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Economic Viability and Environmental Benefits of Integrating Solar Photovoltaics in Public Community Buildings

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Abstract: Saudi Arabia relies heavily on fossil fuels for electricity generation, leading to significant environmental challenges, including high levels of greenhouse gas emissions. This study evaluates the environmental and financial impacts of integrating solar PV systems in public buildings, specifically mosques and schools, in the central region of Saudi Arabia. Using machine learning-based forecasting, we analyzed power consumption and solar generation patterns. The results show that the integration of solar photovoltaic (PV) systems could lead to a reduction of 1.02 million tons of CO_2 emissions annually and a 48% decrease in net present cost. These findings highlight the potential of solar PV to mitigate environmental harm while offering financial benefits in alignment with Saudi Arabia's renewable energy objectives

Keywords: load forecasting; machine learning; solar PV; ToU tariff; net present cost

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1. Introduction

Following the second industrial revolution, the transition from steam engines to electricity transformed transportation, communication, and industry, significantly improving lifestyles and health. Over time, electricity became integral to daily life, driving a rapid increase in energy consumption, with the demand rate doubling the average growth rate since 2010 [1]. This surge in energy consumption has led to environmental challenges, particularly those linked to fossil fuel use in electricity generation, which is a significant contributor to CO_2, SO_2, and greenhouse gas (GHG) emissions, exacerbating climate change and air pollution. Renewable energy, such as solar PV, is seen as a solution to mitigate these impacts and transition toward more sustainable energy practices. Recent studies have highlighted the potential of facade-integrated PV solutions in reducing the energy demand of buildings, contributing to the transition toward less energy-hungry buildings [2]. A community–government partnership framework has also been proposed as an effective strategy to reduce carbon emissions in residential buildings, specifically within the context of Saudi Arabia [3].

Power utility companies are expanding generation capacities to meet the growing demand. Compared with the global average of 1.8%, Gulf Cooperation Council (GCC) countries experienced an average increase of 6.8% in electricity demand [4]. In 2018, Saudi Arabia's annual electricity consumption was 290 TWh, with a peak load of 65 GW in a single day [5]. Governmental and residential sectors account for 60% of energy consumption, and the average energy consumption per capita is 8643 kWh/year. According to [6], the average annual growth in electricity demand ranges between 8 and 10%. The Saudi Electricity Company (SEC) aims to increase power generation capacity to 101 GW by 2025, compared with 52 GW in 2015 [7]. SEC produced 74% of the total energy in the country.

The increased demand for energy has led to harnessing different types of resources to produce electricity, with fossil fuels, such as oil and natural gas, playing a key role in meeting those demands. SEC relies on combined cycle, steam, and gas turbines for power generation, which are primarily dependent on these fossil fuels. By 2025, SEC will have a capacity of 56.5 GW from combined cycle, 21.8 GW from steam turbines, and 23.3 GW from gas turbines. While these projected capacities will help meet the growing energy demand, they also imply significant reliance on fossil fuels, leading to lower energy efficiency compared to renewable energy sources and contributing to higher environmental impacts. Fossil fuel-based electricity generation directly produces CO_2 and SO_2, which have adverse environmental consequences. CO_2, as a major greenhouse gas, traps heat in the atmosphere, leading to global warming, while SO_2 contributes to acid rain, which can damage ecosystems and infrastructure. In Saudi Arabia, CO_2 emissions have grown from 252,000 Gg in 2000 to 446,000 Gg in 2019 [8]. Additionally, CO_2 emissions per person have increased from 0.012 Gg to 0.016 Gg over the same period. In 2012, Saudi Arabia was responsible for 2.8% of global CO_2 emissions and ranked as the ninth-largest emitter globally, with electricity and heat production accounting for 56.34% of the country's overall CO_2 emissions [9]. These emissions pose challenges to sustainability efforts and highlight the need for further investment in cleaner energy alternatives, particularly renewable energy sources, such as solar energy, which offer a sustainable solution to alleviate environmental impacts and ensure a stable energy supply for the future.

Load profiles for summer and winter days in the central region were drawn based on the analogy used in [10], with the region's power consumption ratio to the country being 0.32 in the summer and 0.27 in the winter. The significant difference in these ratios highlights the impact of weather, particularly the heavy use of air conditioning in the summer months.

In his review on the economics of climate change, Nicholas Stern discussed the effect of global warming on the world economy. He mentioned that GHGs should be limited to 450–550 ppm CO_2. He recommended that countries modify environmental policies to reduce carbon dioxide emissions, support energy research and development, and use clean energy sources [11]. Renewable energy comes from sources such as sunlight, wind, or geothermal resources that do not deplete over time. In addition to being clean, renewable energy enhances a country's energy security by supplying reliable power, diversifying fuel sources, and reducing the need for imported fuels. The renewable energy sector also positively impacts the economy through job creation and domestic supply chains [12]. For instance, in 2016, the solar power industry employed more than 260,000 people in the United States. The rapid deployment of solar power has also led to significant reductions in the cost of photovoltaic (PV) cells, down to 0.24 USD/W compared with 76 USD/W in 1977 [13].

Despite the benefits of solar PV systems, high PV penetration presents challenges, such as reverse power flow and voltage fluctuations in electrical grids [14]. Increased PV generation can lead to overvoltage issues, malfunctioning protective devices, and degraded system frequency response. Harmonics introduced by power electronic devices can also contribute to line losses and transformer overheating [15]. To address these challenges, several solutions have been proposed, including energy storage, smart inverters, and power regulation through devices like STATCOM and SVC [16,17]. Additionally, PV generation curtailment (PVGC) can be used to manage system voltage levels [18].

Saudi Arabia has significant untapped renewable resources, particularly solar energy. Studies have shown high levels of solar irradiance across the country, making solar PV a promising energy solution [19]. The average intensity of solar radiation is around 2200 kWh/m^2/year with average daily totals close to 5992 Wh/m^2. The National Renewable Energy Program (NREP), established in 2017, aims to diversify the country's energy mix by increasing the use of renewables. Notable projects include the Sakaka solar PV and Dumat Al Jandal wind energy projects with capacities of 300 MW and 400 MW, respectively [20]. Twelve bids were analyzed to add 3100 MW, with 2225 MW coming from solar and 850 MW from wind. These initiatives, along with local manufacturing capacity for PV components, are expected to create significant employment opportunities and strengthen the domestic renewable energy sector [21]. The authors estimated that 45% of components related to solar energy can be provided through local suppliers, with potential job creation of 60,000 jobs based on NREP employment data [22].

In this study, we focused on the central region of Saudi Arabia, which covers 573,000 km^2 and has a population of 10.6 million people, representing 31% of the country's population. The region experiences long, hot summers and cool, dry winters, making it well suited for solar PV implementation [23]. We considered community solar projects targeting public schools and mosques, which have large rooftop spaces and predictable load patterns. These buildings consume relatively low amounts of electricity during the summer, contrary to the overall consumption trend in the country. The central region consists of 24,931 mosques and 4099 public schools that consume 5.32 million barrels of oil equivalent [24].

To further understand the potential of public building solar PV projects, we examined similar initiatives implemented globally. Governments worldwide have successfully launched programs to install solar PV systems on public buildings, providing useful insights for Saudi Arabia's efforts. For instance, China's Golden Sun program installed 100 MW of rooftop PV systems in schools, significantly reducing PV module prices [25]. Similar programs have been undertaken in Toronto and the West Bank, with projects targeting schools and other public buildings to generate clean energy and reduce emissions [26,27]. In the U.S., solar PV on educational buildings could generate 100 TWh of energy annually and yield environmental benefits worth USD 4 billion per year [28]. These international examples demonstrate the effectiveness of solar PV projects in public institutions and offer valuable lessons for implementing such projects in Saudi Arabia's central region.

In this paper, we estimate the potential electricity generation and emissions reductions from installing solar PV systems on the rooftops of mosques and public schools in Saudi Arabia's central region. We analyze the technical specifications, financial feasibility, and environmental impact of these systems, providing insights for policymakers on renewable energy integration, tariff modification, and climate change mitigation.

2. Methodology

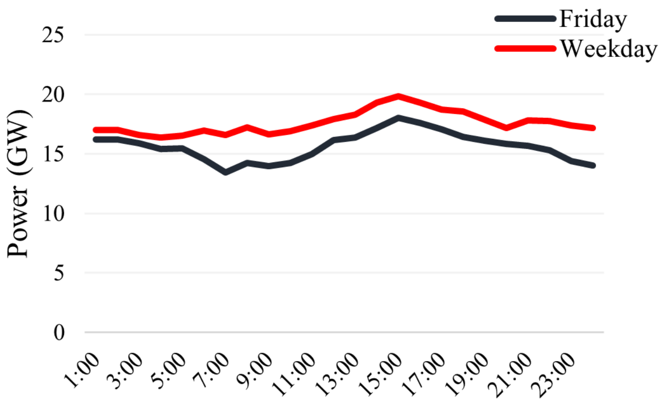
2.1. Dataset

To study the impact of solar PV implementation and ToU tariffs on religious and educational buildings in the central region of Saudi Arabia, we analyzed the power consumption for several mosques and schools over a complete year.

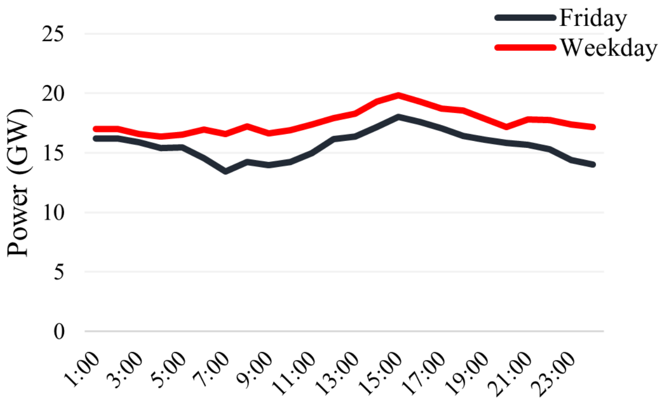
Load profiles for summer and winter days in the central region of Saudi Arabia were drawn based on the analogy used in [10] and applied to the 2018 country's load, as shown in Figure 1. The ratio of power consumption in the central region of Saudi Arabia to the entire country is 0.32 in the summer and 0.27 in the winter. This difference highlights the impact of weather on power consumption, particularly due to the heavy use of air conditioning during the summer months. The central region of Saudi Arabia is the focal point of this analysis due to its significant population density, favorable climatic conditions, and its high potential for solar PV energy generation.

Figure 2 shows the average hourly loads in a mosque with a capacity of 1500 persons. The difference between the Friday load and other days of the week is related to the congregational prayer (Jummah), which lasts for an average of 40 min and encounters the maximum number of attendees for a prayer. As a result, the day of the week and time of day have a strong influence on the load of a mosque. For example, the load during weekdays is much lower than on weekends since many people are at their offices or schools during the day and will not be able to pray at mosques located in residential areas. In addition, power usage varies across different months due to seasonal factors, such as changes in weather conditions and fluctuations in mosque schedules. For instance, during hotter months, there may be an increased usage of air conditioning systems, while school schedules also influence the number of attendees and thus the power consumption in mosques. These variations contribute to the annual fluctuations in power consumption patterns [29].

Figure 3 presents the monthly load profile for a school in Riyadh. The pattern of the school's load is consistent during academic terms. On weekdays, the load starts at 5 am, reaches its peak at 10 am, and falls off at 1 pm. On weekends (Fridays and Saturdays), the load is negligible for most of the time. A similar behavior is observed during holidays.



(**a**) Friday



(**b**) Weekday

Figure 1. Load profile in central region. (**a**) During summer (**b**) During winter.

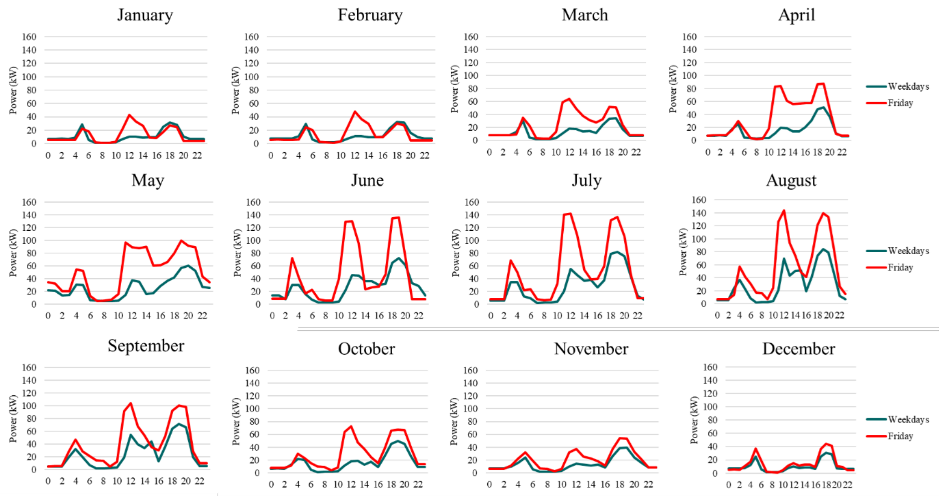


Figure 2. Monthly power consumption for a mosque.

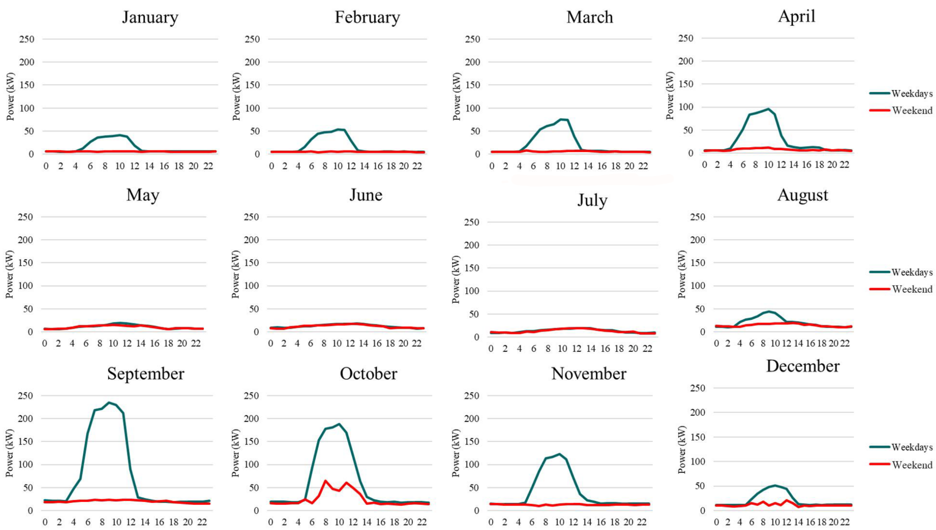


Figure 3. Monthly power consumption for a school.

To provide accurate data for analysis, we also considered the academic term and holiday periods as well as the typical school hours, which span from 7 am to 2 pm. The weekend days are Friday and Saturday. For mosques, prayer schedules and additional activities such as religious lectures were considered. These distinctions between school and mosque activity are crucial for understanding energy consumption patterns. While schools and mosques generally exhibit similar energy consumption patterns influenced by weather throughout the year, notable differences emerge between May and August due to their differing operational schedules. During this period, schools experience a significant reduction in energy use due to summer holidays, whereas mosques remain fully operational and even see an increase in energy consumption during Ramadan, when nightly prayers and religious activities draw larger congregations. Additionally, while the intense summer heat in Riyadh leads to increased air conditioning demand for both types of buildings, the reduced occupancy of schools during this time results in substantially lower energy consumption compared to mosques, which continue to require energy for cooling systems. These operational and seasonal variations account for the distinct differences in their load profiles during these months.

To determine the rooftop spaces in mosques and schools, surveys were conducted on these types of buildings in the central region. Schools have an average area of 1610 m^2.

The situation for mosques is different as areas vary greatly. Five models of mosques were created based on capacity, which is defined as the maximum number of worshippers they can accommodate at a single prayer. According to the Ministry of Islamic Affairs statistics book [30], the central region in Saudi Arabia has 24,931 mosques. However, the statistics book did not categorize mosques based on their capacity. Therefore, there is a need to categorize mosques based on capacity and area.

Power consumption data for several mosques and schools were collected for a complete year to use for forecasting and analysis. Forecasting of school loads was straightforward since it has a direct relation with weather and time. An Artificial Neural Network (ANN) with five hidden layers, Adam optimization, and an adaptive learning rate was used. The ANN was fed by the following features: 2 m temperature (T2M), total cloud cover (TCC), wind speed, partial aerosol optical depth at 550 nm for dust (DUAOD550), previous week demand, day of the year, hour, and holiday features. Weather features were extracted from the Copernicus Atmosphere Monitoring Service (CAMS) at the European Centre for Medium-Range Weather Forecasts (ECMWF) [31].

For mosques, multiple records were missing. Pre-processing was required to predict the missing values and make the dataset useful. The pre-processing consisted of three phases: dataset preparation, mosque types, and activity modeling.

In the first phase, a forecasting model of mosques was used to predict the power consumption for the missing days [32]. Prior to this step, power consumption per m^2 was compared between new and old mosques for available days to ensure the suitability of the model. The model predicts loads that include prayers and other events, such as lectures and speeches. Thus, there is a need to subtract those loads from the total load. To do this, a daily load model was created by finding the ratio between the load in each hour and the load during the Maghrib prayer, which is the peak hour most of the time. After that, loads related to lectures and speeches can be identified and subtracted from the total load. In the second phase, the assumption of mosque types was performed by dividing them into five categories similar to the ranking of mosque Imams provided by the ministry. The proposed mosque categories are shown in Table 1.

Table 1. Proposed mosque categories.

Category	Capacity	Criteria for Area	Area (m^2)	# of Mosques
Mosque A	1500	Capacity × 1.3	1950	2967
Mosque B	1000	Capacity × 1.3	1300	3685
Mosque C	700	Capacity × 1.3	910	5459
Mosque D	500	Capacity × 1	500	6428
Mosque E	300	Capacity × 1	300	6387

In the third phase, events other than prayers were modeled using a random process to predict their occurrence. A Poisson process was chosen to model the inter-activity time. The Poisson process can be defined as a renewal process in which the inter-arrival intervals have an exponential distribution function with a rate of occurrence λ [33]. In this process, the time interval [0, t] is divided into n subintervals of very short duration $\delta = \mathrm{t/n}$, with the following conditions holding: (i) the probability of more than one event occurrence in a subinterval is negligible; (ii) event occurrence in a particular interval is independent of the history of outcomes outside this interval. Figure 4 illustrates the Poisson process chosen to model the inter-activity time.

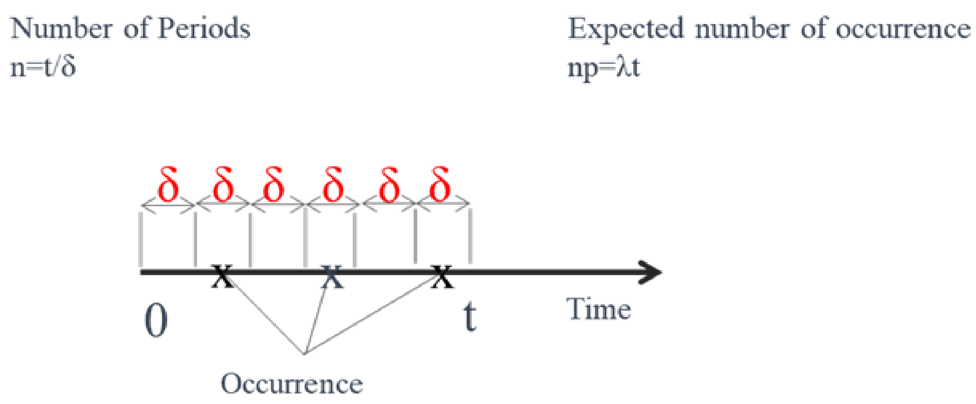


Figure 4. Poisson process.

The probability of an event occurrence $P[N(t) = k]$ is approximately the binomial probability of k occurrences in $n = t/\delta$ independent Bernoulli trials with probability $p = \lambda\delta$ at each trial. In addition, the expected number of event occurrences in the interval $[0, t]$ is equal to np. Similarly, the average number of events in the interval $[0, t]$ is λt, which equals np. While keeping the length t of the interval fixed, let the period length δ reach zero, which implies that the number of periods n goes to infinity while $np = \lambda t$ remains fixed. Then, the binomial distribution approaches a Poisson distribution with parameter λt. Thus, the number of event occurrences $N(t)$ in the interval $[0, t]$ has a Poisson distribution with mean λt:

$$P[N(t) = k] = \frac{(\lambda t)^k}{k!} e^{-\lambda t} \quad \text{for } k = 0, 1, \ldots$$

Since most of the events occur in the mosque after the Isha prayer at night, it is safe to assume that all events will be held at that time and last for one hour.

Regarding the religious educational sessions, the situation is quite simple. These sessions have clear schedules, starting after the Asr prayer in the afternoon and lasting for two hours. These courses are provided twice per year: from September till November and from January till March. Since many mosques do not provide these kinds of courses, a Bernoulli random distribution was used to determine the number of mosques that will have courses to adjust their load profile.

After the completion of the pre-processing phase, a prediction model for consumed power and generated solar PV power was created. Measurements of power consumption for a mosque and a school were joined with the ERA5 dataset from ECMWF. ERA5 provides hourly estimates of a number of atmospheric, land, and oceanic climate variables [34]. The features used for this work are listed in Table 2.

To select features that feed the machine learning model, the Pearson correlation coefficient was used with respect to the consumed power and generated solar PV power.

$$\rho_{X,Y} = \frac{n\sum XY - \sum X \sum Y}{\sqrt{n\sum X^2 - (\sum X)^2}\sqrt{n\sum Y^2 - (\sum Y)^2} \tag{1}$$

where ρ is the correlation coefficient, n is the sample size, and X and Y are random variables. The correlation matrix between all the features is shown in Figure 5.

As illustrated in Figure 5, generated solar PV power has a strong correlation with net thermal radiation, TOA solar radiation, solar radiation, and T2M. On the other hand, consumed power is heavily dependent on T2M, TOA solar radiation, solar radiation, Hijri month, day of the week, holidays, and Dhuhr and Maghrib prayers.

Table 2. ERA5 feature list.

Feature	Min	Max	Unit
u10 Wind (10 m u-component of wind)	−7.49	10.11	m/s
v10 Wind (10 m v-component of wind)	−11.79	11.34	m/s
T2M (2 m temperature)	274.75	319.1	K
D2M (2 m dewpoint temperature)	258.40	293.9	K
HCC (High cloud cover)	0	1	%
LCC (Low cloud cover)	0	1	%
MCC (Medium cloud cover)	0	1	%
Surface Pressure	0	95,049	Pa
Net Thermal Radiation	−0.125	2,432,475	J/m^2
Net Solar Radiation	−1,033,211	−161,325	J/m^2
Solar Radiation Downward	−0.125	3,796,174	J/m^2
Thermal Radiation	794,222	1,570,668	J/m^2
TOA Solar Radiation	−0.25	4,743,000	J/m^2
Total Precipitation	0	0.0028	m

Prior to feature selection, the dataset was integrated and cleaned of null and outlier records. Then, the dataset was divided into three subsets: training, validation, and testing, with proportions of 60/20/20. The validation subset was helpful in tuning the model's hyper-parameters.

To predict power values, K-Nearest Neighbor (KNN) was used. The idea of KNN is based on the similarity of attributes to predict the values of new inputs. In other words, a new point is assigned a value based on a similarity measure and proximity with the points in the training set. The Euclidean distance, defined as the straight-line distance between two points in Euclidean space, was used to calculate the distance between the new point and the points in the training set.

$$D = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2} \quad (2)$$

where n is the number of variables, and x_i and y_i are the variables of vectors x and y, respectively. To determine the number of neighbors, several values were tested. A k of five neighbors and a Radial Basis Function (RBF) were found to be the best combination.

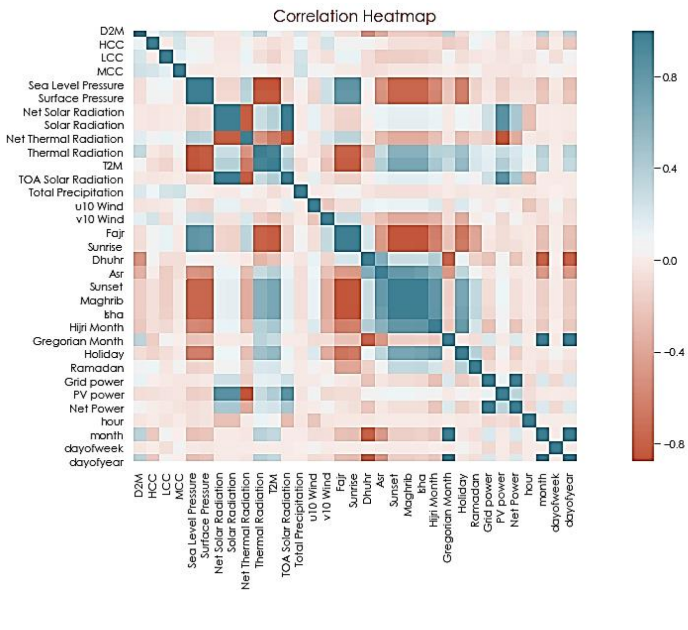


Figure 5. Correlation matrix.

2.2. Setup

The main goal of this work is to explore the possibility of installing renewable resources in public buildings and to quantify the benefits of this integration environmentally and economically. Due to the weather conditions in the central region, solar PV was considered to provide clean energy. The main part of a solar PV system is PV cells, which convert solar irradiation into electric power. PV panels consist of several thin layers of semi-conducting material, such as silicon, that generate electrical charges when exposed to light. PV panels can be classified into four categories based on the material used: mono-crystalline, poly-crystalline silicon, amorphous silicon, and thin film. Thin film PV panels have the lowest cost among the four types but also the lowest efficiency [35]. Similarly, amorphous silicon panels have low efficiency but can be considered a good option since they are less sensitive to high temperatures and shading and have a simple procedure for mass production. Mono-crystalline panels are ranked the best in terms of efficiency, longevity, and space utilization but have a more complicated fabrication process that results in higher costs [36]. In some cases, poly-crystalline panels can be seen as a cost-effective option despite lower efficiency than mono-crystalline panels [35].

A 270 W mono-crystalline solar PV panel with dimensions of 1640 × 992 × 40 mm was considered in this analysis. To determine the costs of the solar PV system, assumptions regarding capital costs (CAPEX) from [36] were applied. A summary of costs associated with the solar PV system is presented in Table 3.

Several scenarios for the impact on the load profile and monthly bills were studied when the solar PV panels were installed on the rooftops of buildings. Scenarios included PV penetration of 25%, 50%, and 75%. PV penetration refers to the percentage of rooftop space covered by PV panels, where 75% penetration indicates that 75% of the roof area is utilized. We also explored variations in the rooftop area utilization at levels of 25%, 40%, 50%, 60%, 75%, 90%, and 100%. This analysis was in addition to a baseline case where no PV panels were installed.

Table 3. Solar PV system costs [36].

Item	Cost (USD)
Module Cost	0.405 USD/W
Inverter	0.133 USD/W
Ground Mounts	0.343 USD/W
DC cables	0.052 USD/W
AC cables	0.011 USD/W
Installation Costs	0.080 USD/W
O&M Cost	15 USD/kW/Yr
DC Junction Box, Protection Relay, Power Meter, Controlled Switch & Controller	USD 3192

Net Present Cost (NPC) was used to study the financial impact of PV system integration. NPC is the present value of all the costs related to the installation and operation of the component. It is subtracted from the present value of all revenues that it earns over the project lifetime. Unlike Net Present Value (NPV), all cash flows in NPC are considered outflows compared to the in or out cash flows for NPV [37]. In NPC calculation, an interest rate of 3% and an inflation rate of 2% were considered. These rates are applied to reflect the time value of money over the lifetime of the project. While interest and inflation rates are crucial in calculating NPC, they are also typically considered in NPV calculations for a comprehensive financial analysis. However, for simplicity, they are primarily discussed here in the context of NPC. Based on these assumptions, a school with 75% PV penetration will have a capacity of 99.6 kW and will cost USD 105,213. This installation will reduce the annual electricity bill to USD 4955. Mosques, for the same PV penetration, will cost between USD 21,163 and USD 120,143 depending on the mosque's size. These costs reflect the varied installation needs based on the building's capacity and energy consumption patterns.

Calculation of GHG emissions avoidance was used to highlight the environmental impact of the PV systems. Reference emissions (RE) are calculated based on the avoided emissions from grid electricity using Saudi Arabia's average grid emission factor of 0.654 tCO_2/MWh [38]. Since solar PV systems do not produce emissions during operation, project emissions (PE) are considered negligible in our analysis. The annual GHG savings are calculated as the difference between RE and PE. The equation for determining annual GHG savings is as follows:

$$\text{Annual GHG savings} = \text{RE} - \text{PE} \tag{3}$$

$$\text{Reference emission (RE)} = EG_y \times EF_{\text{grid}} \tag{4}$$

where EG_y is the energy generated from solar PV in a year in MWh, and EF_{grid} is the average grid emissions factor for a year in tCO_2/MWh.

To quantify the benefits of emission reduction, the social cost of carbon (SCC) was used. SCC is defined as "the monetized damages associated with an incremental increase in carbon emissions in a given year" [39]. SCC includes several factors, such as human health, losses to agriculture due to global warming, and property damages from increased flood risk. In Saudi Arabia, SCC ranges between 27 and 86 USD/tCO_2, with an average of 47 USD/tCO_2, according to Ricke et al. (2018) [40]. This range is used in the analysis to estimate the economic impact of the GHG emissions avoided through the use of solar PV systems.

This methodology was applied to evaluate the environmental and economic benefits of integrating solar PV systems into the energy infrastructure of public buildings in the central region of Saudi Arabia. The combination of accurate data collection, predictive modeling, and financial analysis allows for a comprehensive assessment of the potential impact of renewable energy adoption in this region.

3. Results

3.1. Impact of Small-Scale Solar PV Implementation

To illustrate the impact of implementing solar PV on public buildings, we examined a neighborhood in Riyadh consisting of an elementary school, an intermediate school, a mosque, and 17 two-story houses. Figure 6 presents the study area in Riyadh. A solar PV system was installed on the rooftops of the mosque, schools, and houses and integrated with the electricity grid. The analysis also includes data from the 17 houses, which were not previously discussed in the data or methodology section. These houses have been added to the study to provide a more comprehensive view of the energy exchange in the neighborhood. The main objective of this study is to perform a sensitivity analysis on the solar PV system and evaluate its performance in terms of cost, environmental impact, and effect on the grid. To achieve this goal, power consumption records were collected for each building at 8760 hourly time steps over the course of a year. The dataset was then aggregated into three groups: mosques, schools, and residential buildings.

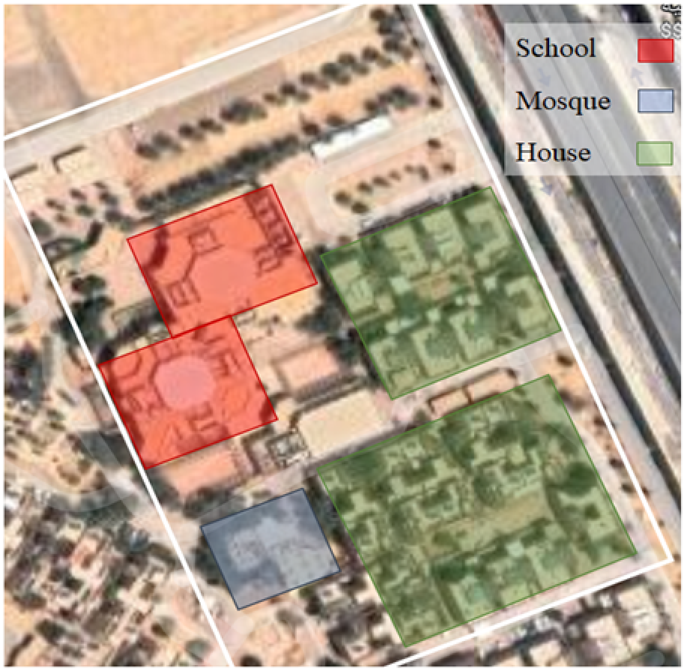


Figure 6. Study area.

Figure 7 shows the load profile for the targeted sectors on the 1st of September. This load profile includes data from the two schools, mosque, and the 17 houses in the neighborhood. The average hourly power consumption during the day is high for schools in that neighborhood with 105 kWh, while the mosque has 23 kWh, and the 17 houses registered 67 kWh. It can be inferred from the figure that the peak load of these buildings occurs at different times: schools have their highest load during the morning hours, the mosque during noon and early evening hours, and houses during the night.

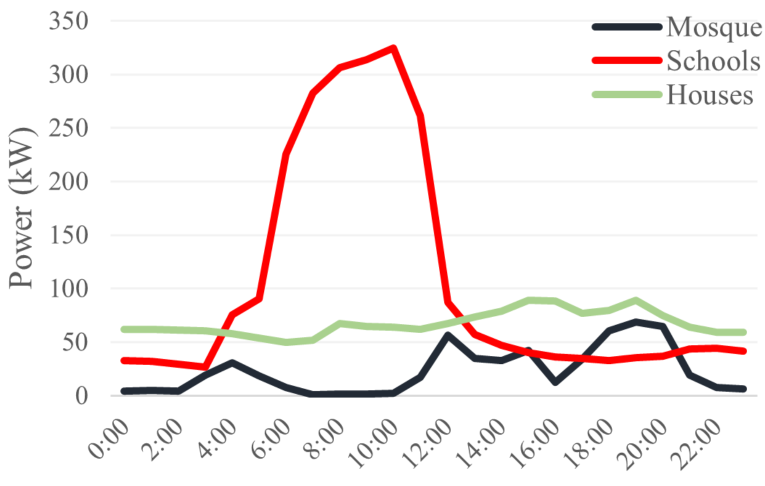


Figure 7. Load profile on the 1st of September.

Table 4 summarizes the sensitivity analysis for different PV penetration levels across all buildings, including the 17 houses, schools, and mosque. In this analysis, we observed that higher PV penetration reduces the power imported from the grid and increases GHG savings. However, at higher penetration levels, more energy is exported back to the grid, which can affect voltage stability and introduce losses. In the 25% scenario, all the generated power from solar PV panels was consumed in the neighborhood except for 15 h in the whole year. The surplus power occurred on weekend days in March, and the reverse power flow was in the range of 10 kWh. When the PV penetration increased to 50%, the NPC decreased to USD 710,000, the maximum imported power from the grid reduced to 472,574 kWh, and the annual GHG savings reached 38 tCO_2. For the 75% setup, NPC reduced as well as the imported power from the grid. However, there was a higher amount of power that flowed from the solar PV cells to the grid, which caused more losses and affected the voltage level.

The calculation of NPC in Table 4 accounts for the total life cycle costs of the solar PV system, including capital expenditures (CAPEX), operational expenditures (OPEX), and savings from reduced energy purchases from the grid. While capital costs increase with higher PV penetration due to the need for additional solar panels, these costs are offset by the significant reduction in grid electricity consumption. The NPC considers not only the initial investment but also the long-term operational savings, discounted to their present value. As penetration increases, more electricity is generated on-site, reducing reliance on expensive grid electricity and thus lowering operational costs over the system's lifetime. This reduction in OPEX leads to a lower overall NPC, even as CAPEX increases. The economic benefit of avoiding grid purchases, combined with the time value of money applied to future cost savings, results in the observed decrease in NPC despite higher capital investments.

Table 4. Sensitivity analysis for PV penetration.

PV Penetration	Capital Cost (USD Million)	NPC (USD Million)	Annual GHG Savings (tCO_2)	Value of Reduced CO_2 (USD)	Max Export Power (kWh)	Max Import Power (kWh)	Exported Power Hours (h)
0%	0	2.04	0	0	0	572,793	0
25%	0.11	0.99	16	492	−14,407	516,056	15
50%	0.21	0.71	38	1168	−87,947	472,574	446
75%	0.31	0.27	98	3012	−159,079	433,176	1336

Results show that the proposed setup will improve the self-consumption of the power generated from solar PV, reducing the power purchased from the grid and lowering GHG levels as well. When increasing the penetration of solar PV in these buildings, the integration of a storage system can be used to store surplus energy, which will reduce losses as feedback energy to the grid is minimized.

3.2. Impact of Large-Scale Solar PV Implementation

To understand the load behavior of the targeted sectors, average hourly loads were combined for all mosques and public schools in the central region during January, July, and September, as illustrated in Figure 8. It can be noticed that schools' load decreases significantly during holidays, as shown in Figure 8b. Thus, the overall load shape differs during the summer period because of schools' inactivity.

In the current setup, NPC is equal to USD 4632 million, which represents the monthly bills over a 25-year period without any PV installation. Figure 9 shows the imported energy from the electricity grid on a monthly basis. While September is not the hottest month of the year, the data show that September is the highest month for power consumption in these sectors due to the semester start.

Table 5 summarizes the capital costs, NPC, and annual GHG savings for all PV penetration scenarios. Although capital costs rise with PV penetration, NPC decreases significantly, making this option economically viable over the 25-year analysis period.

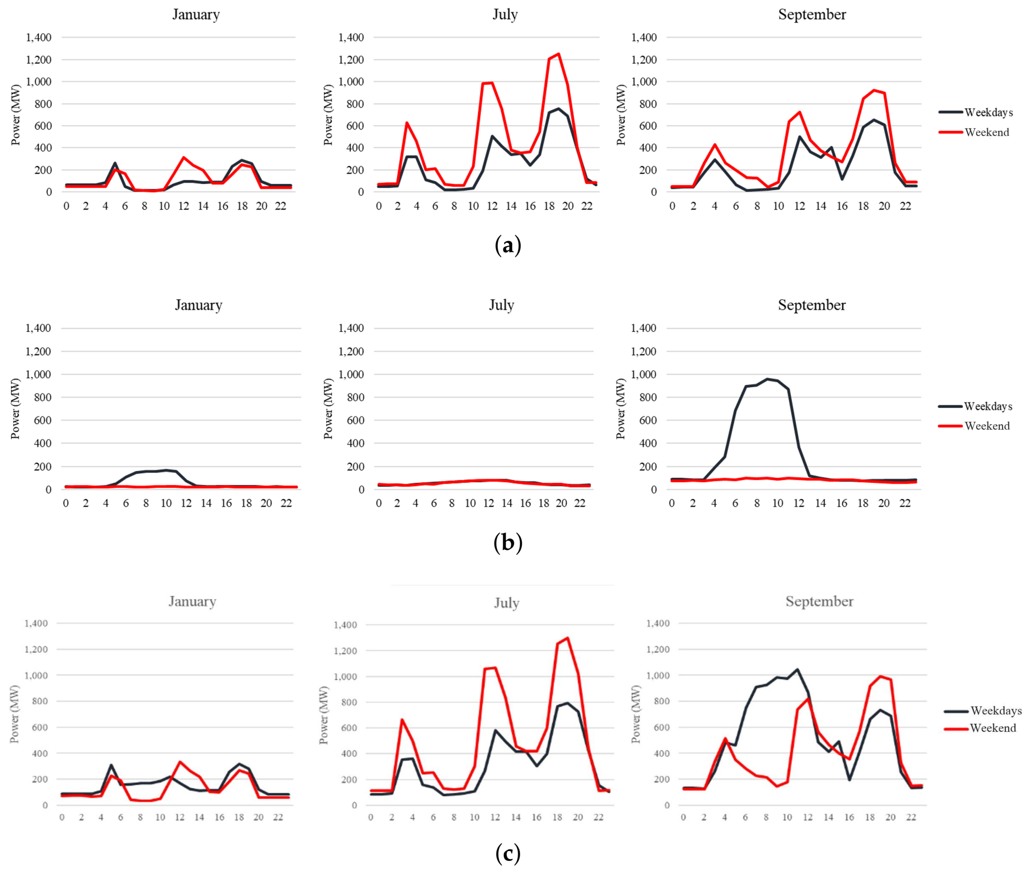


Figure 8. Average hourly load for (**a**) mosques (**b**) schools (**c**) mosques and schools.

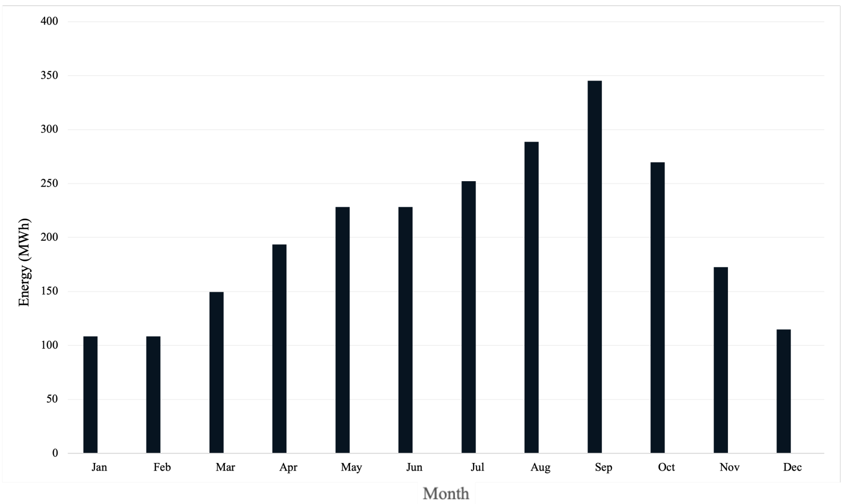


Figure 9. Monthly imported energy.

For a PV penetration of 75%, NPC equals USD 2227 million, with a capital cost of USD 1570 million. The annual electricity bill is reduced by 3.54% from the baseline scenario without PV installation. This significant reduction is due to the ability of mosques and schools to export energy to the grid during their low-demand periods, such as the winter season, as shown in Figure 10. Environmentally, GHG emissions will be reduced by 1 million tCO_2, which is equivalent to a monetary saving of approximately USD 48 million.

Table 5. Combined sensitivity analysis for PV penetration and capital cost, NPC, and annual GHG savings for all scenarios.

PV Penetration	Capital Cost (USD Million)	NPC (USD Million)	Annual GHG Savings (tCO_2)	Value of Reduced CO_2 (USD)	Max Export Power (kWh)	Max Import Power (kWh)	Exported Power Hours (h)	Annual GHG Savings (tCO_2)	Value of Reduced CO_2 (USD Million)
0%	0	4632	0	0	0	572,793	0	0	0
25%	635	3860	221,127	10.39	−14,407	516,056	15	16	492
40%	961	3342	452,170	21.25	–	–	–	–	–
50%	1181	2991	625,455	29.40	−87,947	472,574	446	38	1168
60%	1275	2589	792,779	37.26	–	–	–	–	–
75%	1570	2227	1,021,146	47.99	−159,079	433,176	1336	98	3012
90%	1749	1579	1,398,710	65.74	–	–	–	–	–
100%	2036	1254	1,599,264	75.17	–	–	–	–	–

As shown in Figure 11, mosques and schools are able to export energy from 8 am till 2 pm for most of the year due to the low load during morning times in mosques, except for Friday, and during the afternoon in schools. Figure 10 provides a detailed view of energy exchange, highlighting how buildings export more energy to the grid during off-peak hours. During July, more than 840 MW was exported to the grid in one hour. Note, The PV penetration assumed for Figures 10 and 11 is 75%.

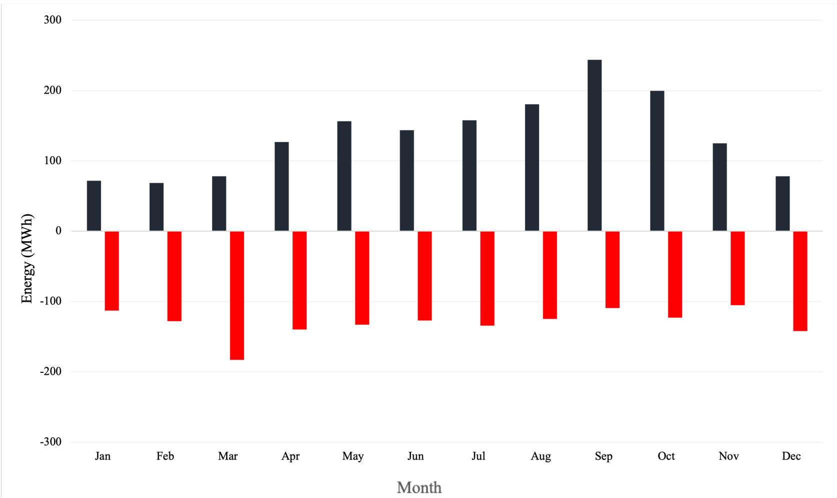


Figure 10. Energy exchange.

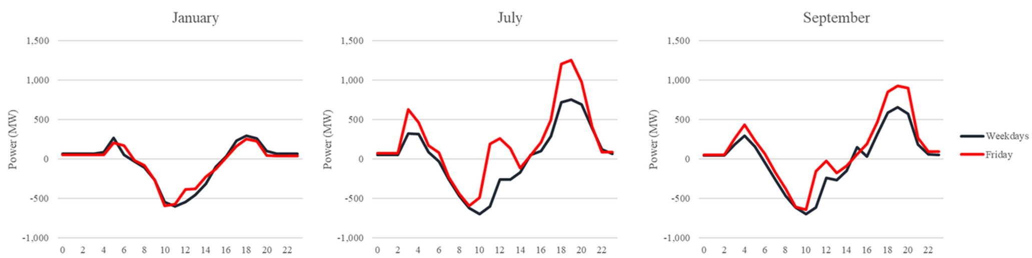


Figure 11. Average hourly load for mosques and schools.

3.3. Impact of ToU Tariff

Shaping peak load is one of the main goals for electricity companies. It is intended to limit investments in capacity expansion which is utilized for short periods of time. One of the solutions is to apply a Time of Use (ToU) tariff which is centered on dividing the day into time periods, then segregating these energy rates based on the time at which this energy is being consumed. The tariff will be higher during peak period hours to match the higher cost of generating electricity during that period. Applying that tariff structure can lower the demand during peak periods. The ToU tariff forces some customers to adjust their electricity consumption to reduce their energy bill. It also helps to increase the integration of renewable energy on the customers' side as experienced in many countries.

The electricity regulator in Saudi Arabia designed the tariff by dividing customers into six categories: residential, commercial, agricultural, industrial, governmental, and private hospital. For the residential sector, a two-tier tariff is used, with 0.048 USD/kWh for the first 6000 kWh and remaining usage charged at 0.08 USD/kWh. Similarly, the tariff for the commercial sector starts with 0.053 USD/kWh and increases to 0.08 USD/kWh. The industrial, governmental, and private hospital sectors have flat rate tariffs where 0.048 USD/kWh, 0.0853 USD/kWh, and 0.048 USD/kWh are assigned to those sectors, respectively. The agricultural sector has the lowest tariff, which ranges between 0.042 USD/kWh and 0.053 USD/kWh [40].

The design of the ToU tariff aims to recover grid capacity costs based on peak electricity consumption over a span of 60 min [41]. A trial of ToU for selected commercial and industrial organizations, with more than 100 participants, over a year was conducted by [42]. The designed ToU rates had two daily summer season pricing periods and one during other seasons. A 4:1 peak to off-peak rate ratio was considered for ToU. It was reported that peak-period load reductions for customers ranged from 86 MW in June to 66 MW in July. The impact of ToU for the residential sector was studied by [43]. The proposed ToU would increase the average electricity price by 24% and raise the revenue of the utility by 33%. The author mentioned that the impact of ToU on customer usage would save 26,000 barrels per day of crude oil over the year.

In this work, the proposed ToU design had two periods during the summer season, which starts in June and ends in September, from 12 pm till 5 PM. Three scenarios were considered in this work. In the first scenario (A), the peak rate is three times the existing price, while the off-peak rate is three-quarters of the existing price. In the second (B) and third (C) scenarios, the peak rate is four times and five times the existing price, respectively, while the off-peak rate is three-quarters of the existing price. Table 6 presents a comparison between the three scenarios.

Unlike other customers, mosques and schools need electricity at a certain time which cannot be shifted or leveled. Therefore, using an energy storage system (ESS), having a standalone generator, or integrating renewable energy resources is required to lower the monthly bill when the ToU tariff is applied. Solar PV integration was selected for that purpose, and NPC was analyzed again. For scenario A, the peak tariff is 0.2559 USD/kWh and the off-peak tariff is 0.06398 USD/kWh. Since schools' loads are light during peak hours and mosques have their peak during evening hours, scenario A will suit them well, because they will benefit from lower tariffs during their high load. For scenario B, the peak tariff is 0.33172 USD/kWh and the off-peak tariff is 0.06398 USD/kWh. If schools and mosques in the central region rely only on the electricity grid, NPC will rise by 8.35%, which equals USD 387,303,525. From Table 5, increasing PV penetration reduces deficiencies with the current tariff. When PV penetration reaches 60%, NPC deficiency is reduced to 3.3% with USD 91 million. When PV penetration reaches 97%, NPC deficiency is reduced to 0.9% with USD 21 million. In scenario C, the peak tariff is 0.4265 USD/kWh and the off-peak tariff is 0.06398 USD/kWh. NPC will rise by 20.18%, which equals USD 934.2 million if no action is taken. When PV penetration reaches 60%, NPC deficiency is reduced to 8.2% with USD 212.9 million. Seventy-five percent of PV penetration will be a better option as the variation will reduce to USD 67.6 million or 3%. When PV penetration reaches 75%, NPC deficiency is reduced to 3% with USD 67.6 million.

Table 6. Comparison of ToU tariff scenarios and impact of PV penetration on NPC.

Scenario	Peak Tariff (USD/kWh)	Off-Peak Tariff (USD/kWh)	NPC Increase (No PV)	NPC Deficiency with 60% PV (USD)	NPC Deficiency with 75% PV (USD)	NPC Deficiency with 97% PV (USD)
A	0.2559	0.06398	N/A (suitable scenario)	N/A	N/A	N/A
B	0.33172	0.06398	8.35% (USD 387.3M)	3.3% (USD 91M)	N/A	0.9% (USD 21M)
C	0.4265	0.06398	20.18% (USD 934.2M)	8.2% (USD 212.9M)	3.0% (USD 67.6M)	N/A

The detailed NPC for 75% PV penetration with the scenario C ToU tariff is presented in Table 7. The baseline scenario refers to the case of the current tariff without installation of a PV system. Despite the upfront PV system cost, installing solar PV on 75% of rooftops will help these sectors minimize NPC by 242.5%, from USD 5566 million to USD 2295 million, and reduce the annual bill by 2832%, as the annual bill will be only USD 8.9 million compared with USD 252.1 million.

Table 7. Net present cost (USD millions).

Year	Baseline (USD Million)	ToU without PV (USD Million)	ToU with 75% PV (USD Million)
1	207.77	249.68	32.52
2	205.76	247.26	32.20
3	203.76	244.86	31.89
4	201.78	242.48	31.58
5	199.82	240.13	31.27
6	197.88	237.79	30.97
7	195.96	235.49	30.67
8	194.06	233.20	30.37
9	192.17	230.93	30.08
10	190.31	228.69	29.78
11	188.46	226.47	29.49
12	186.63	224.27	29.21
13	184.82	222.10	28.92
14	183.02	219.94	28.64
15	181.25	217.80	28.37
16	179.49	215.69	28.09
17	177.75	213.60	27.82
18	176.02	211.52	27.55
19	174.31	209.47	27.28
20	172.62	207.43	27.01
21	170.94	205.42	26.75
22	169.28	203.43	26.49
23	167.64	201.45	26.24
24	166.01	199.50	25.98
25	164.40	197.56	25.73

4. Conclusions

This study focused on leveraging Saudi Arabia's abundant solar radiation, which averages over 2200 kWh/m^2, to achieve multiple goals: providing clean energy, minimizing investment in additional capacities from conventional energy sources, reducing energy bills, and lowering greenhouse gas emissions. The central region, which has more than 10.5 million people and experiences a long and hot summer season each year, was selected for this study. There are more than 29,000 mosques and public schools with a total area of 27.3 million m^2 that can be used for PV rooftop installation. In line with the objectives, we aimed to explore the potential of solar PV installation and its effect on energy consumption, environmental impact, and grid stability. The methodology used involved analyzing several scenarios with varying levels of PV penetration on public buildings. The results indicate that the scenario involving PV installation over 75% of the available rooftops is the most practical due to structural constraints. The key finding from this analysis is that PV penetration can significantly reduce reliance on conventional energy sources while contributing to environmental gains, including annual GHG savings of 1.02 million tCO_2. Typically, increased PV penetration causes instability to the electrical grid. However, since the loads of mosques and schools complement each other most of the time, the impact can be reduced. It is estimated that schools and mosques will import 1.69 GWh in a year from the electricity grid and feed the grid with 1.71 GWh for the same period. In this case, the annual bill will be 3.54% of what is paid now, and annual GHG savings will be 1.02 million tCO_2.

In addition to environmental improvements, the financial benefits of solar PV integration are evident. The NPC decreases substantially with increased PV penetration, particularly in the 75% scenario, where the variation with the existing tariff is reduced to 3%. This demonstrates the economic viability of the solution, in addition to the reduction in emissions. ToU tariffs were also explored as a potential solution for optimizing utility resources by encouraging customers to reduce their electricity consumption or shift some loads out of peak hours. However, since the loads of mosques and schools cannot be leveled or minimized, their monthly electricity bills will increase significantly. Therefore, the integration of solar PV systems can alleviate this issue while providing environmental gains. The findings in this paper will be useful for energy and municipal policymakers because of the models and analysis employed in this study. National policies focused on limiting carbon emissions and increasing renewable energy sources will play a crucial role in shaping emission profiles. The integration of solar PV systems, as demonstrated in this study, offers a path toward reducing emissions and optimizing energy consumption.

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