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RESEARCH ARTICLE

Mostafa REZAEI, Ali MOSTAFAEIPOUR, Mojtaba QOLIPOUR, Mozhgan MOMENI

Energy supply for water electrolysis systems using wind and solar energy to produce hydrogen: a case study of Iran

Abstract Due to acute problems caused by fossil fuels that threaten the environment, conducting research on other types of energy carriers that are clean and renewable is of great importance. Since in the past few years hydrogen has been introduced as the future fuel, the aim of this study is to evaluate wind and solar energy potentials in prone areas of Iran by the Weibull distribution function (WDF) and the Angstrom-Prescott (AP) equation for hydrogen production. To this end, the meteorological data of solar radiation and wind speed recorded at 10 m height in the time interval of 3 h in a five-year period have been used. The findings indicate that Manjil and Zahedan with yearly wind and solar energy densities of 6004 (kWh/m^2) and 2247 (kWh/m^2), respectively, have the greatest amount of energy among the other cities. After examining three different types of commercial wind turbines and photovoltaic (PV) systems, it becomes clear that by utilizing one set of Gamesa G47 turbine, 91 kg/d of hydrogen, which provides energy for 91 car/week, can be produced in Manjil and will save about 1347 L of gasoline in the week. Besides, by installing one thousand sets of X21-345 PV systems in Zahedan, 20 kg/d of hydrogen, enough for 20 cars per week, can be generated and 296 L of gasoline can be saved. Finally, the RETScreen software is used to calculate the annual CO_2 emission reduction after replacing gasoline with the produced hydrogen.

Keywords wind energy, solar energy, water electrolysis, hydrogen production, Weibull distribution function (WDF), Angstrom-Prescott (AP) equation

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Mostafa REZAEI (✉), Ali MOSTAFAEIPOUR, Mojtaba QOLIPOUR, Mozhgan MOMENI
Industrial Engineering Department, Yazd University, Yazd 8915818411, Iran
E-mail: mm.sr6870@yahoo.com

1 Introduction

In recent years, hydrogen has become one of the most popular means of providing energy for different purposes like transportation, while it has a few drawbacks including being much less dense than other fuels, and difficult to store and transport. On the other hand, hydrogen benefits from the high energy density which is between 120 and 142 MJ/kg (almost three times higher than that of oil) and practically produces no greenhouse gas (GHG) emissions [1,2]. In general, its shortcomings can be considered almost negligible in comparison with its merits which have encouraged many countries to view hydrogen as an alternative fuel for vehicles [3]. To reduce GHG emissions and mitigate their consequences, such as global warming and environmental pollution, it is required to stop using fossil fuels and embark on utilizing clean energy sources to address the demand for energy. Hence, hydrogen generation is of significant importance.

There are several methods for producing hydrogen including fermentation [4], natural gas reforming/gasification [5], high-temperature water splitting [6], ethanol reforming [7], and water electrolysis, of which the chief one is the latter [8,9]. To keep the process of hydrogen generation clean, renewable resources of energy can be used as electricity supply. Therefore, in this research to supply the electric energy needed for the water electrolysis process, it is suggested to use wind and solar energies which neither cause air pollution nor have the problem of depleting [10].

Given significant importance of energy and its impact on the world, extensive studies have been conducted to scrutinize different aspects of this controversial subject. In this regard, clean means of generating hydrogen as an alternative fuel using wind and solar energy have been studied. In terms of using solar energy to produce hydrogen, Badea et al. [11] examined three different scenarios pertaining to the sub-systems of the hydrogen production and storage system efficiency. The results showed that to maximize solar/hydrogen conversion, it was necessary to use both electrical energy and thermal energy in the form of steam. Likkasit et al. [12] investigated the different methods for solar-based hydrogen production and concluded that solar steam methane reforming using a volumetric receiver reactor had the lowest cost of hydrogen production. Other studies done in Algeria [13], Jordan [14], Lebanon [15] and Australia [16] showed the importance of utilizing solar energy for hydrogen production.

As regards hydrogen generation using wind energy, GarcíaClúa et al. [17] investigated a wind-powered system to produce hydrogen through water electrolysis and the effect of the size of electrolyzer on minimizing carbon emissions. In another research done by Sarrias-Mena et al. [18], four electrolyzer models for hydrogen production using wind energy were analyzed and compared under variable wind velocity. Douak and Settou [19] examined economic feasibility of 4 wind turbines as input of a water electrolysis system to produce hydrogen in Algeria. The results indicated that the turbine with the rated power of 1500 kW was the most economic one to be used.

Since hybrid systems benefit from significant advantages including improvement in the reliability of the whole system, decrease in cost of implementation and maintenance, and reduction in GHG emissions [2], utilizing at least two types of renewable energies as the input of a hydrogen production system is advantageous. In this regard, Kalinci et al. [20] assessed the techno-economic feasibility of a hybrid wind/solar to hydrogen conversion systems. The results showed that being hybrid could result in a dramatic reduction in current net costs. Blal et al. [21] also scrutinized a system for generating hydrogen in Algeria using wind and solar energy as a hybrid system. In another research, Marchenko and Solomin [22] investigated a system for producing electricity as well as hydrogen by applying PV systems along with wind turbines and found that generating electricity storage is most efficient for short-term time intervals while an increase in the duration of continuous energy "standstills" up to several days makes the storage of hydrogen more cost-effective. In a study done in Saudi Arabia, Al-Sharafi et al. [23] examined different combinations of wind turbines, PV array, batteries and fuel cells in order to find the most cost effective one for power generation and hydrogen production and finally proposed a system with 2 kW PV array, 3 wind turbines, 2 kW converter, and 7 batteries as the best configuration leading to the minimum levelized cost of energy.

Several studies have been conducted in Iran in terms of producing hydrogen using renewable energies such as prioritization of cities of Kerman province for exploiting solar energy to generate hydrogen [24], ranking different cities of Fars province to produce hydrogen using wind energy [25], evaluating wind energy potential for generating hydrogen [26] and socio-economic assessment of hydrogen production using wind energy [2], but these studies are lacking in investigating hydrogen as a fuel for the transportation sector in Iran. Hence, in this study, a renewable-powered system which generates hydrogen via water electrolysis using wind and solar energy is proposed in order to achieve sustainable development in the transportation sector in Iran. What makes this research essential for Iran as well as other developing countries is that no research on using hydrogen cars has been conducted in order to reduce environmental pollution. Therefore, an attempt should be made to close this research gap. Finally, the most important novelties of this work are using electricity generated via wind and solar energy to produce hydrogen in Iran, proposing a green and renewable process to produce hydrogen for transportation purposes, calculating the amount of hydrogen that can be gained in different cities of Iran using wind and solar energy, and estimating CO_2 emission reduction due to using hydrogen for cars instead of gasoline.

2 Renewable energy sources in Iran

2.1 Wind energy in Iran

Due to the special geographic situation of Iran and its location which is situated in low-pressure area with flowing strong air in summer and winter in some locations, this country has very good wind energy potential in many zones. In winter, the country is influenced by the winds from the Atlantic Ocean, the Mediterranean Sea, and central Asia while in summer it is influenced by the winds from the Indian Ocean and the Atlantic Ocean [27,28].

In a study done by the Renewable Energy Organization of Iran, locally called SUNA, it is mentioned that in 26 zones of the country including 45 sites, the wind energy potential is estimated to be about 6500 MW [28].

Considering the wind atlas[1)] and long-term wind speed data pertaining to 15 years from 2000 to 2014 provided by SUNA, it was specified that the cities given in Table 1[1)] had the highest mean wind speed during this period. As a result, in this study these cities are investigated in terms of harnessing wind energy for hydrogen production through water electrolysis.

2.2 Solar energy in Iran

Some regions of Iran are the most suitable areas in the world in terms of receiving solar radiation and enjoying a long sunshine of almost over 2900 h/a. Thus, solar energy could be utilized to meet a significant share of energy demand in the near future. According to the findings of solar energy experts, more than two-thirds of Iran has 300

1) Ministry of Energy, Renewable Energy and Energy Efficiency Organization (SATBA). Wind and solar energy resources in Iran. 2017

Table 1 Geographical characteristics of 10 cities with the highest mean wind speed between 2000 and 2014

City	Longitude	Latitude
Manjil	49°24′ E	36°44′ N
Zabol	61°29′ E	31°02′ N
Eghlid	52°38′ E	30°54′ N
Bushehr	50°49′ E	28°54′ N
Zahak	61°41′ E	30°54′ N
Zarrineh	46°55′ E	36°04′ N
Khoor	58°26′ E	32°56′ N
Noorabad	48°01′ E	34°03′ N
Ardebil	48°17′ E	38°15′ N
Binalood	59°22′ E	35°58′ N

sunny days in a year, receiving solar energy of between 4.5 and 5.4 kWh/($m^2 \cdot$d) [28].

According to the solar radiation map[1)], the central and southern parts of Iran have a high potential for harnessing solar radiation. In this study, top 10 of the most appropriate cities in terms of solar radiation, mentioned in Table 2[2)], were chosen for further investigation because these cities are located in the areas with relatively higher solar radiation.

Table 2 Geographical characteristics of 10 cities for evaluation solar energy

City	Longitude	Latitude
Mehriz	54°28′E	31°35′N
Zarand	56°34′E	30°46′N
Zahedan	60°50′E	29°30′N
Kashan	51°40′E	33°28′N
Abadan	48°22′E	30°21′N
Lar	54°16′E	27°40′N
Saravan	62°20′E	15°22′N
Minab	57°02′E	24°05′N
Jiroft	57°44′E	28°21′N
Nikshahr	60°41′E	27°12′N

3 Methodology

In this section, wind energy is calculated using WDF, solar energy is estimated using the AP equation, and hydrogen generation through water electrolysis by applying the proposed system is discussed.

3.1 Wind energy

It is essential to calculate the wind power density at the height of wind turbine blades, because wind velocity varies by different heights and this variation in wind speed will definitely change the results of estimating wind energy [25]. Since the turbines used commercially in Iran have a height of 40 m, this height is considered for calculations in this study. As the three-hourly data collected from Iranian Meteorological Organization (IMO) pertains to the height of 10 m, the wind velocity at the turbine tower (height of 40 m) must be computed by extrapolation using Eq. (1). Among variables including wind speed, air temperature and air pressure necessary to estimate wind power density, two last ones do not change for the heights less than 100 m from the ground surface [25].

$$V = V_0 \left(\frac{h_1}{h_0}\right)^{\alpha}, \tag{1}$$

where V is the wind speed at the height of h_1, V_0 is the wind speed at the height of h_0, which is 10 min this study. The coefficient α is calculated by Eq. (2) [25].

$$\alpha = \frac{[0.37 - 0.088\ln(V_1)]}{\left[1 - 0.088\ln\left(\frac{h_1}{h_0}\right)\right]}. \tag{2}$$

Then, WDF which is the most common method is used to calculate wind power density. This distribution is shown in Eq. (3) [25].

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} \mathrm{e}^{-\left(\frac{v}{c}\right)^k}, \tag{3}$$

where the two fixed parameters c and k are the scale parameter and shape parameter, which must first be obtained from Eqs. (4) and (5) [29].

$$k = \left(\frac{\sigma_v}{\overline{v}}\right)^{-1.086}, \tag{4}$$

$$c = \frac{\overline{v}}{\Gamma \times \left(1 + \frac{1}{k}\right),} \tag{5}$$

where $\overline{v}$ and σ_v are the mean and standard deviation of wind speed, and Γ is the gamma function whose general relationship is expressed in Eq. (6) [29].

$$\Gamma(x) = \int_0^{\infty} \mathrm{e}^{-u} u^{x-1} \mathrm{d}u. \tag{6}$$

Finally, the general equation of wind power is given in Eq. (7), in which ρ is the density of air, which is calculated by Eq. (8) [25].

$$P(v) = \frac{1}{2}\rho A v^3, \tag{7}$$

$$\rho = \frac{\overline{P}}{R_\mathrm{d}\overline{T}}, \tag{8}$$

1) Ministry of Energy, Renewable Energy and Energy Efficiency Organization (SATBA). Wind and solar resources in Iran. 2017

2) Iranian Astronomy Society, Department of Science, Research and Technology. 2017

where $\overline{P}$ is the average air pressure in Pascal (Pa), $\overline{T}$ is the average air temperature in Kelvin (K), and R_d denotes the gas constant for dry air which equals 287 J/(kg·K) [30]. After these preliminary calculations, the wind power density for the area swept by turbine blades, shown by A, can be gained by Eq. (9) [31].

$$\frac{P}{A}=\int_0^\infty \frac{1}{2}\rho v^3 f(v)\mathrm{d}v=\frac{1}{2}\Gamma\rho c^3\left(1+\frac{3}{k}\right). \tag{9}$$

Then, the wind energy density available in each region is computed by Eq. (10) [25].

$$\frac{E}{A}=\left(\frac{P}{A}\right)\times n\times\Delta t=\frac{1}{2}\Gamma\rho c^3\left(1+\frac{3}{k}\right)\times n\times\Delta t, \tag{10}$$

where n is the number of observations, and Δt is the difference of time intervals in which the data were measured.

The amount of electricity produced by utilizing wind turbines is obtained from Eq. (11) [26].

$$E_{\text{out}} = N_{\text{tb}} \times C_{\text{tb}}\times C_{\text{f}}, \tag{11}$$

where N_{tb} is the number of turbines installed (In this paper, the amount of energy obtained from one turbine is evaluated.), C_{tb} is the nominal capacity of the turbine, and C_{f} is the capacity factor of the turbine, which is calculated by Eq. (12) [26].

$$C_{\text{f}}=\frac{P_{\text{out}}}{P_{\text{r}}}=\frac{\mathrm{e}^{-(v_{\text{i}}/c)^k}-\mathrm{e}^{-(v_{\text{r}}/c)^k}}{(v_{\text{r}}/c)^k-(v_{\text{i}}/c)^k}-\mathrm{e}^{-\left(\frac{v_{\text{o}}}{k}\right)^k}, \tag{12}$$

where v_{i}, v_{r}, and v_{o} are the cut-in speed, rated speed, and cut-out speed, respectively.

3.2 Solar energy

One of the common methods for estimating the solar energy available in an area is the AP equation. Parameters n and N are needed for this purpose, which denote the actual sunny hours and the maximum possible hours of sunshine per day, respectively. N is a function of latitude and is obtained by Eq. (13) [32].

$$N=\frac{2\omega}{15}, \tag{13}$$

where ω is the monthly mean sunrise hour angle. Another parameter that must be calculated is the average daily extraterrestrial irradiance ($\overline{H_0}$) computed by Eq. (14) [28].

$$\overline{H_0}=\frac{24\times I_{\text{so}}}{\pi}\times\left[1+0.033\cos\left(\frac{360d}{365}\right)\right]\times\left[\cos\phi\cos\delta\sin\omega+\frac{\pi\omega}{180}\sin\phi\sin\varphi\right]. \tag{14}$$

In this equation, I_{so} is the solar constant which equals 1367 W/m^2, d denotes the average day of each month, ϕ is the latitude of the location [28,32], δ is the declination of the sun's orbit which moves between the orbits of 23.5 North and South degrees during the year and is calculated by Eq. (15) [33].

$$\delta=23.45\times\sin\left[\frac{360(284+d)}{365}\right], \tag{15}$$

where ω is the sunrise hour angle which shows the sun's position in the sky of each location relative to the meridian of the same place [34], the amount of which is 15 degrees for each hour difference to the solar noon (12 solar hour), and it is assumed to be negative in a.m. hours and positive in p.m., and is calculated by Eq. (16) [28].

$$\cos\omega = -\tan\phi\times\tan\delta. \tag{16}$$

The amount of solar energy reaching the surface of the ground can be obtained by Eq. (17), the unit of which is MJ/m^2 [33].

$$\overline{H}=\overline{H_0}\times\left(a+b\times\left(\frac{n}{N}\right)\right). \tag{17}$$

where a and b are fixed regression coefficients which are dependent on geographic and climatic parameters. a can be defined as the fraction of the monthly average solar radiation ($\frac{\overline{H}}{\overline{H_0}}$) entered to the atmosphere when the cloud cover is complete and b can be defined as the changes in $\frac{\overline{H}}{\overline{H_0}}$ according to $\frac{n}{N}$ and the latitude difference index [28]. Before evaluating $\overline{H}$, the average daily extraterrestrial irradiance ($\overline{H_0}$) should be calculated. Thus, d and δ are extracted from Table 3 [35] and used in related equations.

Equation (18) is used for calculating the amount of electricity (kWh/a) produced by installing PV systems [36,37].

$$E_{\text{out}}=A\times r\times\overline{H}\times \text{PR}. \tag{18}$$

Table 3 Average days of each month and values of declination angle

Month	d/d	δ
January	17	–20.9
February	47	–13
March	75	–2.4
April	105	9. 4
May	135	18.8
June	162	23.1
July	198	21.2
August	228	13.5
September	258	2.2
October	288	–9.6
November	318	–18.9
December	344	–23

In this equation, A is the total area of solar panels, r is the efficiency of the solar modules (depending on the type of PV system), $\overline{H}$ denotes the average annual radiation on solar panels (shadings not included), PR is the performance rate obtained from all wastes in PV systems (PR = 1–sum of losses shown in Table 4[1)]). The performance rate of PV systems depends on the solar site location, the technology used, and the size of the system installed [38]. Thus, in this study, two scenarios, including the worst-case scenario (with the largest losses of 85%) and the best conditions (with minimal losses of 45%) are evaluated.

Table 4 Worst-case scenario and the best conditions for losses of PV systems

Losses	Minimal losses/%	Largest losses/%
Inverter losses	7	15
Temperature losses	6	15
DC cables losses	1	3
AC cables losses	1	3
Shadings (depends of site)	25	40
Losses weak irradiation	4	7
Losses due to dust, snow and etc.	1	2
Sum of losses	45	85
Performance ratio (PR)	55	15

3.3 Hydrogen production system

Water electrolysis was first introduced by Michael Faraday in 1820. In this process electricity is passed through a solution containing water and electrodes. Then, hydrogen and oxygen molecules (H_2 and O_2) are produced from water [39]. In other words, the negative and positive poles are connected to cathode (negative electrode) and anode (positive electrode), respectively. In the anode, the tendency is to pull electrons, and therefore the cathode tends to attract protons [40]. Since water has a poor electrical conductivity, the electrolyte is added in the process [39].

Electricity makes water molecules which are around the cathode electrode, separates and produces OH^- and H^+ ions. This makes the external surface of cathode become totally covered by hydroxide ions (OH^-). Naturally hydroxide ions move toward the anode in order to reach its surface. The anode retakes excessive electrons which hydroxide ions have taken from hydrogen, and the hydroxide ion forms an oxygen gas molecule (O_2) again with three other hydroxide molecules, and gives two water molecules (H_2O). Oxygen molecules are stable and come to the water surface as bubbles. On the other hand, the H^+ ion lacking electron and moving toward the cathode collides with extra e^- and forms H, then a hydrogen gas molecule is generated and finally comes out of the water surface as a bubble [41,42]. This process is shown in Eq. (19) [41].

$$H_2O \xrightarrow{\text{Electricity}} H^+ + OH^- \tag{19}$$

$$4OH^- \rightarrow O_2 + 2H_2O + 4e^-$$

$$H^+ + e^- \rightarrow H$$

$$H + H \rightarrow H_2$$

In this research, in order to produce hydrogen, a stand-alone wind-solar/hydrogen energy conversion system is proposed (Fig. 1). The system consists of a wind turbine (with AC voltage at its output), a PV panel (with DC voltage at its output), two converters, a water electrolyzer, and a control system. After reducing the output voltage of the wind turbine to a lower value, it can be used to supply the considered electrolyzer. Finally, the electrolysis of water occurs using the low voltage/high current, and hydrogen is produced. The final step is to store the produced hydrogen in the storage [25].

The amount of hydrogen produced is calculated by Eq. (20) in $N\cdot m^3$ [25].

$$H_2 = \left(\frac{E_{out}}{E_{con}}\right) \times eff_{con}, \tag{20}$$

where E_{out} is the amount of energy generated after applying wind turbines or PV systems, eff_{con} is the rectifier efficiency, and E_{con} is the amount of energy consumed by the electrolyzer. In this study, a rectifier with the efficiency of 95% and an electrolyzer with the energy consumption of 5 kWh/($N\cdot m^3$) were considered. Equation (21) is used to convert $N\cdot m^3$ to kg [39].

$$kg = N \times m^3 \times \left(\frac{1\ \text{mol}}{0.022414\ N\cdot m^3}\right) \times \left(\frac{0.002016\ \text{kg}}{1\ \text{mol}}\right). \tag{21}$$

4 Calculation

4.1 Hydrogen production using wind energy

Since in this study, all data including wind speed, air temperature, and air pressure needed for calculating the wind energy density for five years (from 2012 to 2016) were measured by IMO in the time interval of 3 h, t is 3 and n equals 365 × 8 × 5. The calculated values for the cities under study are given in Table 5. The results show that Manjil and Ardebil with average wind energy densities of 6004.9 and 3002.6 (kWh/m^2) are the first and second best

1) Photovoltaic software world wide website. How to calculate the annual solar energy output of a photovoltaic system? 2017

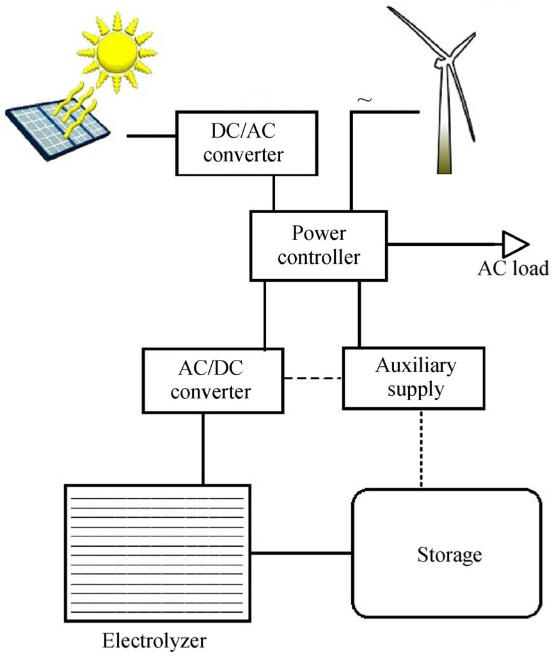


Fig. 1 The examined wind/solar to hydrogen energy conversion system (reprinted with permission from Ref. [25])

Table 5 Average values of k, c, and wind energy density at the height of 40 m

City	Average wind speed/($m\cdot s^{-1}$)	k	c	Wind power density/($W\cdot (m^2\cdot a)^{-1}$)	Wind energy density/($kWh\cdot (m^2\cdot a)^{-1}$)
Manjil	9.13	2.508	10.291	685.49	6004.892
Zabol	7.17	2.218	8.092	337.82	2959.303
Eghlid	6.39	2.098	7.216	225.76	1977.657
Bushehr	6.24	2.072	7.043	246.01	2155.047
Zahak	5.53	1.951	6.239	161.47	1414.477
Zarrineh	6.61	2.132	7.452	266.31	2322.864
Khoor	6.21	2.068	7.011	234.17	2051.360
Noorabad	5.66	1.975	6.385	176.08	1542.437
Ardebil	7.05	2.204	7.960	342.76	3002.574
Binalood	5.73	1.987	6.465	193.35	1693.749

cities in terms of wind energy, respectively. It is evident that Manjil enjoys by far the highest amount of wind energy, followed by Ardebil and Zabol.

To estimate the amount of hydrogen that can be produced via the proposed system using wind energy as a power source, three different types of wind turbines are scrutinized, whose specifications are given in Table 6[1)].

The C_f values, the amount of energy produced by the turbines, the annual CO_2 emission reduction, and hydrogen production are shown in Table 7.

Figure 2 compares the amount of hydrogen (t) produced per year by utilizing the turbines in the cities. It is obvious that as the rated power of a turbine increases, more hydrogen is produced.

One of the main advantages of hydrogen energy utilization such as fuel for vehicles is lack of environmental pollution. Thus, the gasoline consumption and CO_2 emission in the regions under study after using the electricity generated by the turbines at the input of the proposed system is investigated.

According to 2016 Census, every Iranian family contains 4 members and has a car on average[2)]. Moreover, based on Refs. [28,43], one kilogram of hydrogen suffices for supplying energy to drive a car for a week. According

1) Ministry of Energy, Renewable Energy and Energy Efficiency Organization (SATBA). Wind and solar energy resources in Iran. 2017
2) Iranian Students' News Agency (ISNA). Per capita car ownership in Iran. 2017

Table 6 Technical data of selected wind turbines at a hub height of 40 m

Wind turbine	Swept area/m^2	Rated power/kW	Cut-in speed /($m\cdot s^{-1}$)	Rated speed /($m\cdot s^{-1}$)	Cut-out speed /($m\cdot s^{-1}$)
AN BONUS 300 kW Mk III	876.16	300	3	13	25
NORDEX N 27	572.56	150	3	15.5	25
Gamesa G47	1734.94	660	4	15	25

Table 7 C_f values and the amount of energy produced by the turbines, the reduction in annual CO_2 emission, and hydrogen production

City	AN BONUS 300 kW Mk III				NORDEX N 27				Gamesa G47			
	C_f /%	E_{out} /($MWh\cdot a^{-1}$)	CO_2 reduction /($kg\cdot a^{-1}$)	H_2 /($kg\cdot d^{-1}$)	C_f/%	E_{out} /($MWh\cdot a^{-1}$)	CO_2 reduction /($kg\cdot a^{-1}$)	H_2 /($kg\cdot d^{-1}$)	C_f/%	E_{out} /($MWh\cdot a^{-1}$)	CO_2 reduction /($kg\cdot a^{-1}$)	H_2 /($kg\cdot d^{-1}$)
Manjil	45	1182.6	921434.6	55.37	32.5	427.05	332740.3	20	33.7	1948.4	1518114.9	91.22
Zabol	30.5	801.54	624528.0	37.53	21.4	281.196	219096.6	13.17	21.3	1231.48	959520.6	57.66
Gamesa G47	25	657	511908.1	30.76	17.6	231.264	180191.6	10.83	17	982.87	765814.6	46.02
Bushehr	24	630.72	491431.6	29.53	16.9	222.066	173025.2	10.4	16.2	936.62	729776.2	43.85
Zahak	19.5	512.46	399288.2	24	13.8	181.332	141286.6	8.49	12.8	740.05	576613.3	34.65
Zarrineh	26.5	696.42	542622.4	32.61	18.6	244.4	190429.9	11.44	18.1	1046.47	815367.4	49
Khoor	23.8	625.46	487336.5	29.28	16.8	220.75	172000.9	10.34	16	925.06	720766.5	43.31
Noorabad	20.3	533.48	415832.3	24.98	14.4	189.22	147429.8	8.86	13.3	768.95	599137.3	36
Ardebil	29.6	777.89	606099.1	36.42	20.7	272	211930.2	12.74	20.5	1185.23	923482.2	55.49
Binalood	20.8	546.62	425907.4	25.59	14.7	193.16	150501.1	9.04	13.7	792.08	617156.3	37.08

to Iranian Oil Organization, each personal car in this country consumes approximately 772 L of gasoline per year on average, which equals 14.8 L a week[1)]. As it is shown in Table 7, in the case of using one set of Gamesa G47 wind turbine in Manjil, 91.22 kg/d of hydrogen can be generated which is sufficient as fuel for about 91 cars per week (In this study, it is assumed that 1 kg of hydrogen can run a car for a week.). Since each car consumes 14.8 L of gasoline each week, after fueling cars with hydrogen instead of gasoline, 1347 L (91 × 14.8) of gasoline per week or 70222.15 (91 × 14.8 × 52.14) liters of gasoline per year will be preserved. After preventing this amount of gasoline from burning each year, 163.9 tons of CO_2 emission is expected to be reduced in Manjil, calculated by using the RETScreen software. In Table 8, the population, the number of cars, and the average gasoline consumption in the cities are given. Moreover, the amount of hydrogen produced by applying the Gamesa G47 turbine as the input of the proposed system, the gasoline saved per year, and the annual CO_2 emission reduced are computed and shown.

4.2 Hydrogen production using solar energy

The calculated values of parameters *a* and *b* for the cities[2)] were used in this study. Table 9 provides these values and the average annual solar radiation energy. Equation (22) is used to convert J into kWh. As presented in Table 9, Zahedan with the average annual radiation of 2247.074 ($kWh/(m^2\cdot a)$) has the highest amount of solar energy available compared to the other areas under study.

$$1\,J = 2.78\times10^{-7}\ kWh. \tag{22}$$

To estimate the amount of electricity produced by solar energy, 3 types of PV systems with different efficiency and materials were evaluated, whose characteristics are listed in Table 10[2)]. Table 11 presents the amount of electricity (kWh/a) produced by installing PV systems considering 2 scenarios, minimal and largest losses.

Since it is assumed that the rectifier in the hydrogen production system has a high performance with an efficiency of 95%, it is also presumed that the PV systems have the best performance, that is, 85%, for calculation of hydrogen generation, which means they have the lowest amount of losses (15%), the amount of hydrogen produced (t/a) by installation of 1000 PV systems in the cities under study was calculated, considering the fact that significant amount of hydrogen is not produced by utilizing just one set of the PV system (Fig. 3). The results indicate that 7.28 t/a of hydrogen are generated via the installation and utilization of 1000 sets of X21-345 PV system models in Zahedan. To this end, this city has the highest capacity of hydrogen production using the system proposed in this

1) Yaghoubi M. Average fuel consumption per car in Iran. 2017
2) Solar Panel Comparison Website. Technical data of photovoltaic system. 2017

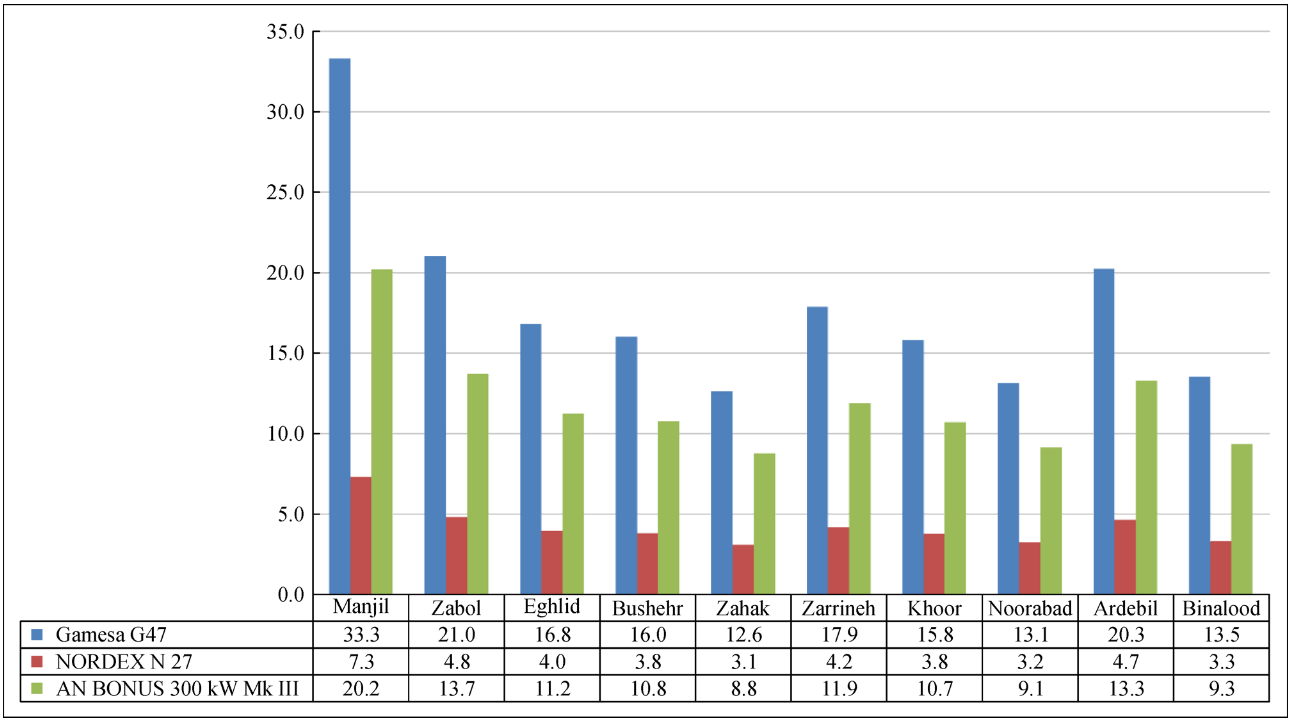


Fig. 2 Hydrogen production (t/a) via the proposed system using wind turbines

Table 8 Hydrogen production by installation of Gamesa G47 turbine, gasoline saved and annual CO_2 emission reduced

City	Population	Cars	Average gasoline consumed/($L \cdot week^{-1}$)	Hydrogen produced /($kg \cdot d^{-1}$)	Gasoline saved /($L \cdot a^{-1}$)	CO_2 emission reduced/t
Manjil	126300	31575	467651.4	91.22	70222.15	163.9
Zabol	167732	41933	621061.7	57.66	43985.30	103.6
Eghlid	98188	24547	363561	46.02	35496.91	82.7
Bushehr	205322	51330	760246.3	43.85	33181.89	78.8
Zahak	85642	21410	317106.9	34.65	26236.85	62.3
Zarrineh	23250	5812.5	86087.84	49.00	37811.93	88.1
Khoor	178232	44558	659940.1	43.31	33181.89	77.8
Noorabad	368452	92113	1364268	36.00	27780.19	64.7
Ardebil	482632	120658	1787043	55.49	42441.96	99.7
Binalood	315274	78818	1167366	37.08	28551.86	66.6

work compared to other cities.

Since hydrogen will be used as fuel for cars instead of gasoline, the hydrogen production which finally leads to saving gasoline after utilizing the PV systems to supply electricity for the proposed system is investigated. The RETScreen software is used for calculating the reduction in CO_2 emission. Table 12 provides the information about hydrogen production, the amount of gasoline saved after using hydrogen as fuel, and the reduction in CO_2 emission by utilizing 1000 sets of X21-345 PV systems as the input of the proposed system in the scenario with the lowest losses.

According to Table 9, Zahedan in Sistan and Baluchestan province situated in the south-east of Iran receives the highest amount of solar energy on average, that is, about 2247 ($kWh/(m^2 \cdot a)$). After developing a site with 1000 sets of X21-345 PV systems and the hydrogen production system proposed in this study, approximately 20 kg of hydrogen is produced in this city each day, which supplies fuel for 20 cars per week.

Table 9 Values of *a* and *b* calculated in Ref. [44] and average annual radiation

City	*a*	*b*	Average annual solar radiation energy	
			(MJ/m^2)	(kWh·(m^2·a)$^{-1}$)
Mehriz	0.345	0.398	7362.32	2046.636
Zarand	0.322	0.421	7601.20	2113.078
Zahedan	0.280	0.433	8083.14	2247.074
Kashan	0.361	0.35	7832.92	2177.296
Abadan	0.359	0.331	7463.47	2074.714
Lar	0.321	0.404	7780.45	2162.840
Saravan	0.275	0.430	7980.65	2218.440
Minab	0.340	0.306	7784.87	2163.952
Jiroft	0.322	0.421	7662.29	2130.116
Nikshahr	0.290	0.415	8012.56	2227.492

5 Conclusions

In this work, a renewable-powered system was proposed to produce hydrogen through water electrolysis process in different cities of Iran. Due to the abundance of wind and solar energy in some regions of the country, the amount of these energies available was computed by using the WDF and AP equation, respectively. Moreover, three different types of wind turbines as well as PV systems were investigated to estimate the amount of electricity produced by them. The results indicate that of all cities under study, Manjil has the largest amount of wind energy density of about 6004 (kWh/(m^2·a)). As regards solar radiation energy, Zahedan receives approximately 2247 (kWh/m^2) solar energy per year.

An investigation of the wind turbines demonstrates that the largest amount of electricity can be generated via the Gasema G47 turbine, which is about 1948 MWh/a for Manil. If one set of this turbine is used for supplying energy for the system proposed, almost 91 kg of hydrogen would be produced per day. This amount of hydrogen provides 91 cars with enough energy to run during a week, saving about 70222 L of gasoline as well as reducing 163.9 tons of CO_2 emission per year.

Additionally, three types of commercial PV systems were evaluated in two scenarios, the highest and lowest losses. It is specified that about 20 kg of hydrogen can be produced per day after utilizing 1000 sets of X21-345 PV systems in Zahedan, which provides energy for 20 cars per week. This means that 15414 L of gasoline will not be burnt per year and approximately 35.9 tons of CO_2 will not be emitted to the atmosphere per year.

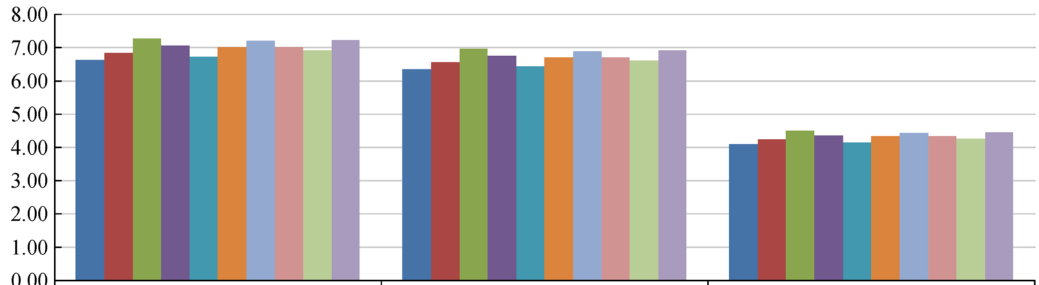
The technical analysis indicates that there are significant potentials for hydrogen production via wind and solar energies in the cities under study, leading to a huge carbon emission reduction by utilizing the hydrogen generated instead of gasoline. It is also required to assess the economic aspects of the hydrogen production system using wind turbines and PV systems. As a result, it is suggested

Table 10 Technical data of selected PV modules

Model	X21-345	PS330P-24/T	KD210GH-2PU
Manufacturer	SunPower	Phono Solar	Kyocera
Module efficiency (or *r* in Eq. (18))	21.16%	17.01%	14.40%
Type	Mono crystalline	Polycrystalline	Polycrystalline
A/m^2	1.63	1.94	1.48

Table 11 Amount of electricity (kWh/a) gained at output of PV systems considering 2 scenarios

City	X21-345		PS330P-24/T		KD210GH-2PU	
	Minimal losses	Largest losses	Minimal losses	Largest losses	Minimal losses	Largest losses
Mehriz	388.25	105.89	371.46	101.31	239.90	65.43
Zarand	400.85	109.32	383.52	104.60	247.69	67.55
Zahedan	426.27	116.26	407.84	111.23	263.39	71.83
Kashan	413.03	112.65	395.17	107.77	255.21	69.60
Abadan	393.57	107.34	376.55	102.70	243.19	66.32
Lar	410.29	111.90	392.55	107.06	253.52	69.14
Saravan	420.84	114.77	402.64	109.81	260.04	70.92
Minab	410.50	111.95	392.75	107.11	253.65	69.18
Jiroft	404.08	110.20	386.61	105.44	249.68	68.10
Nikshahr	422.55	115.24	404.28	110.26	261.10	71.21



	X21-345	PS330P-24/T	KD210GH-2PU
Mehriz	6.63	6.35	4.10
Zarand	6.85	6.55	4.32
Zahedan	7.28	6.97	4.50
Kashan	7.06	6.75	4.36
Abadan	6.73	6.44	4.16
Lar	7.01	6.71	4.33
Saravan	7.19	6.88	4.44
Minab	7.02	6.71	4.33
Jiroft	6.91	6.61	4.27
Nikshahr	7.22	6.91	4.46

Fig. 3 Hydrogen production (t/a) via the system proposed by installing 1000 sets of the examined PV systems

Table 12 Reduction in CO_2 emission after using hydrogen produced as fuel for cars

City	Population	Cars	Average gasoline consumed/$(L \cdot week^{-1})$	Hydrogen produced /$(kg \cdot d^{-1})$	Gasoline saved /$(L \cdot a^{-1})$	CO_2 emission reduced/t
Mehriz	36442	9110	134941.3	18.18	14039.2	32.7
Zarand	66752	16688	247162.8	18.77	14494.9	33.7
Zahedan	670822	167705	2483862	19.96	15413.8	35.9
Kashan	308540	77135	1142432	19.34	14935.0	34.8
Abadan	232366	58091	860389.7	18.43	14232.3	33.1
Lar	68450	17112	253457.4	19.21	14834.6	34.5
Saravan	64800	16200	239935.1	19.70	15213.0	35.4
Minab	66322	16580	245578.1	19.22	14842.4	34.5
Jiroft	122036	30509	451863	18.92	14610.7	34.0
Nikshahr	19688	4922	72898.81	19.78	15274.8	35.5

that further research should be conducted on hydrogen generation in Iran to evaluate the economic feasibility of a wind/solar to hydrogen energy conversion system.

References

1. Bicer Y, Dincer I. Clean fuel options with hydrogen for sea transportation: a life cycle approach. International Journal of Hydrogen Energy, 2018, 43(2): 1179–1193
2. Rezaei M, Salimi M, Momeni M, Mostafaeipour A. Investigation of the socio-economic feasibility of installing wind turbines to produce hydrogen: case study. International Journal of Hydrogen Energy, 2018, 43(52): 23135–23147
3. Singh S, Jain S, Venkateswaran P S, Tiwari A K, Nouni M R, Pandey J K, Goel S. Hydrogen: a sustainable fuel for future of the transport sector. Renewable & Sustainable Energy Reviews, 2015, 51: 623–633
4. Noblecourt A, Christophe G, Larroche C, Fontanille P. Hydrogen production by dark fermentation from pre-fermented depackaging food wastes. Bioresource Technology, 2018, 247: 864–870
5. Schweitzer D, Albrecht F G, Schmid M, Beirow M, Spörl R, Dietrich R, Seitz A. Process simulation and techno-economic assessment of SER steam gasification for hydrogen production. International Journal of Hydrogen Energy, 2018, 43(2): 569–579
6. Aasadnia M, Mehrpooya M. Large-scale liquid hydrogen production methods and approaches: a review. Applied Energy, 2018, 212: 57–83

7. Dou B, Zhang H, Cui G, Wang Z, Jiang B, Wang K, Chen H, Xu Y. Hydrogen production by sorption-enhanced chemical looping steam reforming of ethanol in an alternating fixed-bed reactor: sorbent to catalyst ratio dependencies. Energy Conversion and Management, 2018, 155: 243–252
8. Yan X, Zhang X, Gu C, Li F. Power to gas: addressing renewable curtailment by converting to hydrogen. Frontiers in Energy, 2018, 12(4): 560–568
9. Hao H, Mu Z, Liu Z, Zhao F. Abating transport GHG emissions by hydrogen fuel cell vehicles: chances for the developing world. Frontiers in Energy, 2018, 12(3): 466–480
10. Bekele G, Tadesse G. Feasibility study of small hydro/PV/wind hybrid system for off-grid rural electrification in Ethiopia. Applied Energy, 2012, 97: 5–15
11. Badea G, Naghiu G S, Giurca I, Aşchilean I, Megyesi E. Hydrogen production using solar energy–technical analysis. Energy Procedia, 2017, 112: 418–425
12. Likkasit C, Maroufmashat A, Elkamel A, Ku H, Fowler M. Solar-aided hydrogen production methods for the integration of renewable energies into oil & gas industries. Energy Conversion and Management, 2018, 168: 395–406
13. Saadi A, Becherif M, Ramadan H S. Hydrogen production horizon using solar energy in Biskra, Algeria. International Journal of Hydrogen Energy, 2016, 41(47): 21899–21912
14. Alrabie K, Saidan M N. A preliminary solar-hydrogen system for Jordan: impacts assessment and scenarios analysis. International Journal of Hydrogen Energy, 2018, 43(19): 9211–9223
15. Haddad A, Ramadan M, Khaled M, Ramadan H, Becherif M. Study of hybrid energy system coupling fuel cell, solar thermal system and photovoltaic cell. International Journal of Hydrogen Energy, 2018, in press
16. Assaf J, Shabani B. Experimental study of a novel hybrid solar-thermal/PV-hydrogen system: towards 100% renewable heat and power supply to standalone applications. Energy, 2018, 157: 862–876
17. García Clúa J G, Mantz R J, De Battista H. Optimal sizing of a grid-assisted wind-hydrogen system. Energy Conversion and Management, 2018, 166: 402–408
18. Sarrias-Mena R, Fernández-Ramírez L M, García-Vázquez C A, Jurado F. Electrolyzer models for hydrogen production from wind energy systems. International Journal of Hydrogen Energy, 2015, 40 (7): 2927–2938
19. Douak M, Settou N. Estimation of hydrogen production using wind energy in Algeria. Energy Procedia, 2015, 74: 981–990
20. Kalinci Y, Hepbasli A, Dincer I. Techno-economic analysis of a stand-alone hybrid renewable energy system with hydrogen production and storage options. International Journal of Hydrogen Energy, 2015, 40(24): 7652–7664
21. Blal M, Belasri A, Benatillah A, Hamouda M, Lachtar S, Sahouane N, Laribi S, Mostefaoui M. Assessment of solar and wind energy as motive for potential hydrogen production of Algeria country: development a methodology for uses hydrogen-based fuel cells. International Journal of Hydrogen Energy, 2018, 43(19): 9192–9210
22. Marchenko O V, Solomin S V. Modeling of hydrogen and electrical energy storages in wind/PV energy system on the Lake Baikal coast. International Journal of Hydrogen Energy, 2017, 42(15): 9361–9370
23. Al-Sharafi A, Sahin A Z, Ayar T, Yilbas B S. Techno-economic analysis and optimization of solar and wind energy systems for power generation and hydrogen production in Saudi Arabia. Renewable & Sustainable Energy Reviews, 2017, 69: 33–49
24. Mostafaeipour A, Sedaghat A, Qolipour M, Rezaei M, Arabnia H R, SaidiMehrabad M,Shamshirband S, Alavi O. Localization of solar-hydrogen power plants in the province of Kerman, Iran. Advances in Energy Research, 2017, 5(2): 179–205
25. Rezaei-Shouroki M, Mostafaeipour A, Qolipour M. Prioritizing of wind farm locations for hydrogen production: a case study. International Journal of Hydrogen Energy, 2017, 42(15): 9500–9510
26. Mostafaeipour A, Khayyami M, Sedaghat A, Mohammadi K, Shamshirband S, Sehati M A, Gorakifard E. Evaluating the wind energy potential for hydrogen production: a case study. International Journal of Hydrogen Energy, 2016, 41(15): 6200–6210
27. Mohammadi K, Mostafaeipour A. Economic feasibility of developing wind turbines in Aligoodarz, Iran. Energy Conversion and Management, 2013, 76: 645–653
28. Mohammadi K, Mostafaeipour A, Sabzpooshani M. Assessment of solar and wind energy potentials for three free economic and industrial zones of Iran. Energy, 2014, 67: 117–128
29. Mostafaeipour A, Sedaghat A, Dehghan-Niri A A, Kalantar V. Wind energy feasibility study for city of Shahrbabak in Iran. Renewable & Sustainable Energy Reviews, 2011, 15(6): 2545–2556
30. Rezaei M, Mostafaeipour A, Qolipour M, Tavakkoli-Moghaddam R. Investigation of the optimal location design of a hybrid wind-solar plant: a case study. International Journal of Hydrogen Energy, 2018, 43(1): 100–114
31. Ramli M, Twaha S, Al-Hamouz Z. Analyzing the potential and progress of distributed generation applications in Saudi Arabia: the case of solar and wind resources. Renewable & Sustainable Energy Reviews, 2017, 70: 287–297
32. Li M, Fan L, Liu H, Wu W, Chen J. Impact of time interval on the Ångström-Prescott coefficients and their interchangeability in estimating radiation. Renewable Energy, 2012, 44: 431–438
33. Liu X, Xu Y, Zhong X, Zhang W, Porter J R, Liu W. Assessing models for parameters of the Angstrom–Prescott formula in China. Applied Energy, 2012, 96: 327–338
34. Nikolaidis P, Poullikkas A. A comparative overview of hydrogen production processes. Renewable & Sustainable Energy Reviews, 2017, 67: 597–611
35. Duffie J A, Beckman W A. Solar Engineering of Thermal Processes. 3rd ed. New York: John Wiley & Sons, 2006
36. Bhattacharyya R, Misra A, Sandeep K C. Photovoltaic solar energy conversion for hydrogen production by alkaline water electrolysis: conceptual design and analysis. Energy Conversion and Management, 2017, 133: 1–13
37. Yilmaz F, Balta M T, Selbaş R. A review of solar based hydrogen production methods. Renewable & Sustainable Energy Reviews, 2016, 56: 171–178
38. Strupeit L, Palm A. Overcoming barriers to renewable energy diffusion: business models for customer-sited solar photovoltaics in

Japan, Germany and the United States. Journal of Cleaner Production, 2016, 123: 124–136
39. Sharma S, Ghoshal S K. Hydrogen the future transportation fuel: from production to applications. Renewable & Sustainable Energy Reviews, 2015, 43: 1151–1158
40. Alazemi J, Andrews A. Automotive hydrogen fuelling stations: an international review. Renewable & Sustainable Energy Reviews, 2015, 48: 483–499
41. dos Santos K G, Eckert C T, De Rossi E, Bariccatti R A, Frigo E P, Lindino C A, Alves H J. Hydrogen production in the electrolysis of water in Brazil: a review. Renewable & Sustainable Energy Reviews, 2017, 68: 563–571
42. Rezaei M, Mostafaeipour A, Qolipour M, Arabnia H R. Hydrogen production using wind energy from sea water: a case study on Southern and Northern coasts of Iran. Energy & Environment, 2018, 29(3): 333–357
43. Levene J I, Mann M K, Margolis R M, Milbrandt A. An analysis of hydrogen production from renewable electricity sources. Solar Energy, 2007, 81(6): 773–780
44. Moeini S, Javadi S, Kokabi M, Dehghan-Manshadi M. Evaluating solar radiation in Iran with using an optimum model. Journal of Energy in Iran, 2011, 13: 1–10