Journal of Economic Studies, Vol. 17 (2), pp. 211-226, (Special issue), Articles of the 22nd Annual Conference of Saudi Economic Association, September 10-11, 2025, University of Business and Technology (UBT), Jeddah, Saudi Arabia

DOI: 10.33948/ESJ-KSU-17-2-4

Economic and Environmental Benefits of Energy Transition in Saudi Arabia: A Case Study of Sakaka Solar Power Plant

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(Received: Aug 04, 2024 – Accepted for publication: Oct 20, 2024)

Abstract: In the context of global efforts to transition to renewable energy, the Sakaka Solar Power Plant represents a pivotal development in Saudi Arabia's energy landscape, aligning with Vision 2030 goals of economic diversification and environmental sustainability. This study aims to evaluate the economic and environmental impacts of the Sakaka Solar Power Plant, Saudi Arabia's first utility-scale renewable energy project. Using a comprehensive case study approach, data were collected and analyzed utilizing key financial metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period, Profitability Index (PI), and Benefit-Cost Ratio (BCR), alongside environmental impact assessments. The results indicate a positive NPV of $566 million, an IRR of 20.19%, and a payback period of 4.90 years, confirming the project's financial viability and attractiveness to investors. Environmentally, the project contributes to a significant annual reduction of 430,000 tons of carbon emissions, totaling 10.75 million tons over its lifespan. These findings underscore the potential of renewable energy projects in Saudi Arabia to deliver substantial economic returns and environmental benefits. Policy recommendations include enhancing support for renewable energy projects through financial incentives, fostering public-private partnerships, and promoting localization to stimulate economic growth and technological innovation, thereby advancing the objectives of Vision 2030. Additionally, aligning with global trends highlighted by the World Economic Forum (2023), the successful implementation of the Sakaka project demonstrates Saudi Arabia's commitment to fostering effective energy transition.

Key Words: Renewable Energy, Energy Transition, Solar Energy, Sustainability, Energy Economics, Carbon Emissions**.**

المنافع الاقتصادية والبيئية للتحول الطاقوي في المملكة العربية السعودية: حالة دراسة لمحطة سكاكا للطاقة الشمسية

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(قُدّم للنشر: 04 أغسطس، 2024م – وقُبل للنشر: 20 أكتوبر، 2024م)

المستخلص: في سياق الجهود العالمية للتحول إلى الطاقة المتجددة، تمثل محطة سكاكا للطاقة الشمسية تطورًا محوريًا في مشهد الطاقة في المملكة العربية السعودية، متماشية مع أهداف رؤية 2030 في تنويع الاقتصاد والاستدامة البيئية. تهدف هذه الدراسة إلى تقييم التأثيرات الاقتصادية والبيئية لمحطة سكاكا للطاقة الشمسية، أول مشروع للطاقة المتجددة على نطاق المرافق في المملكة. باستخدام نهج دراسة حالة شاملة، تم جمع البيانات وتحليلها باستخدام مقاييس مالية رئيسية مثل صافي القيمة الحالية (**NPV**)، ومعدل العائد الداخلي (**IRR**)، وفترة الاسترداد، ومؤشر الربحية (**PI**)، ونسبة الفائدة إلى التكلفة (**BCR**)، بالإضافة إلى تقييمات التأثير البيئي. تشير النتائج إلى صافي قيمة حالية إيجابية بمقدار 566 مليون دولار، ومعدل عائد داخلي بنسبة 20.19%، وفترة استرداد تبلغ 4.90 سنوات، مما يؤكد جدوى المشروع المالية وجاذبيته للمستثمرين. بيئيًا، يسهم المشروع في تقليل انبعاثات الكربون بمعدل سنوي يبلغ 430,000 طن، بإجمالي 10.75 مليون طن على مدار عمره. تؤكد هذه النتائج على قدرة مشاريع الطاقة المتجددة في السعودية على تحقيق عوائد اقتصادية كبيرة وفوائد بيئية ملموسة. تشمل التوصيات السياساتية تعزيز الدعم لمشاريع الطاقة المتجددة من خلال الحوافز المالية، وتعزيز الشراكات بين القطاعين العام والخاص، وتشجيع التوطين لتحفيز النمو الاقتصادي والابتكار التكنولوجي، وبالتالي تعزيز أهداف رؤية 2030. بالإضافة إلى ذلك، وبما يتماشى مع التوجهات العالمية التي أبرزها المنتدى الاقتصادي العالمي (2023)، يُظهر التنفيذ الناجح لمشروع سكاكا التزام المملكة العربية السعودية بتعزيز التحول الفعال للطاقة.

الكلمات المفتاحية: الطاقة المتجددة، التحول في مجال الطاقة، الطاقة الشمسية، الاستدامة، اقتصاديات الطاقة، انبعاثات الكربون.

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1. Introduction:

Innovative renewable energy projects are central to achieving the goals of Vision 2030, as Saudi Arabia seeks to achieve economic and environmental sustainability by diversifying energy sources and promoting a knowledge-based economy. In recent years, investments in renewable energy have garnered increasing global attention, driven by the need to achieve sustainable development policies encompassing economic, social, and environmental dimensions [1]. There is a strong relationship between energy consumption and development, as evidenced during the Industrial Revolution when production technology shifted from human labor to machinery, leading to increased use of coal to generate steam [2]. Numerous studies highlight a significantly positive relationship between global growth and energy demand [3]. Future energy demand is expected to rise due to continued population and economic growth [3]. Saudi Arabia's energy consumption is the highest in the Middle East, with an average oil consumption of approximately 4.3 million barrels per day (bpd) by the end of 2019, compared to an average of 4.1 million bpd in 2018 [4]. By the end of 2018, Saudi Arabia consumed around 289.9 terawatt-hours (TWh) of energy, representing a year-on-year increase of 0.42 percent compared to 2017 [5]. Due to high non-oil economic growth, population fertility, and desalination efforts, domestic energy consumption in Saudi Arabia remains exceptionally high [6].

1.1 Motivation and Objectives of the Study

The transition to renewable energy sources is a strategic imperative for Saudi Arabia as it seeks to achieve the goals of Vision 2030, which emphasizes economic diversification and environmental sustainability. The motivation behind this study is to evaluate the economic and environmental benefits of renewable energy projects, using the Sakaka Solar Power Plant as a case study. The objectives are:

- To assess the financial viability of the Sakaka Solar Power Plant using key economic indicators.
- To evaluate the environmental impact, particularly in terms of carbon emission reductions.
- To compare the Sakaka project with similar international projects to position it within a global context.
- To provide policy recommendations that support the expansion of renewable energy in Saudi Arabia.

1.2 Importance of Renewable Energy Globally and in Saudi Arabia:

1.2.1 Importance of Renewable Energy Globally

In recent years, the world has witnessed a significant shift towards renewable energy sources as part of global efforts to combat climate change and promote environmental sustainability. This shift is driven by the growing recognition that renewable energy provides a long-term solution to the increasing global energy demand without adversely affecting the environment [7]. As more countries adopt policies and programs to support renewable energy, it has become evident that renewables will play a critical role in ensuring a sustainable future for future generations [8]. According to the International Renewable Energy Agency (IRENA), the global total renewable energy capacity reached new levels, with an installed capacity of 2799 gigawatts as of 2023 [9].

The United Nations Sustainable Development Goals (SDGs) emphasize the importance of access to sustainable, modern, reliable, and affordable energy for all (SDG 7) [10]. This global goal includes increasing the share of renewable energy in the global energy mix and improving energy efficiency. Previous analyses of future energy pathways indicate that it is technically possible to simultaneously achieve improved energy access, air quality, and energy security while avoiding dangerous climate change [11]. However, achieving these goals requires rapid policy implementation and fundamental political changes to integrate global concerns, such as climate change, into local and national policy priorities [12]. Integrated policy design is crucial for identifying cost-effective solutions that can achieve multiple goals simultaneously [13].

1.2.2 Importance of Renewable Energy in Saudi Arabia

Saudi Arabia has placed renewable energy at the core of its Vision 2030, aiming to diversify its economy and reduce its reliance on oil [14]. The Kingdom leverages its abundant sunshine to develop large-scale solar energy projects and explore wind energy potentials, benefiting from its vast desert expanses [15]. By 2024, Saudi Arabia aims to achieve an installed capacity of 27.3 gigawatts of renewable energy, paving the way for a more diverse and sustainable energy mix [16].

1.2.3 The Importance of Transitioning to Renewable Energy for Sustainable Development

Transitioning to renewable energy is not only an environmental or economic necessity but also a strategic imperative for achieving long-term sustainability and economic diversification. This transition is driven by the urgent need to reduce greenhouse gas emissions, as outlined in the Paris Agreement [17]. Economies heavily reliant on oil face significant risks due to oil price volatility and the finite nature of fossil fuel resources, making energy diversification essential for economic stability [4]. Technological advancements have made renewable energy sources such as solar and wind power more feasible and cost-effective [18]. Saudi Arabia is particularly well-suited to benefit from these advancements, given its high solar radiation and vast desert areas suitable for large solar energy projects [19]. Additionally, investing in renewable energy creates new job opportunities, fosters technological innovation, and attracts foreign investments [3].

An essential element of Saudi Vision 2030 is the transformation of the energy sector, with a focus on increasing the share of renewable energy. The Kingdom aims to generate 9.5 gigawatts of renewable energy by 2023, laying the foundation for a more diverse and sustainable energy mix [16].

1.3 Renewable Energy in Saudi Arabia

1.3.1 Economic Benefits of Transitioning to Renewable Energy

The shift to renewable energy in Saudi Arabia significantly drives job creation and economic growth. Solar and wind projects generate thousands of new jobs in engineering, construction, and maintenance, fostering economic diversification and reducing oil dependency [22]. Additionally, Saudi Arabia's strategic location attracts substantial foreign investments, enhancing infrastructure and advancing local technological capabilities through the National Renewable Energy Program (NREP) [20]. The government supports the private sector by implementing incentivizing policies, including financial facilities and tax incentives, which balance cost-efficiency and stimulate market innovation [23]. Furthermore, renewable energy enhances energy security by diversifying energy sources and reducing reliance on oil imports, ensuring stable energy supplies and mitigating the economic impacts of global oil price fluctuations [26].

1.3.2 Environmental Benefits of Renewable Energy

Renewable energy projects play a crucial role in reducing carbon emissions and other pollutants in Saudi Arabia. By replacing fossil fuels with clean energy sources like solar and wind power, the Kingdom can significantly lower carbon dioxide emissions and improve air quality [24]. Additionally, renewable energy helps preserve natural resources by minimizing the consumption of finite resources such as oil and gas, ensuring their sustainability for future generations and supporting ecosystem health [25]. These initiatives are integral to achieving the United Nations Sustainable Development Goals (SDGs), particularly SDG 7, which focuses on ensuring access to affordable, reliable, sustainable, and modern energy for all, thereby promoting balanced economic, social, and environmental development [26].

1.3.3 Energy Sector Transformation in Saudi Arabia under Vision 2030

Under Vision 2030, Saudi Arabia is undergoing a profound transformation of its energy sector to reduce oil dependence and promote renewable energy as a cornerstone of sustainable development [14]. The National Renewable Energy Program (NREP), launched in 2017 alongside the National Transformation Program 2020, aims to install 27.3 gigawatts of renewable energy capacity by 2024, up from an initial target of 9.5 gigawatts [21]. This ambitious program, with an expected investment of approximately 60 billion Saudi riyals, seeks not only to reduce fuel dependency and emissions but also to create job opportunities, stimulate economic development across all regions, develop advanced renewable technologies, and strengthen public-private partnerships [21].

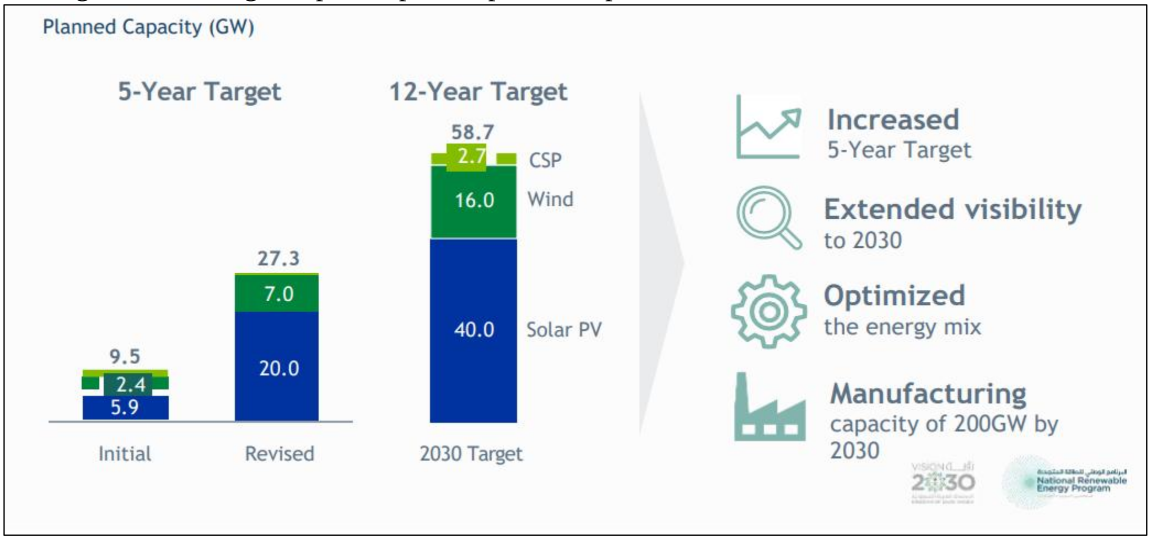

Figure 1. Saudi Arabia significantly increased its renewable energy targets and long-term visibility.
Reference: Saudi Renewable Energy Program

1.3.4 National Renewable Energy Program (NREP)

The National Renewable Energy Program (NREP) was launched in 2017 under Vision 2030 and the National Transformation Program 2020. It is designed to balance local energy sources and meet the Kingdom's commitments to reducing carbon dioxide emissions. According to the new renewable energy strategy, the solar target for 2023 has been raised from 5.9 GW to 20 GW, aiming to modify renewable energy sources from 9.5 GW to 27.3 GW, representing more than 10% of the Kingdom's total energy production. The investment volume in the National Renewable Energy Program projects is expected to reach around 60 billion Saudi riyals. The NREP aims to diversify energy sources in Saudi Arabia, providing sustainable economic stability in line with Vision 2030 goals. The program's objectives are not limited to reducing fuel dependency and emissions but also aim to provide more job opportunities and stimulate economic development in all regions and cities of the Kingdom. Furthermore, it aims to develop modern renewable energy technologies and strengthen partnerships between the public and private sectors. Accordingly, the Ministry of Energy launched the Renewable Energy Project Development Office (REPDO) to achieve the NREP's goals, unify specialized capacities in energy research, and issue renewable energy tenders. In 2019, REPDO offered more than 2000 MW of solar energy [21].

Overview of NREP Projects:

First Phase: Includes the Sakaka Solar Project (300 MW) and Dumat Al-Jandal Wind Project (400 MW), providing electricity to 115,000 homes and reducing 430,000 tons of carbon emissions annually.

Second Phase: Comprises projects in Qurayyat (200 MW), Madinah (50 MW), Rafha (20 MW), Al-Faisaliah (600 MW), Rabigh (300 MW), Jeddah (300 MW), Mahad Dhahab (20 MW), and Yanbu Wind Project (850 MW), totaling 3.07 GW and expected to generate electricity for 226,500 households by 2023 with private sector investments reaching 5.2 billion Saudi riyals [21].

Third Phase: Involves four photovoltaic projects totaling 1,200 MW, including Layla (80 MW), Wadi Al-Dawasir (120 MW), Saad (300 MW), and Al-Rass (700 MW) [21].

1.3.5 Energy Statistics and Transformations

By the end of 2023, Saudi Arabia's installed renewable energy capacity reached 2.8 gigawatts, with ongoing projects pushing this figure beyond 8 gigawatts [24]. The Ministry of Energy targets generating 50% of the Kingdom's electricity from renewable sources by 2030, supported by significant expansions in solar and wind projects, investments in energy storage technology, and smart grids [29]. According to the Saudi General Authority for Statistics (Renewable Energy Statistics 2022), renewable projects are expected to generate 43,698 gigawatt-hours annually, supply electricity to 2.6 million homes, and reduce carbon dioxide emissions by approximately 24.8 million tons each year, as illustrated in Figure 2 and Figure 3 [30].

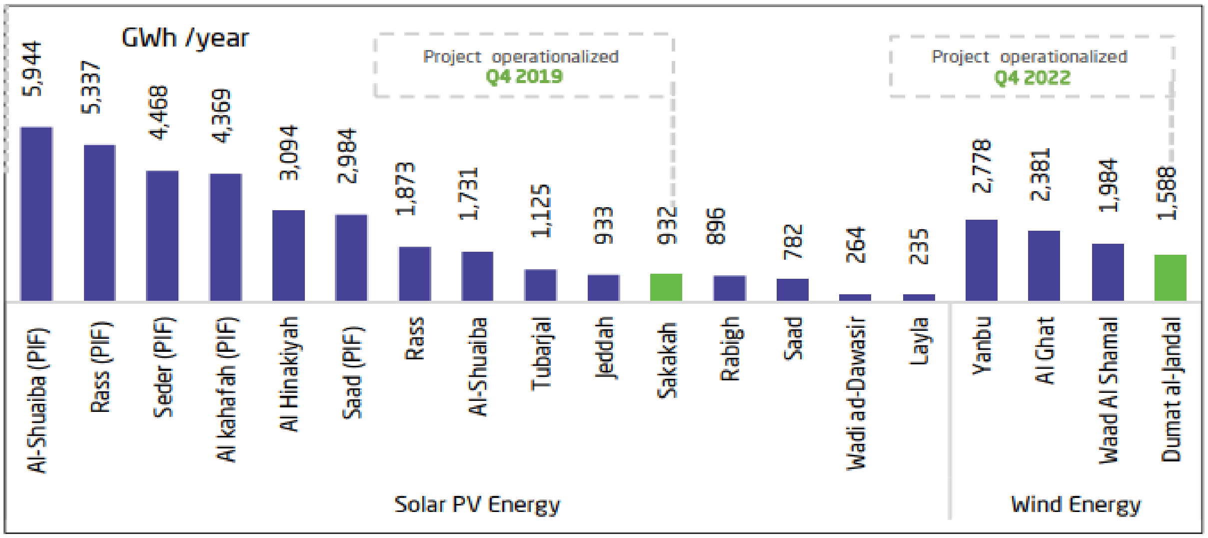

Fig2. Electricity targeted to be generated from renewable energy projects annually. [Reference: Saudi General Authority for Statistics. (2022). Renewable Energy Statistics 2022. Retrieved from Statistics].

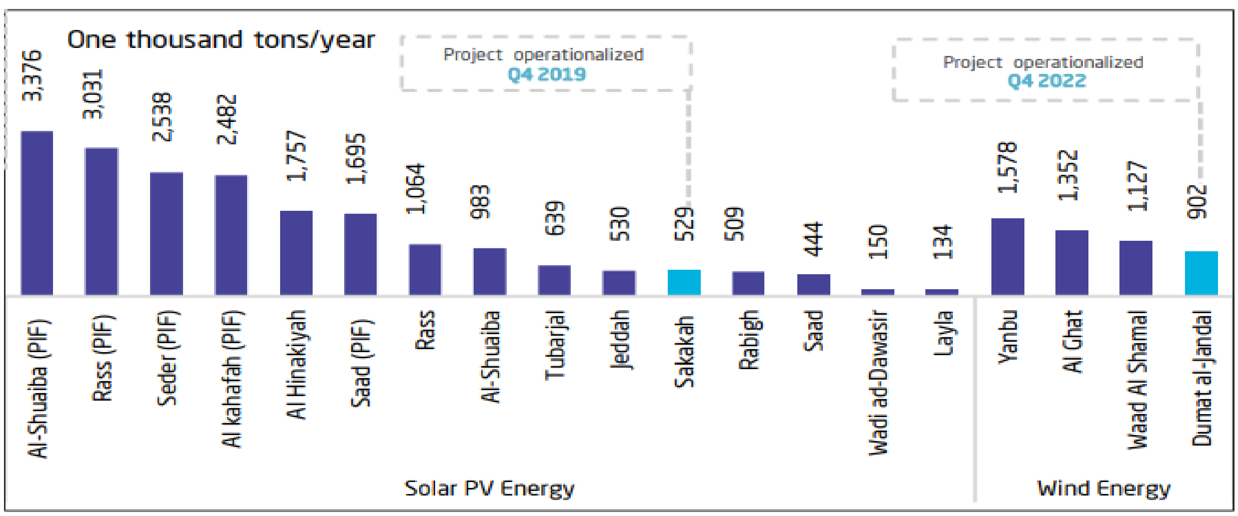

Fig3. Expected environmental impact of projects on reducing carbon dioxide emissions. [Reference: Saudi General Authority for Statistics. (2022). Renewable Energy Statistics 2022. Retrieved from Statistics].

1.3.6 Localization Strategies and Objectives in Saudi Arabia's Renewable Energy Sector under Vision 2030

Localization of the renewable energy sector is a key objective under Vision 2030. The Ministry of Energy, Industry, and Mineral Resources (MEIM) and the Public Investment Fund (PIF) are promoting local manufacturing to achieve global competitiveness and develop resilient supply chains [23]. Key strategies include:

- **Local Content Requirements:** Mandating that a specific percentage of project costs be spent locally, increasing to 40-45% by 2028 to ensure job creation and skills development

[39]. While beneficial, these requirements may raise the levelized cost of energy and affect economies of scale if not aligned with existing industrial capacities [38].

● **Supply Chain Development:** Addressing challenges such as raw material constraints and global trade disruptions by leveraging Saudi Arabia's abundant mineral resources, domestic demand, and competitive energy costs. Establishing large local markets and production facilities is essential, alongside coordinating market policies across the Middle East and North Africa [38].

● **Practical Measures:** Implementing the "Local Content Compliance Mechanism" to award points for locally produced materials, thereby incentivizing local manufacturing and enhancing the renewable energy ecosystem [38].

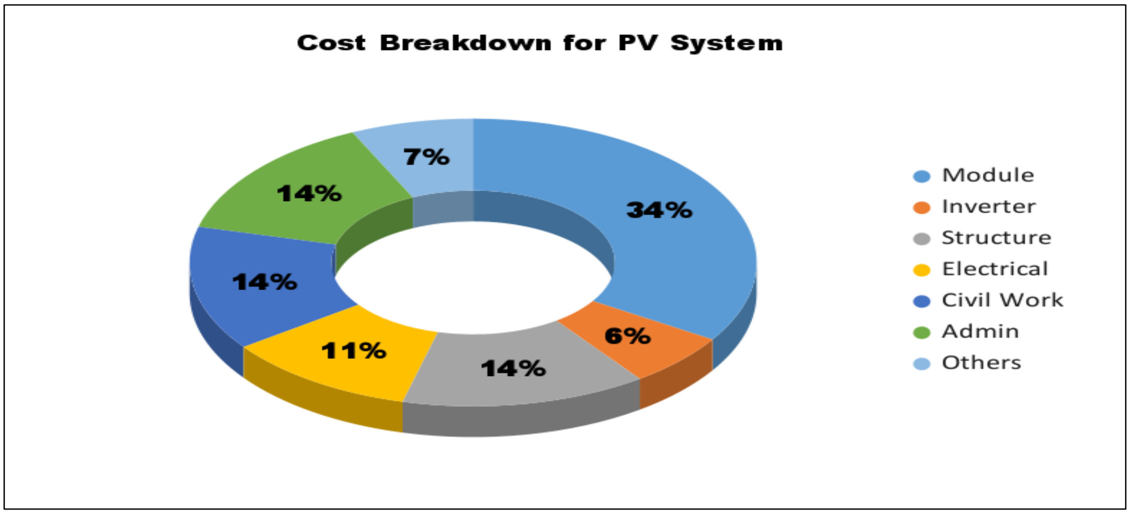

Fig4. Cost Breakdown for PV System. [Reference: AlOtaibi, Z.S., Khonkar, H.I., AlAmoudi, A.O. et al. Current status and future perspectives for localizing the solar photovoltaic industry in the Kingdom of Saudi Arabia. Energy Transit 4, 1–9 (2020). https://doi.org/10.1007/s41825-019-00020-y].

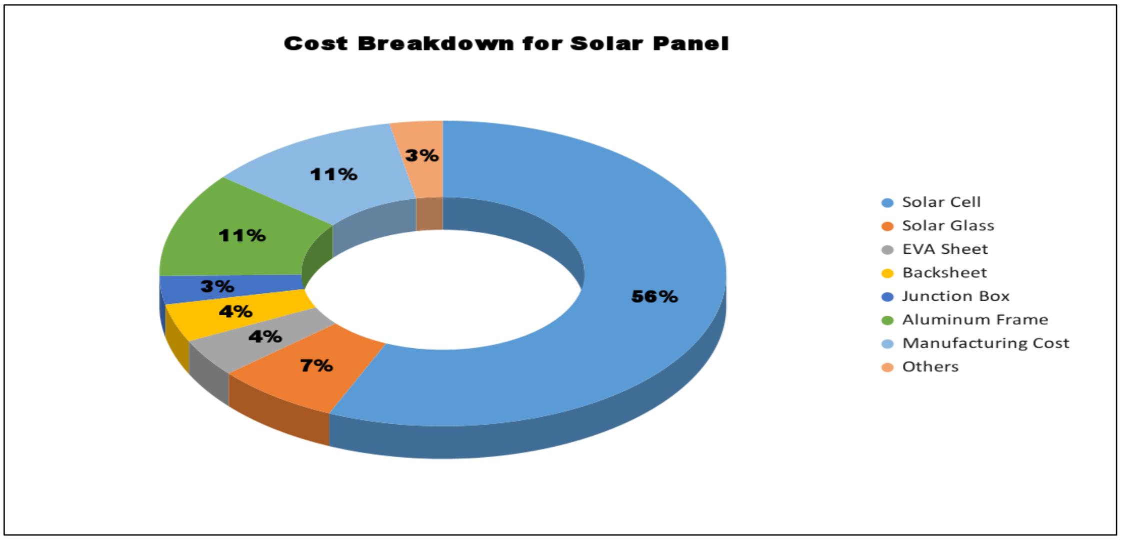

Fig5. Cost Breakdown for Solar Panel. [Reference: AlOtaibi, Z.S., Khonkar, H.I., AlAmoudi, A.O. et al. Current status and future perspectives for localizing the solar photovoltaic industry in the Kingdom of Saudi Arabia. Energy Transit 4, 1–9 (2020). https://doi.org/10.1007/s41825-019-00020-y].

The Importance of the Domestic Market

A crucial factor in developing renewable energy industries is the domestic market's ability to expand into regional and global markets. Saudi Arabia's abundant wind and solar resources, coupled with its strategic location as a trade hub linking Africa, Europe, and Asia, provide significant opportunities to boost investment in local industries and develop the regional market, especially in the Middle East and North Africa [38]. To achieve the goal of 40 GW by 2030, Saudi Arabia must increase its current solar capacity by approximately 110-fold. Large-scale projects such as the 300 MW Sakaka plant must achieve more than 30% local content, which could increase by 19% if all modules were manufactured within the Kingdom rather than imported [39].

Government Initiatives and Incentives

Saudi Arabia is committed to transforming its energy system and building local capacity under Vision 2030, offering various policy-related incentives to boost trade, attract foreign direct investment, develop technology infrastructure, encourage local employment, and enhance local capabilities. For example, support mechanisms have been launched for manufacturers to access export financing through the Saudi Export Development Authority and the Saudi Export-Import Bank [38].

Ministry of Investment's Role

The Ministry of Investment is actively facilitating opportunities in the green energy sector by developing cross-governmental sectoral ecosystems and supporting companies in their investment processes. Saudi companies are gradually establishing themselves in local supply chains, laying the foundation for Saudi-Chinese cooperation [39]. For instance, Desert Technologies established the first solar PV manufacturing plant in Saudi Arabia in 2011, with a production capacity of 300 megawatts per year, and has started exporting its products globally. The Kingdom is expanding its production to include energy storage solutions and electric vehicle charging systems. In 2021, Alfanar acquired India’s Senvion to accelerate the localization of wind energy manufacturing and participate in the development of the Indian market [38].

1.4 Previous Studies and Research Gaps

Extensive research has been conducted on the economic and environmental impacts of renewable energy in Saudi Arabia, highlighting both opportunities and challenges in the sector. Alghamdi et al. (2022) explored the supply chain readiness for solar photovoltaic (PV) expansion in Saudi Arabia, emphasizing the importance of local content policies and the need for robust supply chain infrastructures to support large-scale solar projects [40]. Their study underscores the critical role of government incentives and regulatory frameworks in fostering a conducive environment for renewable energy investments. Similarly, Khaled Abdalla Moh’d Al-Tamimi et al. (2023) examined the broader economic implications of renewable energy adoption in Saudi Arabia, demonstrating that renewable projects significantly contribute to job creation, economic diversification, and enhanced energy security [41]. This research provides valuable insights into the macroeconomic benefits of transitioning to renewable energy sources, aligning with the strategic objectives of Vision 2030.

In the realm of technical and economic feasibility, a study by Al-Otaibi et al. (2019) assessed the viability of utility-scale solar energy conversion systems in Saudi Arabia. The research highlighted the favorable solar irradiance conditions and declining costs of photovoltaic technologies as key factors supporting the expansion of solar energy [42]. Additionally, a recent article published in *Energy Policy* (2024) delved into the integration challenges of renewable energy into Saudi Arabia’s existing energy infrastructure, identifying technical bottlenecks and proposing solutions to enhance grid stability and energy storage capabilities [43].

Despite the significant advancements, several research gaps remain. Firstly, while existing studies have extensively covered the economic benefits and technical feasibility of renewable energy projects, there is a paucity of comprehensive analyses that concurrently evaluate both economic and environmental impacts within a unified framework. Most studies tend to focus on one aspect, thereby overlooking the synergistic effects that can be harnessed from an integrated approach. Secondly, there is limited research on the long-term sustainability and lifecycle impacts of renewable energy projects in

Saudi Arabia, particularly concerning resource utilization and waste management. Lastly, comparative analyses between Saudi Arabian projects and international counterparts are scarce, which hinders the ability to benchmark performance and identify best practices that could be adapted to the local context.

This study aims to address these gaps by providing a holistic assessment of the Sakaka Solar Power Plant, integrating both economic and environmental evaluations. By employing a comprehensive methodology that includes Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period, Profitability Index (PI), and Benefit-Cost Ratio (BCR), alongside an Environmental Impact Assessment (EIA) and Life Cycle Analysis (LCA), this research seeks to offer a more nuanced understanding of the multifaceted benefits of renewable energy projects. Furthermore, the comparative analysis with international projects such as the Tengger Desert and Ivanpah Solar Power Plants will position the Sakaka project within a global context, highlighting its unique contributions and areas for improvement.

2. Methodology

The study is grounded in the principles of environmental economics and sustainable development. Economic indicators such as NPV and IRR are used to assess financial viability, while environmental impact assessments consider the project's contribution to sustainability goals.

2.1 Methodology Overview

This methodology is designed to thoroughly evaluate both the economic and environmental impacts of the Sakaka Solar Power Plant. The analysis consists of several key steps:

1. **Case Study Analysis:** Understanding the specific details of the Sakaka project.
2. **Data Collection:** Gathering data from credible sources about the project's technical specifications, financial metrics, and environmental benefits.
3. **Data Analysis:**
   - **Economic Analysis:** Performing a Cost-Benefit Analysis (CBA) including NPV, IRR, payback period, PI, and BCR.
   - **Environmental Analysis:** Conducting an Environmental Impact Assessment (EIA) and Life Cycle Analysis (LCA).
4. **Comparative Analysis:** Comparing the Sakaka project with similar international projects.
5. **Conclusions and Recommendations:** Summarizing findings and providing actionable recommendations.

Justification of Statistical Methods

The statistical methods used, such as NPV and IRR calculations, are standard in financial analysis for evaluating investment projects [19]. Sensitivity analysis is employed to assess the robustness of the results under different scenarios, enhancing the reliability of the conclusions.

2.2 Case Study

The Sakaka Independent Photovoltaic Solar Power Plant, with a capacity of 300 MW, is the first utility-scale renewable energy project in Saudi Arabia. The project was awarded to ACWA Power at a record-breaking tariff of 2.3417 cents per kWh. The plant spans 6 square kilometers in the Al Jouf region, with an investment of $302 million [20].

2.2.1 Data Collection

Data for the Sakaka Solar Power Station case study was sourced from three primary references and includes: [31,32,33].

- **Capacity:** 300 MW
- **Cost:** $302 million
- **Levelized Cost of Electricity (LCOE):** 2.3417 cents per kWh
- **Operation Year:** 2020
- **Reduced Emissions:** 430,000 tons annually

2.2.2 Data Analysis

Economic Analysis:

The economic analysis utilizes several financial metrics to assess the project's viability:

Cost-Benefit Analysis (CBA):

1. Initial Costs: \$302 million

2. Estimated Annual Revenue:

Annual Revenue = Capacity × Annual Hours × Electricity Price

Annual Revenue = 300 MW × 8760 hours × 0.023417 USD/kWh = 61,608,852 USD

3. Net Present Value (NPV):

$$NPV = \sum (B_t - C_t) / (1 + r)^t$$

Where:

- B_t is the annual revenue.
- C_t is the annual costs.
- r is the discount rate.
- t is the number of years.

Internal Rate of Return (IRR):

IRR = Discount rate where NPV = 0

Payback Period:

Payback Period = Initial Investment / Annual Revenue

Profitability Index (PI):

PI = (NPV + Initial Investment) / Initial Investment

Benefit-Cost Ratio (BCR):

$$BCR = \sum (B_t / (1 + r)^t) / \sum (C_t / (1 + r)^t)$$

Simple Rate of Return:

Simple Rate of Return= (Annual Revenue−Annual CostsInitial Investment)×100%Simple Rate of **Return=** (Initial InvestmentAnnual Revenue−Annual Costs)×100%

- **Explanation**: This measures the percentage return on the initial investment, indicating the project's efficiency.

Environmental Analysis:

Emission Reductions:

Total Emission Reductions = Annual Reductions × Project Duration

Life Cycle Analysis (LCA):

- Production: Use of sustainable materials and technologies.

- Operation: Reduction of carbon emissions and provision of clean energy.

- Disposal: Waste management and recycling after the project lifespan.

2.2.3 Analysis Using MATLAB

After collecting the data for the project and developing the equations that will be relied upon in the economic and environmental analysis, they will be applied to the MATLAB program. Figure 6 shows the code used and the equations.

MATLAB Drive > lk.m

```
% Project data
investment = 302000000; % Initial investment in USD
annual_revenue = 61608852; % Annual revenue in USD
discount_rate = 0.05; % Discount rate
years = 25; % Project duration

% Calculate NPV
NPV = sum(annual_revenue ./ (1 + discount_rate) .^ (1:years)) - investment;

% Calculate IRR
cash_flows = [-investment, repmat(annual_revenue, 1, years)]; % Annual cash flows
IRR = irr(cash_flows);

% Calculate Payback Period
payback_period = investment / annual_revenue;

% Calculate Profitability Index
PI = (NPV + investment) / investment;

% Calculate BCR
BCR = sum(annual_revenue ./ (1 + discount_rate) .^ (1:years)) / investment;

% Display results
disp(['NPV: $', num2str(NPV)]);
disp(['IRR: ', num2str(IRR * 100), '%']);
disp(['Payback Period: ', num2str(payback_period), ' years']);
disp(['Profitability Index: ', num2str(PI)]);
disp(['Benefit-Cost Ratio: ', num2str(BCR)]);

% Plot cash flows
years_array = 0:years;
cash_flows_array = [-investment, repmat(annual_revenue, 1, years)];
figure;
bar(years_array, cash_flows_array);
xlabel('Years');
ylabel('Cash Flows ($)');
title('Cash Flows over the Project Lifetime');
grid on;

% Calculate emission reductions
CO2_reduction_per_year = 430000; % tons annually
total_CO2_reduction = CO2_reduction_per_year * years;
disp(['Total CO2 Reduction: ', num2str(total_CO2_reduction), ' tons']);

% Plot NPV over time
npv_values = cumsum(cash_flows_array ./ (1 + discount_rate) .^ (0:years));
figure;
plot(years_array, npv_values, '-o');
xlabel('Years');
ylabel('Net Present Value ($)');
title('NPV over Project Lifetime');
grid on;
```

Fig6.Code used in MATLAB program.

Table 1 shows the results of the calculations, which were calculated using MATLAB. Figure 7 also shows the cash flow of the project for a period of 25 years with a discount rate of 5% and figure 8 shows Net present value for 25 years.

Table1. Analysis and calculation results.

Parameter	Result
Net Present Value (NPV)	$566311744.8657
Internal Rate of Return (IRR)	20.1949%
Payback Period	4.9019 years
Profitability Index (PI)	2.8752
Benefit-Cost Ratio (BCR)	2.8752
Total CO2 Reduction	10750000 tons

Net Present Value (NPV): $566,311,744.87

- **Analysis:** The positive and substantial NPV indicates that the project is highly profitable over the 25-year period. The project generates significant financial returns that exceed the initial investment costs.

Internal Rate of Return (IRR): 20.1949%

- **Analysis:** The IRR is significantly higher than the assumed discount rate (5%), suggesting that the project offers a good return on investment. This high rate is a strong indicator for attracting investors.

Payback Period: 4.9019 years

- **Analysis:** A relatively short payback period (less than 5 years) indicates that the project recoups its costs quickly. This is a significant advantage for investment projects, as it reduces the risks associated with long-term investments.

Profitability Index (PI): 2.8752

- **Analysis:** A PI greater than 1 indicates that the project is profitable and generates good returns compared to its costs. Specifically, for every dollar invested in the project, the investor receives a return of $2.8752.

Benefit-Cost Ratio (BCR): 2.8752

- **Analysis:** A BCR greater than 1 also indicates that the benefits of the project far outweigh its costs. This makes the project attractive for investment.

Simple Rate of Return: 20.39%

- **Analysis:** This high percentage reflects the project's efficiency in delivering returns on the initial investment.

Total CO2 Reduction: 10,750,000 tons

- **Analysis:** A substantial reduction in CO2 emissions contributes significantly to improving air quality and reducing the environmental footprint. This environmental aspect enhances the project's value and supports sustainability goals.

Sensitivity Analysis

- **NPV over Time**:
  - **Analysis:** The NPV plot shows a steady increase over the project lifespan, indicating growing project value and positive financial stability.
- **Impact of Discount Rate and Electricity Prices**:
  - **Analysis:** Sensitivity to these variables underscores the project's resilience and adaptability under different economic conditions, reinforcing its robust financial outlook.

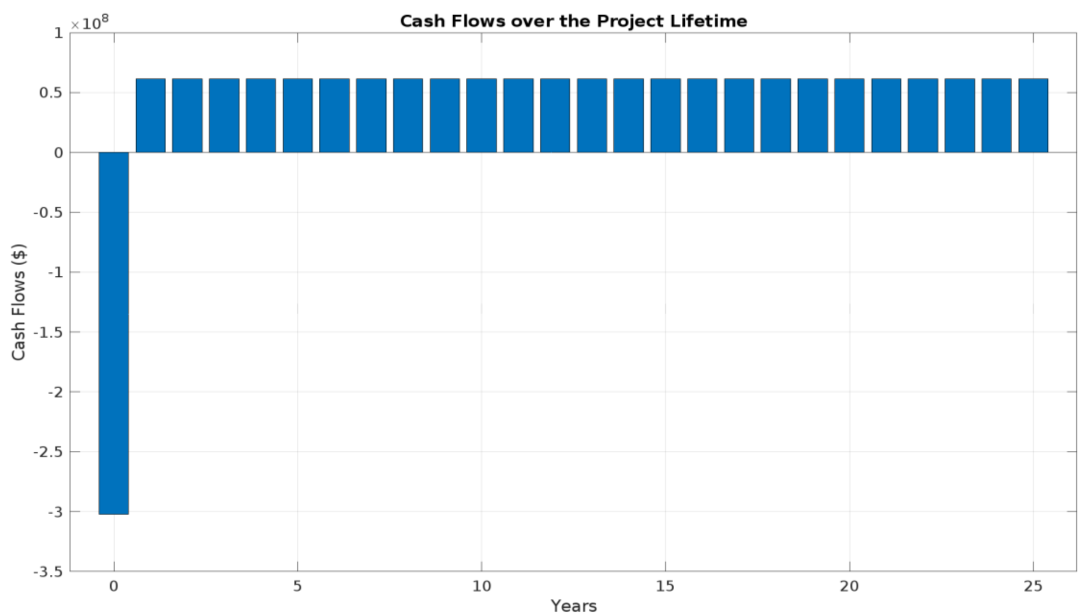

Fig7. cash flow of the project from the MATLAB program.

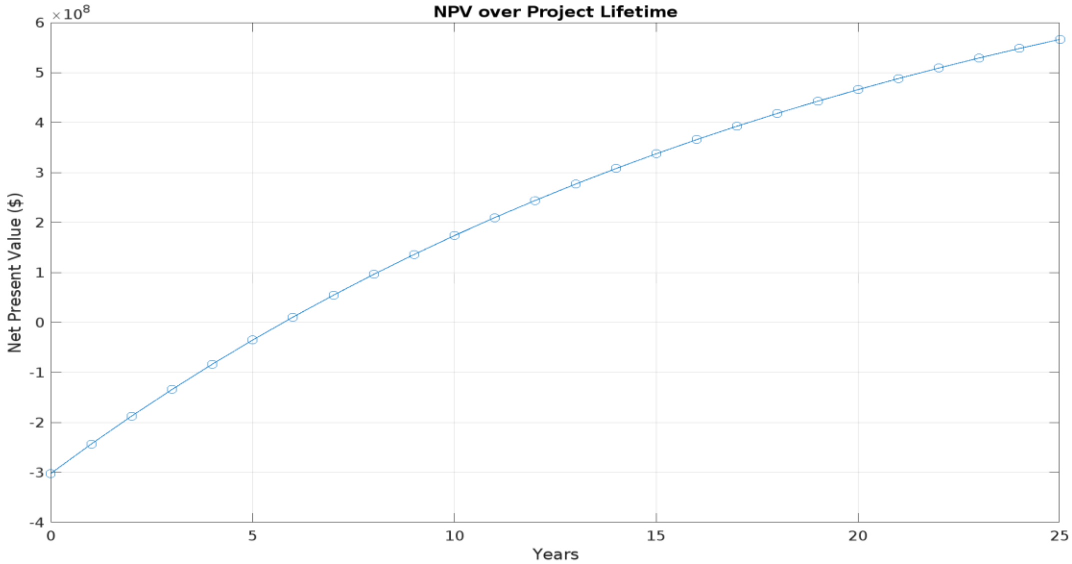

Fig8. Net Present Value of the project from the MATLAB program.

Cash Flows over the Project Lifetime:

- **Analysis:** The graph shows positive annual cash flows following the significant initial investment. This pattern reflects steady and stable cash flows throughout the project's lifespan, indicating good financial stability.
- **Recommendation:** Maintaining this financial stability can help attract more investments and funding for future projects.

Sensitivity Analysis:

- **NPV over Time**:
  - **Analysis:** The NPV plot shows a steady increase over the project lifespan, indicating growing project value and positive financial stability.
- **Impact of Discount Rate and Electricity Prices**:
  - **Analysis:** Sensitivity to these variables underscores the project's resilience and adaptability under different economic conditions, reinforcing its robust financial outlook.

2.2.4 Conclusion and Recommendations

3 **Economic Viability**: The Sakaka Solar Power Plant is financially viable, with strong NPV, IRR, and profitability metrics. Continued monitoring of electricity prices and discount rates is recommended to sustain financial stability.

4 **Environmental Impact**: The project's significant CO_2 emissions reduction aligns with sustainability goals, further enhancing its environmental value.

5 **Future Prospects**: This successful model can be replicated in similar ventures, with recommendations to optimize cost-efficiency and maximize environmental benefits.

- **Additional Economic Analysis**

Long-term Economic Impact Analysis

1. **Job Creation:** The project created approximately 400 jobs during construction and supports permanent local jobs during operation.
2. **Expected Financial Returns:** Using NPV, IRR, Profitability Index, and Payback Period.
3. **Impact on Local Economic Growth:** Enhances local economy by improving infrastructure and providing clean, sustainable energy.

Life Cycle Analysis (LCA)

Evaluating Environmental Impact from Production to Disposal:

- **Production:** Use of sustainable materials and technologies.
- **Operation:** Reduction of carbon emissions and provision of clean energy.
- **Disposal:** Waste management and recycling after the project's lifespan.

- **Additional Environmental Analysis**

1. **Studying the Project's Impact on Biodiversity and Natural Resources:** Analyze how the project affects local wildlife and plants.
2. **Estimating Additional Environmental Benefits:** Such as improved air quality and reduced reliance on fossil fuels.

2.3 Comparative Analysis

2.3.1 Selecting Similar Global Projects:

- Ivanpah Solar Power Plant (USA) [34].
- Tengger Desert Solar Power Plant (China) [35,36].

Table 2 below presents a detailed comparison between these three prominent solar power projects, highlighting their capacity, cost, and CO2 emission reductions.

Table2. comparison between the three projects.

Project	Capacity (MW)	Cost (USD)	CO2 Reduction (Metric tons annually)
Sakaka Solar Power Plant	300	302 million	430,000
Tengger Desert Solar Power Plant (China)	1,547	2.2 billion	3.29 million
Ivanpah Solar Power Plant (USA)	392	2.2 billion	500,000

2.3.2 Comparative Analysis:

Capacity

- Tengger Desert Solar Power Plant leads in capacity with 1,547 MW, making it one of the largest solar power projects globally.
- Ivanpah Solar Power Plant follows with 392 MW, which is a significant capacity for a solar thermal power station.
- Sakaka Solar Power Plant has a smaller capacity of 300 MW compared to the other two, yet it marks a crucial step in Saudi Arabia's renewable energy journey.

Cost

- Tengger Desert Solar Power Plant and Ivanpah Solar Power Plant both have a high cost of 2.2 billion USD, reflecting their large scale and advanced technologies.
- Sakaka Solar Power Plant is relatively more cost-effective at 302 million USD, demonstrating a lower cost per megawatt ratio compared to its counterparts.

CO2 Emission Reductions

- Tengger Desert Solar Power Plant achieves the most significant CO2 reduction, with an impressive 3.29 million metric tons annually. This highlights its efficiency and impact on reducing greenhouse gas emissions.
- Ivanpah Solar Power Plant reduces CO2 emissions by 500,000 metric tons annually, benefiting from its innovative solar thermal technology.
- Sakaka Solar Power Plant contributes to a CO2 reduction of 430,000 metric tons annually, supporting Saudi Arabia's sustainability goals and its Vision 2030 objectives.

Each of these solar power projects exemplifies a unique approach to harnessing solar energy, with distinct characteristics and impacts:

- Tengger Desert Solar Power Plant stands out for its large scale and remarkable emission reductions, representing China's commitment to renewable energy.
- Ivanpah Solar Power Plant showcases advanced solar thermal technology, achieving significant emissions reductions but at a higher cost.

- Sakaka Solar Power Plant is a testament to Saudi Arabia's growing investment in solar energy, balancing cost-effectiveness with substantial environmental benefits.

2.3.3 Conclusions and Recommendations

Conclusions

Economic Viability: The Sakaka Solar Power Plant is financially viable, with a positive NPV, high IRR, and a short payback period. The project demonstrates strong profitability and attractiveness to investors.

Environmental Impact: The project contributes significantly to reducing carbon emissions, supporting Saudi Arabia's sustainability goals and commitments under international agreements.

Strategic Significance: Sakaka serves as a model for future renewable energy projects in the region, showcasing the potential for economic and environmental benefits.

Recommendations and Policy Implications

- **Enhance Government Support:** Increase financial incentives, subsidies, and tax breaks to encourage investment in renewable energy projects.
- **Promote Public-Private Partnerships:** Facilitate collaborations to leverage expertise, share risks, and mobilize capital.
- **Encourage Localization:** Implement policies to develop local manufacturing of renewable energy components, creating jobs and stimulating economic growth.
- **Invest in Research and Development:** Support innovation to improve technology efficiency and reduce costs.
- **Strengthen Regulatory Framework:** Establish clear and stable policies to provide certainty for investors and developers.
- **Increase Public Awareness:** Educate the public on the benefits of renewable energy to build societal support.

Scientific Contribution and Originality

This study provides a comprehensive analysis combining economic and environmental evaluations of the Sakaka Solar Power Plant, filling a gap in existing literature. It offers valuable insights for policymakers, investors, and researchers interested in the renewable energy sector.

3. Conclusion

The Sakaka Solar Power Plant stands as a landmark in Saudi Arabia's renewable energy journey, offering compelling insights into the economic and environmental benefits of transitioning to renewable energy sources. The financial analysis reveals that the project is not only viable but also highly profitable, with an NPV of $566 million and an IRR of 20.19%, which significantly exceeds the benchmark discount rate of 5%. The project's short payback period of 4.90 years highlights its efficiency in recouping investments, while the PI and BCR values indicate substantial returns on investment.

Environmentally, the Sakaka Solar Power Plant contributes to a significant reduction in carbon emissions, with a projected decrease of 10.75 million tons over its lifespan. This reduction supports Saudi Arabia’s Vision 2030 goals of decreasing the carbon footprint and promoting sustainability. The project's use of photovoltaic technology exemplifies Saudi Arabia's commitment to leveraging its abundant solar resources, setting a precedent for future renewable energy projects in the region.

Comparative analysis with other global solar projects, such as the Tengger Desert and Ivanpah Solar Power Plants, underscores the Sakaka project's competitive advantage in cost-effectiveness and environmental impact. While it may have a smaller capacity, its strategic significance in Saudi Arabia's energy diversification strategy cannot be overstated.

In conclusion, the Sakaka Solar Power Plant is a testament to Saudi Arabia's proactive approach to achieving sustainable development through renewable energy. The project's success demonstrates the potential for similar initiatives to contribute to economic growth, job creation, and environmental conservation. Moving forward, Saudi Arabia can build on the Sakaka model to expand its renewable energy capacity, reduce reliance on fossil fuels, and foster a more sustainable and diversified economy.

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