Performance and CO_2 emission evaluation of a grid-connected photovoltaic system at two different climates

Ahmad Saeidavi

Renewable Energy Engineering Department,
Shahid Chamran University of Ahvaz,
Ahvaz, Iran
Email: a.Saeidavi@yahoo.com

Mostafa Kiani Deh Kiani*

Biosystems Engineering Department,
Shahid Chamran University of Ahvaz,
Ahvaz, Iran
Fax: +986133330079
Email: m.kiani@scu.ac.ir
*Corresponding author

Elaheh Mashhour

Electrical Engineering Department,
Shahid Chamran University of Ahvaz,
Ahvaz, Iran
Email: e.mashhour@scu.ac.ir

Abstract: This study simulates the performance of a 21 kW grid-connected photovoltaic (PV) power plant under climate conditions in Tabriz and Ahvaz cities, Iran. The impact of ambient temperature, dust accumulation, and incident solar radiation on the output power of the PV plant, performance ratio, various losses, and CO_2 emission reductions was investigated. The results showed that the power output of the system was 34.82 MWh/year and 35.27 MWh/year in Ahvaz and Tabriz, respectively. Furthermore, the annual performance ratio of the PV system in Ahvaz was 78.1% while this value was 85.8% for the plant in Tabriz. The PV plant losses due to temperature were also obtained to be 12.94% in Ahvaz and 6.45% in Tabriz. It was found that the development of such solar power plants in Ahvaz and Tabriz can save 15.406 and 16.117 tCO_2/year, respectively. The simulation results can be applied to future large-scale PV plants.

Keywords: solar power; photovoltaic system; simulated performance; CO_2 emission.

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Biographical notes: Ahmad Saeidavi graduated in MSc of Renewable Energy Engineering and he works as a Design Supervision Specialist at the South Steel PISHGAMAN Consulting Engineering. His interested research areas are solar and geothermal energies.

Mostafa Kiani Deh Kiani works as an Assistant Professor at the Biosystem Engineering Department, Shahid Chamran University of Ahvaz, Iran. He studies in the field of renewable energies (solar, biofuels) and internal combustion engines. He has several papers in national and international journals.

Elaheh Mashhour received her PhD in Electrical Engineering from the K.N. Toosi University of Technology, Tehran, Iran, in 2010. She worked in the Khouzestan Electric Power Distribution Company for 15 years as the Manager of network and load control office, the manager of power market office and head of DG participation unit. From 2011, she has been a faculty member with the Electrical Engineering Department, Shahid Chamran University of Ahvaz, Ahvaz, Iran. Her research interests are distribution system automation and planning, power market, network resiliency and deep learning.

1 Introduction

Due to the depletion risk of fossil fuels and the environmental pollution generated by using them, energy planners worldwide increasingly focus on renewable energy sources. The use of renewable energy sources has grown in recent decades due to changes in energy policy (Nassar and Abdella, 2018). Among renewable energy sources, solar energy is extensively used in various applications such as photovoltaic (PV) power plants, cooling and heating systems, etc. (Singh et al., 2022; Gao et al., 2023). PV power plants are the common technology to use solar energy. They have received remarkable attention because of their simple structure, ease of installation, low maintenance costs, and potential for decentralisation (Gorjian et al., 2021; Assareh et al., 2021). The world's major oil producers, including Iran, are the world's largest CO_2 emitters per capita. Carbon dioxide emissions are the primary cause of global climate change (Acar and Dincer, 2017). Iran has high potential in solar energy, with 300 sunny days and an average solar radiation of 4.5–5.5 kWh/m^2 per day (Gorjian et al., 2019). Although Iran has good potential for solar energy to fulfil its annual energy needs, the abundance of fossil fuels, their low cost, and climate conditions are major barriers to the deployment of PV technologies.

Some research was conducted on PV systems, to estimate the electricity generation and productivity rates (Rehman et al., 2019). It is suggested that solar radiation, climate conditions (Abu-Rayash and Dincer, 2019), dust accumulation (Menoufi, 2017; Zeedan et al., 2021), and performance of the different components of a typical PV system (such as PV modules and inverters) affect the performance of the whole system (Pourgharibshahi et al., 2015; Ünver and Gören, 2019). The nonlinear interconnection of mentioned factors and their effect on the performance parameters of a PV system necessitate separate studies on different locations where the system is installed. Also, several researchers have undertaken a technical evaluation of solar power plants, some of which are discussed below. Sauer et al. studied the influence of solar irradiance and temperature on the modules of a PV system using PVsyst software. The comparison between simulated and experimental results demonstrated that the PVsyst could simulate the system with high accuracy (Sauer et al., 2014). The annual performance of a PV system was investigated by Ramanan et al. In this study, the performance of two PV arrays was simulated using PVsystst software. The results showed a good agreement between the measured and simulated results (Ramanan and Karthick, 2019). In a comparative study, the performance of an 11.2 kWp grid-connected rooftop solar PV system was simulated under the climate conditions of eastern India. The results indicated that the estimated annual energy yield is close to the actual value (Goel and Sharma, 2020). Malvoni et al. compared the experimental performance of a PV system with the simulated results obtained from SAM and PVsyst simulation tools under different climates. The results showed that the simulated average annual generated energy is underestimated by 3% using SAM and 3.3% using PVsyst (Malvoni et al., 2017). Babatunde et al. simulated and measured the performance of a 1,280 kWp PV system under different tilt angles and orientations, and the impact of dust was evaluated. The results indicated that the energy production is about 5% higher than the simulation results (Babatunde et al., 2018). Sharma and Chandel (2013) investigated the effect of various calamities and technologies on the performance of a solar PV power plant with a capacity of 190 kWp in India. The average annual predicted (using PVsyst) and measured energy yields, with a 1.4% uncertainty, were 823 and 812.76 kWh/kWp, respectively (Sharma and Chandel, 2013). PVsyst and PV-GIS software was used to simulate a 10 MW PV grid-connected plant in a similar study. The performance ratio (PR) and power losses (grid-connected, temperature) were calculated. The results indicated that the experimental performance is very close to the simulated performance (Kumar and Sudhakar, 2015).

The high validity of the simulated results in the literature demonstrates that the software can predict the performance of PV systems with acceptable accuracy. PVsyst is one of the most popular software used for simulating the PV system performance, owing to its functional features such as the ability to use a wide range of meteorological data and PV components, a user-friendly interface, high-quality graphics, and the ability to generate detailed reports and perform high-precision analysis. Researchers and designers have used this software to investigate the feasibility of installing PV solar plants, some of which are discussed as follows. Kalita et al. (2019) used PVsyst software to assess the feasibility of constructing 2 MW PV plants in eight Indian states. The results showed that two locations, including Guwahati and Gangtok, supply a high-PR of 0.855. Vidal et al. (2020) evaluated the influence of ambient temperature, solar irradiation, and wind speed on the PR and energy generation of an 8.2 kWp grid-connected PV system using PVsyst. The findings indicated a good agreement between the simulated and measured energy yield. Using PVsyst, Kumar et al. (2017) examined the feasibility of establishing a 100 kWp grid-connected solar system. The PV array's useful energy output, PR, and the energy injected into the grid were examined. Ramoliya (2015) used PVsyst to investigate the PR and several forms of power losses, including internal network, temperature, and power electronics, and examined the feasibility of installing a 1 MW PV power plant in Gujarat. The results of these publications can assist electrical industry planners and designers in selecting locations, technologies, preparing engineering instructions, and developing manuals.

Given the great potential of Iran in the field of renewable energy, especially solar energy, it is crucial to establish a future vision for solar gain and expansion of its use. This article aims to underscore the importance of ambient temperature in the efficiency of the PV system. The main contribution of this paper is as follows:

- Despite numerous studies conducted by researchers to evaluate the impact of various factors such as solar radiation and weather conditions on technical quality indices of PV systems, including efficiency, energy production, and losses, gaining a deep understanding of the nonlinear relationship between these factors and their nonlinear effect on quality indices necessitates detailed investigations in different locations. This paper addresses this topic for two candidate cities in Iran with entirely different climates to determine which one is more suitable for applying PV power plants.
- Despite the widespread belief that solar radiation is the most important factor in solar energy production, this study shows that the role of other factors such as ambient temperature and dust accumulation can overshadow the effect of radiation.
- Based on what was mentioned above, this paper explores whether the southern regions of Iran, which have higher solar radiation, or the northwest regions, which are mountainous and cold, are more suitable for investing in solar systems. The findings of this research can lead to appropriate investment decisions.

2 Materials and methods

In this section, the geographical locations and climate conditions of Tabriz and Ahwaz cities, the components of the PV power plant, the simulation tool, and the effective parameters on the performance of the PV plant are described.

2.1 Climatic zones in Iran

Figure 1 depicts the geographical locations and map climates of Iran with a focus on Ahvaz and Tabriz. Ahvaz, the capital of the Khuzestan province possesses a latitude of 31.33 N, a longitude of 48.68 E, and an altitude of 22 metres and has a desert environment (Channel, 2017). The annual mean temperature and average yearly horizontal radiation in this city are 1871.6 kWh/m^2 and 24.8°C, respectively. Tabriz is also the capital of the province of East Azerbaijan, and it is located at 38.4 N latitude, 46.18 E longitude, and 1,364 metres above sea level. Tabriz is located in a frigid mountainous region. The city receives an average of 1,675.1 kWh/m^2 of annual horizontal radiation with an average annual temperature of 8.7°C.

The values of global radiation (GR) on a horizontal surface, diffuse radiation (DF), and ambient temperature (T_Amb) for Tabriz and Ahwaz are given in Table 1. As shown in this table, the average annual air temperature difference between these two cities is 16.07°C. Furthermore, the difference between the two cities in their average annual GR is 196.6 kWh/m^2. It is worth noting that the solar and meteorological data sets are taken from NASA, which is a reliable and widely used source for retrieving meteorological data.

Figure 1 The climate map of Iran highlighting case study locations of Ahvaz and Tabriz (see online version for colours)

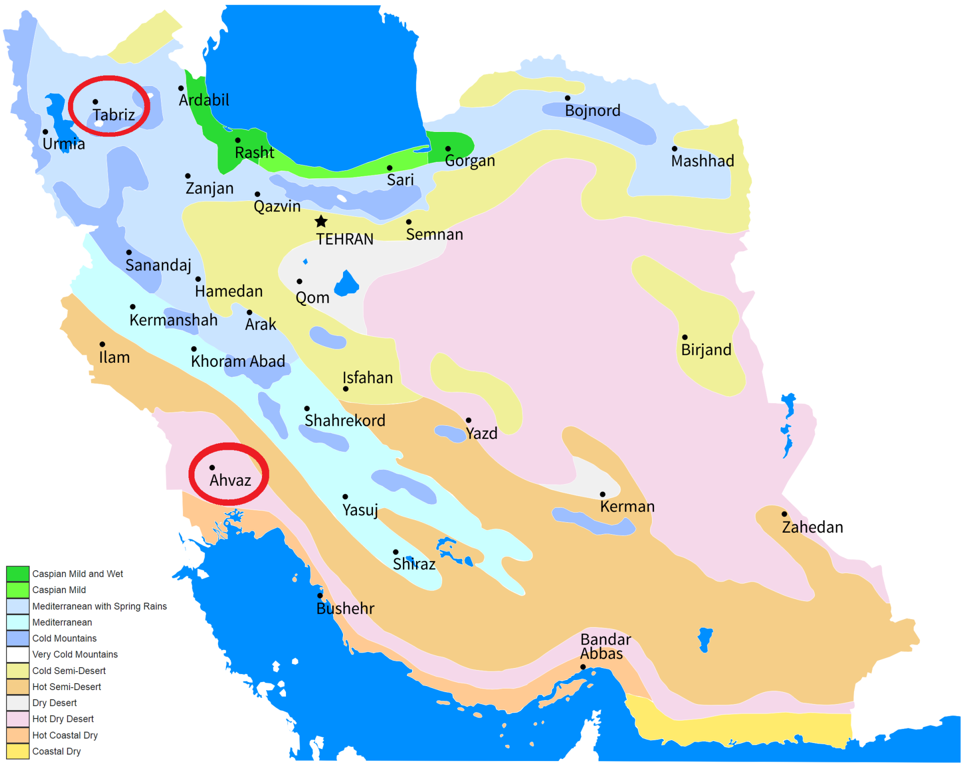


Table 1 Monthly average climate parameters of Ahvaz and Tabriz

	GR(kWh/m^2)		*DF(kWh/m^2)*		*T_Amb(°C)*	
	Tabriz	*Ahvaz*	*Tabriz*	*Ahvaz*	*Tabriz*	*Ahvaz*
January	72.8	101.1	24.80	29.40	–3.48	11.18
February	89.0	122.1	30.20	30.80	–2.44	12.91
March	129.0	151.9	46.80	49.60	2.11	17.35
April	152.4	166.8	58.50	60.60	8.81	27.37
May	190.0	201.8	68.20	67.00	13.42	29.64
June	214.5	220.5	63.60	61.20	18.18	33.84
July	218.9	217.9	62.60	63.90	20.44	36.14
August	195.6	207.7	55.20	55.50	19.62	36.67
September	157.5	165.6	42.60	48.60	15.62	32.74
October	116.3	132.4	35.00	41.50	10.19	27.10
November	76.2	94.8	26.10	33.00	3.81	19.36
December	62.9	89.0	22.90	28.50	–1.45	13.31

Figure 2 Schematic diagram of a grid-connected PV plant in the present study (see online version for colours)

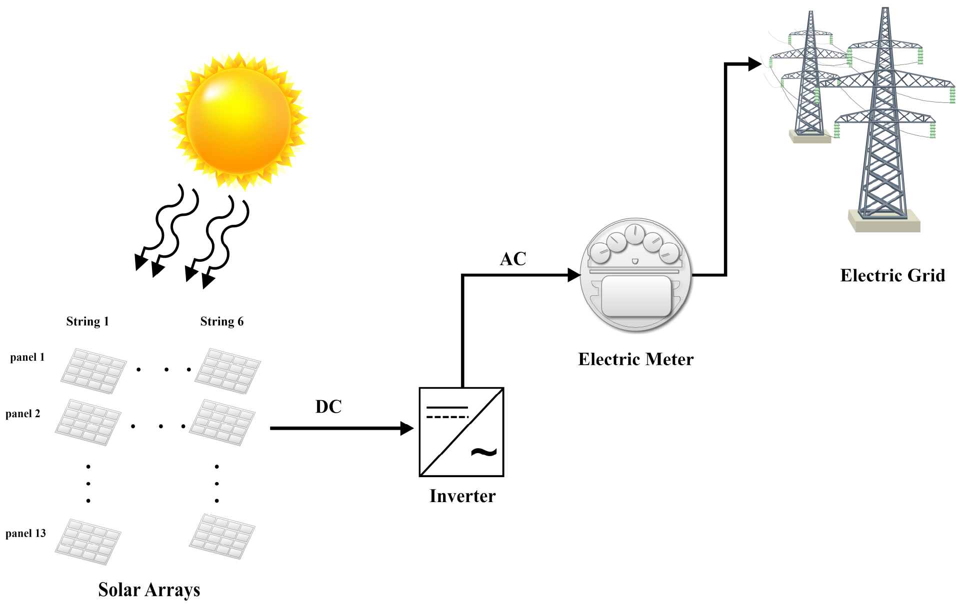


Table 2 The PV module specifications

Model	YL250P-29b
Manufacturer	Yingli Solar
Technology	Polycrystalline Silicon
STC power rating	250 W
Peak efficiency	15.3%
Voltage at P_{max}	30.4 V
Current at P_{max}	8.24 A
Open-circuit voltage	38.4 V
Short-circuit current	8.79 A
Operating temperature range	–40 to 85°C
Number of required modules	84

2.2 *Grid-connected PV plant components*

The simulated PV plant in this study is composed of 84 polycrystalline Si PV modules, each with a capacity of 250 W. PV modules in this plant are arranged in the form of six strings, and each string is composed of 14 PV modules and two inverters with a capacity of 9 kW (Figure 2). Oversizing a PV array can better match the rated AC power of an inverter. This means that an inverter with a lower AC rating (hence, lower cost) can be used. The specifications of the PV modules and the inverter are presented in Tables 2 and 3, respectively. After choosing the PV modules and the inverter, the PV array was created in the PVsyst software. Each MPPT input is capable of being coupled to a single sub-array. This is accomplished by selecting the 'multi-MPPT feature' for multi-MPPT inverters of standard type. Each sub-array should be homogeneous with the same type of PV module and the same number of them connected in series. Additionally, PVsyst provides a technique for inverter sizing based on an acceptable overload loss during operation and hence requires estimations or simulations under the system's actual operating conditions (meteorology, orientation, losses). The schematic flow diagram (Figure 3) depicts the main components of a grid-connected PV power plant.

Figure 3 The flowchart of the simulation steps using PVsyst (see online version for colours)

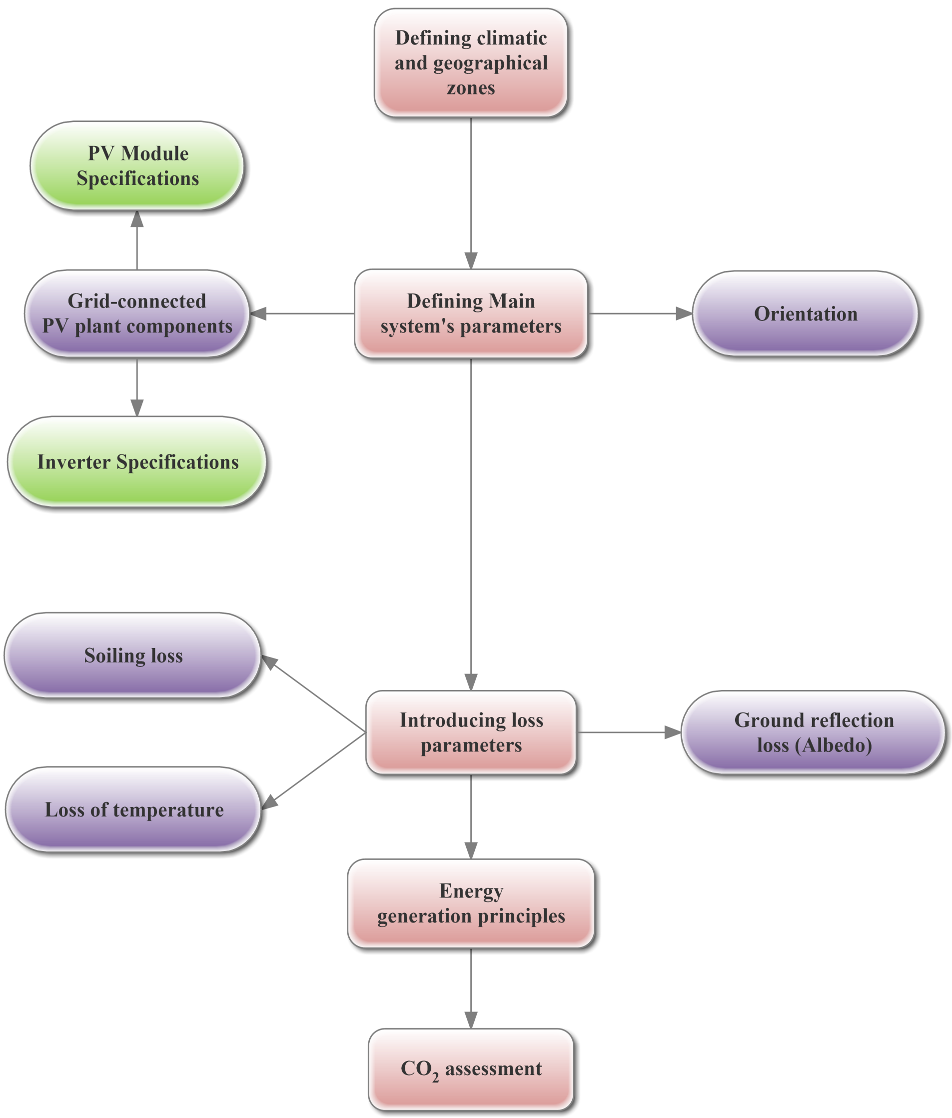


Table 3 Inverter's technical specifications

Model	Sunny Boy 9000TL U-208
Manufacturer	SMA
Max. usable DC power	9,400 W
Max. input voltage	250 W
Max. efficiency	98.6%
MPP voltage range	300 V–480 V
Min. input voltage	300 V
Max. input current	31.0 A
Max. output current	43.3 A
Operating temperature range	–40 to 60°C
Number of required inverters	2

2.3 Simulation method

In this study, PVsyst 7.2 software was used to simulate and analyse the performance and CO_2 emission reductions of a 21 kW grid-connected PV plant. To simulate the PV plant, input parameters, including the site's location and its meteorological data, the orientation of PV modules, the size of the plant, and the system's components (PV module and inverter) were determined. The primary simulation steps are as follows:

1 In the project design menu, a grid-connected PV plant was established by determining the geographical and meteorological data of the location where the plant would be installed.

2 In the second stage, the data from the PVsyst database were utilised to determine the orientation of the PV modules, the required power, the type of PV modules, and the type of the inverter used.

3 After the specification of the required data, the simulation was done. Figure 2 shows a flowchart used to simulate the PV power plant by the PVsyst.

2.4 Loss-inducing environmental variables

2.4.1 Ground reflection loss (albedo)

The fraction of global horizontal irradiance reflected by the ground, which ranges from 0.1 to 0.9, is known as albedo. In winter, Tabriz is mostly snowing and therefore, the albedo was considered as 0.8, and this value was considered as 0.2 for Ahvaz because of its urban environment (Malvoni et al., 2017).

2.4.2 Soiling loss

Dust accumulation and its impact on the performance of PV modules can considerably affect the quantity of electricity produced by the panels. It was found that every 4 g/m^2 of dust on the surface of a PV module reduces the panel's power production by 40% (Okello et al., 2015). The employment of nano-surface coatings, intelligent panel washing robots, and mechanical and electromechanical instruments to clean the panel surface are areas of current research on this subject, which suggest some methods to cope with dust accumulation problem.

2.4.3 Loss of temperature

A PV module's standard test condition (STC) temperature is 25°C, but PV modules typically operate at higher temperatures under actual conditions. The thermal loss of a PV panel increases by 0.4–0.5%/°C as the temperature rises (Tan et al., 2017; Solanki, 2015). The air temperature in Ahvaz is extremely high, especially in summer (it can reach over 50°C) (Channel, 2017).

2.5 Energy generation simulation

Solar cells are simulated by diodes because they are made of semi-conductor materials. The current-voltage circuit of a solar cell performs like a diode. This is applied by PVsyst software to simulate a PV cell (Eidelloth et al., 2012; Islam et al., 2014). The equivalent circuit of the PV cell is presented in Figure 4. The current supplied by module I is obtained by the following equation:

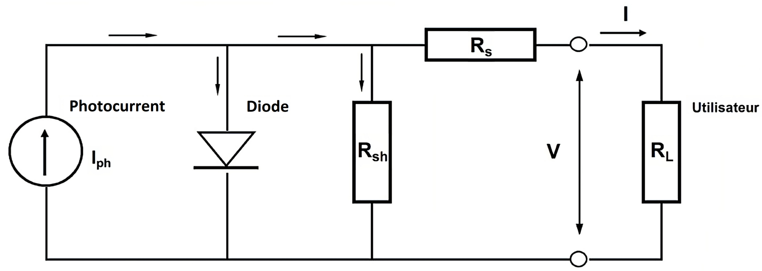
$$I = I_{phR} - I_{OR}\left[\exp\left(\frac{q(V + I.R_s)}{N_{CS}.\gamma.k.T_{ec}}\right) - 1\right] - \frac{(V + I.R_s)}{R_{sh}} \tag{1}$$

where I is the current supplied by the module, V is the voltage at the terminals of the module, I_{phR} is photocurrent, I_{OR} is diode inverse saturation current, R_s and R_{sh} are series shunt resistances, γ is diode quality factor, q is the charge of the electron, k is Boltzmann's constant, N_{cs} is the number of cells in series, and T_{ec} is the effective temperature of the cells. The diode's reverse saturation current is obtained by the following equation:

$$I_O = I_{OR}\left(\frac{T_c}{T_{cR}}\right)^3 \exp\left[\frac{(q.E_{Gap})}{\gamma.k}\cdot\left(\frac{1}{T_{cR}} - \frac{1}{T_c}\right)\right] \tag{2}$$

where E_{Gap} is the energy gap of the semiconductor, and T_{cR} and T_c are effective and reference cell temperatures.

Figure 4 Equivalent circuit of a PV cell



Source: Islam et al. (2014) and Eidelloth et al. (2012)

2.6 CO_2 assessment

The carbon balance tool enables the prediction of CO_2 emission reduction when a PV system is installed and operated. The potential sources of CO_2 emissions may relate to PV modules, the balance of the system, and some additional factors such as maintenance, dismantling, recycling, disposal, etc. The prediction of CO_2 emission reduction is based on life cycle emissions (LCE) analysis. Grid LCE is an important parameter that presents the average CO_2 emissions per unit of electricity injected into the grid. According to the IEA database, GLCE for Iran is 575 gCO_2/kWh (Crippa et al., 2020). LCE of other components was also obtained by IEA. The carbon balance is calculated by the following equation.

$$Carbon\ Balance = \mathrm{E\_Grid} \times PL \times GLCE - SLCE \tag{3}$$

where E_Grid denotes the energy delivered to the grid in kWh, *PL* is project lifetime in a year, *GLCE* represents grid life cycle emission in g CO_2/kWh, and *SLCE* is system life cycle emission in tCO_2.

3 Results and discussion

3.1 Losses analysis

The annual losses of Ahvaz and Tabriz are depicted in Figure 5 and Figure 6, respectively. The findings demonstrate that temperature has the most significant impact on PV panel losses. Temperature-related losses obtained for Ahvaz and Tabriz are 12.94% and 6.45%, respectively. Generally, the loss of PV panels increases as the temperature rises (Goel and Sharma, 2020; Kaldellis et al., 2014). Soiling loss is another PV panel loss. The dust has been affecting the performance of PV panels in Ahvaz in recent years. The soiling loss for Ahvaz accounts for 3% (Hachicha et al., 2019). Removing dust, bird droppings, and other debris from the panels can dramatically lower this loss.

3.2 Energy injected into the grid

Figure 7 shows the energy injected into the grid (E_Grid) and the global incidence (GI) on the collector plane of a PV system at Ahvaz and Tabriz. Ahvaz has a higher annual GI (2,123.91957.3 kWh/m^2) compared to Tabriz (1,957.3 kWh/m^2). The yearly E_Grid for Ahvaz and Tabriz were 34.824 and 35.270 MWh, respectively. Because of temperature and soiling losses, the E_Grid in Ahvaz during eight months (from April to November) is lower than in Tabriz (Figure 7). The ambient temperature in Ahvaz is higher than the standard test temperature (STT) during these months (see Table 1), and thermal loss increases by 0.4–0.5%/°C (Solanki, 2015; Tan et al., 2017). In Ahvaz, there is also soiling loss (Figure 5). The ambient temperature is lower than the STT in other months (January, February, March, and December); hence, the E_Grid in Ahvaz is higher than in Tabriz. The obtained results demonstrate that although the intensity of solar radiation is a significant factor affecting the performance of a solar PV plant, other climate parameters, such as ambient temperature, humidity, and dust accumulation should also be considered as there is a nonlinear relationship between these parameters and PV plant performance.

Figure 5 The detailed loss diagram of the PV power plant installed in Ahvaz during one year (see online version for colours)

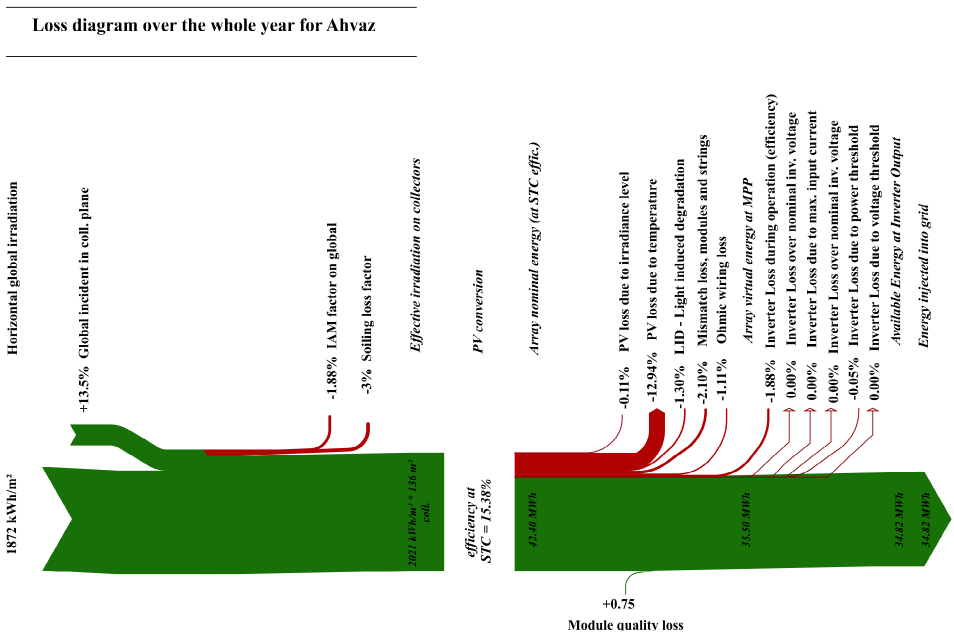


Figure 6 The detailed loss diagram of the PV power plant installed in Tabriz during one year (see online version for colours)

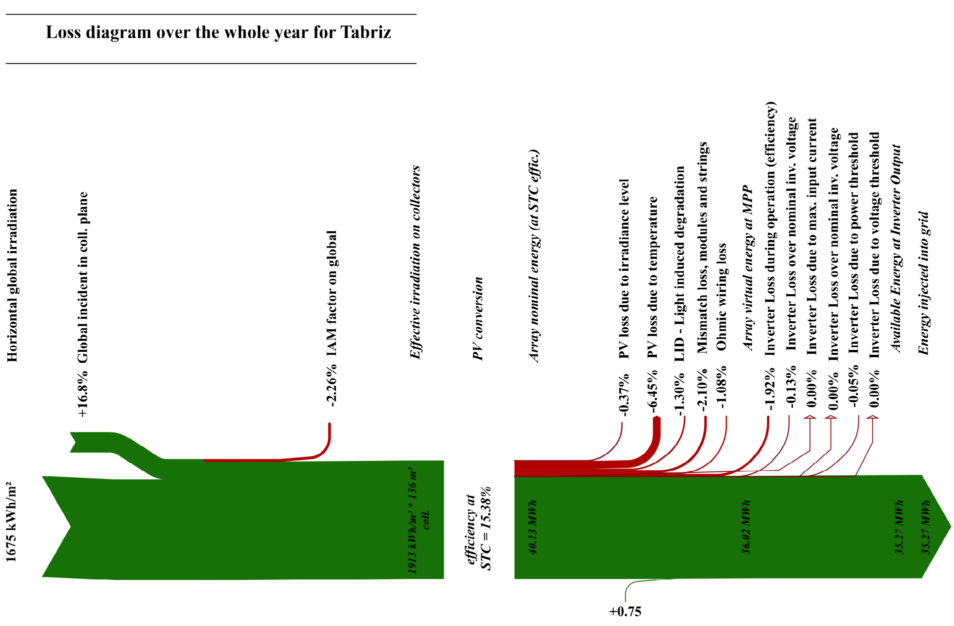
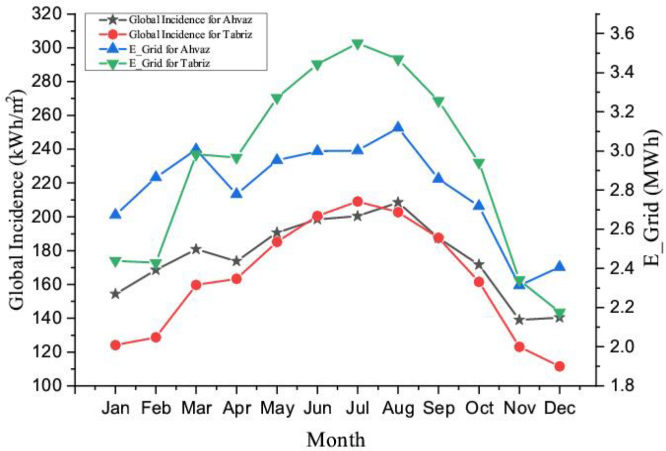


Figure 7 Energy injected into the grid and the GI for Tabriz and Ahvaz (see online version for colours)



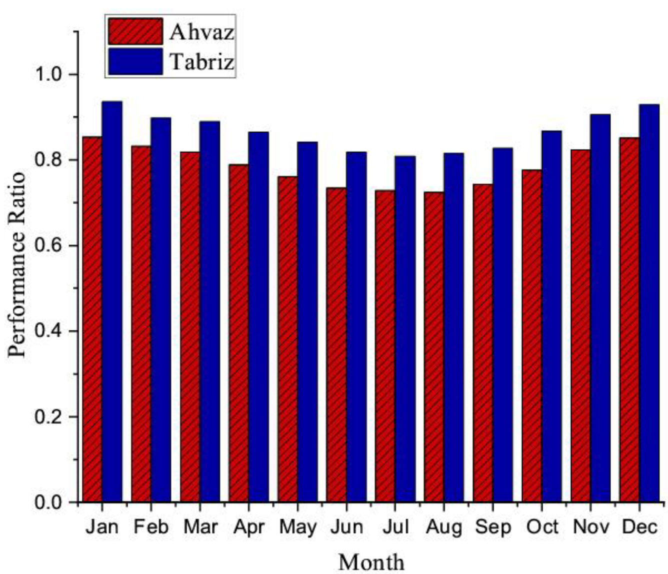
3.3 Performance ratio

The PR is the ratio of a PV system's output energy under actual operating settings to its input energy under STC, and it is calculated as follows (Ayompe et al., 2011):

$$PR = E\_Grid / (GI \times NP) \quad (4)$$

where *E_Grid* denotes the energy delivered to the grid in kWh, *GI* represents the global incidence in the plane of the array in kWh/m^2, and *NP* is the array's nominal power at STC in kWp.

Figure 8 The monthly PR for Ahvaz and Tabriz cities (see online version for colours)



As shown in Figure 8, the PR for the plant installed in Tabriz is higher than that in Ahvaz for all months, with yearly PRs of 0.858 and 0.781 for Tabriz and Ahvaz, respectively. While the GI in Ahvaz is higher (except in June and July), the E_Grid in Ahvaz is lower for eight months (from April to November) due to temperature and soiling losses (Figure 4). Although the E_Grid of the PV plant in Ahvaz is higher than that of the plant installed in Tabriz in other months (from January to March, and December), the GI in this city is much higher than in Tabriz, resulting in higher PR for the PV plant installed in Tabriz. Agai et al. (2011) reported that the average annual PR of the PV system was 0.787. They indicated that the PR level depends on climate conditions and the quality of system components. The performance of a solar PV Plant was compared for two PV modules, one being cooled and another one not subjected to cooling. The cooled module showed 7.2% and 6% higher electrical efficiency and PR, respectively, compared to the module not subjected to cooling (Sajjad et al., 2019). Shiva Kumar and Sudhakar (2015) simulated a 10 MW PV gridconnected power plant. They found that the simulated PR was not significantly different from the actual PR.

3.4 Normalised production

The normalised production is generally expressed by the IEC norms (I. Standard 61724, 1998), which contain standardised values for the PV system evaluation. PV-array losses (LC), system losses (LS), and generated usable energy (Yf) are used to assess the PV system's performance. Temperature loss, module array mismatch loss, module quality loss, ohmic wiring loss, and light-induced degradation are examples of LC. The inverter operation, system unavailability, ohmic losses on the inverter side, external transformer loss, and auxiliaries are the main causes of LS. As shown in Figure 9, the average monthly LC values for Ahvaz and Tabriz are 1.19 and 0.67 kWh/kWp/day, respectively, and the LS values are 0.089 and 0.092 kWh/kWp/day. Because of temperature and soiling losses, the LC for the plant installed in Ahvaz is higher than that in Tabriz. For Ahvaz and Tabriz, the average Yf are 4.54 and 4.60 kWh/kWp/day, respectively.

Figure 9 Normalised production per installed kWp for Ahvaz and Tabriz in different months (see online version for colours)

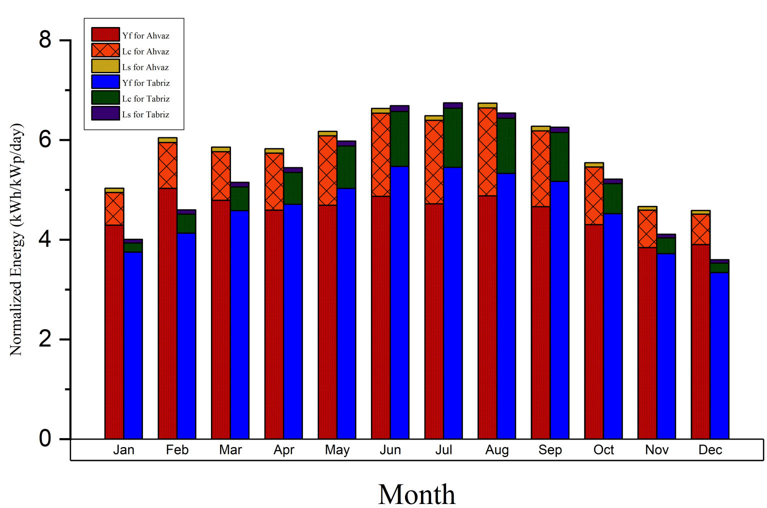


Figure 10 CO_2 emission reduction for Ahvaz and Tabriz over a year (see online version for colours)

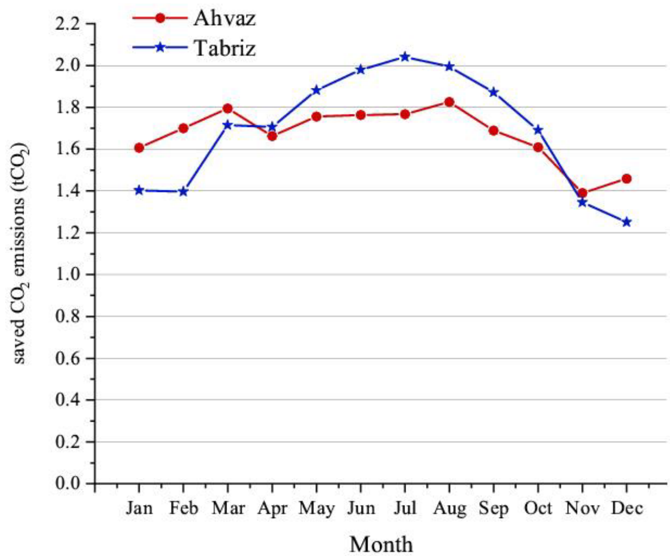
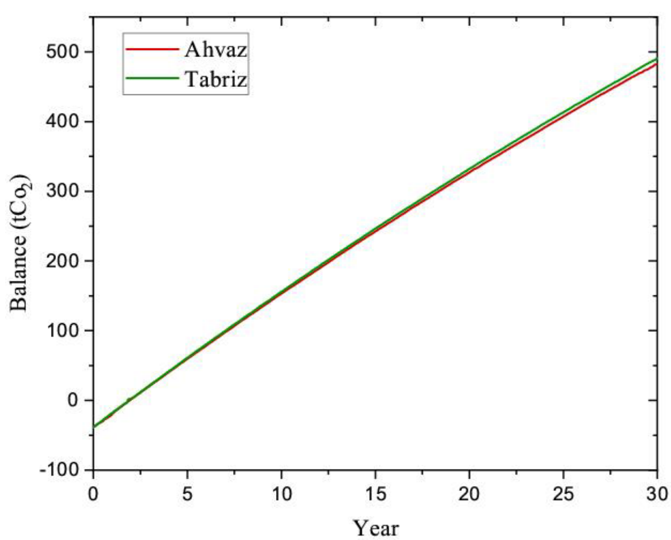


Figure 11 CO_2 emission savings during the PV power plant lifetime (see online version for colours)



3.5 CO_2 emissions reduction

Monthly CO_2 emission reduction for both cities is depicted in Figure 10. The reduction in CO_2 emissions due to the installation of the PV plant in Ahvaz in January, February, March, November, and December is higher than in Tabriz, but in the other months, it is higher for the plant installed in Tabriz. The monthly average reduction in CO_2 emissions was 1.67 and 1.69 tCO_2 for PV plants installed in Ahvaz and Tabriz, respectively. The lower level of CO_2 reduction in Tabriz is due to satisfactory operating conditions of the PV plant installed in Tabriz, which increases the amount of E_Grid.

The value of SLCE for the PV plants installed in Ahvaz and Tabriz, considering a 30-year lifetime, was 37.7 tCO_2 under actual operating conditions (system aging, transportation, etc.). The installation of the PV plant in Ahvaz and Tabriz will prevent 15.406 and 16.117 tCO_2/year emissions, respectively. During the lifetime of the PV power plants, 483.5 and 490.2 tCO_2 emissions may be reduced in Ahvaz and Tabriz, respectively (Figure 11). Given the aging of the PV components, a 1% annual degradation is also considered.

4 Conclusions

In this paper, the performance of a 21 kW grid-connected PV power plant and the resulting reduction in CO_2 emissions were investigated in two Iranian cities, Tabriz and Ahvaz characterised by different climate conditions. The PVsyst software was utilised to investigate the effects of climate parameters, including solar radiation, ambient temperature, and dust accumulation on the performance of the PV plant and CO_2 emission reductions. The following findings are drawn from the study:

- The annual power generated by the PV plant installed in Tabriz and Ahvaz was 34.82 and 35.27 MWh/year, respectively. Although solar radiation in Ahvaz is significantly higher than in Tabriz, generated PV power in this city was higher than that in Ahvaz.
- The temperature losses in Tabriz and Ahvaz were 6.45% and 12.94%, respectively.
- The PR was 0.858 and 0.781 for the same PV plant installed in Tabriz and Ahvaz, respectively.
- The monthly average reductions in CO_2 emissions were 1.67, and 1.69 tCO_2 for the PV plant installed in Ahvaz and Tabriz, respectively.
- The study provides insight into determining the suitable location for installing large-scale PV plants in Iran and other regions with similar climate conditions.

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