Techno-Economic and Environmental Optimization of a Grid-Connected Photovoltaic-Utility Hybrid System for Industrial Applications in Sohar, Oman

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ABSTRACT

The growing need for affordable and eco-friendly sources of industrial energy has increased interest in Photovoltaic (PV)-utility hybrid power plants. Most current studies use synthetic load profiles, thus limiting the design accuracy of PV-utility hybrid systems. In this paper, the performance of grid-connected PV-utility hybrid power plants is analyzed for an industrial plant in Sohar, Oman, based on the actual measured 24 h industrial load profile under three different operating scenarios. HOMER Pro software is employed to estimate the technical, economic, and environmental performance of the system. The novelty of the proposed work is that the actual measured industrial load profile is considered during the optimization of the PV-utility hybrid system, making the design analysis more accurate and specific. Simulation results show that the hybrid system attains a Levelized Cost of Energy (LCOE) of 0.030–0.032 $/kWh, a payback period of 3.7–3.9 years, and an Internal Rate of Return (IRR) of 25–26%, whereas the grid-only LCOE is 0.156 $/kWh. Furthermore, the hybrid system reduces CO_2 emissions by approximately 62%. These results demonstrate that the proposed hybrid system is technically feasible, economically profitable, and environmentally friendly.

Keywords-hybrid energy system; solar Photovoltaic (PV); industrial load optimization; renewable energy integration; grid-connected PV; techno-economic analysis

I. INTRODUCTION

A. *International Energy Demand and Environmental Context*

Electricity consumption throughout the world has risen sharply due to factors such as population growth, industrialization, and technological progress [1]. While the use of renewable energy is gradually rising, non-renewable resources like coal, petroleum, and natural gas are still widely used in producing electricity, causing significant emissions of greenhouse gases [2]. The industrial sector consumes a substantial amount of electricity, along with being responsible for significant greenhouse gas emissions [3]. Hence, switching to cleaner sources of energy is necessary for sustainable development worldwide.

B. Photovoltaic Technology and Hybrid System Development

The development in Photovoltaic (PV) technology and the reduction in the cost of modules have led to widespread PV adoption [4]. Nevertheless, the inherent unpredictability and dependency on weather conditions of PV generation have posed problems for stand-alone applications [5]. The hybrid PV-utility system is a proven technique that provides an uninterrupted energy supply, taking advantage of the economic feasibility of PV power generation and grid stability [6]. Hybrid Renewable Energy Systems (HRES) can enhance system efficiency, reliability, and economy through the complementarity of energy resources [7, 8]. Grid-tied PV systems are ideally suited to industrial facilities, since they lower operating expenses and greenhouse gas (CO_2) emissions without necessitating massive energy storage capacity [9, 10].

C. Renewable Energy Context in Oman

Oman has committed to diversifying its energy portfolio to achieve 30% renewable energy by 2030 [11]. The country receives high levels of solar radiation, especially in industrially important cities such as Sohar, Marmul, and Fahud [12]. Figure 1 illustrates the solar radiation levels in Oman. Government schemes, namely Sahim I and II, encourage distributed PV integration into the grid. Oman's abundant solar resource was validated by authors in [13], along with barriers to the widespread adoption of PV technology, while the future outlook of renewable energy in Oman was reviewed by authors in [12].

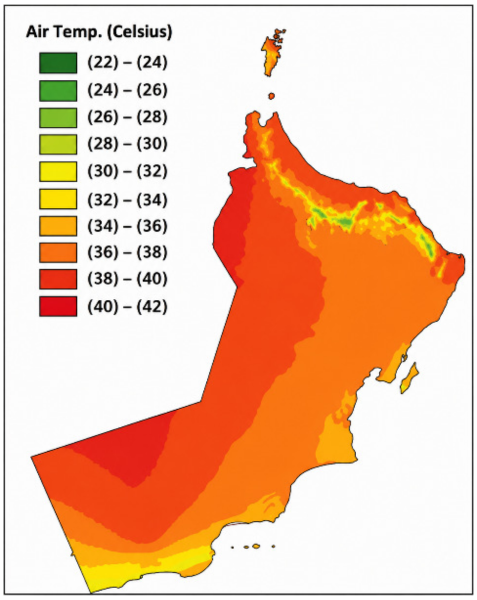


Fig. 1. Solar radiation in Oman.

D. Techno-Economic Optimization of Photovoltaic Systems

Optimization of PV systems from a techno-economic perspective ensures minimum lifecycle cost and maximum energy production [14]. In general, international research studies have indicated good Levelized Cost of Energy (LCOE) performance for rooftop PV systems, but this is highly dependent on solar resource assessment, PV system size, and inverter selection. It is important to highlight that the vast majority of previous studies have used artificial or synthesized load profiles for their analysis, which may undermine the reliability of system design, especially for industrial facilities with irregular load requirements [15, 16].

HOMER Pro has been widely used to simulate and optimize energy systems in previous works [17, 18]. Previous studies that analyzed grid-connected PV systems using the HOMER Pro tool, in particular within the Middle East and Gulf Cooperation Council regions, indicated LCOE values between 0.06 and 0.12 $/kWh [19-21]. Hybrid PV-grid systems with energy storage have been investigated more frequently, whereas hybrid PV-grid systems without energy storage, relevant to the industrial facility considered in this study, are much less common [21].

E. Research Gap, Objectives, and Novelty

Research conducted so far in PV applications has mainly focused on residential rooftop applications, rural electrification, or utility-scale applications. However, the industrial electricity demand profile is highly fluctuating and uncertain; very few research works have used industrial load data to evaluate hybrid PV-utility systems. In fact, most existing research works use synthetic load profiles that cannot be used effectively to design PV systems and perform techno-economic analysis.

In this research, an industrial load profile is used to design and optimize a hybrid PV-utility system connected to the electrical grid in an industrial plant located in Sohar, Oman. Specifically, the research objectives are as follows: (i) optimizing PV system sizing based on an actual 24 h industrial load profile for three scenarios; (ii) evaluating the proposed PV system performance using HOMER Pro software; and (iii) quantifying environmental benefits as a reduction in CO_2 emissions. The main novelty of this research is the use of real industrial load data to design and optimize PV-utility hybrid systems.

II. METHODOLOGY

A. System Configuration

The suggested system consists of a PV system that feeds electricity to the industrial facility (Figure 2). The power generated by the PV system is used to meet the load demand first, whereas excess power is curtailed without being exported to the grid. If the PV-generated power is insufficient to meet the demand, the grid supplies the additional electricity required [22].

B. Measurement Setup and Data Acquisition

The load and PV generation data have been collected using the SMA Sunny Boy SB2000HFUS-30 inverter monitoring system, which tracks the AC power generation along with hourly energy generation. The load testing was carried out on several days at the Sohar University rooftop site (24°17.9′N, 56°46.8′E; tilt: ≈24°, azimuth: 180°). Three different 24 h load test curves were recorded to account for the diversity of industrial operational patterns. The data were further cross-checked by comparing them with the electricity bills of the facility.

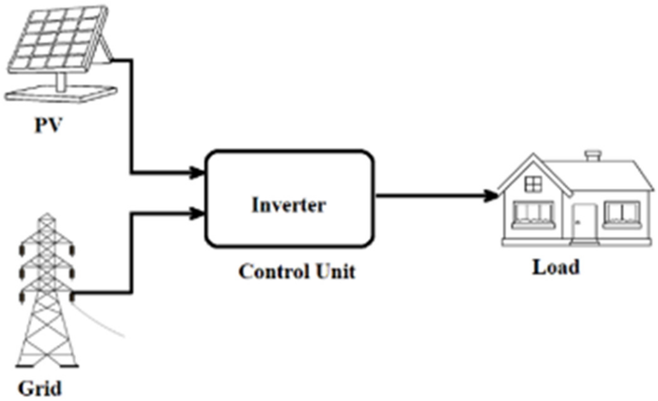


Fig. 2. The suggested hybrid PV-utility system including a grid-tied inverter (control unit).

C. Photovoltaic System Description

The PV system is made up of six modules of the Canadian Solar MaxPower CS6U-340M monocrystalline solar panel, with a total capacity of 2.04 kWp (6S–1P) and an efficiency of 17.49%. The inverter used is the SMA Sunny Boy SB2000HFUS-30 (2.0 kW AC rated capacity, efficiency ≈97%).

Losses incurred in the system include dirt accumulation on the panels (3%), wiring losses (2%), and mismatch losses (1%). A degradation factor of 0.5% annually is included over the 25-year analysis horizon. Table I presents the core system parameters.

D. Load Scenarios

Three industrial load profiles were evaluated to assess system performance under different industrial demand conditions (Table II):

- Load 1: Base load with a single peak at noon (1.80 kW).
- Load 2: Moderate load with a 2 h peak during the day (1.48 kW).
- Load 3: Higher Load with distinct peaks during morning and afternoon (2.32 kW).

TABLE I. CORE SYSTEM PARAMETERS

Item	Specification
Topology	Grid-tied PV-utility, no storage, no export (self-consumption)
Location	Sohar University rooftop (tilt ≈ 24°, azimuth 180°)
PV modules	6 × Canadian Solar MaxPower CS6U-340M (monocrystalline)
Array DC rating	2.04 kWp (6S–1P)
Module efficiency	17.49% (STC)
Inverter	SMA Sunny Boy SB2000HFUS-30 (240 V), P_AC,max = 2.0 kW, η ≈ 97%
Losses (baseline)	Soiling 3%, wiring 2%, mismatch 1%
Degradation	0.5% per year
Load data	Measured 24 h industrial profiles, 1 h resolution; three scenarios
Tariff (imports)	14/17/30 Baisa·kWh^{-1} for 0–4,000 / 4,001–6,000 / >6,000 kWh per month
Analysis horizon	25 years; discount rate per Section II.D scenarios

TABLE II. DAILY SIMULATION LOAD EXTREMES

Scenario	Peak power (kW)	Peak hours (local time)	Notes
Load 1	1.80	12:00–13:00 (1 h)	Single noon peak; base load 0.34–0.50 kW at night.
Load 2	1.48	12:00–14:00 (2 h)	Moderate 2 h mid-day peak; night base as above.
Load 3	2.32	10:00–11:00 and 13:00–14:00 (2 h total)	Separated peaks; night base as above.

The consistency of the results was verified through independent simulations for each case using HOMER Pro. Figure 3 shows the daily load profiles for the three scenarios, whereas Figure 4 presents snapshots of the energy balance obtained from the SMA monitoring system.

E. Economic Assumptions and Simulation Framework

HOMER Pro Version 3.14 (HOMER Energy LLC, https://www.homerenergy.com) was employed for the simulation of system behavior and the calculation of Net Present Cost (NPC), LCOE, and CO_2 reduction potential. The economic assumptions are provided in Table III. The economic study period is 25 years, and the interest rate is 6%. A sensitivity analysis was carried out on the cost of electricity, discount rate, and PV cost.

TABLE III. ECONOMIC INPUTS AND ANALYSIS ASSUMPTIONS

Item	Specification
PV module CAPEX	USD 1,397.50 per CS6U-340M module
PV module replacement	USD 40.50 per module
Inverter CAPEX	USD 1,375.54
Inverter replacement	USD 60.02 (assumed at year 12)
Balance-of-system & installation	Included implicitly in HOMER CAPEX entries
O&M	1% of PV CAPEX per year
PV lifetime/analysis horizon	25 years
Emissions accounting	CO_2 from grid imports only; report % reduction vs. grid-only baseline

F. Performance Metrics and Economic Assessment

Performance indicators include:

- PV power output is estimated as follows:

$$P_{PV} = P_{rated} \times \frac{G}{G_{STC}} \times n_{pv} \quad (1)$$

- NPC is calculated as:

$$\text{NPC} = \frac{C_{ann}}{CRF(i,n)}, CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n-1} \quad (2)$$

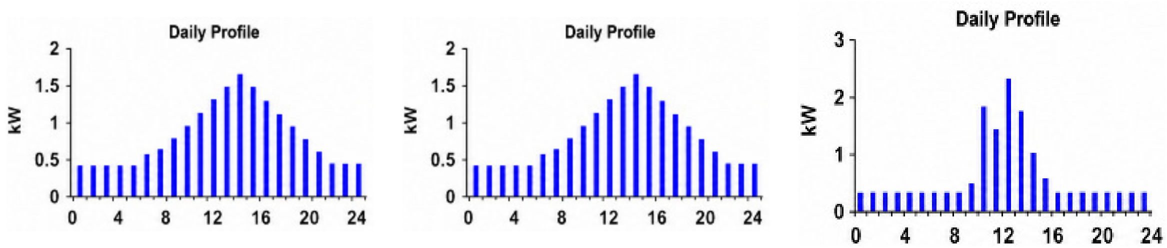
- LCOE is given by:

$$\text{LCOE} = \frac{C_{ann}}{E_{served}} \quad (3)$$

- Carbon emission reduction is calculated as:

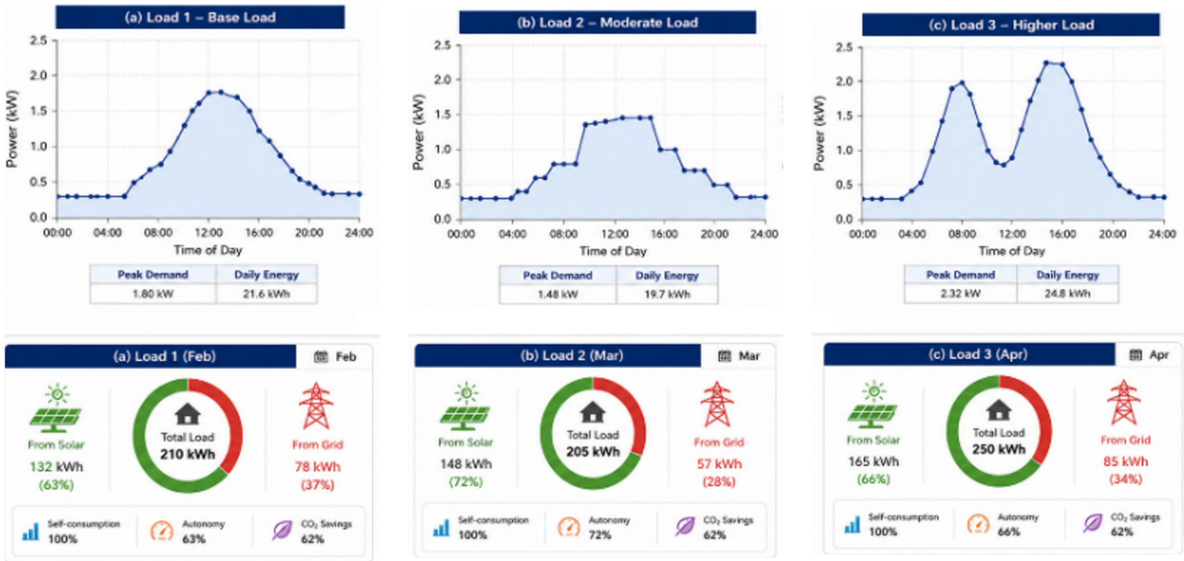
$$CO_{2,avoided} = E_{PV} \times EF_{grid} \quad (4)$$

These indicators measure the cost-effectiveness, energy efficiency, and environmental performance of the grid-only and hybrid systems.



(a) (b) (c)

Fig. 3. Daily load profiles: (a) load 1, (b) load 2, and (c) load 3.



(a) (b) (c)

Fig. 4. Snapshots of the energy balance from the SMA monitoring application: (a) load 1 (Feb), (b) load 2 (Mar), and (c) load 3 (Apr).

III. RESULTS

There are clear economic and environmental benefits to the hybrid solar–utility system when compared to the grid-only system for all load cases. Some of the most important findings are outlined in Table IV.

A. Economic Performance

The hybrid system configuration lowers NPC compared with the grid-only case, decreasing from \$8,295 to a range of \$2,964–\$3,274 across all load scenarios. The LCOE is reduced to 0.030–0.032 \$/kWh, compared with 0.156 \$/kWh for the grid-only energy source configuration, corresponding to an approximate 80% reduction. Figure 5 illustrates the lowest-cost system configuration, whereas Figure 6 presents the cost comparison between both systems.

The key outcomes are:

- NPC decreased from \$8,295 USD (grid) to \$2,964–\$3,274 (hybrid).
- LCOE: 0.03–0.032 \$/kWh.
- Payback period: 3.7–3.9 years.
- Internal Rate of Return (IRR): 25–26%; Return on Investment (ROI): 21–22%.

TABLE IV. ECONOMIC AND ENVIRONMENTAL PERFORMANCE COMPARISON

Description	Load 1		Load 2		Load 3	
	Hybrid	Grid	Hybrid	Grid	Hybrid	Grid
Peak power of load profiling [kW]	1.800	–	1.448	–	2.320	–
NPC [\$]	2,964	8,295	3,274	8,295	3,101	8,295
Initial capital [\$]	2,234	0.00	2,195	0.00	2,157	0.00
Operation cost [\$/yr]	56.42	641.62	83.40	641.62	73.02	641.62
Levelized cost [\$/kWh]	0.0300	0.156	0.0322	0.156	0.0316	0.156
CO_2 emissions [kg/yr]	919	2,599	1,075	2,599	975	2,599
PV generation [kWh/yr]	8,796	–	8,643	–	8,489	–
Inverter output [kWh/yr]	6,191	–	6,170	–	6,040	–
Converter losses [kWh/yr]	191	–	191	–	187	–
IRR [%]	26	–	25	–	26	–
ROI [%]	22	–	21	–	22	–
Simple payback [yr]	3.8	–	3.9	–	3.7	–
Total production [kWh/yr]	10,251	–	10,343	–	10,031	–
Total consumption [kWh/yr]	7,646	–	7,870	–	7,582	–

ROI: Return on Investment; IRR: Internal Rate of Return.

B. Environmental Performance

With respect to CO_2 emissions, the integrated system decreases annual CO_2 emissions from 2,599 kg/yr (grid-only configuration) to 919–1,075 kg/yr, corresponding to a reduction of approximately 59%–65% per year, averaging

62%. Figure 7 shows an example of CO_2 savings from the SMA monitoring system.

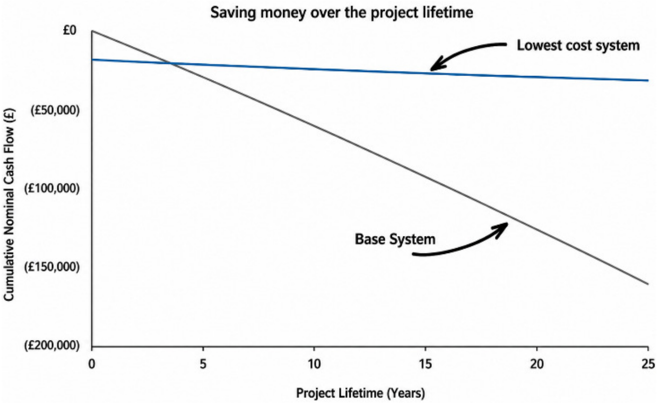
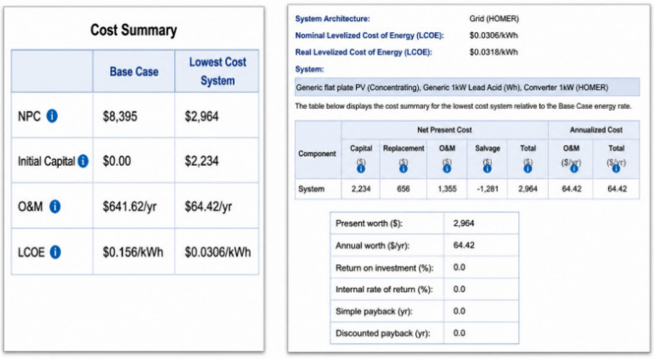


Fig. 5. Lowest-cost system configuration (proposed system) versus base case (grid-only).



Cost Summary

	Base Case	Lowest Cost System
NPC	$8,395	$2,964
Initial Capital	$0.00	$2,234
O&M	$641.62/yr	$64.42/yr
LCOE	$0.156/kWh	$0.0306/kWh

System Architecture: Grid (HOMER)
Nominal Levelized Cost of Energy (LCOE): $0.0306/kWh
Real Levelized Cost of Energy (LCOE): $0.0318/kWh
System:
Generic flat plate PV (Concentrating), Generic 1kW Lead Acid (Wh), Converter 1kW (HOMER)
The table below displays the cost summary for the lowest cost system relative to the Base Case energy rate.

Component	Net Present Cost					Annualized Cost	
	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)	O&M ($/yr)	Total ($/yr)
System	2,234	656	1,355	-1,281	2,964	64.42	64.42

Present worth ($):	2,964
Annual worth ($/yr):	64.42
Return on investment (%):	0.0
Internal rate of return (%):	0.0
Simple payback (yr):	0.0
Discounted payback (yr):	0.0

Fig. 6. Cost comparison chart between both systems.

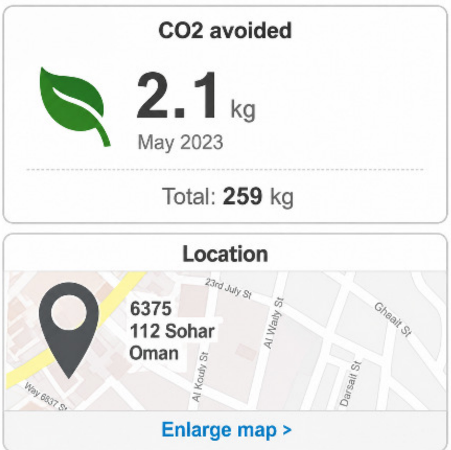


Fig. 7. CO_2 savings on May 28, 2023, using the SMA monitoring system.

C. Energy Production

Annual PV generation ranges from 8,489 to 8,796 kWh/yr across the scenarios. Inverter output accounts for 6,040–6,191 kWh/yr after conversion losses of 187–191 kWh/yr. Total system consumption (PV + grid) is 7,582–7,870 kWh/yr. Figure 8 shows the annual production and consumption profiles of the hybrid system.

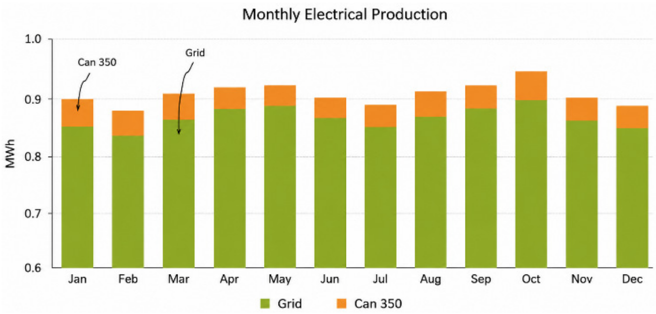


Fig. 8. Energy production and consumption of the hybrid system.

IV. DISCUSSION

In conclusion, the results indicate that integrating PV with the utility grid provides considerable techno-economic and environmental benefits for industrial operations in Sohar, Oman [23]. The optimized LCOE is in the range of 0.030–0.032 $/kWh, which is significantly lower than the grid electricity cost of 0.156 $/kWh.

A. Comparison with Previous Studies

It is evident that the LCOE obtained in this study (0.030–0.032 $/kWh) is lower than those reported in related literature: authors in [14] reported an LCOE of 0.07–0.09 $/kWh for residential grid-connected PV systems in Queensland; authors in [21] reported 0.06–0.10 $/kWh for a similar PV–utility hybrid system in GCC countries; and authors in [24] reported 0.05–0.08 $/kWh for industrial rooftop PV systems in Europe. The lower LCOE in this study is mainly attributed to the high solar irradiance in Sohar (annual average of 5.521 kWh/m²/day), the absence of battery storage costs due to grid backup, and the optimization of PV sizing based on actual industrial load data. The payback period of 3.7–3.9 years is also shorter compared with 5–8 years reported in similar studies in the MENA region.

B. Limitations

Several limitations of this study should also be acknowledged. First, the system size considered is relatively small (2.04 kWp), and scalability to industrial-scale installations requires further validation. Second, battery storage was not included; although this aligns with the grid-connected no-storage topology, it may limit potential demand management benefits [25]. Third, only one year of load data was considered, and yearly variations in industrial and solar resources were disregarded [26]. Finally, electricity tariffs were assumed fixed, and any future changes could impact the calculations.

V. CONCLUSIONS

This research presents the techno-economic optimization and development of a grid-connected PV-utility hybrid system for an industrial facility in Sohar, Oman, based on actual load demand data and HOMER Pro simulations. The main findings based on the results of simulations are:

- The optimized PV system (2.04 kWp) generates a Levelized Cost of Energy (LCOE) of 0.030–0.032 $/kWh, which corresponds to a reduction in the cost of electricity from 0.156 to 0.030–0.032 $/kWh, representing an approximate 80% saving compared with the grid-only tariff.
- The simple payback period of the system is 3.7–3.9 years, whereas the Internal Rate of Return (IRR) is 25–26% and the Return on Investment (ROI) is 21–22%, demonstrating strong economic attractiveness under the considered assumptions.
- CO_2 emissions are reduced annually by approximately 62% (from 2,599 to 919–1,075 kg/yr), indicating the significant environmental benefits of the PV system.
- The results indicate that PV system performance is sensitive to the shape of the industrial load profile. Different load scenarios influence grid consumption, system cost, and renewable energy percentage.
- The results are specific to the considered system size and tariff structure. Under these conditions, grid-connected PV-utility hybrid systems represent a feasible, economically beneficial, and environmentally friendly solution for industrial electricity supply in high solar irradiation regions such as Oman.

The main contribution of this study is the use of real measured industrial load profiles obtained over a 24 h period from an operational industrial setup in Sohar, Oman. Most previous studies have relied on synthetic or assumed load profiles, which may not accurately represent real industrial demand variability. By incorporating measured data across three load scenarios, this study provides a more realistic system design and evaluation framework.

In comparison with the existing literature, the results are highly competitive. The achieved LCOE of 0.030–0.032 $/kWh is lower than values reported in [14] (0.07–0.09 $/kWh), [21] (0.06–0.10 $/kWh), and [24] (0.05–0.08 $/kWh). This improved performance is mainly attributed to high solar irradiance in Sohar (5.521 kWh/m²/day), the absence of battery storage costs, and optimization based on real industrial load data. The system also demonstrates strong economic performance, with a payback period of 3.7–3.9 years, IRR of 25–26%, and approximately 62% reduction in CO_2 emissions.

DECLARATIONS OF COMPETING INTERESTS

The authors declare no competing interests.

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DATA AVAILABILITY

The 24 h industrial load profile datasets used in this study were collected from the rooftop PV installation at Sohar University. The datasets are available upon request from the corresponding author, subject to institutional data-sharing policies.

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