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Feasibility of Using Solar Photovoltaics to Decarbonize the Natural Gas Compressor Station Along the East–West Pipeline in Saudi Arabia

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ABSTRACT

This study evaluated the techno-economic and environmental feasibility of integrating a grid-connected solar photovoltaic (PV) system to decarbonize natural gas compressor stations along the East–West pipeline of Saudi Arabia. The objective of this study was to assess whether solar PV can reliably offset the annual electricity demand of 23,520 MWh while maintaining economic viability. Simulations were conducted using the System Advisor Model (SAM) software for two representative locations, namely Abqaiq and Al-Duwadimi, under fixed-tilt and single-axis tracking configurations. All systems were sized to meet and slightly exceed the required demand over a 25-year lifetime while exporting excess energy to the grid. Single-axis tracking delivered a similar year-1 alternating current (AC) energy with a smaller direct current (DC) array. Under an equal PV module capacity, it produced a higher annual AC output than fixed-tilt systems. Seasonal variability led to higher grid-imported energy during low-irradiance periods, whereas a 0.5%/year DC degradation caused a gradual decline in PV generation over time. Financial analysis under a net-zero billing framework illustrated a reduction of ~50% in payback time compared to conventional billing, with significant first-year savings of $ 1.78–1.83 M and additional export revenues of $ 0.33–0.36 M. The calculated levelized cost of energy ranged from 2.94–3.62 (¢/kWh), with the Abqaiq single-axis scenario offering superior performance. Environmentally, displacing grid electricity with solar PV mitigates 670,729–688,292 tons of CO_2 emissions over the entire project lifecycle, whereas the lifetime PV emissions represent only 1–1.5% of the avoided grid emissions, confirming a substantial net environmental benefit.

Keywords: decarbonization, net-zero billing, solar PV, fixed-tilt, single-axis tracking, photovoltaic

1. INTRODUCTION

In Saudi Arabia, which is ranked among the world's leading producers of oil and gas, compressor stations support gas transport and maintain stable flow and pressure. To meet demand, the East–West pipeline, the longest and highest-capacity pipeline in Saudi Arabia, transports large volumes of gas, requiring multiple compressor stations along its route to ensure efficient gas transport.

Combusted natural gas is the primary energy source for compressor station operation, rendering it a major source of operational and carbon emissions[1]. Continuing these practices will further increase greenhouse gas (GHG) emissions, which is inconsistent with the objectives of Saudi Vision 2030 and the Saudi Green Initiative[2,3]. Specifically, these initiatives aim to transform the energy landscape, lower greenhouse gas emissions, and expand renewable energy capacity[2–4]. Aligned with such national strategies, industries operating within Saudi Arabia are increasingly expected to adopt sustainability-driven practices that contribute to national emission reduction objectives.

In this region, natural gas compression stations are major CO_2 emitters due to the substantial amount of natural gas combusted during operation[1]. To implement Saudi Vision 2030, it is essential to evaluate the feasibility of replacing conventional combustion practices with sustainable alternatives capable of reducing CO_2 emissions and overall GHG levels. A typical gas compressor consumes large amounts of energy and emits significant quantities of CO_2 annually, rendering it a suitable candidate for decarbonization.

1.1. Literature Review.

Combusted natural gas is not the sole means of powering compression stations, with alternative technologies also being available. For instance, the Dahshour Compression Station in Egypt uses gas turbines powered by electricity generated from burning natural gas. To improve efficiency and reduce emissions, exhaust gases from a gas turbine are used to generate additional electricity through an Organic Rankine Cycle (ORC) system. This technique leads to improved thermal efficiency and lowers the amount of natural gas burned per kWh of work output, producing additional energy to power the compressors installed during station expansion. Therefore, the ORC reduces operational emissions and increases savings by improving the overall system efficiency (Table S1, in the Supplementary Information (SI) file)[5].

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According to numerous studies, Saudi Arabia exhibits high solar potential (estimated at 4–6 kWh/m^2/day), resulting in high energy output, with a specific yield of 1.42 kWh/yr per watt and a capacity factor of 16.3%. Such solar energy deployment could enable a reduction of up to 93% in GHG emissions compared with the local electricity grid[6].

Additionally, a case study was conducted at the Haradh Gas Plant (HdGP) Department of Saudi Arabia regarding the implementation of an Energy Management System (ISO 50001 [7]) to identify significant energy users and opportunities for improving energy performance. This implementation helped HdGP achieve a 4.4% reduction in overall energy consumption and energy intensity, in addition to energy cost savings of $845,459, and a reduction of 49,000 metric tons of CO_2 emissions over 2 years, while maintaining the same production levels.

Furthermore, a feasibility analysis conducted in South Africa using RETScreen software revealed that a 75.0 MW solar PV plant, situated in a region with abundant solar resources and nearby thermal power infrastructure, is both technically and economically viable, as shown in Table S2, reducing annual GHG emissions by 117,987.0 tCO_2 [8].

Further studies have demonstrated that rooftop solar and nature-based solutions can contribute to energy independence and reduce urban carbon emissions[9]. At the household level in Northern Ireland, solar PV has been shown to reduce electricity costs by 26–43% in certain contexts, lowering the risk of fuel poverty and further decreasing emissions when paired with energy-efficiency measures[10]. Moreover, a grid-connected rooftop PV system in Najran City generated an annual output of 14,791 kWh, closely matching the electricity demand of the <?pag ?>property<?pag ?> (i.e., 19,952 kWh), and accounting for ~75% of the annual energy consumption[11].

Nevertheless, these benefits are highly country-specific and depend on both rooftop location and electricity consumption patterns. The successful implementation of solar PV in Northern Ireland, despite its low solar irradiance, frequent cloud cover, and wet climate, further demonstrates the viability of the technology. In Saudi Arabia, where fossil fuels are domestically abundant, adopting solar PV systems may not lead to immediate cost savings or substantial gains in energy independence owing to high cooling demand, with annual electricity consumption reaching 33,576 kWh in 2023 due to seasonal heating, ventilation, and air conditioning loads[11]. However, such systems are essential for reducing CO_2 emissions and supporting long-term energy diversification.

These studies highlight the potential of solar PV in regions with high solar irradiance, such as Saudi Arabia. Integrating solar PVs as an alternative to natural gas could therefore significantly reduce CO_2 emissions and increase fuel savings. As shown in Figure S1, the PV power potential across Saudi Arabia is high in the central and western regions, with practical PV outputs ranging from ~4.5 to 5.9 kWh/kWp[12].

As shown in Figure 1, a reduction of >50% in solar PV prices over the last decade has rendered such systems a cost-effective and practical choice for power generation. This reduction in solar PV prices can be attributed to the use of lower-cost raw materials and manufacturing, larger-scale production, and improved efficiency driven by research and development. These lower costs, accompanied by an increase in panel efficiency, have enabled solar PV systems to achieve electricity prices comparable to or

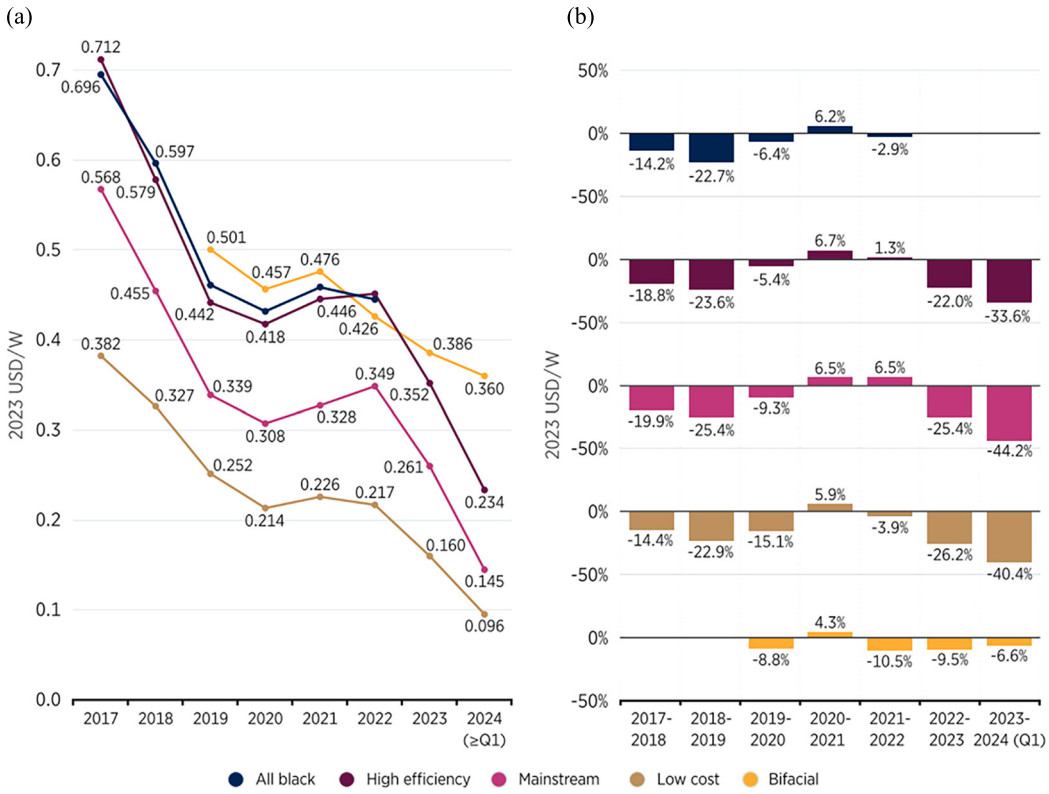


Figure 1. Average yearly solar PV module costs according to European technology: (a) average costs and (b) percentage increases relative to the previous year[13]

lower than those of conventional grids, thereby significantly facilitating their deployment.

The module categories, in Figure 1, include all-black, high-efficiency, mainstream, low-cost, and bifacial photovoltaic modules, representing different commercial products existing in the European PV market.

Various industries, governments, and companies are adopting solar energy not only because it reduces costs but also because it significantly lowers carbon and operational emissions while supporting national sustainability and decarbonization goals. Thus, in the current study, a grid-connected solar PV system is evaluated for full and partial offset of the annual electricity demand of a representative compressor station.

1.1.1. Research gap and study objectives. Based on the studies reviewed above, although earlier studies considered the techno-economic performance of grid-connected solar PV systems, they tended to focus on commercial, residential, or general industrial applications. A clear research gap therefore exists regarding the decarbonization of natural gas compressor stations along large-scale pipeline infrastructures, such as the East–West pipeline of Saudi Arabia. Similarly, few studies have systematically compared fixed-tile and single-axis tracking systems under comparable capacity conditions, while accounting for long-term degradation and a net-zero billing framework, particularly in the KSA.

Accordingly, the aim of this study is to address these gaps through a comprehensive techno-economic and environmental assessment of solar PV integration for compressor stations along the East–West pipeline. The study objectives include comparing tracking configurations with identical and differing capacities, evaluating lifecycle CO_2 emissions, and assessing financial performance under Saudi tariff structures.

2. METHODOLOGY

In the present study, System Advisor Model (SAM) software (version 2025.04.16)[14] was employed to simulate grid-connected solar PV integration. Moreover, to assess the technical and economic feasibility of decarbonizing operations at natural gas compressor stations along the East–West pipeline in Saudi Arabia, simulations were conducted at two locations, namely Abqaiq, where the pipeline starts, and Al-Duwadimi, where the pipeline passes through in the middle of its route.

2.1. Solar PV System. The solar PV system was sized to meet an annual electricity demand of 23,520 MWh/y, as identified from a feasibility study conducted in a natural gas compressor station for 8400 operating hours per year[5] (see Table S3). The system was intentionally oversized to ensure that the total exports to the grid exceed imports, enabling evaluation of the net-zero billing condition. A grid-connected PV configuration was designed to operate the compressor station using the energy generated during the daytime, allowing excess energy to be exported to the grid, as shown in Figure 2. At night, or when the solar output does not meet the demand, the system relies on the grid to cover the deficit.

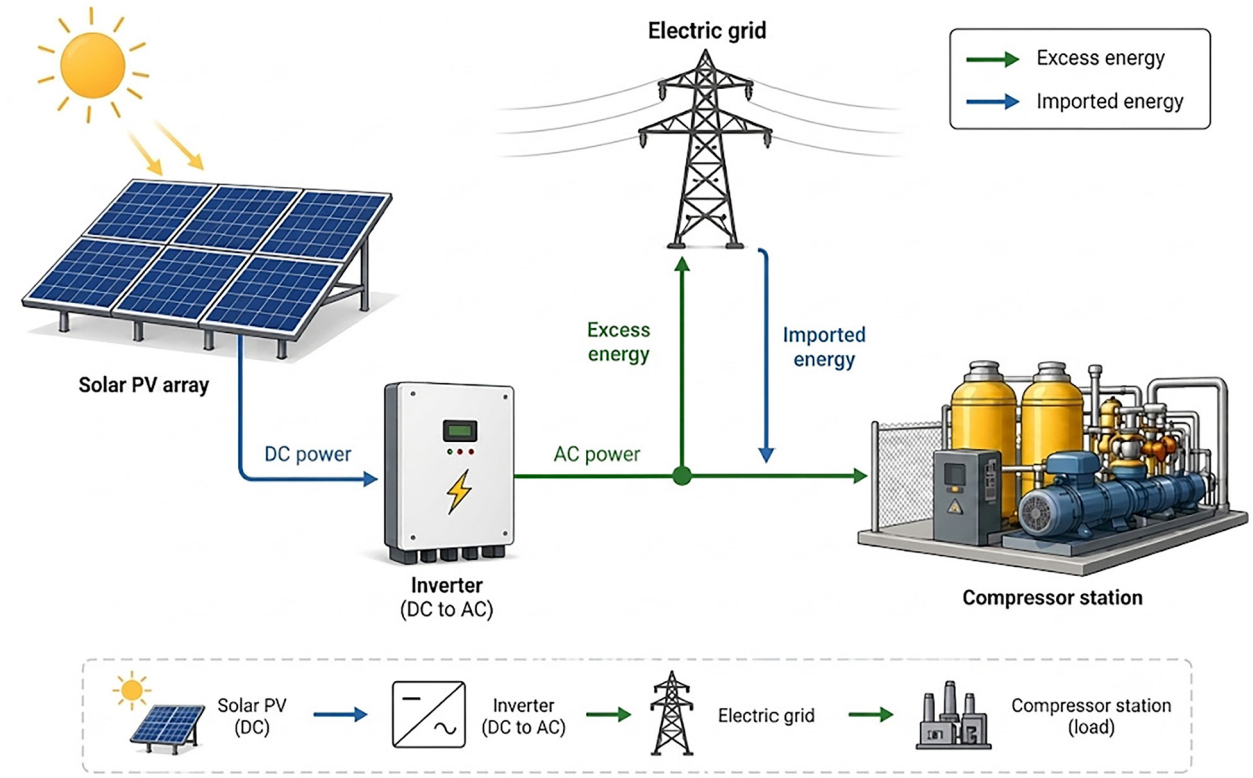


Figure 2. Schematic diagram showing electricity production by a solar PV system

Table 1. *Technical parameters used during PV design*

Description	Value	Units
PV module	Philadelphia Solar PS-M156(HC)-600W	
Maximum power (P_{PM})	600.896	W
Current at maximum power (I_{PM})	13.1	A
Voltage at maximum power (V_{PM})	45.8	V
Short circuit current (I_{SC})	13.8	A
Open circuit voltage (V_{OC})	55.2	V
Maximum system voltage	1300	V
Module efficiency	21.69	%
Single panel area	2.770	m^2
Number of cell modules (N)	78	
Degradation rate	0.5	%
Tracking (axis)	Fixed and single-axis	
Inverter model	Sungrow Power Supply Co., Ltd. SG250HX-US [800V]	
Inverter efficiency	98	%
Power converter	AC-connected	

2.1.1. Matching the minimum monthly load . The system was also sized to ensure that the solar PV produced at least the minimum monthly electricity demand of the compressor station, as detailed in Table S4. This reduces the risk of seasonal variation in solar resources and ensures that an annual electricity demand of 23,520 MWh/y is met for 350 days per year.

2.2. PV Model. In this modeling study, the solar PV module employed at both locations consisted of a monocrystalline silicon module rated at 600 W (Philadelphia Solar, Amman, Jordan; Model: PS-M156(HC)-600W)[15]. The PV model was combined with an inverter for DC-to-AC power conversion, as detailed in Table 1. The number of panels and their total area were determined using Eqs. (1) and (2).

$$Total\ Modules = Modules\ per\ String \times Strings\ in\ Parallel \quad (1)$$

$$Total\ Area\ (m^2) = Number\ of\ Modules \times Module\ Area\ (m^2) \quad (2)$$

2.3. Tracking and Orientation. The current model incorporates a fixed configuration and a single-axis tracking system at both locations to assess the enhancement of energy output. The subarray, which is illustrated in Figures 3a and 3b, remains stationary with a fixed tilt and does not track the sun. In contrast, the single-axis system rotates during the day to follow the sun's movement, thereby enhancing energy production[14,16]. Although fixed-tilt systems yield lower outputs than other tracking configurations, they are more cost-effective and easier to implement[17]. The inclination angle of the PV panels was varied to determine the optimum tilt of each location, which was approximately equal to the latitude, as detailed in Table 2.

(a) PV array facing south in the fixed configuration *(b) Single-axis tracking PV array with the axis-oriented south*

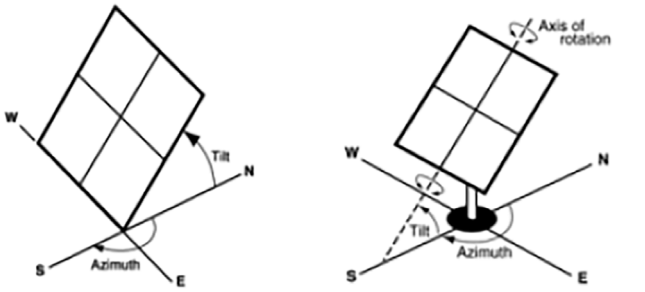


Figure 3. Solar PVs in the (a) fixed configuration and (b) with single-axis tracking[14]

2.4. Environmental Analysis. The advantages of implementing a solar PV system over an extended period can be computed through a detailed environmental impact evaluation[18]. One of the main objectives of this study was to evaluate the changes in GHG emissions caused by the applied system and assess its contribution to decarbonization. The emission factor for electricity generation was 972 gCO_2eq/kWh[19] and the PV lifecycle GHG emissions were taken as 35.4 gCO_2eq/kWh[16], as reported for Saudi Arabia.

2.5. Financial Metrics. The primary aim of the economic assessment was to demonstrate the cost-effectiveness of the intended solar PV systems for decarbonizing gas compressor stations along the East–West pipeline. Moreover, the proposed system balances energy consumption with billing restrictions by assuming a net-zero billing condition for grid-connected solar PV. This involves equating the financial value of the excess electricity exported to the grid with the value of electricity imported

Table 2. *Optimum tilt angles based on location*

Location	Latitude	Optimum Tilt	
		Fixed	Single axis
Abqaiq	21.29	23.6	18.2
Al-Duwadimi	24.69	27.6	23.6

Table 3. *System sizing and outputs from the Abqaiq and Al-Duwadimi scenarios with fixed and single-axis tracking*

	Abqaiq		Al-Duwadimi	
Tracking	Fixed	Single axis	Fixed	Single axis
Desired array size (kWdc)	14500	12000	14900	12700
Annual AC energy for year 1 (kWh)	30,692,256	30,583,592	30,473,066	30,102,128
Number of modules	24,127	19,964	24,794	21,137
Total module area (m^2)	66,831.79	55,300.280	68,679.380	58,549.490

from the grid, resulting in a zero annual electricity bill, with some revenue from selling excess energy to the grid. The total installed solar PV cost (CAPEX) in the KSA is 794 USD/kW, and the fixed operating cost (OPEX) is USD 9.2/kW/yr[13]. Additionally, electricity consumption was assumed to be 18 Halalah/kWh, based on the Saudi heavy consumption tariff structure[20].

2.6. Levelized Cost of Energy. The levelized cost of energy (LCOE) estimates the cost of a project's lifetime per unit of energy ($/kWh)[16], representing a powerful metric for comparing the power production expenditure efficiencies of different systems[21]. The LCOE can be calculated according to Eq. (3):

$$LCOE = \frac{FCR \times TCC + FOC}{AEP} + VOC \tag{3}$$

where *FCR* is the fixed charge rate, *TCC* is the installed capital cost in $, *FOC* is the fixed annual operating cost in $, *AEP* is the annual electricity production in kWh, and *VOC* is the variable operating cost in $/kWh. A discounted cash flow approach was adopted for the SAM LCOE calculations, assuming a 25-year project lifetime and a 2.5% annual inflation rate. The financing structure assumed a 13% nominal internal rate of return (IRR) per year, with 60% of the capital cost financed at 7% annual interest[16].

2.7. Payback Time. The payback is the period required for a project to cover its original implementation costs[22], while accounting for electricity generation benefits, together with installation and operating costs, incentives, and income tax. The simple payback time under net-zero billing conditions can be calculated according to Eq. (4) using the annual cost savings, as defined in Eq. (5):

$$\text{Simple Payback Time} = \frac{CAPEX}{(\text{Annual Cost Savings} - \text{Annual OPEX})} \tag{4}$$

$$\text{Annual Cost Savings } (net - zero) = (E_{PV\ used} + E_{excess}) \times 0.048 \left(\frac{USD}{Kwh}\right) \tag{5}$$

Additionally, a scenario excluding the net-zero billing framework was considered in the payback time analysis to observe changes over the period and assess the financial feasibility of the system using the annual cost savings, as defined in Eq. (6):

$$\text{Annual Cost Savings} = (E_{PV\ used}) \times (P_{buying}) + (E_{excess} \times P_{selling}) \tag{6}$$

where $E_{PV\ used}$ represents the PV electricity directly consumed by the system in kWh, P_{buying} denotes the price of electricity purchased from the grid (18 Halalah/kWh, equivalent to 0.048 USD/kWh), and $P_{selling}$ denotes the price of electricity sold to the grid (assumed to be 7 Halalah/kWh, equivalent to 0.0186 USD/kWh).

3. RESULTS AND DISCUSSION

3.1. Solar PV System. All four scenarios—Abqaiq and Al-Duwadimi, each with fixed-tilt and single-axis tracking—were designed to have a comparable initial AC energy production range in the first year, i.e., ~30,000,000 kWh. Table 3 lists the

Table 4. *System sizing with equal capacities and for fixed-tilt and since-axis tracking at both locations*

	Abqaiq		Al-Duwadimi	
Tracking	Fixed	Single axis	Fixed	Single axis
Desired array size (kWdc)	14500		14900	
Annual AC energy of year 1 (kWh)	30,692,256	36,931,884	30,473,066	35,303,928
Number of Modules	24,127		24,794	
Total module area (m^2)	66,831.79		68,679.380	

Table 5. *Abqaiq payback period incorporating annual avoided cost*

Tracking	Item	Conventional billing	Net-zero billing
Fixed-tilt	Annual avoided cost (USD)	876,079.7	1,488,168
	Payback time (yr)	15.50	8.50
Single axis	Annual avoided cost (USD)	886,800.7	1,482,890.6
	Payback time (yr)	12.27	6.94

Table 6. *Al-Duwadimi payback period incorporating annual avoided cost*

Tracking	Item	Conventional billing	Net-zero billing
Fixed-tilt	Annual avoided cost (USD)	868,826.9	1,477,545
	Payback time (yr)	16.17	8.83
Single axis	Annual avoided cost (USD)	874,039.1	1,459,552.2
	Payback time (yr)	13.32	7.51

desired array size, annual AC energy for year 1, number of modules, and total module area for each scenario.

Single-axis tracking at both locations resulted in year-1 AC energies similar to those of the fixed-tilt scenarios but required a smaller DC array size. Consequently, single-axis tracking reduces the number of PV modules and the total panel area compared with the fixed-tilt configuration. Additionally, the Abqaiq configurations achieved higher energy yields with fewer solar panels than the Al-Duwadimi configurations.

3.1.1. Optimization of the tilt angle. It was observed that different tilt angles affected solar PV energy production. For each of the four systems, depending on location, latitude, and whether fixed-tilt or single-axis tracking was employed, a unique optimal tilt was identified that resulted in the highest annual AC output, as shown in Figure 4. The optimal tilt angles for Abqaiq and Al-Duwadimi under fixed-tilt and single-axis tracking configurations are listed in Table 2.

3.2. Monthly Production of the Solar PV During Year 1.

To verify that the monthly minimum load of the gas compressor station was satisfied, the variation in monthly electricity production was evaluated during the first year, as shown in Figures 5a and 5b, highlighting the seasonal fluctuations and variations in solar irradiance and day length.

As shown in the figure, single-axis tracking does not outperform the fixed-tilt system every month; instead, its advantages are evident only in certain months. Additionally, in most months, the energy output at Abqaiq was higher than that of Al-Duwadimi. Furthermore, during the lower-generation months, grid imports are expected to increase to meet demand.

3.3. Electricity Export to the Grid.

Economic performance can be improved by selling excess energy to the grid, thereby offsetting initial investment costs. The total energy exported to the grid over the system lifetime was 482.36 and 466.5 GWh for the Abqaiq cases, and 475.6 and 455 GWh for the Al-Duwadimi cases, considering fixed-tilt and single-axis configurations, respectively. Fixed-tilt cases therefore result in higher excess energy generation, while Abqaiq generally exports more energy than Al-Duwadimi under both configurations.

3.4. Degradation Effect.

A 0.5% DC degradation rate was applied to the system to account for the increasing electricity demand of the compressor station over time and to model the annual decline in PV output over the project lifetime. Figure 6 shows the effect of degradation on electricity generation for the four scenarios in Abqaiq and Al-Duwadimi, each with fixed-tilt and single-axis tracking. It was observed that the PV-generated energy decreased gradually in accordance with the degradation rate. Additionally, throughout the project lifetime, Abqaiq consistently achieved higher net electricity generation than Al-Duwadimi, reflecting its superior solar resource availability.

3.5. Effectiveness of Single-Axis Tracking vs the Fixed-Tilt Configuration.

Upon sizing the systems at each location with equal DC capacities (see Table 4), the single-axis tracking scenarios for both locations demonstrated higher AC energy production than the fixed-tilt scenarios. This confirms the superior energy-generation capability and improved efficiency of single-axis tracking under the same installed PV capacity. Since the PV module count was identical in both cases, the additional energy can be attributed to improved irradiance capture throughout the day, while the degradation remains the same for equal DC capacities.

The net electricity generation of the four cases over the project lifetime is shown in Figure 7, illustrating a gradual decline in annual net electricity generation from year 1 to year 25 due to the applied 0.5%/yr PV degradation rate.

Abqaiq consistently maintained a higher output than Al-Duwadimi over time, as illustrated in Figure 7, indicating stronger solar resource availability. Output from the single-axis tracking cases remains higher than that of the corresponding fixed-tilt cases, confirming that the tracking benefits persist despite gradual module performance degradation. Overall, degradation leads to reduced annual output over time but does not alter the relative ranking of locations and configurations, implying increased grid reliance and reduced surplus energy exports as the system ages.

3.6. Financial Analysis.

As stated above, the solar PV systems were sized to deliver similar outputs for all four scenarios, as listed in Table S9. Due to the implementation of the net-zero billing framework, the annual cost savings in the first year

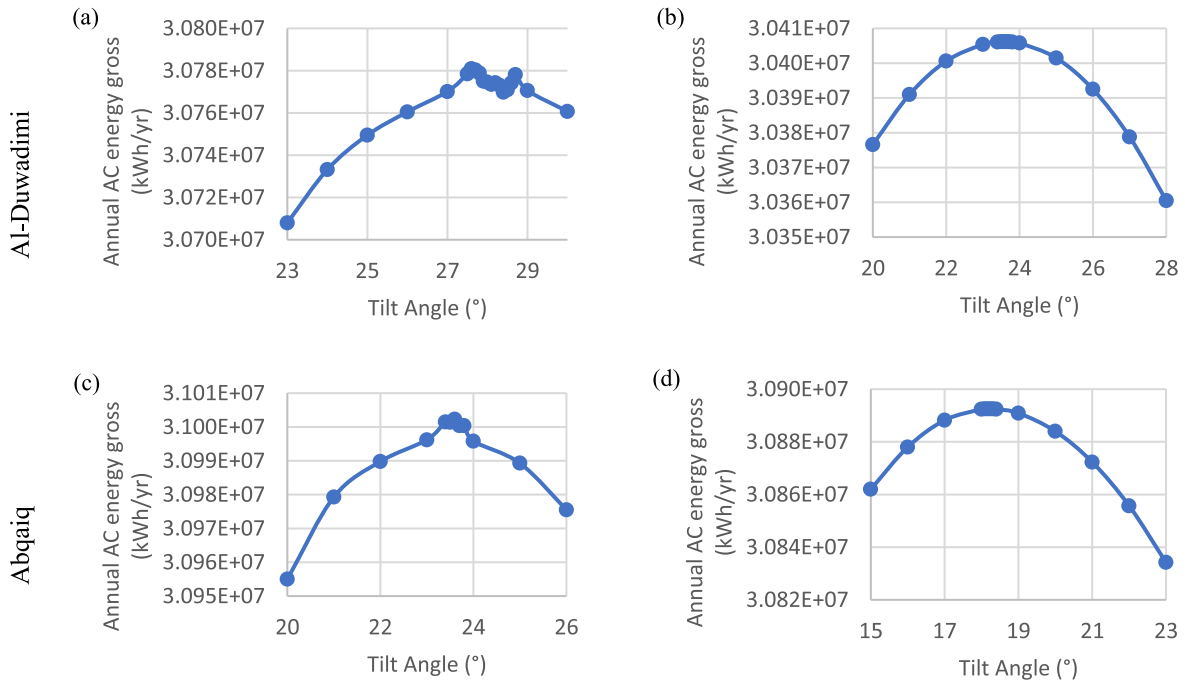


Figure 4. Optimal tilts for the various scenarios based on annual AC energy variations with the tilt angle: (a) Al-Duwadimi under a fixed-tilt configuration, (b) Al-Duwadimi with single-axis tracking, (c) Abqaiq under a fixed-tilt configuration, and (d) Abqaiq with single-axis tracking

(i.e., $1.78–1.83 million), reflect strong potential for operational cost reduction. Furthermore, the additional revenue generated in year 1 by exporting excess electricity to the grid is $0.33–0.36 million, which can help reduce the payback period and improve economic feasibility, thereby contributing to achieving net-zero billing conditions.

Additionally, the LCOE was determined to be 3.62 and 3.03 ¢/kWh for Al-Duwadimi and 3.51 and 2.94 ¢/kWh for Abqaiq, considering fixed-tilt and single-axis cases, respectively. Compared with the Al-Duwadimi scenario, Abqaiq yielded a higher energy output at a lower LCOE for both configurations. This confirms that Abqaiq offers a slightly superior techno-economic performance and suggests greater solar PV resource availability. Abqaiq single-axis tracking is the most economically favorable scenario, whereas the Al-Duwadimi fixed-tilt configuration is the least favorable.

3.6.1. Payback time. In this study, incorporation of the net-zero billing condition resulted in a substantial reduction in payback time, with a ~50% decrease compared to the scenario without net-zero billing (see Tables 5 and 6). The net-zero payback time for the Abqaiq location is lower than that of Al-Duwadimi due to the lower degradation effect and enhanced electricity production in Abqaiq.

3.7. Environmental Analysis.

3.7.1. Avoided CO_2 emissions. A representative compressor station in a grid-connected solar PV system was analyzed under both full and partial offsets of the annual electricity demand. By replacing the grid with a solar PV system, the project avoids significant carbon emissions, with total lifetime avoided emissions of 688,291.7 tons of CO_2 for the Abqaiq fixed-tilt case and 684,432 tons of CO_2 for the Abqiad single-axis tracking case over 25 years. Additionally, the total lifetime avoided carbon emissions for the fixed-tilt system of Al-Duwadimi were 680,009.3 tons of CO_2, and 670,729.3 tons of CO_2 for the single-axis system. Figure 8 presents the annual avoided CO_2 over the project lifetime for the four scenarios.

Figure 8 also revealed that the avoided CO_2 emissions decline over the project lifetime due to annual PV module degradation and a corresponding reduction in solar PV efficiency, which gradually increases the system's reliance on the grid.

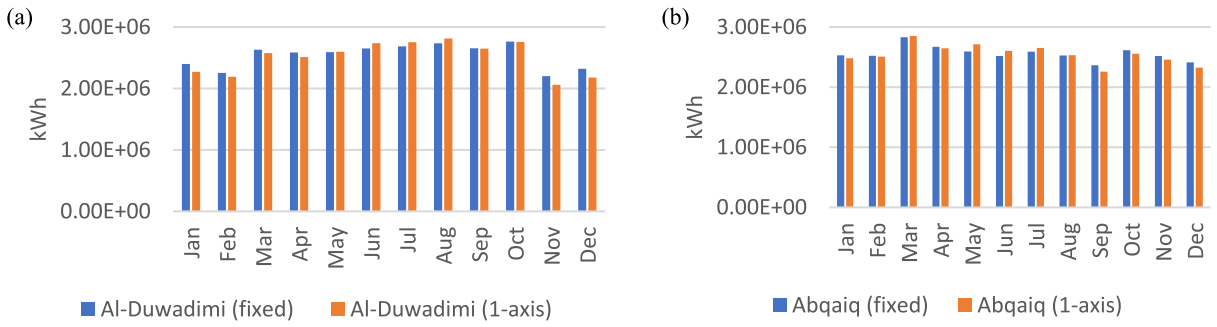


Figure 5. Monthly AC energy during the first year for (a) Al-Duwadimi and (b) Abqaiq, comparing the fixed-tilt and single-axis tracking configurations

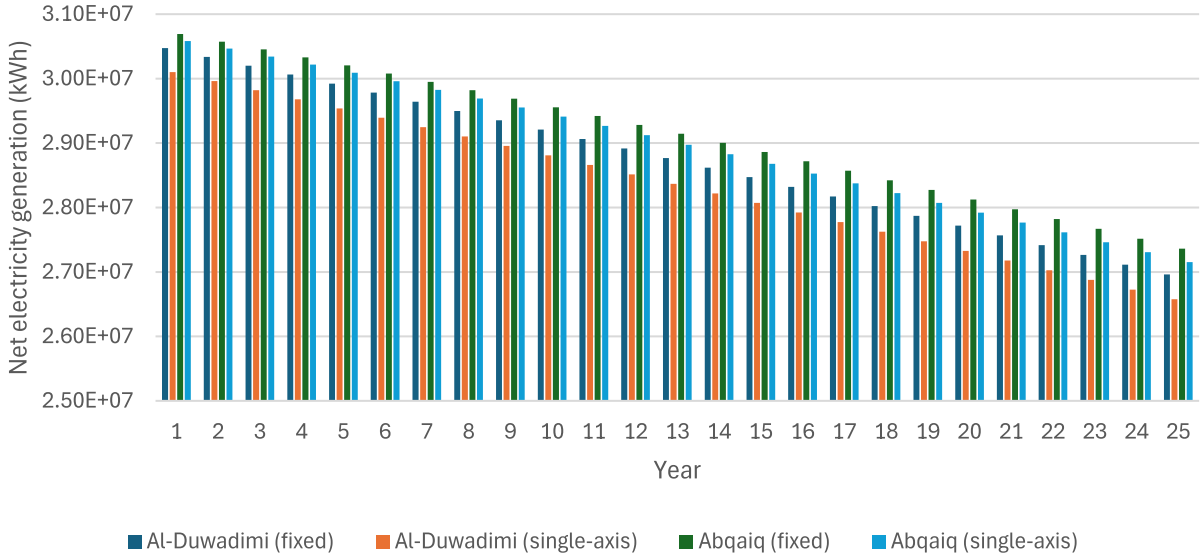


Figure 6. Degradation in electricity net generation by year for the Al-Duwadimi and Abqaiq systems, with fixed-tilt and single-axis tracking

3.7.2. Solar PV CO_2 emissions. Additionally, solar panel lifecycle emissions were evaluated over the project lifetime. Although PV systems produce negligible direct operational CO_2 emissions when generating electricity from solar irradiation, indirect lifecycle emissions from manufacturing, installation, and end-of-life processes are allocated per unit of electricity generated. Specifically, the PV panels have total lifecycle carbon emissions of 8,939.3 tons of CO_2 for the Abqaiq fixed-tilt case and 9,355.509 tons of CO_2 for the Abqaiq single-axis tracking case over 25 years. For Al-Duwadimi, the total lifetime carbon emissions were 8,865.2 tons of CO_2 for the fixed-tilt system and 9,244.5 tons of CO_2 for the single-axis system. In contrast, the avoided CO_2 emissions from replacing grid electricity (670,729–688,292 tons of CO_2) are substantially higher than the PV system emissions, which account for only 1–1.5% of the avoided emissions. This confirms the environmental advantages of solar PVs over grid electricity.

3.7.3. CO_2 emissions from grid electricity imports. Despite the above benefits, carbon is emitted upon the importation of grid electricity to meet the operational demands of the gas compressor station. Such demands are driven by annual PV module degradation and the resulting decline in system performance over the lifecycle. As shown in Figure 9, Al-Duwadimi is more dependent on imported electricity due to lower output. In contrast, Abqaiq exhibits superior performance, with the single-axis configuration resulting in the lowest CO_2 emissions.

Although grid-import emissions remain nonzero due to low-irradiance periods and nighttime grid electricity demand, solar PV generation displaces a significant amount of electricity, resulting in grid-related emissions of 314,656–326,082 tons of CO_2 and avoided emissions of 670,729–688,292 tons of CO_2 over the 25-year project lifetime. The avoided emissions are approximately twice those associated with the grid-connected solar PV system, confirming its substantial environmental benefits.

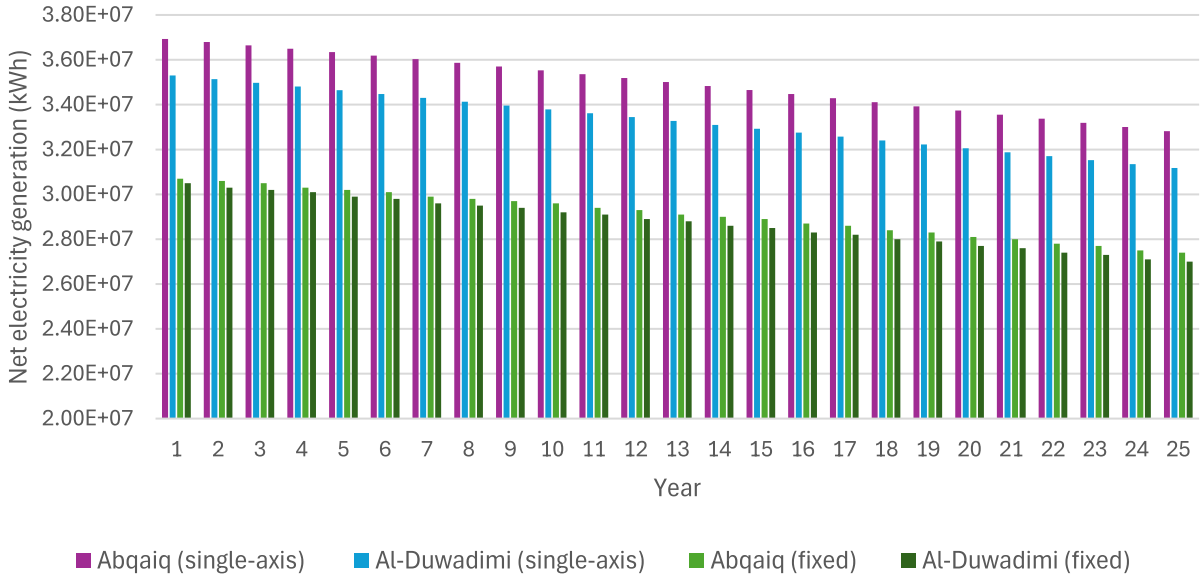


Figure 7. Degradation in net electricity generation over time, considering equal capacities for fixed-tilt and single-axis tracking at both locations

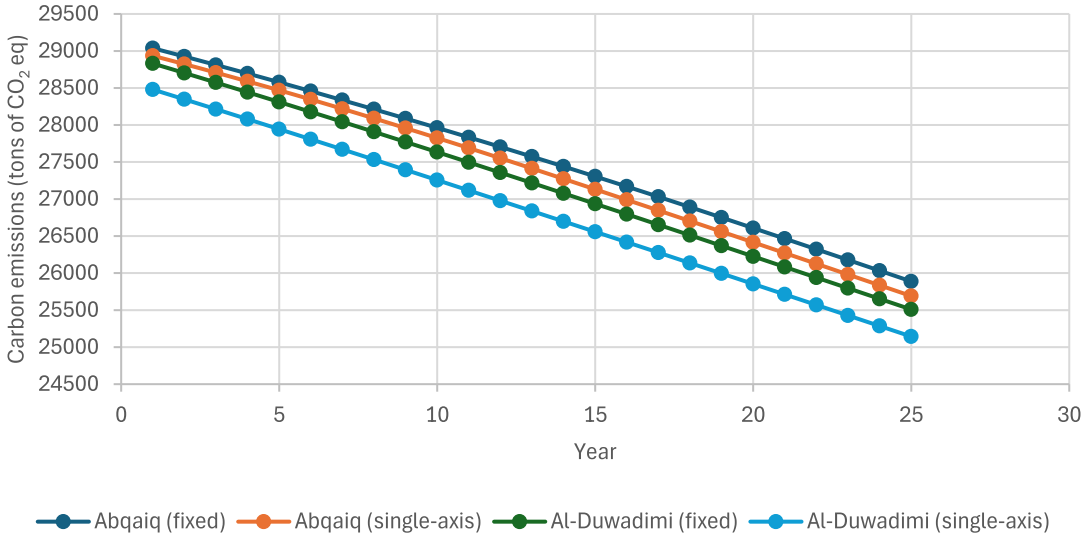


Figure 8. Yearly avoided CO_2 emissions for the Al-Duwadimi and Abqaiq systems, with fixed-tilt and single-axis tracking

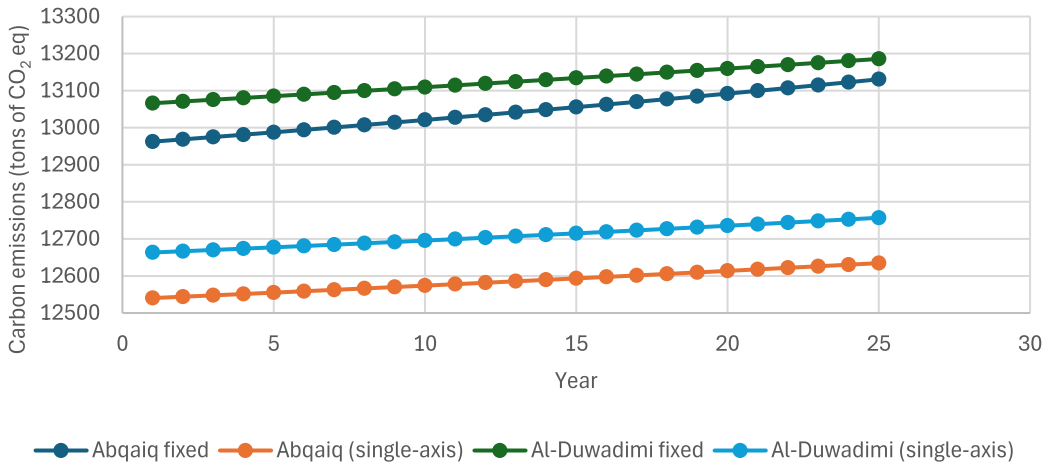


Figure 9. Annual CO_2 emissions from grid electricity imports for the Al-Duwadimi and Abqaiq systems under fixed-tilt and single-axis tracking configuration

The conclusions of this study are consistent with previous research demonstrating the technical and economic viability of grid-connected solar PV systems for reducing carbon emissions and electricity costs. In line with earlier studies, the results show substantial emission declines and favourable LCOE values. However, unlike most previous work focusing on residential, commercial, or general industrial applications, this study specifically evaluates natural gas compressor stations along the East–West pipeline. It assesses the influence of tracking configurations, degradation effects, and net-zero billing conditions.

This study is subject to several limitations. The analysis was performed for two representative locations and assumes fixed electricity tariffs, net-zero billing conditions, and a constant annual degradation rate over the project lifetime. Future changes in electricity prices, policy frameworks, financing conditions, and equipment costs were not considered. In addition, the results are based on simulation outputs from SAM and do not account for operational uncertainties, major equipment failures, unplanned outages, or detailed grid constraints.

4. CONCLUSIONS

This study investigated the technical, environmental, and economic feasibility of decarbonizing natural gas compressor stations along an East–West pipeline in Saudi Arabia using solar PV systems. The results of the SAM simulations confirmed that grid-connected PV can reliably offset the required annual demand of 23,520 MWh while delivering measurable economic and environmental benefits over a 25-year period. All cases were designed to generate more than the required annual demand of 23,520 MWh until year 25, enabling surplus electricity export to the grid and additional economic benefits. At a DC degradation rate of 0.5%/yr, the annual net generation declined over time. Moreover, Abqaiq generally exhibited higher LCOE values than Al-Duwadimi under identical configurations. Monthly variation was observed owing to seasonality, with low-generation months leading to increased grid imports. When the systems were evaluated under equal DC capacities, single-axis tracking consistently generated higher annual AC energy outputs than fixed-tilt systems, demonstrating its superior energy-capture

effectiveness. Under the net-zero billing framework, a reduction in payback time of ~50% was observed, with significant savings of $1.78–1.83 M in year 1, in addition to an export revenue of $0.33–0.36 M. Environmentally, PV integration mitigates ~670,729–688,292 tons of CO_2 emissions over the 25-year period. Regarding environmental benefits, PV lifecycle emissions accounted for only 1–1.5% of the avoided grid electricity emissions. Compared with the Al-Duwadimi scenarios, Abqaiq yielded higher energy outputs with lower LCOE values, namely 3.51 and 2.94 ¢/kWh for the fixed-tile and single-axis configurations, respectively, indicating superior solar resource availability and system performance. Overall, the Abqaiq single-axis configuration represents the optimal techno-economic case, whereas the Al-Duwadimi fixed-tilt configuration is the least favorable. Future work should focus on the application of artificial intelligence and machine-learning techniques for PV forecasting, degradation modeling, and grid optimization.

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