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Techno-Economic Optimization of a Grid-Tied Photovoltaic System for Schools in Saudi Arabia

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ABSTRACT

The educational sector in Saudi Arabia represents a significant portion of the national energy load, with government-constructed buildings accounting for approximately 13% of the total consumption, largely driven by air conditioning demands in the harsh climate of the Eastern Province. This project investigates the techno-economic feasibility of integrating a grid-tied photovoltaic (PV) system into a standard elementary school in Dammam to reduce operational costs and align with the renewable energy targets of Saudi Vision 2030.

Using HelioScope for physical design and HOMER Pro for economic optimization, a 149 kWp solar PV system was modeled for the "Al Madinah Al Munawwarah School." Although initially modeled to evaluate hybrid configurations, the optimization demonstrated that a strictly grid-tied PV system was the most viable. The design utilized the building rooftop and football court structure to overcome space constraints, deploying 240 high-efficiency panels. The simulation results indicate that the proposed system generates sufficient energy to reduce the grid reliance of the school from 100% to 52.1%, reducing the peak demand during active academic hours.

The techno-economic analysis reveals a levelized cost of energy (LCOE) of 0.23 SAR/kWh, which is significantly lower than the governmental tariff of 0.32 SAR/kWh. The project demonstrates strong financial viability with a net present cost (NPC) reduction of 15% compared with the base case, a simple payback period of 7.5 years, and an internal rate of return (IRR) of 12.6%. Replicating this model could significantly relieve the municipal grid, validating the strategic advantage of school rooftops for decentralized generation.

Keywords: grid-tied photovoltaic, HOMER Pro, school energy profiling, distributed generation, Saudi Vision 2030, techno-economic analysis

1. INTRODUCTION

The educational sector in Saudi Arabia represents a major portion of government facilities, contributing significantly to the national energy demand. According to Alshibani [1], government-constructed buildings account for approximately 13% of the total energy consumption in Saudi Arabia. The majority of this consumption is driven by air conditioning (AC) due to the harsh hot and humid climate of the Eastern Province.

This project utilizes the "Standard Reference School" profile derived from real-world datasets of 352 operating schools to design a hybrid renewable energy system (HRES). The goal is to lower the specific energy consumption and reduce operational costs under the governmental tariff of 0.32 SAR/kWh.

1.1. Literature Review. Driven by the Vision 2030 goals, the integration of renewable energy into public facilities has gained significant traction within the Saudi Arabian research community. Recent state-of-the-art research has emphasized the necessity of decarbonizing the educational sector. Alshibani (2020) established foundational energy consumption patterns for Saudi schools and identified air conditioning as the primary load driver, with a 97% correlation with total usage [1]. Building on this, Almasri et al. (2025) conducted an updated techno-economic analysis of Saudi government schools, reporting that energy use intensity (EUI) typically ranges between 20.4 and 38.8 kWh/m^2/yr, concluding that achieving "zero-bill" status is technically feasible but requires significant retrofitting [2].

Furthermore, state-of-the-art 2024 research in Buraidah City focused on the "zero-bill" concept for schools, finding that surplus generation during weekends and summer breaks is critical for offsetting the high costs of peak operational hours [3]. This is further supported by a comprehensive 2024 study by Imam et al., which validated the techno-socioeconomic feasibility of widespread solar photovoltaic (PV) integration across Saudi Arabia, emphasizing that grid-tied configurations significantly outperform off-grid setups in urban environments because of the elimination of expensive battery storage requirements [4].

Recent optimization studies in 2025 using the HOMER Pro engine also confirmed these findings. Almohammadi and Allouhi (2025) conducted a techno-economic assessment of grid-connected solar PV systems in the Saudi building sector and established that optimized distributed generation architectures are highly effective at lowering both the levelized cost of energy (LCOE) and greenhouse gas emissions[5]. Similarly, studies on grid-connected PV systems in other regions of Saudi Arabia have demonstrated promising economic indicators. Research conducted at Al Baha University optimized a hybrid grid/PV system to achieve a cost of energy (COE) of approximately 0.29 SAR/kWh, validating the economic advantage of renewable integration over standard grid tariffs[6].

Despite these recent advancements, a research gap remains regarding localized, highly specific techno-economic optimization mapped to the distinct operational constraints of the Eastern Province. This project bridges this gap by proposing a grid-tied PV system explicitly tuned to this region. To achieve this goal, this study utilized statistical mean data from Alshibani[1] to establish an accurate baseline electrical load profile for a standard reference school. Building upon this baseline, HelioScope was employed to physically design and maximize the solar array output across the available rooftop area. Finally, HOMER Pro was used to conduct a rigorous techno-economic optimization aimed at minimizing the net present cost (NPC) and reducing the heavy air-conditioning consumption of the facility[7,8].

2. METHODOLOGY AND SYSTEM DESIGN

The design methodology bridges statistical load findings with simulation tools, utilizing the multistep workflow shown in Figure 1 to assess the technical and economic viability[1].

2.1. Site Selection and Load Assessment. All facility parameters and statistical load profiles utilized in this section were derived directly from billing data encompassing 352 public schools in the Eastern Province. The site parameters are detailed in Table 1, establishing a statistical baseline rooftop envelope of 1,524.5 m^2 and indicating high cooling demands. However, for the specific installation site at Al Madinah Al Munawwarah Elementary School in Dammam (latitude 26.419°, longitude 50.047°), the analysis revealed an actual usable rooftop area of approximately 1,244.8 m^2. This actual usable space was utilized for the physical PV array design and was aligned closely with the statistical average. The energy consumption metrics established a mean annual baseline of 410,968 kWh/yr, heavily driven by an AC capacity of 160.12 TR.

2.2. Solar Design in Helioscope. The solar PV system was designed to maximize the available 1,244.8 m^2 of actual usable rooftop space established in the site analysis. To minimize shading effects and avoid structural obstructions, the PV system was divided between the football court rooftop structure (160 panels) and the main school building (80 panels), as shown in Figure 2. The system utilizes 240 PV modules (Canadian Solar CS6.1-72TB-620H) and two Huawei SUN2000-65KTL-M0 inverters, with 6 mm^2 copper cabling to mitigate resistive losses. The system losses and technical specifications are detailed in Figures 4 and 5.

2.3. Load Profiling in HOMER Pro. An electrical load profile was constructed using HOMER Pro to reflect specific academic schedules. High-load active hours (07:00–13:00) cover classes, whereas passive hours (14:00–06:00) represent base loads when the building is unoccupied.

The annual consumption was distributed across the year to account for three critical factors:

1. **Weekly Cycles:** Consumption peaks during weekdays and drops significantly during weekends.
2. **Academic Calendar:** Consumption is drastically reduced during the summer break (July–August) when the facility is non-operational.
3. **Weather Impact:** High consumption rates are modeled during the hot summer school months owing to peak AC usage, whereas winter months reflect lower consumption owing to reduced cooling requirements.

The resulting seasonal profiles are shown in Figure 6. The key load metrics derived from this model are summarized as follows:

- **Average Daily Consumption:** 1,156 kWh/d
- **Average Load:** 48.17 kW
- **Peak Load:** 385.41 kW
- **Load Factor:** 0.12

2.4. Hybrid System Optimization in HOMER Pro. An initial comprehensive model was developed, which included a

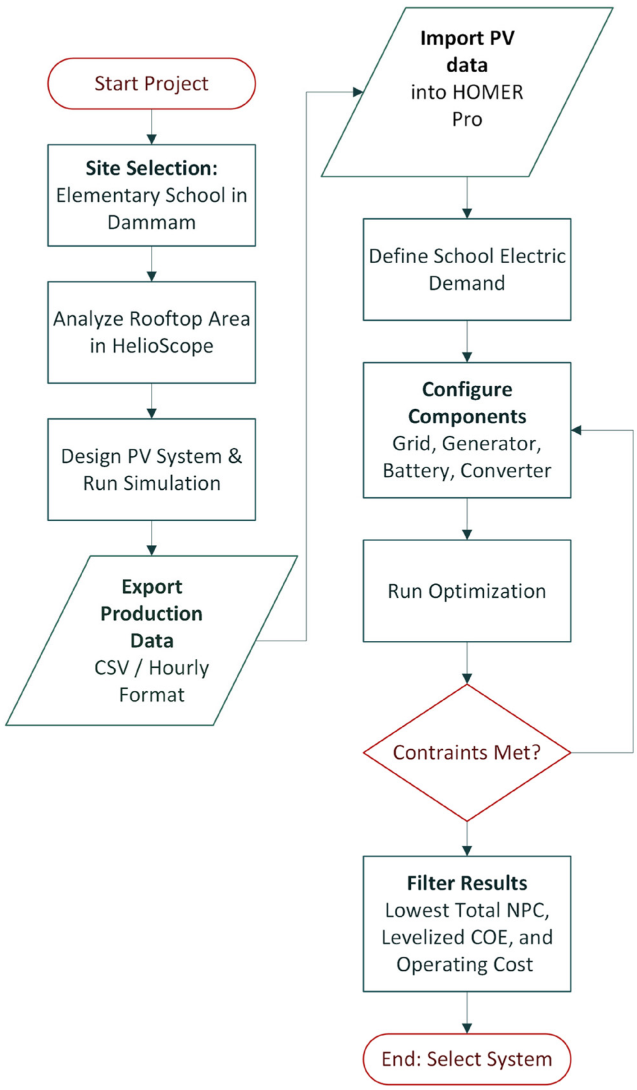

Figure 1. Hybrid system design workflow

Table 1. *Standard Reference School Profile (Mean Values)*

Parameter	Value	Description
Location	Eastern Province	Hot & humid climate (high latent load).
Total Built Area	4,165.6 m^2	Average gross floor area of the sample.
Total Roof Area	1,524.5 m^2	Available envelope for PV installation.
AC Conditioned Area	817.7 m^2	Only 19.6% of the school is actively cooled.
Building Age	32.8 years	Indicates prethermal code construction.
Occupancy	381 Students	Plus ~28 staff members.
Mean Annual Energy	410,968 kWh/yr	The foundational baseline for this project.
AC Capacity	160.12 TR (Tons Refrigeration)	Primary driver of load (R=0.97).
Net Energy Use Intensity (EUI)	502 kWh/m^2/yr	Calculated based on conditioned area (817 m^2).
Peak Load Driver	Cooling	Increases exponentially with consumption.
Current Tariff	0.32 SAR/kWh	Governmental rate.

utility grid, a diesel generator, battery storage, and the electrical load, as shown in Figure 7. The PV component was coupled directly to the AC bus because the imported production data accounted for the inverter efficiencies.

Although the term "hybrid energy system" was used during the initial modeling phase, the optimization constraints revealed that adding battery storage or diesel generation created an unnecessary financial burden for this specific load profile without providing proportional benefits. Consequently, these components were excluded, and a strictly grid-tied PV system was selected as the optimal configuration.

2.5. Model Formulation and Techno-Economic Assumptions. Techno-economic optimization relies on minimizing the NPC and LCOE. The NPC is expressed as follows:

$$NPC = \frac{C_{ann,tot}}{CRF\left(i, N_{proj}\right)}, \tag{1}$$

where $C_{ann,tot}$ represents the total annualized cost, i is the real discount rate, N_{proj} is the project lifetime, and CRF is the capital recovery factor. The LCOE is defined as:

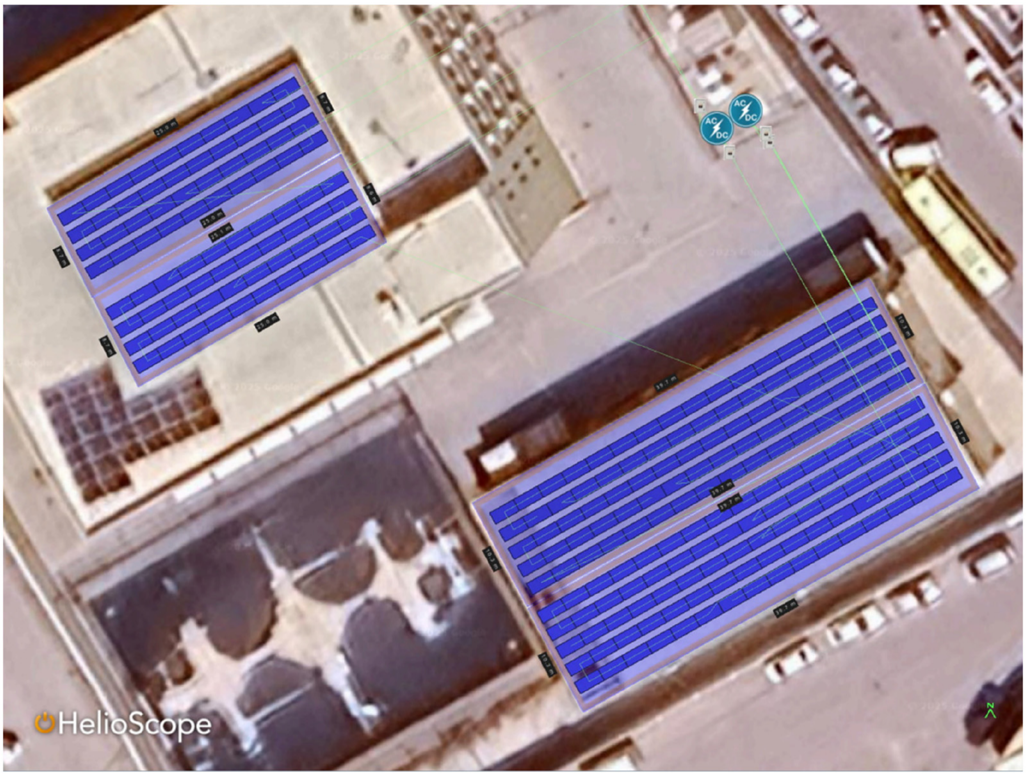

Figure 2. Proposed PV system layout on the school rooftop and football court

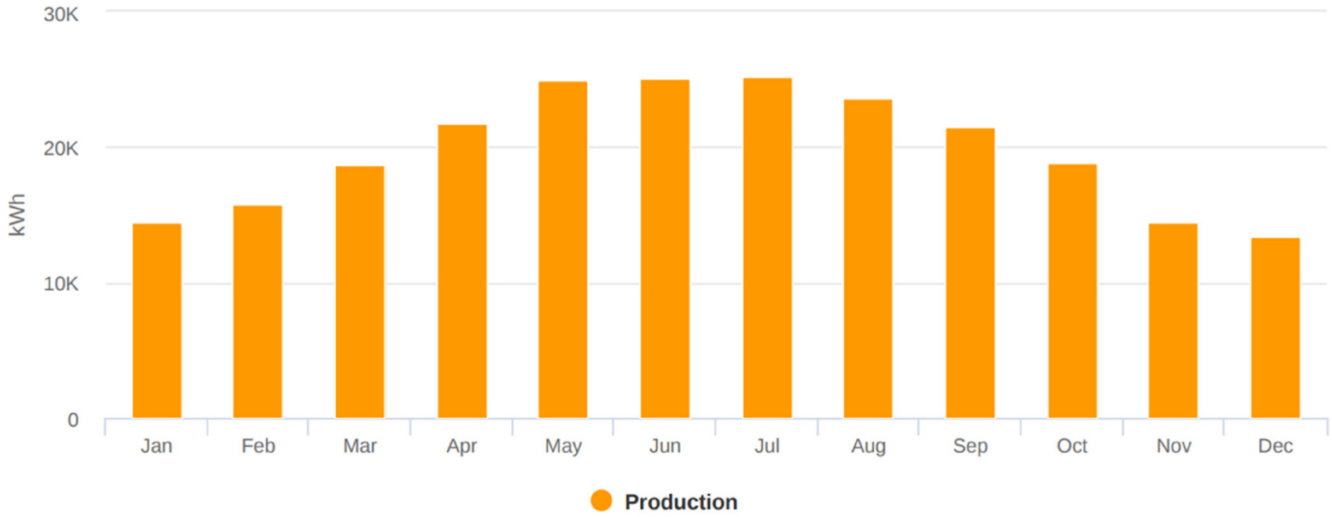

Figure 3. Simulated monthly energy production

$$LCOE = \frac{C_{ann,tot}}{E_{served}}, \quad (2)$$

where E_{served} represents the total electrical load served by the system annually.

The accuracy of these financial outputs relies heavily on the input of baseline economic parameters into the simulation. Table 2 outlines the key techno-economic assumptions used to model the system over its projected lifespan.

3. RESULTS AND DISCUSSION

Following the comprehensive simulation in HOMER Pro, a detailed analysis was conducted to evaluate the technical and economic feasibility of the proposed grid-tied PV system. The proposed design emerged as a superior solution, achieving the lowest cost among all the design alternatives. Table 3 presents a core techno-economic comparison between the current base case and the optimized proposed case.

The calculated LCOE for the proposed system is 0.23 SAR/kWh, representing a 28% reduction compared with the standard governmental tariff of 0.32 SAR/kWh. This aligns with recent findings in the literature demonstrating that distributed renewable systems in Saudi Arabia could achieve a COE significantly lower than the national grid rate [3]. To visualize the financial viability of the project over its 25-year lifespan, a cumulative cash flow analysis was performed (Figure 8). The break-even point occurs at approximately 7.5 years, after which the system generates net positive savings.

3.1. Economic Sensitivity. This economic analysis relied on key baseline assumptions, including tariff stability at 0.32 SAR/kWh, a fixed 8% nominal discount rate, and current PV capital expenditure. Fluctuations in these parameters, such as potential tariff structural reforms by the utility provider, changes

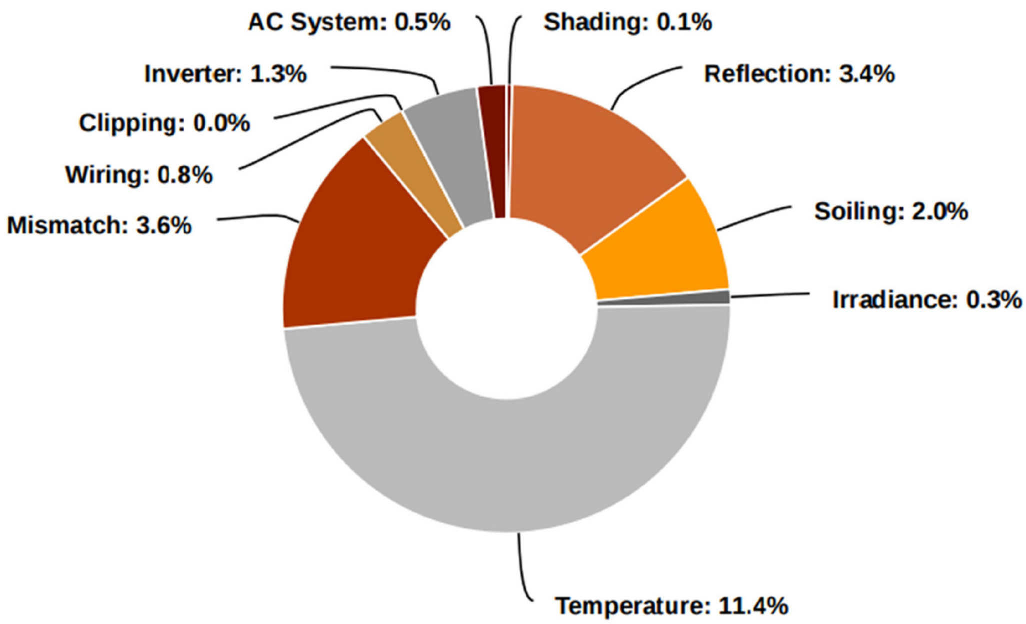

Figure 4. System loss diagram

Table 2. *HOMER Pro Key Economic and System Assumptions*

Parameter	Value	Unit	Description/Justification
Project Lifetime	25	Years	Standard operational lifespan for PV systems.
Grid Tariff	0.32	SAR/kWh	Fixed governmental rate for public facilities.
Nominal Discount Rate	8	%	Standard baseline opportunity cost for energy investments
Expected Inflation Rate	2	%	Typical long-term macroeconomic assumption.
Annual Capacity Shortage	0	%	Appropriate for a grid-tied system with full utility backup.
PV System Capital Cost (CAPEX)	371,975	SAR	Aggregated turnkey cost for the 149 kWp system derived from HelioScope sizing (approx. 2,496 SAR/kW).
PV System O&M (OPEX)	96,960	SAR	Estimated lifetime operations and maintenance budget (equating to standard ~1% of CAPEX annually).

Table 3. *Techno-Economic Comparison*

KPI	Base Case (Grid Only)	Proposed Case (Grid-tied PV)
Annual Consumption	410,968 kWh	260,429 kWh (Grid Purchase)
Grid Purchase	100%	52.1%
Annual Bill	131,510 SAR	83,337 SAR
Net Present Cost (NPC)	1,738,729 SAR	1,470,731 SAR
Payback Period	N/A	7.51 years
Return on Investment	N/A	9.3 %
Internal rate of return	N/A	12.6 %

Note: "Annual Consumption" in the proposed case represents the energy purchased from the grid. This difference was compensated for by the PV system.

in the national discount rate, or variations in PV component pricing, could significantly alter the resulting NPC and LCOE, thereby impacting the payback period of the system.

The technical performance was further detailed by comparing the load of the facility against solar generation. Figure 9 shows the time-series relationship between consumption and production, and the seasonal and hourly performances of the solar array are visualized in the data map shown in Figure 10. A key finding of this study is the grid purchase frequency, as shown in Figure 11. The system successfully offsets 47.9% of the annual load; however, the remaining 52.1% grid reliance is largely inevitable owing to the "passive hours" (nighttime) when solar generation is zero. Integrating battery storage to capture this load was evaluated during the HOMER optimization but was deemed economically inefficient because the NPC was significantly increased without providing proportional returns.

Furthermore, the heatmap of the energy sold to the grid shown in Figure 12 highlights a strategic advantage unique to educational facilities: the summer break. In July and August, the school exports the vast majority of its generation to the municipal grid. This coincides precisely with the peak national demand period in the Eastern Province, suggesting that schools can act as distributed generation nodes to support the grid when it is most stressed.

Finally, this study evaluates the ecological benefits of renewable energy integration. Figure 13 outlines the environmental impact, detailing the reduction of 160 tons of CO_2 emissions

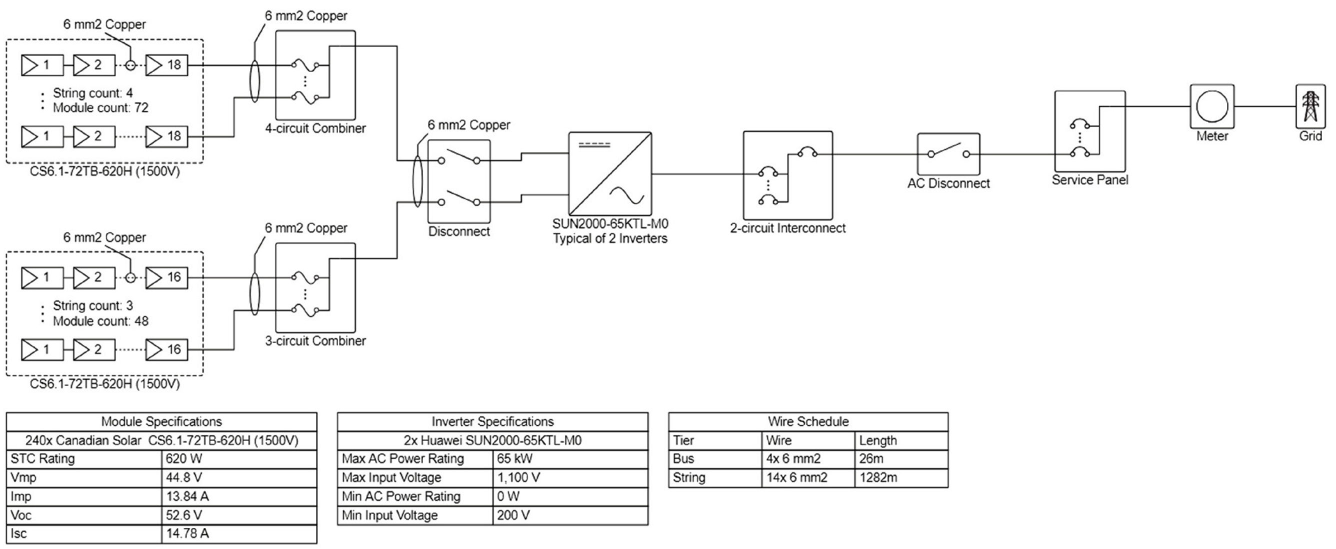

Figure 5. Single line diagram of the proposed PV system

- **Average Daily Consumption:** 1,156 kWh/d
- **Average Load:** 48.17 kW
- **Peak Load:** 385.41 kW
- **Load Factor:** 0.12

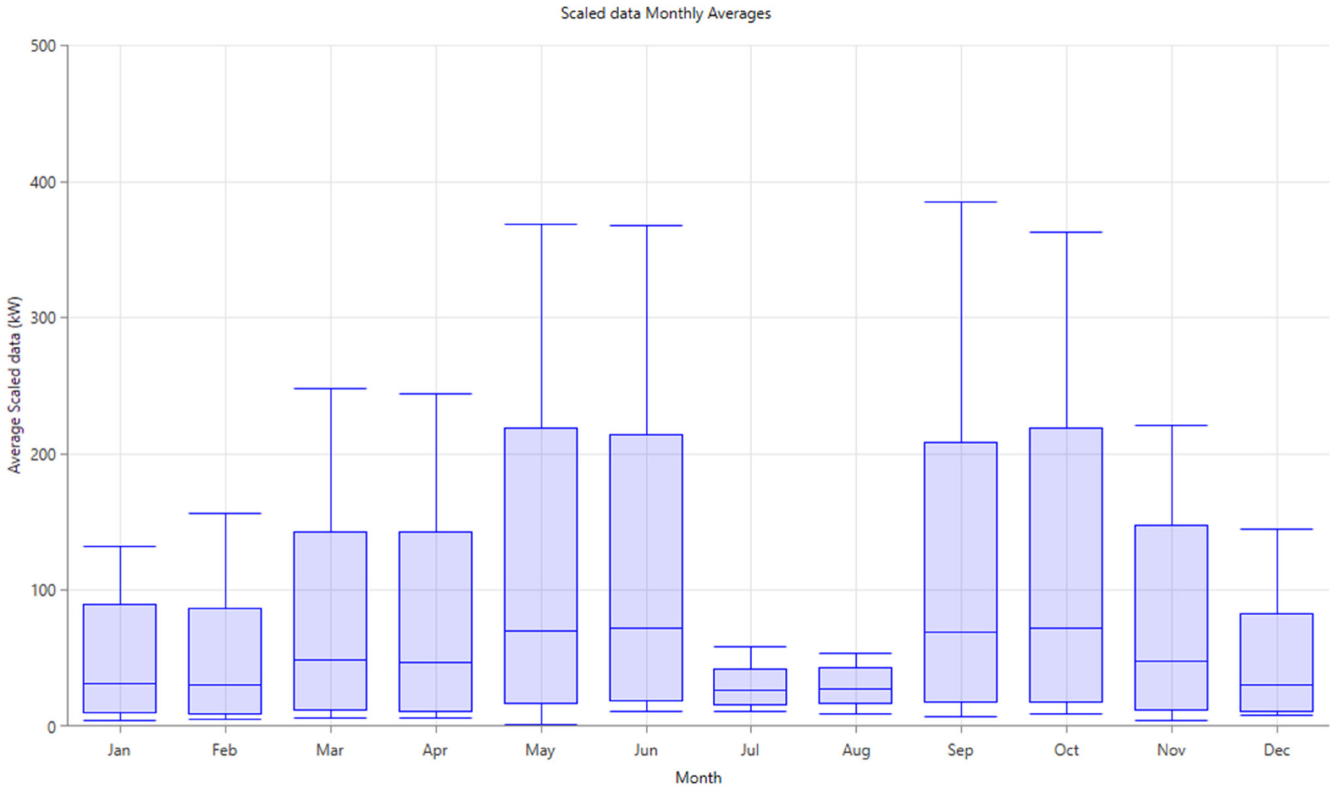

Figure 6. Monthly seasonal electrical load profile

annually, demonstrating how localized grid-tied systems can directly contribute to the broader decarbonization targets of the Saudi Green Initiative.

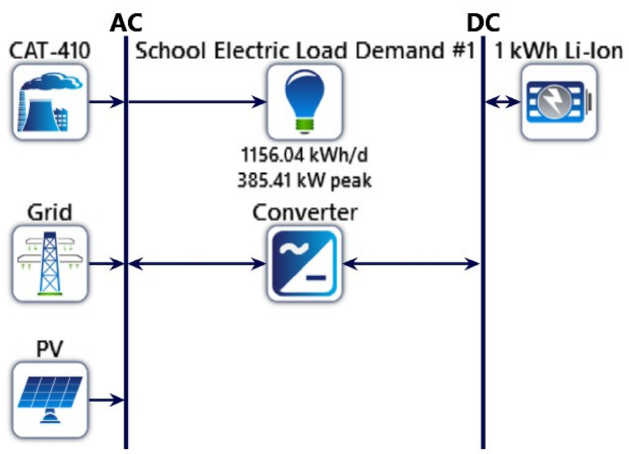

Figure 7. HOMER Pro system schematic

4. CONCLUSIONS

This study validated the techno-economic feasibility of integrating grid-tied solar PV systems into educational facilities in the Eastern Province of Saudi Arabia. For the modeled standard elementary school, a 149 kWp rooftop system reduced grid reliance from 100% to 52.1%, presenting a highly compelling financial case with a payback period of 7.5 years and an IRR of 12.6%. Ecologically, the system avoids significant carbon emissions and directly supports the Saudi Green Initiative.

4.1. Limitations and Scalability. To illustrate the macro-level impact, theoretically scaling this specific 149 kWp design across 100 standardized schools in the region could yield an annual municipal grid relief of approximately 15 GWh and save more than 4.8 million SAR in utility costs. However, although educational buildings utilize standardized architectural designs that theoretically make this model highly replicable, a critical limitation is the inherent variability among existing infrastructures. Differences in the available unshaded roof areas, localized load profiles, building ages, and regional climate disparities must be carefully assessed before broadly projecting these results across all schools.

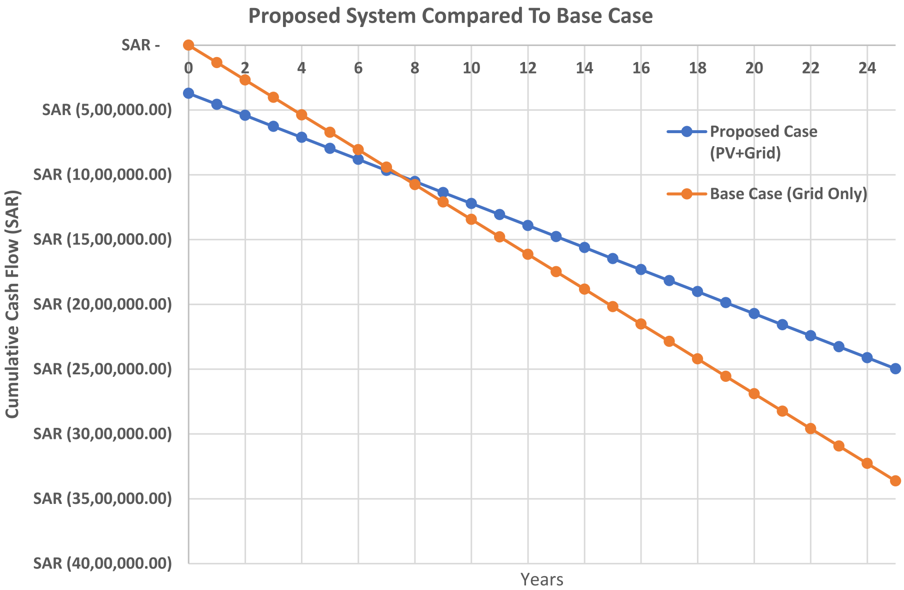

Figure 8. Cumulative cash flow analysis

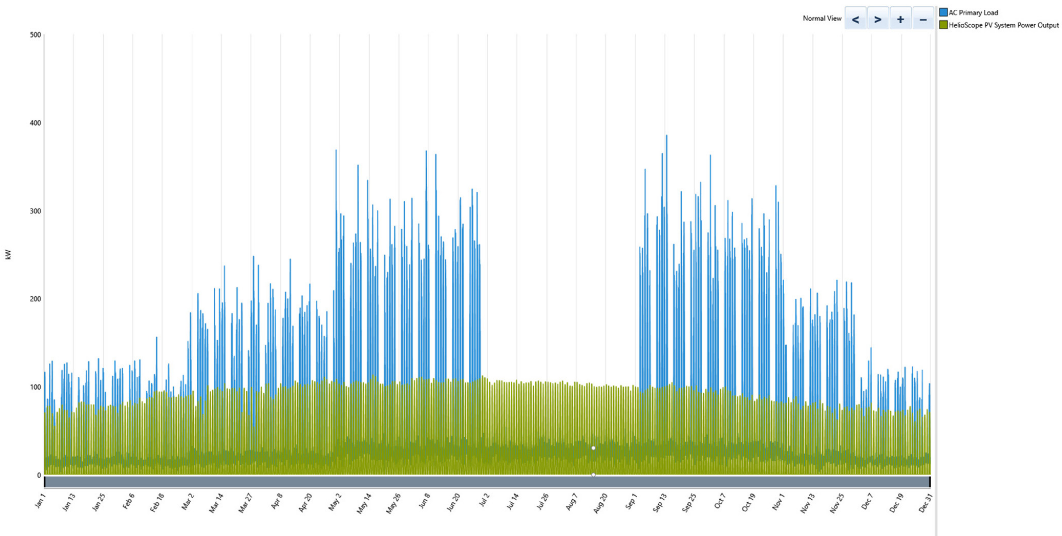

Figure 9. Time series comparison of electrical consumption vs. solar production

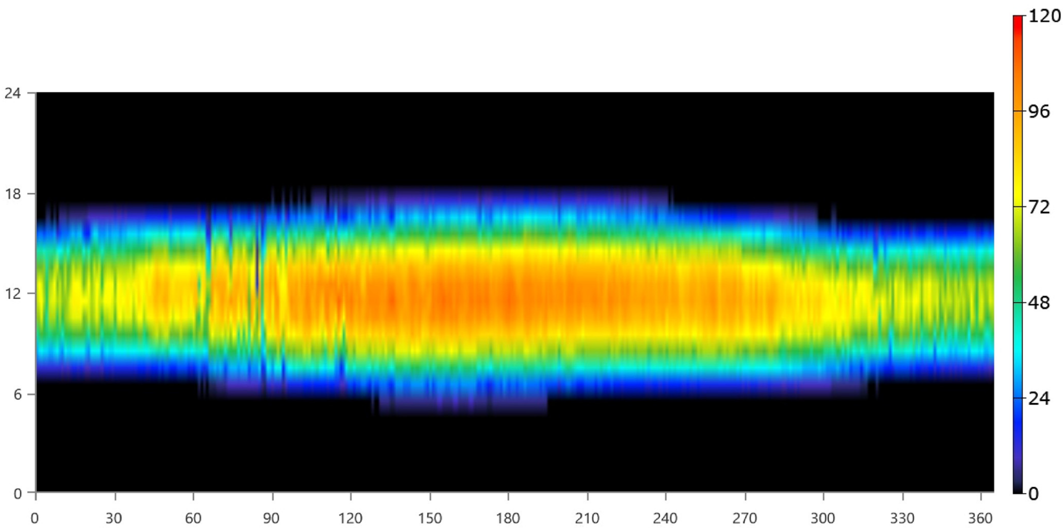

Figure 10. Heat map of PV power output (kW)

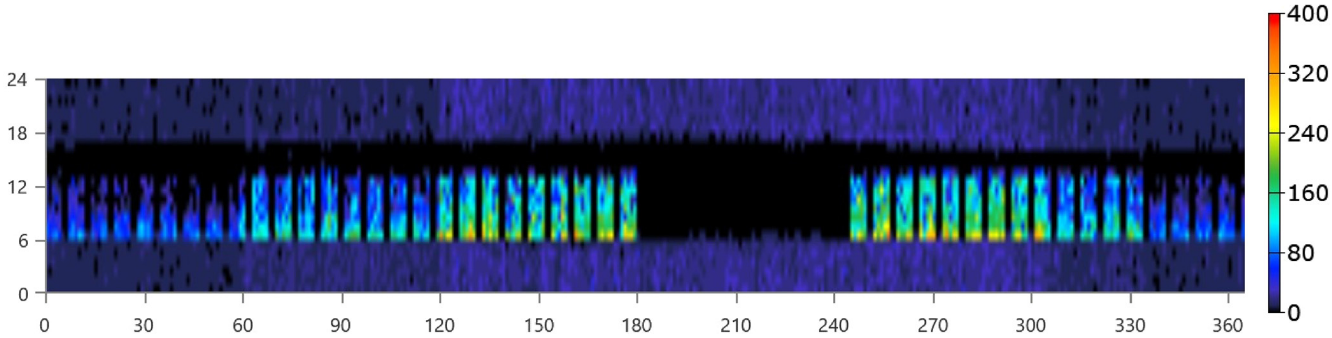

Figure 11. Heatmap of grid energy purchases (kW)

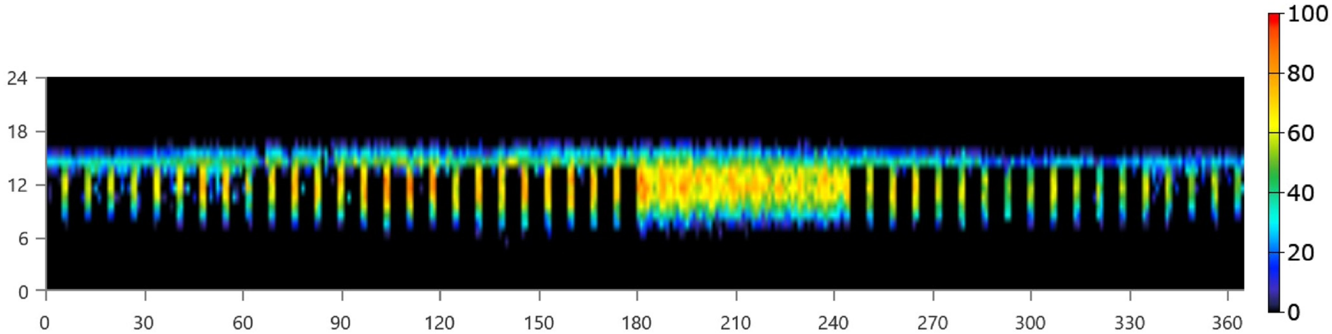

Figure 12. Heatmap of energy sold to the grid (kW)

Figure 13. Environmental impact and emissions reduction summary

4.2. Future Work. Future research should investigate the impact of implementing dynamic energy-efficient retrofits (e.g., upgrading HVAC infrastructure or building envelopes) in tandem with PV deployment to further reduce the initial required solar capacity and drive schools closer to the true zero-bill status.

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