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A new systematic decision support framework based on solar extended exergy accounting performance to prioritize photovoltaic sites

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ABSTRACT

Determining locations is important for researchers and policymakers involved in developing photovoltaic (PV) plants. Here, solar extended exergy accounting performance is proposed as a new systematic decision support framework for prioritizing PV sites from environmental, technical, financial, and social viewpoints. The space-time solar extended exergy accounting performance of a 500 kW grid-connected PV system is determined for different Iranian climates as an example to show how the proposed tool can enhance site selection for PV power systems. The simulations are carried out for all 12 months of the year using the actual climatic, technical, economic, environmental, and social databases. Results for January, April, July, and October, representing winter, spring, summer, and autumn, respectively, are discussed in detail. The outcomes of the proposed method are compared with those for total irradiance, solar irradiance exergy, power generation, and exergy efficiency. In addition, several space-time maps are developed for facilitating comparison among PV installation priorities obtained using various criteria. The average monthly total irradiance and solar irradiance exergy in Iran respectively varies in the range 120−184 kWh/m^2/month and 112−172 kW/m^2/month, respectively. The average monthly power generation, exergy efficiency, and extended exergy accounting performance of the developed plant are respectively found to be in the range of 45.3−66.0 MWh/month, 13.6–14.8%, and 9.46−10.5% for different Iranian climates. Overall, southeast, central, and northwest cities of Iran are shown to be promising candidates for solar PV power systems based on the extended exergy accounting approach. The outcomes show that the proposed tool can be much more helpful than conventional methods for ranking candidate locations for building PV plants. The proposed extended exergy accounting performance framework can be applied for other stand-alone and hybrid renewable energy systems for various environmental and climatic conditions.

1. Introduction

Energy plays a key role in promoting the goals of sustainable development in our modern era (Aghbashlo et al., 2018a). Nowadays, conventional energy resources like coal, oil, and natural gas account for about 80% of the global energy consumption (Rajaeifar et al., 2019). However, environmental pollution, climate change, fossil fuels exhaustion, oil price volatility, and increasing energy

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demands have spurred research and development activities into the use of renewable energy resources (Aghbashlo et al., 2018b). Exploiting widely available solar energy in the forms of heat, electricity, and chemicals is one the most attractive strategies to tackle the above-mentioned issues (Armaroli and Balzani, 2016). In this sense, solar electricity generation has emerged as one of the most promising pathways for harnessing the energy from the sun's radiation (Jordehi, 2016). Among technologies commercialized to date, PV systems have become globally accepted devices to harvest solar radiation and convert it into electricity (Sampaio and González, 2017).

PV systems can be used either as large-scale grid-connected systems or domestic standalone systems (Khare et al., 2016). These renewable electricity generation systems have several advantages like environmental compatibility, modularity, scalability, location flexibility, and government incentives (Uyan, 2013). Finding suitable locations for solar PV power plants is an important issue to boost their performance and to appeal to investors (Gastli and Charabi, 2010). Traditionally, energy-based solar radiation maps or data are employed to recognize the most appropriate locations for solar PV farms.

These insights can provide managers and investors with useful information regarding the most suitable locations for harvesting solar energy (AlYahya and Irfan, 2016). However, areas with the highest solar radiation are not always techno-economically feasible for solar PV power plants. This is because a variety of parameters like technical, financial, climatic, and environmental constraints affect the site selection of PV fields (Uyan, 2013). In addition, energy-based solar radiation databases cannot provide a realistic picture of the potential of solar energy received at the earth's surface for producing useful work (Arslanoglu, 2016). This issue can be effectively addressed using the concept of exergy. The quantity exergy quantifies the upper limit of useful work that can be derived from a thermodynamic system as it reversibly comes to an equilibrium state with the surroundings (Mehrpooya et al., 2018a). Notably, the system must be in mechanical (pressure), thermal (temperature), and chemical (composition) equilibrium with the surroundings (Mehrpooya et al., 2018b), and as well it must have zero velocity and minimum potential energy at the final state.

In spite of the fact that the quantity exergy can be utilized to weigh reliably the ability of an energy carrier to produce useful work (Aghbashlo and Rosen, 2018a), there is no significant difference in the conclusions drawn from energy- and exergy-based solar radiation databases reported in the published literature. This is due to the fact that the variations in the ambient temperature of different locations are too low compared with the sun's temperature. Accordingly, the ambient temperature does not significantly affect the quality factor, i.e., exergy-to-energy ratio, of solar energy delivered to the earth's surface. This problem can be resolved in a satisfactory manner using exergy-based performance metrics.

In general, exergy-based performance metrics can improve understanding of solar energy potential of candidate sites. However, exergy analysis has some weaknesses, e.g., it only takes into consideration physical flows (energy and material) of an energy system, and not its non-energetic and non-material externalities (capital, human labor, and environmental impact) (Ehyaei et al., 2019). The advantages and disadvantages of the solar maps developed to date for locating solar PV farms are summarized in Table 1.

The above-mentioned issues associated with exergy-based solar performance maps can be satisfactorily resolved using the extended exergy accounting method of Sciubba (2019). This approach expresses all inputs to a system on a common exergy basis (Joules), which can be obtained by multiplying externalities by their exergetic equivalences (Seckin, 2016). Accordingly, the present work aims at developing a systematic decision support framework based on the concept of extended exergy accounting for the first time, so as to simultaneously prioritize potential sites for PV installations thermodynamically, economically, environmentally, and socially. More specifically, the novelty of this work lies in introducing a new framework called "solar extended exergy accounting performance" for identifying the most preferred locations for hosting PV power plants.

This paper is organized as follows. In Section 2, a literature review which includes relevant studies pertaining to developing solar maps is presented. The research methodology used in order to implement the extended exergy accounting concept for solar PV power plants is detailed in Section 3. A case study is also considered in that section in order to determine the capability of the proposed tool for providing new perspectives on prioritizing PV sites. The performance of a 500 kW grid-connected PV power system is simulated on the basis of actual climatic data. Thereafter, solar extended exergy accounting performance values are computed for different Iranian climates for all 12 months of the year using real-world technical, financial, environmental, and social data. In section 4, results are reported for January, April, July, and October, representing winter, spring, summer, and autumn, respectively. Furthermore, several space-time maps are developed for facilitating comparisons among PV installation priorities obtained using different criteria. In section 5, to show the soundness and completeness of the proposed approach, the conclusions drawn from the solar extended exergy accounting performance values and maps are compared with those for total irradiance, solar irradiance exergy, power generation, and exergy efficiency criteria. Finally, in section 6, recent developments and future directions in this field are discussed.

2. Literature review

Decision-making about potential sites to build solar PV farms is not straightforward since climatic, technical, economic, environmental, and social factors concurrently affect the site selection process. This difficult task is traditionally accomplished with the aid of space-time solar radiation maps. Much research has been performed on compiling and analyzing space-time solar radiation for many regions of the world.

For example, Munzhedzi and Sebitosi (2009) developed solar radiation maps for PV installations in South African climatic conditions. Azoumah et al. (2010) gathered a solar radiation database applicable to concentrating solar power plants in Burkina Faso. Kaygusuz (2011) published solar radiation values for Turkey for promoting concentrating solar power plants. Zawilska and Brooks (2011) prepared a solar radiation database including direct and diffuse solar radiation on a horizontal surface for South Africa. Rumbayan et al. (2012) computed space-time solar energy values using an artificial neural network on the basis of a geographical information system for Indonesia. Alamdari et al. (2013) reported solar horizontal radiation data for Iran for PV applications. Yaiche et al. (2014) applied numerical models and determined global solar radiation values for Algeria. Azizkhani et al. (2017) prepared global horizontal radiation infromation for PV installations for Iranian climatic conditions.

In order to address the shortcomings of energy-based solar maps in revealing the usefulness and productiveness of solar photons delivered to the surface of solar energy systems, exergy-based solar radiation maps have been developed for several regions around the world. For instance, Alta et al. (2010) provided a space-time solar radiation exergy database for Turkish climatic conditions. Hepbasli and Alsuhaibani (2014) computed exergetic solar radiation values for several Saudi Arabian and Turkish regions. Arslanoglu (2016) evaluated mean horizontal daily global solar

Table 1
Advantages and disadvantages of the solar maps developed to date for locating solar PV farms.

Method	Advantages	Disadvantages
Energy-based solar map	-Measures the quantity of solar energy received at the earth's surface -Provides a rough estimation of solar energy potential of the regions under investigation -Distinguishes potential locations for further evaluation -Can be easily generated using both experimental and theoretical data	-Does not contain the quality of solar energy delivered to the earth's surface -Does not consider climatic conditions of the regions under investigation -Does not account for technical, economic, environmental, and social aspects of solar PV systems -Considers only physical aspects of solar PV systems -Neglects the majority of qualitative factors
Exergy-based solar map	-Determines both the quantity and quality of solar energy delivered to the earth's surface -Presents primary information concerning solar energy potential of the study regions -Identifies locations with a high priority for further detail exploration -Can be generated with a little effort using both experimental and theoretical data	-Does not account for all climatic factors of the study regions -Disregards technical, economic, environmental, and social aspects of solar PV systems -Does not take into consideration non-physical aspects of solar PV systems -Does not include most qualitative factors
Exergy-based solar performance map	-Considers both the quantity and quality of solar energy received by the earth's surface -Provides a good estimation of solar energy potential of the study regions -Recognizes locations with good potential for solar PV farms -Incorporates the majority of climatic factors of the study regions -Takes into account the main technical parameters of solar PV systems	-Does not take into account economic, environmental, and social aspects of solar PV systems -Needs more computational efforts and time -Does not account for non-physical terms of solar PV systems -Ignores the majority of qualitative factors

radiation exergy values for several Turkish provinces utilizing three empirical models. Edalati et al. (2016) trained an artificial neural network to determine solar radiation exergy values for a southern province of Iran (Kerman). Kurtgoz and Deniz (2016) computed solar radiation exergy for Goksun Station in Turkey based on global solar radiation estimated by an artificial neural network. Jamil and Bellos (2019) calculated global solar radiation exergy for 23 Indian cities.

By comparing the patterns obtained from energetic and exergetic solar maps for different regions, it is evident that there is no appreciable difference between these approaches in diagnosing potential locations for solar PV farms devolvement. In order to fill this gap, exergy-based performance metrics have been introduced and determined for various solar energy conversion systems under numerous climatic conditions. For example, Joshi et al. (2009) assessed the exergetic performance of a photovoltaic/thermal (PV/T) system for several Indian and US cites, and later extended that work by measuring exergy destruction for a PV/T system under Indian and US climatic conditions (Joshi et al., 2014). In addition, a solar exergetic efficiency database based on the performance of a PV/T system was developed for Europe by Le Corre et al. (2013).

The above-mentioned performance-based solar exergy maps are more meaningful and helpful for finding the most suitable locations for solar PV farms than both energetic and exergetic solar radiation maps. However, performance-based solar exergy maps alone are not be sufficient to make decisions on the potential locations for installing solar PV farms, since they do not incorporate economic, environmental, and social constraints of solar energy systems.

Given the unique strengths and soundness of the extended exergy accounting method in integrating thermodynamic, economic, environmental, and social aspects of an energy system into a single indicator, worthwhile insights can be obtained into the most preferred sites for establishing solar PV farms using this approach. This holistic framework has attracted the interest of many researchers due to its effectiveness in measuring the degree of sustainability in various contexts, ranging from simple energy systems to very complex social systems (Seckin, 2016). For example, Sciubba et al. (2008) applied extended exergy accounting for analyzing the province of Siena in Italy. Talens Peiró et al. (2010) assessed and compared two biodiesel production pathways, i.e., from used cooking oil and rapeseed crops, by means of extended exergy accounting. Seckin et al. (2012) analyzed Turkish society using extended exergy accounting. Seckin and Bayulken (2013) applied extended exergy accounting for investigating a wastewater treatment plant in Turkey. Seckin (2016) also studied an integrated gasification combined cycle treating Turkish refinery and coke processing wastes using the extended exergy accounting method. Aghbashlo et al. (2018b) utilized extended exergy accounting to assess the performance of a large-scale wind power plant in Iran.

Many believe that the extended exergy accounting method, which is capable of considering all inputs of a system simultaneously, is a useful tool for evaluating the overall sustainability of both energetic and non-energetic systems (Song et al., 2019). The present literature survey revealed that no work has been reported to date on the use of the "extended exergy accounting" concept for exploring potential sites for PV installations. That is, there appears to be no holistic approach available in the published literature to prioritize PV sites from thermodynamic, economic, environment, and social viewpoints simultaneously.

Accordingly, the concept of extended exergy accounting performance is applied here to several Iranian climates as an example to elucidate how this approach can enhance site selection for solar PV power systems. Notably, the proposed exergetic methodology systematically attempts to convert all energetic (material and energy flows) and non-energetic (labor, capital, and environmental costs) into flows of equivalent exergy in order to account for all exchanges between a solar PV power plant and its environment on a rigorous thermodynamic basis. It is believed that the outcomes of using such a framework can be of great interest to researchers and policymakers for developing thermodynamically efficient, economically viable, environmentally sustainable, and socially acceptable solar PV power plants.

3. Research methodology

Fig. 1 illustrates the research methodology used in this study. The steps considered in developing solar extended exergy accounting performance maps are explained in detail in the following subsections.

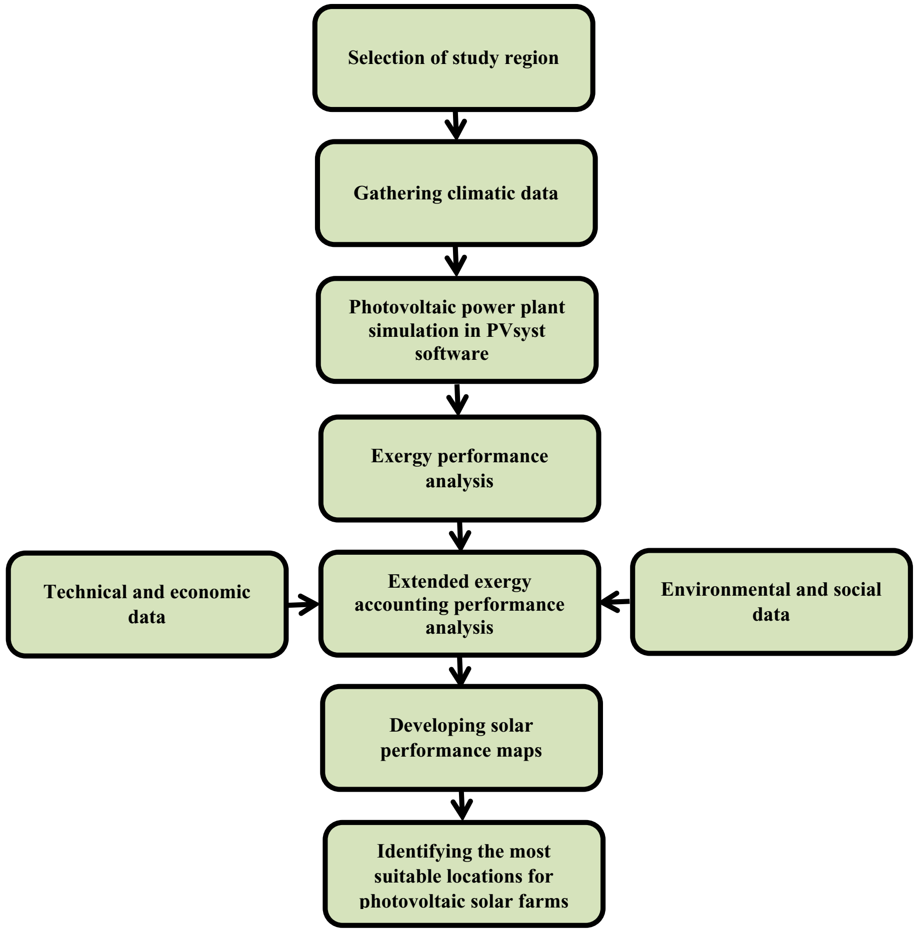

Fig. 1. Research methodology used in this study.

3.1. *Selection of study region*

The solar energy potential in Iran is immense as it is located in the solar belt region with a yearly mean solar irradiation of 20–30 MJ/m^2. Accordingly, a case study is performed for different Iranian climates to assess the reliability and validity of the proposed method in comparison with the solar exergy efficiency methods for siting solar PV plants. The solar performance metrics are determined for various regions of Iran taking into considerations different climatic zones. More specifically, the centers of 30 Iranian provinces covering latitude and longitude ranges of 26–40° E and 44–61° N respectively are considered.

3.2. *Gathering climatic data*

The required information for simulating the performance of the developed plant for 30 Iranian cities, including solar radiation (global and diffuse horizontal) and environmental data (ambient temperature and wind velocity), are obtained using Meteonorm software (version 7.1.11).

3.3. *Photovoltaic power plant simulation with PVsyst software*

In order to determine the solar performance data for Iran's climatic conditions, a 500 kW gird-connected solar PV farms is first designed using PVsyst computer software (Mermoud, 2012) for the rectangular zone under investigation. The software has been widely used in previous research studies aimed at developing and evaluating solar PV power plants (Roche and Blanchard, 2018). The performance of the developed plant obtained using PVsyst for various locations is then used in the calculations. To this end, the data acquired from Meteonorm software are manually imported into PVsyst software.

The plant consists of 1923 PV modules and two 250 kW power inverters. The developed PV power plant is shown in Fig. 2. In this design, the solar modules are divided into two arrays. Each array consists of 53 parallel rows of modules in which each row is composed of 18 modules connected in series. Overall, each array includes 953 modules. The generated electrical power of each array is transferred to a power inverter after passing through a DC combiner. Finally, the power inverter output, i.e., the AC electrical power injected into the power distribution network through a transformer, is determined. Tables 2 and 3 tabulate characteristics of the PV modules and power inverters considered in the simulation. These design and operational data of the components used in

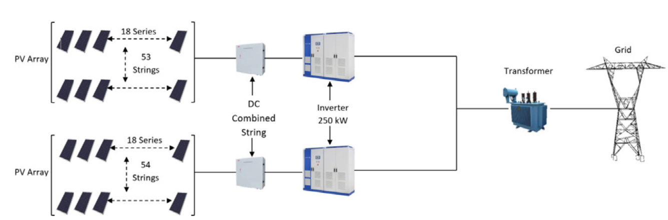

Fig. 2. Schematic representation of the designed solar PV farm.

Table 2
Characteristics of PV modules (http://www.yinglisolar.net/en/).

Company	Yingli Solar
Model	YL250P-29b
Cell material	Poly-Si
Cell number	60 in series
Surface area	1.62 m^2
Peak power	260 W_p
Voltage at peak power point	30.8 V
Current at peak power point	8.43 A
Open circuit voltage	38.2 V
Short circuit current	9.01 A
Operating temperature range	−40 to 85 °C
Nominal operating cell temperature	46±2 °C
Electrical efficiency	16.0 %

Table 3
Characteristics of power inverters (" https://kaco-newenergy.com/home/).

Company	Kaco new energy
Model	Powador XP250-HV
Nominal AC power	250 kW_p
Voltage range at peak power point	450–830 V
Voltage AC	400 V
Number of peak power point inputs	3
Number of string inputs	12
Electrical efficiency	97.4%

the simulation runs are taken from the websites of the relevant manufacturing companies. A ground albedo value of 0.2 is used in the simulation. The inclination angle is considered to be 30° toward the south. The global wiring resistance is set to 54.7 mΩ. A loss fraction of 1.5% is considered for the standard test condition.

3.4. Exergy performance analysis

The exergy efficiency (ψ_{EE}) of a solar PV power system can be obtained as follows:

$$\psi_{EE} = \frac{\dot{E}x_P}{\dot{E}x_{PHY}} \tag{1}$$

where $\dot{E}x_P$ represents the exergy rate of the generated electrical power and $\dot{E}x_{PHY}$ the physical exergy rate of energy fluxes (solar radiation, wind kinetic energy, heat, etc.).

The exergy rate of power generated in the plant can be obtained as a function of fill factor (FF), open circuit voltage (V_{OC}), and short circuit current (I_{SC}) as follows (Joshi et al., 2014):

$$\dot{E}x_P = FF \times V_{OC} \times I_{SC} \tag{2}$$

The solar irradiance exergy as the sole energy flux received by the system can be expressed as a function of ambient temperature (T_a), temperature of the sun (T_s), solar irradiance intensity on the module surface (S_T), surface area of the solar PV module (A_c), and number of PV modules (N) as follows (Joshi et al., 2014):

$$\dot{E}x_{PHY} = \left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right] \times S_T \times A_c \times N \tag{3}$$

3.5. Extended exergy accounting performance analysis

The extended exergy accounting performance (ψ_{EEA}) of the plant can be written as follows:

$$\psi_{EEA} = \frac{\dot{E}x_P}{\dot{E}x_M + \dot{E}x_{PHY} + \dot{E}E_L + \dot{E}E_C + \dot{E}E_{ENV}} \tag{4}$$

where $\dot{E}x_M$ denotes the exergy rate of the material (feedstock), $\dot{E}E_L$ the equivalent exergy rate of labor, $\dot{E}E_C$ the equivalent exergy rate of capital cost, and $\dot{E}E_{ENV}$ the equivalent exergy rate of environmental remediation.

The exergy rate of the material is zero for the plant since it does not consume fuels, minerals, and matter. In addition, the equivalent exergy rate of environmental remediation can be assumed to be zero for the plant since it does not generate pollutants and greenhouse gases during operation.

The equivalent exergy of labor can be determined by multiplying the working hours (L) by the exergetic equivalent of labor (ee_L) as follows (Seckin, 2016):

$$EE_L = L \times ee_L \tag{5}$$

The obtained equivalent exergy of labor from the above equation can be presented in a rate form by dividing by the time period of interest. The exergetic equivalent of labor can be determined as a function of the primary exergy fraction of labor (α), the society's overall exergy inflow (Ex_{in}), and the total working hours (N_{wh}) as follows (Jawad et al., 2015):

$$ee_L = \frac{\alpha \times Ex_{in}}{N_{wh}} \tag{6}$$

The primary exergy fraction of labor can be determined by dividing the society's exergy consumption for survival (Ex_{used}) by the society's overall exergy inflow (Ex_{in}) as follows (Sciubba, 2011):

$$\alpha = \frac{Ex_{used}}{Ex_{in}} \tag{7}$$

Society's exergy consumption for survival can be determined by multiplying the exergy consumption for survival (ex_{surv}) by the number of inhabitants (N_h) and the exergy consumption amplification factor (f) as follows (Sciubba, 2011):

$$Ex_{used} = 365 \times f \times ex_{surv} \times N_h \tag{8}$$

The exergy consumption amplification factor can be obtained by dividing the Human Development Index (HDI) of the society under investigation by the Human Development Index of a primary society (HDI_0) as follows (Sciubba, 2019):

$$f = \frac{HDI}{HDI_0} \tag{9}$$

The capital cost rate ($\dot{C}$) can be translated into exergy by multiplying by the exergetic equivalent of the capital (ee_C) as follows (Sciubba, 2011):

$$\dot{E}E_C = \dot{C} \times ee_C \tag{10}$$

The exergetic equivalent of the capital can be defined as a function of the primary exergy fraction of labor (α), the amplification factor taking into consideration the wealth development created by exclusively financial activities (β), the integration of both money and quasi-money indices (M_2) and the overall costs of wages and salaries in the society (S) as follows (Sciubba, 2011):

$$ee_C = \frac{\alpha \times \beta \times Ex_{in}}{M_2 - S} \tag{11}$$

The amplification factor (β) can be written as (Sciubba, 2011):

$$\beta = \frac{M_2 - S}{S} \quad (12)$$

The capital cost rate ($\dot{C}$) of the PV power system can be computed as a function of initial capital cost (C), capital recovery factor (CRF), and maintenance factor (ϕ) as follows (Aghbashlo et al., 2019):

$$\dot{C} = \frac{C \times CRF \times \phi}{H} \quad (13)$$

The capital recovery factor can be determined as a function of interest rate (i) and plant life time (n) as follows (Aghbashlo et al., 2018d):

$$CRF = \frac{i \times (1+i)^n}{(1+i)^n - 1} \quad (14)$$

3.6. Technical, economic, environmental, and social data

The electricity generation rate of the designed solar PV farm is simulated for all 12 months of the year. Using the exergy rates of electrical power generated and the solar irradiance received by the panels, the exergy efficiency of the plant is computed at the selected months for the 30 cities under investigation. To compute the equivalent exergy rate of capital cost, actual local market costs for equipment and their assembly are taken into consideration (Table 4). The total annual working hours of the plant, maintenance factor, interest rate, and plant life time respectively are considered to be 8760 h, 1.06, 10%, and 25 years. The fixed parameters considered in the extended exergy accounting calculations are listed in Table 5. The exergetic equivalent of labor and capital cost respectively are considered to be 72.5 MJ/h and 91.5 MJ/USD for Iran socio-economic conditions according the calculations carried out previously by Aghbashlo et al. (2018a). In addition, two laborers are considered for every work shift.

3.7. Developing solar performance maps

Once the simulations are completed, the obtained solar performance metrics are applied for ranking the investigated cites in terms of their potential for PV installation. Results are reported and discussed for January, April, July, and October, representing winter, spring, summer, and autumn, respectively. Note that the average monthly results are computed by averaging the values for the 12 months in a year.

4. Results and analysis

Table 5 reports total irradiance values for four months and different Iranian climates representing different climatic conditions. The average monthly total irradiance data is also summarized in Table 5. Fig. 3 displays the average monthly (average per month) space-time total irradiance maps for different Iranian climates. Clearly, the total irradiance is highest in July and lowest in January. The southeast of Iran exhibits the highest total irradiance over the year except in July, when the northwest of Iran has the highest value. In general, the total irradiance for lower latitudes exceeds that for higher latitudes in January, April, and October. However, the highest total irradiance in July is observed for a zone with a latitude range of 32–40° E and a longitude range of 44–47° N. The total irradiance in January, April, July, and October respectively lies in the following ranges: 67–118, 142–196, 181–260, and 93–176 kW/m^2/month. The highest total irradiance in January (118 kW/m^2/month), April (196 kW/m^2/month), and October (176 kW/m^2/month) is observed in Zahedan, while Urmia exhibits the highest total irradiance in July (260 kW/m^2/month). The lowest total irradiance in April (142 kW/m^2/month) and October (93 kW/m^2/month) is observed in Rasht, while Tabriz and Sari respectively exhibit the lowest values in January 67)kW/m^2/month) and July (181 kW/m^2/month). The average monthly total irradiance in Iran varies in the range 120–184 kWh/m^2/month. The highest value of average monthly total irradiance is observed in Zahedan, while Rasht depicts the lowest value.

Table 6 presents solar irradiance exergy values for four months and different Iranian climates. Table 6 also contains the average monthly solar irradiance exergy data. The average monthly space-time total irradiance exergy map for different Iranian climates is shown in Fig. 4. Similar to the total irradiance, July has the highest solar irradiance exergy while the lowest value is seen in January. A zone having a latitude range of 26–33° E and a longitude range of 54–61° N exhibits the highest solar irradiance exergy in January, April, and October, while the highest value in July is observed for northwest of Iran with a latitude range of 32–40° E and a longitude range of 44–47° N. The solar irradiance exergy in January, April, July, and October respectively lies in the range of 63–111, 132–183, 169–242, and 87–164 kW/m^2/month. The upper limit of the solar irradiance exergy in January, April, and October is observed in Zahedan, while Urmia exhibits the maximum value in July. The lower limit of solar irradiance exergy in April and October is observed in Rasht, while Tabriz and Sari exhibit the minimum values in January and July, respectively. The average monthly solar irradiance exergy ranges from as low as 112 kW/m^2/month in Rasht to as high as 172 kW/m^2/month in Zahedan.

Table 7 tabulates the power generation values for four months and average monthly power generation data for different Iranian climates. The average monthly space-time power generation map of the developed PV plant for different Iranian climates is illustrated in Fig. 5. The maximum power generation occurs in July while the minimum value is generated in January. The highest power generation in January and October is generated in the southeast, while the highest value in July is generated in a zone with a latitude range of 34–40° E and a longitude range of 44–46° N. In addition, the highest power generation in April is generated in the northwest and southeast parts of Iran. The power generation in January, April, July, and October respectively lies in the range of 27.7–46.3, 54.5–70.3, 64.8–91.4, and 35.3–63.3 MWh/month. The average monthly power generation ranges from a minimum value of 45.3 MWh/month in Rasht to a maximum value of 66.0 MWh/month in Zahedan.

Table 8 lists exergy efficiency values for four months for different Iranian climates, again representing different climatic conditions. The average monthly exergy efficiency is presented in Table 8 and its corresponding space-time map for different Iranian climates is exhibited in Fig. 6. Unlike the previously discussed parameters, the highest exergy efficiency is seen in January while the lowest value occurs in July. Generally, the exergy efficiency for higher latitudes exceeds that for the lower latitudes during the

Table 4
Real local market costs for components and their assembly.

Component	Cost (USD)
PV panel	292,000
Power inverter	57,100
Structure	46,600
Electrical wiring	14,000
Installation cost	35,000
Electrical accessories	55,700

Table 5
Values of total irradiance for various months and average monthly total irradiance for different Iranian climates.

City	Position in country			Total irradiance (kW/m^2/month)				Average monthly total irradiance (kW/m^2/month)	PV power system installation priority
	Longitude E	Latitude N	Region	January	April	July	October		
Urmia	45°1′	37°5′	Northwest	82	185	260	133	165	9
Tabriz	46°3′	38°1′	Northwest	67	176	246	135	157	20
Ardabil	48°3′	38°3′	Northwest	69	166	220	118	142	26
Zanjan	48°5′	36°7′	Northwest	89	173	232	131	155	21
Sanandaj	47°0′	35°3′	West	78	175	234	136	158	19
Kermanshah	47°1′	34°4′	West	89	175	233	138	161	16
Khoramabad	48°8′	33°5′	West	90	173	231	142	161	15
Ilam	46°4′	33°6′	West	85	170	236	141	161	17
Hamedan	48°5′	34°9′	West	86	171	226	131	154	22
Ahwaz	48°7′	31°3′	Southwest	94	178	227	151	164	11
Rasht	49°6′	37°3′	North	69	142	182	93	120	30
Sari	53°1′	36°6′	North	80	154	181	109	128	29
Gorgan	54°5′	36°8′	North	78	156	186	117	132	28
Tehran	51°6′	35°8′	Central	81	173	221	131	152	23
Qom	51°0′	34°6′	Central	99	181	231	142	164	12
Isfahan	51°7′	32°8′	Central	106	185	236	157	174	4
Semnan	53°6′	35°6′	Central	101	189	223	141	163	13
Qazvin	50°0′	36°3′	Central	83	169	220	127	151	24
Arak	49°7′	34°1′	Central	94	172	226	135	159	18
Yazd	54°4′	31°9′	Central	102	183	232	160	172	5
Shahrekord	50°8′	32°5′	Central	70	176	228	151	162	14
Shiraz	52°5′	29°6′	South	103	184	230	169	174	3
Kerman	57°1′	30°3′	South	111	187	234	168	176	2
Yasuj	51°6′	30°7′	South	82	174	232	162	167	7
Bandar-e-Abbas	56°3′	27°3′	South	112	188	206	153	164	10
Bushehr	50°8′	28°9′	South	100	177	219	161	166	8
Bojnurd	57°3′	37°5′	Northeast	82	168	208	133	146	25
Mashhad	59°6′	36°3′	Northeast	76	155	214	123	141	27
Birjand	59°2′	32°9′	East	108	186	239	158	172	6
Zahedan	60°8′	29°5′	Southeast	118	196	241	176	184	1

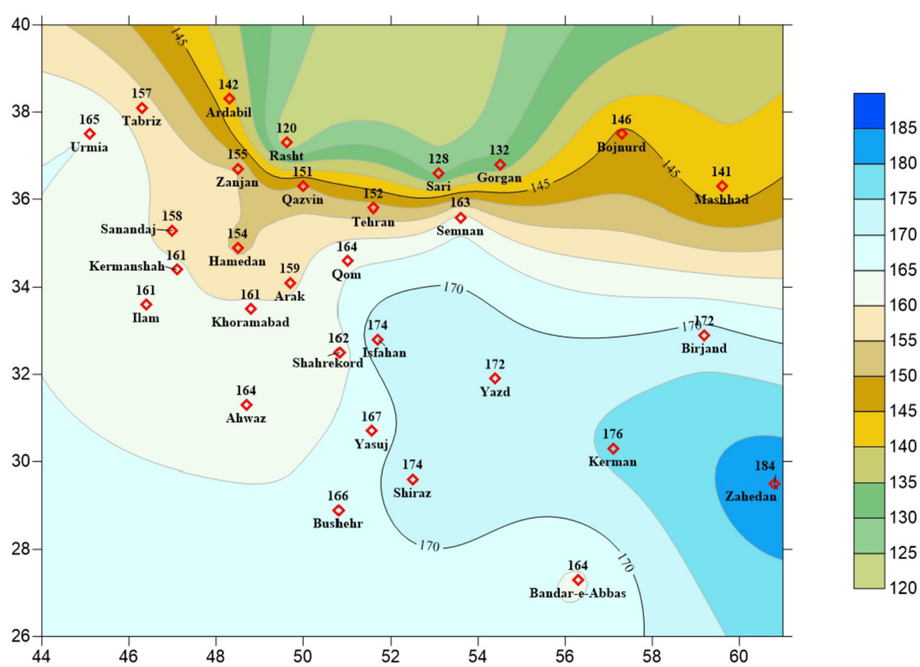

Fig. 3. Average monthly space-time total irradiance (kW/m^2/month) map for different Iranian climates.

year. The exergy efficiency of the plant in January, April, July, and October respectively is found to lie in the range of 14.4–16.1%, 13.6–14.8%, 12.6–14.0%, and 13.2–14.6%. The minimum value of the exergy efficiency in January and April is observed in Bandar-e-Abbas, while Ahwaz and Ilam respectively exhibit the lowest values in July and October. Arak shows the highest values of exergy efficiency in January, while Ardabil exhibits the highest value in April, July, and October. The average monthly exergy efficiency

Table 6
Values of solar irradiance exergy for four months and average monthly solar irradiance exergy for different Iranian climates.

City	Solar irradiance exergy (kW/m^2/month)				Average monthly total irradiance exergy (kW/m^2/month)	PV power system installation priority
	January	April	July	October		
Urmia	77	173	242	124	154	9
Tabriz	63	164	229	126	147	20
Ardabil	65	155	205	110	133	26
Zanjan	83	162	216	122	145	21
Sanandaj	73	164	218	127	148	19
Kermanshah	83	163	217	129	151	16
Khoramabad	84	161	215	132	151	15
Ilam	79	159	219	131	150	17
Hamedan	80	160	211	122	144	22
Ahwaz	88	165	211	140	153	11
Rasht	64	132	170	87	112	30
Sari	75	144	169	101	119	29
Gorgan	73	146	173	109	123	28
Tehran	76	162	206	122	142	23
Qom	92	168	215	132	152	12
Isfahan	100	172	219	146	162	4
Semnan	94	176	207	131	152	13
Qazvin	78	158	205	118	141	24
Arak	88	161	210	126	148	18
Yazd	95	171	215	149	160	5
Shahrekord	65	164	212	141	151	14
Shiraz	97	171	214	157	162	3
Kerman	104	175	218	157	164	2
Yasuj	77	163	216	151	156	7
Bandar-e-Abbas	104	175	191	142	153	10
Bushehr	93	165	203	150	154	8
Bojnurd	77	157	194	124	136	25
Mashhad	72	145	199	115	131	27
Birjand	101	174	223	147	160	6
Zahedan	111	183	225	164	172	1

ranges from a minimum value of 13.6% in Ahwaz to a maximum value of 14.8% in Tabriz.

Table 9 presents extended exergy accounting performance values for four months as well as the average monthly extended exergy accounting performance data for different Iranian climates. Fig. 7 depicts the average monthly extended exergy accounting performance map of the developed PV plant for different Iranian climates. The highest extended exergy accounting performance is observed in April and July while the lowest occurs in January. The extended exergy accounting performance in January, April, July, and October respectively are computed to be in the following ranges: 8.3−9.9%, 10.3–11.1%, 10.0−11.1%, and 8.9−10.5%. The upper limit of extended exergy accounting performance in April and October is observed in Yasuj, while Zahedan and Ardabil respectively exhibit the highest values in January and July. Rasht exhibits the lowest values of extended exergy accounting performance in January and October, while the lowest values in April and July are observed in Mashhad and Ahwaz, respectively. The average monthly extended exergy accounting performance varies from as low as of 9.46% in Rasht to as high as 10.5% in Yasuj.

5. Discussion

According to Table 5 and Fig. 3, solar radiation values provide a good overview of solar potentials of different areas, but the most suitable places for hosting PV power systems cannot be satisfactorily identified solely based on such information. It is well-documented that site selection for solar PV farms is a multi-attribute decision-making problem in which various factors like climatic, economic, environmental, technical, and social parameters should be taken into account (Zoghi et al., 2017). Therefore, a reasonable site selection approach that considers all of these influential parameters together needs to be developed to ensure the successful implementation of solar PV farms around the world.

A comparison of data reported in Tables 5 and 6 demonstrates that the solar irradiance exergy of a given location is slightly lower than its corresponding total irradiance since the quality factor of solar radiation is somewhat lower than unity. However, both monthly and average monthly solar irradiance exergy values follow similar trends to those of monthly and average monthly total irradiance magnitudes. The solar irradiance exergy values tabulated in Table 6 and depicted in Fig. 4 provide reasonable estimates of locations where solar resources can be efficiently converted to useful work. However, this metric cannot provide new relevant insights into the most eligible locations for PV systems when compared with the total irradiance. Indeed, both solar radiation energy and exergy values can only provide an approximate picture of the potential of a given site for solar applications. Hence, comprehensive decision-making tools considering almost all influential parameters need to be developed and applied for identifying and selecting the most appropriate places for solar PV farms.

A comparison among data presented in Tables 6 and 7 that there is no direct association between quantities of solar irradiance exergy and power generation values. That is, several other factors such as ambient temperature and wind velocity can notably affect the electrical efficiency of PV modules. This demonstrates why implementing PV power plants according to the solar irradiance exergy can be misleading. The power generation databases can substantially aid in the development of PV systems, but they cannot alone determine optimal locations to place solar PV farms. In fact, reliance on technical infromation, i.e., power generation data alone is insufficient as such insights cannot satisfactorily provide all the details needed by decision-makers for siting and sizing solar PV power plants. This shortcoming of power generation data can be addressed effectively by incorporating technical, financial,

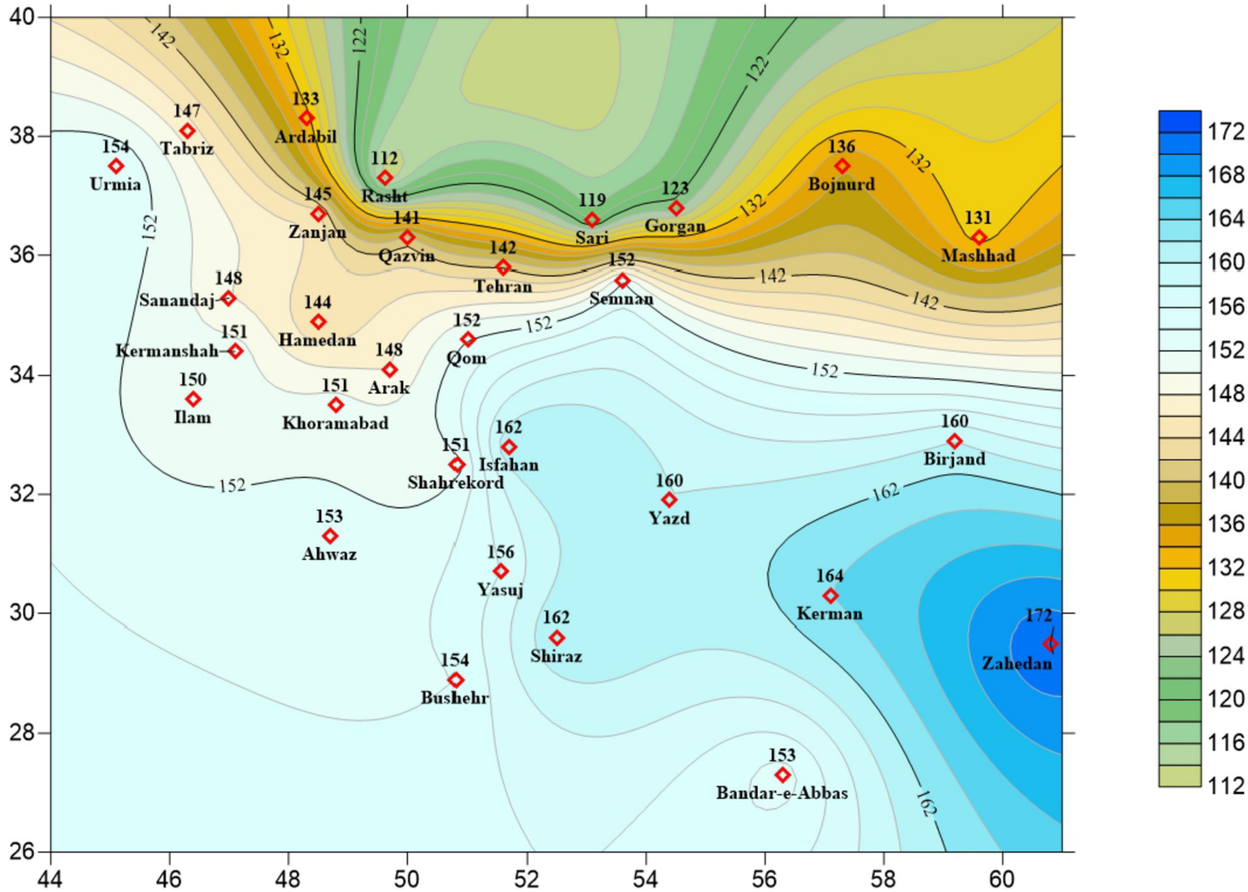

Fig. 4. Average monthly space-time total irradiance exergy (kW/m^2/month) map for different Iranian climates.

environmental, and social perspectives into siting and sizing decisions.

Surprisingly, an inverse association between the solar irradiance exergy and the system's exergetic efficiency is observed when comparing data given in Tables 6 and 8 This is because the solar radiation cannot be converted efficiently to useful work in regions with higher amounts of solar irradiance exergy. Moreover, the higher ambient temperature at sunny regions, which negatively affects the PV modules performance, also is a reason for this finding. In addition, a comparison of data reported in Tables 7 and 8 shows that the exergy efficiency values do not follow the trends of the power generation data. This means that the solar radiation is not a dominant parameter in the performance of PV systems. Dimensionless exergy efficiency can provide a reliable metric for comparing the suitability of different sites for hosting solar energy systems, but it may result in misleading decisions regarding the development of solar PV farms. That is, conventional exergy analysis does not include economic, environmental, and social factors (Aghbashlo and Rosen, 2018b). Accordingly, an enhanced exergetic decision-making rationale should be developed taking into consideration these constraints (Aghbashlo et al., 2018c).

The PV installation priority obtained using the extended exergy accounting theory is significantly different from that provided by total irradiance, solar irradiance exergy, power generation, and exergy efficiency approaches (Table 5–9). A comparison of data provided in Tables 8 and 9 shows that the extended exergy accounting performance of the plant for a given location at a given time is lower than the corresponding exergy efficiency. That is, the extended exergy accounting theory incorporates the exergy associated with the non-energetic and non-material terms, unlike the conventional exergy analysis. Generally, the extended exergy accounting approach identifies the southeast, central, and northwest regions of Iran as having the highest performance and as the most suitable regions for PV power systems. The northwest part of Iran receives moderate levels of solar irradiance exergy, but the ambient temperature in this region is more appropriate for the optimal performance of PV modules. Even though the ambient temperature is somewhat higher than desired for PV modules in the southeast part of Iran, good values of solar irradiance exergy and its availability during the year make this region more favorable for solar PV farms. In addition, the solar irradiance exergy value is relatively high in the central part of Iran while the ambient temperature is not critical for the optimal operation of PV systems.

According to the results obtained with the solar extended exergy accounting performance values, the most suitable areas for PV power plants siting are located in the southeast, central, and northwest regions of Iran. This finding differ from the results of Alamdari et al. (2013), who identify the southwest and northeast parts of Iran as the most appropriate regions for harvesting solar irradiation. Those results are based on mean radiation per month on a horizontal surface. In another study, Besarati et al. (2013) reported that solar PV power systems would be efficient in central and southern parts based on solar radiation values. However, solar exergy accounting performance values identify the entirety of Iran's southern region as unsuitable for PV power plants. In further contrast to the findings of Besarati et al. (2013), the northwest of Iran is found here to be a proper region for PV power systems. In a different study, Vafaeipour et al. (2014) ranked Yazd city first

Table 7
Power generation values for 4 months as well as average monthly power generation data for different Iranian climates.

City	Power generation (MWh/month)				Average monthly power generation (MWh/month)	PV power system installation priority
	January	April	July	October		
Urmia	34.2	69.7	91.4	50.7	61.4	7
Tabriz	27.7	66.2	85.5	50.3	58.7	13
Ardabil	28.2	64.2	80.8	45.1	53.9	25
Zanjan	37.0	65.8	82.4	49.4	58.1	17
Sanandaj	32.0	65.8	80.9	50.6	57.9	18
Kermanshah	35.9	64.9	79.3	50.8	58.5	15
Khoramabad	36.6	64.6	78.7	52.0	58.6	14
Ilam	34.1	63.2	81.6	48.8	57.8	20
Hamedan	35.4	64.5	79.1	48.8	56.9	22
Ahwaz	36.8	63.7	74.5	52.9	57.3	21
Rasht	27.8	54.5	66.0	35.3	45.3	30
Sari	32.2	58.6	64.8	40.9	47.8	29
Gorgan	31.2	59.4	66.7	43.8	49.3	28
Tehran	33.1	64.1	76.2	48.0	55.5	24
Qom	39.7	66.6	78.1	51.9	59.1	11
Isfahan	42.6	68.3	80.0	57.0	62.7	4
Semnan	40.4	68.8	76.2	51.4	58.9	12
Qazvin	34.2	63.3	76.7	47.2	55.7	23
Arak	39.6	65.8	80.2	51.7	59.8	9
Yazd	40.4	66.4	77.9	57.5	61.3	8
Shahrekord	27.7	63.3	77.9	54.3	57.8	19
Shiraz	41.0	67.5	78.2	60.4	62.5	5
Kerman	43.5	68.0	80.4	60.4	63.2	2
Yasuj	34.2	67.4	83.1	61.1	62.8	3
Bandar-e-Abbas	42.3	66.7	71.6	53.8	58.3	16
Bushehr	38.6	64.9	76.3	56.6	59.6	10
Bojnurd	33.6	62.2	72.2	49.3	53.8	26
Mashhad	31.1	57.4	74.4	45.6	51.3	27
Birjand	42.8	67.2	81.7	56.9	61.8	6
Zahedan	46.3	70.3	82.9	63.3	66.0	1

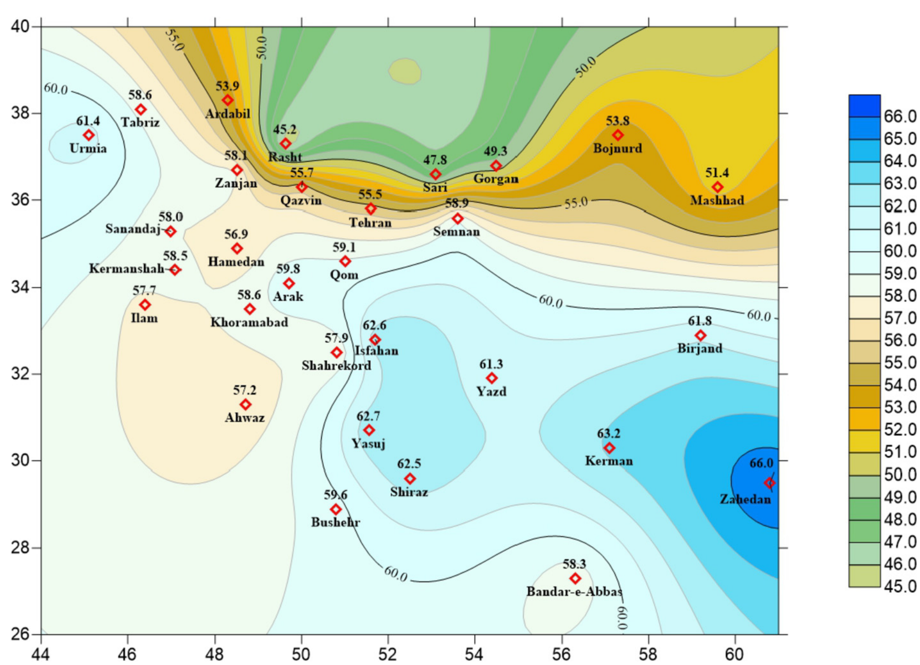

Fig. 5. Average monthly space-time power generation (MWh/month) map of the developed PV plant for different Iranian climates.

among 25 Iranian cities for solar projects on the basis of a hybrid multi-criteria decision making approach. The solar extended exergy accounting performance values do not introduce this city as the most preferred location for building PV systems. Recently, Azizkhani et al. (2017) proposed Fars as well as Sistan and Baluchistan provinces of Iran as appropriate locations for PV power plants through an analytical hierarchy process that considers solar radiation, economic, technical, and geographical factors. Further, some locations in the central and northwest regions of Iran are also identified as promising candidates for PV power systems throughout this study.

Overall, solar extended exergy accounting performance can provide valuable insights to policymakers, and can support decision-making concerning the selection of potential sites for

Table 8
Exergy efficiency values for 4 months as well as average monthly exergy efficiency data for different Iranian climates.

City	Exergy efficiency (%)				Average monthly exergy efficiency (%)	PV power system installation priority
	January	April	July	October		
Urmia	15.9	14.4	13.5	14.5	14.5	7
Tabriz	15.8	14.4	13.3	14.3	14.8	1
Ardabil	15.6	14.7	14.1	14.6	14.7	2
Zanjan	15.9	14.5	13.6	14.4	14.5	6
Sanandaj	15.6	14.3	13.2	14.2	14.3	13
Kermanshah	15.4	14.2	13.0	14.1	14.1	17
Khoramabad	15.4	14.3	13.0	14.0	14.1	16
Ilam	15.3	14.2	13.3	13.2	13.9	23
Hamedan	15.7	14.4	13.4	14.2	14.3	11
Ahwaz	14.9	13.7	12.6	13.5	13.6	30
Rasht	15.4	14.7	13.9	14.5	14.6	5
Sari	15.3	14.5	13.7	14.4	14.5	8
Gorgan	15.2	14.5	13.7	14.3	14.4	9
Tehran	15.5	14.1	13.2	14.0	14.2	14
Qom	15.3	14.1	13.0	14.0	14.1	19
Isfahan	15.2	14.1	13.0	13.9	14.0	20
Semnan	15.3	13.9	13.1	14.0	14.1	18
Qazvin	15.7	14.3	13.3	14.2	14.4	10
Arak	16.1	14.6	13.6	14.6	14.6	3
Yazd	15.1	13.9	12.9	13.7	13.9	27
Shahrekord	15.1	13.7	13.1	13.8	13.9	25
Shiraz	15.1	14.0	13.0	13.7	13.9	22
Kerman	15.0	13.9	13.1	13.7	13.9	21
Yasuj	15.8	14.8	13.7	14.4	14.6	4
Bandar-e-Abbas	14.4	13.6	13.3	13.5	13.7	29
Bushehr	14.8	14.0	13.4	13.5	13.9	26
Bojnurd	15.6	14.2	13.3	14.1	14.3	12
Mashhad	15.5	14.1	13.3	14.1	14.2	15
Birjand	15.1	13.8	13.1	13.8	13.9	24
Zahedan	14.9	13.7	13.2	13.7	13.8	28

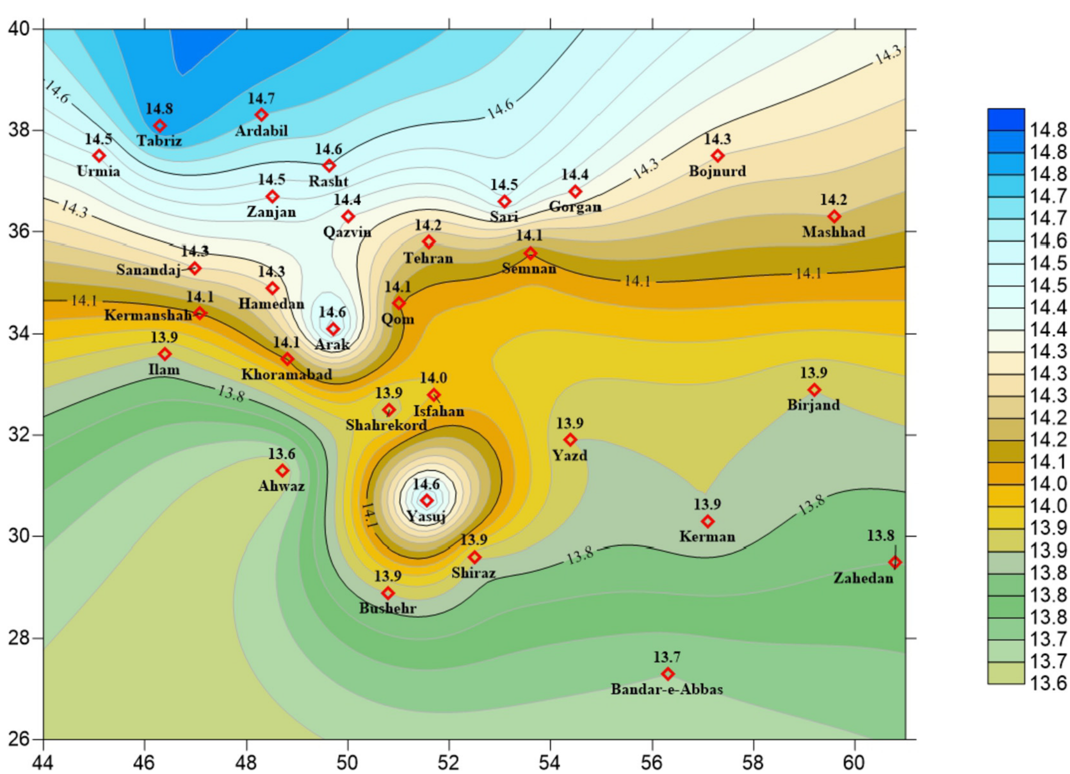

Fig. 6. Average monthly exergy efficiency (%) map of the developed PV plant for different Iranian climates.

solar power farms and their sizing. The strength of solar extended exergy accounting performance method is that it precludes the subjectiveness and inconsistencies of expert opinions from imposing a bias on the results, unlike what occurs with weighting-

Table 9
Extended exergy accounting performance values for four months and average monthly extended exergy accounting performance data for different Iranian climates.

City	Extended exergy accounting performance (%)				Average monthly extended exergy accounting performance (%)	PV power system installation priority
	January	April	July	October		
Urmia	9.20	11.0	11.0	10.0	10.3	4
Tabriz	8.36	10.8	10.7	9.89	10.2	7
Ardabil	8.36	10.9	11.1	9.72	10.0	20
Zanjan	9.50	10.9	10.8	9.90	10.2	8
Sanandaj	8.87	10.8	10.6	9.87	10.0	18
Kermanshah	9.23	10.7	10.4	9.83	10.1	15
Khoramabad	9.30	10.7	10.4	9.87	10.1	14
Ilam	9.02	10.6	10.6	9.30	9.87	24
Hamedan	9.29	10.8	10.6	9.78	10.0	17
Ahwaz	9.15	10.4	10.0	9.63	9.77	26
Rasht	8.27	10.4	10.4	8.85	9.46	30
Sari	8.79	10.6	10.3	9.28	9.66	29
Gorgan	8.64	10.6	10.4	9.46	9.73	27
Tehran	8.97	10.6	10.4	9.64	9.92	22
Qom	9.57	10.7	10.3	9.86	10.1	13
Isfahan	9.78	10.8	10.4	10.1	10.2	6
Semnan	9.62	10.7	10.3	9.82	10.1	11
Qazvin	9.13	10.7	10.5	9.67	10.0	19
Arak	9.84	10.9	10.8	10.1	10.4	2
Yazd	9.52	10.5	10.2	10.0	10.1	12
Shahrekord	8.15	10.4	10.4	9.86	9.84	25
Shiraz	9.60	10.7	10.4	10.1	10.2	9
Kerman	9.73	10.6	10.5	10.1	10.3	5
Yasuj	9.18	11.1	10.9	10.5	10.5	1
Bandar-e-Abbas	9.42	10.4	10.3	9.69	10.0	21
Bushehr	9.26	10.6	10.5	9.83	10.1	16
Bojnurd	9.04	10.5	10.3	9.76	9.91	23
Mashhad	8.70	10.3	10.4	9.53	9.68	28
Birjand	9.75	10.5	10.5	9.99	10.2	10
Zahedan	9.94	10.6	10.5	10.2	10.3	3

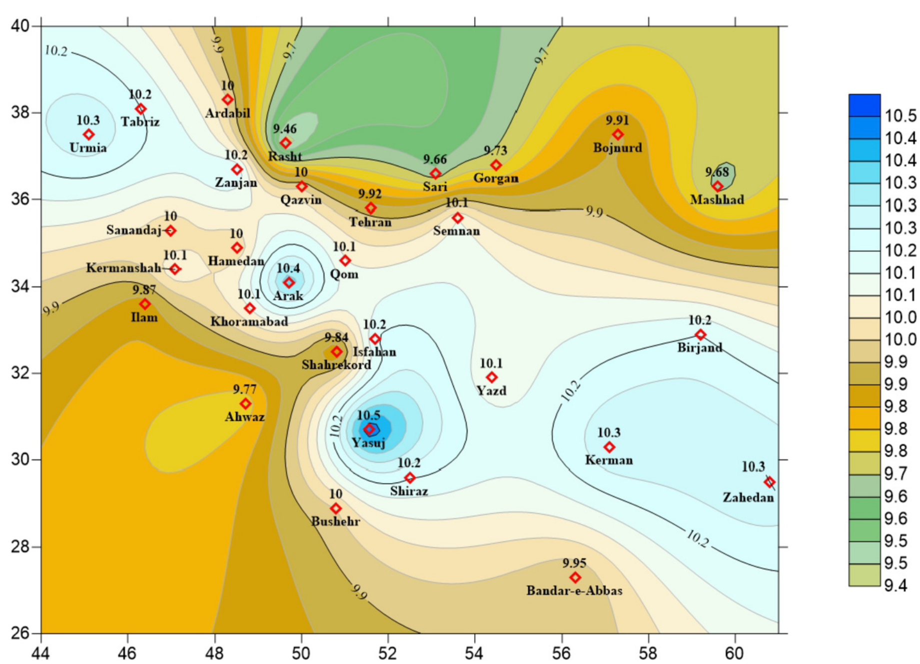

Fig. 7. Average monthly extended exergy accounting performance (%) map of the developed PV plant for different Iranian climates.

based decision-making approaches. This can be attributed to the fact that the unique conceptual features of the exergy method which value all streams by accounting for their quantity and quality dimensions simultaneously (Aghbashlo et al., 2017). In addition, all energetic/non-energetic and material/non-material terms of thermodynamic and non-thermodynamic systems can be translated to a common exergy basis using the extended exergy accounting concept. This approach can also effectively associate technical aspects of a production process with its surroundings, i.e., society and environment (Song et al., 2019). Moreover, determining the solar extended exergy accounting performance data is substantially time and cost saving compared with multi-criteria decision making methods.

6. Recent developments and future directions

For several years the selection of suitable locations for installing PV systems was limited to energy- or exergy-based solar radiation maps. This because the goal was no longer to generate cost competitive, environmentally compatible, and socially acceptable electricity but rather to develop lab- or pilot-scale demonstration solar PV systems. With increasing demand for implementing large-scale solar PV power plants around the world, several researchers have attempted to develop comprehensive decision-making tools for locating and dimensioning such renewable energy systems. For instance, Fang et al. (2018) developed an integrated approach on the basis prospect theory in order to select sustainable sites for PV power plants. Merrouni et al. (2018) combined a geographic information system and analytical hierarchy process techniques to evaluate the propriety of Eastern Morocco for hosting large-scale PV systems. Doorga et al. (2019) developed a multiple criteria decision making combined with analytical hierarchy process method in order to model solar PV potential of tropical islands. Ghasemi et al. (2019) coupled geographic information system with analytical hierarchy method to find the most appropriate locations for installing solar PV power plants. Nadizadeh Shorabeh et al. (2019) presented a multi-criteria spatial decision analysis including the concept of risk for selecting solar PV power plant sites.

Even though the above-mentioned approaches can help decision makers to find the most appropriate places for setting solar PV farms, they do not account for all the quantitative factors required for comprehensive decision-making. On the other hand, the solar extended exergy accounting performance method developed throughout this study does not include all the qualitative features needed for siting solar PV farms. Accordingly, future work should strive to integrate all qualitative and quantitative factors simultaneously in order to boost the quality of the conclusions derived from solar maps. In addition, the approach proposed here has some weaknesses. Despite the fact that extended exergy accounting performance information for a given solar energy harnessing technology can provide very informative and beneficial results, the obtained conclusions are not valid for other solar technologies. This means that solar extended exergy accounting performance databases should be developed for each solar energy technology. Finally, future works should be oriented towards providing extended exergy accounting databases for hybrid renewable energy systems since stand-alone renewable energy systems cannot provide continuous energy generation.

7. Conclusions

The present work is devoted to developing and examining a new decision support system based on the extended exergy accounting concept for the first time for prioritizing potential sites for PV installations from thermodynamic, economic, environment, and social viewpoints simultaneously. More specifically, the novelty of the present work is the introduction of a new framework called "solar extended exergy accounting performance" for identifying the most preferred locations for hosting PV power plants. A detailed description of the theory of the proposed framework is presented. A case study is conducted to determine the capability of the developed decision-making framework for providing new perspectives on prioritizing PV sites. The performance of a 500 kW grid-connected PV power system is simulated on the basis of climatic data. Thereafter, the space-time solar extended exergy accounting performance values are computed for different Iranian climates for all 12 months of the year using real-world technical, financial, environmental, and social data. The conclusions drawn from solar extended exergy accounting performance values are also compared with those of total irradiance, solar irradiance exergy, power generation, and exergy efficiency. The following conclusions can be drawn from the current study:

1) The average monthly total irradiance and solar irradiance exergy in Iran respectively are found to be in the range 120−184 kWh/m^2/month and 112−172 kW/m^2/month.
2) The average monthly electricity generation of the developed solar power plant is found ranging from 45.3 to 66.0 MWh/month for different Iranian climates.
3) The average monthly exergy efficiency and extended exergy accounting performance of the developed plant are respectively determined in the range of 13.6–14.8% and 9.46−10.5% for different Iranian climates.
4) The trends of solar irradiance exergy data are almost identical to those of total irradiance values.
5) The solar radiation databases in both energetic and exergetic forms cannot satisfactorily help policymakers and investors in siting and sizing PV power systems.
6) Unlike the informative character of power generation data, they cannot alone determine the most appropriate sites for solar PV development projects.
7) Exergy efficiency values may result in misleading decisions concerning the development of solar PV farms.
8) Solar extended exergy accounting performance values show that southeast, central, and northwest of Iran are feasible for PV power plants.
9) The most suitable places in Iran for hosting PV power systems recognized using the various developed space-time solar maps demonstrate the reliability and consistency of the solar extended exergy accounting method over the other existing approaches.

The developed framework appears to be a reasonable and reliable tool that supports the decision-making process concerning site selection for solar PV farms. The obtained results demonstrate that extended exergy accounting can enable researchers and policymakers to identify the most suitable locations for solar electricity generation by consolidating all energetic/non-energetic and material/non-material data of solar power plants. However, the use of the extended exergy accounting approach is associated with some challenges such as difficulties in determining the exergetic equivalents of labor and capital and in bypassing double-counting errors. Future research work is merited on the determination of extended exergy accounting databases for other stand-alone and hybrid renewable energy systems. Such information can aid in developing and implementing more efficient, productive, and sustainable renewable energy systems and technologies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Mortaza Aghbashlo: Conceptualization, Writing - review & editing. **Meisam Tabatabaei:** Conceptualization, Writing - review & editing. **Ehsan Rahnama:** Investigation, Software, Data curation. **Marc A. Rosen:** Writing - review & editing.

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