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Economic assessment of bifacial solar modules under incentive policies in rich-solar potential regions: A multiscale practical approach

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ABSTRACT

The installation of grid-connected photovoltaic systems (GCPVS) has been steadily increasing due to techno-socio-economic-environmental advantages. The bifacial module is one of the latest evolutions in improving the GCPVS efficiency, which captures rear sun radiation. Despite the higher energy generated, the installation of bifacial modules needs additional investment for the structure and the site's ground cover. Therefore, the economic viability of bifacial modules cannot be ensured. In most current studies, the economic viability of bifacial modules excluded the incentive policy. In addition, the literature mainly focuses on the economic analysis rather than precise modeling for GCPVS energy estimation (e.g., neglecting the efficiency of PV modules and inverters). Last but not least, existing works focus on specific applications and sizes (e.g., floating systems and agrivoltaics). To fill these gaps, this paper proposes a multiscale practical approach to assess the economic viability of bifacial GCPVS, with the focus on high solar potential regions with more than 4.5 kWh/m^2 daily global radiation on a horizontal surface. Simulations are conducted on the PVsyst platform for various cities in Iran, and the economic indices are computed under the existing feed-in tariff (FiT) action. The results demonstrate the high viability of the bifacial modules in different cities and under various albedos. For Shiraz with the highest solar potential, the net present value (*NPV*), payback period time (*PBT*), and internal rate of return (*IRR*) are 102,809 €, 4.09 years, and 62.2% under albedo = 0.9, respectively. These values are 38,668 €, 6.22 years, and 32.5%, respectively, for Rasht with the lowest solar potential, confirming the high feasibility of the bifacial solar module. The outcomes motivate individuals to construct a GCPVS with bifacial modules in high solar potential regions and provide valuable insights for policymakers to exploit a well-modified incentive, considering solar potential and economic conditions.

1. Introduction

The shift towards renewable energy resources is mandatory to mitigate the consequences of global warming. In addition to the environmental gains, they propose techno-social advantages, promoting environmental awareness and offering job opportunities for different education levels [1]. Due to these advances, the global investment in renewable energy reached a $ 2.1 trillion record, including 46% of the total installed power capacity [2].

Among the existing renewable energies, the grid-connected photovoltaic system (GCPVS) has been installed the most over the past years. This technology can be installed in both distributed and centralized forms, ranging from a building-scale (a few kW) to city-scale (hundreds of MWs). Clean energy generation, hybrid installation with other resources [3], simple operation, low maintenance, and peak load shaving are among the advantages of the GCPVS [4]. These advances and the continuous cost reduction of solar cells have led to the steady installation of GCPVS worldwide. For several years, GCPVS has recorded the highest installed capacity among all renewable energies [5]; for example, global capacity reached ~447 GW in 2023, representing 27.5% of the cumulative capacity [6].

Despite these merits, low efficiency is one of the main bottlenecks in the PV industry. In this regard, efforts have been dedicated to enhancing PV module efficiency, utilizing solar trackers [7] and improving the maximum power point tracking algorithm in grid-tie solar inverters [8]. One recent development in the PV module industry is the bifacial module, which provides the opportunity to capture solar radiation from the rear side [9]. Based on the cover of the GCPVS ground, bifacial modules can generate more energy than conventional monofacial ones.

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Nomenclature

Abbreviations

BIPV	Building-integrated photovoltaic
FiT	Feed-in tariff
FPV	Floating photovoltaic
GCPVS	Grid-connected photovoltaic system
LCOE	Levelized cost of electricity
SAM	System Advisor Model

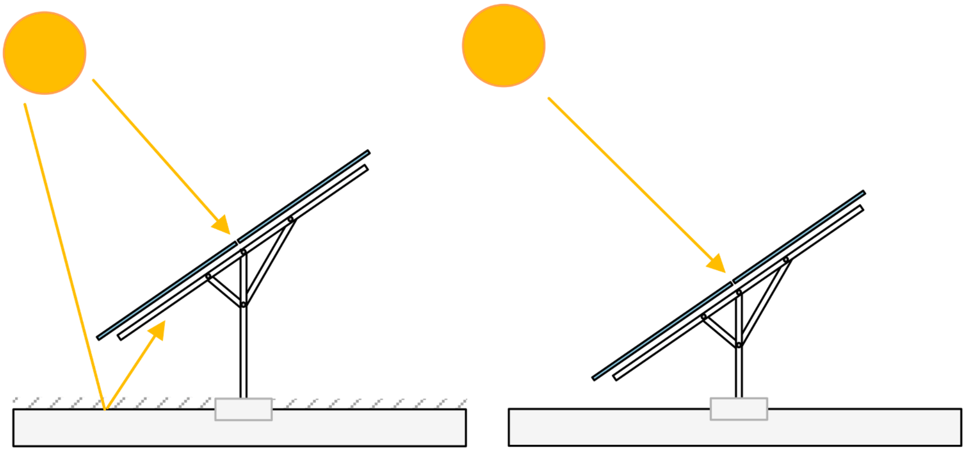
Units

BCR	Benefit-cost ratio
C_C	Capital cost [€]
C_M	Maintenance cost at commissioning year [€]
C_R	Repair cost at commissioning year [€]
d	PV module's degradation factor [%/year]
E_A	Annual generated energy [kWh]
i	Annual discount rate [%]
IRR	Internal rate of return [%]
j	Annual inflation rate [%]
n	Contract period [years]
NPB	Net present benefit [€]
NPC	Net present cost [€]
NPC_M	NPC of maintenance [€]
NPC_R	NPC of repair [€]
NPV	Net present value [€]
PBT	Payback period time [years]
r	The year in which the repair is performed [years]
tax	Tax rate of the sold GCPVS energy [%]
u	Annual updating factor of *FiT* [%]

On the other hand, since bifacial modules and their solar structure, which should be installed at a higher height, would cost more, the total cost of GCPVS increases. Also, the site's ground should be covered by special materials (e.g., Gravier and concrete) to further utilize the backward radiation.

Considering the higher cost and greater yield of bifacial modules, the main question arises (Fig. 1): Do GCPVSs with bifacial modules yield more economic gains than those with monofacial modules? The answer to this question has been partially discussed in the literature. A few recent studies addressed this topic for the main applications of bifacial modules, including floating PV (FPV) systems [10], small islands [11], agrivoltaics [12,13], combined GCPVS and geothermal system [14], building-integrated photovoltaic (BIPV) [15], and highways [16]. In the economic analysis, however, practical systems in a high solar potential region have yet to be considered under an incentive policy.

Focusing on monofacial studies in high solar potential regions, with >4.5 kWh/m^2 normalized energy, several papers have been published in the literature. A techno-economic analysis of residential and farm-based GCPVSs in South Sumatra, Indonesia, has been presented [17]. The results indicate that both systems achieve around 82% performance ratio. Also, their payback period time is 9.8 and 8.6 years for residential and large-scale GCPVSs, respectively. The authors emphasized the substantial effect of subsidies, e.g., the cost of electricity in the net metering scheme, on the economic results. A similar study has been conducted for a 120 kW ground-mounted GCPVS in Iran [18]. The outputs indicate a 3.36 benefit-cost ratio (*BCR*) and 5.24 years payback period of time (*PBT*), confirming the high viability of monofacial modules under the existing feed-in tariff (FiT). A PVsyst-based simulation study has been reported for Zallaq, Bahrain, with 6.25 kWh/m^2 [19]. The results corroborate the economic feasibility of monofacial modules (e.g., *PBT*



Parameter	Monofacial	Bifacial
Module, inverter, cables, enclosures	Almost the same	
Land cost and surface cover	Lower	Higher
Structure cost	Lower	Higher
Income (e.g., sold energy under FiT)	Lower	Higher

Fig. 1. Problem statement of the proposed work.

near 9 years), due to the high solar potential of the studied site. In [20], the authors used one-year radiation and ambient temperature data for estimating the annual generated energy of a 1 MW GCPVS. Through the computed energy, they found the GCPVS with a monofacial module economically viable.

Due to the techno-environmental advantages of FPV systems, a technical assessment of bifacial modules in such generation units has been presented in Bui, Ghana [21]. The experimental and simulation outputs indicated a slight increase in the yield of bifacial modules in floating applications due to the low albedo of water, i.e., the amount of radiation reflected by the surface. The deviation of the simulation and field data for 400 kW floating and 5 MW ground-based GCPVSs is less than 5%, demonstrating the high accuracy of the presented formulation. The same approach has been adopted in Catania, Italy [10]. It was highlighted that PVsyst estimates the energy yield of east- and west-oriented FPV more accurately than the System Advisor Model (SAM). Hsieh et al. presented the techno-economic comparison of three bifacial and two monofacial modules for FPV application in Taiwan [22]. The results unveil that the monofacial option results in 5.3 kWh/day output at the most, while it can be 5.6 kWh/day for the bifacial one. From the economic perspective, however, the monofacial module provides lower levelized cost of electricity (LCOE). The results are based on five days of experimental data in the summer. Due to the short-term recorded data, the study outcomes cannot be concluded over a protracted timeframe.

Bifacial and polycrystalline modules were compared on the Fiji Islands in [11]. The authors simulated 13 MW and 12.9 MW bifacial and monofacial GCPVSs in a 52 ha space in the PVsyst platform. The results corroborate that bifacial modules are more attractive than monofacial modules from an economic perspective, e.g., $ 42.4 million net present value (*NPV*) against $ 36.1 million. Desai et al. conducted the same analysis for a rooftop 5 kW GCPV in Gujarat, India [23]. The outputs remarked that the annual energy yield of 13 pcs 385 W bifacial modules is 9.7% greater than that of the 16 pcs 335 W monofacial module, reducing the LCOE by 5.5%. The study lacks modeling for the grid-tie inverter and DC and AC cabling, and considers a fixed efficiency for PV modules. Also, energy yield encompasses performance ratio, which is assumed to lie within the 0.5–0.9 range without considering the operating point of the GCPVS over a predefined interval (e.g., a year). These assumptions/simplifications reduced the reliability of the results.

The utilization of bifacial modules and sun trackers is another state-of-the-art direction in the literature. Rodríguez-Gallegos et al. assessed the yield and LCOE of GCPVS for various solar structures and bifacial and monofacial modules [24]. They showed that although the bifacial module with a dual-axis tracker produces the highest amount of energy, the LCOE of the single-axis tracker is minimal. This implies that maximum yield does not necessarily result in the highest profit. Furthermore, the study disregards the accurate modeling of the PV module and the inverter in energy estimation. The techno-economic viability of bifacial and sun tracker systems has been explored at seven Brazilian sites [25]. Among the outcomes, the authors revealed that the generated energy of a GCPVS with more diffusion radiation increases and decreases for bifacial modules and sun trackers, respectively. Thus, a fixed system with a bifacial module with a fixed structure has potentially more economic gain than a bifacial module mounted on a dual-axis tracker. Another study evaluated the feasibility of installing GCPVS with vertical bifacial modules on the Dhaka-Mawa Express highways [16]. The total capacity is expected to be 52.75 MW with 455 W PV modules in the considered highways. The analysis outlines the low LCOE and high CO_2 savings of GCPVS with bifacial modules due to the significant diffuse radiation in the studied application. Nevertheless, incentives to motivate for supporting the $ 25.7 million in investment remain unanswered.

Table 1 summarizes the economic studies conducted on the bifacial modules, highlighting the main gaps in the literature. Several studies pertained to the economic evaluation of bifacial modules without considering an incentive action, except for [11]. In addition, the studies on bifacial modules have mainly focused on tropical, sub-tropical, and marine regions with moderate/low solar potentials [16,22,25] and have been limited to specific applications/sizes (e.g., small islands [11], agrivoltaics [12], highways [16], and FPV [21,22]). These gaps highlight the need to conduct an economic assessment of bifacial modules for regions with abundant solar potential, covering a wide range of applications. Last but not least, the reliability of the analysis depends on the levels of the model's accuracy and the practicality of the studied case, which most papers lack in support. Motivated by these research gaps, this paper proposes a multiscale practical approach to evaluate GCPVS with bifacial modules under an incentive policy. To fulfill this objective, a practical case study with a precise representation is adopted to ensure the reliability of the results. The main highlights of the presented work are as follows:

- To the best of our knowledge, this paper presents the first economic assessment of a practical GCPVS with bifacial solar modules under an

Table 1

Summary of the existing works studying bifacial solar modules from an economic perspective.

Ref.	Location (solar potential)[1]	Studied module (bifacial/ monofacial)	Including incentive?	Modeling accuracy?	Considering electrical design?	Application range
[11]	Fiji island (Moderate)	Bifacial and monofacial	FiT	High	Yes	Power plant GCPVS
[15]	N/A	Bifacial	No	Low	No	BIPV
[16]	Dhaka-Mawa (Moderate)	Bifacial	No	High	No	Highway installation
[17]	Sumatra, Indonesia (High)	Monofacial	No	High	Yes	Residential and power plant
[18]	Iran (High)	Monofacial	Yes	High	Yes	Commercial GCPVS
[19]	Zallaq, Bahrain (High)	Monofacial	No	High	Yes	Power plant GCPVS
[20]	Oman (High)	Monofacial	No	Low[2]	No	Power plant GCPVS
[21]	Ghana (High)	Bifacial and monofacial	No	High	Yes	Power plant ground- mounted and FPV
[22]	Taiwan (moderate)	Bifacial and monofacial	No	High	No	Single floating PV module
[23]	Gujarat, India (High)	Bifacial	No	Low[2]	Yes	Residential
[24]	Several regions	Bifacial and monofacial	No	Low[3]	N/A	Single module
[25]	Grembergen, Belgium (Low)	Bifacial	No	High	Yes	Commercial GCPVS
Proposed work	**Iran (High)**	**Bifacial**	**FiT**	**High**	**Yes**	**Multiscale**

[1] Daily global horizontal radiation: <3 kWh/m^2, 3 – 4.5 kWh/m^2, and >4.5 kWh/m^2 for low, moderate, and high.

[2] Considering a fixed efficiency term for the PV module and disregarding the inverter and cables' losses.

[3] Disregarding the efficiency model for inverter, cables, etc., except for the PV module.

incentive policy, while several papers have been reported for monofacial ones [17–20].

- The majority of the existing works have focused on tropical and marine climates with limited solar potential. In addition, the case study encompasses a specific application, e.g., small islands [11], agrivoltaics [12], BIPV [15], and highways [16], FPV [21,22], and combined GCPVS with a geothermal system [26]. In contrast, the proposed research is multiscale and covers a wide range of applications, such as rooftop and ground-mounted GCPVSs.
- The annual yield of GCPVS is determined by PVsyst software, which accurately models the components of the GCPVS, ensuring the high reliability of the results [27]. Conversely, some studies suffer from low accuracy in estimating GCPVS generated energy, e.g., [15,24].
- The examined system in several studies suffers from reduced practicability; for example, the studies in [22,24] considered a single module, whilst the electrical design is disregarded in [16,20], i.e., the implementation of the studied GCPVS may not be feasible. In contrast, this investigation considers a GCPVS with an electrical design for a commissioned GCPVS.
- Although the method is formulated under the FiT scheme, it can be simply realized for other incentive actions.

The rest of the paper is organized as follows: Section 2 elaborates on the proposed methodology and the 150 kW GCPVS studied under the existing FiT policy. The economic analysis is then presented in Section 3 for different cities in the country. Sensitivity analyses are conducted for the key parameters to elucidate the effect of uncertainties on the simulation outputs. This section also discusses and compares the work with existing literature. Finally, concluding remarks and suggestions for future direction are explained in Section 4.

2. Materials and method

2.1. Methodology description

This work investigates the economic viability of bifacial solar modules under an incentive policy. This assessment can be conducted via various economic indicators, including the *NPV*, internal rate of return (*IRR*), benefit-cost ratio (*BCR*), and payback period time (*PBT*). This subsection presents the expressions used to quantify *NPV, IRR, BCR*, and *PBT*. Moreover, the annual energy generation of the GCPVS is a vital parameter in the analysis, as mentioned in the Introduction. Therefore, this parameter is determined through a GCPVS simulation in the PVsyst platform since this tool is known as a reliable software for such purposes with precise modeling of the components [27,28]. In the PVsyst software, Hay's model and optimization orientation with respect to annual yield are used [29]. The prior provides an accurate model for quantifying the solar radiation in tilted modules. The latter also ensures maximum annual energy yield of GCPVS for the studied cities. Note that these two stages require the site, GCPVS, and economic data, to be imported in the "initialization" stage, as shown in the methodology's flowchart in Fig. 2.

The net present benefit (*NPB*) of a GCPVS under the FiT framework over a contract term (n) can be quantified as follows:

$$NPB = \sum_{k=1}^{n} \frac{E_A \times (1 - \ d \times (k-1)) \times FiT \times (1+u)^{k-1} \times (1 - tax)}{(1+i)^{k-1}} \tag{1}$$

where, i is the annual discount rate and E_A is the GCPVS generated energy at the commissioning year [19,30]. The E_A is determined in the second stage of the method, "energy determination" in Fig. 2. This energy is reduced by the PV module degradation factor (d), which can be found in the PV module datasheet, presented by the manufacturer. Furthermore, k and tax represent the year number and taxation rate of the sold energy, respectively. Last but not least, the FiT is assumed to be updated once a year by u in Eq. (1). Note that although Eq. (1) is formulated for the FiT framework, it can be merely reproduced for other incentives such as net metering.

On the other hand, the net present cost (*NPC*) of the project includes capital (C_C), repair (NPC_R), and maintenance costs (NPC_M). C_C includes the cost of PV modules, inverters, land and its surface cover, engineering and design, installation and wiring, etc. Further, NPC_R and NPC_M can be computed as follows:

$$NPC_M = \sum_{k=1}^{n} \frac{C_M \times (1+j)^{k-1}}{(1+i)^{k-1}} \tag{2}$$

$$NPC_R = \frac{C_R \times (1+j)^{r-1}}{(1+i)^{r-1}} \tag{3}$$

here, C_M and C_R are, respectively, the cost of maintenance and repair in the commissioning year. These costs are yearly increased by the annual inflation rate (j), i.e., by the $(1+j)^{k-1}$ factor. Also, r is the year in which the repair shall be performed. Hence, the numerator part in Eqs. (2) and (3) compute the maintenance and repair costs at year k and r. The net present worth of these costs is then determined by the denominator term, using the annual discount rate (similar to Eq. (1)). Thus, the project's *NPC* can be determined as in Eq. (4):

$$NPC = C_C + NPC_M + NPC_R \tag{4}$$

After computing *NPB* and *NPC, NPV* can be quantified as $NPV = NPB - NPC$. Also, other economic indices, including *IRR, PBT*, and *BCR*, can be determined as in Eqs. (5), (6), and (7), respectively:

$$\begin{aligned} &\sum_{k=1}^{n} \frac{E_A \times (1 - \ d \times (k-1)) \times FiT \times (1+u)^{k-1} \times (1 - tax)}{(1+IRR)^{k-1}} - C_C \\ &\quad - \sum_{k=1}^{n} \frac{C_M \times (1+j)^{k-1}}{(1+IRR)^{k-1}} - \frac{C_R \times (1+j)^{r-1}}{(1+IRR)^{r-1}} \\ &\quad = 0 \end{aligned} \tag{5}$$

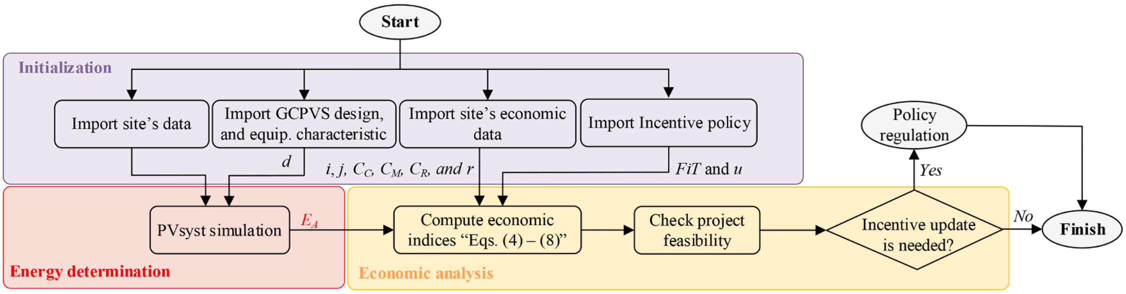


Fig. 2. Flowchart of the proposed work.

$$\sum_{k=1}^{p}\frac{E_A\times(1-\ d\times(k-1))\times FiT\times(1+u)^{k-1}\times(1-tax)}{(1+i)^{k-1}}-C_C-\sum_{k=1}^{p}\frac{C_M\times(1+j)^{k-1}}{(1+i)^{k-1}}-\frac{C_R\times(1+j)^{r-1}}{(1+i)^{r-1}}=0 \qquad (6)$$

$$BCR=\frac{NPB}{NPC} \qquad (7)$$

The project is economically viable when $BCR\geq 1$, i.e., it is expected that NPB would be greater than NPC. Also, PBT represents the time when the revenues equal the NPV of the costs. Hence, a smaller PBT ensures an earlier return of the costs by the sold energy. Finally, IRR refers to the investment rate of return, i.e., the annual discount rate with $NPV=0$. From the IRR perspective, the project is economically feasible when $IRR> i$. All these variables are determined in the last stage of the methodology, “economic analysis” in Fig. 2.

In summary, the GCPVS characteristics and the sites economic and meteorological data of the site are imported in the first stage. Using the GCPVS and the site’s data, PVsyst simulates the GCPVS to quantify the annual yield. Based on the computed E_A and the site’s economic data (imported in initialization), the economic indicators are defined using Eqs. (4)–(8).

2.2. Case study system specifications

The Middle East is a region with abundant fossil fuel resources. Therefore, electricity is mainly supplied by centralized fossil fuel-based power plants, such as those powered by oil and natural gas. The electricity rate is eminently low in most countries, resulting in a sharper rise than the global trend. The Energy Information Agency (EIA) anticipates that the Middle East will need 225 GW of additional electricity capacity by 2035 [31]. Another severe challenge in the electricity sector is to meet the air-conditioning-based peak demands at noon in summer. Since solar radiation is high at this time, the GCPVS can naturally support this peak load [32]. Most countries have adopted renewable energy incentives to motivate individuals to construct GCPVSs to shave these peaks. In addition, the findings support the technical viability of GCPVS, given the region’s rich solar potential [33]. This leads to an increase in GCPVS installation, expecting a 7 GW installation in 2024, which accounts for 30% of the total capacity.

Considering the explanations above, Iran (lying between 44 and 64° E and 25 and 40° N) is among the Middle Eastern countries with a power shortage. The country suffers from a 15% power shortage during the midday summer, leading to controlled power cuts accross both the industrial and residential sectors. Similar to most other countries in the region, Iran benefits from an abundant solar potential, especially in the East, South, and West (with >4.5 kW/m^2), as shown in Fig. 3. In this figure, the country is grouped into three regions considering the solar potential, i.e., <3 kW/m^2, 3–4.5 kW/m^2, and >4.5 kW/m^2 average daily solar radiation ranges on a horizontal surface for low, moderate, and high solar potential, respectively. Therefore, the country has planned to adopt GCPVSs to combat the growing electricity demand by establishing the FiT policy in 2014 [30]. The current FiT scheme allows all private individuals to install the GCPVS and sell the whole-generated energy for 20 years. The details of this incentive action are:

- This scheme includes all PV module technologies, monofacial and bifacial, and fixed and movable structures. In addition to GCPVSs, the hybrid systems (GCPVS and battery energy storage) are included as an amendment [34].
- The *FiT* rate at the commissioning year is 3.14 Cent €/kWh and 3.57 Cent €/kWh for GCPVSs with ≤20 kW and 20–200 kW capacity, respectively.
- The *FiT* increases yearly, considering the annual inflation rate and the Euro to the domestic currency exchange rate. As shown later, this updating factor (u) ensures the economic feasibility of the GCPVS investment under a high inflation rate and a low value of the domestic currency.
- The great increase in *FiT* due to the updating factor is limited by applying a −40% step in years 8, 12, and 16. Hence, $FiT(k)$ can be quantified as follows:

$$\begin{cases} FiT(k)=FiT\times(1+u)^{k-1}\times 0.6, & k=8,\ 12,\ 16\\ FiT(k)=FiT\times(1+u)^{k-1}, & k=otherwise\end{cases} \qquad (8)$$

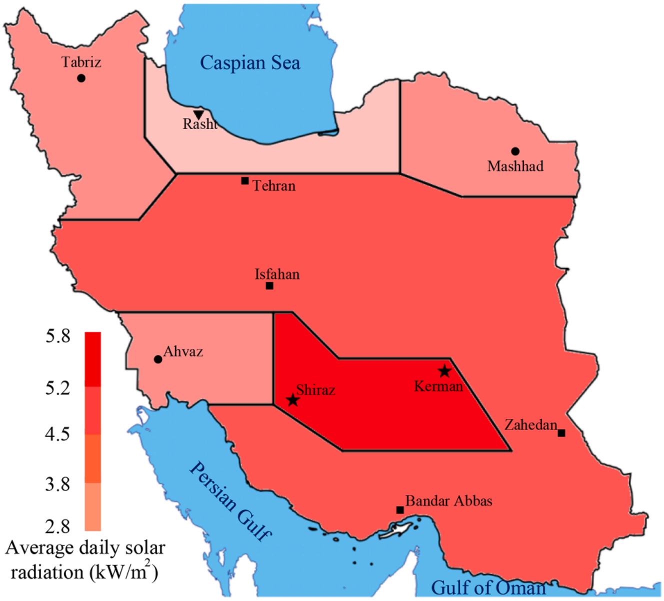


Fig. 3. Selected cities and their solar potential for the economic analysis [30].

Fig. 4 displays the *FiT* of a GCPVS with 20–200 kW power capacity and a 30% annual updating factor over the contract term (20 years).

The studied commercial GCPVS comprises 255 pieces of 580 W bifacial solar modules with an 80%±10% bifaciality factor [35]. These modules are installed as 15 strings, each with 17 series modules, to meet the electrical design limitations [36]. These strings are connected to 50 kW and 100 kW Fronius Tauro inverters [37]. Also, these PV modules and inverters are protected against overcurrent and overvoltage through DC and AC enclosures, respectively. These modules are mounted in three rows with appropriate heights and distances, as illustrated in Fig. 5. For the prior, the maximum utilization of the rear radiation is ensured by a 1-meter height

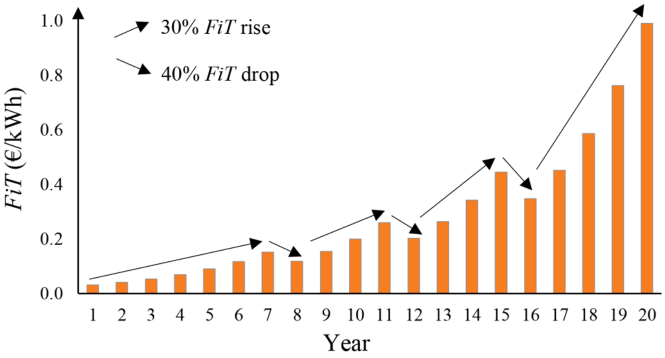


Fig. 4. *FiT* rate over the contract term.

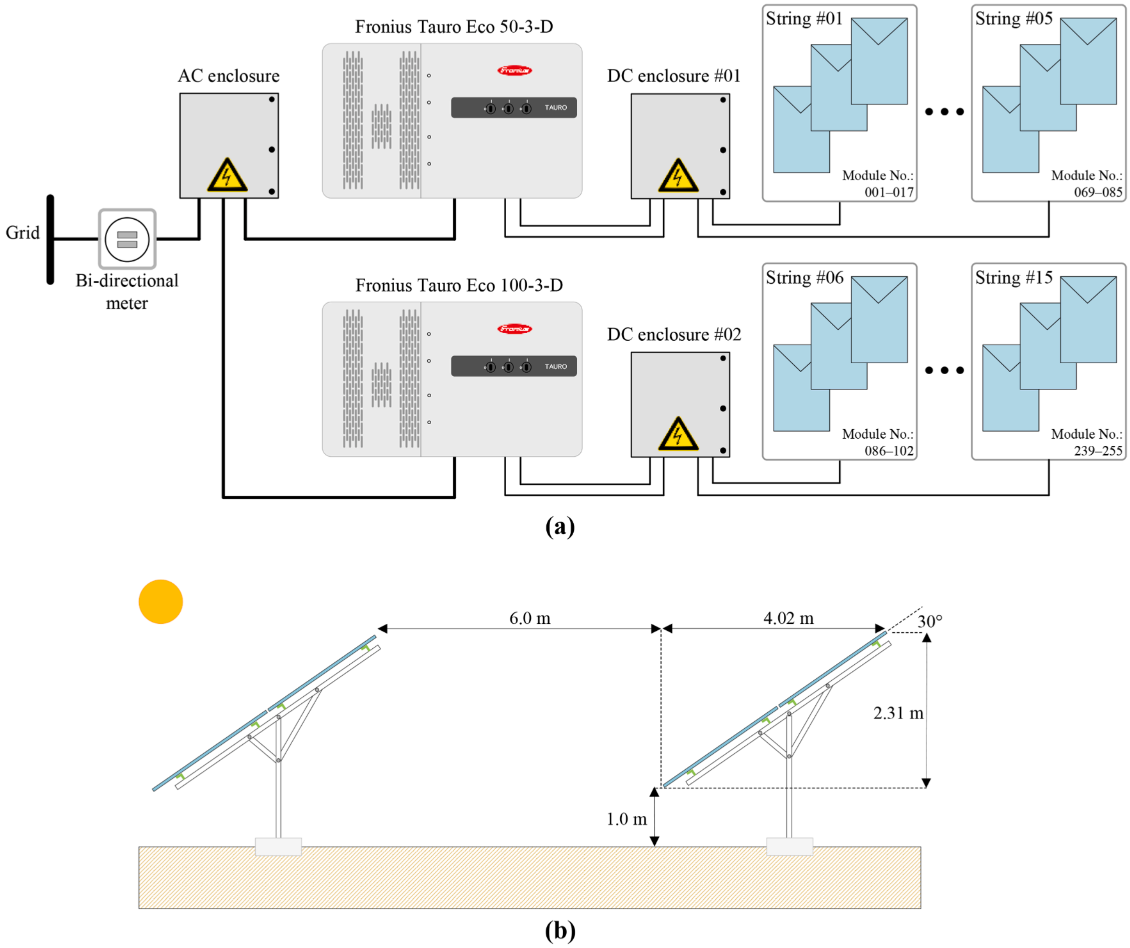


Fig. 5. Studied 150 kW GCPVS: a) Layout, b) Distance between rows.

on the front side of the modules. For the latter, the distance between two rows should be at least 2.5 times the difference between the front and rear heights, e.g., 2.31 m in the studied case.

In the initialization stage, the cost of GCPVS should be included in the economic analysis. In this regard, Fig. 6 displays the cost breakdown of the 150 kW GCPVS with a 49,000 € investment, derived from the PV market in Iran. As mentioned earlier, PVsyst determines the annual yield of GCPVS. This software benefits from an accurate single-diode model for PV modules [38] and a polynomial expression for inverter losses [39]. Other losses, including shading and mismatches between strings, are also taken into account.

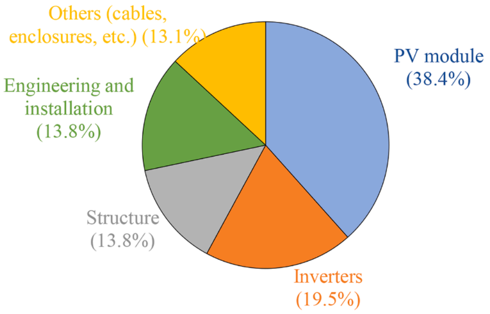


Fig. 6. Cost breakdown of the studied 150 kW GCPVS with bifacial solar modules [40].

3. Results and discussion

3.1. Economic assessment

The economic viability of the studied case is investigated across several cities in Iran. The *FiT* rate in the commissioning year is 3.14 Cent €/kWh, which is assumed to be as in Fig. 4 over the contract term ($n = 20$ years). Note that the 30% updating factor is derived from historical data of the Mehrsun national platform [40]; nonetheless, the results for different sets of u are presented later. In addition, the maintenance cost in the commissioning year equals 1% of the C_C (i.e., 490 €), increasing 30% per year. Finally, the annual discount rate is supposed to be 25%, and the whole sold energy is tax-free ($tax = 0\%$) [41]. Table 2

Table 2
Techno-economic inputs of the work.

Parameter	Description
System characteristics	5 × 17, 580 W bifacial modules connected to Tauro Eco 50–3-D 10 × 17, 580 W bifacial modules connected to Tauro Eco 100–3-D
Energy yield	As in Fig. 4 in the commissioning year, reduced yearly by $d = 0.5\%$
Initial investment	490,000 €
Annual maintenance cost	490 € at the commissioning year, increasing annually by 1.30
Inverters ‘replacement cost	95,550 € at the commissioning year, supposed to be replaced at the beginning of the 11th year
Annual discount rate	25%
FiT	3.14 Cent €/kWh, rising annually by $(1.3)^{k-1}$ factor

summarizes the techno-economic inputs used in this study.

The output of economic analysis relies markedly on the energy output of the GCPVS. Therefore, the studied GCPVS is simulated in the PVsyst platform for several cities across the country, with low, moderate, and high solar potential (Fig. 3). In addition, Fig. 7 illustrates the annual energy for different ground albedo levels, assumed to be constant throughout the year. It is worth mentioning that the orientation (tilt and azimuth angles) of the fixed structure in each city is defined to maximize the generated energy.

The outputs of the economic analysis are presented in Fig. 8 (only for *NPV*) and Table 3 (all economic indices for the possible E_A range). The cash flow and cumulative *NPV* of the worst (Rasht with albedo = 0.1) and best (Shiraz with albedo = 0.9) scenarios are also depicted in Fig. 9.

The results reveal the sfeasibility of the project, even in Rasht, which has the lowest solar potential. In this case, the *NPV* is larger than 18,238 €, *PBT* is at most 7.55 years, and *IRR* is greater than 32.5%. This project is highly profitable for other cities with moderate and rich solar potential. In Kerman, for example, the *NPV* is within 68,125–96,157 € (*BCR* = 2.39–2.96), the *IRR* is at least 50.2%, and the revenues cover the capital expenditure in less than five years under minimum albedo. The outputs corroborate the country's promising FiT policy.

3.2. Sensitivity analysis

The analysis is extended to other scenarios, i.e., various sets of initial costs, updating factors, annual discount rates, and annual inflation rates.

3.2.1. Initial cost

The first analysis pertains to the initial cost, which can be changed due to national (e.g., the change of domestic currency to the Euro) and international reasons (e.g., cost increase of components). The analysis is carried out up to a 60% rise in $C_C = 49{,}000$ € due to the unstable economic conditions in the country. Fig. 10 shows the project's feasible range, i.e., the minimum E_A at which the *NPV* with an increased C_C is zero. This line can be approximated as 163.6 + (1.63 × Deviation from C_C). For example, by a 20% increase in C_C, the minimum E_A with $NPV = 0$ is 196.2 MWh. Therefore, the project is feasible when $E_A \geq 196.2$ MWh. Table 4 presents the range of E_A for the studied cities under 0.1–0.9 ground albedo. The feasible range for various cities can be accordingly determined using Table 4 and Fig. 10.

3.2.2. Economic variables

The next study considers the updating factor, annual discount rate, and annual inflation rate. The first factor affects the project's revenue in the upcoming years, i.e., a greater updating factor leads to a higher income. Also, the annual discount rate determines the net present worth of the benefits (Eq. (1)), repair, and maintenance costs (Eqs. (2) and (3)). Since C_C constitutes mainly the *NPC*, it is expected that the effect of the discount rate on the *NPB* would be greater than that on the *NPC* in most scenarios. Finally, the annual inflation rate affects the NPC_R and NPC_M according to Eqs. (2) and (3). These explanations are studied in the last analysis, where *i* and *j* are varied, and the minimum *u* with positive *NDZ* is computed. The results are illustrated in Figs. 11(a) and (b) for the low and moderate solar potential cases with 207 MWh and 290 MWh of E_A, respectively. In all graphs, the discount rates are changed from 5% to 40% by a 5% step change. The region above each line implies the feasible range.

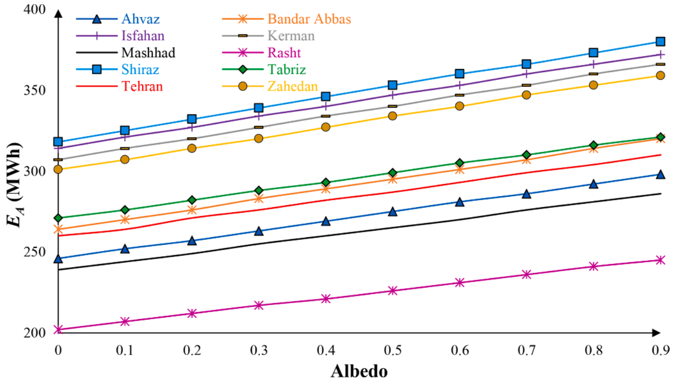


Fig. 7. Annual energy generation of the studied GCPVS in various cities.

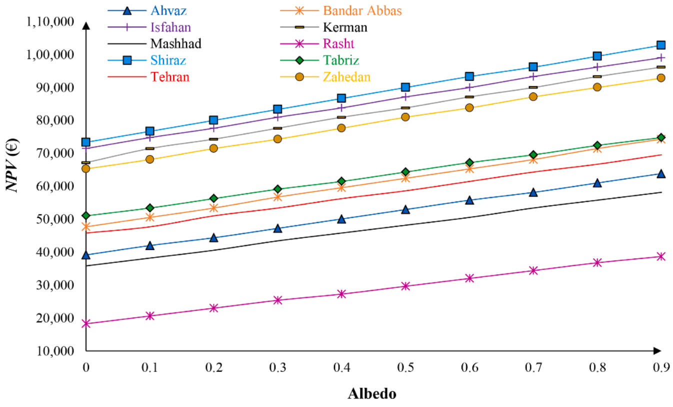


Fig. 8. *NPV* of the studied GCPVS in various cities of Iran.

Table 3
Techno-economic outputs of the studied GCPVS in various cities.

City	*NPV* (€)	*PBT* (years)	*IRR* (%)	*BCR*
Ahvaz	39,143–63,849	5.14–6.20	40.1–48.7	1.80–2.30
Bandar Abbas	47,695–74,302	4.81–5.78	43.1–52.3	1.97–2.52
Isfahan	71,451–99,008	4.17–4.89	51.3–60.9	2.46–3.02
Kerman	68,125–96,157	4.24–5.00	50.2–59.9	2.39–2.96
Mashhad	35,818–58,148	5.35–6.38	38.9–46.7	1.73–2.19
Rasht	18,238–38,668	6.22–7.55	32.5–39.9	1.37–1.79
Shiraz	73,352–102,809	4.09–4.83	52.0–62.2	2.50–3.10
Tabriz	51,021–74,777	4.79–5.64	44.3–52.4	2.04–2.53
Tehran	45,795–69,551	4.95–5.87	42.4–50.6	1.93–2.42
Zahedan	65,275–92,831	4.31–5.09	49.2–58.7	2.33–2.89

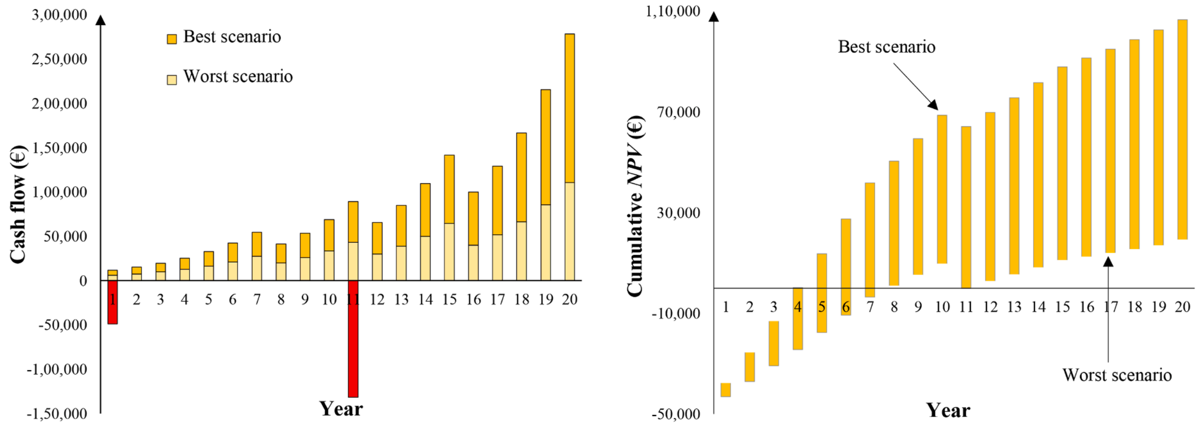
It is evident from the outputs that these three factors and energy yield have significant effects on the feasible range. Clearly, a larger *u* is needed to ensure project viability for lower E_A, i.e., the low energy would be supported by a larger FiT rate (greater *u*). In the lowest energy yield case, for example, the minimum required *u* under $i = j = 20\%$ is 16.75% to achieve a positive *NPV*. The corresponding values are 9.25% and 1.63% for moderate and high energy generation levels, respectively.

The effect of the discount rate is mainly on the net present value of the future incomes. Therefore, when *i* is small, the worth of future incomes would be large. In such cases, the project is economically feasible even for small *u* sets and large *j* values. For the moderate energy case and under $j = 20\%$, the project is feasible for *u* values greater than 6.05%, 7.3%, and 9.25% under $i = 10\%$, 15%, and 20%, respectively.

Finally, the *NPB* is independent of the annual inflation rate, while *NPC* would be greater for higher *j*. The results in Fig. 11 corroborate this effect, i.e., a greater *u* is required for a larger *j*. When the annual discount rate is 20% in the previous case, the minimum *u* to have a profitable project under $j = 15\%$, 20%, and 40% is 7.25%, 9.25%, and 23.03%, respectively.

3.2.3. System size

As an advantage of the presented work, it can be applied to all PV scales. This feature is shown in this part, where the analysis is extended to two more case studies, residential and power plant systems with around 5.2 kW and 1 MW power. The details of these PV systems are given in Table 5. In all systems, the same PV module with 580 W is used.



(a) (b)

Fig. 9. Results for the minimum (Rasht with Albedo = 0.1) and maximum (Shiraz with Albedo = 0.9) energy yield: a) Cash flow, b) Cumulative *NPV*.

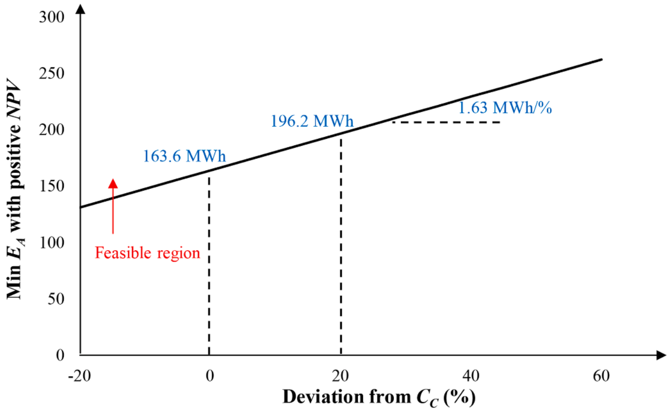


Fig. 10. Feasible region for various capital cost levels and 0.1–0.9 ground albedo.

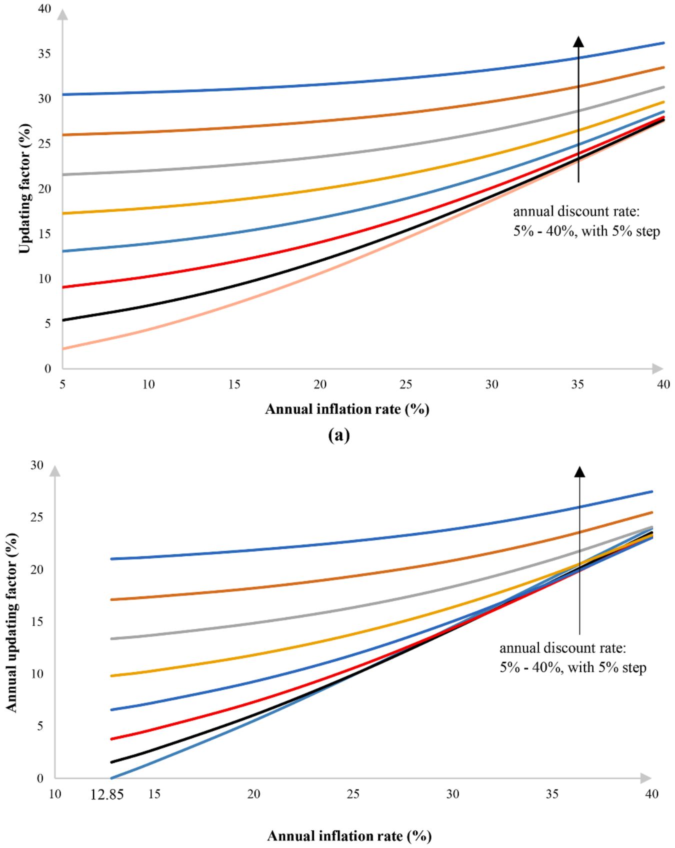
Table 4
Energy range for the studied cities under 0.1–0.9 ground albedo.

City	E_A (albedo = 0.1)	E_A (albedo = 0.9)
Ahvaz	252 MWh	298 MWh
Bandar Abbas	270 MWh	320 MWh
Isfahan	321 MWh	372 MWh
Kerman	314 MWh	366 MWh
Mashhad	244 MWh	286 MWh
Rasht	207 MWh	245 MWh
Shiraz	325 MWh	380 MWh
Tabriz	276 MWh	321 MWh
Tehran	264 MWh	310 MWh
Zahedan	307 MWh	359 MWh

Also, the annual maintenance cost, inverter(s)' replacement costs, *i, j*, and *u* are considered with the settings, elaborated on previously. The economic outputs for Mashhad city, as an example, are presented in this table. The results confirm the high viability of bifacial modules in all PV scales. Also, the slight deviation of the economic indices relies on the cost/kW and yield.

3.3. Discussions and comparison with existing literature

This study, for the first time, evaluates the economic viability of bifacial solar modules in a high-potential region under an incentive policy. The simulation results of this work demonstrate a higher energy yield of the GCPVS with bifacial modules than the monofacial ones. For a specific site, this additional yield depends on the albedo, e.g., it is 1.5%–2.4% under albedo = 0.1 and 18.4% – 21.2% under albedo = 0.9 for the studied cities. These ranges are in line with the findings of the existing literature [11,23,24].



(a)

(b)

Fig. 11. Economic outputs for: a) low energy generation (E_A = 207 kWh), and b) moderate energy generation (E_A = 290 kWh).

This work presents several advances over the existing literature, as summarized in Table 1. First, it evaluates the GCPVS economic viability under a FiT framework, while no study has touched on bifacial modules' economic assessment under an incentive policy. This highlights the need to legalize new incentive actions to motivate bifacial installation. Second, it covers practical scales and applications of GCPVS, including residential, commercial, and power plants, both rooftop and ground-

Table 5
Assumptions and outputs for three scales in Mashhad under albedo 0.1 – 0.9.

Parameter	5.2 kW	150 kW	1 MW
System layout	1 × 9 × 580 W, 1 × Primo 5.0–1	5 × 17 × 580 W, 1 × Tauro Eco 50–3-D 10 × 17 × 580 W, 1 × Tauro Eco 100–3-D	100 × 17 × 580 W, 10 × Tauro Eco 100–3-D
Investment (€)	19,500	490,000	3050,000
NPV (€)	10,725–19,110	35,818–58,148	2592,500–4056,500
PBT (years)	5.56–6.72	5.35–6.38	5.08–6.05
IRR (%)	34.9–41.8	38.9–46.7	40.1–48.5
BCR	1.55–1.98	1.73–2.19	1.85–2.33

mounted installations. This is a step forward, since most studies considered a special application, such as BIPV [15], highways [16], and FPV [21,22].

Furthermore, a few works have modelled GCPVS components and considered electrical design limitations in their studies [21]. Since they may affect the energy yield and analysis, this paper relies on PVsyst software, a strong tool that supports both accurate modelling and GCPVS design.

Last but not least, by focusing on the studied country, it is seen that the utilization of bifacial modules would lead to higher profitability. Comparing the results of a 100 kW system in [18] with the outputs of the cities with high solar potential highlights that the *PBT* for monofacial module is around 5.24 years, while it is less than 5 years for bifacial modules. Also, the *IRR* is around 32% and at least 50% for monofacial and bifacial modules, respectively, confirming more profit for the project's life time. These two indices ensure higher profitability of the bifacial modules compared to monofacial for both short-term and long-term. For the prior, the investment is covered by the incomes in a shorter period of time. For the latter, the investor benefits from a 18% higher annual profit in the 20 years of the contract.

4. Conclusion and future directions

This paper evaluates the economic viability of a grid-connected PV system with bifacial solar modules under an incentive policy in a region with rich solar potential. The methodology is based on system simulation in the PVsyst platform and computing the economic indices. The simulation outputs for several cities in the studied country highlight the high feasibility of the studied real project, even when initial costs increase. In addition, the sensitivity analysis demonstrates how variations in feed-in tariff (annual updating factor), discount rate, and inflation rate affect the feasibility of the project. Nonetheless, the studied commercial PV project is profitable due to the abundant solar potential and high yield of bifacial modules. The outputs provide experts with valuable insights for the implementation of the approach in the target region and for adopting an effective policy that guarantees the steady development of the GCPVS. The current study includes detailed modeling of the components, a feed-in tariff policy in the assessment, and a high-potential region for the first time. Moreover, the analysis is carried out for various sets of ground albedo; thus, the system owner has a clear picture of what should be realized. The outputs can highlight the necessity of legalizing/modifying an incentive, considering the solar potential and economic conditions. For example, while the studied country needs an increase in FiT to offset the high inflation and discount rates, a country/region with a stable economy can adopt a fixed FiT or net metering policies.

Future studies can further enrich the obtained outcomes. From the grid-connected PV system characteristic, an optimization can be performed. For example, the PV size and system design can be optimized so that the *NPV* of the project is the greatest. To this end, the *NPV* can be formulated in terms of the PV's annual generated energy, which depends on the system design. This nonlinear optimization is expected to be solved using computational algorithms, such as the genetic algorithm and particle swarm optimization. Also, the modeling can be matured by including various parameters in the economic analysis (e.g., environmental costs) and energy determination (e.g., analytical methodologies to estimate the solar radiation); however, these considerations may limit the destination regions/countries, as some of them lack a policy for CO_2 saving/adequate measurement for energy yield determination. Finally, the albedo is considered fixed over the year in the presented analysis. As a more realistic case, the monthly ground albedo can be imported into PVsyst for energy estimation. This simulation boosts the accuracy of the estimated yield and, accordingly, the economic assessment.

This study focuses on a specific country, supportive policy, and GCPVS size. However, the developed model is multiscale and can be applied to all locations and incentive policies. Thus, it is a systematic and practical approach to assess the economic feasibility of bifacial solar modules in the designated country/incentive policy/GCPVS size.

CRediT authorship contribution statement

Reza Bakhshi-Jafarabadi: Methodology, Software, Supervision, Writing – original draft. **Nazanin Nemati-Yazdi:** Software, Writing – original draft.

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.

Data availability

No data was used for the research described in the article.

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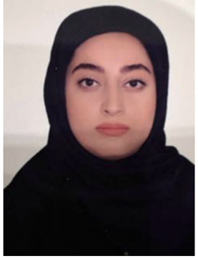

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