Prospects of large-scale photovoltaic-based power plants in the Kingdom of Saudi Arabia

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Abstract
The techno-economic analyses of 67 MW and 144 MW photovoltaics (PV) power plants are performed and the results are compared with the diesel power plants situated in two cities in the Kingdom of Saudi Arabia. The feasibility analysis is conducted with the aim to show the technical and economic viability of replacing the conventional fossil fuel-based plants with clean production systems in the country. The production capacity of the proposed PV plants based on the single-axis tracking configuration is around 35% higher than that of the tilted-fixed configuration, equivalent to a reduction in the production cost by more than 20% for both the plants. PV plants with a tracking system can produce up to 23% excess electricity than the base-case diesel plants. Moreover, the production costs at the Bisha plant can be as low as 1.77 €/kWh, considering the credit resulting from the reduction of greenhouse gas (GHG) emissions. The feasibility of installing a 144 MW PV plant in six cities in the country is also evaluated. The results indicate that the average cost of electricity production is 2.22 €/kWh and the average annual reduction of GHG emissions is 462 tCO2/GWh with the replacement of a diesel power plant of similar capacity. The effects of subsidies, feed-in tariff rates, and electricity export escalation rates are also evaluated.

KEYWORDS
energy policy, government incentives, photovoltaic, solar energy, techno-economic analysis

1 INTRODUCTION

About 2 billion people around the world living in rural areas do not have access to electricity and another 2 billion are severely undersupplied.1 The conventional means of power generation are regarded by researchers, scientists, and engineers all over the world as detrimental to the environment because of their role in climate change and global warming. According to the UN reports, the average global temperature will rise up by 5.8°C over the next century if the emissions continue to increase at the current rate.2,3 Hence, many countries are using alternate sources of energy and promoting zero carbon or low carbon technologies.4-6

Moreover, the vulnerability of oil prices, as well as the bleak future of crude oil, have affected the strategies set by different countries, focusing more towards the green technologies in fulfilling their energy demand.7 The governments around
the world are keen to adopt the energy pricing policies to favor renewable energy systems in order to give it a platform to compete with the conventional energy systems.\textsuperscript{8-10} For instance, the U.S government has implemented several policies and measures to encourage the use of PV systems. One of such policies is permitting the customers to export electricity generated by their PV systems to the grid and offset the excess electricity generated against consumption at other times, in effect receiving credit for all PV generation at the prevailing retail electricity rates.\textsuperscript{11} The Republic of Korea prioritized the wind and photovoltaic-based power system and adopted policies to encourage the green power generation system including feed-in tariff (FIT) compensation for renewable energy and planning to increase the contribution of renewable energy to 11\% by 2030.\textsuperscript{12} The Indian government has shown exhaustive efforts in increasing the renewable energy share in the country by extensively participating and arranging international meetings and attracting foreign investors to the renewable sector. The country is targeting to increase the on-grid solar installed capacity from 20 to 100 GW by 2022.\textsuperscript{13} One of the fastest growing economies, China, is not lagging behind the global race for the renewable energy and has implemented various policies to ensure a sustainable growth. The republic is targeting to achieve 15\% of its energy demand to be fulfilled by renewable energy sources.\textsuperscript{14} European countries have adopted several devices, including FIT, to promote renewable energy and have so far have proved very effective.\textsuperscript{15}

Around 25\% of the world’s energy requirements are met by the renewable sources today and is expected to hold the largest power source share by 2030 by surpassing coal and is likely to increase up to 60\% of the total energy share by 2070.\textsuperscript{16} The high dependence of the countries in the Middle East on fossil fuels has limited the use of renewable energy to around 1\% in this region. However, the share is expected to increase to 16\% by 2035.\textsuperscript{17}

Saudi Arabia is a land of abundant energy resources, primarily dependent on energy derived from petroleum products for power generation and industries. However, use of non-conventional sources for electricity generation has always been of great interest to the research community in the Kingdom. Several studies conducted on the implementation of renewable energy in the region has been found to be promising.\textsuperscript{18-21} Due to its location and topography, all parts of Saudi Arabia receive ample annual solar radiation, which can be efficiently utilized as a source of clean energy. Photovoltaic (PV) technology, which directly converts solar radiation into electricity, is a convenient and efficient way of harnessing solar energy. Recent developments associated with PV technologies have brightened the prospects of exploiting solar energy at economically competitive prices.

PV power plants have some limitation as compared to conventional means of electric power generation.\textsuperscript{22,23} However, the energy storage, system flexibility, integration of the PV systems with grid and load shifting as options that can enable solar photovoltaics (PV) to overcome their limitations as compared to conventional electric power systems.\textsuperscript{24-26} Moreover, the effects of the surface temperature of PV panels and dust deposition on them on the power output of a solar power plant cannot be ignored and appropriate derate factors needs to be applied.\textsuperscript{27,28}

Extensive studies have been conducted on the prospects of renewable energy production in terms of costs, capacity, savings, and environmental benefits.\textsuperscript{29-31} Moreover, several comparative studies of PV-based power generation system with the diesel-based plants show promising results and can be implemented with proper support and incentives for the renewable energy.\textsuperscript{32-34} Some attempts were also made in the direction of integrating diesel plants with renewable energy in order to meet the load demands in the remote areas.\textsuperscript{33,35,36} Cost of electricity production has been calculated for a various combinations of standalone and hybrid solar power generation system, ranging from 21 to 16 €/KWh in this region.\textsuperscript{35,37-39} The studies also reported the environmental benefit that can be achieved by installing the renewable energy project in terms of reduction in the greenhouse gases (GHGs) emissions. Several other studies on solar PV and hybrid solar PV systems with other renewables focusing on the application, simulation, engineering, monitoring, and performance in different countries and locations can be found in the literature.\textsuperscript{40-42} Mathematical models for the calculation of present and future values of levelized cost of electricity were also developed for the PV-based systems.\textsuperscript{43,44} Moreover, use of tracking system has been found to economically viable for a solar PV system due to reduced cost of installation. Savings of up to 18.2\% can be attained if appropriate sun-tracking technology in a hybrid photovoltaic-pumped storage hydro system is selected.\textsuperscript{42}

In the recent years, the prices of PV modules, tracking systems, inverters, and the balance of the system (BoS) have dropped exponentially. Initial investment has a large impact on the production cost and hence, it is the determining factor for a project to be a success. As the above discussions highlight the present and future techno-economic growth of the PV-based energy generation system around the world, it is vital to have the updated analysis of the system for a country to formulate its energy policies towards the green and sustainable development. Moreover, due to the volatility of the global crude oil market, oil-based economies like Saudi Arabia have suffered a lot. The Kingdom is already reducing the subsidies on the domestic petrol consumption, resulting in around four times hike in the petrol price in the last couple of years. The electricity tariffs have been raised in the same proportion and the government is keen to generate revenues using these
measures in the near future. There is an urgent need to overhaul the economic structure of the country by reducing its dependency on oil. For any policies to be formulated in this direction, a clearer picture of the project feasibility should be available. The literature review suggests that the techno-economic analysis of large-scale PV-based power plants, with the updated scenario for the region, are not available. The renewable energy market is changing rapidly over the last few years, necessitating updated study to track the trend and viability of such projects.

In the present study, two diesel-based power plants were selected as the base case scenarios for the technical and economic analysis of a PV-based electricity generation system. Cost of electricity production is evaluated with and without the GHGs reduction credit for tilted-fixed and single-axis tracking configurations. The system was investigated considering the electricity export rates (EERs) of the proposed plants equivalent to the calculated cost of electricity (COE) of the base case scenarios. A 10% subsidy on the total initial investment was considered to assess the project’s feasibility, and the financial indicators are presented for both the proposed plants. In addition, the performance and feasibility of a 144 MW PV plant, with a single-axis tracking system, has been examined for six cities located at the different parts of the Kingdom. Selection of different cities are based on varied climatic conditions, presenting a holistic view of the plant feasibility around the globe with similar conditions. Several scenarios of the combination of the FIT, subsidies, and electricity export escalation rates (EEERs) are considered, and a sensitivity analysis of the variables are also presented.

2 | DATA AND METHODOLOGY

In this study, a solar panel with the properties of the poly-Silicon (Si) solar PV panel from Canadian Solar (CS6X-300P) rated at 300 W is considered. The peak module efficiency of the panel is 15.6% with a specific surface area of 6.4 m²/kW. The module efficiency decreases considerably with temperature, which is an important parameter to be considered for Saudi Arabia, with large-scale desert (arid and hyper-arid) conditions. RETScreen software has an inbuilt function to account for this property and it assumes an average decrease in the efficiency of 0.4% for each degree of temperature increase above 45°C. The software has been validated in several studies, with a reported variation of less than 6% from the actual energy production.

The efficiency of PV panels can be further affected by the deposition of sand and dust on their surfaces. In the arid climatic conditions of Saudi Arabia, characterized with frequent sandstorms, soiling effect cannot be ignored. It has been reported an average derate factor of 0.95 due to the effect of soiling. Therefore, an efficiency loss of 5% has been assumed to account for the effects of sand and dust deposition on the panels, which results in an effective peak module efficiency of 14.8%.

An inverter capacity equivalent to 95% of the plant’s rated power is considered, which is a safe assumption. The loss of 2% is due to the DC to AC conversion by the inverter as suggested in NREL report. The panels are considered to be at the slope equal to the latitude of the locations facing southward, for both configurations, tilted-fixed and single-axis tracking to obtain a maximum efficiency.

2.1 | Meteorological data

The meteorological data are obtained from the RETScreen database, which is connected to NASA satellites and 6700 ground-station locations around the globe. Geographical locations of the cities selected in this study are mapped in Figure 1. Monthly averaged solar radiation on the horizontal surface and average annual solar radiation on the horizontal and tilted surfaces at both locations are presented in Figures 2 and 3. Bisha has the highest annual solar radiation of 2.56 MWh/m² on the horizontal surface, followed by Medina with 2.11 MWh/m². Dhahran has the lowest among the selected cities with the annual solar radiation of 2.05 MWh/m² on the horizontal surface. The panels are considered to be tilted to the angles equal to the latitudes of the locations of the PV plants.

2.2 | Base cases description

The two base case power plants were selected based on the highest electricity production cost in the Kingdom and the city with the highest annual solar radiation. The diesel power plant (67 MW) at Tabarjal does have the highest cost of electricity production in the Kingdom. Tabarjal is situated at 30.5°N and 38.22°E. As environmental data for Tabarjal
**Figure 1** Geographical locations of the selected cities

**Figure 2** Monthly averaged daily solar radiation on a horizontal surface for the selected cities in Saudi Arabia for the study

**Figure 3** Average annual solar radiation on the horizontal and fixed-tilted surface
| TABLE 1 Details of the base case power plants | **Tabarjal (Al-Jawf)** | **Bisha** |
|---|---|---|
| Capacity | 67 MW | 144 MW |
| COE | 4.93¢/kWh | 2.72¢/kWh |
| Type of fuel | Diesel | Diesel |
| Annual electricity production | 146,349 MWh | 353,676 MWh |
| Annual CO₂ emission | 67,096.3 tons | 150,347 tons |

are not available in the RETScreen database, Al-Jawf (29.8°N–39.9°E) was selected for the analysis. Bisha, situated at 20°N and 42.6°E, has been reported as the best city for solar-based power generation systems. Thus, the 144 MW diesel-fired power plant at Bisha was selected as the second base case. Table 1 provides the details of the selected base case power plants used in the analysis.

### 2.3 Mathematical modeling

The thermo-economic analysis of the PV-based plant was conducted using RETScreen software, a Microsoft Excel-based analysis tool for clean energy projects developed by Energy Diversification Research Laboratory (CEDRL), Government of Canada. The software has embedded climatic and geographical conditions database of most of the major cities around the world. The software is also integrated with the database of various PV modules (mono-Si, poly-Si, amorphous-Si, and spherical-Si) fabricated by different manufacturers. The characteristic parameters of the PV modules (like optimum efficiency, nominal output temperature, and solar collector area) for various models are integrated in its database.

Solar irradiation on a horizontal surface outside the Earth’s atmosphere \( (H) \) and on the Earth’s surface \( (H_o) \) could be calculated using isotropic model using the following equations:\(^\text{51}\)

\[
H_o = \frac{86,400}{\pi} \times G_{sc} \left\{ 1 + 0.033 \cos \left( \frac{2\pi n}{365} \right) \right\} \left[ \cos \varphi \cos \delta \sin \omega_s + \omega_s \sin \varphi \sin \delta \right] \tag{1}
\]

\[
H = H_o \times K_T \tag{2}
\]

where, \( G_{sc} \) is the solar constant, \( n \) is the day of the year, \( \omega_s \) is the solar hourly angles, \( \varphi \) is the latitude angle of the place, and \( K_T \) is the sky clearness index which varies between 0.3 and 0.8 depending upon the location and time of the year. \( \delta \) is the solar declination angle, calculated using Cooper’s Equation:\(^\text{51}\)

\[
\delta = 23.45 \sin \left( \frac{2\pi}{365} \left( 284 + n \right) \right) \tag{3}
\]

To convert the monthly average solar radiation on the horizontal surface to their plane-of-array equivalent, RETScreen utilizes Klein and Theilacker algorithm\(^\text{52}\) modified for tracking surfaces. The average efficiency \( (\eta_p) \) of the PV module is characterized by average module temperature \( (T_c) \) and can be calculated by:

\[
\eta_p = \eta_r [1 - \beta_p (T_c - T_r)] \tag{4}
\]

where \( \eta_r \) and \( T_r \) are the module reference efficiency and temperature (25°C), respectively, and \( \beta_p \) is the temperature coefficient of the PV module. \( T_c \) is the module temperature evaluated from mean monthly ambient temperature using Evans formula.\(^\text{53}\)

To study the feasibility of the project, various financial indicators were used to evaluate the project over different scenarios. Net Present Value (NPV) indicates the current value of future cash flow generated by a project given by:

\[
\text{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1 + i)^t} - C_o \tag{5}
\]
where, $C_t$ is the net cash flow during the period, $C_0$ is the initial capital investment, $i$ is the discount rate, and $t$ is the number of time periods. Internal rate of return (IRR), another financial indicator, is the discount rate at which the NPV of the project becomes zero and can be obtained using same formula as:

$$\text{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1 + i)^t} - C_0 = 0$$

(6)

IRR shows the attractiveness of a proposed project. If the IRR exceeds the company’s desired rate of return, the project is considered to be feasible. Payback period is the duration of time required to recover the capital investment of the project through the net cash inflows over the period.

### 2.4 Financial assumptions

The total cost of the PV power plant can be subdivided into the total initial cost, annual cost, periodic cost, and the end-of-life cost. Table 2 gives the cost breakdown of both power plants. Although cost estimates for PV power plants are reported in various studies,54–57 the economics of PV are constantly changing. In recent years, the technology associated with the manufacturing of PV cells has undergone major advances, resulting in a significant reduction in production costs. The cost of crystalline-silicon PV modules dropped below 1 $/W mark in 2011 with prices as low as 0.71 $/W reported.58 A study conducted by the US Department of Energy has projected the module prices to fall below 0.5 $/W by 2017.59 The cost of the poly-Si solar PV panel from Canadian Solar (model number CS6X-300P) considered in this study is assumed to be 0.22 $/W based on the current market research. The total initial cost includes the cost incurred for development, PV panels, inverters, mounting system, installation, the balance of system (BoS), and miscellaneous costs. For the tilted-fixed PV system, the total initial investment is estimated to be $60.3 million for Al-Jawf and $129.6 million for Bisha. The total initial cost of a single-axis tracking PV panel system is estimated to be $65.7 million and $141.1 million for Al-Jawf and Bisha, respectively. In addition to the total initial cost, an annual operation and maintenance cost for the plants was included. The life cycle of an inverter was assumed 10 years and the periodic cost of inverter replacement is estimated to be $4.02 million for the Al-Jawf power plant and $8.64 million for the Bisha power plant. Based on a study by the International Energy Agency, the end of life cost of the plants after 25 years was assumed to be 10% of the total initial investment.60

Other assumed parameters for the financial analysis of the power plants are presented in Table 3. The annual increase in the cost of electricity production was considered to be 4% and the annual inflation rate of 2.5% was assumed based on the current economic data of the country. The inflation rate in Saudi Arabia has been varying significantly over the last

| Type of cost     | Al-Jawf (67 MW) | Bisha (144 MW) |
|------------------|----------------|---------------|
|                  | Tilted-fixed $USD (in thousands) | Single axis tracking $USD (in thousands) | Tilted-fixed $USD (in thousands) | Single axis tracking $USD (in thousands) |
| PV panels cost   | 14,740         | 14,740        | 31,680         | 31,680         |
| Inverters        | 4020           | 4020          | 8640           | 8640           |
| Hardware BoS     | 13,400         | 16,750        | 28,800         | 36,000         |
| Soft costs – install labors | 8710           | 9380          | 18,720         | 20,160         |
| Soft costs – others | 19,430        | 20,770        | 41,760         | 44,640         |
| Total initial costs | 60,300        | 65,660        | 129,600        | 141,120        |
| Inverter replacement cost (every 10 years) | 4020           | 4020          | 8640           | 8640           |
| Operation and maintenance (annually) | 1032           | 1240          | 2218           | 2664           |
| Salvage value    | 6030           | 6566          | 12,960         | 14,112         |
TABLE 3  Financial parameters

| Parameter                        | Value |
|----------------------------------|-------|
| Fuel escalation rate             | 4%    |
| Inflation rate                   | 2.5%  |
| Nominal discount rate            | 5%    |
| Project life                     | 25 years |
| Debt ratio                       | 0%    |
| Electricity escalation rate      | 2%    |

few years due to the implementation of new policies and transformation of economy. The data show an inflation rate of 3.2% in 2020, −2.1% in 2019, and 2.5% in 2018.61 The nominal discount rate for the economic study has been assumed to be 5% based on previous studies for the region.62 All the financial figures in the study are presented in US Dollars to which the local currency (Saudi Arabian Riyal) is pegged at the rate of 3.75.63 Another key assumption made is that the Saudi government will fund the entire project and loans will not be required.

2.5  | Emission analysis

Total annual CO₂ emission of both plants are presented in Table 1. The software calculates the reduction of total CO₂ emission when the conventional power plants are replaced with the proposed PV electricity generation system. Emission factors of 0.509 tCO₂/MWh and 0.472 tCO₂/MWh are obtained for Tabarjal and Bisha plants with assumed transmission and distribution losses of 10% for the base case power plants, respectively. A part of the GHG credit has to be paid each year to the crediting agency, which is utilized to help developing countries adapt to climate change. For underdeveloped countries, this tax is levied. However, for Saudi Arabia, it is set at 2% of the gross annual GHG emission.

3  | RESULTS AND DISCUSSION

3.1  | Electricity production

The capacity factor for the tilted-fixed mounted configuration of the proposed power plants at Al-Jawf and Bisha are 21.9% and 25.5%, respectively. The capacity factor is the ratio of the actual power generated to the rated power of the plant. The calculated total annual electricity production of the Al-Jawf power plant is 128.7 GWh, which is 12.0% less than the annual production (146.3 GWh) of the base-case diesel power plant. The calculated annual production of the proposed plant at Bisha is 321.6 GWh, which is 9.0% less than the annual production capacity (353.7 GWh) of the base-case plant. Due to the lower annual solar radiation at Al-Jawf, the specific surface area of the panels required for the plant is 16.4% higher than that required for the plant at Bisha.

Although panels, which can track the sun, can significantly increase the production capacity of a power plant, the mounting and tracking system requires extra investment. Most of the previous studies have considered fixed mounted panels due to the higher capital cost of the tracking system. However, the recent decrease in the cost of the tracking systems has made its application feasible.48 If single-axis tracking panels are used for the Al-Jawf PV plant, the electricity production can be increased to 171.8 GWh, equivalent to 33.5% higher production than the fixed case (Table 4). The effect is even more pronounced for the proposed plant at Bisha (436.7 GWh), resulting in a 35.8% higher production than the fixed case. Installation of a tracking system increases the capacity factor of the plants at Al-Jawf and Bisha to 29.3% and 34.6%, respectively, corresponding to 17.4% and 23.5% surplus annual electricity production compared to the base-case diesel power plants.

3.2  | Financial analysis

NPV is the indicator of a project’s future net cash flow in terms of the current value of the currency.47 An NPV value of zero indicates that the total income of the plant is equal to the total cost of production. The calculated COE production, without
considering the credit from GHG reduction, for the tilted-fixed configuration of the proposed power plant at Al-Jawf, is $3.62/\text{kWh}$, which is about 26.6% lower than that of the base-case diesel power plant ($4.93/\text{kWh}$). The production cost ($3.12/\text{kWh}$) of the PV plant at Bisha is less than that of the Al-Jawf plant. However, it is about 14.7% higher than that of the base-case diesel power plant at Bisha because of the much lower cost of energy production ($2.72/\text{kWh}$) for that plant. However, this study predicts a significant drop in the COE as compared to the average COE of $25/\text{kWh}$ for Saudi Arabia reported in a previous study. The large reduction in the production cost is attributed to the significant reduction of the PV system cost of utility-scale plants in recent years.

Use of a tracking system increases the cost of the PV system by $0.08/\text{W}$, equivalent to a 8.9% increase over that of the fixed system. However, as the installation of a tracking system increases the plant’s production capacity by more than 30%, it can significantly decrease the power production cost, as discussed above. Therefore, when the tracking system is used, the COE at the Al-Jawf plant decreases to $3.01/\text{kWh}$ from $3.62/\text{kWh}$, while that for Bisha plant decreases to $2.51/\text{kWh}$ from $3.12/\text{kWh}$. The percentage decrease in the production costs is 16.8% and 19.5% for Al-Jawf and Bisha plants, respectively.

The above analysis does not take into account the benefits resulting from the reduction of the GHG emissions. As a power plant based on renewable energy significantly reduces CO$_2$ emissions, a credit rate of 16 $/\text{tCO}_2$ is assumed for both cases to account for the monetary benefit of GHG reduction. The resulting value of COE is found to be reduced to $2.07/\text{kWh}$ and $1.77/\text{kWh}$, corresponding to a further reduction of 31.2% and 29.4% for the Tabarjal and Bisha plants, respectively.

Being one of the largest producers of crude oil in the world, Saudi Arabia mainly uses natural gas, heavy fuel oil, and diesel to produce electricity. Due to the availability of conventional fuels at low prices, the cost of electricity production in Saudi Arabia is among one of the lowest in the world. Price of diesel in the Kingdom is reported to be 3.6 $/\text{barrels}$ of oil as compared to the international price of 66.0 $/\text{BBL}$. Thus, the price of diesel in Saudi Arabia is about 94% less than the market value. However, with the recent volatility in the global crude oil market, a high concern is given to reduce the dependence of kingdom’s economy on oil under Saudi Vision 2030. Hence, a scenario where the government would provide a 10% subsidy on the total initial investment to promote renewable energy usage is considered without considering the GHG credit reduction rate benefit. In addition, the EER was assumed to be equal to the COE for the base-case power plants. The financial viability of the two plants, based on a single-axis tracking system, was evaluated and the results are tabulated in Table 5.

The cost of electricity production for Al-Jawf and Bisha plants was calculated to be $2.79/\text{kWh}$ and $2.36/\text{kWh}$, respectively. However, Al-Jawf PV plant gives more attractive financial figures with a simple payback period and an equity payback period of 8.2 and 7.5 years, respectively. The NPV of the project is $64.4 million with annual life cycle savings of $4.5 million and benefit to cost ratio of 1.98. Despite Bisha being the more favorable site for a PV power plant with a capacity factor of 34.6%, the financial viability of the project is lower than the Al-Jawf case. This is because of the lower EER assumed in this case. The simple payback and equity payback periods of the project are around 13.8 and 13.2 years, respectively. NPV of the project is evaluated to be $27.0 million and the benefit to cost ratio of 1.19. The IRR for the Tabarjal plant and Bisha plant is estimated to be 13.2% and 6.8%, respectively. COE production reduces to $1.85/\text{kWh}$ and $1.58/\text{kWh}$ for Al-Jawf and Bisha, respectively, when a GHG reduction credit of 16 $/\text{tCO}_2$ is considered and the financial indicators turns even more attractive.
TABLE 5  Summary of the financial indicators of the proposed PV plants

| Financial indicators               | Al-Jawf | Bisha |
|-----------------------------------|---------|-------|
| Electricity export rate (€/kWh)   | 4.93    | 2.72  |
| COE without GHG credit (€/kWh)    | 2.79    | 2.36  |
| COE with GHG credit (€/kWh)       | 1.85    | 1.58  |
| Grants (% of initial cost)        | 10      | 10    |
| Annual life cycle savings ($/year)| 4,566,441| 1,918,675|
| Net present value ($)             | 64,359,160| 27,041,698|
| Internal rate of return (%)       | 13.2    | 6.8   |
| Simple payback (years)            | 8.2     | 13.8  |
| Equity payback (years)            | 7.5     | 13.2  |
| Benefit to cost ratio             | 1.98    | 1.19  |

FIGURE 4  Monthly averaged electricity production for different cities in Saudi Arabia

### 3.3 Sensitivity analysis

The performance of a 144 MW PV power plant was compared at six locations in Saudi Arabia, to determine the power generation and economic feasibility of such a plant. A power plant based on the single-axis tracking configuration is used in this comparison, as the production cost of the single-axis tracking configuration is considerably less than that of the tilted-fixed configuration. Figure 4 shows the monthly averaged electricity production of the proposed power plant in six cities of Saudi Arabia. The maximum power production is predicted to be between May to August for all the cities except for Bisha, maximum production for which is in the month of October. This is due to the fact that Bisha is the closest to the equator (20° latitude), and thus, receives the maximum daily average solar radiation on the surface when titled to the angle equal to the corresponding latitude, in the month of October. Figure 2 shows that Bisha has a more uniform distribution of average monthly solar radiation on a horizontal surface as compared to the other cities. Moreover, the average annual ambient temperature of Bisha is the second lowest among all the cities, which directly affects the efficiency of the panels. Bisha also has the highest electricity production capacity, with the annual average of 436 GWh, followed by Medina, Al-Jawf, Jeddah, Riyadh, and Dhahran with an annual production of 391, 369, 352, 348, and 338 GWh, respectively (Figure 5). The production capacity at Bisha is 11.5% higher than the next best location and 29.0% higher than the lowest. An average annual reduction of 462 tCO₂/GWh is predicted if a diesel power plant is replaced with a power generation system based on renewable energy.

The COE production in the six cities is presented in Figure 6. The calculated average cost of electricity production is 2.22 €/kWh. Due to the significant drop in the cost of PV systems, the average COE production is 91% lower than that estimated in a previous study. Bisha has the lowest production cost of 1.77 €/kWh, while Dhahran is the most expensive location (2.51 €/kWh) for a PV system, with the COE production about 41.8% higher than that at Bisha.
A project becomes economically viable when the IRR becomes greater than the discount rate. Generally, investors set a targeted IRR higher than the discount rate, and any value greater than the targeted IRR is considered favorable. In the first scenario, the effect of the government subsidy on the total initial investment of the project and the equity payback period is evaluated and the results are shown in Figures 7 and 8. In this evaluation the assumed EER, the EEER, and the credit for GHG emission reduction were set at 2 €/kWh, 2%, and 16 $/tCO₂, respectively (Figure 7). Bisha is the most favorable city for the installation of a PV-based power plant with an IRR ranging from 6.1% to 8.3% as the subsidy is increased from 5% to 20%. The equity payback period is as low as 11.7 years if the government gives a subsidy of 20% on the total initial cost of the renewable energy project. Dhahran is the least favorable, with the project being financially viable only if the government provides a subsidy of 25% or more.

FIT is a policy mechanism under which the government pay a price, usually higher than the conventional cost, to the producer who supply renewable electricity to the grid, in order to make the renewable technologies more attractive and
encourage its production. In the second scenario the effect of the FIT, when increased from 2 to 4 ¢/kWh, on the IRR and equity payback period is evaluated and the results are shown in Figures 9 and 10, respectively. The same values of EER, EEER, and GHG emission reduction as in the first scenario were used, while the government subsidy was set at zero. For Bisha, any value of FIT above 2.0 ¢/kWh is feasible. While, the minimum FIT required for the project to be economically viable for all the other cities is 2.5 ¢/kWh. The equity payback period can be as low as 7.1 years (for Bisha) at a FIT of 4 ¢/kWh and as high as 18.9 years (for Dhahran) at a FIT of 2 ¢/kWh.

EEER is the projected average annual rate of increase of the EER. As the economy of Saudi Arabia is largely dependent on crude oil exports, the recent fluctuations in the oil prices are expected to affect the future budgets. Subsidies on
petroleum products for domestic use have decreased significantly and is projected to follow the trend, which has and will eventually increase the electricity production cost. Thus, in a third scenario, the effect of the increase of EEER on the economic aspects of the project was evaluated. The effects of EEER on IRR and equity payback period at an EEER of 2 ¢/kWh and GHG emission reduction benefit of 16 $/tCO₂ are shown in Figures 11 and 12, respectively. Power plants at all locations except Bisha are not economically viable at an EEER of 2%. The power plants are favorable for any city if the projected EEER is 4% or more. Again, the best location for a PV power plant is Bisha with the maximum predicted IRR and the lowest equity payback period of 10.1% and 11.4 years at an EEER of 6%, respectively.

In the last scenario the effect of the FIT was evaluated for three cases; (a) no subsidy, (b) 10% subsidy on the initial investment, and (c) 20% subsidy on the initial investment. Figures 13 and 14 present the financial indicators for consideration at Bisha plant.
FIGURE 14  Variation of IRR and equity payback period with feed-in tariff for different scenarios of subsidies consideration at Dhahran plant

the best location (Bisha) and the worst location (Dhahran), respectively. An increase of 100% in the FIT from 2¢/kWh to 4¢/kWh increases the IRR to 14.0% from 6.1% for Bisha, and to 9.9% and from 3% for Dhahran, without a subsidy. The value increases to 15.5% from 7.1% for Bisha and to 11.2% from 3.9% for Dhahran, for a 10% subsidy. The IRR increases by 3.5% for Bisha and 2.8% for Dhahran when the subsidy is increased from 0% to 20%, at a FIT of 4¢/kWh. Equity payback period is as low as 5.9 years (for Bisha) and as high as 7.8 years (for Dhahran) at a FIT of 4¢/kWh and a 20% subsidy.

4  |  CONCLUSIONS

A detailed feasibility and policy study of two PV power plants to replace two existing diesel power plants was conducted. The selected base-case power plants are the 67 MW and 144 MW diesel operated power plants located at Tabarjal (Al-Jawf) and Bisha, respectively. The study aims at evaluating the PV project feasibility while replacing the conventional diesel plants in the country. The proposed plants at Al-Jawf and Bisha with a tilted-fixed panel configuration are predicted to produce 128.7 GWh and 321.6 GWh of electricity annually, respectively. The production capacity increases by 33.5% for Al-Jawf and 35.8% for Bisha for the single-axis tracking configuration. The proposed PV power plants, with single axis tracking configuration at Al-Jawf and Bisha, are able to generate 29.3% and 34.6% of their rated power, respectively. This is 17.1% and 23.5% higher than the total annual power production of the base-case power plants at Al-Jawf and Bisha, respectively.

The COE production for the power plants of fixed-tilted configuration at Al-Jawf and Bisha is 3.62¢/kWh and 3.12¢/kWh, respectively. Although the single-axis tracking configuration increases the initial investment by 8.9%, the production cost comes down by around 20% as a result of the increased production capacity. Considering the monetary penalties equivalent to 16 $/tCO2 due to GHG emissions, the COE production of a PV power plant of the single-axis tracking configuration at Al-Jawf and Bisha is 2.07 and 1.77¢/kWh, respectively.

An analysis was performed assuming that the Saudi government provides a 10% subsidy on the total initial investment. Results show that the proposed PV power plant at Al-Jawf is very attractive, with an estimated IRR of 13.2%, equity payback period of 7.5 years, and benefit to cost ratio of 1.98. Although the proposed plant at Bisha can still make a profit, the financial indicators are not that favorable, mainly because of the lower EER considered for the plant. The calculated IRR, equity payback period, and benefit to cost ratio for the Bisha plant are 6.8%, 13.2 years, and 1.19.

Finally, a sensitivity analysis of a 144 MW PV plant located at six cities in the Kingdom was also performed. The calculated average COE production for the six locations is 2.22¢/kWh, which is around 91% lower than the previously reported study. Results indicate that the sharp drop in the cost of PV systems in the recent years has significantly reduced the electricity production cost, enabling solar energy production being competitive to the diesel power plants in the Kingdom even without any incentives. Global efforts in general and the country’s aim, in particular for reducing the share of fossil fuels, necessitate the policy makers to have clearer picture of the updated trend. The technical and financial indicators of the PV panel-based power generation system, presented in this study, indicate the viability of a solar project in the dry hot climatic condition of Saudi Arabia.
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CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

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