Proceedings of the 2nd GCC International Conference on Industrial Engineering and Operations Management Muscat, Oman, December 1-3, 2024

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/GC02.20240114
Published: December 01, 2024

Viability Assessment of Large-Scale Solar Farms in Rustaq-Juma: A Life Cycle Analysis

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Abstract

This paper presents an analysis and development of a 22 MW photovoltaic solar power plant at Rustaq-Juma, Sultanate of Oman, using a convective procedure and PV-SYST software. The location was chosen due to its high annual solar irradiance, with the proposed plant expected to produce 38.009 GWh of energy annually, providing electricity to approximately 1,466 homes and reducing carbon emissions by 15,900 tons. The grid-connected PV solar plant is assessed as technically, environmentally, and economically feasible, with a Levelized Cost of Electricity of \$0.06/kWh, a discounted payback period of 11 years, and a net present value of \$13 million.

Keywords
Photovoltaic Plant, PV-SYST Software, Photovoltaic Performance, Levelized Cost of Electricity, Sultanate of Oman.

1. Introduction

As the global community increasingly shifts towards sustainable energy solutions, the development of renewable energy sources has become essential for addressing climate change and reducing dependence on fossil fuels. In this context, solar energy has emerged as a particularly promising option due to its abundance and declining costs. Oman, situated in the Arabian Peninsula, boasts an exceptionally high solar irradiation level, making it an ideal candidate for solar energy projects (Figure 1).

The Sultanate of Oman is endowed with high solar radiation levels, ranging from 2000 to 3000 Wh/m²/day (Gastli & Charabi, 2010), which positions it as a prime candidate for solar energy production (Tabook & Khan, 2021). The Oman Energy Master Plan 2040 envisages a substantial increase in electricity demand, projected to rise from 7221 MW in 2020 to approximately 21,840 MW by 2040, presenting both an opportunity and a challenge for the country's energy sector (Bentouba, Bourouis, Zioui, Pirashanthan, & Velauthapillai, 2021) (Sweetnam, 2014) (OQ, 2022) (Hindocha & Shah, 2020).

This study focuses on the proposed construction of a 22 MW photovoltaic (PV) solar power plant located in Rustaq-Juma, a region within the Al Batinah South Governorate of Oman, find it on Figure 1. Rustaq, known for its historical significance and rich cultural heritage, offers distinct geographical advantages for solar energy generation. The area benefits from ample sunlight exposure, with an average annual solar irradiance exceeding 7.17 kWh/m²/day, alongside relatively low cloud cover and minimal atmospheric obstructions (Solargis, 2023).

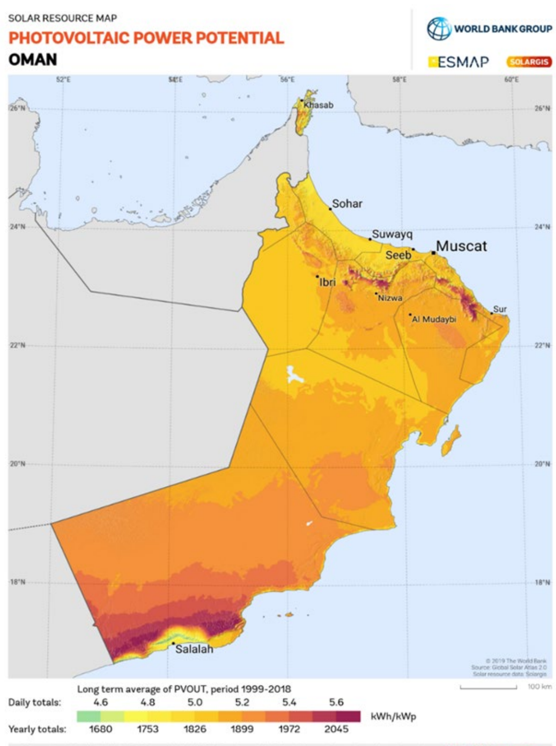

Figure 1. Map of Oman's solar irradiation

The geographical proximity of Rustaq to established infrastructure, including roads and electrical grids, further enhances the feasibility of the solar project. This placement not only supports efficient energy distribution but also facilitates potential grid interconnections that are critical for integrating renewable sources into the national energy grid. As Oman continues to diversify its energy portfolio, initiatives such as the Rustaq-Juma solar power plant are vital in contributing to the national goal of generating 30% of its energy from renewable sources by 2030, as outlined in the Sultanate's Vision 2040 strategy (OQ, 2022).

1.1 Motivation
This research aims to provide a comprehensive evaluation of a proposed 22 MW photovoltaic solar power plant located at Rustaq-Juma. Given Oman's commitment to diversifying energy sources and promoting renewable energy, this project aligns with national goals of reducing carbon footprints and ensuring energy security.

1.2 Objectives
The objectives of this study include:
- Evaluating the technical feasibility of solar power generation at Rustaq-Juma.
- Conducting an economic analysis to determine the viability of the solar project.
- Assessing environmental implications and contributions to sustainability.

2. Literature Review
The increasing demand for sustainable and renewable energy sources has led to an intense focus on solar energy solutions, particularly in regions with high solar irradiation, such as the Middle East. This literature review synthesizes findings from various studies, emphasizing both the potential and challenges associated with solar energy implementation in Oman and similar environments.

Recent research highlights the significant advancements in photovoltaic (PV) technology which have contributed to the decreasing cost of solar energy production. (Feldman, et al., 2024) indicated that the global average levelized cost of electricity (LCOE) for solar photovoltaics fell by over 70% from 2010 to 2017, making it a competitive alternative to fossil fuels. This trend aligns with the technological innovations in solar cell materials and manufacturing processes that have resulted in improved efficiencies and lower production costs.

In Oman specifically, the works of (Gopinath, 2018) demonstrate the country's strategic move towards renewable energy as part of its Vision 2040 initiative, which aims to diversify its energy mix and reduce reliance on fossil fuels. The authors conducted a comprehensive feasibility study of solar energy projects in Oman, emphasizing the importance of localized solar irradiance assessments. Their findings revealed an annual average solar irradiance of approximately 7.17 $kWh/m^2/day$ at optimal sites, supporting the case for large-scale solar installations, such as the proposed plant in Rustaq-Juma.

Furthermore, (Saadi & Ghosh, 2024) conducted a comparative analysis of different renewable sources in Oman, concluding that solar energy holds the most promise for large-scale deployment due to the country's favorable climatic conditions and vast land availability. They emphasized the need for supportive government policies, adequate infrastructure, and investment in grid connectivity to harness the full potential of solar energy.

Addressing environmental implications, a study by (Tabook & Khan, 2021) highlighted that transitioning to solar energy in Oman could significantly reduce greenhouse gas emissions. Their model estimated that a transition to 20% solar energy could lead to annual reductions of approximately 3.2 million tons of CO_2 equivalent emissions, positively impacting local air quality and contributing to global climate change mitigation efforts.

There are also challenges noted in the literature regarding solar energy deployment in arid regions. Dust accumulation on solar panels can significantly decrease their efficiency. (Said, et al., 2024) explored the effects of dust on PV systems and suggested that regular cleaning and innovative anti-soiling technologies are crucial for maintaining optimal energy output. Similarly, the intermittency of solar power generation necessitates the incorporation of energy storage solutions and improved grid management practices to ensure reliability and stability in energy supply (Maka & Chaudhary, 2024)

Overall, the literature reveals that while the potential for solar energy in Oman is substantial, strategic planning, governmental support, and innovative technological solutions must be incorporated to overcome existing challenges. The proposed solar power plant in Rustaq-Juma stands to reduce greenhouse gas emissions significantly while contributing to the local energy supply, thus reflecting the findings of various studies aimed at promoting sustainable energy practices in Oman and beyond.

References

3. Methods

To assess the viability of the proposed 22 MW photovoltaic solar power plant at Rustaq-Juma, a comprehensive methodology encompassing site assessment, system design, simulation modeling, and economic analysis was employed. This multidisciplinary approach integrates technical, environmental, and economic perspectives to ensure a thorough evaluation of the project.

3.1 Site Assessment

The initial phase involved a detailed site assessment, focusing on the solar resource availability and geographical characteristics of Rustaq-Juma. Key steps included:

- **Solar Irradiance Data Collection**: Long-term solar irradiance data were obtained from NASA's Langley Research Center and local meteorological stations. This data provided insights into average daily solar radiation, seasonal variations, and local weather patterns, essential for understanding the site's solar potential. The mean annual solar irradiance was determined to be approximately 7.17 kWh/m²/day.

- **Geographical and Climatic Analysis**: Evaluating geographical factors such as terrain, shading from surrounding structures, and land availability played a crucial role in determining the optimal placement and orientation of the solar arrays. Geographic Information System (GIS) tools were utilized to model the site and identify potential obstacles to solar exposure.

3.2 PV System Design

The design of the photovoltaic system was grounded in established engineering practices, supported by simulation technologies:

- **Configuration Selection**:

Various configurations were considered, including module type, array layout, and inverter specifications (Ahshan, Nasiri, Al-Badi, & Hosseinzadeh, 2020). High-efficiency mono- and polycrystalline solar panels were evaluated to determine their performance under local conditions.

- **Simulation Using PV-SYST**:

The PV-SYST software was employed for detailed performance modeling of the proposed system. This software facilitates simulation of the various components, including photovoltaic panels, inverters, and balance-of-system elements (Table 1). The PV systems program is designed according to the specifications given in Table 1, for all components, taking into account all information about the solar panels and inverters (Figure 2 and Figure 3).

Table 1. Summary of specifications for miscellaneous equipment.

S.No	Input Parameters	Results
1	Total power (kW)	22, 000 kW
2	Annual yield (kWh)	44, 506, 000 kWh
3	Capacity factor	22. 4%
4	CO2 avoided (t/y)	33, 400 tCO2eq

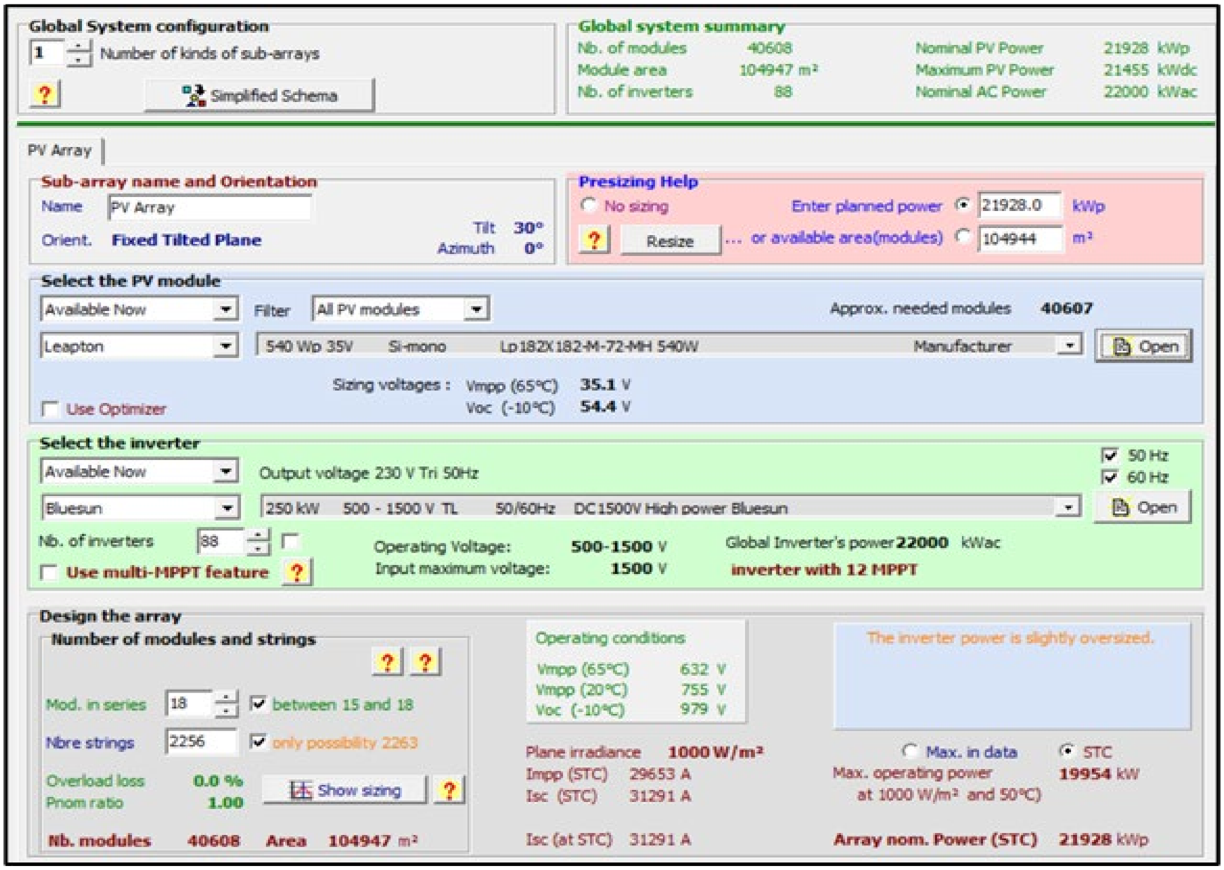

Figure 2. Illustration of the grid system definition (solar modules, inverters, array design)

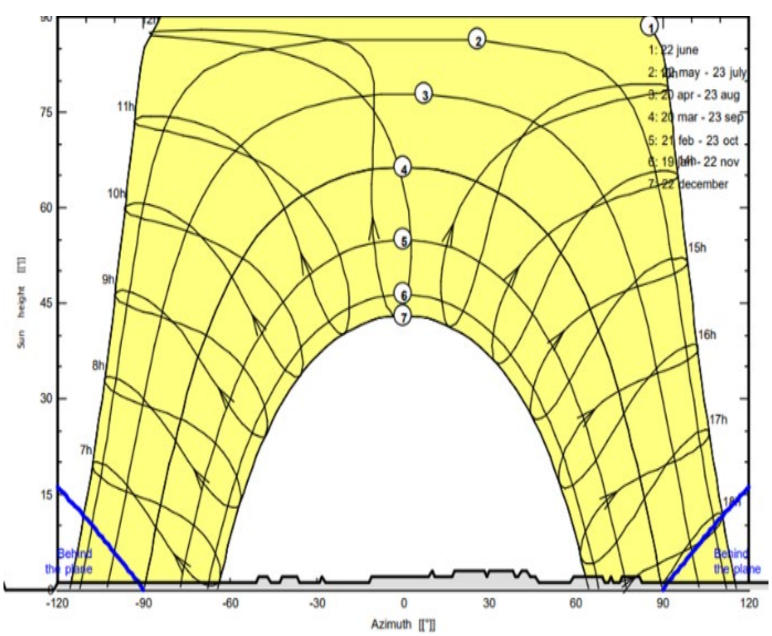

Figure 3. Depiction of solar paths at the station using Meteonorm horizon for latitude (23.548°) and longitude (57.559°)

Key output metrics, such as energy production estimates, system losses due to shading, and temperature impacts, were calculated to project annual energy generation. Successively, the data shown in Table 2 was obtained as a result of the simulation in the software.

Table 2. Geographical site parameters of the proposed site.

Months	Horizontal global irradiation (kWh/m^2)	Horizontal diffuse irradiation (kWh/m^2)	Ambient Temp (℃)	Wind velocity (m/s)
Jan	128. 9	42. 9	19. 31	1. 7
Feb	124	55. 1	20. 95	1. 69
Mar	177. 2	68. 6	24. 93	1. 79
Apr	176. 4	82. 8	29. 23	2. 1
May	207. 6	83. 5	34. 68	1. 99
Jun	190	93	34. 78	2. 01
Jul	194. 9	97. 8	33. 41	1. 9
Au	200	92. 9	31. 71	1. 71
Sep	185. 1	67. 3	29. 87	1. 9
Oct	163. 8	59. 1	28. 65	1. 71
Nov	131. 8	44	24. 5	1. 3
Dec	117. 5	43. 1	21. 13	1. 39
Year	1997. 2	830. 1	27. 8	1. 7

3.3 Economic Analysis

The economic assessment of the solar plant was conducted through a comprehensive cost-benefit analysis:

- **Capital and Operational Costs**:

Detailed estimates of the capital expenditure (CAPEX) were generated based on current market prices for solar technology components, installation labor, and grid connection. Operational expenditure (OPEX) parameters, including maintenance, insurance, and property taxes, were also considered.

- **Levelized Cost of Electricity (LCOE)**:

The LCOE was calculated using the formula:

$$LCOE = \frac{CAPEX + OPEX}{Total\ Electricity\ Production}$$

Where **CAPEX** (Capital Expenditure) is the upfront cost required to build and install the energy generation facility. This includes costs related to equipment, construction, and other initial investment. **OPEX** (Operational Expenditure) is the ongoing costs of operating and maintaining the facility. This can include fuel, labor, maintenance, and other operational costs incurred over the facility's lifespan. **Total Electricity Production**: The total amount of electricity the facility is expected to produce over its operational life, usually measured in megawatt-hours (MWh).

The LCOE provides a cost-per-unit of electricity produced, typically expressed in $/MWh or €/MWh, and it helps compare the cost-effectiveness of different energy generation technologies by normalizing costs over the lifespan of each project.

This metric facilitates comparison with other energy sources by providing a standardized cost per unit of electricity generated.

- **Discounted Payback Period and Net Present Value (NPV)**:

Financial viability was further analyzed through a discounted cash flow model. Key financial indicators such as the discounted payback period and NPV were assessed to evaluate the profitability of the investment over its expected lifespan, typically estimated at 25 years for solar projects (Mansouri, et al., 2016).

3.4 Environmental Impact Assessment

Environmental implications of the proposed solar power plant were systematically evaluated:

- **Carbon Emission Reductions**:

The potential reduction in greenhouse gas emissions was estimated by comparing the emissions from conventional energy sources displaced by the solar plant. The carbon offset was projected using emission factors for fossil fuels based on regional energy consumption data.

- **Ecological Considerations**:

A preliminary evaluation of the ecological impact, including land use and effects on local biodiversity, was conducted to ensure alignment with Oman's environmental regulations and commitments.

3.5 Risk Assessment

A risk assessment was performed to identify potential project risks related to financial, technological, and environmental factors. Risk mitigation strategies were outlined to address uncertainties surrounding market fluctuations, technological changes, and environmental regulations.
This multifaceted methodology ensures a comprehensive evaluation of the proposed solar power plant's viability, ultimately contributing to informed decision-making for stakeholders and regulators.

4. Data Collection

Data collection for the proposed 22 MW photovoltaic solar power plant at Rustaq-Juma involved a systematic and rigorous approach to ensure the accuracy and relevance of the information required for analysis. This section outlines the methodologies used to gather quantitative and qualitative data necessary for the feasibility assessment of the solar energy project.

4.1 Solar Irradiance Data

The primary data source for solar irradiance was derived from a combination of local meteorological stations, satellite imagery, and historical climate datasets:

Local Meteorological Stations: Data from the Oman Meteorology Department was accessed, which included historical records of solar radiation measurements. This data, spanning at least 10 years, provided a reliable basis for understanding annual solar patterns and variability.

Satellite Data: NASA's Surface meteorology and Solar Energy (SSE) database was utilized for obtaining satellite-derived solar irradiance data. This source offers comprehensive data on solar energy potential, enabling comparisons with local measurements to ensure consistency and accuracy.

Data Validation: To validate the obtained solar irradiance data, a cross-comparison was conducted with ground measurements from permanent weather stations within a 50 km radius of Rustaq-Juma. This triangulation confirmed the reliability of the solar resource estimations.

4.2 Climatic Data

In conjunction with solar irradiance, other climatic parameters were collected to assess their impact on the photovoltaic system's performance:

Temperature Data: Historical temperature records were obtained from the same local meteorological stations. Daily temperature averages, minimum, and maximum values were compiled to inform the thermal performance of PV modules.

Humidity and Wind Speed: Humidity and wind speed data were also collected to evaluate their effects on the efficiency and longevity of solar panels. This data assisted in modeling the overall energy production potential under various climatic conditions.

4.3 Site-Specific Data

To ensure an accurate assessment of the physical site conditions, several site-specific factors were considered:

Geographical Information: Geographic Information Systems (GIS) were employed to analyze the topographic characteristics and land availability of the Rustaq-Juma site. This included elevation data, land use surveys, and proximity to infrastructure.

Soil Analysis: A preliminary assessment of the soil type and condition was conducted to evaluate its suitability for installation and the potential need for stabilization measures, especially for mounting structures.

4.4 Economic and Market Data

In order to perform a robust economic analysis, data were collected regarding costs and market conditions:
Cost of Equipment and Installation: Pricing information for various photovoltaic technologies was sourced from industry reports, supplier price lists, and recent market studies. Quotes were obtained from local contractors for installation costs, which included detailed line items such as labor, materials, and auxiliary components.

Government Incentives and Policies: Information regarding local and national incentives for renewable energy projects was gathered from official government publications and policies. This data is crucial for understanding potential financial support mechanisms available to the project.

4.5 Stakeholder Consultations

To ensure the alignment of the project with community interests and regulatory requirements, stakeholder consultations were conducted:

Interviews and Surveys: Engaging with local stakeholders, including community leaders, government officials, and industry experts, facilitated the collection of qualitative data regarding community perceptions of solar energy and potential barriers to implementation.

Regulatory Framework Review: An in-depth review of environmental regulations and governmental policies governing renewable energy projects in Oman was undertaken to guarantee compliance and to identify any required permits and approvals.

4.6 Data Consolidation and Analysis

Once collected, data were consolidated into a centralized database, ensuring comprehensive organization and accessibility for analysis. Statistical tools and software were employed to analyze and visualize the data, enabling the derivation of insights about the potential performance of the proposed solar power plant.

This structured approach to data collection establishes a solid foundation for evaluating the feasibility, effectiveness, and implications of the solar power project, ensuring informed decision-making moving forward.

5. Results and Discussion

5.1 Performance Metrics

The simulation results indicated that the proposed 22 MW solar power plant would produce approximately 38.009 GWh of energy annually, with a performance rate of around 0.82. The output was seen to fluctuate seasonally, peaking in spring months due to optimal irradiance.

Figure 4 illustrates the relationship between the energy injected into the grid (MWh) and the performance ratio of the PV plant. It is essential to evaluate the performance ratio of a PV plant before installation because it is a quality factor that evaluates the effectiveness of the plant. The performance ratio indicates the deviation of the actual output of the plant from the theoretical or realistic electrical output shows in b. Energy losses occur during the conversion of DC energy from the PV array to AC energy and due to AC wiring losses. Additionally, the efficiency of the PV system decreases with high ambient temperatures, resulting in lower production in summer months and higher losses in winter months illustrated in c (Figure 5 and Figure 6).

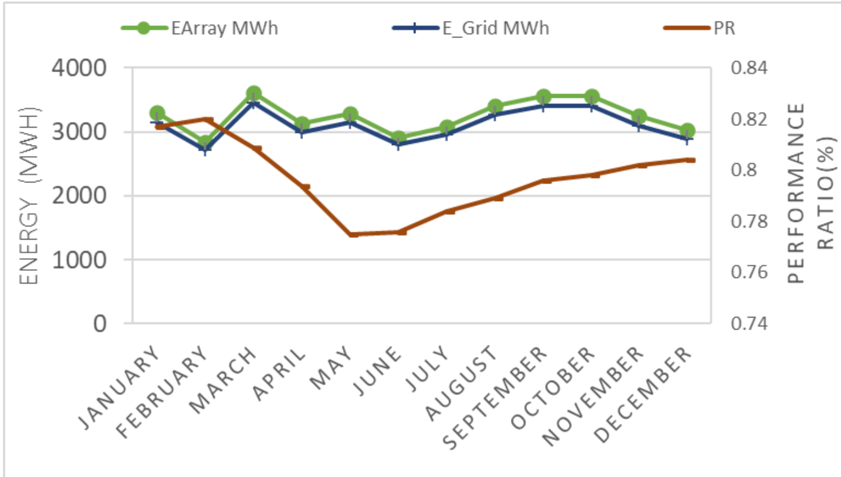

Figure 4. Relationship between the energy injected into the grid (MWh) and the performance of the PV plant

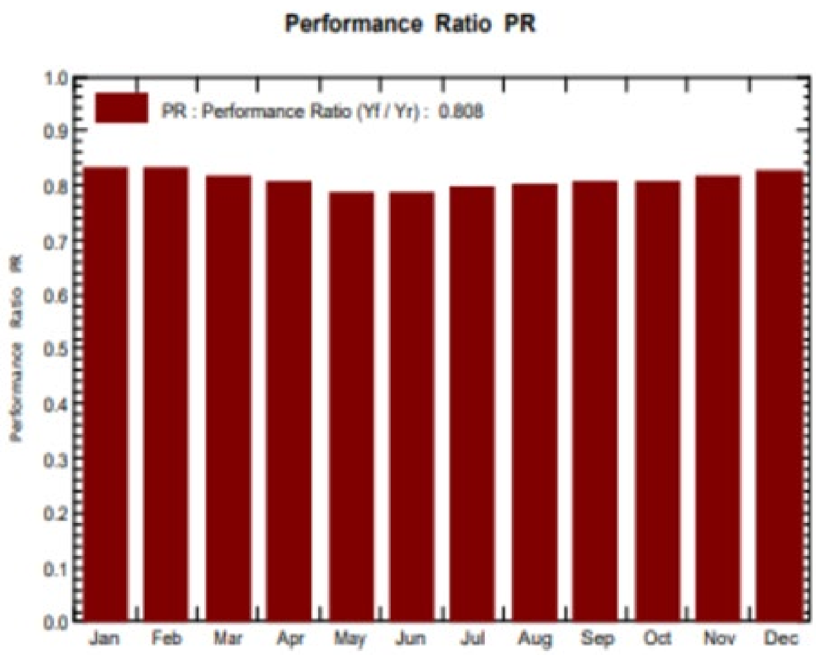

Figure 5. Energy losses occurred during the conversion of DC energy from the PV array to AC energy and due to AC wiring losses

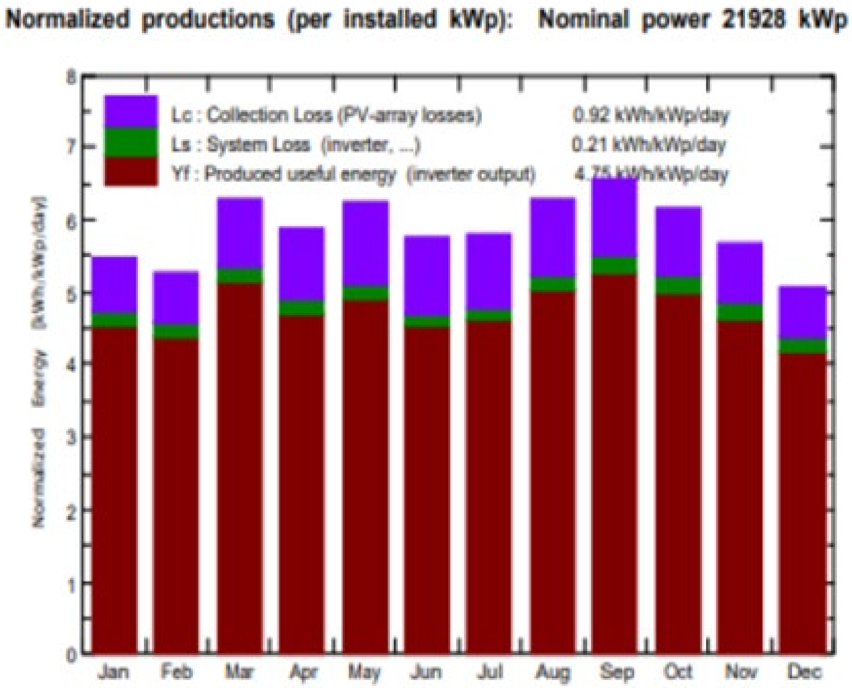

Figure 6. Decrease in efficiency of the PV system with high ambient temperatures

5.2 Economic Feasibility

The Levelized Cost of Electricity was calculated at $0.06 per kWh, positioning the project competitively against conventional fossil fuel alternatives, which are expected to increase in price as reserves deplete. The discounted payback period of 11 years suggests a viable return on investment, considering potential policy incentives for renewable energy initiatives. Table 3 shows that the annual production of the power plant is 3. 8 GWh/year, and the revenue generated from the electricity sales ranges from 1. 977 M USD to 2. 767 M USD, depending on the selling price.

Table 3. Revenue from electricity sales of the power plant

Annual Production	Price 1 (USD/kW)	Price 2 (USD/kW)	Price 3 (USD/kW)
3. 8 GWh/year	0. 052	0. 065	0. 0728
Annual Revenue	1. 977 M USD	2. 471 M USD	2. 767 M USD

5.3 Environmental Implications

The development of the solar power plant is projected to offset approximately 15,900 tons of CO2 emissions annually, contributing positively to the local and global environmental landscape. The integration of solar technology not only fulfills energy needs but also enhances sustainability goals set forth by Oman's Vision 2040 initiative.

6. Conclusion

This study highlights the significant potential for solar energy development in Rustaq-Juma, Oman, supported by favorable solar conditions and economic metrics. The proposed 22 MW photovoltaic solar power plant offers a sustainable solution to meet increasing energy demands while reducing carbon emissions. Continued investment and focus on solar technologies can accelerate Oman's transition to a more sustainable energy future.

As Oman seeks to diversify its energy resources, this analysis serves as a foundational framework for policymakers and stakeholders to explore the viability of renewable energy projects, ultimately contributing to the nation's long-term energy security and environmental objectives.

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Biographies

Navid Nasiri is a PhD candidate in Electronics at Sultan Qaboos University, specializing in advanced electronics systems. With a Master's degree in Electronics from Sepidan Islamic Azad University, where he focused on the telemetry of methane using carbon dioxide lasers, Navid has cultivated a strong foundation in renewable energy solutions, solar energy systems, and robotics. His research encompasses innovative projects like oil spill detection using UAVs, microgrid inverter design, and water harvesting technologies. He has contributed extensively to academia through multiple publications in high-impact journals and is co-authoring a book chapter on AI and robotics applications in the oil and gas industry. In addition to his academic achievements, Navid has held leadership roles in green energy companies, focusing on solar and biomedical engineering projects. His work bridges the gap between academia and industry, driving innovations that address real-world energy challenges while advancing academic research in the field of electronics.

Dr. Sulaiman Al Hasmi holds a B.Sc. in Physics from Nizwa University, an M.Sc. in Renewable Energy and Architecture from Nottingham University, and a Ph.D. in Energy Resources from Leeds University. He has extensive experience in solar technology engineering, renewable energy design and manufacturing, and teaching. Al Hashemi has published several research papers on solar thermal systems, energy storage, and renewable energy technologies. Currently, he is a research assistant at the Center for Environmental Studies and Research at Sultan Qaboos University and is focused on solar concentrator with Stirling engine and PCM-storage hybrid model in Oman.

Rayyan Muhammad Rafikh is an undergraduate in Engineering from Manipal Institute of Technology, majoring in Mechatronics. My interests lie in research in the fields of Robotics, Artificial Intelligence, Autonomous Systems, Aerospace, Energy and Sustainability. An engineering student of an inter-disciplinary majors looking forward to contribute to the advancement of technology and wanting to discover and learn more about aerospace, automobile, autonomous, and AI systems, thereby implementing the knowledge of mechanical, computer science, robotics and electronics in research and developing solutions that could help the earth, humanity and nations.

Dr. Hooman Nasiri is an Assistant Professor of Economics at the Islamic Azad University, Bushehr Branch. He was born on February 6, 1980, and is fluent in English. He obtained his Ph.D. in International Economics from the Islamic Azad University, Shiraz Branch, in 2020. Since then, he has been actively teaching and conducting research in his field. His areas of expertise include economic modeling and international trade, with a particular focus on the economic stability of Iran's industrial sector. He has been a faculty member at the Islamic Azad University, Bushehr Branch, since 2007, where he also serves as the Head of the Department of Economics and Customs. He has published several research papers in reputable journals, with his work exploring topics such as the impact of industrial export diversification on revenue stability and the use of composite leading indicators to forecast business cycles. Dr. Hooman has co-authored with various researchers and contributed to both national and international publications, showcasing his ongoing commitment to advancing knowledge in the field of economics.

Maryam Farrizi is an accomplished electronics engineer with expertise in project management and innovative design, particularly within renewable energy and electronic systems. She holds an M.Eng. in Electronic Engineering from Islamic Azad University of Sepidan, where her research focused on solar-based cooling systems. With over a decade of experience in R&D, Maryam has led significant projects in inverter design and solar power systems across multiple roles, including her current position as a Research Assistant at Sultan Qaboos University. She has published numerous articles and contributed to various international conferences, establishing herself as a knowledgeable figure in sustainable energy. Beyond her technical skills, Maryam has a creative side, actively participating in activities like swimming, dancing, and singing. She has recorded four music clips and maintains a presence on social media. Skilled in tools like MATLAB and Proteus, she brings a hands-on approach to her work, complemented by her background in training and teaching in robotics and solar energy system design.