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Solar energy potential and performance assessment of CSP plants in different areas of Iran

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Abstract

Concentrating solar power (CSP) plants only exploit direct beam solar radiation in order to generate electricity. It is generally assumed that CSP systems are economic only for locations with direct normal irradiation (DNI) above 1800 kWh/m^2/year (about 5 kWh/m^2/day). In the present study, talented regions of Iran to install CSP plants are identified by using the available measured data of global horizontal irradiation (GHI) from 21 cities. A computational code converts the measured GHI to DNI and by comparing the calculated data, six most talented city area of Iran are selected as the case study. By applying geographical, radiation and meteorological parameters to SAM software, the generation of electricity for a typical CSP plant for these locations are evaluated. The selected CSP plant is a parabolic trough (PT) power plant with capacity of 100 MW and 6 hour thermal storage. Results show that areas around the cities of Bandar-e Abbas, Bushehr, Esfahan, Kerman, Shiraz, and Yazd have more solar energy potential to establish CSP plants in Iran. Annual electricity power for these cities are calculated to be about 234 GWh, 245 GWh, 283 GWh, 318 GWh, 321 GWh and 318 GWh, respectively. Furthermore, employment of solar energy in these areas for electricity generation, considerably conserve fossil fuels and reduces CO_2 emission. Also, a comparison of DNI and power plant electricity generation in the 6 talented cities of Iran and 4 cities of Algeria are performed.

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Keywords: Assessment; CSP; Direct normal irradiation; Iran; Parabolic trough; SAM; Solar potential

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1. Introduction

Energy demand has a significant growth in the recent century due to population growth, development programs and attempt of growth in developing countries as well as new industrial growth in the globe. Fossil fuels have the main role to supply this energy requirement among different types of energy sources. Unavailability of fossil fuel in all regions, high cost, their depletion and air pollution are the most disadvantages of fossil fuels consumption. As a solution to these concerns, development and implementation of new energy resources like nuclear and renewable energies are undeniable. Solar energy as one of the most accessible and reliable renewable energies has experienced an extensive development in the last two decades. Lower cost and higher production efficiency of CSP leads to extend CSP in commercial scale in several countries. CSP technologies exist in four forms; Parabolic Trough, Dish Stirling, Concentrating Linear Fresnel Reflector and Solar Power Tower, among which, solar power tower and parabolic trough are the two main approaches of a large-scale application of CSP systems.

Establishment of a CSP plant requires pre-feasibility study which is included solar energy resource, cost and water supply analysis. The first step in pre-feasibility of CSP plants is solar energy potential assessment. Total solar horizontal energy, GHI, consists of two terms; Beam Horizontal Irradiation (BHI) and Diffuse Horizontal Irradiation (DHI). The CSP technologies only exploit DNI (BHI⁄cos(z), where z is zenith angle) to produce electricity and CSP plants have economic justifiability only for locations with DNI above 1800 kWh/m^2/year [1]. The NREL's SAM software (System Advisor Model) is able to evaluate the plant's energetic and economic performances. SAM software receives the geographical, meteorological and radiation data like latitude, temperature and DNI and by simulating the CSP system, presents desirable outputs such as annual energy output, capacity factor and efficiency.

Several researches have studied CSP plants for different consideration in some countries. Abbas et al. [2] had an assessment of a 100 MW plant for electricity generation based on parabolic trough technology in four typical sites of Algerian climate conditions by using SAM software. Donaji et al. [3] used SAM to assess an annual production between the parabolic trough systems and power tower in Mexico and Spain. Malagueta et al. [4] simulated four types of 100 MW CSP plants with parabolic troughs (simple plants, plants with hybridization and plants with thermal energy storage) based on the SAM at two sites: Bom Jesus da Lapa and Campo Grande. Purohit [5] had a techno-commercial feasibility of four types of CSP plants for 23 locations in India. Izquierdo et al. [6] studied the effect of the solar multiple, the capacity factor and the storage capacity on the cost of electricity from CSP plants. Le Fol et al. [7] first determined suitable areas for CSP and estimated the CSP ceiling generation and subsequently, offered a map of the Levelized Cost of Electricity (LCOE) for a 50 MW CSP plant.

In the present study, DNI for 21 cities of Iran is calculated by available measured data of GHI. By comparing the calculated data, 6 city areas of Bandar-e Abbas, Bushehr, Esfahan, Kerman, Shiraz and Yazd which are more convenient to establish CSP plant are selected as the case study. By using SAM software and applying the calculated value of DNI and the selected meteorological data, output of electricity power for a typical CSP plant with capacity of 100 MW and 6 hour thermal storage for these locations is calculated. Based on electricity generation, values of CO_2 emission reduction and preservation of natural gas are also estimated. Furthermore, a comparison of DNI and power plant electricity generation in the 6 talented cities of Iran and 4 cities of Algeria are performed.

Nomenclature

G_{SC}	solar constant (W/m^2)	K_T	clearness index
H	daily irradiation (J/m^2)	$\bar{K}_T$	monthly average clearness index
H_0	daily extraterrestrial irradiation (J/m^2)	n	day of the year
H_d	daily diffuse irradiation (J/m^2)	nd_k	day of the month
$\bar{H}$	monthly average irradiation (J/m^2)	ndm	number of days of the month
$\bar{H}_0$	monthly average extraterrestrial irradiation (J/m^2)	z	zenith angle (radians)
I	hourly radiation (J/m^2)	δ	declination angle (radians)
I_b	hourly beam irradiation (J/m^2)	ϕ	latitude (radians)
I_d	hourly defuse irradiation (J/m^2)	ω	hour angle (radians)
I_{dn}	hourly direct normal irradiation (J/m^2)	ω_s	sunset hour angle (radians)

2. Methodology

To convert available GHI data into hourly database, a computational code according to the previously mentioned methodology in literature is employed. This methodology is based on the clearness index (K_T), which is the ratio between daily radiation in a horizontal surface and the extraterrestrial radiation. The selected procedure is also used by Larraín et al. [8] and is described essentially by Duffie and Beckmann [9] to precede the calculations.

First it is necessary to compute monthly average clearness index ($\overline{K}_T$) for each month and location, which is defined in [10] as:

$$\overline{K}_T = \frac{\overline{H}}{\overline{H}_0} \tag{1}$$

Where $\overline{H}$ is monthly average radiation and $\overline{H}_0$ is monthly average extraterrestrial radiation, computed for each day and location by the following formula which is presented in [9]:

$$H_0 = \frac{24 \times 3600 \times G_{sc}}{\pi}\left(1 + 0.033\cos\frac{360n}{365}\right)\left[\cos(\phi)\cos(\delta)\sin(\omega_s) + \omega_s \sin(\phi)\sin(\delta)\right] \tag{2}$$

Here, G_{SC} is the solar constant, which is the energy of the sun per unit time, received on a unit area of a surface perpendicular to the propagation direction of the radiation, at mean earth–sun distance, outside of the atmosphere. A value for G_{SC} of 1367 (W/m^2) is used in this paper. Also n is the n-day of the year, ϕ is the latitude in radians, δ is the declination angle in radians, and ω_s is the sunset hour angle in radians. The declination angle is defined by the equation of Cooper [11] as:

$$\delta = 23.45\sin\left(360\left(\frac{284+n}{365}\right)\right) \tag{3}$$

And the sunset hour angle, when the incidence angle is 90°, needed for CSP plants [12], is defined as:

$$\cos(\omega_s) = -\tan(\phi)\tan(\delta) \tag{4}$$

Then, it's assigned a special distribution to the frequency of days with a value of the clearness index K_T. To obtain a daily clearness index, Santos et al. [13] defines daily K_T as:

$$K_T = \frac{1}{\gamma}\ln\left[\left(1 - \frac{nd_k - \frac{1}{2}}{ndm}\right)\exp(\gamma K_{T,\min}) + \left(\frac{nd_k - \frac{1}{2}}{ndm}\right)\exp(\gamma K_{T,\max})\right] \tag{5}$$

Where nd_k is the day of the month, ndm is the number of days of the month and γ is a dimensionless parameter given by:

$$\gamma = -1.498 + \frac{1.184\xi - 27.182\exp(-1.5\zeta)}{K_{T,\min} - K_{T,\max}} \tag{6}$$

Where ξ is also a dimensionless parameter given by:

$$\xi = \frac{K_{T,\min} - K_{T,\max}}{K_{T,\min} - \overline{K}_T} \quad (7)$$

The values of $K_{T,\min}$ and $K_{T,\max}$ are given by:

$$K_{T,\max} = 0.6313 + 0.267\overline{K}_T - 11.9\left(\overline{K}_T - 0.75\right)^8 \quad (8)$$

$$K_{T,\min} = 0.05 \quad (9)$$

Solving above equations for a specific location, artificial months with artificial daily radiations (H) are created, where months are arranged from lowest to highest H. Although this procedure neglects the autoregressive nature of solar radiation, according to Larraín et al. [8], it can be used as a first approximation that, nevertheless, constitutes an improvement from monthly mean computations.

The daily diffuse radiation (H_d) is defined by Erbs correlations in [12], depending on the sunset hour angle (ω_s). According to [12] the daily total diffuse fraction is defined as:

$$\text{For } \omega_s \leq 81.4° : \frac{H_d}{H} = \begin{cases} 1.0 - 0.2727K_T + 2.4495K_T^2 - 11.9514K_T^3 + 9.3879K_T^4 & , \quad K_T < 0.715 \\ 0.143 \quad , \quad K_T \geq 0.715 \end{cases} \quad (10)$$

$$\text{And for } \omega_s > 81.4° : \frac{H_d}{H} = \begin{cases} 1.0 + 0.2832K_T - 2.5557K_T^2 + 0.8448K_T^3 & , \quad K_T < 0.715 \\ 0.175 \quad , \quad K_T \geq 0.715 \end{cases} \quad (11)$$

With H and H_d calculated for each day, hourly radiation (I) is obtained by the ratio of hourly to daily total radiation (r_t), which is defined as the following equation from [9] as a function of hour angle (ω) and sunset hour angle (ω_s):

$$r_t = \frac{I}{H} = \frac{\pi}{24}\left(a + b\cos(\omega)\right)\left(\frac{\cos(\omega) - \cos(\omega_s)}{\sin(\omega_s) - \left(\frac{\pi\omega_s}{180}\right)\cos\omega_s}\right) \quad (12)$$

Where constants a and b are given by:

$$a = 0.409 + 0.5016\sin\left(\omega_s - \frac{60\pi}{180}\right) \quad (13)$$

$$b = 0.6609 - 0.4767\sin\left(\omega_s - \frac{60\pi}{180}\right) \quad (14)$$

Then, based on [10] and [14] assumption that I_d/H_d is the same as I_0/H_0, where I_0 is the hourly extraterrestrial radiation, the hourly diffuse radiation I_d is obtained with the ratio of hourly diffuse to daily diffuse radiation r_d as:

$$r_d = \frac{I_d}{H_d} = \frac{\pi}{24}\left(\frac{\cos(\omega)-\cos(\omega_s)}{\sin(\omega_s)-\left(\frac{\pi\omega_s}{180}\right)\cos\omega_s}\right) \quad (15)$$

Hourly beam radiation (I_b) is calculated by subtracting I_d from I and finally, hourly DNI (I_{dn}) is determined by Eq. (17). In this equation, z is zenith angle.

$$I_b = I - I_d \quad (16)$$

$$I_{dn} = \frac{I_b}{\cos(z)} \quad (17)$$

3. Results

3.1. Solar energy potential assessment

One of the aims of this study is assessment of solar energy potential for various areas of Iran to establish CSP plant; hence, 21 cities in different locations of Iran are selected. These cities with their coordinates are presented in Table 1.

Table 1. Some main cities and their location latitude and longitude of Iran (degrees)

City	(Latitude,Longitude)	City	(Latitude,Longitude)	City	(Latitude,Longitude)
Bandar-e Abbas	(27.18,56.27)	Karaj	(35.84,51.01)	Shiraz	(29.62,52.53)
Birjand	(32.86,59.20)	Kerman	(30.28,57.08)	Tabas	(33.60,56.92)
Bojnurd	(37.48,57.33)	Kermanshah	(34.31,47.07)	Tabriz	(38.07,46.30)
Bushehr	(28.97,50.83)	Khur	(33.78,55.08)	Tehran	(35.70,51.42)
Esfahan	(32.63,51.65)	Mashhad	(36.30,59.60)	Yazd	(31.90,54.37)
Hamedan	(34.80,48.52)	Orumiyeh	(37.56,45.07)	Zahedan	(29.50,60.86)
Jask	(25.64,57.77)	Ramsar	(36.90,50.66)	Zanjan	(36.68,48.48)

In order to analyze solar radiation of these cities, average GHI is determined according to measured data for a period of 10 years. The mean GHI values per square meter per month for the selected cities are shown in Fig. 1. This figure shows that nearly in all considered cities, the mean GHI is more than 1600 kWh/m^2.

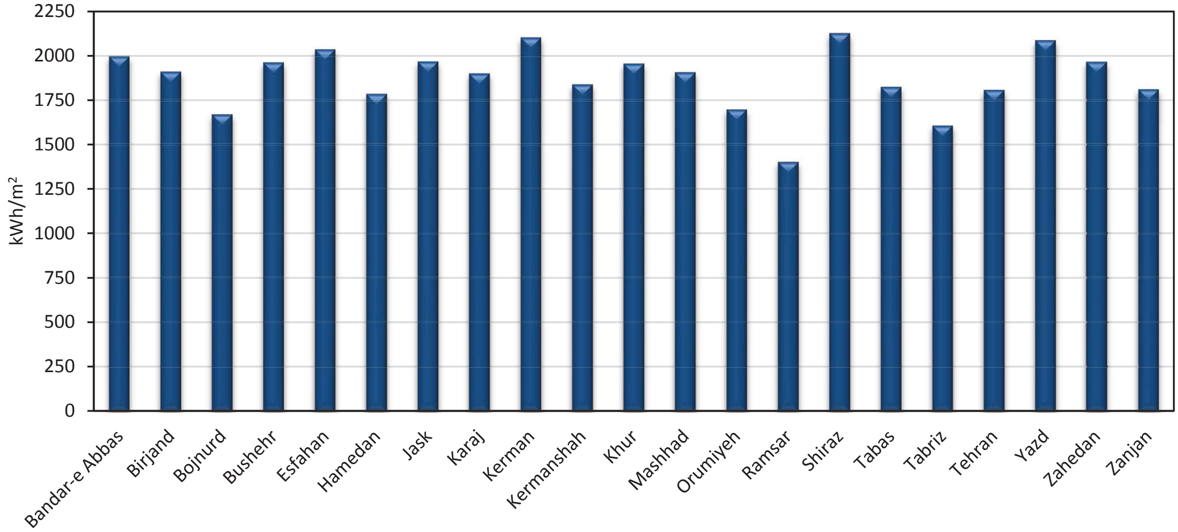

Fig. 1. Average monthly global irradiance in the selected locations of Table 1

Solar map provided by solarGIS organization is depicted in Fig. 2. Acquired GHI values by this figure have a good agreement with the calculated mean GHI. According to the average GHI and other weather condition like the value of humidity and aerosol, six city areas of Bandar-e Abbas, Bushehr, Esfahan, Kerman, Shiraz and Yazd are the best locations to establish a CSP plant. These 6 cities are specified in the solar map, Fig. 2.

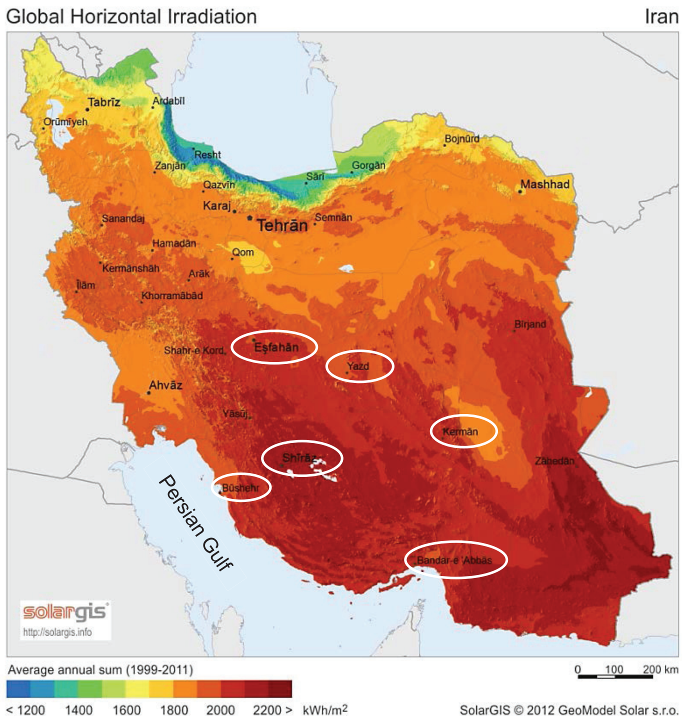

Fig. 2. Solar map of Iran [15] with position of the selected city areas for CSP plant

Since the CSP plants only accept direct solar beam, hourly value of GHI, DNI and DHI are calculated by a computational code developed with the method described in section 2. As an example, the hourly GHI and DNI values for Shiraz is shown in Fig. 3.

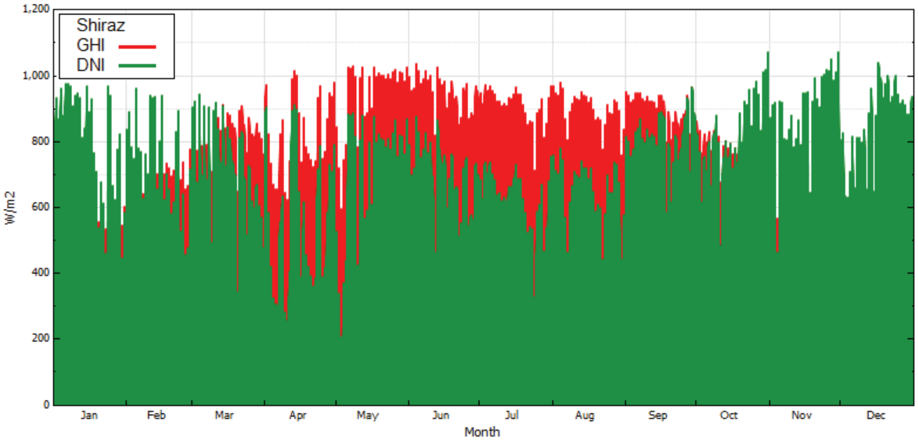

Fig. 3. Hourly values of GHI and DNI in a year for Shiraz, Iran

3.2. CSP plant performance assessment

The analysis of a parabolic trough power plant performance is carried out by using National Renewable Energy Laboratory's (NREL) SAM software [16]. SAM provides modeling capability for several technologies including the parabolic trough technologies [17]. SAM combines an hourly simulation model with performance, cost and finance models to calculate energy output, energy costs and cash flows. The selected parabolic trough power plant has a capacity of 100 MW and 6 hour thermal storage. Other design characteristics are presented in Tables 2 and 3.

Table 2. Specification of parabolic trough collectors selected for simulating the power plant

Parameters	Value	Parameters	Value
Collector type	Luz LS-3	Number of modules per assembly	12
Aperture width	5.75 m	Length of single module	8.33 m
Reflective aperture area per SCA	545 m^2	Mirror reflectivity	0.94
Length of collector assembly	100 m	Focal length	2.1 m

Table 3. Design characteristics of the proposed parabolic trough power plant [2]

Characteristics	Value	Characteristics	Value
Total plant capacity	100 MWe	Absorber tube outer diameter	0.07 m
Total land area	3,152,501 m^2	Glass envelope outer diameter	0.12 m
Condenser type	Air-cooled	Absorber material type	304 L
Collectors and Solar field		HTF type	VP-1
Total field reflector area	861,590 m^2	Design loop outlet temperature	391°C
Number of loops	198	Design loop inlet temperature	293°C
Single loop aperture	4360 m^2	**Thermal Energy Storage (TES)**	
Solar multiple	2	Full load hours of TES	6 hours
Row spacing	15	Storage type	Two tank
Number of field subsections	2	Storage fluid	Solar salt
Thermal receiver and HTF properties		Storage volume	26268.7 m^3
Receiver type	Schott PTR70 2008	Tank diameter	40.9 m
Absorber tube inner diameter	0.066 m	Tank loss coefficient	0.4 $W/m^2.K$

The results of SAM simulation are shown in Figs. 4 and 5. Figure 4 illustrates the annual energy flow that includes incident solar radiation, thermal energy from solar field, thermal energy to power block, gross electric output and net electric output for the considered city areas. The annual electricity generated by the parabolic trough plant is about 234 GWh, 245 GWh, 283 GWh, 318 GWh, 321 GWh and 318 GWh for Bandar-e Abbas, Bushehr, Esfahan, Kerman, Shiraz and Yazd, respectively. It can be seen that Shiraz and Yazd have higher electricity generation which is due to their higher received solar radiation and better weather conditions.

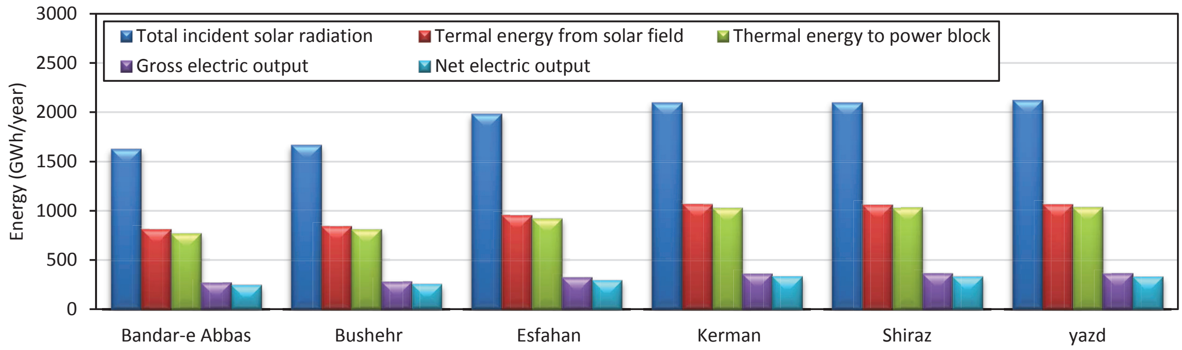

Fig. 4. The parabolic trough power plant waterfall chart, yearly performance and potentials for the selected areas

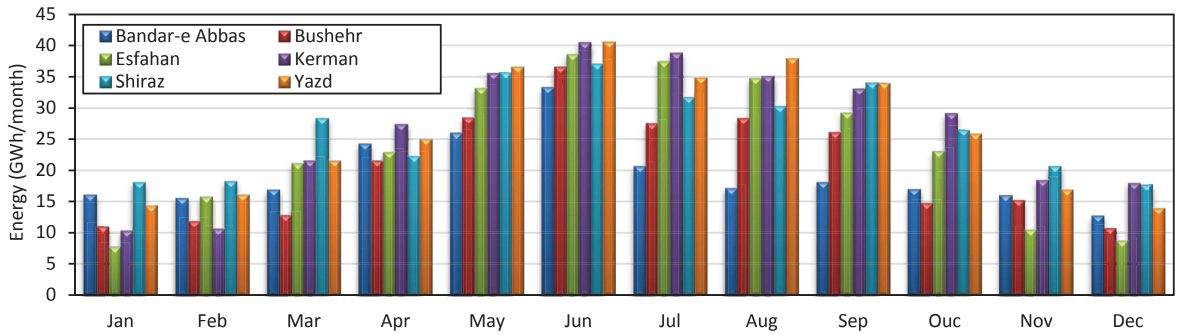

Fig. 5. Monthly energy generation for the selected sites during a year

Monthly electricity generation of the selected cities are shown in Fig. 5 and accordingly the amount of electricity generation has the same trend of solar radiation changes in different months and the best result belongs to month of June.

Gross electric output and some other annual performance parameters of the parabolic trough plant like the capacity factor and global efficiency is summarized on Table 4 for the selected cities. Note that the capacity factor is the ratio of the system's predicted electrical output in the first year of operation to the nameplate output, which is equivalent to the quantity of energy the system would generate if it operated at its nameplate capacity for every hour of the year.

Table 4. Annual performance parameters of the proposed parabolic trough power plant based on Tables 2 and 3

Annual performance parameters	Value					
	Bandar-e Abbas	Bushehr	Esfahan	Kerman	Shiraz	Yazd
Gross electric output (GWh/year)	268.2	281.0	322.5	362.0	363.0	362.8
Capacity factor (%)	26.7	28.0	32.3	36.4	36.6	36.3
Global efficiency (solar to electricity (%))	15.5	15.3	14.9	15.8	15.9	15.6

3.3. Comparison of results

An assessment of solar parabolic trough power plant for electricity generation in the 4 cities of Algeria is done in [2]. A comparison of DNI and electricity generation of parabolic trough power plant in the 6 selected cities of Iran and 4 cities of Algeria (Tamanrasset, Bechar, Ghardaia and Algiers) is shown in Fig. 6. This figure illustrates that highest and lowest solar potentials belong to the cities of Tamannrassat and Algiers of Algeria.

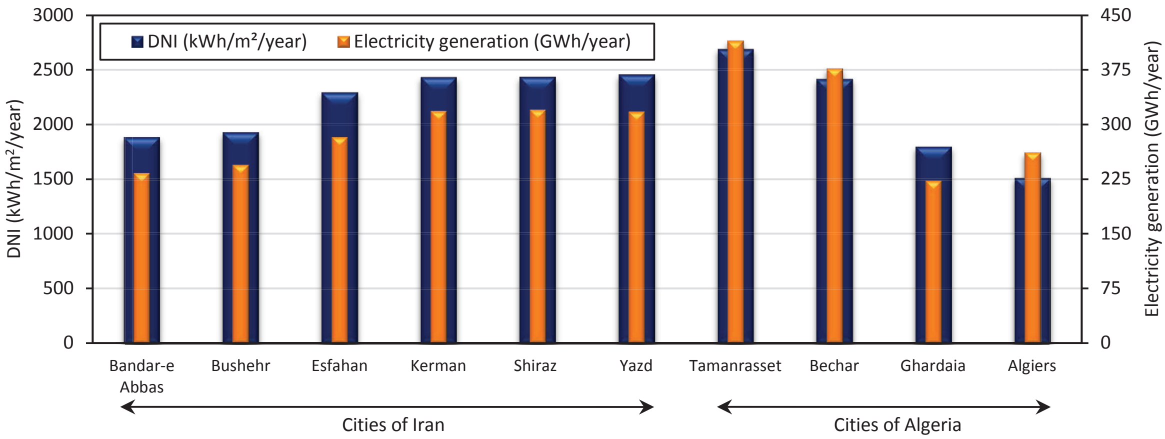

Fig. 6. Comparing the DNI and electricity generation in cities of Iran and Algeria

3.4. CO_2 mitigation and fuel preservation

Renewable energy plants such as CSP plants help to preserve fossil fuels and result in CO_2 reduction. An amount of 28.32 m^3 natural gas is needed to generate 1 kWh electricity [18] and 1 kWh electricity generation is equivalent to 0.63 kg CO_2 (0.35 m^3) emission [19]. Table 5 shows the amount of reducing CO_2 emission and natural gas preservation for the considered plant in the selected cities.

Table 5. The amount of yearly CO_2 mitigation and fuel preservation for parabolic trough in the selected cities (m^3)

	Bandar-e Abbas	Bushehr	Esfahan	Kerman	Shiraz	Yazd
Natural gas preservation	7,594,546,080	7,956,787,200	9,132,520,320	10,251,443,520	10,280,131,680	10,275,204,000
CO_2 mitigation	93,859,150	98,336,000	112,866,600	126,695,100	127,049,650	126,988,750

Table 5 illustrates that yearly values of fossil fuel conservation is considerable. Such amount of natural gas can be used for better quality and higher conversion efficiency materials. Table 5 also indicates that utilizing solar energy can help the country's plan to reduce CO_2 emission which is very high presently due to the current power plant with fossil fuel consumption.

4. Conclusion

The first step of pre-feasibility study for the establishment of a parabolic trough power plant is implemented in this study. By using the measured GHI data for 21 cities of Iran, 6 city areas with higher solar potential are selected. Simulation is done for a 100 MW parabolic trough power plant with 6 hour thermal storage by SAM software. Outputs show that:

1- The site of Shiraz area has the highest potential to generate electricity and Bandar-e Abbas (at Persian Gulf) has the lowest potential.

2- From the sites analyzed; Shiraz, Yazd and Kerman have area with higher solar radiation as illustrated in the solarGIS map. All these areas suffer from water shortage and therefore dry cooling tower are the best condensing system for these locations.
3- The vast arid land around these areas as shown in the solarGIS map is the main advantage of the above sites.
4- Fossil fuel consumption can reduce considerable in these areas and CO_2 emission reduces in line of sustainable development program.
5- Both Iran and Algeria are in the sun-belt region of the world, and computations indicate that there is good opportunity to harness solar energy for electricity generation in both countries.

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