Techno-Economic Analysis of Solar Power Plants in Kuwait: Modelling the Performance of PV and CSP Systems

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Abstract- In order to evaluate the provision of solar power plants in Kuwait, techno-economic analysis has been performed for photovoltaic (PV) and concentrated solar (CSP) power plants with a capacity of 100 MW. The optimal location for the power plants is determined to be Al-Wafra in Kuwait. The analysis results have been compared, and the advantages and disadvantages of each technology are reported. The CSP power plant requires USD 480million, and the PV power plant requires USD 100million capital investment. The annual cost of the CSP plant is estimated at USD 9.5 million, while the annual cost of the PV plant is estimated at USD 0.8million. Conversely, the annual revenue and savings from CSP plants would be over USD 46million, whereas PV plants would be around USD 20million. According to simulations and market research, PV systems are a lower cost option when compared to CSP facilities, require more space, and pose more significant technological challenges. Prices for PV panels are expected to fall further. The low initial cost and short payback period for PV power plants are estimated at around five years compared to approximately 13 years for CSP, making photovoltaic power plants more attractive to investors. Nevertheless, the long-term prospects and higher power capacity of CSP plants will likely attract investors seeking longer-term and higher-capacity outcomes.

Keywords: Photovoltaic (PV) power plant; Concentrated solar power (CSP) power plant; Techno-economic analysis (TEA); RETScreen.

1. Introduction

The world's need for energy to generate power continues to increase, and that energy is derived from several resources. The US Energy Information Administration report of 2020 [1] estimated fossil fuel consumption at 75%, as illustrated in Fig. 1. This ratio has remained relatively consistent over the past decade. However, according to predictions and projected energy consumption, energy demand may rise by about 50% by 2050 [1]. Over the last three decades, renewable resources have already been used to generate power and have produced fewer emissions, and they are expected to contribute more to overall energy consumption in the coming years. The research seeks the best solutions using these alternative and more environmentally friendly ways to reduce the emissions created by fossil fuels and other sources.

Natural gas and liquid oil are the principal sources of electrical energy in Kuwait. According to the Kuwaiti Ministry of electricity and water [2], thermal power stations are the primary production method. While this accounts for around 28.7% of installed capacity, gas turbines (GT) are also used, representing approximately 28.7% of total capacity. GTSs are employed in situations where time is of the essence, such as during an emergency or during periods of high consumption, because of their high operational costs and low thermal efficiency [3].

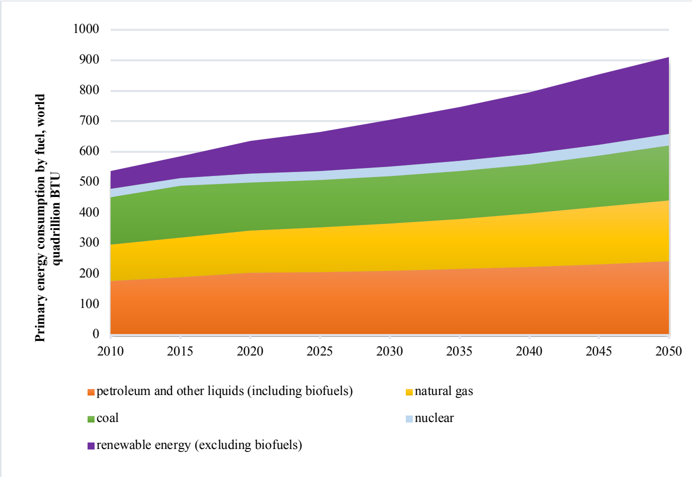


Fig. 1. World energy consumption from primary energy sources.[1]

In Kuwait, the existing environmental conditions favor solar PVs and solar thermal power over wind power due to the abundance of solar resources and limited wind resources throughout the year [4]. Specifically, the climatic conditions that characterize most parts of Kuwait make it possible to harvest solar energy throughout the year with high cost-efficiency. However, the performance of solar thermal power is more reactive to environmental variations and seasonal changes, which makes it less reliable than solar PVs.

Kuwait has one of the highest CO_2 emissions per capita rates at 30.2 tons per year [5] due to the widespread use of conventional power plants. The adoption of solar energy through PV energy systems has helped reduce carbon emissions by almost 23 million tons per year [6].

There has been significant interest in enhancing the energy conversion efficiency of newly developed renewable energy harvesting methods. The construction of such renewable energy plants is an important decision, given that they are expected to consume a colossal budget and take considerable time. However, recently developed simulation tools and more accurate weather predictions have made these renewable energy harvesting techniques more economically feasible and accurately estimated.

The principal challenges are selecting the most suitable geographical location and the most efficient renewable energy technology to maximize the electrical power output, reducing the payback period for newly constructed renewable energy plants. Essentially, a shorter payback period for such a project would incentivize investors, leading to a higher dependence on renewable energies.

1.1. Aim and Objectives

This research primarily aims to compare concentrating solar power (CSP) and photovoltaic (PV) renewable energy harvesting methods while investigating the energy generation rate that influences their expected payback period, as well as their economic and environmental benefits. Moreover, this research will consider the environmental, economic, and financial impacts and perform a life cycle assessment (LCA) of these two main technology fields. The RETScreen software package will simulate the economic feasibility and environmental benefits of constructing the CSP and PV systems in a selected geographical location in Kuwait.

2. Literature review

2.1. Background of Photovoltaic and CSP power Plants

Solar power is capable of meeting the rapidly growing worldwide need for electricity. While all types of solar radiation come from the solar spectrum, the amount of radiation generated influences the heat produced.

PV solar power plants rely on PV techniques and heat engines for their solar power output. A big mirror or other reflector is used to capture solar power and create vapor at high pressure and temperature, utilizing the heat engine technique. The higher the enthalpy (pressure and temperature), the greater the rotational force applied to the turbine shaft to generate electricity. It is critical to note that PV systems produce direct current energy straight from solar power. Solar power may be utilized to generate electricity, space cooling, heating, and various industrial purposes in several settings [7].

Solar thermal systems harness solar energy to energize a heat-transfer fluid circulated in a receiver to produce steam. The generated steam is tapped to run a turbine that turns the generator's rotor to produce electric power. Solar thermal energy (STE) technologies are implemented using three significant designs: solar dish/engine systems, solar power towers, and linear concentrating systems, specifically Fresnel reflectors and parabolic troughs [8]–[10][11].

Solar dishes/engines use polished concave mirrors to concentrate sunlight onto a heat absorbent, thermal receiver for the onward transfer of heat energy to a particular engine generator. Solar power tower systems utilize heliostats to focus sunlight on a heat-transfer fluid contained at the top of a centrally placed tower [12]. The heliostats track the sun's path in the sky to maintain maximum efficiency of sunlight concentration throughout the day. Linear concentrating systems, in contrast, employ long U-shaped mirrors to focus sunlight onto receiver tubes to energize a heat-transfer fluid that boils water to run a steam turbine generator [11]. The efficiency and effectiveness of solar thermal energy systems are dependent on several factors, including climatic variations, the orientation of the solar panel, and the pitch of the roof where the panel is placed. Solar panels, thus, need to be adjusted at least twice a year for maximum efficiency.

Solar towers and solar ponds are some of the technologies used to generate electricity from solar energy. However, the solar dish or Stirling engine is the most energy-efficient with an efficiency of 40% and may produce electrical power of approximately 25 kW with a conversion efficiency rate of 40.7%. As solar plants do not consume fossil fuels, most costs incurred are operational and capital [13].

Photovoltaic energy has the smallest carbon footprint and uses little water on a lifecycle basis. As a result, life cycle energy consumption is 1,200 MJ/m^2, equivalent to the embedded energy of 0.333 MWh/m [14].

Several types of research have been related to Photovoltaic and Concentrated solar power plants techno-economic analysis in different regions. On a large-scale Photovoltaic power plant in Bahrain, Pillai and Naser [15] carried out a techno-economic assessment. According to their research, the Levelized cost of energy (LCOE) was $0.0423/kWh, and the NPV was $1,512,334. Adaramola [16] examined the financial viability of a 2.07 kW roof-tops grid-connected photovoltaic power plant in Scandinavia. According to the findings of the research, the system had an LCOE of US$0.246 per kWh. Bhakta and Mukherjee [17] studied a Solar photovoltaic plant for an Indian island for its techno-economic efficiency. Their research found a net present cost of $ 9637, an electricity cost of $ 0.398/kWh, and an operational cost of $ 224/year. According to Al-Saqlawi et al. [18], Oman's roof-top solar PV/battery setup has significant technological and economic prospects for producing power. As a result of their findings, grid-independent PV systems were determined as a viable option.

Using the HOMER software, Li et al. [19] evaluated the techno-economic performance of 14 roof-top photovoltaic (PV) power stations in five distinct climate zones of China. Kunming was the most creditworthy location in their research, with an LCOE of 0.073 dollars per kWh and an NPC of $113,382. The technological and economic viability of an Iranian grid-connected solar system was studied by Edalati et al. [20]. Concerning capacity factor (CF), in Ramsar, the value was 12 percent, whereas the value was 23.13% in Kerman. Furthermore, the LCOE varies from 19.92 $/kWh in the nation's southern region to 38.38 $/kWh in the country's northern province. Two grid-connected photovoltaic (PV) power plants in Meknes, Morocco, were similarly examined by Allouhi et al. [21] in terms of performance, economics, and environmental benefits. The plants' LCOE ranges from 0.073 to 0.082 $/kWh, with a payback period ranging from 11.10 to 12.69 years. In Sindh, Pakistan, Xu et al. [22] conducted a techno-economic study on an off-grid Power system. As per their study, the PV system can generate electricity for Rupees (PKR) 6.87/kWh.

A study was undertaken by Soomer et al. [8] analyzed different CSP plants (PT, SPT, and LFR) connected to the DCMD system. Seawater is used as the condenser cooling water, while solar energy is used to produce electricity. DCMD, which heated saltwater in the condenser, provided the water source. 80-megawatt power was used in the study. CSP plants have been examined to see how much energy is produced and how much freshwater is retrieved. CSP facilities coupled with the DCMD system can be monetized to produce electricity and water at the cost of just about $1/W or less. Simulation results show that increasing irradiance increases electricity output. 353.87 GWh of electricity was produced by the SPT facility year. The PT facility generated 246.9 GWh of energy. SPT plant capital costs were the highest, while LFR plant capital costs were the lowest. The maximum useable capacity of the SPT plant was 56.1%, and the PT plant was 39.1%. The LCOE was 4.51 ¢/kWh for the PT plant and 13.39 ¢/kWh for the SPT plant[8].

In the research of Abdelhady [23], SAM has been used to design and evaluate the Egyptian 50MW solar dish, and the projected LCOE was 13.38 cents/kWh. In India, PT and LFR technologies were contrasted and examined by Chen et al. [24]. In a research completed by Shah et al. [25], four alternative CSP technologies in Australia were examined for their economic viability. The solar tower came out on top as the more cost-effective option. Janjai et al. [26] studied Thailand's economy using the Transient System Simulation (TRNSYS) and its solar thermal electric component (STEC) subroutine. The analysis indicates that the parabolic dish type is less expensive, with an LCOE of 0.30 US$/kWh. Zhu et al. [27] firstly analyzed the financial feasibility of three CSP technologies (parabolic trough, solar tower, and solar dish) in Xinjiang in 2015, and the findings demonstrate that at the present phase, the LCOE value of the three technologies range between 1.2 and 2.7 RMB/kWh, and the solar tower was the most cost-effective one.

The results obtained identify niche areas for short-term or immediate solar energy use for CSP in India [28].

A rigorous explanation of the applied methodology to calculate the LCOE for CSP and PV was proposed by Hernández [29]. A mathematical model was also proposed based on this knowledge that yields an analytical expression for the LCOE and its future evolution. Furthermore, the study explained how to assign a specific value to the independent variables used in the LCOE formula [30]– e.g., the discount and learning rates, solar resource, operational cost, maintenance cost, the lifetime of the system, and initial cost. Generated graphs and sensitivity analysis curves on the LCOE evolution and calculated the years to achieve the grid parities by simulation. It was determined that the representation presented in the study demonstrated efficiency in energy planning policies, such as tax exemptions and tariff-in schemes, as it compared the costs of CSP and PV technologies from 2010 to 2050. Moreover, it was observed that PV technologies are more appropriate for middle to high latitudes, while CSP technologies are more appropriate in low latitudes areas.

Hirbodi [31] conducted research to assess the solar tower's environmental, economic, and technical aspects and parabolic dish power for plants in Iran, specifically in south-central regions where the average direct solar radiation reaches 6 kWh/m^2/day. The study examined the effect of power plant capacity, thermal energy storage, and solar multiple (SM) on the power plant's techno-economic performance. The study also evaluated the environmental metrics involving the energy payback time, fossil fuel savings, and emissions of CO_2, in addition to investigating four power plants with various capacities along with two cooling options (wet and dry cooling). According to the climatic conditions in this region, the results revealed that the power plant using dry cooling with an SM of 3.0, a 14 h storage system, and a capacity of 100 MWe was the most efficient configuration. The solar-to-electricity efficiency was calculated and equated 14.7%, while the LCOE equaled 11.3 ¢/kWh[31].

Agyekum and Velkin [32] evaluated the techno-economy relating to the performance of two CSP technologies, namely parabolic trough (PT) and solar tower (ST), in two regions in Ghana – Tamale and Navrongo. The analysis was performed using the System Advisor Model (SAM). In this case, LCOE values of 14.73 ¢/kWh and 13.67 ¢/kWh were recorded for the ST modules located in Tamale and Navrongo, respectively. For the PT power plant, the LCOE values were 25.83 ¢/kWh for Navrongo and 28.83 ¢/kWh for Tamale. It was observed for the ST that the range of the optimum SM was 1.4–1.9, as the LCOE values for thermal energy storage were in this range. In the case of the PT plant, the results obtained from the analysis indicate that the optimum range of the SM was 2.4–4.0 in the climatic conditions in Ghana. In Langsa, a considerable amount of energy and electricity is required for the fisheries during the production process due to increased production.

3. Materials and Methods

The power plants' optimal location is Al-Wafra in Kuwait, as shown in Fig. 2. The simulation and analysis were performed using RETScreen software. The main steps taken are shown in Fig. 3.

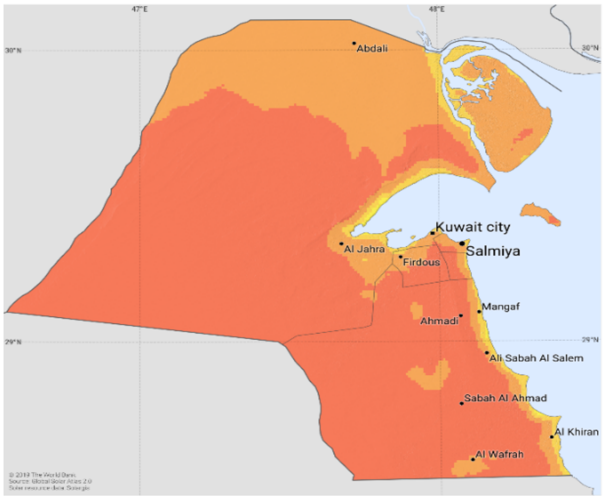


Fig. 2. Solar energy harvesting potential map over Kuwait territory

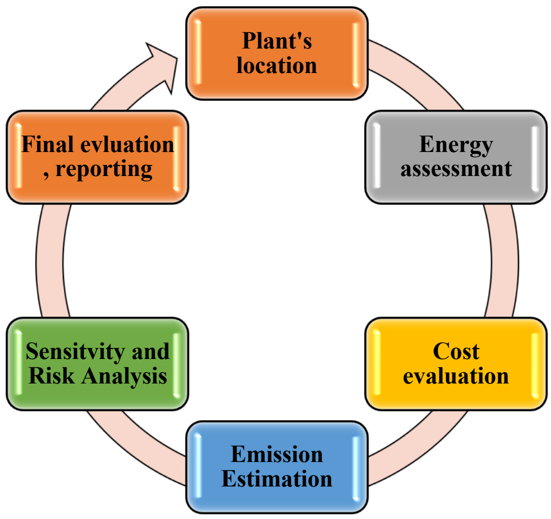


Fig. 3. Main steps for the techno-economic analysis of the study

3.1. Photovoltaic Solar Power Plant

A variety of components are used in constructing a PV system. Cells, generally composed of silicon, are stacked on a module, then coupled with other modules to create the appropriate device size. When exposed to sunlight, these cells provide a trim level of DC electricity that, when combined, produces a vast amount of electrical power without any moving components, noise, or pollution. The electricity is then directed to an inverter, which converts the DC to AC in our homes.

In the RETScreen software, 'Photovoltaic' was selected as the facility type to simulate the PV system's performance to predict the economic and environmental outcomes. Installing tracking systems would increase the energy generation rate. However, installing the solar trackers would also result in a higher initial cost for the plant.

The PV solar power plant to be constructed will not be installed with a solar tracker. The slope and azimuth were left as their default values according to the software database. Based on the panel installation parameters set on RETScreen, the average daily solar radiation for horizontal and tilted panels, the detailed expectations of the electricity export rate ($/kWh), and the electricity exported to the grid (MWh) were calculated. Table 1 shows this data over a year. It is worth mentioning that the annual solar radiation (MWh/m^2) decreases when the azimuth angle is changed[33].

Table 1 . Average monthly solar radiation and expected outputs for the PV plant[34].

	Daily solar radiation -	**Daily solar radiation**			**Electricity exported to**
	horizontal	**tilted**		**Electricity export rate**	**grid**
Month	**kWh/m'/d**	**kWh/m/d**		**$/kWh**	**MWh**
January	3.26	**4.43**		0.05	12,953.536
February	4.27	5.31		0.05	13,791.193
March	5.09	5.62		0.05	15,847.745
April	**5.88**	5.83		0.05	15,500.121
May	7.03	6.41		0.05	17,046.869
June	7.91	6.87		0.05	17,292.532
July	7.61	6.75		0.05	17,425.993
August	7.21	6.92		0.05	17,804.227
September	6.21	6.65		0.05	16,836.822
October	**4.88**	5.91		0.05	15,933.717
November	3.44	4.55		0.05	12,443.599
December	2.77	3.79		0.05	11,044.362
Annual	**5.47**	**5.75**		**0.05**	**183,920.716**
Annual solar radiation - horizontal		MWh/m^2	2.00		
Annual solar radiation - tilted		MWh/m^2	2.10		

3.2. Assumptions made for PV plant

The expected performance of the PV solar power plant depends on the panel and its energy conversion efficiency. Monocrystalline solar panels are commonly considered to be more efficient. Additionally, monocrystalline panels tend to be of superb quality with stylish aesthetics.

Silicon is extruded into slabs and sliced into wafers to make solar cells for monocrystalline solar panels. The term "monocrystalline" refers to the usage of single-crystal silicon in these panels. The electrons that create the flow of electricity have a greater area to move since the cell comprises a single crystal. As a result, monocrystalline panels are more productive than polycrystalline cells.

Fortunately, the software employed was included seven different kinds of PV solar panels. The seven choices from the list are: 'mono-Si,' 'poly-Si,' 'a-Si,' 'CdTe,' 'CIS,' 'spherical-Si,' and 'Other.' From this list, monocrystalline panels ('mono-Si') were chosen for consideration. Table 2 shows detailed data regarding the selected PV panel type.

Table 2. Assumptions made for the PV power plant.

Variable	Unit	Value/model	Ref.
Power capacity	MW	100	
Manufacturer		mono-Si Apin Solar	[35]
Model		mono-Si - SPP280	[35]
Number of units		357,143	
Efficiency	%	14.4%	[36]
Nominal operating cell temperature	º C	45	[35]
Temperature coefficient	%/º C	0.4%	[35]
Solar collector area	m^2	694,445	
Bifacial cell adjustment factor	%	11%	[37]
Miscellaneous losses	%	9%	[38]
Inverter Efficiency	%	97%	[39]
Capacity	kW	100,000	[35]
Miscellaneous losses	%	1%	[40]
Capacity factor	%	21%	[41]

3.3. Concentrating Solar Power Plant

Unlike the PV solar power plant, the components used in constructing a CSP plant vary. Solar collectors, typically made of materials characterized by extremely high thermal conductivity (low thermal resistance), are arranged on a module. The solar collectors collect solar thermal energy using a heat transfer fluid to generate electricity or heat water. The energy is then supplied to the consuming sector in the heat energy or the National Grid in the collected heat and is used to produce electricity.

It is assumed that the CSP plant to be constructed will be installed in the exact geographical location.

The main issue related to the CSP plant's performance depends on the type of solar collector, its ability to collect thermal energy, and heat transfer. Therefore, a solar collector manufacturer called Solel Solar Systems Ltd. was selected due to its high-quality products. Furthermore, the software is supplemented with a database which is necessary to predict the performance of these types of solar collectors.

The exact capacity of 100MW for the PV plant was assumed for the CSP plant, and the solar receivers were acquired [42]. The plant's capacity factor was assumed to be 50%, which refers to the ratio of the average power produced by the power plant over a year to its rated power capacity. The initial costs include both the initial and the installation costs. Typically, increment of the plant capacity will result in reducing of the installed cost per unit capacity due to the economies of scale and O&M costs or savings (negative value) or costs for all of the energy system components of the proposed case, including the inverter replacements that had been clarified too[43].

Table 3. Assumptions made for the CSP power plant [35]

Parameters	Unit	Value/model	Ref
Power capacity	MW	100	
Manufacturer		Abengoa Solar	[35]
Model		Solana	[35]
Number of units		1000	
Efficiency	%	14.4%	[44]
Solar collector area	m^2	694,445	
Capacity factor	%	60%	[35]

3.4. Mathematical relations

The thermo-economic study of the PV-based plant was done using RETScreen software, a Microsoft Excel-based analytical tool for renewable energy technologies. The program contains an inbuilt meteorological and geographical conditions database of most of the main cities across the world. The program is also connected with the database of several PV modules (mono-Si, poly-Si, amorphous-Si, and spherical-Si) produced by different companies. The distinctive properties of the PV modules (including optimal efficiency, nominal output temperature, and solar collector area) for different models are incorporated in its repository.

Solar irradiation on the level ground outside the Earth's atmosphere (H) and on the Earth's surface (H_o) may be estimated using an isotropic approximation using the following formulas [34]:

$$\boldsymbol{H_0 = \frac{86400}{\pi} \times G_{sc} \times \left[1 + 0.033 \times \cos\left(\frac{2n\pi}{365}\right)\right] \times (cos\varphi\ cos\delta\ sin\omega_s + \omega_s\ sin\varphi\ sin\delta)} \quad (1)$$

$$\boldsymbol{H = H_0 \times K_T} \quad (2)$$

Where G_{sc} is the solar constant, n is the number of days, ω_s is the solar hourly angles, φ is the latitude angle of the site [45], and K_T is the sky clearness score, which ranges between 0.3 and 0.8 during a year [45]. δ is the solar declination angle, determined using Cooper's Formula [35] as:

$$\delta = 23.45 \sin 2\pi \left(\frac{284 + n}{365}\right) \quad (3)$$

The average efficiency (η_p) of the PV module is described by mean temperature (T_c) and could be computed using [47]:

$$\eta_p = \eta_r \left(1 - \beta_p (T_c - T_r)\right) \quad (4)$$

Where η_r and T_r are the module benchmark efficiency and temperature, which is 25 ºC, and β_p is the temperature parameter of the PV module. is the module temperature estimated from average monthly air temperatures using the Evans equation [46].

Different financial indicators could be utilized to evaluate the risk involved in the project. Net Present Value (NPV) reflects the current value of expected cash flows produced by a project and is determined by [47]:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+i)^t} - C_0 \quad (5)$$

C_t is the net cash flow throughout the period, C_0 is the initial investment, is the discount rate, and is the duration of the analysis. Internal rate of return (IRR), another financial metric, is the discount rate at which the NPV of the project turns zero and could be calculated using the same relation and substituting IRR instead of the discount rate [48].

$$\boldsymbol{NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0 = 0} \quad (6)$$

IRR reflects the desirability of a proposed project. If the IRR surpasses the company's targeted rate of return, the project is regarded as viable. The payback period is the time duration necessary to reimburse the project's initial investment with the net cash flow during the considered time[49].

4. Result

The results of the study are reported in a technical and economic context. The following section provides the results and the sensitivity and Risk analysis performed for both power plants.

4.1. Photovoltaic Power Plant

The energy price was expected to be almost 0.054 \$/kWh, with the entire plant producing roughly 183,921 MWh annually. The planned plant is expected to occupy 692,857 m^2, which increases the initial cost. Because the power generated will be collected from the environment, the projected PV facility can minimize CO_2 emissions by about 144,790.2 tonnes per year in terms of environmental advantages. Fig. 4 and Fig. 5 provide a detailed numerical representation of the expected yearly outcome and cumulative cash flows of the designed PV solar power plant for 20 years of operation. Thus, the plant payback period can be easily projected and is expected to be 3.7 years.

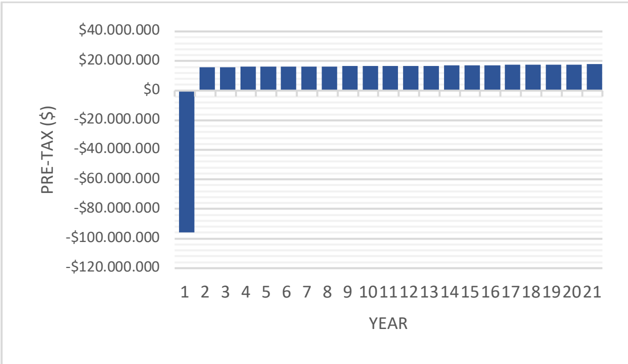


Fig. 4. Expected yearly cash flow for the designed PV solar power plant.

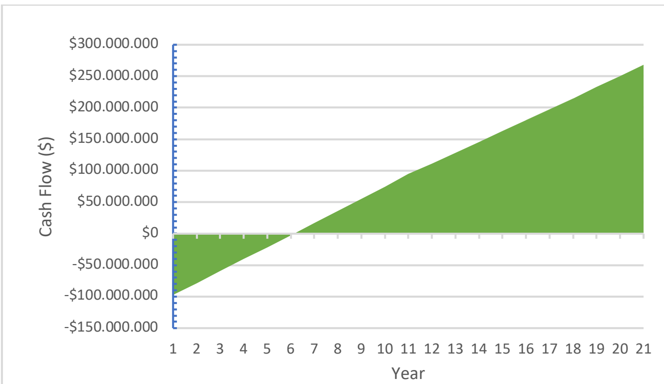


Figure 5 Expected cumulative cash flow for the designed PV

4.1.1. Sensitivity Analysis

The project's economic feasibility is evaluated using the IRR and discount rate. A project with an IRR higher than the discount rate would be considered viable. Generally, investors set a goal IRR above the discount rate, and any value more significant than the targeted IRR is considered desirable. The sensitivity analysis of NPV and Pre-tax IRR-equity for electricity export rate and CHG reduction credit rate in a range of -25% to +25% is completed. Results found by the sensitivity analysis of the Photovoltaic power plant are shown in the figures.

The sensitivity analysis o of the NPV for the designed PV solar power plant is presented in Fig. 6.

For example, this figure shows the change in the IRR value when both the initial cost and O&M cost increase from -25% to 25%.

O&M		Electricity export rate ($/MWh)				
		37.50	43.75	50.00	56.25	62.50
$		-25.0%	-12.5%	0.0%	12.5%	25.0%
595,238	-25.0%	177,544,115	199,381,353	221,218,591	243,055,829	264,893,067
694,445	-12.5%	175,659,483	197,496,721	219,333,958	241,171,196	263,008,434
793,651	0.0%	173,774,850	195,612,088	**217,449,326**	239,286,564	261,123,802
892,858	12.5%	171,890,218	193,727,456	215,564,693	237,401,931	259,239,169
992,064	25.0%	170,005,585	191,842,823	213,680,061	235,517,299	257,354,537

Initial costs		Electricity export rate ($/MWh)				
		37.50	43.75	50.00	56.25	62.50
$		-25.0%	-12.5%	0.0%	12.5%	25.0%
72,892,799	-25.0%	198,072,450	219,909,688	241,746,925	263,584,163	285,421,401
85,041,598	-12.5%	185,923,650	207,760,888	229,598,126	251,435,364	273,272,601
97,190,398	0.0%	173,774,850	195,612,088	**217,449,326**	239,286,564	261,123,802
109,339,198	12.5%	161,626,051	183,463,288	205,300,526	227,137,764	248,975,002
121,487,998	25.0%	149,477,251	171,314,489	193,151,726	214,988,964	236,826,202

GHG reduction credit rate		Electricity export rate ($/MWh)				
		37.50	43.75	50.00	56.25	62.50
$/tCO$_2$		-25.0%	-12.5%	0.0%	12.5%	25.0%
71.40	-25.0%	141,380,695	163,217,933	185,055,171	206,892,409	228,729,647
83.30	-12.5%	157,577,773	179,415,011	201,252,248	223,089,486	244,926,724
95.20	0.0%	173,774,850	195,612,088	**217,449,326**	239,286,564	261,123,802
107.10	12.5%	189,971,928	211,809,166	233,646,403	255,483,641	277,320,879
119.00	25.0%	206,169,005	228,006,243	249,843,481	271,680,719	293,517,957

Fig. 6. Sensitivity analysis of the NPV for the PV plant.

Likewise, the IRR is 18.7% for the base assumptions of the electricity export rate, the minimum IRR is found for the -25% export rate, and the 25% increment of the installation cost equals 11.9%. The IRR for the CHG credit rate reduced to -25%, and the electricity export rate decreased by 25% is 13.6%. Also, sensitivity analysis of the IRR - equity for the PV plant is shown in Fig. 7.

O&M		Electricity export rate ($/MWh)				
		37.50	43.75	50.00	56.25	62.50
$		-25.0%	-12.5%	0.0%	12.5%	25.0%
595,238	-25.0%	16.1%	17.6%	18.9%	20.3%	21.6%
694,445	-12.5%	16.0%	17.4%	18.8%	20.2%	21.5%
793,651	0.0%	15.9%	17.3%	**18.7%**	20.1%	21.4%
892,858	12.5%	15.8%	17.2%	18.6%	19.9%	21.3%
992,064	25.0%	15.6%	17.1%	18.5%	19.8%	21.2%

Initial costs		Electricity export rate ($/MWh)				
		37.50	43.75	50.00	56.25	62.50
$		-25.0%	-12.5%	0.0%	12.5%	25.0%
72,892,799	-25.0%	22.1%	23.9%	25.6%	27.3%	29.0%
85,041,598	-12.5%	18.6%	20.2%	21.7%	23.2%	24.7%
97,190,398	0.0%	15.9%	17.3%	**18.7%**	20.1%	21.4%
109,339,198	12.5%	13.7%	15.0%	16.3%	17.6%	18.8%
121,487,998	25.0%	11.9%	13.2%	14.3%	15.5%	16.6%

Electricity export rate		GHG reduction credit rate ($/tCO$_2$)				
		71.40	83.30	95.20	107.10	119.00
$/MWh		-25.0%	-12.5%	0.0%	12.5%	25.0%
37.50	-25.0%	13.6%	14.8%	15.9%	17.0%	18.1%
43.75	-12.5%	15.1%	16.2%	17.3%	18.4%	19.5%
50.00	0.0%	16.5%	17.6%	**18.7%**	19.8%	20.8%
56.25	12.5%	17.9%	19.0%	20.1%	21.1%	22.1%
62.50	25.0%	19.3%	20.4%	21.4%	22.4%	23.5%

Fig. 7. Sensitivity analysis of the IRR-equity of the PV plant.

3.1.2. Risk Analysis

The risk analysis reveals the relative influence of uncertainty on each of the parameters associated with the variability of the financial indicator. When used with various input parameters, a horizontal bar of equal length affects the financial variable's variability. The financial indicator is sorted by the type of input parameters that are used. In terms of how much influence each input parameter has on the variability of the financial predictor, the top input parameter (y-axis) contributes the most, while the bottom input parameter (x-axis) contributes the least. The link between the input and financial indicators is confirmed when a positive or negative bar is above the input. The financial indicator has a positive connection with the input parameter when the value of the input parameter raises the financial indicator's value.

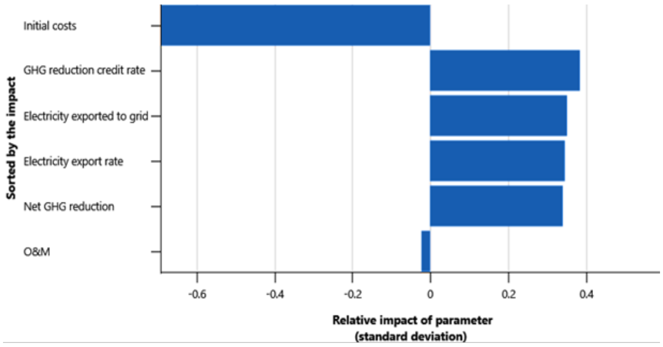


Fig. 8. Risk analysis of the IRR- equity payback for the PV solar plant.

Fig. 8 represents the distribution of the financial indexes that were calculated by running the Monte Carlo simulation. Each vertical bar corresponds to the percentage of data falling inside the range defined by the horizontal bar's width. When the midpoint of each range is determined, the appropriate value is displayed on the x-axis. Also, the distribution analysis of the equity payback and the Risk analysis of the NPV impact for the PV solar plant is presented in Fig. 9 and Fig. 10.

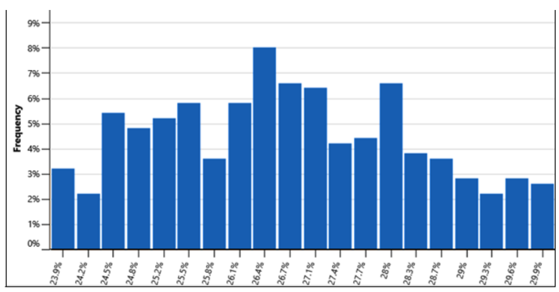


Fig. 9. Distribution analysis of the IRR - equity payback for the PV solar plant.

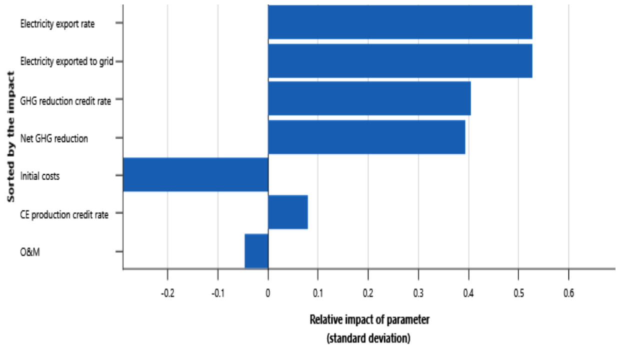
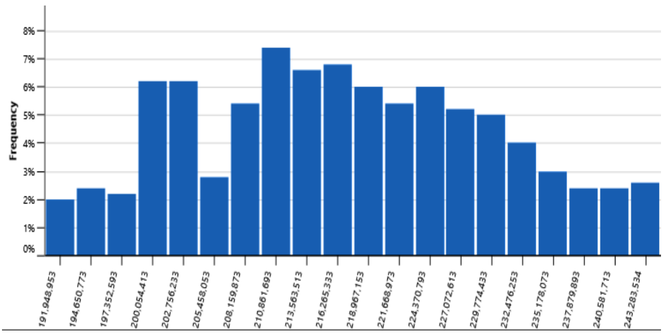


Fig. 10. Risk analysis of the NPV impact for the PV solar plant.



Fi. 11. Distribution analysis of the NPV impact for the PV solar plant.

Fig. 11 presents the distribution analysis of the NPV impact for the PV solar plant.

4.2. Concentrating Solar Power Plant

The designed CSP plant allowed for predicting the plant's performance, which helps determine the economic feasibility based on certain assumptions considered for all other energy harvesting technologies. Fig. 12 and 13 provide a detailed numerical representation of the expected yearly outcome and cumulative cash flows of the designed PV solar power plant for 20 years of operation. This section presents the results in more detail. It was estimated that the energy price would reach $0.088 per generated kWh, while the entire plant would generate almost 438,000,000 kWh. In addition, the designed plant was estimated to occupy the same land area (692,857 m^2), which increased the initial cost.

Regarding the environmental advantages, it was evaluated that the designed CSP plant would reduce annual CO_2 gas emissions by approx. 192,651 tonnes as the generated electricity would be harvested from the environment. It was predicted that this would save $23,652,000 over 20 years of operation. The environmental benefits were compared with other activities that produce emissions, where the reduction in emissions when the CSP plant is used is equivalent to reducing the number of cars and lorries in the country by around 35,284 vehicles.

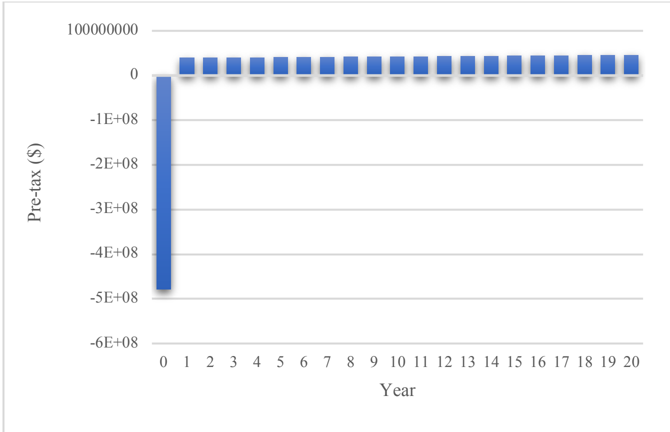


Fig. 12. Expected yearly cash flow for the CSP plant.

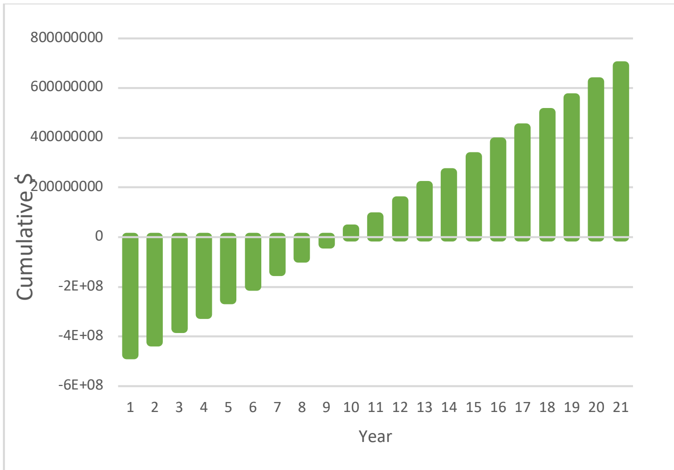


Fig. 13. Expected cumulative cash flow for the designed CSP plant.

4.2.1. Sensitivity Analysis

The project's economic feasibility is evaluated using the IRR and discount rate. A project with an IRR higher than the discount rate would be considered viable. Generally, investors set a goal IRR above the discount rate, and any value more significant than the targeted IRR is considered desirable. The sensitivity analysis of NPV and Pre-tax IRR-equity for electricity export rate and CHG reduction credit rate in a range of -25% to +25% is completed. The sensitivity analysis of the NPV of the CSP power plant for different variables is shown in Fig. 14.

GHG reduction credit rate		Electricity export rate ($/MWh)				
		40.50	47.25	54.00	60.75	67.50
$/tCO₂		-25.0%	-12.5%	0.0%	12.5%	25.0%
71.40	-25.0%	-48,295,334	2,463,747	53,222,827	103,981,908	154,740,988
83.30	-12.5%	-9,722,627	41,036,454	91,795,535	142,554,615	193,313,696
95.20	0.0%	28,850,081	79,609,161	**130,368,242**	181,127,323	231,886,403
107.10	12.5%	67,422,788	118,181,869	168,940,949	219,700,030	270,459,110
119.00	25.0%	105,995,496	156,754,576	207,513,657	258,272,737	309,031,818

Initial costs		Electricity export rate ($/MWh)				
		40.50	47.25	54.00	60.75	67.50
$		-25.0%	-12.5%	0.0%	12.5%	25.0%
358,920,038	-25.0%	148,490,093	199,249,174	250,008,255	300,767,335	351,526,416
418,740,044	-12.5%	88,670,087	139,429,168	190,188,248	240,947,329	291,706,409
478,560,051	0.0%	28,850,081	79,609,161	**130,368,242**	181,127,323	231,886,403
538,380,057	12.5%	-30,969,925	19,789,155	70,548,236	121,307,316	172,066,397
598,200,063	25.0%	-90,789,932	-40,030,851	10,728,229	61,487,310	112,246,390

Electricity exported to grid		GHG reduction credit rate ($/tCO₂)				
		71.40	83.30	95.20	107.10	119.00
MWh		-25.0%	-12.5%	0.0%	12.5%	25.0%
328,500.00	-25.0%	-48,295,334	-9,722,627	28,850,081	67,422,788	105,995,496
383,250.00	-12.5%	2,463,747	41,036,454	79,609,161	118,181,869	156,754,576
438,000.00	0.0%	53,222,827	91,795,535	**130,368,242**	168,940,949	207,513,657
492,750.00	12.5%	103,981,908	142,554,615	181,127,323	219,700,030	258,272,737
547,500.00	25.0%	154,740,988	193,313,696	231,886,403	270,459,110	309,031,818

Fig. 14. Sensitivity analysis of the NPV for the CSP plant.

Likewise, for the IRR-equity of the CSP plant, the sensitivity analysis was completed, and the results are shown in Fig. 15.

GHG reduction credit rate		Electricity export rate ($/MWh)				
		40.50	47.25	54.00	60.75	67.50
$/tCO₂		-25.0%	-12.5%	0.0%	12.5%	25.0%
71.40	-25.0%	0.4%	1.6%	2.6%	3.6%	4.6%
83.30	-12.5%	1.3%	2.4%	3.4%	4.3%	5.3%
95.20	0.0%	2.1%	3.1%	**4.1%**	5.0%	5.9%
107.10	12.5%	2.9%	3.9%	4.8%	5.7%	6.6%
119.00	25.0%	3.6%	4.6%	5.5%	6.4%	7.3%

Initial costs		Electricity export rate ($/MWh)				
		40.50	47.25	54.00	60.75	67.50
$		-25.0%	-12.5%	0.0%	12.5%	25.0%
358,920,038	-25.0%	5.4%	6.5%	7.7%	8.8%	9.8%
418,740,044	-12.5%	3.6%	4.7%	5.7%	6.7%	7.7%
478,560,051	0.0%	2.1%	3.1%	**4.1%**	5.0%	5.9%
538,380,057	12.5%	0.9%	1.9%	2.8%	3.7%	4.5%
598,200,063	25.0%	-0.1%	0.8%	1.7%	2.5%	3.3%

Electricity exported to grid		GHG reduction credit rate ($/tCO₂)				
		71.40	83.30	95.20	107.10	119.00
MWh		-25.0%	-12.5%	0.0%	12.5%	25.0%
328,500.00	-25.0%	0.4%	1.3%	2.1%	2.9%	3.6%
383,250.00	-12.5%	1.6%	2.4%	3.1%	3.9%	4.6%
438,000.00	0.0%	2.6%	3.4%	**4.1%**	4.8%	5.5%
492,750.00	12.5%	3.6%	4.3%	5.0%	5.7%	6.4%
547,500.00	25.0%	4.6%	5.3%	5.9%	6.6%	7.3%

Fig. 15. Sensitivity analysis of the IRR - equity for the CSP plant.

4.2.2. Risk Analysis

Similar to the PV power plant, the Impact of different IRR-equity, NPV, and equity variables were analyzed, and the results are demonstrated. Fig. 17 presents the CSP plant's impact - equity payback risk analysis.

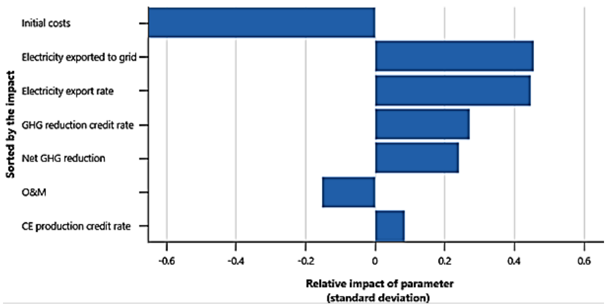


Fig. 16. Risk analysis of the IRR - equity for the CSP plant.

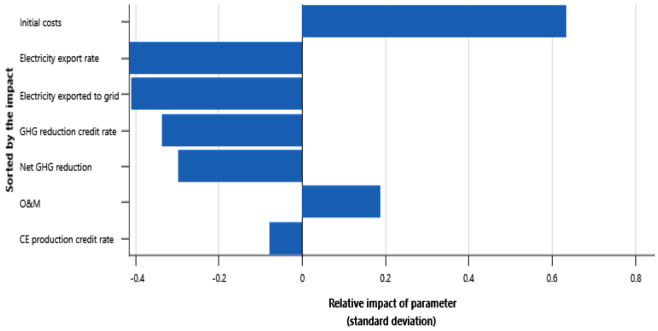


Fig. 17. Risk analysis of the Impact - equity payback for the CSP plant.

Fig. 18 shows the probable values of the financial indicator as a consequence of the Monte Carlo simulation is also available. Each vertical bar shows the percentage of values that fall in the defined range, with the height of each bar representing the frequency (percent). Also, the risk analysis of the NPV and the distribution analysis of the NPV for the CSP plant are shown in Fig. 19 and Fig. 20.

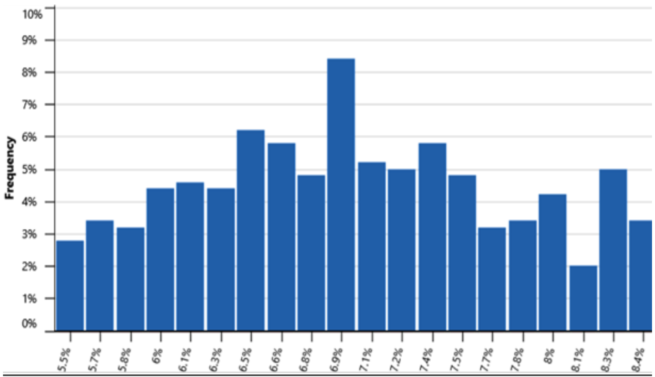


Fig. 18. Distribution analysis of the IRR - equity payback for the CSP plant.

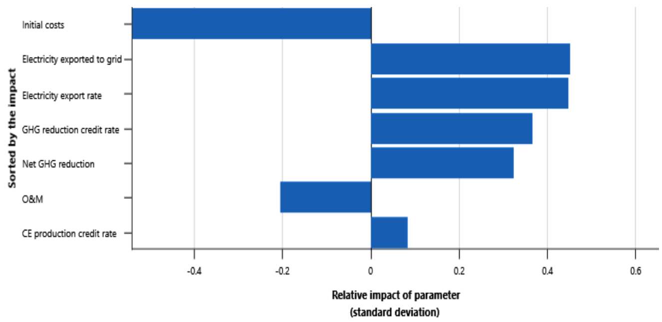


Fig. 19. Risk analysis of the NPV for the CSP plant.

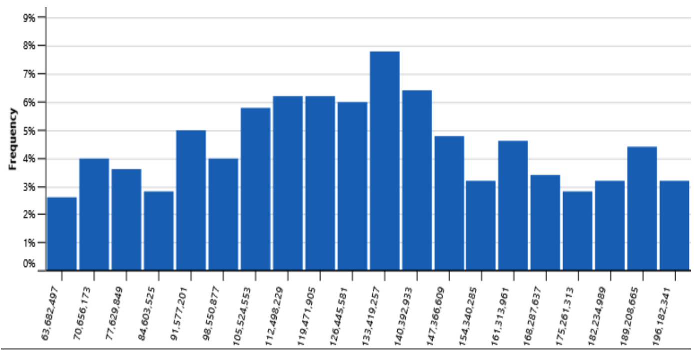


Fig. 20. Distribution analysis of the NPV for the CSP plant.

5. Discussion

The findings show that many carbon dioxide emissions are avoided, proving that solar energy has little to no influence on pollution. Furthermore, PV is the cleanest energy generation of all solar energy methods.

PV energy has the lightest carbon footprint and uses little water for solar technologies and their lifetime. It consumes 1200 MJ/m of energy during its lifetime, equating to 0.333 MWh/m^2 of embedded energy. However, after its lifespan is through and the modules are disposed of in landfills, the contents may seep out and end up in the ocean, causing pollution.

The power storage system for solar energies is another challenge with limited solar energy applications to small projects because an extensive (and, therefore, expensive) storage system is required to store the produced electric power. This challenge was overcome by connecting the solar energy systems directly to national grids where the generated power is consumed. However, the storage system's cost remains a significant challenge in arid regions when the national grid is unavailable. Consequently, this has limited the use of small solar energy projects in these regions.

In comparing the solar energy applications with other renewable energy technologies, it can be noted that this technology is applied more in micro-scale projects than in large-scale projects. Similarly, this technology can be easily integrated into different applications to produce thermal or electrical energy, such as solar energy in a residential building for water heating or electrical power generation.

Table 4. Financial Comparison of the two plants.

	Unit	CSP	PV
IRR – equity	%	7%	26.80%
MIRR – equity	%	4.20%	14%
IRR – assets	%	7%	26.80%
MIRR – assets	%	4.20%	14%
Simple payback	yr	10.4	3.7
Equity payback	yr	10.5	3.7
Net Present Value (NPV)	$	298,382,840	355,611,305
Annual life cycle savings	$/yr	17,379,528	20,712,842
Benefit-Cost (B-C) ratio	%	1.6	4.6
GHG reduction cost	$/tCO$_2$	92.072	129.472
Energy production cost	$/kWh	0.0884	0.03536

Table 5. Cost and revenue comparison of the two plants.

Parameter	CSP			PV		
Initial costs						
Initial cost	99.50%	$	476,190,476	97.50%	$	94,800,038
land	0.50%	$	2,369,574	2.50%	$	2,390,360
Total initial costs	**100%**	**$**	**478,560,051**	**100%**	**$**	**97,190,398**
Yearly cash flows - Year 1						
Annual costs and debt payments						
O&M costs (savings)	$		9,523,810	$		793,651
Debt payments	$		0	$		0
Total annual costs	**$**		**9,523,810**	$		**793,651**
Annual savings and revenue						
Electricity export revenue	$		23,652,000	$		9,196,036
GHG reduction revenue - 20 yrs	$		17,973,566	$		7,547,286
Other revenue (cost)	$		0	$		0
CE production revenue - 20 yrs	$		4,380,000	$		2,758,811
Total annual savings and revenue	**$**		**46,005,566**	**$**		**19,502,132**
Net yearly cash flow - Year 1	**$**		**36,481,756**	**$**		**18,708,481**

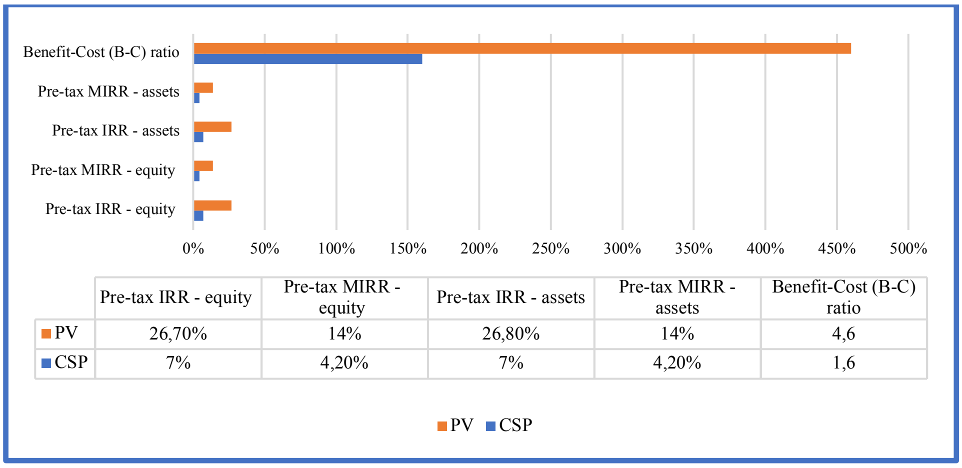


Fig. 21. Comparison of the risk of the two plants.

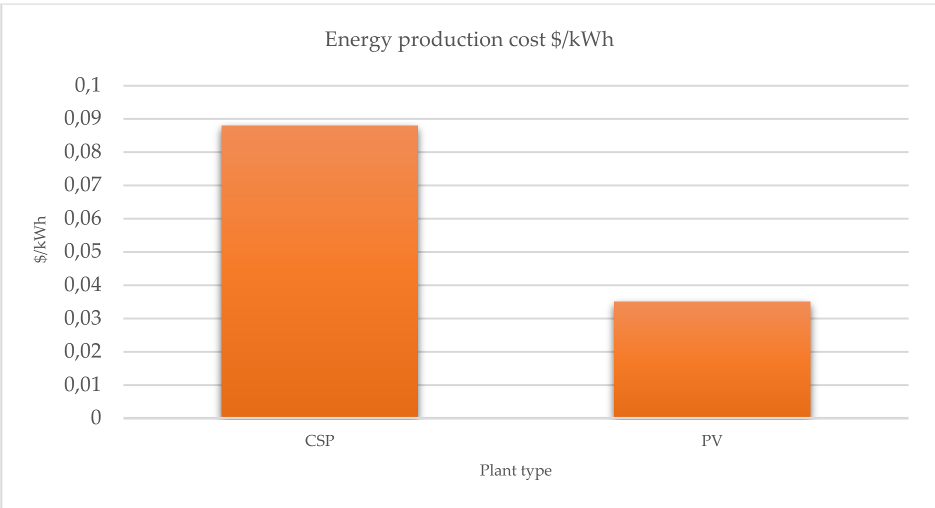


Fig. 22. Comparison of the annual saving and costs of two plants.

Fig. 21 compares the risk of PV and CSP plants. Moreover, a Comparison of these two plants' annual saving and costs is shown in Fig. 22.

According to the Ministry of Electricity and Water [2] statistics, Kuwait produces electric power using four different technologies: steam turbines, gas turbines, combined-cycle turbines, and renewable energy. The capacities of these technologies are 8970 MW, 8151 MW, 3032 MW, and 70 MW, respectively. Therefore, this project would boost the electric power production of renewable energy to 170 MW. However, establishing renewable energy technologies in Kuwait requires further improvements as power generation using renewable sources would still be less than 1% even if this project is actualized.

6. Conclusion

This study compared three separate sites, namely Al-Wafra, Al-Jahraa, and Umm Qasr. The solar radiations for these locations were 250.12 W/m^2, 244.91 W/m^2, and 243.98W/m^2, respectively. Based on the Comparison of the three sites, it was determined that Al-Wafra should be considered to simulate the renewable energy harvesting techniques. The decision was made considering the average, minimum, and maximum temperatures and the comparatively higher number of hours a year that renewable energy solutions are required to work, resulting in a higher degree of stability.

The simulation studies were applied to the two solar energy harvesting methods, PV cells and CSP, each plant producing around 100 MWh.

- The studied sustainable power plants are not expected to have CCS systems installed, saving over 20 years of operation. The CSP plant achieves the highest revenue.
- The cumulative profit is expected to reach its maximum value for the CSP plant.
- The PV solar power plant is expected to achieve the shortest payback period of 5 years.
- Comparing the initial costs, CSP has the highest value with approximately $478,560,000, and the lowest cost for installation of power plant belongs to the PV power plant with around $97,190,398.

According to the simulation findings and market research, PV systems are a more viable technology that can be installed more efficiently, at a cheaper cost, and in a much shorter period than CSP plants, which require more area for various technologies and are linked with more significant concerns, including higher investment and challenges with thermal storage and cooling.

6.1. Recommendations for future studies

Concerning renewable energy and the harvesting technique selected in the proposed study (i.e., the CSP plant), comparing the expected benefits with conventional electricity generation technologies, such as power stations fired with natural gas, gas turbines, and reciprocating engines is essential, and steam turbines. Thus, future studies could improve the understanding of the achieved outcomes compared with traditional techniques and encourage decision-makers to invest in the renewable energy sector.

It is worth considering combining renewable energy harvesting methods to investigate the possibility of achieving more significant benefits. For example, the 100 MW capacity plant could be constructed from a PV and wind turbine farm. This could improve the expected economic and environmental benefits and reduce the payback period for the project.

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