Techno-Economics of Solar PV on Mosque Rooftops: Results from a Pilot Study in Saudi Arabia

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About KACST

King Abdulaziz City for Science and Technology (KACST) is a scientific government institution that supports and enhances scientific applied research. It coordinates the activities of government institutions and scientific research centers in accordance with the requirements of the development of the Kingdom. It also cooperates with the relevant authorities in identifying national priorities and policies in technology and science so as to build a scientific and technological basis that serves development in agriculture, industry, mining, etc. It also aims at developing national competences and recruiting highly qualified specialists to help develop and control modern technology in order to serve development in the Kingdom. KACST comprises all the requirements of scientific research, such as laboratories, means of communications, information sources and all necessary facilities.

About SEC

The Saudi Electricity Company (SEC) is the core producer of electrical power across the Kingdom of Saudi Arabia. The main activities of the company include the generation, transmission and distribution of electrical power, where these services are provided to governmental, industrial, agricultural, commercial, and residential sectors. The organizational structure of the company includes major electrical organizational activities (business units) engaged in the generation, transmission, distribution and customer services, as well as common organizational support activities.

About KACST-SEC Joint R&D Center for the Distribution Sector

The center aims at establishing bilateral knowledge exchange channels between the two entities by conducting joint research pertaining to the distribution sector. The focus is on advanced topics that help with improving the operational efficiency of the sector, maximizing the utilization of the distribution network assets, and creating opportunities that are more economical. The center focuses on scopes related to the distribution sector including electrical power quality, protection systems, renewable resources integration, automation, communication, control, and training. More than 45 personnel from the two entities, along with external collaborators with various backgrounds (PhDs, MScs, BScs, Technicians, Administrative, and Experts), are working in the center either full or part time, and the number is expected to increase. The center participates in workshops and exhibitions, both locally and internationally, and collaborates with local and international universities and experts to ensure quality research is being performed and to further expand the center's capacity. Advanced laboratories have been established, and others are under preparation, to accommodate the requirements of current and future projects.

About KAPSARC

The King Abdullah Petroleum Studies and Research Center (KAPSARC) is a non-profit global institution dedicated to independent research into energy economics, policy, technology and the environment, across all types of energy. KAPSARC's mandate is to advance the understanding of energy challenges and opportunities facing the world today and tomorrow, through unbiased, independent, and high-caliber research for the benefit of society. KAPSARC is located in Riyadh, Saudi Arabia.

Legal Notice

Key Points

A 124 kilowatt solar photovoltaic (PV) system was installed and commissioned on the rooftop of a mosque in Riyadh, Saudi Arabia.

Load profiles at mosques are highly predictable because the times of congregation – and thus power use – are governed by the sun's movement. This also means that prayer times change with the seasons throughout the calendar year, but do not change from year to year.

Capital expenditure (capex) requirements for the commissioned solar PV system were approximately $1.18 per watt when purchased in 2017. PV prices have since dropped.

The installed PV system met nearly 25% of the mosque's energy needs.

The capacity factor of the commissioned system was found to be 18.2%, compared to the theoretical modeled result of 18.6%.

If the mosque were to sell excess power generated by the solar panels to the grid via a net-metering mechanism, the mosque would reduce its annual electricity bill by more than 50%.

With appropriate planning in the early stages of the mosque construction, net metering could bring the mosque's power bill down to zero.

Summary

There are an estimated 3.5 million mosques worldwide. The relatively large surface area of most mosque rooftops and their ubiquity in the Muslim world make them excellent candidates for solar photovoltaic (PV) installations. Muslims congregate for prayers at mosques five times a day: at dawn, noon, afternoon, sunset, and evening. Because these times are governed by the sun, they change chronographically within the year, according to the season, but are perpetual. As such, mosque electricity load profiles are highly predictable across each year and experience limited annual variation.

We performed a techno-economic analysis on a 124 kilowatt (kW) solar photovoltaic (PV) system commissioned and installed on the roof of a mosque in the Saudi Arabian capital city of Riyadh in 2017. This pilot study assesses the financial viability of installing a PV system on a mosque rooftop as a means to reduce the financial burden on the Ministry of Islamic Affairs. Currently, the Ministry of Islamic Affairs, which is an arm of the government, pays the electricity bills of mosques to the Saudi Electricity Company.

At a capital cost of $1.18 per watt, we found that, assuming a net metering policy mechanism is being implemented, the mosque's annual electricity bill could be reduced by more than 50%. If a solar PV installation considerations were incorporated into the design and planning of a similar-sized mosque's construction, by maximizing accessible roof area and minimizing shading, the annual net electricity bill could potentially be zero.

We compared our theoretical modeling results with the real-case commissioned system that served as our pilot project, and the results supported our theoretical expectations. The capacity factor obtained from the physical system was 18.2%. Explicitly, the installed PV system was able to cover nearly 25% of the mosque's energy needs. With appropriate modifications, the results of this study could be extended to other houses of worship, community halls and public buildings.

Our study shows that solar PV deployment is financially viable for mosques in Saudi Arabia under current conditions. If net metering is implemented, as planned, the net present cost (NPC) of such schemes would decline by 22%. This study can thus serve as a basis to guide policymaking related to solar PV deployment in Saudi Arabia.

Introduction

The cost of solar photovoltaic (PV) technology has fallen significantly over the past four decades. From over $100 per watt ($/W) in the mid-1970s, the cost of rooftop solar modules is now around 0.40 $/W. This significant cost decline, coupled with a growing desire on the part of consumers and governments around the world to reduce fossil-fuel-based carbon emissions, have served as the main drivers for many countries to increase or maintain a steady rate of PV installation (Chawla 2018; Isik, Dogru, and Turk 2018; Pegels and Lütkenhorst 2014). From virtually no installations in 1990, cumulative installed global capacity of PV worldwide was nearly 400 gigawatts (GW) by the end of 2017 (REN21 2018).

Solar PV systems fall broadly into three size categories (Sahu 2015): residential systems, which typically have a power range of 2 kW-10 kW, commercial and industrial systems (100 kW-500 kW), and utility-scale systems (~1 megawatt [MW] and above). Residential and commercial systems are also often referred to as distributed generation (DG), where the term DG refers to power generation units that are located within the distribution network or by/near the load (Zhang et al. 2015).

In this paper, we focus on commercial-scale systems, and will do so through a techno-economic analysis of a solar PV system installed on a mosque rooftop. The financial analysis and technical performance will be buttressed with experimental data from a pilot project commissioned in Riyadh, Saudi Arabia. Similar DG performance assessment studies have been carried out before, for example, by Huang et al. (2001), Kumar and Sudhakar (2015), and Moore and Post (2008). These and other studies have helped inform policymakers, researchers and businesses about the technical and economic aspects of renewable power DG installations. Mosques are considered suitable buildings for rooftop solar power installations because they generally have relatively large, and flat, roof surface areas. Once a solar PV system has been installed, it can contribute to reducing the energy bill considerably as the capital expenditure (or capex) of solar PV systems is the only major barrier to entry (Elshurafa et al. 2018).

Islam is a religion with 1.6 billion followers worldwide, almost a quarter of the world's population. Islam is the majority religion in nearly 50 countries (Elshennawy and Abdallah 2017). Muslims gather at mosques for their daily prayers, weekly sermons, annual festivities and other religious events and social activities. Mosques vary significantly in size, from small buildings used by 50-100 people to grand structures that can accommodate tens of thousands of worshippers. An estimated 3.5 million mosques exist globally (Deloitte 2015). Given their ubiquity in Muslim countries, governments in many of those countries are giving increased attention to mosques' energy use and to the cost of that energy.

There has been significant research on various aspects of mosques, as will be shown in this paper. Previous studies have conducted life cycle analyses for mosques (Mawed et al. 2014) and the implications of implementing sustainable solutions in mosque construction and operation. It was found that such solutions could reduce life cycle costs by as much as 9%. Outside of academia, UK-based consultancy firm Deloitte has presented a 'smart mosque' concept, aimed at reducing mosques' energy footprint through improved energy efficiency and renewable energy initiatives (Deloitte 2015).

A 2014 study that examined the potential for rooftop PV deployment at the roughly 1,400 mosques in Kuwait found that payback would take 13 years at then-prevailing energy and PV technology prices (Almutairi 2014). The objective of the study was to assess peak-shaving opportunities through

DG deployment. If the same analysis were to be conducted now, the payback period would doubtless be shorter, given today's lower technology costs.

Another 2014 study designed a hybrid microgrid system for a mosque in Libya (Mustafa et al. 2014). The mosque was located in a rural area and a diesel-powered generator provided its electricity. Because maintaining a stable diesel supply was costly, the study's authors proposed incorporating a rooftop PV system to reduce the building's reliance on fuel. The study concluded that adding a PV system, coupled with battery storage, would be the most cost-effective route. The dynamics and constraints for a grid-connected mosque will be different from those applying to an off-grid mosque. A separate study, of a mosque in Malaysia, concluded that installing a PV system would reduce the building's annual energy bill by 47% (Rashid, Alwi, and Manan 2011).

The financial attractiveness of installing solar PV systems on mosque rooftops has increased in recent years given the decreasing capital costs of the technology. The business case is more compelling in countries with high electricity tariffs. For example, in Jordan, where electricity prices have been rising since 2012, the annual power bill for an average-size mosque is approximately $17,000. The Jordanian government announced in 2015 that the country's 6,300 mosques would all eventually use, to the extent possible, solar PV for electricity generation (Abdulhamid 2015). Solar has particular appeal in Jordan, which has high solar irradiance but currently imports almost all of its energy (Alrabie and Saidan 2018).

Similarly, Morocco, home to almost 50,000 mosques, aims to install rooftop PV at 600 mosques by 2019, with help from the German government, and at more mosques thereafter (Osborne 2017). Like Jordan, Morocco relies on imports for almost all of its energy needs (Kousksou et al. 2015). In addition to the cost savings that can result from installing solar panels on mosque roofs, many governments view 'green mosques' as a way of raising awareness of energy issues and encouraging wider acceptance and adoption of renewable technologies (Neslen 2016).

Although Saudi Arabia is an energy-rich country, it is also considering the widespread deployment of rooftop solar PV systems at the country's 90,000-plus mosques. Although there are some similarities with the mosque solar power initiatives that have been, or are being launched, in other parts of the Muslim world, some characteristics are specific to Saudi Arabia. These include extremely high daytime temperatures in the summer months, requiring high levels of electricity consumption to power mosques' air conditioning units, generally large mosques, and the significant number of mosques in the Kingdom: more than 90,000, as already mentioned (Alkhotani 2016).

Saudi Arabia's electricity regulator, the Electricity & Cogeneration Regulatory Authority (ECRA), has released provisional bylaws that would govern DG installation within the Kingdom. On that front, Saudi Arabia aims to introduce a net metering mechanism to promote solar DG deployment (Comello and Reichelstein 2017; Hagerman et al. 2016). These state-level policy initiatives justify a dedicated and tailored assessment of the financial viability of installing solar PV systems on mosque rooftops in Saudi Arabia. This study can also help further fine-tune the net metering policy for this area of the Kingdom's power consumption. The Ministry of Islamic Affairs pays mosques' electricity bills in the Kingdom.

This paper presents, for the first time, a detailed and comprehensive analysis of the costs of installing a solar PV system on a mosque rooftop in Saudi

Arabia, along with other policy implications. A key element of this study is that the theoretical modeling, technical assumptions, and natural resource parameters have been cross-checked and verified with a real-world, operational, rooftop PV installation on the roof of a mosque. The results from the in-place system supported the theoretical results generated by our model.

We have also modeled the effect of the future implementation of net-metering on the financial viability of the project. We found that if net metering, as proposed, is applied to the mosque it would further increase the financial attractiveness of the project. Our results show that solar PV deployment is financially viable for mosques in Saudi Arabia: if net metering were implemented, the net present cost (NPC) would decline by 22%. The study, given its granularity, can serve as a basis to guide policymaking related to solar PV deployment in Saudi Arabia, which can be relied upon in the future for any projects in the same orbit.

Assumptions and Methodology

Overview and scope

This paper studies the design and installation of a 124 kW solar PV power generation system on the roof of a large mosque in the city of Riyadh, the capital of Saudi Arabia, with a focus on its economic impact. Given its generation capacity, the PV system in the study would generally be classified as being of 'commercial' scale, even though mosques are places of worship, not commercial buildings.

On a 'micro' level, previous assessments of DG schemes have focused on aspects that pertain to the systems themselves, including their financial viability (Numbi and Malinga 2017; Nyholm et al. 2017; Sommerfeldt and Madani 2017); engineering analysis (Koo et al. 2018; Lupangu and Bansal 2017); and the role of energy storage technology (e.g., batteries) (Lang et al. 2016; Merei et al. 2016; Wang et al. 2016).

At a 'macro' level, the literature has also evaluated policy support options (Atsu et al. 2016; Dusonchet and Telaretti 2010; Zhao et al. 2015); environmental and carbon footprint implications (Kannan et al. 2006; Qian et al. 2008); job creation (Fischer et al. 2016; Pegels and Lütkenhorst 2014; Wei et al. 2010); business models (Hanna et al. 2017; Richter 2013; Tongsopit et al. 2016); and grid stability concerns and/or benefits accruing from the two-way flow of power when excess energy generated from the PV system is exported to the grid (Ansari and Lo 2016; Coster et al. 2011; Passey et al. 2011). This study will not cover all of the above-mentioned topics. Rather, it will focus on the financial attractiveness of installing solar PV panels on the roofs of mosques. The above-cited macro aspects are beyond the scope of this paper.

Saudi Arabia has announced renewable energy targets and is considering both utility- and DG-scale systems. The Saudi regulator has released the code that would govern DG adoption. Although the regulations had not been approved at the time of writing (December 2018), the draft of the regulation is available online (www.ecra.gov.sa). As noted above, the policy proposed by and for Saudi Arabia is a net metering mechanism (Parnell 2017). Other relevant issues for residential and commercial PV, such as size limitations and installer requisites are also outlined in the proposed regulations.

Assumptions

Site information and load profile

The Riyadh mosque used in this study is large, with an approximate footprint of 2,300 square meters . For any PV-sizing (optimization) exercise to be meaningful, the load profile has to be known. Hence, a full year of load data for the mosque was collected, with a five-minute resolution. However, we have used an hourly resolution (i.e., 8,760 data points for the full year) to strike a balance between accuracy and model tractability.

Practicing Muslims congregate for prayers in mosques five times a day: at dawn, noon, afternoon, sunset, and evening. This means that the exact timing of the prayers is governed by the movement of the sun and will hence change with the seasons throughout the calendar year. Despite these solar-dependent time shifts, the timings are known precisely throughout the year and, because they are dependent on the sun, they do not change from year to year. This regularity makes the load profile of mosques highly predictable, with little room for deviation. The timings also include weekly sermons, which take place every Friday at noon. If a particular mosque does not add to its footprint by extending the building, and does not invest in energy efficiency measures, for example by buying new, more efficient air conditioners, or does not otherwise take measures that will affect its electricity consumption, little load variation would be expected from one year to the next.

Figure 1 shows two load profiles for the study mosque: one representing a day in summer and another representing a day in winter. From the data shown in Figure 1, we observe:

> As expected, a significant difference in load exists between summer and winter due to higher air conditioning requirements during the summer months. This load difference exceeds 100 kW during peak summer periods.

> Because days are shorter in the winter than in the summer (at Riyadh's latitude), there is almost one hour's difference in the timing of peak summer and winter dawn prayers.

> Although no prayers are held between afternoon and sunset prayers, other activities do take place at mosques during this period. Hence, air conditioners still function in the summer months during this time of day.

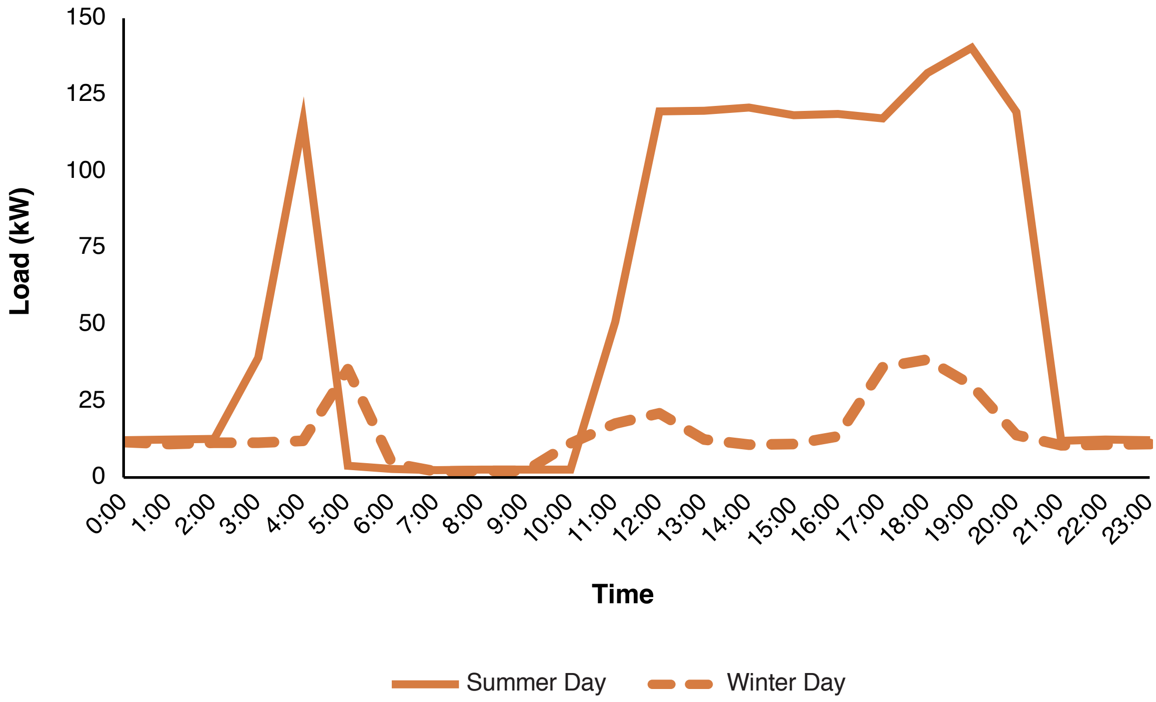
> The highest load (as per the sample of Figure 1) is approximately 140 kW. However, the peak load for the mosque was 176 kW and occurs during the evening.

> The period between dawn and noon prayers witnesses the lowest load magnitudes: the load during this time drops to around 2 kW. The latter observation is an important one and will be examined further later in the paper.

We also identified when the maximum daily loads occurred – information that can help decide how much PV capacity to install. As a sample, Figure 2 shows the time at which the peak load occurs for the months of July through December. It shows that the mosque's daily peak power consumption occurs mostly during the early evening, coinciding with sunset prayers. However, the difference between the noon peak and the evening peak is relatively small and is mainly attributable to the additional lighting needed in the evening.

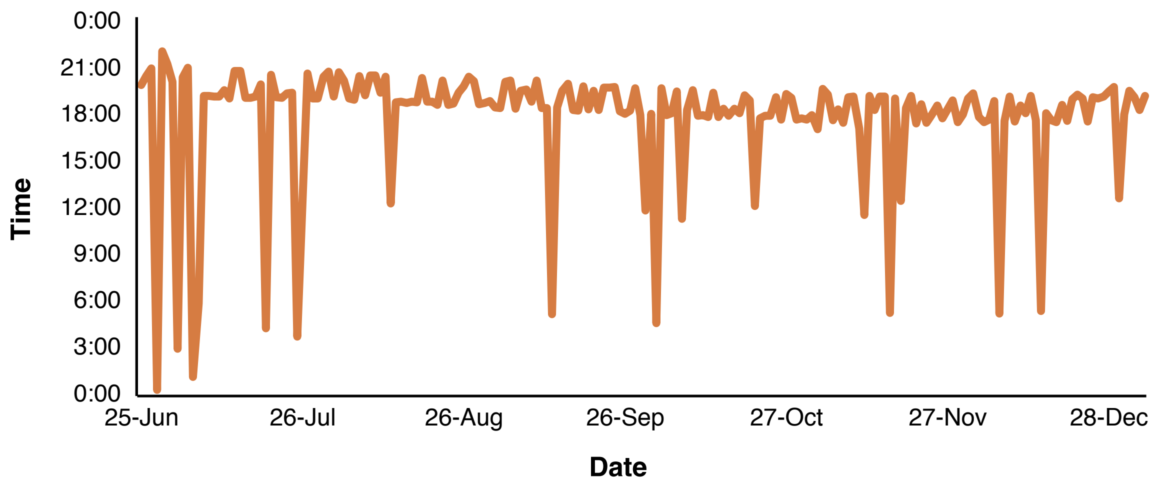
For comprehensiveness, Figure 3 depicts maximum daily loads over the same period as shown in Figure 2. As expected, the maximum daily load starts to drop significantly in October as the ambient temperature starts to fall and as the use of air conditioning drops accordingly. The peak daily load was 176 kW, recorded at the end of June.

Figure 1. Representative load profiles for the mosque using a sample summer day and a sample winter day. The profiles are constructed from the measured data.



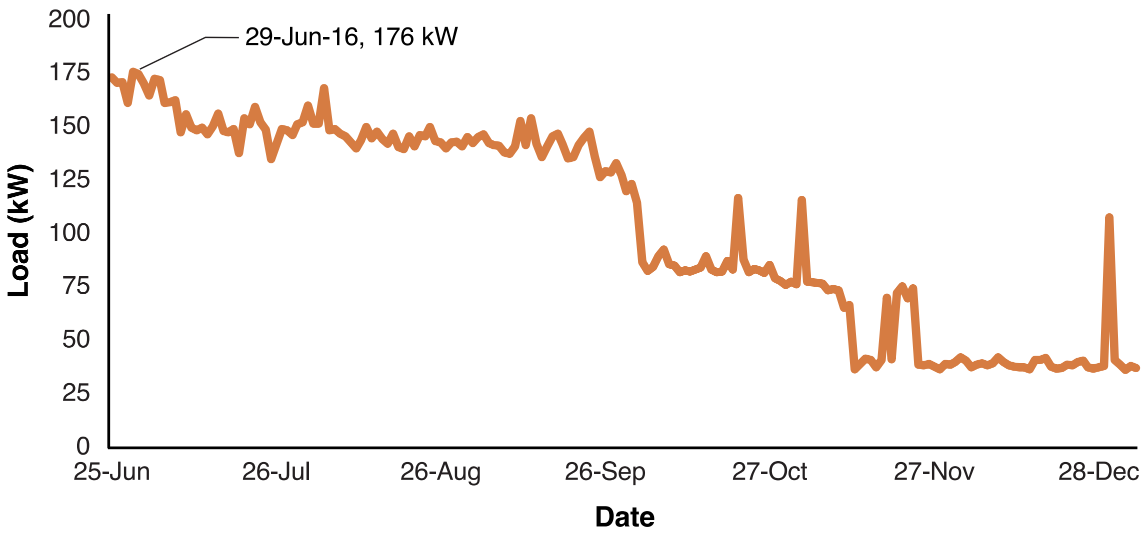
Source: Authors' data and analysis.

Figure 2. The time of day at which the peak load occurs. Note that the peak load mostly occurs around 6:00 p.m., coinciding with sunset prayers.



Source: Authors' data and analysis.

Figure 3. Maximum daily load (in kW) for the second half of 2016. The peak daily load was 176 kW, recorded on Jun. 29.



Source: Authors' data and analysis.

Financial Assumptions

Renewable energy technologies, such as solar PV, benefit from having low operation and maintenance (O&M) costs. More specifically, variable O&M costs, which are usually associated with fuel costs, are practically nonexistent. This leaves a small fixed O&M cost component to be catered for. For this reason, the marginal cost of generation for most renewable power technologies is nearly zero (Lai and McCulloch 2017).

As such, the capital cost of purchase and installation is a key cost element that influences the decision on whether or not to install a solar PV system. Table 1 summarizes the costs associated with installing the study's rooftop solar system, as provided by local vendors. Note that some cost elements were provided in dollar per watt terms ($/W), whereas others were provided in dollar terms because they were sold on a per-unit basis. We have restricted the study's cost assumptions to capex of the PV system itself. Other financial assumptions that may affect the buyer's decision on installing rooftop solar, but are not tied to the physical installation itself, such as the discount rate and the local grid electricity price will be covered shortly. The price of the solar panel module used in this study is the price that applied in early 2017. If the project were to be commissioned at the time of writing, the cost would likely be lower.

Table 1. Capital costs of installing pilot study rooftop PV system.

Item	Cost	Unit
Module (monocrystalline)	0.405	$/W
Inverter	0.133	
Ground mounts (mechanical structure)	0.343	
DC cables	0.052	
AC cables	0.011	
Labor (installation) costs	0.080	$
DC junction box	782	
Protection relay	1,970	
Power meter	230	
Controlled switch	75	
Controller	135	

Source: Authors' analysis based on quotes from local vendors with the exception of modules and some design activities. (The modules and inverters were provided through King Abdulaziz City for Science and Technology at cost price; the design activities were conducted as part of the authors' research).

Technical and Operational Assumptions

Technical and operational assumptions, in addition to capital cost assumptions, have a major effect on the financial viability of solar installations. These assumptions are summarized in Table 2 and encompass specifications related to the PV system itself, the solar resource, and 'external' financial assumptions (e.g., the discount rate and inflation).

The parameters included in Table 2 are self-explanatory. However, three of these parameters deserve some elaboration: namely the derating factor of 85%, the discount rate of 3%, and the electricity price. The derating factor is the parameter that describes the efficiency of the solar PV system. A derating factor of 85% is equivalent to losses of 15%. In our case, the derating factor entails all the losses of the PV system, including the losses that occur due to shading, but excludes losses of the inverter, which are taken into account separately.

It is well established in the literature that arriving at the 'correct' discount rate is not straightforward. Because the discount rate quantifies the time value of money, discount rates vary across individual investors, the private sector, and government. For individuals, discount rates tend to materialize via surveys and can be as high as 60% (Benzion, Rapoport, and Yagil 1989; Enzler, Diekmann and Meyer 2014; Harrison, Lau, and Williams 2002, Meier and Whittier 1983). For the private sector, one way to view the discount rate is through the lens of the opportunity cost of the project relative to other investments (which is also applicable to individuals). This will vary by sector.

For government investments, note that governments do not necessarily pursue projects for profits. Because this is a research and development project, we opted to use a discount rate of 3%, which is lower than that used in the private sector (Grout 2003; Park 2012). We understand that the discussion surrounding discount rates and their choice is not a topic of consensus, but this paper will not address the subject further as it is not one of its core objectives. However, even if a higher discount rate were used (e.g., 5%), the main insights of this paper would still be relevant.

One key factor that affects the attractiveness of solar PV installations is the electricity price. The governmental sector in Saudi Arabia pays the highest rate of all sectors: a flat 0.32 Saudi riyals (SAR)/kWh ($0.085/kWh) irrespective of consumption. The residential and commercial sectors, for example, pay 0.18 SAR/kWh and 0.20 SAR/kWh for the first 6,000 kWh of consumption respectively, and both pay 0.30 SAR for every additional kWh. To keep industries competitive, the industrial sector pays a flat tariff of 0.18 SAR/kWh ($0.048/kWh). These prices, despite tariff reforms in early 2018, are still lower than global averages. Before 2018, Saudi electricity prices were much lower. For the purpose of this paper, the relatively high price paid by the governmental sector would favor PV installation.

Table 2. Technical and operational assumption used for the analysis of the PV system.

Parameter		Value	Unit
Environmental	Solar resource	“Riyadh”	W/m²
	Temperature	“Riyadh”	°C
	Ground reflectance	20	%
Technical	Module efficiency at standard test conditions	16.6	%
	Nominal operating cell temperature (NOCT)	47	°C
	Annual degradation of module efficiency	0.5	%
	Temperature-dependent power loss	0.4	%/°C
	Zenith	65	Degrees
	Azimuth (east of south)	20	Degrees
	Inverter lifetime	10	Years
	Inverter efficiency	96	%
	Inverter replacement cost	0.10	$/W
	System lifetime	25	Years
	Derating factor	85	%
Financial	O&M cost	15	$/kW/Year
	Nominal discount rate	3	%
	Annual inflation	2	%
	Price of grid electricity	0.0853	$/kWh

Source: Authors’ data and analysis.

Methodology

The purpose of this study is to assess the techno-economics of installing a PV solar system on a mosque's rooftop with the aim of saving money. The latter objective would be achieved by minimizing the net present value (NPV) of the costs, which we refer to as net present cost (NPC) hereafter. To aid in optimization and to link all the parameters presented in the previous section, we use HOMER, a commercially available software product, to facilitate the analysis of renewable power generation and its interactions with the grid.

Note that the regulatory and policy details are of importance as the type and magnitude of support, if any, would affect the sizing of the PV system (Watts et al. 2015; Yamamoto 2012). In a setting where no net metering or no feed-in-tariffs is implemented, the system size would be designed to meet the (peak) load. Conversely, if net metering were implemented, there would be value in increasing the size of the PV system. At any point in time, if the generated PV energy is higher than the load, then the excess energy would be instantaneously exported to the grid at the electricity price. If at the end of the billing cycle (monthly or annual), the customer was a net importer of energy, then he or she would pay the utility for the energy used. Likewise, if the customer were a net exporter of energy at the end of the billing cycle, the utility would pay the customer at a predetermined rate, referred to as the net excess export price. This net export price is generally lower than the electricity price, and most net metering programs would require utilities to buy back this excess generation from the property owner at either the day-ahead wholesale electricity price (Borenstein 2017) or the avoided cost (Wan 1996). The latter usually refers to the fuel cost component, without incorporating capacity and transmission costs. The Saudi Arabian power regulator has not specified the net excess export price. For the purposes of this paper, we have assumed a net excess export price of $0.02/kWh.

Our analysis considers two main scenarios: a no-policy support scenario and a net metering scenario. As with any other modeling exercise, the results, after being acquired, would have to be contextualized and interpreted within our project setting to account for factors such as budget and space constraints.

Model Results

Summary of results

Table 3 (below) summarizes the results of our analysis. In addition to the two scenarios mentioned above (no policy support and net metering), we have included a 'do-nothing' scenario, where rooftop PV would not be installed. These three scenarios are hereafter referred to as A, B, and C respectively.

The minimum NPC for scenario A was found to be $726,522 assuming a PV installed capacity of 65 kW. At this capacity, nearly 16% of the mosque's annual electricity requirements would be met from the rooftop solar system. The amount of power sold back into the grid, or exported energy, which amounted to 38,927 kWh, is not compensated for in this scenario because there is no net metering policy in place. When the annual net metering policy is implemented, the model finds that an optimal PV capacity of ~250 kW achieves the minimum NPC, assuming there are no space constraints for the PV panels and the net excess export price is 0.02 $/kWh.

However, the accessible area of the study mosque's roof only allowed for a maximum installation of 124 kW PV capacity (see below for more details). At 124 kW, the NPC was found to be $581,606, while capex and the share of the mosque's power provided by solar increased to $134,030 and 25% respectively. The levelized cost of energy at this PV capacity would be 0.054 $/kWh, significantly lower than the standard electricity price of 0.0853 $/kWh.

Although the capex values provided may initially seem to contradict the information in Table 1, it should be noted that for scenario A, the model chooses to build an inverter of any size (45 kW in this case). However, for scenario B, an overall inverter capacity with multiples of 30 kW was dictated to the model. This is because the inverters provided by King Abdulaziz City for Science and Technology (KACST) for the project were 30 kW inverters. A total inverter capacity of 124 kW was deemed optimal – as a result, five 30 kW inverters were installed on the mosque's roof, bringing the total inverter capacity on site to 150 kW.

The overall $/W equivalent value for scenario B, the scenario implemented, was 1.08 $/W. Given the nature of this project, both the modules and inverters were provided at cost, and many of the design aspects were provided free of charge. We approximated these non-captured costs to be $0.10/W and added them to capex, resulting in an overall capex of $ ~1.18/W. To reiterate, these costs reflect prevailing conditions in early 2017 when the project was in its design phase. We would expect project capex to be considerably lower at the time of writing (December 2018).

Table 3. Capital costs of installing pilot study rooftop PV system.

Scenario	Installed PV capacity (kW)	Net Present Cost $	Capex ($)	Share of Load met by PV (%)	Annual energy exported (kWh)
A. PV without policy support	65	726,522	65,785	16	38,927
B. PV with net metering (annual)	124	581,606	134,030	25	94,184
C. Do nothing (grid only)	--	747,685	--	--	--

Source: Authors' data and analysis.

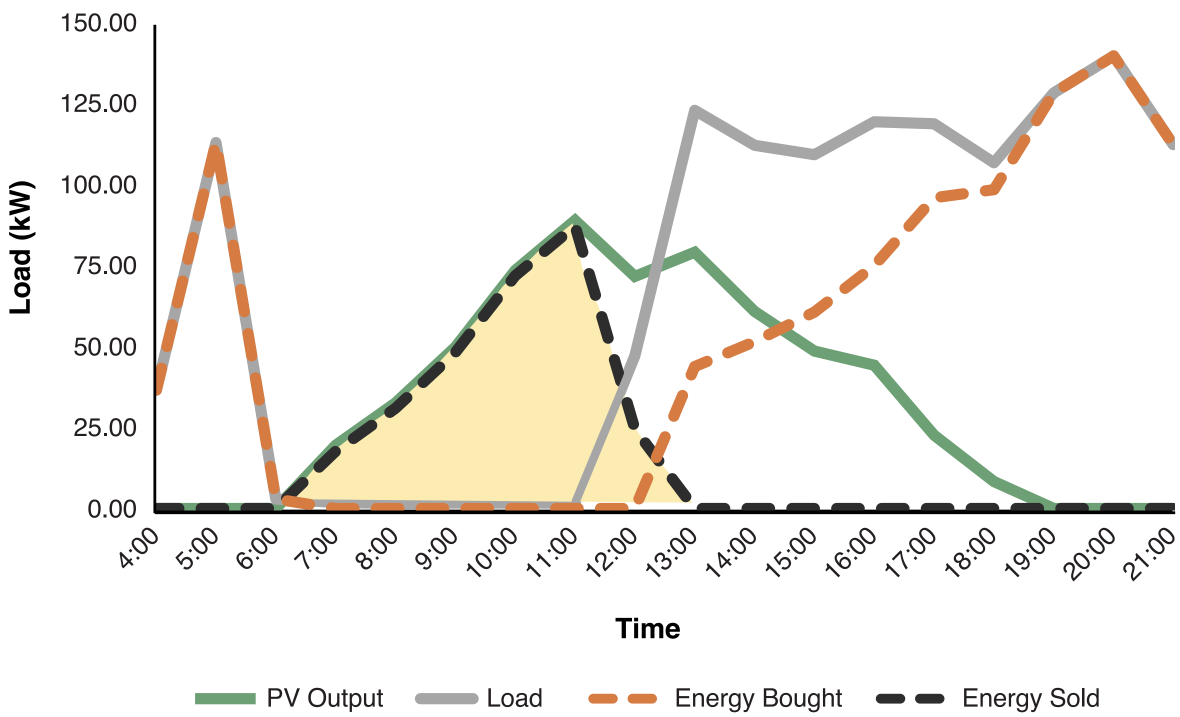
Role of net metering

Even though the net metering scenario nearly doubles the capex for the study project, compared to the no-policy case, the NPC for the net metering scenario is significantly lower. To understand the reason for this, we analyzed the load profile, PV generation, grid purchases, and grid sales. As Figure 1 shows, almost no load occurs between the end of dawn prayers and shortly before noon prayers during the summer and winter months. During this morning period any energy generated from the solar system can easily be exported to the grid.

This phenomenon is depicted in Figures 4 and 5, where the power generated from the PV system, the mosque's load, grid purchases (i.e., energy bought from the grid), and grid sales (i.e., energy sold back to the grid) are shown for a typical summer day and a typical winter day. In Figure 4 (a summer day), the energy generated from the rooftop PV exceeds the load from 6 a.m. until approximately noon. Nearly all of the energy generated during this period is exported to the grid. Beyond noon, the load becomes larger than the power generated on site, and the need to buy power from the grid starts to increase until the grid provides all power to the mosque at or around sunset.

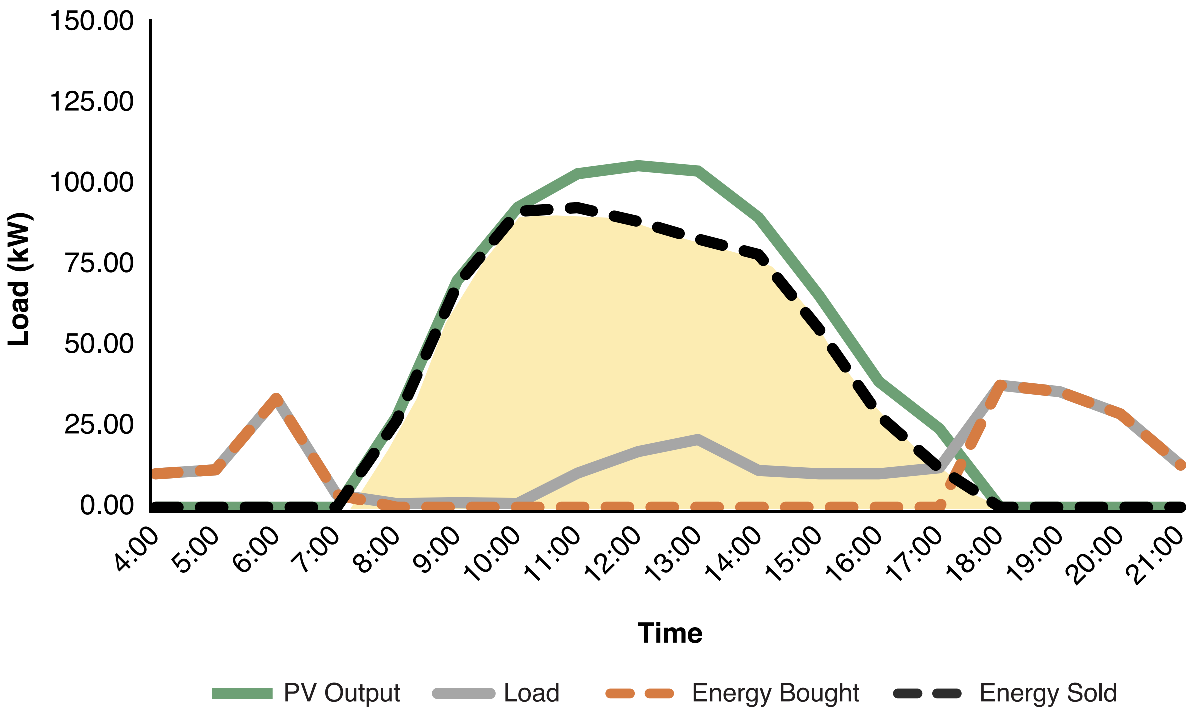
On the other hand, as shown in Figure 5, the energy generated via the PV system during a winter day is always larger than the load, except for a short time before sunset. Hence, a small percentage of the solar-generated energy is used to satisfy the load and the rest is exported to the grid. As expected, and given this load and PV generation profile, the mosque would be a net exporter of energy during the winter months.

Figure 4. Electricity generated from the PV system, the load, power bought from the grid, and electricity sold into the grid during a sample summer day. The yellow region represents total power sold back to the grid.



Source: Authors' data and analysis.

Figure 5. Electricity generated by the PV system, the load, the energy bought from the grid, and the energy sold to the grid during a sample winter day. The yellow region represents the total amount of power sold back to the grid.



Source: Authors' data and analysis.

Translating the above information into monetary terms, Table 4 (below) shows the monthly energy consumption for the mosque and contrasts the 'do-nothing' case with the net metering scenario. In the do-nothing scenario, the mosque's annual power consumption is 397,043 kWh at a cost of $33,880. With PV installed and subject to net metering, the building's annual energy bill is reduced by more than 50% to $16,546. The sources of the savings are twofold: the energy that is exported (102,068 kWh), which amounts to approximately a quarter of the year's overall consumption, and the energy that is generated by PV and self-consumed, amounting to 101,006 kWh (not shown in Table 4). As expected, under this scenario the mosque is a net-importer overall, although it is a net-exporter during January, February, November, and December.

Table 4. The mosque's monthly electricity consumption and subsequent power bill for the grid-only and net metering scenarios. Any discrepancies are due to rounding.

		Grid only		Grid + PV (124 kW) with net metering			
Month	**Load**	**Energy purchased**	**Bill to be Paid**	**Energy purchased from the grid (kWh)**	**Energy sold to the grid (kWh)**	**Net energy purchased from the grid (kWh)**	**Final annual electricity bill ($) ***
Jan	10,505	10,505	896	7,542	11,706	(4,164)	-
Feb	9,455	9,455	807	6,518	11,924	(5,405)	-
Mar	28,622	28,622	2,442	18,673	7,400	11,273	-
Apr	44,991	44,991	3,839	33,976	5,997	27,979	-
May	45,614	45,614	3,892	33,890	6,602	27,288	-
Jun	70,845	70,845	6,045	60,170	7,718	52,452	-
Jul	46,243	46,243	3,946	33,935	6,356	27,579	-
Aug	46,418	46,418	3,961	34,266	6,525	27,742	-
Sep	45,438	45,438	3,877	33,960	6,375	27,585	-
Oct	28,200	28,200	2,406	18,502	8,438	10,064	-
Nov	10,146	10,146	866	7,089	12,152	(5,064)	-
Dec	10,564	10,564	901	7,516	10,876	(3,360)	-
	Total	**397,043**	**33,880**	**296,037**	**102,068**	**193,969**	**16,546**

Source: Authors' data and analysis.

Note: * Because the net metering mechanism is implemented annually, there will be no monthly bills to be paid.

Comparing the Model to Physical Measurements

For the physical installation, a total of 460 modules were used, with a power rating of 270 W each, bringing the total capacity of rooftop PV installation, at standard test conditions, to 124.2 kW. As previously mentioned, five inverters were used for the system, each with a rating of 30 kW. A photograph of the overall installed system is shown in Figure 6.

The rooftop PV system was commissioned in August 2017 and has been monitored closely since then. Two power quality measurement devices were installed as part of the project: one at the transmitting end of the medium voltage feeder that supplies the power to the mosque, and the other at the main circuit breaker at the mosque. A communications system was also installed and linked to a human machine interface (HMI) to enable real-time system monitoring and control.

A significant amount of data was generated in the project's first year of operation. In the interests of brevity, this paper only compares the results of power generation: Table 5 compares actual system performance versus predicted performance from September 2017 to August 2018. As can be seen in Table 5, the results from the theoretical model closely match those of the commissioned system – with average discrepancy over the year of approximately 6% per month.

Figure 5. The installed and commissioned 124 kW solar PV system on the mosque's rooftop.

Table 4. Monthly generation from the rooftop PV system, as calculated via the model and as measured from the installed system.

Month	Total PV generation in kWh (from model)	Actual PV generation in kWh (from field)	Discrepancy in %
Sep. 2017	17,853	17,434	2.3
Oct. 2017	18,136	17,671	2.6
Nov. 2017	15,209	12,978	14.7
Dec. 2017	13,924	13,371	4.0
Jan. 2018	14,669	12,466	15.0
Feb. 2018	14,861	12,861	13.5
Mar. 2018	17,349	19,246	10.9
Apr. 2018	17,012	16,850	1.0
May. 2018	18,326	17,772	3.0
Jun. 2018	18,393	18,250	0.8
July. 2018	18,664	19,483	4.4
Aug. 2018	**18,677**	**19,451**	**4.1**
		Average monthly discrepancy	**6.4**

Source: Authors' data and analysis.

Note: * Because the net metering mechanism is implemented annually, there will be no monthly bills to be paid.

Based on the results shown in Table 5, we conclude that the capacity factor for the PV system using the model is 18.7%, compared to 18.2% using the measured data. We regard this numerical value obtained from the field as transferable to similar-scale projects in the region.

Looking at the financial health of the project from a different angle, we may calculate the internal rate of return (IRR) of the project assuming that the avoided costs of installing PV (self-consumption) and credit received from exporting energy to the grid are defined as income. Based on this assumption, capital costs and fixed O&M costs would comprise the outflow of funds, whereas the energy generated from the PV (used and exported) comprise the inflow of funds. The IRR is easily calculated as 11%, which means that any discount rate lower than this value would make the project viable. Note that we have chosen 3% for our analysis, but a higher discount would not change the core message of this paper.

Discussion

Securing capital

The capital cost of a PV system is considered the main financial barrier to installation. For public buildings, mosques included, there are two main sources of capital: state-funding or a third-party ownership (TPO) model (Davidson et al. 2015; Hong et al. 2018). Under the TPO financing model, an energy services company (ESCO), for example, installs the solar power system, usually bearing all or most of the capex costs, and is responsible for maintaining the system for an agreed period after commission. The ESCO would then typically recover its investments through a power purchase agreement (PPA) (Lam and Yu 2016) or a lease agreement (Rai and Sigrin 2013). TPOs are popular in many parts of the world (Strupeit and Palm 2016), especially in the United States(Fu et al. 2017). Other variations and financing models also exist (Horváth and Szabó 2018).

Another source of funding for mosques, and houses of worship more generally, is from charitable donations. Changes to global economic, social and political environments are making resources allocated to charitable organizations increasingly scarce (Grace and Griffin 2006). As for the motives of general philanthropic acts, or donations, these can be: (a) political: to build political status or change public opinion; (b) financial: to receive financial benefits such as tax credits; or (c) religious: to attain spiritual benefits or eternal happiness (Degasperi and Mainardes 2017). Donations to houses of worship, whether from individuals or organizations, fall under the last category and are relied upon as an important financing mechanism throughout the world and across different faiths.

Globally, and in Saudi Arabia particularly, there is a growing interest in developing financial endowments and managing their returns (Obaidullah 2016). To that end, The General Authority of Islamic Affairs and Endowments in Saudi Arabia launched its Investment Funds Project. The project aims to achieve financial stability and sustainability for non-profit bodies (Arab News 2018). Although there would be no financial returns if solar PV systems are commissioned on mosque rooftops, they would nonetheless bring significant cost savings.

Impact on power bills

It has been shown that installing a PV system on the rooftops of large mosques in Saudi Arabia is a financially viable endeavor, even without any financial policy support. When the net metering mechanism proposed for Saudi Arabia was studied, the initial results from the model indicated that ~250 kW would have to be installed to minimize the NPC. The annual electricity bill for that size and type of solar PV installation was found to be near-zero – revenues from excess power exported to the grid almost equaled the cost of buying power from the grid.

However, it was not possible to install this amount of capacity on the study mosque rooftop. Although the overall area of the roof, in absolute terms, could theoretically have accommodated 250 kW, the actual area of the mosque's roof that was accessible and suitable for mounting solar panels was not large enough. When the mosque was built, the architects did not consider the possibility of installing a rooftop PV system in the future. Figure 7 shows a schematic aerial view of the mosque rooftop, and where the PV modules were installed. The diagonally shaded areas represent the installed PV system. The rest of the roof's surface area is occupied by air conditioning units, ducts, and other service units.

The installation of 124 kW solar PV with net metering reduced the mosque's annual power bill by nearly 50%. The net export energy price, which we assumed to be $0.02/kWh, did not come into play in our analysis because the mosque was a net importer of energy on an annual basis. At the end of the billing cycle (annually in this case), the mosque's net imports from the grid totaled 194,000 kWh (see Table 4).

If a monthly net metering policy were to be implemented, the mosque would be a net exporter of energy for four months of the year (see Table 4). Under this scenario, the mosque would be credited each month with a value equal to the product of the net monthly exported energy and the net energy exported price. This case would save the mosque less money than under the annual net metering scenario, because in the latter case the monthly excess energy is being compensated for at the electricity price for the following months, and the electricity price is higher than the net export energy price.

If the net export energy price were high enough, it could incentivize the installation of larger-than-needed rooftop PV systems (provided the capital could be secured), allowing for arbitrage with the grid. However, the main policy objective of installing a PV system on mosque rooftops is to reduce the mosque's power bills as much as possible – not necessarily to make money. As such, it is important to design a policy that provides the right incentives to achieve the desired objectives.

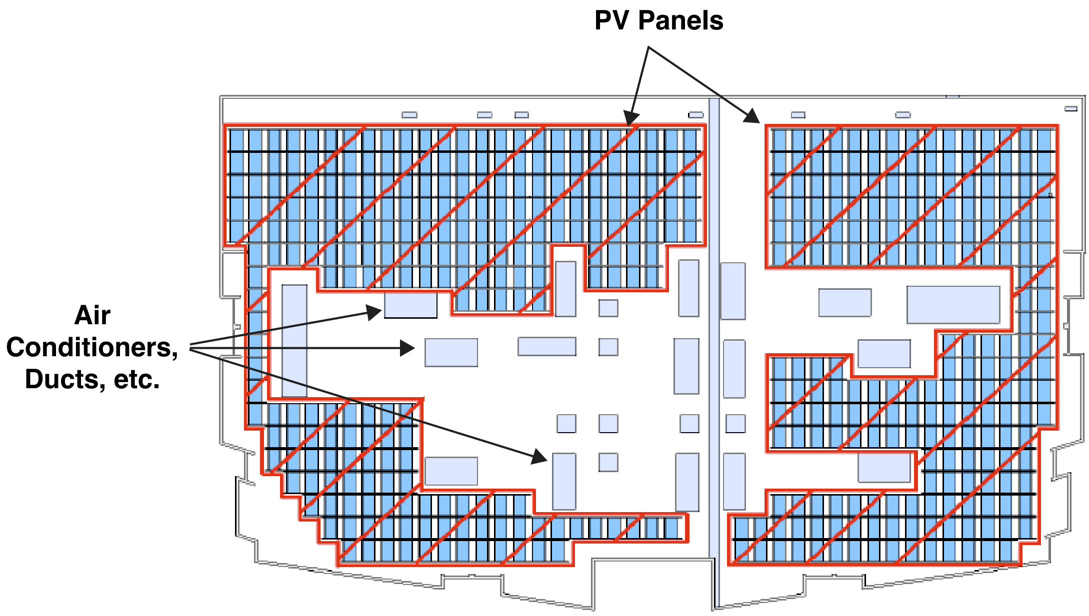
Implications for the grid and the utility

As mentioned earlier in this paper, the PV system installed on the mosque rooftop for this study is categorized as distributed generation (DG). While we have concluded that installing PV is beneficial for the mosque, DG offers several benefits to the grid. For example, it can contribute to a reduction in peak loads (Yang et al. 2014), provide frequency control and correction (Guo et al. 2015), and defer capital investments that the utility might need to make to meet growing demand (Brown et al. 2001).

On the other hand, DG poses some challenges, including the potential overloading of the distributed network (Ackermann and Knyazkin 2002) and protection malfunction (Mahat et al. 2011) due to the two-way flow of electricity. Further, when DG systems are deployed, the utility stands to lose revenue because customers no longer rely on the grid for all of their electricity needs.

These benefits and challenges all need to be assessed when formulating policy. Careful siting of DG systems can also aid in meeting utilities' strategic goals (Georgilakis and Hatziargyriou 2013). These benefits and costs become apparent only at relatively high penetration levels – the impact of a few DG systems on the grid is negligible. This paper has focused on the financial viability of solar PV for mosques. The financial implications for utilities and grid operators are beyond the scope of this paper. Tailored studies would be needed for different cases, given the local factors applying to distribution networks in different jurisdictions, even within the same country.

Figure 7. Aerial view of the mosque's roof, showing that PV panels could not be installed on 100% of the rooftop because of the existence of air conditioning units, ducts, and so forth.



Source: Authors' data and analysis.

Conclusions

This paper has assessed the economic implications of installing a solar PV system on a mosque rooftop in Riyadh, Saudi Arabia. Our results indicate that, at 2018 electricity prices and prevailing PV capex costs, it is financially viable for mosques to install PV systems, even without policy support.

Our analysis has shown that the mosque's annual electricity bill can be reduced to nearly zero under a net metering mechanism. To complement the theoretical analysis, the study compared its theoretical model with a physical PV system that was installed and commissioned at a cost of $1.18/W in 2017. Overall, results from the theoretical model closely matched those of the physical system. The measured capacity factor from the physical installed system was 18.2%.

Mosques are among the very few types of buildings that have highly predictable load profiles. Congregation at mosques takes place at specific times that are governed by the movement of the sun and most of the load occurs during these times. The time between dawn and noon prayers, in particular, is when most of the energy generated by the PV system can be exported to the grid. If the rooftop area is large enough to allow for the installation of a relatively large PV capacity, the mosque can become a net exporter of energy. It is advisable to formulate an upper limit as to how much energy can be exported, or equivalently, how much capacity can be installed to disallow arbitrage.

We further note that a trade-off exists between the capital invested and the reduction in electricity bills. Further – as in the study case – although funds may be available to install a system with optimal generating capacity, the accessible roof area for solar panel installation may not allow for such optimal capacity. While there is little that can be done to alter the roofs of existing mosques, we recommend that the design of mosques in future incorporates the option to build and install rooftop solar PV systems. Although this study has focused on mosques, the same analysis could be extended to other houses of worship or community halls, with appropriate modifications. For example, thousands of churches in the United Kingdom are currently using 100% renewable electricity (BBC 2018).

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About the Project

KAPSARC, in collaboration with King Abdulaziz City for Science and Technology (KACST) and Saudi Electricity Company (SEC), investigated, with the aid of a theoretical model and a physical commissioned system serving as a pilot, the financial implications of installing a solar photovoltaic (PV) system on a mosque rooftop in Saudi Arabia. The analysis showed that, even without any policy support, solar PV is financially viable. This study serves as a seed to subsequent economic and technical studies intended to maximize the benefit of potential Kingdom-wide initiatives relating to PV deployment on the roofs of the 90,000-plus mosques in Saudi Arabia.

Notes

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