various clean hydrogen production technologies are shown in Figure 2 [21]. As shown, the present study examines the hydrogen produced by the process of electrolysis using solar energy. In other words, the material, method, and energy source used in the present work are marked in yellow in Figure 2.

Water electrolysis is the process of breaking down water into oxygen and hydrogen, which is caused by an electric current. Today, about 4% of the world's hydrogen is produced by electrolysis. Economically, the cost of producing green hydrogen is 1.5-5 times greater than producing hydrogen from natural gas but with a 50% reduction in the price of electrolysis, as well as a reduction in the price of RE, green hydrogen will eventually become economical and be promoted [18]. The price range of hydrogen production technologies based on the energy source is shown in Figure 3 [21]. Based on the results of Figure 3 for hydrogen produced from solar energy, the price per kilogram will be \$ 3.41-16.01 [21]. According to studies conducted by the authors of the present work, the reason for this wide range can be the difference in radiation intensity, cloudiness index, air temperature, the wide price range of different solar cell technologies, etc., in different parts of the world. Despite the high price, solar energy is the most abundant and available type of RE, which makes it a very likely option for future hydrogen production [22].

The performance ranking of different sources of hydrogen production is shown in Figure 4 [23]. As can be seen, solar energy has the best performance in terms of social, environmental, and reliability performance among different types of RE. Also, in terms of economic performance, solar energy ranks second after hydro energy. In terms of technical performance, after nuclear and wind energy, solar energy is in third place.

1.4. Different Uses of Hydrogen. Reducing carbon and decarbonizing for use in transportation and electricity generation sectors is one of the goals of hydrogen production from various energy sources [18]. As shown in Figure 5, hydrogen can facilitate the connection between electricity and buildings,

FIGURE 1: The share of different types of RE in Iran's electricity generation [20].

transportation, and industry [24]. Hydrogen produced from fossil fuels, which is widely used in several industrial sectors such as refineries, ammonia production, and chemical can be technically replaced by renewable hydrogen. In the home sector, injectable hydrogen into the gas network can reduce natural gas consumption. In addition, excess electricity can be converted to hydrogen and used as heat in winter [24]. In the transportation sector, vehicles based on fuel cells (FCs) that consume hydrogen have been considered because of their low carbon production. The important point is that in this regard, due to the limited capacity of batteries for long distances, the market for FC-based vehicles is very expandable [24].

1.5. Electrolysis Technologies in Iran. Electrolysis technologies are classified based on the electrolyte used in the electrolysis cell [25]. Proton exchange membrane (PEM) electrolysis is more common in Iran and is used in transportation, home generators, and small power plants [26] and has the greatest potential in the Iranian market for portable applications [27]. After PEM-type electrolysis, alkaline electrolysis with liquid electrolyte is widely used in Iran due to its high process efficiency. However, due to the possibility of liquid electrolyte leakage, it is not used for transportation, and its use is limited to military industries and small space applications [28].

1.6. Literature Review. In order to achieve a fully developed hydrogen economy and turn hydrogen into an important element for the energy market, extensive and significant research has been conducted on the potential for renewable hydrogen production in various parts of the world. Table 1 shows the literature review of recent studies in Iran.

1.7. Novelties of Present Work. According to the literature review of work done in Iran, so far, all studies have been case studies and have been limited to a specific city or province.

FIGURE 2: Different hydrogen production technologies [21].

FIGURE 3: The price range of hydrogen production technologies based on energy source [21].

Given the important role of hydrogen in the future portfolio of global energy, it is necessary to do comprehensive work to find the potential of all stations in Iran. Also, finding the most suitable solar hydrogen station can help Iranian energy policymakers. In addition, most of the works done are purely potential assessment, and technical-economic optimization has not been done. Therefore, in the present work, for the first time, the potential of hydrogen production from water electrolysis in 102 stations in Iran at home-scale has been evaluated. The cost of renewable electricity produced for water electrolysis is calculated taking into account the up-to-date prices of equipment as well as the actual annual interest rate, and the results are presented in the form of GIS maps for ease of decision-making.

2. Under Study Stations

A total of 102 stations have been evaluated to assess the potential of solar electricity and hydrogen in Iran. The reason for choosing these stations was the availability of 20-year average climate data on the NASA website. The location of the under study stations on the Iran map and their annual average climate data, i.e., the solar radiation intensity and the air clearness index, are shown in Figures 6(a) and 6(b), respectively. Solar radiation data and air clearness index will be used as input to the HOMER software to perform technical-economic calculations.

3. Software's and Data Used

The HOMER and ArcGIS softwares are used for the analysis in the present study. The HOMER software is used to find the

FIGURE 4: Performance ranking of different sources of hydrogen production [23].

FIGURE 5: Performance ranking of different sources of hydrogen production [24].

amount of electricity generated by solar cells, and the ArcGIS software is used to display suitable and unsuitable places to use solar energy.

3.1. Solar-Based Electricity Production. The HOMER software uses the following equation for the amount of solar elec-

tricity generated [47]:

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

where Y_{pv} is the rated capacity of PV cells in terms of kW, f_{pv} is the derating factor, $\bar{H}_T$ is the solar radiation collides with the surface of the PV under operating conditions in

TABLE 1: Literature review about renewable hydrogen production in Iran.

Ref.	Purpose	Methodology	Results
Qadrdan and Shayegan 2008 [29]	Economic assessment of hydrogen fueling station in Iran	HOMER software	(i) Hydrogen cost from natural gas: 3-7 \$/kg (ii) Hydrogen cost from electrolysis: 6-10 \$/kg
Shiroudi and Taklimi 2011 [30]	Solar hydrogen production in Taleghan, Iran	HOMER software	Excess electricity can be stored in the form of hydrogen
Shiroudi et al. 2013 [31]	Assessment of photovoltaic- (PV-) hydrogen system in Taleghan, Iran	HOMER software	Total net present cost (NPC) and levelized cost of energy (LCOE) are 237509 \$ and 3.35 \$/kWh, respectively
Nasiri et al. 2015 [32]	Status of hydrogen and FC in Iran	Technological innovation system approach	Supportive laws and regulation are needed for the mobilization of financial resources
Mostafaipoor et al. 2016 [33]	Wind hydrogen production in Fars Province, Iran	Statistical and analytical solution	Abadeh has better potential with producing hydrogen for 22 cars/week
Homayouni et al. 2016 [34]	Techno-econo-enviro assessment of solar hydrogen to supply combined cooling, heat, and power load in Tehran, Iran	Particle swarm optimization simulation	The most economic system has solar and fossil fuel with avoided 75% of CO ₂ emission in comparison by standalone diesel system
Fazelpour et al. 2016 [35]	Economic analysis of FC-based in Tehran, Iran	HOMER software	Wind-hydrogen-battery system with total NPC 63190 \$ is the most economical system
Alavi et al. 2016 [36]	Wind-hydrogen assessment in Sistan and Baluchestan Province, Iran	Statistical and analytical solution	Highest amount of hydrogen is 39.82 ton/year that related to Lutak station
Ramazankhani et al. 2016 [37]	Hydrogen production from geothermal in Iran	Multicriteria decision-making methods	East Azarbaijan is the best location for hydrogen production
Alavi et al. 2017 [38]	Wind-hydrogen feasibility in Chabahar, Iran	Statistical and analytical solution	Highest amount of hydrogen is 194.36 ton/year that related to Vestas V164 wind turbine
Qolipour et al. 2017 [39]	Wind-solar feasibility for electric and hydrogen production for Hendijan, Iran	HOMER software	3153.7 MWh of electricity and 31680 kg hydrogen are produced
Mostafaipoor et al. 2017 [40]	Assessment of solar-hydrogen in Kerman Province, Iran	Data envelopment analysis (DEA) and Technique for Order of Preference by Similarity to Ideal Solution methods	Lalezar is the first priority
Rezaei et al. 2018 [41]	Hydrogen production from seawater using wind turbine in coasts of Iran	Statistical and analytical solution	Anzali has the best potential, and 22 EWT direct wind 52/900 could produce the hydrogen for all cars in Anzali
Ashrafi et al. 2018 [42]	Hydrogen production from wind in 5 regions of Iran by 3 extrapolating Weibull methods	Statistical and analytical solution, geographic information system (GIS) software	Amount of hydrogen production is shown by GIS maps
Rezaei et al. 2019 [43]	Hydrogen production from wind-solar in 10 cities of Iran	Statistical and analytical solution, RETScreen software	Manjil has the greatest amount of wind hydrogen (91 kg/day), and Zahedan has the greatest amount of solar hydrogen (20 kg/day)
Mostafaipoor et al. 2019 [44]	Wind-hydrogen assessment in Firuzkuh, Iran	HOMER software, DEA, and DEMATEL methods	Annually 1014 kg hydrogen produce by using GE 1.5 sl wind turbine
Jahangiri et al. 2019 [45]	Provision of electricity and hydrogen for Bandar Abbas, Iran	HOMER software	Lowest prices of produced hydrogen and electricity are 0.496 \$/kg and 1.55 \$/kWh, respectively

FIGURE 6: Climatic data of under study stations in Iran: (a) solar radiation intensity; (b) air clearness index [46].

terms of kW/m^2 , $\bar{H}_{T,STC}$ is the solar radiation collides with the surface under standard test conditions and is equal to

1 kW/m^2 , and P_{PV} is the output power from PV in terms of kW.

FIGURE 7: Weighting in IDW method.

For the solar cells used in the present work, the lifetime is 20 years [48], the derating factor is 90% [49], the angle of the solar cells is equal to the latitude of the under study site [50], the orientation of the solar cells is to the south [51], and the ground reflection coefficient is 20% [52]. The cost of buying and replacing solar cells is \$ 3200 and \$ 3000 per kW, respectively [53]. Also, the annual operating and maintenance cost of solar cells, which mainly includes cleaning and can be done by the operator itself, are considered zero [54].

The HOMER software calculates the air clearness index ($\overline{k_T}$), which is a very important and influential parameter in the performance of solar cells by the following equation [55]:

$$\overline{k_T} = \frac{\overline{H}}{\overline{H_{oh}}}, \quad (2)$$

where $\overline{H}$ is the monthly average daily irradiation on a horizontal plane at the Earth's surface and $\overline{H_{oh}}$ is the monthly average daily value of extraterrestrial radiation energy falling on a horizontal plane. $\overline{H}$ is given to the software as input, and the software calculates the value of $\overline{H_{oh}}$ using latitude and by the following equations [55]:

$$H_{oh} = \frac{24 \times 60}{\pi} G_{sc} \times d_r \times \left(\omega_s \cdot \sin \varphi \cdot \sin \delta + \cos \varphi \cdot \cos \delta \cdot \sin \omega_s \right), \quad (3)$$

$$d_r = 1 + 0.033 \cos \left(\frac{2\pi n}{365} \right), \quad (4)$$

$$\delta = 0.409 \sin \left(\frac{2\pi n}{365} - 1.35 \right), \quad (5)$$

$$\omega_s = \arccos (-\tan \varphi \cdot \tan \delta), \quad (6)$$

where H_{oh} is the extraterrestrial radiation in terms of $\text{Mj/m}^2\text{-day}$, G_{sc} is the solar constant and equal to $0.082 \text{ Mj/m}^2\text{-min}$, d_r is the inverse relative distance earth-sun, n is the number of day in the year, ω_s is the sunset hour angle in terms of radian, φ is the latitude in terms of radian, and δ is the declination of the sun in terms of radian.

Economic calculations in the HOMER software include determining the LCOE parameter performed by the following equation [56]:

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

where $C_{\text{ann,total}}$ is the sum of the annual costs and $E_{\text{Load served}}$ is the cost of the system's actual electrical load in terms of kWh/year.

3.2. Hydrogen-Based Electricity Production. Water electrolysis requires an external energy carrier to carry out the process of separating oxygen and hydrogen. Among the types of energy carriers, solar energy is one of the main and justifiable

TABLE 2: Results of simulations.

Station	LCOE (\$/kWh)	Hours of operation	Capacity factor (%)	PV production (kWh/yr)	Hydrogen production (kg/yr)
Abadan	0.193	4380	22.4	3925	74.7
Abadeh	0.193	4385	22.4	3929	74.8
Ahar	0.235	4384	18.4	3225	61.4
Ahwaz	0.204	4382	21.2	3706	70.5
Alvand	0.225	4384	19.2	3368	64.1
Anzali	0.271	4390	15.9	2792	53.1
Aq Qaleh	0.242	4368	17.9	3133	59.6
Arak	0.205	4384	21.1	3703	70.5
Ardakan	0.192	4390	22.5	3942	75.0
Ardistan	0.189	4385	22.9	4007	76.3
Babol	0.267	4387	16.2	2842	54.1
Babolsar	0.266	4388	16.3	2847	54.2
Bafq	0.192	4389	22.5	3936	74.9
Baft	0.189	4389	22.9	4004	76.2
Bam	0.193	4391	22.3	3916	74.5
Bandarabbass	0.199	4390	21.8	3816	72.6
Bandar-e Genaveh	0.192	4383	22.5	3942	75.0
Bandar-e Lengeh	0.191	4385	22.6	3958	75.3
Bandar-e Mahshahr	0.200	4381	21.6	3781	72.0
Birjand	0.202	4367	21.4	3747	71.3
Bojnurd	0.218	4375	19.8	3469	66.0
Borujen	0.196	4386	22.1	3868	73.6
Bukan	0.200	4381	21.6	3785	72.0
Bushehr	0.178	4382	24.4	4267	81.2
Chah Bahar	0.199	4399	21.8	3812	72.6
Chalus	0.264	4387	16.4	2868	54.6
Darab	0.286	4387	15.1	2648	50.4
Dargaz	0.234	4381	18.4	3231	61.5
Dehloran	0.185	4380	23.3	4084	77.7
Dezful	0.189	4382	22.9	4019	76.5
Deyr	0.178	4381	24.3	4254	81.0
Do Gonbadan	0.199	4383	21.7	3804	72.4
Do Rud	0.188	4383	23.0	4033	76.8
Esfahan	0.188	4384	23.0	4025	76.6
Firuzabad	0.196	4385	22.1	3864	73.6
Garmsar	0.212	4386	20.4	3566	67.9
Gonabad	0.201	4373	21.5	3762	71.6
Gonbad-e Qabus	0.237	4353	18.3	3199	60.9
Gorgan	0.232	4368	18.6	3261	62.1
Hamedan	0.188	4383	23.0	4026	76.6
Ilam	0.206	4382	21.0	3676	70.0
Iranshahr	0.193	4362	22.5	3934	74.9
Jahrom	0.191	4385	22.7	3969	75.6
Jask	0.172	4381	25.1	4401	83.8
Jiroft	0.192	4391	22.6	3953	75.2
Kamyaran	0.202	4384	21.4	3745	71.3
Kangan	0.193	4382	22.4	3927	74.8
Karaj	0.207	4387	20.8	3652	69.5

TABLE 2: Continued.

Station	LCOE (\$/kWh)	Hours of operation	Capacity factor (%)	PV production (kWh/yr)	Hydrogen production (kg/yr)
Kashan	0.205	4386	21.1	3692	70.3
Kashmar	0.208	4374	20.8	3643	69.3
Kazerun	0.196	4383	22.0	3858	73.4
Kerman	0.196	4391	22.1	3867	73.6
Kermanshah	0.217	4383	19.9	3495	66.5
Khalkhal	0.267	4386	16.2	2838	54.0
Khash	0.195	4348	22.1	3877	73.8
Khomeyn	0.199	4383	21.7	3802	72.4
Khormuj	0.200	4382	21.6	3785	72.0
Khorramabad	0.190	4385	22.8	3990	76.0
Khoy	0.219	4383	19.8	3462	65.9
Kuhdasht	0.185	4382	23.3	4086	77.8
Langarud	0.256	4385	16.9	2963	56.4
Lar	0.203	4385	21.3	3728	71.0
Mahabad	0.222	4381	19.5	3420	65.1
Maragheh	0.213	4383	20.3	3565	67.9
Marand	0.211	4383	20.5	3584	68.2
Marivan	0.203	4381	21.3	3732	71.0
Mashhad	0.219	4380	19.8	3466	66.0
Masjed-e Soleyman	0.200	4383	21.6	3787	72.1
Mianeh	0.217	4385	19.9	3492	66.5
Minab	0.195	4388	22.1	3878	73.8
Naiin	0.187	4387	23.1	4053	77.2
Neyriz	0.190	4387	22.8	3997	76.1
Neyshabur	0.212	4377	20.4	3574	68.0
Orumieh	0.208	4381	20.8	3637	69.2
Parsabad	0.250	4386	17.3	3030	57.7
Qaen	0.199	4372	21.7	3800	72.3
Qom	0.203	4385	21.3	3724	70.9
Ramsar	0.193	4384	22.4	3920	74.6
Ravar	0.191	4390	22.6	3963	75.4
Sabzevar	0.208	4374	20.8	3638	69.3
Sanandaj	0.209	4384	20.7	3630	69.1
Saravan	0.191	4372	22.6	3956	75.3
Sari	0.198	4386	21.9	3831	72.9
Semnan	0.186	4389	23.2	4070	77.5
Sepidan	0.194	4384	22.3	3900	74.2
Shahr-e Babak	0.191	4387	22.6	3960	75.4
Shahr-e Kord	0.194	4384	22.3	3898	74.2
Shahrud	0.187	4370	23.1	4050	77.1
Shiraz	0.192	4385	22.5	3944	75.1
Sirjan	0.192	4388	22.5	3938	75.0
Tabas	0.189	4389	22.8	3999	76.1
Tabriz	0.222	4384	19.5	3413	65.0
Takab	0.188	4384	23.0	4030	76.7
Taybad	0.205	4381	21.0	3688	70.2
Tehran	0.209	4386	20.7	3620	68.9
Torbat-e Jam	0.215	4382	20.1	3525	67.1

TABLE 2: Continued.

Station	LCOE (\$/kWh)	Hours of operation	Capacity factor (%)	PV production (kWh/yr)	Hydrogen production (kg/yr)
Torbat-Heydarieh	0.208	4377	20.8	3640	69.3
Yasuj	0.195	4384	22.2	3890	74.0
Yazd	0.204	4388	21.2	3716	70.7
Zabol	0.198	4376	21.8	3825	72.8
Zahedan	0.196	4363	22.0	3862	73.5
Zanjan	0.186	4387	23.2	4071	77.5

forms of energy [57]. To calculate the potential of solar hydrogen production in different stations located in eight climates of Iran (cold, very cold, moderate and rainy, semimoderate and rainy, semiarid, hot and dry, very hot and dry, and very hot and humid), the amount of generated solar power (P_{PV}) was first calculated by the HOMER software (equation (1)). Then, using an analytical analysis according to equation (8), the amount of hydrogen produced per year per kilowatt of solar cells used to generate electricity was estimated [58]. Also, due to the high efficiency, conditions in the Iranian market, and the longer average lifetime [59], the type of technology desired for water electrolysis in the present work is PEM.

$$M_{H_2} = \frac{P_{PV} \times \eta_{ele}}{HHV_{H_2}}. \quad (8)$$

In the above relation, η_{ele} is the electrolyzer efficiency in terms of percentage, which is considered 75% in the present work, and HHV_{H_2} is the high heating value of hydrogen, which is 39.4 kWh/kg.

3.3. Assessment of the Areas by GIS Map. GIS technology by collecting and combining information from a conventional database provides information for map preparation by illustrating and using geographical analyzes. This information is used to make events clearer, to predict results, and to draw maps [60].

The use of spatial relationships between data in interpolation methods increases the accuracy of estimating radiation potential for different regions. In the present paper, the inverse distance weighting (IDW) internalization method is used. Calculations in IDW depend on two factors: select the power of p in formula $w = (1/d)^p$ and the position of the adjacent points, or in other words, the position of the neighboring units. The default value for p is considered to be 2, and for this value, the name of the method is the inverse distance squared weighted [61]. As shown in Figure 7, the point weight window includes a list of weights given to each point that are used to predict a value at the target location. In the IDW method, the points closest to the desired location weigh more than the farthest points, and the weight decreases with increasing distance.

4. Results

Table 2 shows the results of the studies. As can be seen, Jask stations with a LCOE of \$ 0.172 and Darab with \$ 0.286 have the highest and lowest prices per kWh of solar electricity produced, respectively. Bushehr and Deyr stations with 0.178 \$ are in the second place of lowest LCOE value, and Anzali station with \$ 0.271 is in the second place of largest LCOE value. The average LCOE for the 102 under study stations is \$ 0.206.

According to the results of Table 2, the highest and lowest operating hours of solar cells during the year with values of 4399 and 4348 are related to Chabahar and Khash stations, respectively. Also, the average operating hour of solar cells for the under studied stations is 4382. The reason why the maximum and minimum operating hours of solar cells do not correspond to the highest and lowest solar power generation and therefore the highest and lowest LCOE values can be due to factors such as air cloudiness and radiation intensity.

According to the results of Table 2, Jask and Darab stations have the highest and lowest capacity factor with 25.1% and 15.1%, respectively. The capacity factor, which is actually the average output power divided by the nominal capacity of solar cells, is on average 21.21% for all under study stations.

Based on the results, it can be seen that the top 3 stations in the field of solar power generation are Jask, Bushehr, and Deyr stations, which produce 4401, 4267, and 4254 kWh of electricity per year, respectively. Based on the location of renewable power plants in Iran, which are mainly in the central of Iran [62] and given that the top stations generate solar electricity in the southern margins of the country, more attention needs to be paid to Jask, Bushehr, and Deyr stations. The three stations that have produced the least solar electricity are Darab, Anzali, and Khalkhal, which generated 2648, 2792, and 2838 kWh of electricity per year, respectively. The reason for this low production can be climatic factors such as high cloudiness and low radiation intensity. According to the results, the total solar power generated in the 102 stations surveyed will be 380 MWh per year which the average of each station is about 3.7 MWh per year. This result can be very important for decision-makers and policymakers in the field of a distributed generation because so far no comprehensive work has been done to assess the production of solar electricity in Iran.

According to the results, Jask station with an annual production of 83.8 kg of hydrogen was able to obtain the first

FIGURE 8: Map of solar hydrogen production potential in Iran.

rank in the production of hydrogen on a home scale. The lowest amount of hydrogen production with 50.4 kg per year is related to Darab station. Other top stations in the field of hydrogen production are Bushehr and Deyr, and other unsuitable stations in the field of hydrogen production are Anzali and Khalkhal. According to statistical calculations, the total amount of hydrogen produced in the under studied stations was 7.2 tons per year, with each station producing an average of 70.8 kg of hydrogen per year. In order to better evaluate and understand finding suitable and unsuitable areas for home-scale hydrogen production in Iran, the hydrogen production map in Iran has been drawn using the GIS software in Figure 8. Based on Figure 8, it is clear that the southern half of Iran, especially the coasts of the Persian Gulf and the Gulf of Oman, is suitable for hydrogen production, and the northern, northeastern, northwestern, and one region in southern of Iran are unsuitable for hydrogen production.

5. Conclusion

Hydrogen can become an important medium for storing RE to become clean electricity if needed. In other words, by using hydrogen, RE can be effectively stored and transferred over long distances and over a long period of time [23]. Therefore, hydrogen is an essential element for becoming 100% RE sys-

tems and eliminating the phenomenon of global warming. Since it is very important for decision-makers and policy-makers in the field of distributed generation to know the potential of electricity and hydrogen production on a home scale, in the present work, this issue has been studied for the first time in Iran. Technical-economic investigations have been conducted by the HOMER software on the average 20-year radiation data of 102 stations in Iran. Finally, for better understanding, the ArcGIS software provides a home-scale hydrogen production potential map. The main results are as follows:

- (i) Jask with a LCOE of \$ 0.172 and Darab with \$ 0.286 have the highest and lowest prices per kWh of solar electricity produced, respectively
- (ii) The average LCOE for the 102 under study stations is \$ 0.206
- (iii) Jask and Darab stations have the highest and lowest capacity factor with 25.1% and 15.1%, respectively
- (iv) The average capacity factor is 21.21% for all under study stations
- (v) Top 3 stations in the field of solar power generation are Jask, Bushehr, and Deyr stations, which

produce 4401, 4267, and 4254 kWh of electricity per year, respectively

- (vi) The three stations that have produced the least solar electricity are Darab, Anzali, and Khalkhal, which generated 2648, 2792, and 2838 kWh of electricity per year, respectively
- (vii) The total solar power generated in the 102 under study stations is 380 MWh per year
- (viii) Jask with the production of 83.8 kg/year has the first rank in the production of hydrogen
- (ix) The lowest amount of hydrogen production with 50.4 kg/year is related to Darab station
- (x) The total amount of hydrogen produced in the under studied stations was 7.2 tons/year
- (xi) The southern half of Iran, especially the coasts of the Persian Gulf and the sea of Oman, is suitable for hydrogen production, and the northern, north-eastern, northwestern, and one region in southern Iran are unsuitable for hydrogen production

Nomenclature

RE:	Renewable energy
PEM:	Proton exchange membrane
FC:	Fuel cell
PV:	Photovoltaic
NPC:	Net present cost (\$)
LCOE:	Levelized cost of energy (\$/kWh)
DEA:	Data envelopment analysis
GIS:	Geographic information system
IDW:	inverse distance weighting
P_{PV} :	Output power of PV cells (kW)
Y_{PV} :	Output power of solar cell under standard conditions (kW)
f_{PV} :	Derating factor (%)
$\overline{H_T}$:	Incident radiation on the cell's surface on a monthly basis (kW/m ²)
$\overline{H_{T,STC}}$:	Incident radiation on the cell's surface under standard conditions (1 kW/m ²)
k_t :	Clearness index (-)
ω_s :	Sunset hour angle (radian)
M_{H_2} :	Mass of hydrogen (kg/year)
G_{sc} :	Solar constant (0.082 MJ/m ² -min)
η_{ele} :	Electrolyzer efficiency (%)
$\overline{H_{oh}}$:	Extraterrestrial radiation (MJ/m ² -day)
ϕ :	Latitude (radian)
d_r :	Inverse relative distance earth-sun
n :	Number of the day during the year (-)
$C_{ann,total}$:	Total annual cost (\$)
$E_{load\ served}$:	Real electrical load by the system (kWh/year)
δ :	Declination of the sun (radian)
$\overline{H}$:	Monthly average daily radiation on a horizontal plane (MJ/m ² -day)
HHV_{H_2} :	Higher heating value of the hydrogen (39.4 kWh/kg).

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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