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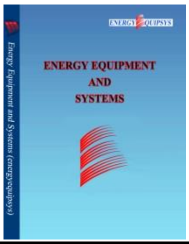

An experimental investigation of a solar photovoltaic system: economic, environmental, and performance assessment

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ABSTRACT

This paper presents an experimental study of a 10 kW grid-connected photovoltaic (PV) system installed on the roof of a government building located in Ilam, Iran. The purpose of this study is threefold: firstly, to assess the quality of the electrical power generated by the system; secondly, to analyze the CO_2 mitigation potential of the system; and thirdly, to investigate the economic viability of the system. The economic analysis of the system is performed considering three different scenarios. In the first and the second scenarios, it is assumed that the PV system is installed for complete self-consumption, while in the third scenario, it is supposed that the PV power plant is built to sell its generated electricity. Besides, the first and the second scenarios are based on the average retail electricity price of 5.79 cents of US dollars per kWh and 8.22 cents of US dollars per kWh, respectively, while the third scenario assumed that the government purchases the electricity generated by the power plant at a fixed rate of 21.33 cents of US dollar per kWh. Each scenario is assessed in two modes, with and without including greenhouse gas (GHG) emissions reductions credit.

Keywords: Grid-Connected PV Power Plant; Economic Analysis; Net Present Value; Greenhouse Gases; Economic Analysis.

1. Introduction

Solar or photovoltaic cells directly convert sunlight to electricity. The electricity generation process in solar cells is eco-friendly (clean and noiseless) and competitive with fossil-based sources. Therefore, the temptations of using PV panels are constantly increasing. By the end of 2016, cumulative global installed solar PV capacity reached about 303 GW, while the total capacity for solar heating was about 4.8 GW [1]. The significant cost reduction of solar PV over the last decade and the zero-fuel cost volatility are the key drivers behind the rapid growth of the solar PV sector all over the world.

The PV power generation applications can be conceptually divided into two categories, including standalone systems and grid-connected systems. In standalone or off-grid PV systems, the generated electricity are used for a

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variety of applications, including remote power, desalination, remote monitoring, lighting and water pumping. On the other hand, grid-connected or on-grid PV systems can provide energy for local loads and exchange power with utility grids. Easy installation and operation, high efficiency, the lack of complex equipment and the lack of a battery to save electrical energy are the advantages of these systems. They range from small residential and commercial rooftop systems to large utility-scale solar power stations.

In recent years, numerous theoretical and experimental studies have been developed to investigate the performance of grid-connected PV systems. Kazem et al. [2] numerically analyzed the techno-economic feasibility of Oman's 1 MW grid-connected PV plant. They found that the plant's energy cost is around 0.2258 USD/kWh, which is economically feasible. Besides, the results showed that the capacity factor of the proposed system is 21.7%. It is worth mentioning that the capacity factor (CF) is the actual annual output energy divided by the energy generation of a PV if it was operated for 24 h a day under full rated power for a year. Al-Shamani et al. [3] experimentally assessed the performance of a rooftop grid-connected photovoltaic/thermal system with SiC nanofluid under tropical climate conditions. The results revealed that this system has better performance and efficiency than the grid-connected PV systems. Their analysis revealed that using SiC nanofluid for grid-connected PV systems for March, the PV array efficiency and performance ratio could be enhanced from 8.77% to 133.52 and from 77.14% 95.72, respectively. Anzalchi and Sarwat [4] presented an overview of the available techniques, standards and grid interface of the grid-connected PV systems in distribution and transmission levels. Additionally, they investigated the adopted topologies of the converters, thorough control strategies for grid-connected inverters, as well as their applications in PV farms. Lima et al. [5] analyzed the performance of a 2.2 kW PV system installed at the State University of Ceara, Fortaleza, Brazil. It was reported that the annual average array, system and inverter efficiencies are 13.3%, 12.6% and 94.6%, respectively. Wang et al. [6] compared the seasonal performance of three grid-connected PV systems based on different technologies (poly-Si, a-Si and CdTe) operating under the same conditions. According to the indoor test results, it was revealed that the total three-year performance ratio of the system with poly-Si, a-Si and CdTe modules are 81.89%, 81.01% and 81.01%, respectively. Al Garni et al. [7] used HOMER software to compare grid-connected PV systems' optimal design and analysis with different tracking systems. They considered the horizontal axis (monthly adjustment, weekly adjustment, daily adjustment, continuous adjustment), vertical-axis (continuous adjustment), and two-axis tracking systems. It was reported that the maximum net present cost and the highest Levelized cost of energy belong to the horizontal tracker with continuous adjustment.

Iran is one of the world’s largest providers of fossil fuel subsidies. At around 25.93 cents of US dollar per liter, the price of gasoline is near that of a bottle of mineral water in Iran, and at just 1.3 cents of US dollar per kilowatt of electricity, citizens pay far below the global average [8]. Because of this high fuel subsidization, electrical energy has been supplied from the power plants for many years, consuming considerable amounts of fossil fuels. In 2009, the power plant sector used 374.8 Mboe (Million Barrels of Oil Equivalent), including 95.7 Mboe from oil, 273.4 Mboe from natural gas and 1.3 Mboe from coal and 4.4 Mboe from renewable sources to generate electricity equivalent to 130.2 Mboe [9]. In March 2010, the Iranian parliament ratified the Targeted Subsidies Reform Act calling for a gradual increase of energy prices within five years (2010-2015) to address the increasing economic and social problems associated with high energy subsidies. In the first year, the average electricity tariff doubled (increased from 208.7 IRR/kWh in 2010 to 409.5 IRR/kWh in 2011, IRR/USD in 2010 was 10353 and 11145 in 2011) with the highest increase for the agricultural sector (by 268%) [10].

According to the targeting of energy subsidies in Iran, the new price rates for the electricity consumption by the public sector during 2016 are classified into three stages:

- Consumption during average-demand hours (e.g. 7 AM to 7 PM) will have a rate of 5.672 cents of US dollar per kWh.
- Consumption during high-demand hours (e.g. 7 PM to 11 PM) will have a rate of 11.344 cents of US dollar per kWh.
- Consumption during low-demand hours (e.g. 11 PM to 7 AM) will have a rate of 2.836 cents of US dollar per kWh.

The usual working hours in the public sector in Iran are from 7 AM to 4 PM, which is within the average-demand hours as per the above classification. Intending to increase the average retail price of electricity for the public sector, the government of Iran recently decided to change the above classification in the following way:

- Consumption during average-demand hours (e.g. 7 AM to 11 PM and 3 PM to 11 PM) will have a rate of 5.672 cents of US dollar per kWh.
- Consumption during high-demand hours (e.g. 11 AM to 3 PM) will have a rate of 11.344 cents of US dollar per kWh.
- Consumption during low-demand hours (e.g. 11 PM to 7 AM) will have a rate of 2.836 cents of US dollar per kWh.

According to the first classification, the average retail price of electricity for the public sector is 5.79 cents/kWh, while it is increased to 8.22 cents/kWh in the new classification.

Among renewable energy sources, Iran has high solar energy potential. Iran's unique geographical position means 90% of the country has enough sun to generate solar power 300 days a year. The average solar radiation for the entire of Iran is about 19.23 MJ/m^2, and it is even higher in the central part of Iran. The solar energy in the country varies from 2.8 kWh/m^2 in a day in the north to 5.4 kWh/m^2 in a day in the south. The average sunshine hours are estimated at 2800 h per year nationally and 3200 h in the central part of Iran due to the hot and dry climate [11]. Iran is reached 22.1 MW of cumulative PV capacity to date, according to official statistics provided by the Renewable Energy Organization of Iran (SUNA), which is run by the country's Ministry of Energy [12]. Besides, the Iranian government plans to install 540 MW of PV capacity by 2020 [12]. The use of solar energy, on the other hand, can help to diminish Iran's growing environmental issues, including air pollution and global warming emissions. Iran is the 10th worldwide country in carbon dioxide generation, and the energy-related carbon emission is reported to be 624.855 million tons in the year 2011 [13].

Despite the implementation of fuel subsidy targeting in Iran, the country is still the largest provider of fossil fuel subsidies globally. For the public sector, the electricity price is increased dramatically after the subsidy targeting. To solve this problem, office buildings and government institutions, banks and municipalities are required by the government to supply 20% of their consumed electricity from solar power plants. To help achieve this goal, SUNA is offering to cover up to 50% of the plant capital cost. Besides, SUNA offers an attractive option for PV plants that are not installed for self-consumption but are built to sell their generated electricity. For these cases, SUNA does not pay any credit for installing a power plant, but it offers a 20-year guaranteed electricity purchase tariff (21.33 cent/kWh). In this regard, Ilam Gas Company has installed a 10 kW grid-connected PV power plant on its roof. In the present study, the specifications of this plant are presented, and then its performance in 2016 is assessed from technical and environmental points of view. Additionally, the economic analysis of the plant is performed by considering three scenarios with two modes, namely with assigning GHG emissions reductions credit and without assigning GHG emissions reductions credit. To the authors' best knowledge, this is the first assessment of the effect of energy subsidy removal on the financial justification of PV power plants in Iran.

2. Specifications of PV power plant

The system under study is a 10 kW grid-connected PV plant installed on the rooftop of Ilam Gas Company, as shown in the Fig. 1. The company is located on the latitude 33.64°N and longitude 46.43°E, and about 1387 m above sea level. The system consists of four parallel-connected strings, each having 10 modules covering a total area of 65 m^2. The Renesola JC250M-24/Bb of 250 W polycrystalline modules were used. As shown in Fig. 1, each string is mounted on a fixed angle structure. The system faces the south and is sloped at an angle equal to the local latitude.

The Growatt three-phase 10 kW inverter was implemented to convert DC power from the PV modules into AC power to be transferred to the utility grid. The inverter had a rated maximum efficiency of 98%. It was connected to a monitoring system to observe the system's stability and performance. Data recorded at 5 min intervals in the monitoring system was extracted via an SD card and read directly into a computer. This system allowed users to view all plant performance parameters, including voltage, current, and instantaneous power. In addition, the system could calculate the amount of GHG emissions avoided by the PV power plant in terms of the tons of CO_2. More detail about the technical characteristics of the used PV panels and inverter are given in Table 1 and Table 2, respectively.

Fig. 1. PV plant under examination.

Table 1. Technical characteristics of polycrystalline PV panels used in the studied PV power plant [24].

Parameter	Value	Unit
Nominal power output in standard condition	250	Watt
Maximum efficiency	15.37	%
Number of cells	60	-
dimensions	164×99.2×4	cm
weight	19	Kg
Short circuit current	8.83	Ampere
Open circuit voltage	37.4	Volt
Maximum power point current	8.31	Ampere
Maximum power point voltage	30.1	Volt
Maximum voltage	1000	Volt
Temperature coefficient of power	-0.4	Kelvin

Table 2. Technical specifications of inverter used in the studied PV power plant [25].

Parameter	Value	Unit
Maximum DC input power	11000	Watt
Maximum DC input voltage	1000	Volt
Start voltage	350	Volt
Nominal power	10	Kilowatt
PV voltage range	180–1000	Volt
Maximum output current	16	Ampere
AC nominal voltage range	184–275	Volt
Maximum efficiency	98	%
Dimensions (W/H/D)	74×44×23.5	cm

3. Scenarios

In the present investigation, three scenarios are considered for economic analysis of the studied 10 kW grid-connected PV power plant of Ilam Gas Company. In the first scenario, the average retail price of electricity is assumed to be 5.79 cents of US dollar per kWh, while it is assumed to be 8.22 cents of US dollar per kWh in the second scenario. Also, in the first and the second scenarios, it is supposed that SUNA pays 50% of the plant capital cost. In the third scenario, it is assumed that all the electricity generated is injected into the grid and sold at a fixed rate of 21.33 cents of US dollar per kWh. Each scenario is evaluated in two modes, with and without assigning GHG emissions reductions credit (22$ per abated ton of CO_2 [14]).

4. Modeling

4.1. Economic analysis

The cost-benefit analysis is a method of valuation and measure to predict a project from financial usefulness point of view. The primary purpose of economic analysis is to determine the costs and benefits of an investment. In general, different economic indicators can be used for financial project assessment that includes: the net present value (NPV), the internal rate of revenue (IRR) and discounted payback time (DPT). The NPV is a standard technique for economic appraisal of projects using discounted annual cash flow. The following relation calculates the value of NPV [15, 16]:

$$\mathrm{NPV} = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{1}$$

Here, R_t is the net cash flow, t is the cash flow time, and i represents the interest rate (the return that could be earned per unit of time on investment with similar risk). Based on this indicator, a project with a positive NPV is profitable and a negative, leading to a net cash flow loss [17].

The initial cost of a grid-connected PV panel includes the purchase price of the equipment, engineering cost, and maintenance cost [18]. In the general form, the initial cost can be expressed as [19]:

$$R_0 = (1-\alpha_{sub})(C_{panel} + C_{inverter} + C_{inst}) \tag{2}$$

Here R_0 is the cost of PV system, C_{panel} is the total cost of PV panels, $C_{inverter}$ is the inverter cost, C_{inst} is the installation and engineering cost and α_{sub} is the ratio of financial subsidy provided by government to encourage organization to use solar energy supply [20].

4.2. Levelized cost of electricity (LCOE)

The levelized cost of electricity (LCOE) concept is used to compare the energy cost from different sources. This criterion allows the comparison of various technologies (e.g. solar, wind, natural gas) of unequal lifespan, size, different capital investment costs, return, and capacities. LCOE as a benchmark is highly sensitive to assumptions are made as well as economic indicators. The general calculation of LCOE method is introduced in [21-23]. Here, the below relation is used to calculate LCOE:

$$\mathrm{LCOE} = \frac{\sum_{t=0}^{T} (I_t + F_t + M_t)/(1+i)^t}{\sum_{t=0}^{T} S_t (1-d)^t/(1+i)^t} \tag{3}$$

where, S_t is the energy generated in a year or energy output per year multiplied by the degradation factor $(1-d)$, which decreases the energy with time. Also, t is the year, T indicates the total lifetime of the plant and F_t represents the fuel cost which is zero for a solar thermal power plant. Also, M shows the operation and maintenance cost.

4.3. Environment analysis

In addition to generating electricity to cover the lack of electricity in the utility grid, a sizable advantage of PV systems is the reduction of GHG emissions. GHGs most relate to energy projects analysis are CO_2, CH_4, NO_x and fluorinated gases. Worldwide, net emissions of GHGs from human activities increased by 35 percent from 1990 to 2010. Carbon dioxide emissions, which account for about three-fourths of total emissions, increased by 42 percent over this period [24].

Given the importance of carbon dioxide emissions as the most important GHGs, the calculation of the cost of emission will be discussed. To assess the environmental impacts of carbon dioxide emission, the respective flow rate of CO_2 can multiply by corresponding unit damage cost [25]. The cost of CO_2 is a function of different factors. According to an analytical report by Synapse Energy Economics Inc., which propose three scenarios for carbon dioxide prediction cost from 2022 to 2050, here the damage cost of CO_2 is considered 0.022$ per kilogram [14].

$$\dot{C}_{inv} = C_{CO_2} . m_{CO_2} \tag{4}$$

Here, C_{CO_2} is the cost of damage to CO_2 per kilogram emission, m_{CO_2} is the annual emission of carbon dioxide in terms of kilograms and $\dot{C}_{inv}$ is the annual total environmental damage cost of CO_2 or save on the costs to be paid for environmental degradation annually. It should be noted that the amount of CO_2 emitted per kWh of electricity over its lifetime is approximately 960 g for coal-powered technology [35].

5. Results and discussion

In the following section, the actual data of the studied grid-connected PV power plant is reported. Firstly, the technical and environmental analyses of the installed PV power plant are presented, and then, the economic aspect of the project using appropriate economic indicators is conducted.

5.1. Technical and environmental analyses

In order to study the performance of the investigated PV power plant, output frequency, effective output voltage, effective output current, and power output are presented.

The daily variation of the output frequency in 2016 is demonstrated in Fig. 2. As it can be seen, although the output frequency shows an oscillation, it does not exceed 0.1% of the base frequency of 50 Hz, which is very good and acceptable. According to the standard, this deviation can be up to 0.3%.

The change of output voltage at different hours of four selected days in 2016 is illustrated in Fig. 3. The days are selected to cover all seasons a year with different radiation intensities. Regarding the three phases of the output voltage (V_r, V_s and V_t), the uniformity of the voltage of different phases is one of the parameters that is considered in the PV power plants to check the power production quality. As shown in Fig. 3, the variation of the voltage of different phases are of the same pattern, and the difference between the two phases is always less than 5.21 volts, which is about 2.36% of 220 volts, and that is in the domain of acceptable changes.

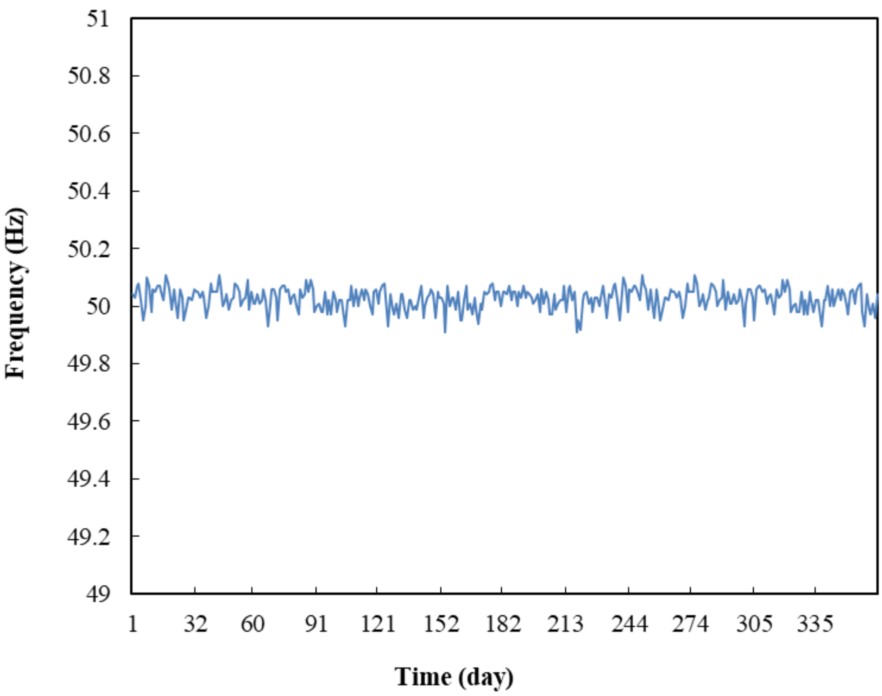

Fig. 2. Daily variation of the output frequency of PV in 2016 for power plant.

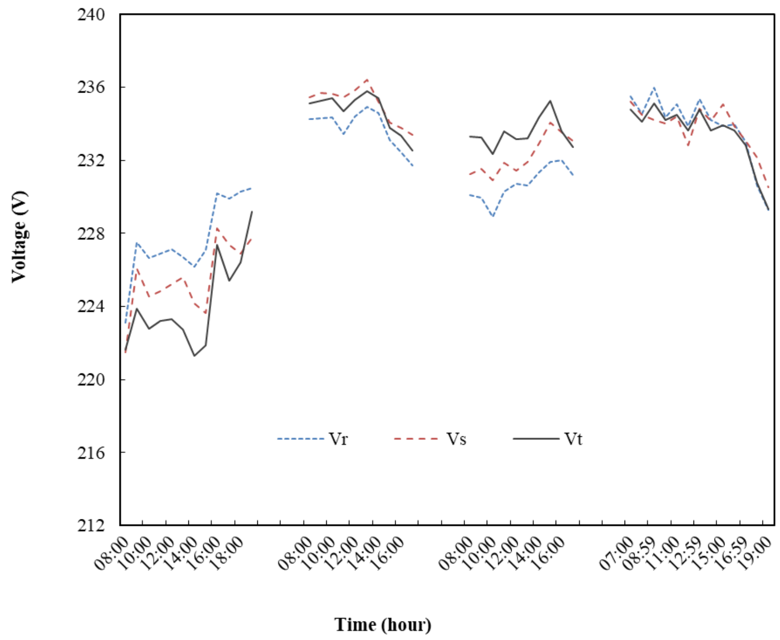

Fig. 3. Hourly variation of effective output voltage for four different days in 2016 (from left to right – 7 Jul., 18 Nov., 22 Jan. and 23 Apr.).

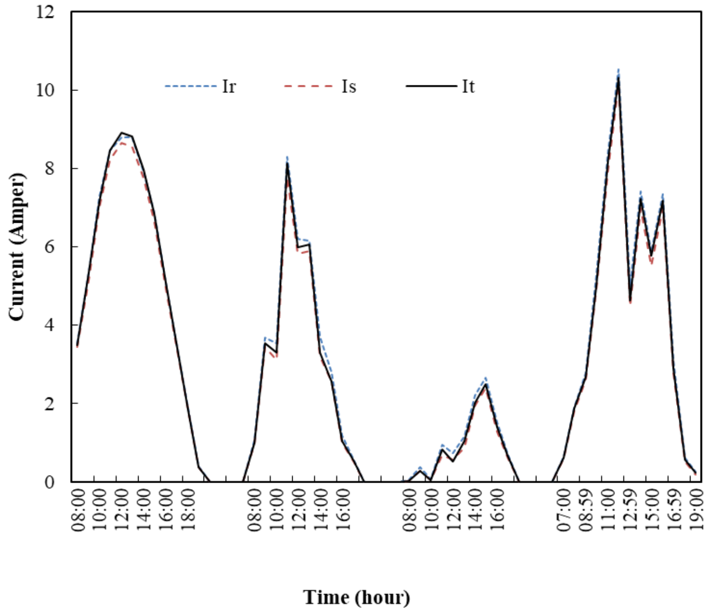

Fig. 4. Hourly variation of effective output current for four different days in 2016 (from left to right – 7 Jul., 18 Nov., 22 Jan. and 23 Apr.).

The hourly variation of the output current of different phases (I_r, I_s and I_t) at different hours of four selected days in 2016 is depicted in Fig. 4. The output current is directly affected by the solar radiation intensity and the PV panels' temperature. Therefore, when the radiation intensity is higher, the output current and thus the maximum output power are higher. As shown in Fig. 4, the current in different phases are very similar, and it can be said that all three phases have the same current.

The power output during four different days of 2016 is shown in Fig. 5. It should be noted that the values shown in this figure are the total power of the three different phases. As can be seen, the maximum amount of power generated by the studied power plant occurred about noon hours, with high radiation intensity except for 22 Jan. The maximum output power takes place at around 3:00 PM. According to the obtained results, the highest output power during the considered days (i.e. 7 Jul., 18 Nov., 22 Jan. and 23 Apr.) is about 5946.48 watts, 5667.09 watts, 1758.12 watts, and 7971.28 watts, occurring at 12:00 Noon, 11:00 PM, 3:00 PM and 1:00 PM, respectively. The meteorological data shows that the sky was cloudy on 22nd January, and this is the main reason for the lower power output during this day compared to the other three days.

Figure 6 displays the amount of electricity produced by the studied power plant in different months of 2016. According to the obtained results, the minimum electricity production occurs in January (955.03 kWh), while the maximum electricity is generated during August (2014.55 kWh). Also, the total electrical energy generated by the power plant in 2016 is about 14667 kWh.

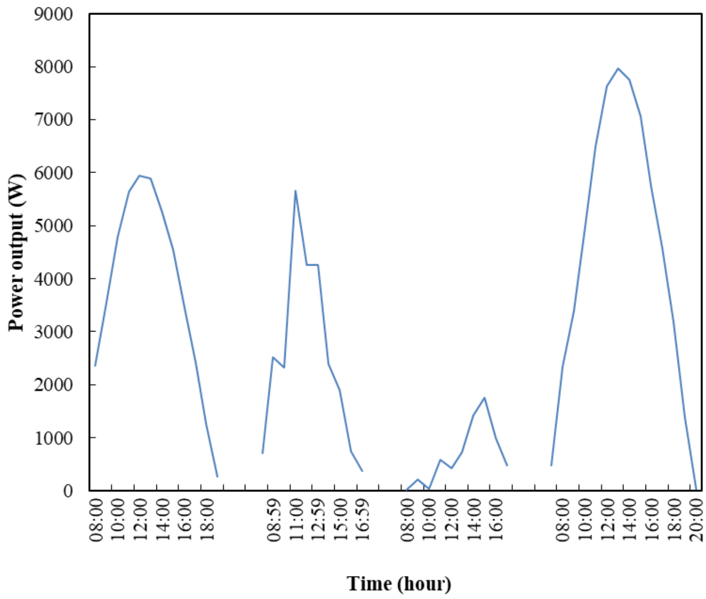

Fig. 5. Hourly variation of power output for four different days in 2016 (from left to right – 7 Jul., 18 Nov., 22 Jan. and 23 Apr.).

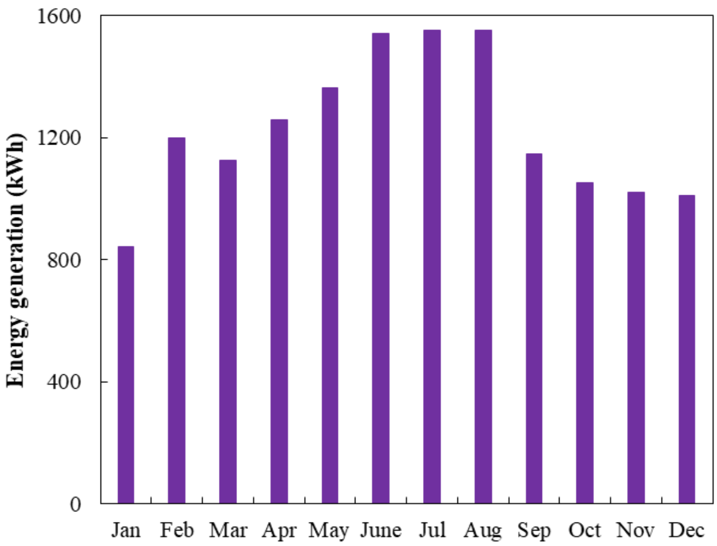

Fig. 6. Monthly energy production for 2016.

One of the advantages of using a PV power plant to generate electricity is reducing GHG emissions. Fig. 7 shows the amount of carbon dioxide reduction in different months of 2016 by using the studied PV power plant. The results revealed that the highest reduction in carbon dioxide emission occurred in July and August, amounting to 1.49 tons. Besides, the results show that the total reduction in carbon dioxide emission in 2016 was 14.88 tons.

5.2. Economic analysis

The economic analyses of the studied grid-connected PV power plant are performed precisely by using the LCOE and cost-benefit analysis. Table 3 shows the cost of different components of the studied grid-connected PV power plant. Additionally, the main economic parameters used in this study to find the NPV, cumulative cash flow, and time of return investment cost for the considered scenarios are reported in Table 4.

To perform the economic assessments, the following assumptions are made:

- The interest rate is 10% based on the goods, and consumer services cost indicator in Iran's different city areas in the year 2016.
- The power output of the studied PV plant is fixed during its lifetime.
- Operation and maintenance cost is 1% of the capital investment cost.
- The degradation rate is 0.5% reduction in efficiency per year.

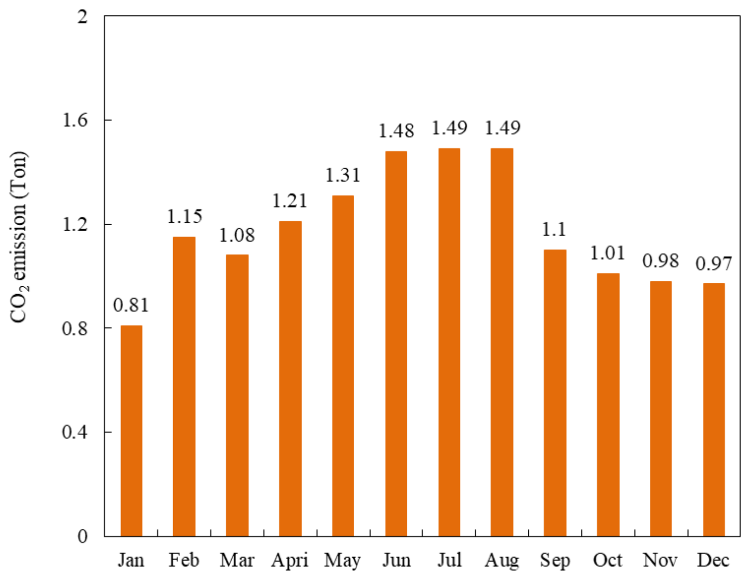

Fig. 7. Monthly CO_2 mitigation in 2016.

Table 3. The project cost of the studied grid-connected PV power plant of 10 kW capacity.

PV panel cost	15560$
Inverter cost	3840$
Installation and engineering cost	1210$
Other costs	140$
Value-added tax (VAT) price	1860$
Total cost	22610$

Table 4. Main parameters used in economic analysis of the studied 10 kW grid-connected PV plant.

Parameter	Value	Unit
Solar panel system lifetime	20	Year
α_{sub} for the third scenario	0.5	-
Interest rate	10	%
CO_2 emission cost	0.022	$/kg

The LCOE strongly depends on the implemented technology and region of the project. It should be noticed that the LCOE as a helpful indicator can give an excellent insight to compare different projects in different locations.

Calculations for the present project show that for two cases with and without incentive from the government, the LCOE of the studied PV power plant is 176.45 $/MWh and 352.1 $/MWh, respectively. For comparison, the LCOEs for various technologies and regions for projects completed in 2015 without government support are reported in Table 5. As can be seen, the LCOE for solar PV projects in buildings in the United States, European Union, China, and India is 310 US dollars per MWh, 190 US dollars per MWh, 150 US dollars per MWh and 128 US dollars per MWh, respectively. The higher LCOE for solar PV projects in Iran can be attributed to the fact that the main equipment needed for the project (including PV panels and inverters) is imported from other countries, causing prices to rise above what many other countries may pay for those items. Additionally, Table 5 reveals that the LCOE of the fossil fuel technologies is much lower than that of the solar PV projects in buildings. Hence, it can be concluded that to be able to compete with other types of technologies, the government incentives for renewable technologies should be implemented appropriately.

Figure 8 presents the cumulative cash flow for different years of operation based on various scenarios in the mode without assigning GHG emissions reduction credit. The results indicate that the cumulative cash flow in the first years of operation for the first and the second scenarios are better than the third scenario, while the third scenario is more profitable for the long term. In fact, although the cumulative cash flow for the third scenario is not beneficial shortly, it is more dividend in the future farther away. Calculations show that at the end of the system's lifetime, the cumulative cash flow is 40870$, 62742$ and 169562$ based on the first, second, and third scenarios, respectively.

Table 5. Average Levelized costs of electricity by technology and region for projects completed in 2015 [26].

	PV buildings	Onshore wind	Bioenergy	Gas CCGT*	Coal supercritical
United State	310	76.5	131	51.3	76.5
European Union	190	107	220	67.2	81.8
China	150	73.6	148	62.8	45.2
India	128	89.7	169	71.5	49.8

* CCGT: combined cycle gas turbine

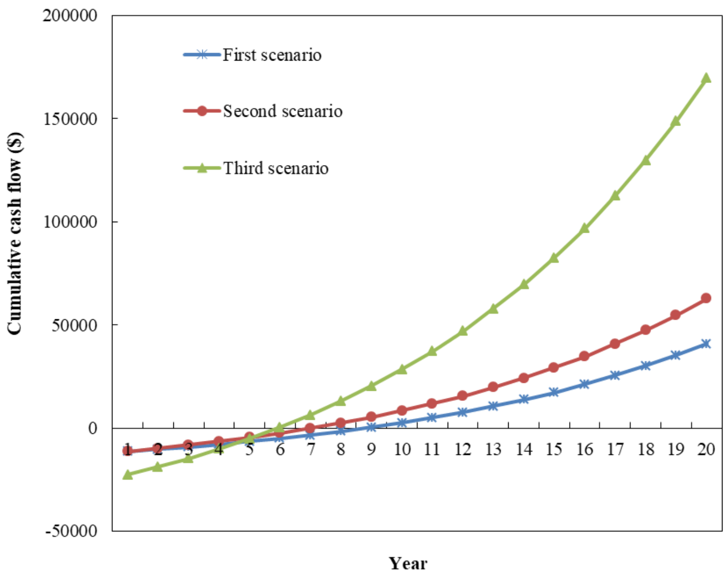

Fig. 8. Cumulative cash flow for different scenarios during PV operation years with 10% interest rate in the mode of without assigning GHG emissions reductions credit.

Because the interest rate influences the capital investment cost and has a severe effect on the cost of electricity, a sensitivity analysis for this parameter is critical. Fig. 9 shows the variation of the cumulative cash flow at the end of the project lifetime with the change of interest rate for three scenarios in the mode without assigning GHG emissions reductions credit. The results indicate that the cumulative cash flow reduces with an increase in interest rate, and the amount of decrement is higher for the third scenario than for the first and the second scenarios.

Figure 10 depicts the cumulative cash flow for various scenarios considering GHG emissions reduction credit. With regard to the fact that the CO_2 emission reduction using the studied grid-connected PV power plant is 14.36 tons per year, the economic justification of the project can be more advisable. As observed in Fig. 10, at the end of the system's lifetime, the cumulative cash flow for the first, second and third scenarios are 47290$, 69162$, and 175983$, respectively. These results indicate that the cumulative cash flow is about 15.7%, 10.2% and 3.8 % better than those for the mode of without including GHG emissions reductions credit.

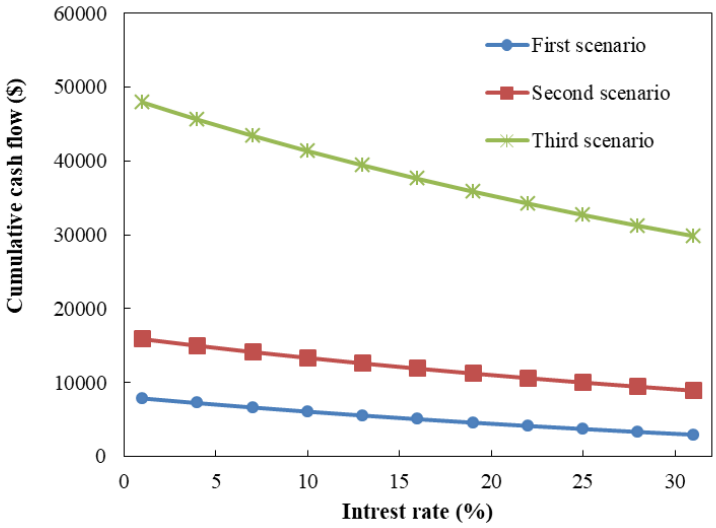

Fig. 9. Cumulative cash flow versus interest rate for three scenarios in the mode of without including carbon credit.

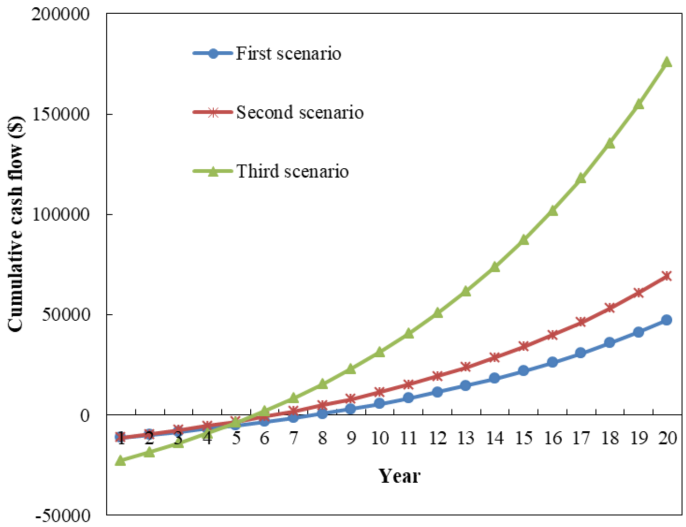

Fig. 10. Cumulative cash flow for different scenarios during PV operation years with 10% interest rate to assign GHG emissions reductions credit.

The variation of the cumulative cash flow at the end of the project lifetime versus interest rate for three scenarios in the mode of assigning GHG emissions reduction credit is demonstrated in Fig. 11. It is evident that the increment of interest rate leads to a descending trend for cumulative cash flow and the amount of decrement is higher for the third scenario is more significant for the third scenario compared to the first and the second scenarios. In addition, it can be seen that the slope of the cumulative cash flow degradation is higher when the GHG emissions reductions credit is considered; however, the difference between the net cash flow at the end of the project lifetime for the two modes of the third scenario is not considerable, so that the net cash flow for the first (with assigning GHG emissions reductions credit) and a second mode (without assigning GHG emissions reductions credit) of the third scenario is 30917.7$ and 29835.9$, respectively.

A suitable indicator to assess the economic viability of a PV project is payback time for the capital investment of the project. It is obtained by counting the number of years it will take to recover the cash invested in a project. Fig. 12 shows that the payback time for the third scenario is lower than those associated with either of the other scenarios. Moreover, the achieved results show that the GHG reduction credit assignment reduces the payback time in the first and second scenarios, whereas it does not affect the payback time in the third scenario. In each mode of the studied scenarios, the first scenario has the maximum payback time, while the minimum payback time belongs to the third scenario. As it can be seen in Fig. 12, the minimum payback time of the studied project is 5.5 years, which is a very acceptable value and indicates that the construction of a grid-connected PV power plant in Iran can be an attractive investment; although, the obtained maximum value of the payback time (i.e. 8.5 years) is also considered acceptable in many countries.

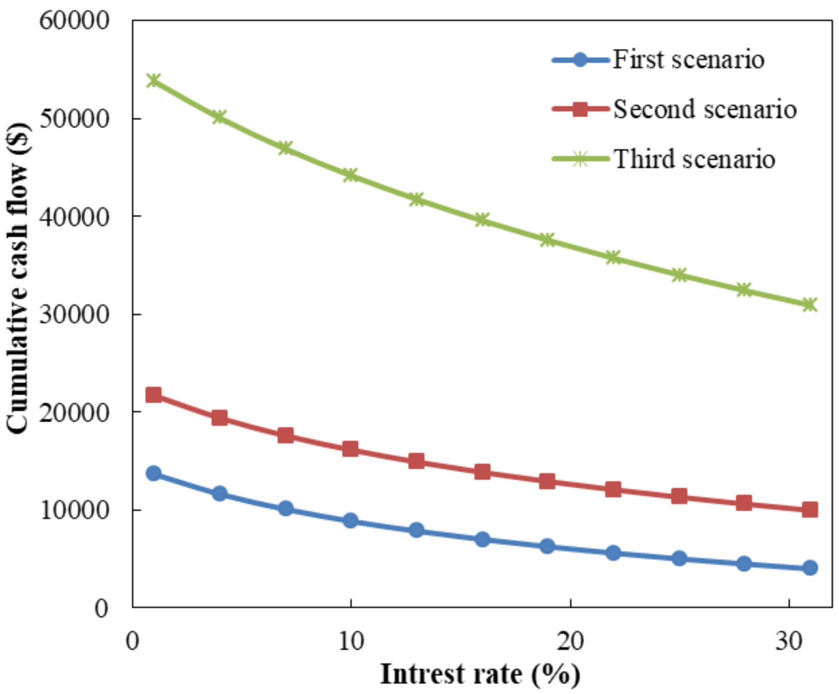

Fig. 11. Cumulative cash flow versus interest rate variation for n=20 years (lifetime of PV panel), including carbon dioxide emission cost saving.

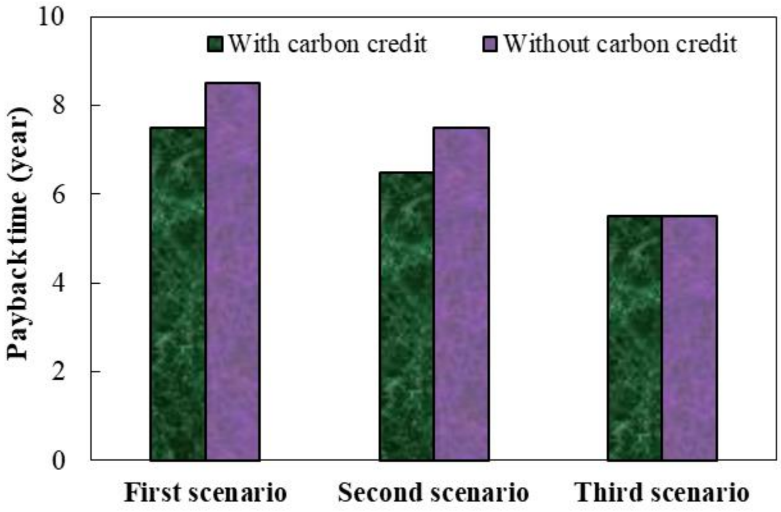

Fig. 12. Payback time of capital investment cost of PV system based on three defined scenarios.

6. Conclusion

A technical, economic, and environmental assessment of a 10 kW on-grid PV power plant is considered in this research. This power plant is installed on the roof of Ilam Gas Company in Ilam, Iran. The survey results show that the studied system has a significant potential to provide electrical power for a typical office building located in the western region of Iran. The main concluding remarks are as follows:

- An installed system can generate 14667 kWh of electricity per year, which is higher than the average norm of solar electricity generation in Iran.
- The environmental analysis of the studied system indicates that the plant can decrease the total carbon dioxide emission by up to 14.88 tons per year.
- LCOE analysis reveals that this parameter for the current project is 176.45 $/MWh and 352.1$/MWh with and without incentive from the government, respectively.
- The economic analysis shows that, based on all three defined scenarios, investment in such a project leads to positive benefits at the end of the project life span. The results also represent that, if the feed-in tariff provided by the government is used, the project is more beneficial than the two other scenarios.
- Taking into account the cost of CO_2 emissions, project implementation, is more justifiable in terms of profit and payback time.
- In each mode of the studied scenarios, the minimum payback time belongs to the third scenario, while the maximum payback time occurs in the first scenario.

References

[1] Snapshot of global PV markets 2017, International Energy Agency.

[2] Kazem H.A., Albadi M., Al-Waeli A.H., Al-Busaidi A.H., and Chaichan M.T., Techno-economic feasibility analysis of 1 MW photovoltaic grid-connected system in Oman. Case studies in thermal engineering, 2017. 10: p. 131-141.

[3] Al-Shamani A.N., Sopian K., Mat S., and Abed A.M., Performance enhancement of photovoltaic grid-connected system using PVT panels with nanofluid. Solar Energy, 2017. 150: p. 38-48.

[4] Anzalchi A. and Sarwat A., Overview of technical specifications for grid-connected photovoltaic systems. Energy Conversion and Management, 2017. 152: p. 312-327.

[5] de Lima L.C., de Araújo Ferreira L., and de Lima Morais F.H.B., Performance analysis of a grid connected photovoltaic system in northeastern Brazil. Energy for Sustainable Development, 2017. 37: p. 79-85.

[6] Wang H., Muñoz-García M.A., Moreda G., and Alonso-García M.C., Seasonal performance comparison of three grid connected photovoltaic systems based on

different technologies operating under the same conditions. Solar Energy, 2017. 144: p. 798-807.

[7] Al Garni H.Z., Awasthi A., and Ramli M.A., Optimal design and analysis of grid-connected photovoltaic under different tracking systems using HOMER. Energy Conversion and Management, 2018. 155: p. 42-57.

[8] Wheeler E. and Desai M., Iran's renewable energy potential. Middle East Institute. Jan, 2016. 26: p. 2016.

[9] Mirzahosseini A.H. and Taheri T., Environmental, technical and financial feasibility study of solar power plants by RETScreen, according to the targeting of energy subsidies in Iran. Renewable and sustainable energy reviews, 2012. 16(5): p. 2806-2811.

[10] Moshiri S., The effects of the energy price reform on households consumption in Iran. Energy Policy, 2015. 79: p. 177-188.

[11] Karegar H.K., Zahedi A., Ohisa V., and Khalaji M. in *the Australasian Universities Power Engineering Conference (AUPEC)*, . http://itee.uq.edu.au/∼aupec/aupec02/home.pdf [accessed 03.01.12].

[12] Iran Renewable Energy Organization (SUNA), http://www.suna.ir/homeen.html.

[13] Hosseini S.E., Andwari A.M., Wahid M.A., and Bagheri G., A review on green energy potentials in Iran. Renewable and sustainable energy reviews, 2013. 27: p. 533-545.

[14] A report on: National Carbon Dioxide Price Forecast: Spring 2016, http://www.synapse-energy.com/.

[15] Mitscher M. and Rüther R., Economic performance and policies for grid-connected residential solar photovoltaic systems in Brazil. Energy Policy, 2012. 49: p. 688-694.

[16] Bhandari R. and Stadler I., Grid parity analysis of solar photovoltaic systems in Germany using experience curves. Solar Energy, 2009. 83(9): p. 1634-1644.

[17] Dincer I., Rosen M.A., and Ahmadi P., Optimization of energy systems2017: John Wiley & Sons.

[18] Alirahmi S.M., Mousavi S.B., Razmi A.R., and Ahmadi P., A comprehensive techno-economic analysis and multi-criteria optimization of a compressed air energy storage (CAES) hybridized with solar and desalination units. Energy Conversion and Management, 2021. 236: p. 114053.

[19] Bernal-Agustín J.L. and Dufo-López R., Economical and environmental analysis of grid connected photovoltaic systems in Spain. Renewable Energy, 2006. 31(8): p. 1107-1128.

[20] Karimi M.H., Chitgar N., Emadi M.A., Ahmadi P., and Rosen M.A., Performance assessment and optimization of a biomass-based solid oxide fuel cell and micro gas turbine system integrated with an organic Rankine cycle. International Journal of Hydrogen Energy, 2020. 45(11): p. 6262-6277.

[21] Branker K., Pathak M., and Pearce J.M., A review of solar photovoltaic levelized cost of electricity. Renewable and sustainable energy reviews, 2011. 15(9): p. 4470-4482.

[22] Darling S.B., You F., Veselka T., and Velosa A., Assumptions and the levelized cost of energy for photovoltaics. Energy & Environmental Science, 2011. 4(9): p. 3133-3139.

[23] Ocampo M.T., How to Calculate the Levelized Cost of Energy-a Simplified Approach. Energy Technology Expert, 2009. 28.

[24] United states Environmental Protection Agency (EPA), www.epa.gov/climate-indicators/greenhouse-gases.

[25] Bernow S. and Marron D., Valuation of environmental externalities for energy planning and operations [Internet]. Boston;[cited 2015 Sep 10], 1990.

[26] World Energy Outlook 2016 Part: B Special Focus on Renewables, https://www.iea.org.