Residential rooftop PV power generation to support cooling loads and national targets in Saudi Arabia

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Abstract: Saudi Arabia (SA) has a high per capita electricity consumption, predominantly supplied from fossil fuels. The residential sector accounts for about 50% of total electricity consumption with approximately 70% of which is used for air-conditioning (AC) loads. This research investigates the role of rooftop photovoltaic (PV) systems to displace cooling loads, hence reducing residential electricity demand. Daily and annual electrical demands were monitored in a villa in Jeddah, and a range of PV systems were modelled to determine their ability to support AC and other household loads. Seasonal performance data of such systems were compared to monitored load variations to understand variability and yields. The monitored electrical demand of the villa was in the range 66-167 kWh/day which was used to estimate the required PV systems’ capacities. The results indicate that PV systems in the range 2-10 kWp present significant shortfall to support the full demand. However, a 15kWp system was found to meet the daytime total loads. These results indicate that appropriately sized rooftop PV systems can shave-off peak air-conditioning loads. The paper discusses the importance of utilising building integrated PV in such applications in SA, and highlights the need for dissemination at scale through country wide policy framework.

1. Introduction

The energy sector of Saudi Arabia (SA) is predominantly based on fossil fuels. The country has one of the highest electricity consumptions in the world with an annual per capita consumption of 10.2 MWh [1]. Furthermore, the electricity consumption has been increasing annually at a rate in the range 5-8% [2, 3]. In its ‘energy sector transition plan 2030’ SA sets a renewable energy generation capacity target of 58.7GW, 40GW of which is to come from solar photovoltaic (PV) [4, 5]. The residential sector in SA accounts for about half of the electricity demand, and about 70% of such demand is for cooling loads [6]. Such loads are driven by the hot and arid climate of the country coupled with the very low electricity tariff and poor energy performance of older buildings [7]. Air conditioning (AC) loads tend to be highest during the summer months [8,9,10] with the peak demand occurring between 11:00 and 17:00

Figure 1: Daily/yearly PV power (kWh/kWp) in Saudi Arabia [12].
hours, while winter peak occurs between 14:00 and 17:00 hours [11]. Daily abundant solar resource intensity of SA ranging between 4.8 and 5.8kWh/kWp PV/day, (Figure 1) [13], and peak cooling demands are in phase and occur between 11:00 to 17:00 hours. This presents a great potential of building-installed solar photovoltaic (PV) systems that could satisfy some of the air conditioning (AC) loads within the highlighted demand period and beyond.

Shifting or reducing the peak cooling loads is crucial to reduce fossil fuel use and support the utility grid at peak demand. Different solutions are suggested in literatures to reduce and shift residential peak AC loads. These include the introduction of efficient air conditioning units and building retrofits to improve thermal efficiency [14, 15] as well as the potential applications of (i) scheduling advance control of AC units, and (ii) remotely setting thermostat temperature setpoints by utilities [11]. The later study indicates that these approaches coupled with occupancy behaviour change can reduce AC energy consumptions by 30% to 40% [11]. However, solutions leading to indoor temperatures above 25°C will not be acceptable to households [16]. While retrofits for achieving optimum thermal efficiency need planning, investment and time, occupants' behavioural change and acceptance of remote thermostat control by utilities require substantial socio-cultural shifts which are in turn long-term efforts.

Three different cooling cycle techniques are in commercial use. These are, (i) absorption cycles, (ii) desiccant cycles, and (iii) solar mechanical cycles. While solar cooling has been applied in various industrial settings, the domestic cooling systems often are not yet economically viable because of their expected high cost and low efficiency [17]. Here we advocate the use of solar electricity generated through building installed systems to drive the conventional electric vapour-compression AC units. The following sections provide a discussion of SA approaches to such system deployment as well as an outline of the methodology followed by the results, discussions and conclusions arising from this study.

2. PV to support cooling loads in SA

Benefits of PV bases micro generation in buildings was studied in the UK and elsewhere and demonstrated its benefits in reducing consumption in social housing [18] and as cost effective shading solution while reducing carbon footprint of large buildings [19]. In addition, the potential of integrating PV systems for power generation in carports for shading was also studied in Saudi Arabia [20, 21]. Such approaches can be adapted in SA residential building sector. However, despite the abundance of the solar resource [12, 13], the utilisation of rooftop PV in Saudi housing sector is almost non-existent compared other countries such as China, USA and the EU [22]. To encourage building integrated PV power generation, the Electricity and Co-generation Regulatory Authority (ECRA) of SA updated its Regulatory Framework for Small Scale Solar PV Systems in 2019 [23]. This framework only includes grid connected PV systems in the range 1kWp to 2MWp. To be eligible for connecting such a system to the local Distribution Service Provider (DSP), the aggregated capacity of the PV generator should not exceed 3% of the preceding year’s peak load of the power system, and the PV capacity should not be bigger than 15% of the rated capacity of the service transformer. However, while a suitable feed-in tariff is yet to be developed, ECRA’s regulatory framework outlines a net energy metering provision [23]. Under this provision surplus electricity produced by a rooftop PV system at any time of the day will be exported to the grid, and equivalent units will be offset against the consumption of the customer from the grid at each billing cycle. At the end of each billing cycle all surplus units will be rolled over for a period of three years, there after the DSP will provide a rebate to the customer at a tariff to be proposed by ECRA at that time. Local grid integration capacity limitations for distributed PV systems coupled with an unclear feed-in tariff regime may hinder PV deployment in buildings at scale.

Saudi Arabia at present has no policy guideline or regulatory framework to support the residential PV systems which are not connected to the utility grid. Smaller PV systems which are just about the right size to serve cooling loads in part or full may not have enough financial justification to connect to utility grid. Appraising the dissemination of such PV systems requires appropriate regulatory supports.

Nevertheless, Saudi Arabia has an ambitious PV power generation plan and financial support for localising PV industry along with the recent energy sector reform initiatives [5]. Limited number of studies have been carried out to explore the potential of residential rooftop power generation in several Saudi cities [24, 25, 26, 27]. Study in Hail city, SA indicates that 24.4% of the total 9 million m² rooftop area is suitable for PV power generation which can produce around 347 GWh electricity [24]. Another study carried out on 13 major cities of SA estimates that 30% of residential rooftop area are suitable for PV power generation with an estimated annual potential of 51TWh [20]. Types of residential
buildings related to their architectural and social aspects predominantly determine the suitability of available rooftop areas for PV system installations. Saudi housing consists of ~53% apartments, 17% traditional houses and 15% villas [26]. Research carried out in Al-Khobar city indicates that 21% roof space of apartment buildings is suitable for PV installation compared to 28% for villas [27].

3. Methodology
To design appropriate rooftop PV power generating systems to support residential loads, knowing household consumption profile is crucial. This methodology (Figure 2) addresses: (i) household electrical demand, (ii) simulating range of PV systems, and (iii) evaluating suitability of existing policy frameworks to understand the uptake of building integrated PV power generation in Saudi Arabia.

Electricity consumption of a monitored villa in Jeddah including three floors was used as the profile for modelling. The latter included PV system design and analysis based on (i) total electrical demand, (ii) cooling load, (iii) daily load profile, and (iv) seasonal variations. Here we use the consumption data for the 1st floor of the villa which presents highest load among three floors. This floor has a total area of 300 m², contains all the family bedrooms and cooling is used most of the time.

Figure 2: Outline of the methodology for the assessment of rooftop PV to support cooling loads.

The villa has a rooftop area of 227 m² with fewer obstructions compared to standard apartment rooftops in SA housing sector (Figure 3). An initial assessment of PV system size range and seasonal variations was carried out based on the total electrical and cooling load data. Parameters considered for the PV system simulation are as follows: (i) System architecture: Grid connected (net metering), (ii) PV module: 325Wp/module, Poly-crystalline, 16.94% efficiency, temperature coefficient -0.41, (iii) Inverter: 15kW, three phase, grid-tied, maximum PV-grid efficiency 98.1%, and (iv) Energy storage: No storage.

4. Results and discussions
Total daily electrical demand of the villa floor varied between 66kWh in February and 167kWh in June (Table 1). It is clear from the monitored data that the electrical loads are higher for the months between May and September (Figure 4). Such high electrical demands are related to high ambient temperatures in the region [30] leading to higher cooling requirements whilst, due to temperature effects PV output drops compared to the rest of the year (Figure 5). Cooling loads for the high consumption months varied between 117kWh/d in June to 101kWh/d in September (Figure 6). Other months present varying cooling demand patterns, and peak loads are spread over day and night.

Table 1: Annual average daily electrical demand, daytime load and daytime air conditioning loads.

| Load (kWh/d) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Total load   | 69  | 66  | 80  | 106 | 149 | 167 | 150 | 146 | 145 | 112 | 85  | 72  |
| Total daytime load | 41  | 35  | 45  | 60.6| 82.6| 91.6| 80.6| 95  | 78  | 58  | 47  | 45  |
| Daytime AC load | 28.7| 24.5| 31.5| 42.42| 57.82| 64.12| 56.42| 66.5| 54.6| 40.6| 32.9| 31.5|

Initial assessment indicates that PV systems ranging from 2kWp to 8kWp will have significant capacity shortfall in serving total daily electrical demands as well as cooling loads. While a 10kWp PV system meets 46% of the total daily load, 66% of the daytime load and serves the daytime cooling load
with only about 3 kWh/d shortfall, a 12kWp PV can serve 79% of the total daytime load and meets cooling load with a 7kWh/d surplus energy (Table 2).

Simulation results indicate that a 15kWp PV is the optimum size to serve total daytime load in full (99%). This system may incidentally suffer few instances of energy shortfall over the year. However, increasing the size of PV system to 17kWp would result in oversizing the system if an energy storage is not used (Table 2). On the other hand, cost of including a storage provision should be carefully compared, especially in the case of Saudi Arabia where electricity tariff is heavily subsidised. Furthermore, a PV system with additional capacity to support loads in the evening may require larger non-shaded roof area and expensive infrastructure in addition to energy storage.

Table 2: Power generation by different PV systems and their capacity to serve the total load and air conditioning loads of the study household.

| PV size (kWp) | Power generation (kWh/year) | Proportion of load served | Energy balance to cooling load (kWh/d) |
|---------------|-----------------------------|--------------------------|---------------------------------------|
|               |                             | % of total load (110kWh/d) | % of daytime load (76kWh/d)             | Daily cooling (88kWh/d) | Daytime cooling (53kWh/d) |
| 10            | 18328                       | 46                        | 66                                     | -38                     | -3                        |
| 12            | 21993                       | 55                        | 79                                     | -28                     | 7                         |
| 15            | 27500                       | 69                        | 99                                     | -13                     | 22.3                      |
| 17            | 31340                       | 78                        | 113                                    | -2                      | 32                        |

PV systems modelled for this study are grid connected without energy storage. Therefore, any spare energy generated by the proposed 15kWp PV system will be exported to the grid, and any shortfall to serve the required load will be imported from the grid. Figure 7 depicts hourly electricity generated by the optimally sized 15kWp PV, total load served by the PV and utility grid, and PV energy balance at different quarters of the year. During the first quarter, January to March (Figure 7.a) total PV power generation is greater than total daily load served, and as a result the study household becomes a net energy exporter to the grid. In contrast, during each of the three other quarters electrical loads of this...
household are greater than the overall power generated by the PV, and it needs to import power from the grid to satisfy the required loads (Figure 7.b – 7.d).

Figure 7: Seasonal PV power generation compared to monitored combined load (AC and other), and PV energy export to grid by the 15kWp PV system. (a) January to March, (b) April to June, (c) July to September, (d) October to December.

5. Conclusions
This study investigated the optimum rooftop PV system sizes to support residential cooling and other loads based on consumption of a monitored villa in Jeddah. The aim is to create the baseline understanding to support larger rooftop PV deployment. Figure 8 shows that a 15kWp PV system meets daytime cooling loads along with the other daytime loads with an annual energy surplus of 4.37MWh. The daily energy surplus is exported to the grid (Figure 7-8 and Table 3). The annual household combined electrical demand is ~40MWh (AC and other loads; day and night), and energy generated from the 15kWp PV will be short by about 16.17MWh to support total load, which is imported from the grid. Under the ECRA net metering provision the study villa will be billed for 11.8MWh/y (16.17 – 4.37 MWh) as there is no approved feed-in tariff in place. The financial attractiveness of such PV deployment is likely to be acceptable to building owners. This issue will be tested in our future research programme as highlighted below.

There is lack of available data of domestic energy consumption in SA, and to our knowledge the data used here, albeit for a large villa is the first of its kind at high resolution. Such villas represent the building types targeted in this study. Furthermore, this is the first phase of an ongoing project which will be expanded through monitoring at least 40 randomly selected villas, some with PV systems installed, which will augment data resilience needs and provide robustness in future analyses.

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