

A combined monitoring and modelling approach to understand cooling loads for residential PV system sizing: Case study of a villa in Jeddah

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Abstract— The Kingdom of Saudi Arabia (KSA) is ranked third in the world for electrical cooling demand. Almost half of its currently generated electricity is consumed by the residential sector and around 70% of this is used to support cooling loads. KSA has an aspiration to be net zero carbon by 2060, which will require transitioning its current fossil fuel-based energy supply to renewable resources, such as solar photovoltaic (PV). The Saudi ‘Energy sector transition plan 2030’ includes 40 GWp of PV capacity to be delivered through large scale solar farms but lacks emphasis on the contribution from PV on building roofs.

This research provides evidence on how optimally deployed PV on roofs can contribute to reducing air-conditioning electrical loads. A year-round electricity consumption dataset from a continuously monitored villa in Jeddah with a floor space of 757m² was used to provide the basis for modelling optimum PV systems. Results show that daily cooling loads varied between 76 kWh in December and 187 kWh in July. Regardless of seasonality, all cooling peak loads occur in daytime. The highest peak loads which are related to ambient temperature were found to be 18.5 kW in July (summer), and 7.5 kW in December (winter). Analyses of optimised PV sizing to address such loads coupled with economics are presented. All three potential PV systems modelled showed substantial return on investment under the higher tariff of USD 0.08/kWh scenario and not at the lower tariff of USD 0.048/kWh for the same export rate. Therefore, a tariff reform coupled with some kind of financial support towards rooftop PV installation is recommended. The presented methodology is generalisable and projects how PV deployed in domestic

sector can contribute to the national low carbon target at the city level.

Keywords—Photovoltaics, Saudi Arabia, Domestic, Rooftop, Cooling, Electrical loads

I. INTRODUCTION

THE Kingdom of Saudi Arabia (KSA) is the eighth largest electricity consuming country in the world (10MWh/per capita), and its electricity generation almost fully dependent on fossil fuel (natural gas ~61% and crude oil ~39%) [1]. The residential sector is the largest consumer of electricity (49.4%, 289.33GWh) [2], where approximately 70% of the electrical demand comes from cooling loads. This high demand is related to the hot and arid weather of the country [3]. KSA has an aspiration to be net zero carbon emitter by 2060 requiring transitioning its current fossil fuel-based energy supply to low carbon technologies such as renewable resources, especially solar photovoltaic (PV). In its ‘energy sector transition plan 2030’ KSA has a target of 40 GWp PV capacity mainly derived from large scale solar farm projects, and as such lacks an emphasis on microgeneration technologies such as contribution from residential rooftop PV [4-7].

The following characteristics of KSA makes it an ideal country for PV deployment on building roofs: (i) countrywide high solar resource availability (4.8 - 5.8kWh/kWp PV) [8] (ii) suitable roof spaces across different housing types [9], and (iii) high domestic cooling demands occurring between 11 AM and 5 PM [10, 11]. However, recent studies [11, 12] indicated that the existing

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ambiguous net metering provision and low electricity tariff (USD 0.048/kWh for consumption <6MWh/month and USD 0.08/kWh for consumption ≥6MWh/month) [13] in Saudi Arabia are the main reasons for unattractive return on investment for the rooftop PV systems. Considering these opportunities and challenges, this research, aims to provide evidence on how appropriately sized rooftop PV on domestic buildings can support electrical cooling loads and increase renewable energy contribution to the national low carbon target at the city level.

II. METHODOLOGY

Data of the electricity usages of a villa in Jeddah with a floor space of 757m² spread over three levels, occupied by a family of six was monitored and used as the basis for analyses. The villa, which is independently and continuously monitored, is fitted with three separate utility meters serving each floor. Electricity consumption data for the daytime hours (06:00 – 18:00) was selected to simulate the required PV systems sizes using ‘HOMER Grid’ modelling tool with no energy storage. Turnkey installation costs of range of grid connected gravity mount rooftop PV systems were collected from the local installers in Jeddah for economic analysis (Table 1). Furthermore, a maintenance cost of USD 10/kWp/year over the 25-year project life was also considered along with 4% interest on initial capital expenditure (CAPEX). With the application of seasonal variations of the daytime electricity demand (cooling and other) from the time series dataset of the villa, the optimum PV system size was determined to support the demand for cooling with minimum export to the grid. Economic suitability of the optimum PV system was analysed in comparison with current electricity tariffs for Saudi residential sector (USD 0.048 and USD 0.08/kWh) and net-metering tariff (USD 0.02/kWh).

III. RESULTS

Monitored data indicated that the daily total cooling load variation of the villa is between 76 kWh in December and 187 kWh in July (Fig.1). However, while the daytime minimum cooling demand remains in December (52 kWh), the maximum cooling load shifts to August (117 kWh). Regardless of seasonality, all cooling peak demands occur during the daytime hours.

Fig.2 presents the daytime (6AM – 6PM) hourly electrical load distributions of the villa with prominent seasonal variations in winter and summer months which are related to ambient temperatures at different months with varying air conditioning needs. For example, while the maximum and minimum demand peaks in December were observed as 7.5 kW and 3 kW, in July these values were 18.5 kW and 7.1 kW (Fig.2), in respect of ambient temperature average value ranging from 20°C to 30°C in December and from 27°C to 39°C in July [14]. An optimally sized PV should be able to meet the upper

TABLE I. RANGE OF PV SYSTEMS AND THEIR INSTALLATION COSTS AS QUOTED BY THE INSTALLERS

PV system capacity	Cost ^a (USD/kWp)
3 ≤ kWp < 5	2300
5 ≤ kWp < 8	1750
8 ≤ kWp < 10	1600
10 ≤ kWp < 12	1450
12 ≤ kWp < 15	1250

^a2023 values

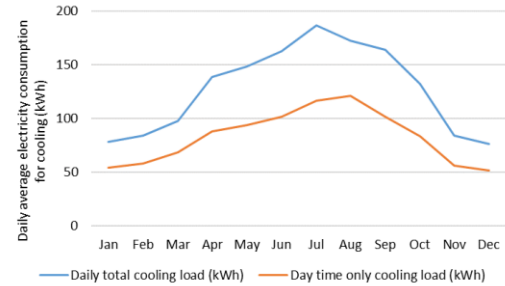


Fig. 1. Variation of electricity consumption for cooling over different months by the study villa in Jeddah.

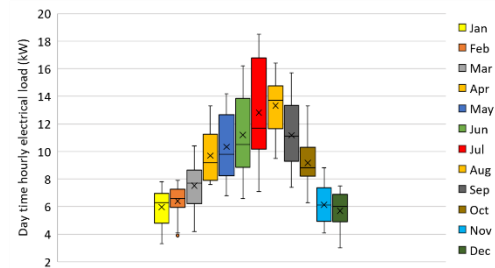


Fig. 2. Day time electrical load distribution at different months for the study villa in Jeddah.

quartile loads of the months from October to March and the lower quartiles of April to September (Fig.2) without much power export to the grid. Fig.3 presents the modelled load serving capacities of different PV systems ranging from 5 kWp to 15 kWp in terms of proportion of daytime load served by each system, power import from the grid and export to the grid. Considering the yearly high import (34.4 MWh) from the grid by the 5 kWp PV, and high export (2.8 MWh) to the grid by the 15 kWp PV (Fig.3), these two systems were excluded from further techno-economic analysis.

Techno-economic analyses summary is presented in Table 2, for a 4% interest on initial capital. The results show the suitability of optimised PV systems in relation to initial investment (CAPEX), renewable fraction (power generation by PV, grid import-export), yearly savings on electricity bill and payback periods for both tariffs levels.

All three PV systems (8 kWp, 10 kWp and 12 kWp) present substantial return on investment under the high tariff (USD 0.08/kWh) scenario. With the high tariff scenario, the 12 kWp PV system offers the best financial

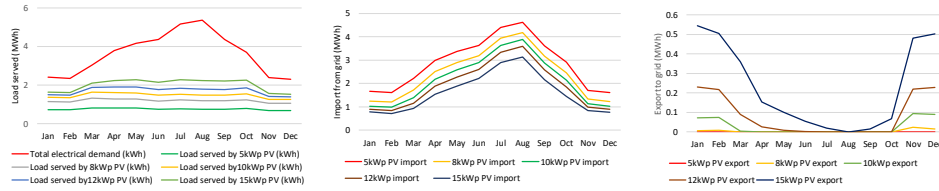


Fig. 3. Day time load served compared to total demand (left), power import from the grid (middle) and power export to grid (right) by different PV systems while serving daytime loads of the study villa across the year by different PV systems.

TABLE II. TECHNO-ECONOMIC ANALYSIS OF POTENTIAL PV SYSTEMS WITH 4% INTEREST ON CAPITAL

PV system	Tariff (USD /kWh)	CAPEX ^a (USD)	Generat ion (MWh)	Export (MWh)	Import (MWh)	PV fraction %	Annual saving (USD)	Pay back year	Total return (USD)
8 kWp	0.048	12800	14.7	0.05	29.1	32.9	688	22	2390
	0.08						1147	14	13400
10 kWp	0.048	14500	18.3	0.34	25.8	40.8	869	20	4623
	0.08						1432	13	18379
12 kWp	0.048	15000	22.0	1.00	23.0	48.3	1030	18	8220
	0.08						1717	11	24700

return (USD 24,700) with the shortest payback periods 11 years (Table 2). Similarly, the 10 kWp or 8 kWp system can also be considered for deployment under the higher tariff scenario where return on investment is USD 18,370 and USD 13,400 respectively. However, under the lower tariff regime (USD 0.048/kWh), none of the PV systems offer any significant return on investment, and related payback periods remain very long (18 – 22 years).

IV. DISCUSSION

Due to the low electricity tariffs in KSA, smaller grid connected rooftop PV systems requiring relatively higher investment (CAPEX) present lower return on investment as shown in Table 2. However, all the larger PV systems may not be techno-economically suitable if they have excessive export to the grid because of the mismatch between power generation and seasonal load variability. In such cases, existing low tariff against export (USD 0.02/kWh) results in poor return on investment. Therefore, knowing the electrical loads and cooling demands are critical to design appropriately sized PV system to be optimum to avoid poor return on investment. The 12 kWp PV system modelled here based on the daytime electrical load variations across different months and cooling demands of the study villa is the most suitable option when considering the higher tariff option of USD 0.80/kWh.

Nevertheless, for the case study villa which has separate meters for each of the three floors and pay the lower tariff (USD 0.048/kWh), an investment in deploying such a PV system will be unattractive for the owner. This is likely to be the case for many residential buildings in KSA on the same low tariff. Hence, it is important that appropriately designed support mechanisms are put in place to provide incentives for householders that are likely to result in market development of PV in urban areas. Furthermore, the strategic future electricity tariff reform aspiration of the Saudi Government [15] in line with other G20 countries may support integration of rooftop PV across the cities.

V. CONCLUSIONS

Techno-economic analyses are presented for the case of deploying PV on roofs of buildings based on monitored data, and PV system size modelling to support cooling demand reductions in the domestic sector in KSA. The results clearly indicate that optimally sized rooftop PV systems only offer attractive return on investment for the case of the higher electricity tariff (USD 0.08/kWh). Therefore, a tariff reform coupled with some kind of financial support towards rooftop PV installation is recommended. Such incentives are likely to result in market development of PV in urban areas, to support shifting the cooling loads to local PV power generation which will result in reducing the demand on electricity utilities. This paper has principally been based on simulation and estimation loads; further work will refine these techno-economic estimates with real cost and performance data from deployed systems in Jeddah.

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