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Techno-Economic and Environmental Analysis of Floating Photovoltaic Power Plants: A Case Study of Iran

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Abstract

Solar energy, as a renewable and clean energy, has a remarkable share in improving the water-energy-food nexus. However, due to occupying a vast area of land, the development of large-scale photovoltaic systems is a serious challenge, particularly in regions with land restrictions. As a solution, it has been argued that the installation of the floating photovoltaic systems on the water reservoirs can save land as well as reduce the evaporation rate. The aim of this work is to economically and environmentally evaluate the feasibility of the installation of a 10-megawatt floating photovoltaic power plant on a water reservoir. The results obtained show that the payback period of investment and internal rate of return are achieved at 5.2 years and 20.4%, respectively. It is also found that if only 0.3% of the water reservoir surface is covered, the evaporation volume will be decreased from 441.2 up to 515.2 thousand cubic meters. Moreover, the environmental assessment demonstrates that 8470 to 15311 tons of CO_2 and 27 to 52.3 tons of NO_x are not released into the atmosphere. Ultimately, the sensitivity analysis proves that if the capital cost is reduced by 30%, the payback period will be shortened to 3.6 years. Furthermore, such a project in Chah-nimeh will be profitable as long as the electricity purchasing tariffs are more than US$ 0.096/kWh.

Keywords: *Economic assessment, Environment, Floating photovoltaic, Greenhouse gas, Water evaporation.*

1. Introduction

Installation of the photovoltaic (PV) modules on the water surface may be a key to overcome the PV drawbacks such as lower efficiency and land occupation. The efficiency of monocrystalline and polycrystalline silicon solar cells declines around 0.45% and 0.25%, respectively with increasing ambient temperature by 1 ºC [1]. Adding tracking solar system aka MPPT, using high-efficiency twin-Si cell panels, and cooling approaches are three ways that improve the efficiency of panels. For example, changing the tilt of panels per month would increase energy generation by 4.17% per year, and would decrease overall losses by 5.06% [2]. But adding tracking solar ration systems is expensive, and makes the system more complex.

The floating photovoltaic (FPV) systems can be installed on the surface of seas, lakes, ponds, open water reservoirs, dams, and water and/or wastewater treatment plant to reduce evaporation. It is notable that dust cumulation on panels, which is another drawback of land-based PV, is less on the water surface. Another benefit is that the shading effect of FPV modules on the water surface decreases the growth of algae, which is hazardous for the fish and fishing activities. By comparing the cooling types of PV systems, it has been revealed that water-cooling is more suitable than air-cooling even if the water temperature is more than air [3]. Sukarso and Kim, 2020 [4], have shown that in a similar condition, the temperature near the water is lower than on land by 8 ºC, which, in turn, can cool the back of the PV panels. The lower temperature on the back of solar panels can increase the heat loss coefficient (the measure of assessing the cooling effect) by nearly 22 W/m^2K compared to the land-based PV systems [5]. Due to this cooling effect, the panels' efficiency improves by 11% [6] and at most 12.5% [7], compared to the land-based PV system, and also the annual energy generation will rise to 6%.

In addition to the ambient temperature, the wind speed, shading effect, intensity, and duration of radiation all affect the PV systems' performance. It has been found that the efficiency of floating PV has been improved by increasing the radiation intensity up to 14.58% compared to the land-based PV when the radiation intensity reaches 834

W/m^2 [8]. Also, the wind speed can increase the FPV performance. In a recent study, it has been proposed that installing the FPV power plants in windy regions increases the panel efficiency by cooling effect, and improves the output energy yield by 20.28% [9].

Figure 1 shows the advantages and disadvantages of the FPV system. Corrosion effect, impact on shipping, fishing activities, and risk of seasonal storms are the main sources of concern for installing the FPV systems. Moreover, some technical, economic, and social challenges such as lack of trained workforces and subsidizing in local electricity tariffs may lead to discouraging the investors from investing in the FPV power plants [10], and finally, the environmental concerns of local people and job creation must be taken into account [11].

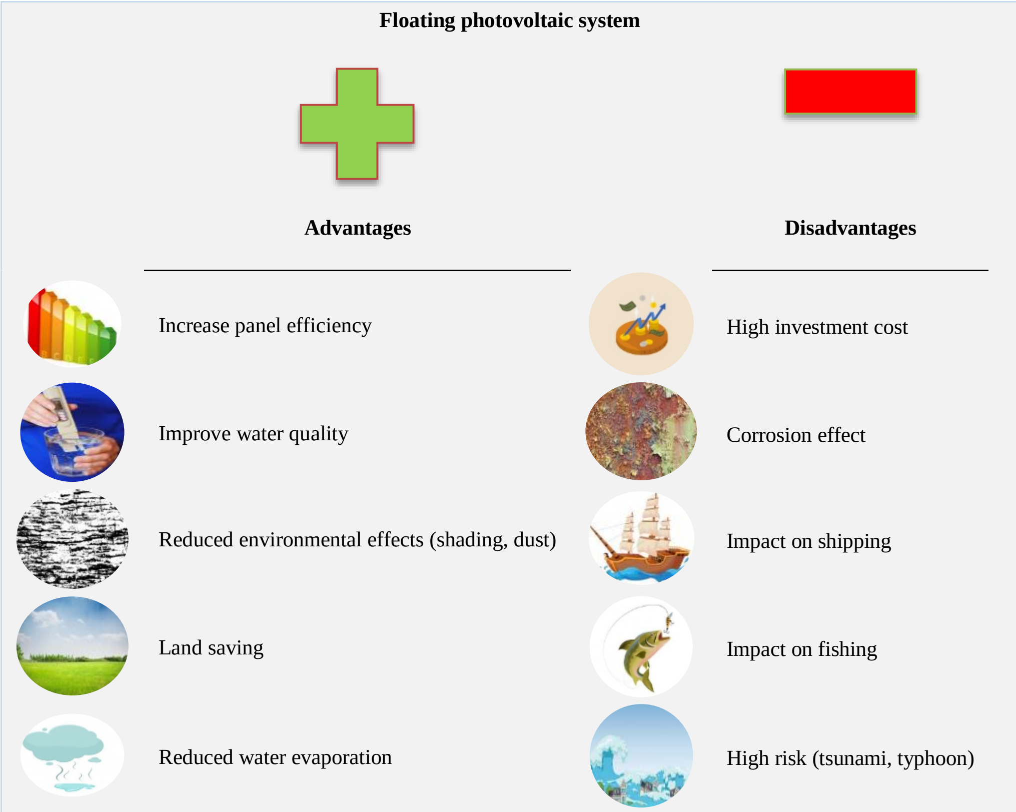

Figure 1. Advantages and disadvantages of FPV system [12].

The main difference between the land-based PV and FPV systems is structures and junctions. In order to design the structure for FPV systems, some considerations must be well-thought-of such as anti-corrosion [13], firmness contrasted, non-toxic [14], and long durability. These are especially the source of concern in the offshore system, and not in the freshwater reservoirs [15]. Reinforced fiber polymeric plastic (RFP) and elastic polyethene floating cubes are the most frequent structure for the FPV systems due to their balance capabilities with the water level. The researchers have found that the installation of FPV power plants on modular structures decreases LCOE by 2 cents/kWh [16]. Table 1 shows the investment cost for several installed FPV power plants.

Table 1. Investment cost for several FPV power plants [17].

Location	Country	Capacity (MW)	Investment cost (US$/W)	Year
Three Gorges	China	150	0.99	2018
Anhui Sungrow	China	40	1.13	2017
Anhui Xinyi	China	20	1.48	2016
West Bengal Auction	India	5	0.83-1.14 *	2018
Andhra Pradesh	India	2	0.92	2018
Yamakura Dam	Japan	13.7	0.97	2018
Queen Elizabeth II	United Kingdom	6.3	1.22	2016

* Lowest and average price

In the past, the investment cost of the FPV systems was more than the land-based ones. However, today this price has reached US$ 0.8-1.13/W [17]. In one study, the investment cost and payback period for a 2 MW FPV power plant in India were estimated at US$1.6 million and 6 years, respectively [18]. In another feasibility study, the total investment costs for 1 MW of floating PV construction in Australia were estimated at USD 1.1 million [19]. Generally, the generation of 1 kW electricity by PV panel requires approximate 8 m^2 of land [20]. Therefore, the solar PV development can turn into a challenge in some areas since the land is both restricted and expensive. The utility-scale FPV systems have an appropriate market in the high populated countries like China and India, as well as land-constraint regions such as Korea and Japan. For example, in Indonesia, installation of an FPV system compared to a land-based PV led to a lower levelized cost of electricity (LCOE) by 3.37 cents/kWh and improved the internal rate of return (IRR) by almost 6% [4]. Similarly, it has been revealed that the payback period (PP) of investments in FPV in Iran is estimated under 6 years [21].
Additionally, FPVs can be valuable in the countries with droughts and drinkable water crises. The water crisis is and will be more tangible in the Middle East, India, West America, North Africa and Australia in the coming years. For example, it is estimated that the scarcity of drinking water required by the Iranians will reach 42 billion m^3 soon [22]. The dams and open water reservoirs' evaporation is one of the main sources of water shortage. The evaporation in the agricultural sectors' reservoirs is up to three times worse than the dams' losses [23]. It has been demonstrated that 40% of the volume of the open water reservoirs evaporates per annum [24].
In order to reduce the evaporation rate, the water surface can be covered by the chemical and physical techniques. The chemical methods such as alcohol mixtures may have undesirable impacts on the environment, specifically on the water quality. The chemical methods can reduce evaporation from 20% to 40%, annually [25]. Nevertheless, the physical approaches like using FPV panels can be more effective from the environmental aspect. They can decrease the evaporation rate by up to 70% [26]. Several papers have studied water-saving using FPV installation on lakes. The researchers have demonstrated that more than 16000 m^3 of water evaporation can be saved annually if 2% of the surface of the dam is covered by floating panels [27]. It was revealed that covering water surfaces with FPV panels generally could save water from 15 to 25 thousand m^3 for each MW of installed capacity [19]. A study in Spain has declared that 300 kW of FPV could reduce water evaporation by 5000 m^3, which is equal to one-fourth of the total capacity of the reservoir [28]. In terms of conservatism, the FPV's advantages have been briefly examined. For instance, a feasibility study has displayed that water and CO_2 savings could reach 37 thousand m^3 and 1733 ton/year, respectively, by the installation of a 1 MW of FPV system in India [29]. Another work has disclosed that a 2 GW of FPV system that occupies 23% of a dam could save water by 95 thousand m^3 every year [20]. It has been predicted that if 10% of Korean water reservoirs' surface is covered by the FPV systems, 1.2 million tons of CO_2 is not produced and emitted into the atmosphere [30].
Most of the previous studies have focused on the technical analysis of the FPV systems, their structure types, and evaporation reduction. Also, the effect of CO_2 reduction was the only issue discussed amongst other pollutants. To date, a techno-economic-environmental analysis of a given FPV power plant in a warm and arid region has not yet been studied, comprehensively. Because of the long-term drought crisis in the Middle East, and the importance of the role of water to achieve sustainable development and energy security, Iran is selected as a case study. In this paper, the feasibility study of the installation of a 10 MW of FPV power plant on the open water reservoir in SE Iran is evaluated technically and economically. The level cost of electricity, payback period, internal rate of return, and greenhouse gases reduction such as CO_2, NO_x, and SO_x will be discussed in detail. In this regard, the results obtained will be discussed from the private and the government viewpoints. Finally, a sensitivity analysis of the economic parameters will be performed.

2. Method and materials

Figure 2 shows a schematic view of the FPV system.

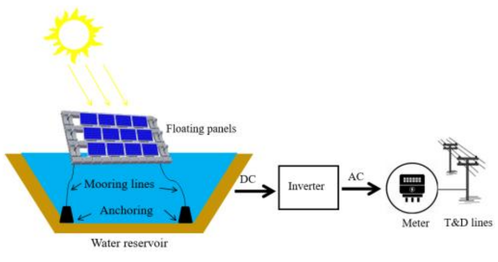

Figure 2. A schematic view of FPV system.

As stated earlier, the structure is different between the FPV and PV system components. Mooring and anchoring systems are used to fix and solidify the floater parts from the wind and waves. In order to design these systems, some limitations such as the depth of water, wind speed, and waves power must be considered. Therefore, the mooring and anchoring designs are varied from site to site.
The PVSyst software is used to investigate the technical parameters for the 10-MW FPV power plant. The capacity factor (CF), performance ratio (PR), optimized panel slop, electricity generation, energy loss diagram, and CO_2 and other gas pollutant emission reductions will be calculated. The economic parameters such as the payback period (PP), internal rate of return (IRR), and levelized cost of electricity (LCOE) will also be computed. To end, a sensitivity analysis is performed to generalize the results for each country. Figure 3 displays the used methodology in this work.

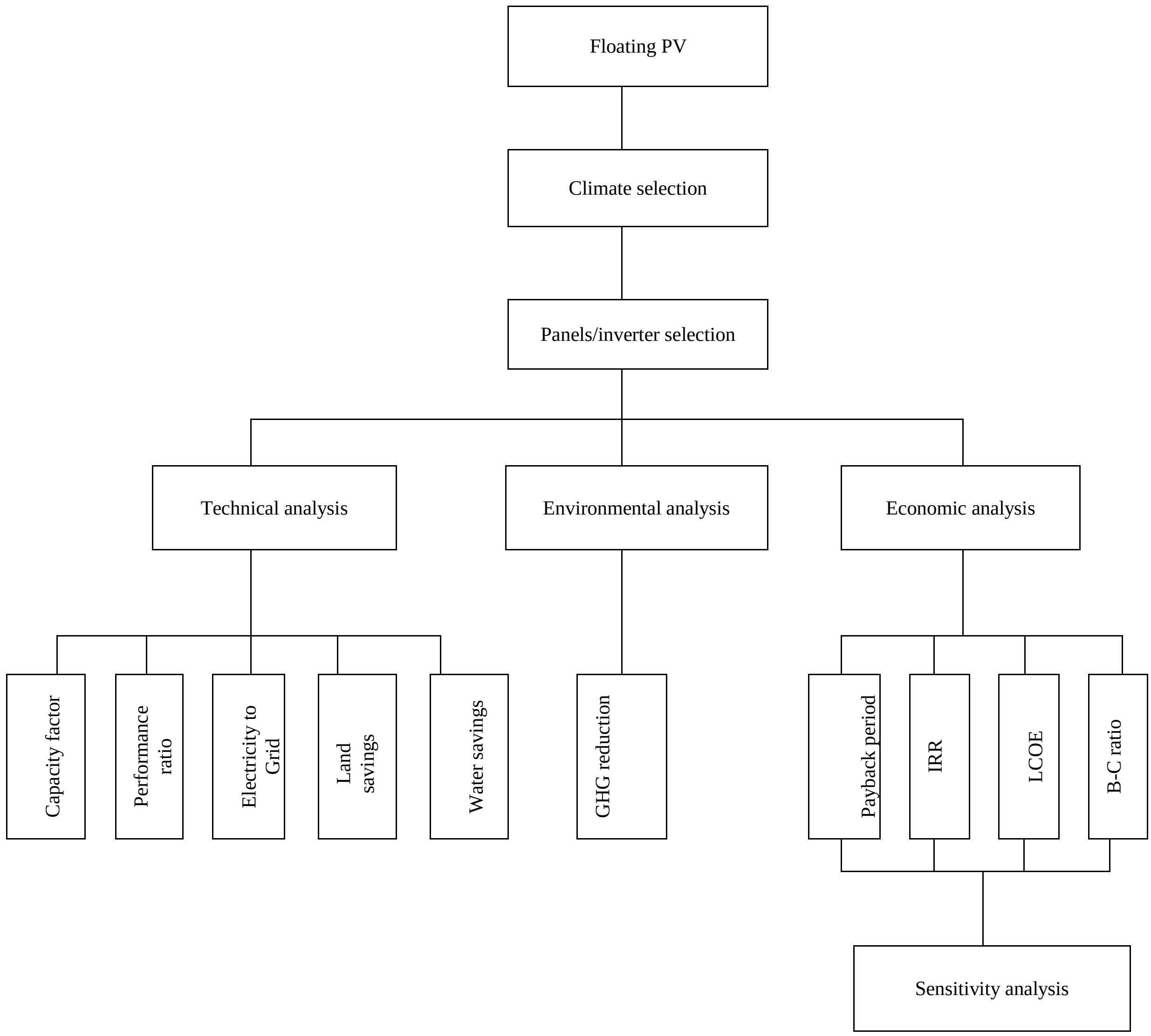

Figure 3. Methodology used in this work.

2.1. Studied area and data

Selecting an appropriate location is an essential decision when evaluating a PV system. The share of solar irradiation in Iran has been reported 17% higher than the worldwide average [31]. Although the statistics argue that there are more than 280 sunny days in a year in over 90% of Iran, some economic and environmental concerns are still the main factors that should be taken into account [32]. Since the most share of oil-rich countries' income like Iran comes from oil and other fossil fuels exports, the utilization of renewable energy is developing slowly. However, in order to achieve a sustainable development, it is necessary to rely more on the share of available renewable energies such as solar [33]. Figure 4 demonstrates the direct normal irradiation (DNI) contour in Iran. The annual average DNI reaches 2100-2400 kWh/m^2 that is more available in the southern regions. Thereby, there is a significant potential to use the solar energy technologies in these areas.

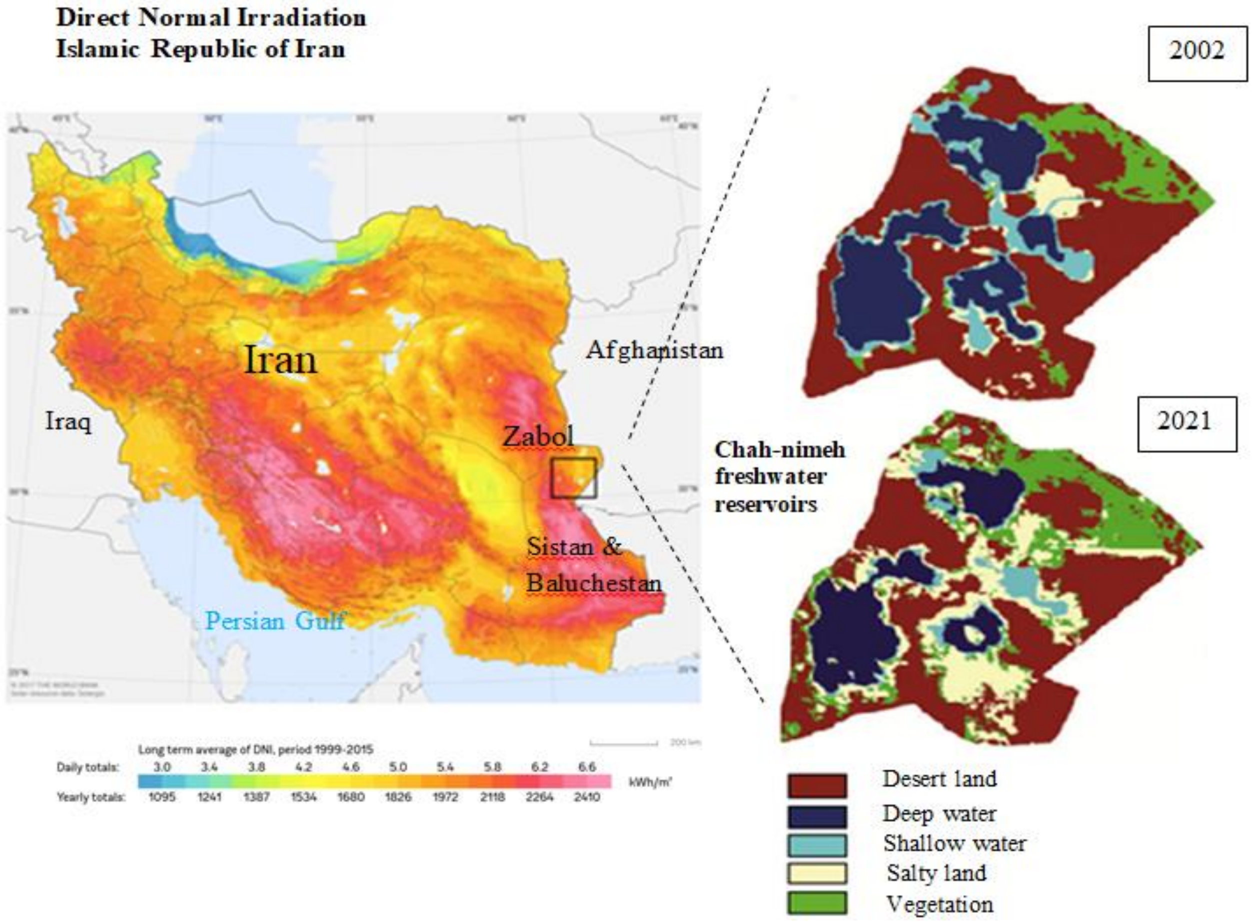

Figure 4. Direct normal irradiation contour and level of water for studied area.

The city of Zabol in the Sistan and Baluchestan province, located in SE Iran, was selected as the case study. This region with warm and windy climate has the lowest rainfall, and it is one of the least developed areas in Iran. The meteorological data proves that the average annual precipitation in this region is less than 70 mm [28]. According to figure 5, the average daily solar irradiation reaches 5.28 kWh/m^2/d [34]. On the other hand, the average air temperature is approximately 30°C, and even up to 40 °C in the warm months. This, in turn, will lead to the panel's efficiency reduction and a raise in the water evaporation rate from open water reservoirs.

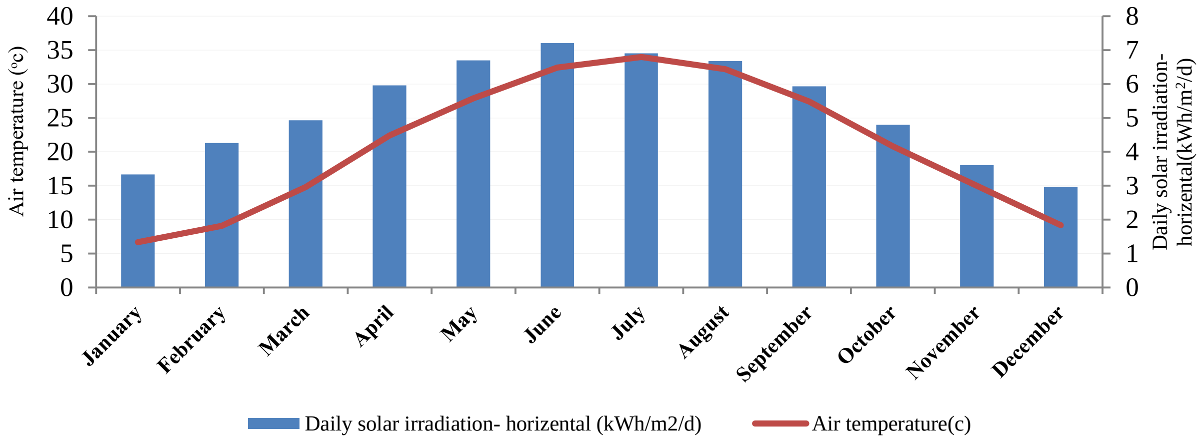

Figure 5. Climate conditions for Zabol [35].

A large proportion of the drinking and agricultural water demand in the north of the province is mainly provided by four open water reservoirs known as Chah-nimeh. The total capacity of the reservoirs is 680 million m^3, from which 300 million m^3/year is consumed and 135 million m^3/year evaporated [6]. As it can be seen in figure 4, the absence of precise local policies for managing water harvesting, high evaporation rates, high temperature, and long-term droughts have critically reduced the level of freshwater in Chah-nimeh [36]. The water crisis has led to the complete demolition of agriculture in this region. Today, even supplying drinking water is faced with serious challenges, creating many problems such as the migration crisis, emergence of suburbanites to other cities, and poverty. Covering the water reservoir surface with FPV panels may be a key factor to reduce the annual evaporation. The specifications and assumptions of the proposed power plant will be discussed in the next section.

2.2. Technical parameters

The technical specifications of the suggested 10-MW FPV power plant are shown in table 2.

Table 2. Technical specification of FPV power plant.

Location	Name	Zabol, SE Iran
	Latitude	31.0˚N
	Longitude	61.0˚E
	Altitude	480 m
Panel	Type	Poly-Si
	Brand	Lightway solar
	Model	P 1640 × 990 series
	Power	255 Watts
	Efficiency	15.7%
	Slope	30˚
	Azimuth	0˚
	Voltage (STC)	30.10 (V_{mpp}), 37.88 (V_{OC})
	Current (STC)	8.48 (I_{mmp}), 8.90 (I_{SC})
	Structure material	Elastic polyethene prefabricated block
	Performance Guarantee	25 years
Inverter	Brand	WEG Equip. Eletricos
	Model	SIW700-T1665-33-v1
	Capacity	1.66 MW
	Efficiency	98%
	Voltage (3-phase)	1000 V (nominal), 850 V (at operating)
	Operating temperature range	-10 ˚C to +45 ˚C
Power plant	Total capacity	10 MW
	Type	Connected to grid
	Useful lifetime	> 20 years
	Solar tracker system	None (fixed)
	Energy storage system	None

In order to simulate the technical parameters, PVSyst was used, which is a powerful software to investigate the PV power plants. The following considerations were taken:

- The panels were fixed; thus there was no solar tracking system.
- It was a grid-connected power plant, and had no energy storage system.
- Elastic polyethene was used in prefabricated blocks for the structure.

The electricity generated by the solar panels was direct current (DC). In this work, 6 inverters with the capacity of 1665 kW each were used to convert DC to alternating current (AC). The optimum slope of the PV panels was achieved by (1). The parameter L denotes the latitude of the area.

$$\textbf{Optimized panel's slope} = \mathbf{0.95} \times \mathbf{L} \qquad (1)$$

According to (2), the comparison between the actual and nominal energy output of the FPV power plant is defined as the performance ratio [37].

$$\mathbf{PR} = {}^{\mathbf{Y_f}}/_{\mathbf{Y_R}} \qquad (2)$$

The actual energy output (Y_f) is equal to the amount of electricity exported to the grid. The nominal energy output (Y_R) is the theoretical energy that can be achieved taking into account solar irradiation, panel temperature, and other climate impediments. Indeed, PR is demarcated as a quality factor that represents the actual energy output after applying all thermal, environmental, and electrical losses.

2.3. Economic parameters

The RETScreen software that is a commercial Canadian software to develop clean and renewable energy programs is used to investigate the economic parameters. According to the literature [17], the total investment cost for the proposed FPV system is assumed US$ 11.3 million, and the annual operation and maintenance cost (O&M) is equal to 1% of it. Based on the Iran's renewable energy and energy efficiency known as SATBA, the guaranteed purchasing price (PPA) of renewable electricity for a 10 MW PV power plant is US$ 0.12/kWh for twenty years [38]. The annual inflation (i) and discount (d) rates are considered 12 [39] and 15% [40], respectively.

Payback period, IRR, and other economic indices are calculated by the following equations:

$$\mathbf{NPV} = \sum_{j-1}^{n} \frac{\mathbf{CF_n}}{(\mathbf{1}+\mathbf{d})^{\mathbf{n}}} \quad (3)$$

$$\mathbf{CF_n} = \mathbf{A}(\mathbf{1}+\mathbf{i})^{\mathbf{n}} \quad (4)$$

$$\mathbf{if\ NPV}\ (\mathbf{d}^*) = \mathbf{0} \ \rightarrow \ \mathbf{d}^* = \mathbf{IRR} \quad (5)$$

$$\mathbf{Payback\ Period} = \mathbf{B} + \frac{\mathbf{CCF_B}}{\mathbf{CCF_B} - \mathbf{CCF_{B+1}}} \quad (6)$$

In the above equations, CF_n is the investment cash flow over the power plant lifetime, n is the power plant lifetime, A is total investment cost, IRR in NPV (vertical axis) versus discount rate (horizontal axis) plot is a point where the NPV graph is zero and it is equivalent to the new discount rate (d^*), payback period (PP) in the NPV graph (vertical axis) versus the power plant lifetime (horizontal axis) is the point the NPV axis meets the horizontal axis, B is an integer where the cumulative cash flow is zero, and CCF_B and CCF_{B+1} are the cumulative cash flow in years B and B+1, respectively.

3. Results and discussion

3.1. Technical simulation

Table 3 demonstrates the technical analysis results for the Chah-nimeh FPV power plant.

Table 3. Technical results of FPV power plant.

Parameter	Value	Unit
Capacity factor	20.6	%
Performance ratio	83	%
Electricity export to the grid	18026	MWh/year
Land saving	15	Hectare
Water saving	440000	m^3/year

According to (7), CF is defined as the ratio of the actually produced energy to the total power it can be produced by the power plant per year.

$$\mathbf{CF} = (\mathbf{Actual\ energy\ generation}\ (\mathbf{MWh}))\ /\ (\mathbf{Power\ plant\ capacity}\ (\mathbf{MW}) \times \mathbf{365}\ (\mathbf{day}) \times \mathbf{24}\ (\mathbf{hours})\ ) \quad (7)$$

A higher CF, the more energy out of the same power capacity of the power plant. Also, a higher CF, the lower the cost of generating electricity. The findings show that CF of the FPV system is achieved by 20.6%, which is remarkable. Notably, the achieved CF is in the case of fixed panels; thus, using the solar tracker system will increase this parameter, and, in turn, the revenue of the power plant owner.

The results obtained specify that the proposed FPV system can generate 18026 MWh of clean electricity per year without land occupation, while the same capacity land-based PV requires approximately 1.5 hectares of land per megawatt [41]. Hence, covering the Chah-nimeh reservoir with floating panels will save 15 hectares of land, which can be used in other applications, so it is a source of revenue. Water savings are calculated by (8) and (9).

$$\mathbf{W_s} = \mathbf{W_a} + \mathbf{W_c} \quad (8)$$

$$\mathbf{W_c} = \mathbf{E} \times \mathbf{W_e} \quad (9)$$

In the mentioned equations, W_s is total water savings (m^3), W_a is not-evaporated water by covering the water surface (m^3), W_c is not-consumed water by thermal power plants during not-generating electricity (m^3), E is electricity generation by the FPV power plant that is equal to electricity that is not generated by thermal power plants (MWh), and W_e is water consumption per electricity generation by thermal power plant (m^3/MWh).

The FPV power plant covers about 15 out of 4700 hectares of the total surface of the Chah-nimeh water reservoir, which is equal to 0.3 % of it. Based on the total annual evaporation from the reservoir, W_a is calculated at 440 thousand m^3. It is found that the annual clean energy generated by FPV power plant, E, is 18026 MWh. Replacing E as the electricity that is not produced by thermal power plants, and the water consumption per power generation (W_e), W_c is obtained. Table 4 shows the water savings by decreasing evaporation with the covering of the reservoir and the operation of the FPV system. It is obtained that the FPV system can prevent evaporation and water consumption from 441.2 to 515.2 thousand m^3/year. The largest water savings are realized due to the electricity that is not generated by a steam-turbine power plant equipped with the cooling towers system.

Table 4. Water savings for covering reservoir and operation of FPV power plant.

Type of plants (Gas as fuel)	Cooling system	We (m^3/MWh) [43]	W_c ($10^3\ m^3$)	W_a ($10^3\ m^3$)	W_s ($10^3\ m^3$)
GT	Non-usual	0.2-1.3	3.6-23.4	440	443.6-463.4
ST	Cooling tower	2.12-4.17	38.2-75.2	440	478.2-515.2
	Once-through	0.7-1.5	12.6-27	440	452.6-467
	Cooling pond	1.02	18.4	440	458.4
CCPP	Cooling tower	0.17-1.14	3.1-20.5	440	443.1-460.5
	Once-through	0.07-0.87	1.2-15.6	440	441.2-455.6
	Cooling pond	0.9	16.2	440	456.2

The daily Iranian water consumption per capita is 250 Litre/person [42]. Thus, the total water saved by covering the Chah-nimeh reservoir's surface can meet the demand of 1208 up to 1411 subscribers, annually.

As it can be seen in figure 6, the annual average performance ratio is obtained by 83%. Despite the temperature increase in the warm months (May-Sep), PR is calculated to be almost 80%. This is a result of the cooling effect of the water surface on the floating panels; hence, the FPV system performance is appropriate even in the warm months. The power loss diagram is shown in figure 7. The greatest loss rate occurs due to the impact of ambient temperature on the panels. According to figure 5, the average air temperature in the warm months reaches 40 °C. Thus, using a land-based PV system has a less PR than FPV with the same capacity.

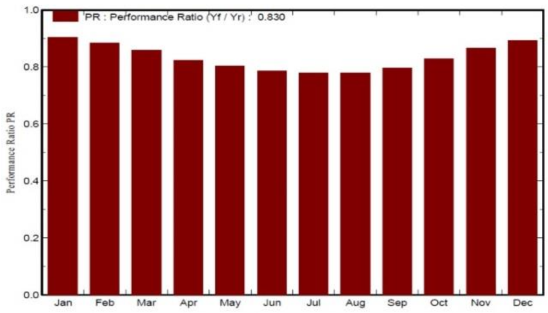

Figure 6. Performance ratio of FPV power plant.

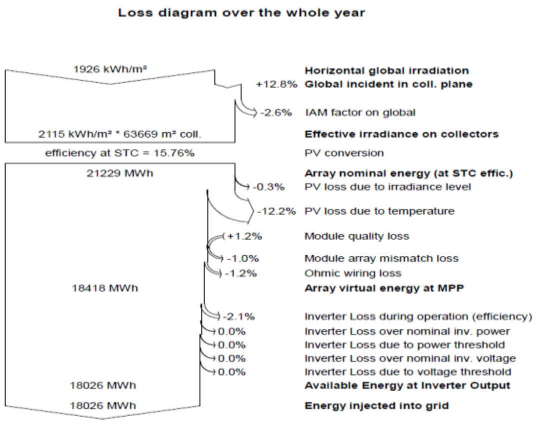

Figure 7. Power generation loss graph.

3.2. Environmental assessment

Table 5 demonstrates the GHG emission rates from several thermal power plants. CO_2 and other pollutant emission reduction are calculated by the use of GHG emission rates from table 5 and the electricity not produced by thermal power plants, E, by (10). The results obtained are shown in table 6.

$$\textbf{GHG emission savings}\left(\frac{\textbf{ton}}{\textbf{year}}\right)= \mathbf{E}\,(\mathbf{MWh})\times\textbf{GHG emission rate}\left(\frac{\textbf{ton}}{\textbf{MWh}}\right) \tag{10}$$

The results reveal that CO_2 has the highest emission reduction among the other pollutants in all thermal power plant types. Moreover, it is revealed that NO_x, SO_x, and SPM that are hazardous pollutants for air quality are reduced significantly by electricity generation using the FPV power plant. In addition to the thermal power plants, it seems that the FPV system in comparison with the land-based PV can reduce more GHG emissions due to the higher CF and annual energy generation.

The proposed FPV power plant will avoid the production and emission of 8470-15311 tCO_2/year. This amount is equivalent to CO_2 absorbed by 778 up to 1407 hectares of forests or 19692-35598 barrels of crude oil that are not burnt by the gas turbine power plant to supply the same amount of electricity [31].

3.3. Economic assessment

Table 7 shows the economic analysis results of the FPV power plant. The PP is achieved at 5.2 years. The level cost of electricity or LCOE is calculated at US$ 0.10/kWh as well. Considering the renewable electricity guaranteed purchasing price (US$ 0.12/kWh), the achieved LCOE is appropriate. It seems that the cost of generated electricity in the Chah-nimeh FPV power plant is US$ 0.02/kWh less than the sales cost, which provides a secure profit margin for owners.

Table 5. GHG emission rates from thermal power plants [31].

Type of plants	Emission rate (gr/kWh)							
	NO_x	SO_2	SO_3	CO	SPM	CO_2	CH_4	C
GT*	2.4	0.5	0.001	0.1	0.1	849.4	0.02	231.6
ST**	2.3	7.8	0.03	2.5	0.2	824.9	0.02	225
CCPP***	2.9	0.3	0.01	0.1	0.1	469.9	0.01	128.2
Diesel	1.5	4.6	0.1	0.001	0.3	826.4	0.04	225.4

GT*: Gas turbine power plant

ST**: Steam turbine power plant

CCPP***: Combined cycle power plant

Table 6. GHG emission savings for FPV power plant.

Type of plants	Emission savings (ton/year)							
	NO_x	SO_2	SO_3	CO	SPM	CO_2	CH_4	C
GT*	43.2	9	0.018	1.8	1.8	15311	0.36	4174
ST**	41.4	140.6	0.5	45	3.6	14869	0.36	4056
CCPP***	52.3	5.4	0.18	1.8	1.8	8470	0.18	2311
Diesel	27	82.9	1.8	0.018	5.4	14896	0.72	4063

GT*: Gas turbine power plant
ST**: Steam turbine power plant
CCPP***: Combined cycle power plant

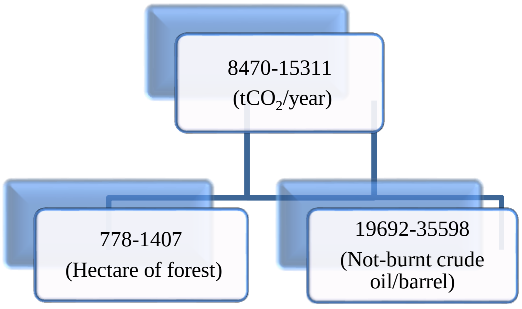

Figure 8. Crude oil and forest savings by FPV power plant.

The annual revenue of the power plant owner obtained US$ 2.23 million.

Table 7. Economic analysis results for FPV power plant.

Parameters	Value	Unit
PP	5.2	Year
LCOE	0.10	US$/kWh
B-C ratio	1.3	-
IRR	20.4	%
Annual revenue (electricity sales to the grid)	2.23	Million US$

The benefit-cost ratio (B-C ratio) is achieved at 1.3. This ratio is a foreshadowing for the investors before starting a project. Accordingly, if the B-C ratio value is equal and/or more than one, a project will be economic. The internal rate of return is another parameter that is calculated at 20.4%. It is found that the achieved IRR is more than the discount rate (15%); thus, the installation of the FPV power plant on the Chah-nimeh reservoir provides the economic demands for the investors.

So far, the revenue and other economic aspects have been investigated from the capital owner's viewpoint. Now, table 8 describes the cost savings of the government by the FPV power plant construction on the Chah-nimeh reservoirs.

Table 8. Government cost savings by installation of the Chah-nimeh FPV power plant.

Cost saving types		Value	Unit
Crude oil barrels are not burnt to generate electricity		1-1.9	Million US$
Land savings		15	Hectare
Water savings (Taking into account)	drinking water price [44]	105-123	Thousand US$
	mineral water price [45]	210000-245000	

The final cost of the drinking water for the Iranian government is reported to be 10000 Riyals/m^3 (US$ 0.24/m^3) [44]. It was also made known that covering the Chah-nimeh reservoir surface with floating panels can prevent the evaporation of 441.2-515.2 thousand m^3/year of drinking water. Hence, the value of saved water reaches 4.4-5.1 billion Riyals (US$ 105-123 thousand) per year. As stated earlier, the Sistan and Baluchestan province is some of the least developed areas in Iran. Many villages and areas do not have access to adequate drinking water. In order to solve this problem, the government distributes mineral water (bottles) among people, especially during the warm months. Regarding 20000 Riyals per litre (US$ 0.47/L) [45] as mineral water price, 8824-10340 billion Riyals (US$ 210-245 million) is saved for the government. The cost savings can assist the government to improve sustainable development in this region. Furthermore, it may be spent on social viewpoints such as decreasing unemployment and immigration rates as a result of the drinking water crisis.

As shown in figure 8, 19692-35598 barrels of crude oil will be saved by the construction of a 10 MW FPV power plant on the Chah-nimeh reservoir. Regarding US$ 54 per barrel [22] as the average price of Iran's crude oil exports, the government’s annual savings is reached US$ 1-1.9 million.

There are some challenges in the way of the development of FPV power plants such as the low price of fossil fuels and low tariffs for electricity generated by thermal power plants that will be sold to the subscribers. These problems will be solved by ratifying laws and regulations by the policy-makers. They can increase electricity tariffs for subscriber’s step-wisely and consider incentives for the investors to invest in the FPV systems. Installation of FPV structure is easy due to the availability and mass production of elastic polyethene blocks but the construction of FPV power plants is rather modern than other types of renewable energies. Thus, finding trained workforces for construction is still a challenge in this region.

In the North of the Sistan and Baluchestan province, specifically in the city of Zabol, the wind speed is a serious challenge that leads to dust storms in the warm months. It seems that it is the main challenge on the way of installing an FPV power plant on the Chah-nimeh reservoirs in practice. The appropriate and right mooring and anchoring system installation is a must. In this regard, providing a standard procedure and guidelines for installation is essential.

4. Sensitivity analysis

Sensitivity analysis is an approach to realize how the output variables are affected during the fluctuations of the input variables. Figure 9 shows the sensitivity analysis of the economic variables. As declared in the literature, the capital cost of solar systems is decreasing rapidly. It is proven that the fluctuations of the FPV system's capital cost have a dominant factor in all economic results. The payback period (PP) of investment will be decreased by 31% and reaches 3.6 years provided that the capital cost decreases by 30%. Also, an increase in purchasing price by 30% will decrease PP to 4 years. In contrast, a 30% decrease in purchasing price (US$ 0.084/kWh) may increase PP to 7.5 years. Similarly, IRR improves from 20.4% to 29.6%, which is a significant increase if the capital cost decreases by 30%. It is found that changes in the inflation and discount rates have a low effect on the payback period and IRR.

In terms of the economic viewpoint, LCOE is a key factor for the investors. As seen, LCOE must be lower than the renewable electricity guaranteed purchasing price. It is visible that IRR and payback period of investment will be more suitable by increasing the electricity purchasing price tariffs, particularly in the utility-scale capacity of FPV. However, LCOE has a low sensitivity to the electricity purchasing tariff changes as well as the inflation rate. However, both the discount rate and capital cost changes will have a significant impact on LCOE, and change it linearly. The results show that LCOE will be decreased by 3.1 cents and will reach US$ 0.074/kWh, which is comparable with the conventional thermal power plants provided that the capital cost decrease by 30%.

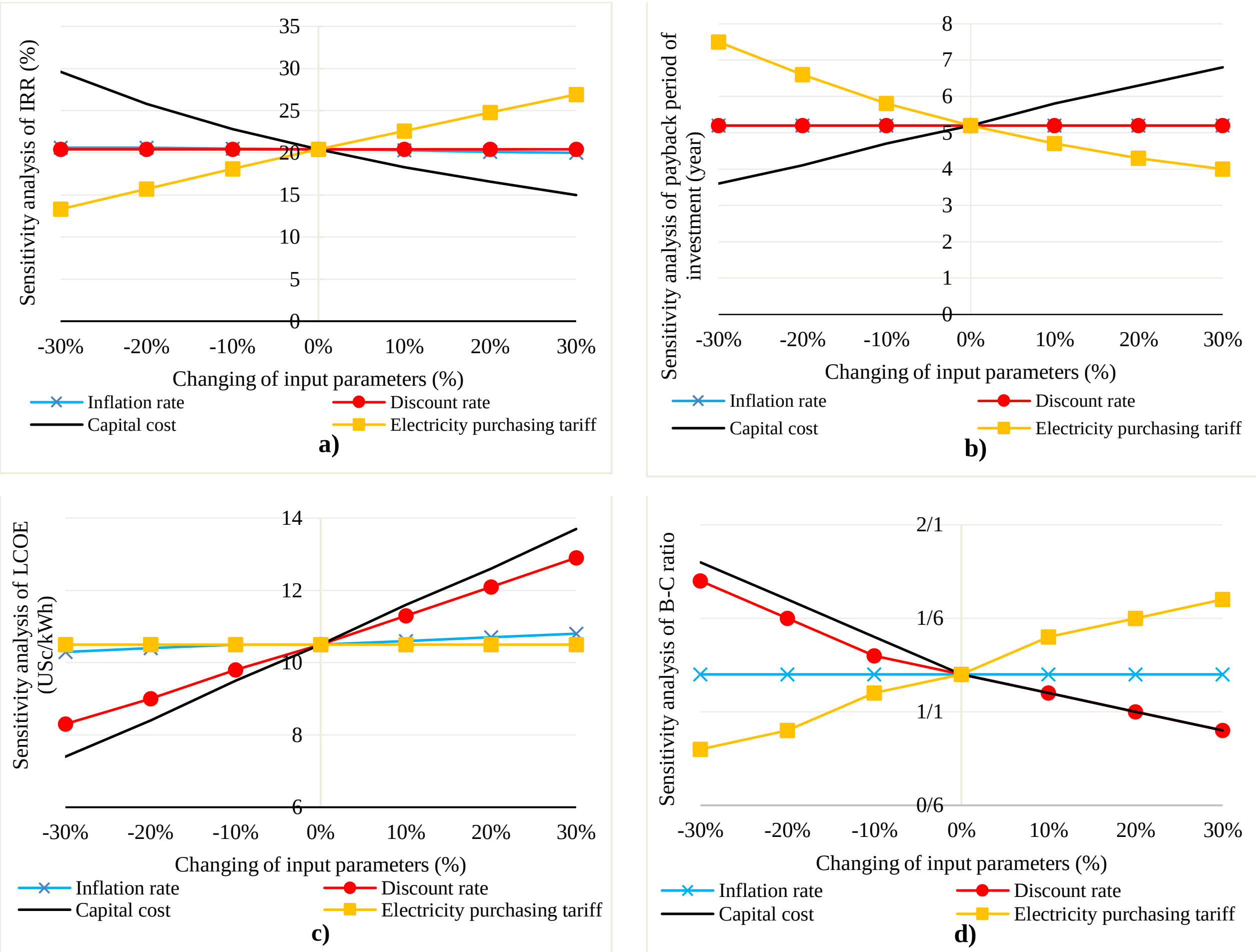

Figure. 9. Sensitivity analysis of economic variables: a) IRR; b) payback period; c) LCOE; d) B-C ratio.

In order to provide a comprehensive economic viewpoint for the investors, the sensitivity of the B-C ratio is analyzed. It is revealed that decreasing capital cost, discount rate, and increase in electricity purchasing tariffs have significant impacts on the B-C ratio, respectively.
The results also indicate that this project in Chah-nimeh is beneficial as long as the electricity purchasing tariffs are higher than US$ 0.096/kWh.
Therefore, the development of utility-scale construction of FPV power plants has a low dependence on the domestic policies; it is rather more dependent on the capital cost that is dropping dramatically day by day. In this regard, the incentive policies such as incremental electricity purchasing tariffs, cost of land savings, and water savings can accelerate the development of FPV systems. These incentives will lead to major impacts on PP, IRR, and B-C ratio indices.

5. Conclusion

This paper has provided a deeper insight into an economic and environmental evaluation of a 10-MW FPV power plant. For this purpose, an open freshwater reservoir in SE Iran (the Chah-nimeh) was selected. The results obtained disclose that the payback period and IRR are achieved at 5.2 years and 20.4%, respectively.
The sensitivity analysis of the economic variables exposes that the changes in the electricity purchasing tariffs and capital costs have a major influence on the payback period and IRR. If the capital cost falls by 30%, the investment's payback period will be reduced to 3.6 years. In addition, a 30% rise in the purchasing price reduces PP to four years. However, a 30% reduction in the purchasing price (US$ 0.084/kWh) would extend PP by 44%. Likewise, if the capital cost is reduced by 30%, IRR rises from 20.4% to 29.6%, which is a considerable gain. The results demonstrate that LCOE has a linear relationship with the discount rate and capital cost. In that, LCOE is reduced by 3.1 cents and reaches US$ 0.074/kWh, making it competitive with electricity production price from the conventional thermal power plants, if the investment costs are reduced by 30%. The sensitivity analysis in this work identifies that besides the global decrease in floating PV investment costs, allocating incentives policies can encourage the investors, and will end to significant impacts on economic indices, for instance payback period, IRR, and B-C ratio.
The Chah-nimeh FPV power plant can generate 18026 MWh of clean electricity annually, which meets the electricity demands of 6000 residents in this region. Moreover, it was found that the annual water evaporation reduced by 441.2 up to 515.2 thousand m^3 with only covering 0.3% of the Chah-nimeh reservoir's surface. The achieved water savings can be provided 1208 to 1411 subscribers' water demand per annum. From the environmental aspect, generation of the clean energy by FPV power plants can significantly reduce GHG and hazardous gases like CO_2, NO_x, SO_x, and SPM emissions. The results showed that CO_2 emission decreased by 8470 up to 15311 tons per year, which is equal to 19692 to 35598 barrels of crude oil that are not burnt by a gas turbine power plant to supply the same residential electricity demand. Thus, the construction of utility-scale FPV power plants in warm and windy regions can be beneficial, economic, and environmental-friendly for households and social aspects.
It is suggested that in the future, it will be important to explore the challenges and restrictions of the practical installation of FPV with similar capacity, utilization of FPV power plants in other regions with different climates, and more technical analysis such as adding one-axis or two-axis solar tracking systems seems to be required.

6. Nomenclature

A	Total investment cost
AC	Alternating current
B	Point that leads to zero of cumulative cash flow-year diagram
B-C ratio	Benefit-cost ratio
CCF_B, CCF_{B+1}	Cumulative cash flow in years B and B + 1, respectively
CCPP	Combined-cycle power plant
CF	Capacity factor
Cf_n	Cash flow of investment over power plant lifetime
d	Discount rate
d^*	It is equal to IRR (new discount rate)
DC	Direct current
DNI	Direct normal irradiation
E	Electricity is not generated by thermal power plants (MWh)
FPV	Floating photovoltaic
GHG	Greenhouse gas
GT	Gas-turbine power plant
i	Inflation rate
IRR	Internal rate of return
L	Latitude
LCOE	Level cost of electricity

MW	Megawatt
n	Power plant lifetime
NPV	Net present value
PP	Payback period
PR	Performance ratio
PV	Photovoltaic
SPM	Suspended particulate matter
ST	Steam-turbine power plant
US$	United States Dollar
W_a	Water is not evaporated by covering water surface by FPV system (m^3)
W_c	Water is not consumed by thermal power plants for electricity generation (m^3)
W_e	Water consumption by thermal power plant (m^3/MWh).
W_s	Total water saving during FPV construction and operation (m^3)
Y_f	Actual energy output
Y_R	Nominal energy output

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