

Article

Evaluating the Opportunities and Challenges of Domestic PV Installation in Saudi Arabia Based on Field Deployment in Jeddah

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Abstract: Despite the abundance of solar resources and significant electrical demand during the daytime, residential PV installations are rarely found in Saudi Arabia due to unfavorable economics, resulting from low electricity tariffs by global standards. This work reports on opportunities and challenges of residential PV installation in Saudi Arabia based on the deployment process and analyses of the performance of two 15 kWp PV systems installed on the rooftops of two similar villas in Jeddah, Saudi Arabia. For each villa, 18 months of electrical consumption and ambient temperature were available pre-installation, followed by 24 months of post-installation PV system monitoring, including incident radiation, generation, and import from the grid. A linear model of the consumption of the villas fitted between 0.016 and 0.019 kWh/m² per cooling degree day, with varying levels of interception. No significant change was observed post-installation of the PV system. On average, the reduction in overall electrical import from the grid was 20–30%. A financial analysis based on the real costs and performance of the installed systems found that the net billing feed-in tariff should be increased to SAR 1.0–1.5 (USD 0.27–0.40), depending on a range of other possible measures, in order to stimulate the growth in residential rooftop PVs.



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1. Introduction

1.1. Context of Emissions Reductions

Saudi Arabia (KSA), a major fossil fuel-producing Gulf State, pledged to achieve net-zero emissions by 2060 during the COP26 Climate Change Conference. At present, its economy and energy sectors are dominated by natural gas and oil. KSA's strategic pathway to net zero emissions without diminishing its leading role in global fossil fuel supply focuses mainly on (i) carbon capture and storage, (ii) technology adaptation to manage and reduce emissions, and (iii) sourcing half of the country's electricity generation from renewables by 2030 [1].

The Saudi government is yet to set out detailed plans for its carbon capture and emission reduction technology adaptations. However, the Saudi 'Energy sector transition plan 2030', which is embedded in its 'Vision 2030' strategy already has a target of 58 GWp of installed capacity of electricity generation to come from renewable resources [2,3], out of

which it is expected that almost 40 GWp will be from solar photovoltaics (PVs) [3]. Persistent growth in per capita electricity consumption over the last two decades, which reached 10.5 MWh in 2019 [4], and the dependency of electricity generation on fossil fuels [5] led the emission intensity of the KSA power sector to be as high as 732 gCO₂/kWh compared to the average value of the G20 countries of 458 gCO₂/kWh [6]. While natural gas contributed 213 TWh and oil contributed 149 TWh in the Saudi electricity generation mix in 2019, solar PVs and wind had only tiny shares of 0.16 TWh and 0.005 TWh, respectively [6,7]. Therefore, to achieve 50% decarbonization of its electricity sector by 2030, the country needs a holistic approach including retail price reform and efficiency measures [8,9] besides the integration and promotion of suitable renewable technologies at scale while reducing the existing fossil fuel subsidies [10].

1.2. Potential for PV Power Generation in Saudi Arabia

Saudi Arabia has a huge potential for PV power generation with significant solar resources [11]. The average daily PV power output prospect from solar resources ranges between 4.8 and 5.8 kWh/kWp across the country [12,13]. Studies [13,14] indicate the high suitability of both solar PV and concentrated solar power (CSP) technologies in all regions of the country to significantly increase the renewable energy mix in its power sector. Despite very high solar resource availability [12–14], Saudi Arabia only had a very small installed PV capacity of 409 MW in 2020 (this figure only includes the deployed capacities but not the solar projects that were approved to be deployed) [15] compared to other leading countries in this sector, i.e., China (252 GW), USA (71 GW), Germany (54 GW), UK (13.4 GW) [16]. Despite around half of the total electricity consumption of the country (578 TWh) being in the residential sector (275 TWh) (followed by industry (116 TWh), commercial (83 TWh), government (71 TWh), and other sectors (33.4 TWh) [17]), it was reported that only around 1.45% of households in Saudi Arabia used solar energy in 2018 [14]. The ‘Saudi Energy Efficiency Centre’ reported that approximately 70% of the electricity consumption in residential buildings is used for cooling purposes, which is related to four key factors: (i) hot arid climate of the country, (ii) poor energy efficiency of cooling units, (iii) poor thermal properties of older building stocks, and (iv) lack of user awareness [18]. According to official statistics [18], different cooling units across all the consumer settings (residential, government, industrial, other) consume more than half of the electrical energy produced in the Kingdom.

A report by the ‘King Abdullah Petroleum Studies and Research Centre’ (KAPSRC) indicates that electrical peak loads in Saudi Arabia during the summer months are driven by the cooling demands from the residential sector [19]. In 2018, the lowest peak demand was recorded as 25.2 GW in January, and the highest peak was 61.7 GW in September [19], which are related to the ambient air temperature. Studies in the USA have indicated that utility grids suffer technical complexities and financial burdens to meet seasonal peak cooling loads [20,21]. Similar issues were also reported in China [22].

1.3. Rationale for Rooftop-Mounted PVs

Saudi Housing Survey 2019 data [23] indicate the distribution of housing units (occupied by Saudi households) as 44% apartments, 30% villas, and 18% traditional houses, and the remaining 8% consists of other types, for example, households occupying floors in traditional residential buildings. Regardless of the type of building units, high cooling demand periods in the residential sector of Saudi Arabia occur between 11:00 am and 5:00 pm during the summer months [24–27]. A study [28] conducted across 13 major administrative regions of the country, examining 1.9 million apartment buildings, 0.83 million villas, 1.22 million traditional houses, and 0.27 million other residential types, reveals

that nearly 31.8% of these rooftops have the potential to generate 51 TWh of electricity annually through photovoltaic (PV) systems. This equates to the potential of meeting 30% of the country's residential electricity demand using the PV power generated from these rooftops [28]. However, the availability of suitable rooftop space for PV installation depends on the type of buildings [29,30]. For instance, a study specific to Al-Khobar city, Saudi Arabia, found that 28% rooftop space of villas is suitable for PV installation compared to 21% rooftop space of apartment buildings [27]. Additionally, the type of occupancy and ownership in residential buildings would play a key role in rooftop PV installation. Single occupancy and ownership, as seen in villas, differ from the multiple occupancy and individual ownership of flats in apartment buildings, influencing the feasibility of PV installation.

Taking into account the factors outlined above, including (i) the significant portion of electrical demand in the residential sector is driven by cooling loads; (ii) the alignment of peak cooling demand with periods of high solar resource availability; and (iii) the availability of suitable rooftop space, particularly in villas, for solar PV deployment to meet electrical demands partially or entirely, it is clear that residential rooftop PV systems present a valuable opportunity for distributed power generation, reducing reliance on utility transmission and distribution grids. It should be noted that although solar thermal cooling (using absorption chillers) is an alternative to PVs combined with standard vapor-compression air conditioning units, the cost is higher [31] (especially as in retrofit applications, air conditioning units are already in place), and it is not considered further here.

1.4. Growth of Rooftop PVs in a Global Context

Although the cost of electricity from utility-scale solar PVs has proven to be cheaper compared to fossil fuel and nuclear power sources in any unsubsidized case scenario, residential-scale PV systems (typically ranging from around 3 to 15 kWp) remain relatively expensive [32]. Furthermore, establishing a new residential rooftop PV market is a complex process that requires consumer education, creation of a supporting policy environment, and the implementation of appropriate financing mechanisms and technical standards [33].

A recent PV market report [34] shows that the rooftop solar market saw significant growth in 2019 and 2020, with strong adoption in countries like Vietnam, Australia, Germany, and the United States. Of the 138 GWp of global PV capacity installed in 2020, 57 GWp came from the rooftop PV category [34]. In contrast, residential rooftop PV penetration in Saudi Arabia remains virtually non-existent compared to countries like Australia, the U.S., and many countries in Europe and Asia. Historically, Saudi building owners have been reluctant to invest in rooftop solar due to the lower cost of subsidized fossil fuel-based grid tariffs [35]. On the other hand, many European nations were early adopters of large-scale rooftop PV systems, driven by attractive 'feed-in-tariffs' (FiT). Countries such as Germany, Denmark, Italy, and Spain introduced favorable FiTs in the early 2010s [36–39], and nations like France, Italy, and the UK experienced rapid microgeneration uptake between 2008 and 2012 [40]. To encourage the adoption of residential rooftop PVs, the Saudi Electricity Regulatory Authority (SERA) updated its small-scale photovoltaic power generation regulatory frameworks in 2019, in alignment with the Kingdom's 'Vision 2030' [41]. However, the current FiT of USD 0.02/kWh [41] remains less attractive when compared to the subsidized electricity tariff of USD 0.048/kWh for the customers consuming less than 6 MWh monthly [42].

1.5. Grid Readiness for Rooftop PV Integration

Even when the uptake of rooftop PVs is driven by favorable policy measures, the capacity of the distribution network may limit the maximum allowable rooftop PV penetration in a particular distribution service area. However, integration of the optimal capacity of distributed PV generation can support the local utility grid by reducing transmission and distribution losses while enhancing system resilience [43]. Additionally, incorporating residential PV systems that comply with the local grid code can optimize building energy balance, increase financial sustainability for the PV systems, and provide added value to the grid [44]. With the increased penetration of distributed PVs, conventional low-voltage networks are required to be transformed to accommodate bidirectional power flow from downstream to upstream [45,46]. Such transformations require managing grid frequency and voltage stability in the event of correlated PV generation exceeding the local demand [46]. In such cases, smart grids with advanced automation and control technologies offer a path forward, enabling grid resilience while accommodating a substantial number of distributed renewable power sources, such as rooftop PVs [46–49]. Recent innovations in power electronics, particularly in grid-tied PV inverters, have enhanced anti-islanding protection and optimized power quality, further supporting the integration of distributed PVs into conventional grids [50].

To establish grid readiness requirements, SERA established a comprehensive strategy in 2013 to incorporate smart metering and emerging technologies, aiming to transform conventional grid infrastructures into smart grids capable of integrating large-scale distributed renewable energy generation [51]. As the digital transformation of distribution grids progresses nationwide, SERA's current regulatory framework for small-scale PV integration imposes certain limits on rooftop PV penetration [41]. According to these regulations, (i) the total installed capacity of PV systems must not exceed 3% of the previous year's peak load of the local power system, and (ii) PV capacity cannot exceed 15% of the rated capacity of the service transformer of the designated distribution service provider (DSP). These capacity limits, along with low electricity tariffs and even lower FiTs [42], underscore the need for careful rooftop PV system size optimization to benefit both the utilities and building owners based on accurate building energy consumption data.

1.6. Building Energy Efficiency, Thermal Comfort, and Cooling Load Reductions

The focus of the present work is on the field deployment of rooftop PVs. However, it is important to place this in the wider context of a suite of available measures for reducing emissions due to residential buildings. According to the International Energy Agency, the building sector presents a potential for almost 41% energy savings by 2035 [52]. Given that 70% of electricity consumed in the Saudi housing sector is attributed to cooling, coupled with the poor thermal efficiency of older buildings [18], there is significant potential for energy savings through improving building insulation [53], and integrating rooftop solar power generation [27,30]. However, residential rooftop PV power generation alone, without implementing building energy efficiency measures and raising user awareness, is unlikely to provide a sustainable solution for reducing cooling loads as well as achieving the net-zero emissions target of the country. Studies [53,54] indicate that around 30–40% of cooling loads can be reduced through improved building envelope insulation. The Saudi Energy Efficiency Program (SEEP) published a Royal Decree (No. 7/905/M, dated 1 September 2010) that made thermal insulation compulsory for all new residential buildings, along with other buildings included in the previous decree (No. 7/905/M, dated 22 January 1985) [55]. However, the Saudi Household Energy Survey of 2019 reveals that 57% of building units lack thermal insulation, around 23% have some form of insulation on either exterior walls, roofs, or both, while the remaining units have no specific data regarding

insulation. Improving the thermal efficiency of older building stocks requires a planned approach of sustained investment for retrofit [56].

Raising occupant awareness, leading to positive behavioral changes regarding thermal comfort, can help reduce cooling demand. Remote thermostat control for air conditioning, combined with behavior adjustments, can reduce cooling energy consumption by 30–40% [27]. A study related to Saudi Arabia reported energy savings of around 11% by increasing the air conditioning set point from 22 °C to 24 °C [55]. Similarly, a study in Malaysia's tropical climate demonstrated a 36% electricity saving when the cooling set point was adjusted from 24 °C to 26 °C [57]. Another significant factor that has been suggested is improving the efficiency of air conditioning units [18].

Therefore, when implementing schemes to increase PV uptake, e.g., through FiTs, support should be linked to wider energy efficiency measures and raising occupant awareness in order to maximize the effectiveness of public funds in reducing carbon emissions from the residential sector.

1.7. Scope and Objectives of This Study

The work presented here aims to evaluate the potential of integrating residential solar power generation through field deployment and performance monitoring of a range of rooftop PV systems, on the way to scaling up the adoption of residential PVs [58]. For the purpose of this research, only residential villas were considered for PV system deployment as this segment of building type represents almost 30% of the national housing stock [23], and generally has no complication of shared ownership of roof area, as is the case with apartment buildings. The study objectives are pursued through documenting the deployment process of two 15 kWp PV systems in two residential villas in Jeddah of the same built form, and analyzing monitored operational performance data from these PV systems for a period of two years, to understand the opportunities and challenges of integrating rooftop solar systems in Saudi Arabia. The two villas were previously the subject of a theoretical study by the lead author [59], which assessed the potential and viability for PV generation from the villas. The assumptions used in that study were simplified (no discount rate applied) and have proved optimistic in practice (the assumed PV installed cost in 2019 was less than half of the real cost in 2022, and the PV array size assumed in 2019 was nearly double that achieved in practice). In this present work, the real costs and performance of the PV array were used to produce more refined estimates of economic feasibility.

2. Materials and Methods

The methodology followed in this research is described under four sequential steps.

1. Electricity usage data collection from Villa 1 in 2019;
2. Survey of selected sample villas for PV system deployment;
3. Supplier selection, PV system installation, and connection to the grid;
4. Performance of PV systems monitoring and analysis (two villas) from June 2022 to June 2024. A summary of these datasets is included in Appendix A, Table A1.

2.1. Baseline Electricity Consumption

For details of Villa 1 and 2, including internal layout, please see the authors' previous publication [59]. For the present study, electricity consumption in each of the meters corresponding to the three floors of this villa was monitored using Open Energy Monitor hubs communicating wirelessly with EmonTx3 low-power remote sensor nodes manufactured by OpenEnergyMonitor (trading name of Megni Partnership, Brynrefail, UK) [60]. Data were gathered for 308 days in 2019 at approx. 20 s resolution. In order to estimate the

savings due to PV installation for the whole villa, we have assumed that the proportion of the total demand has remained the same between the floors since 2019. We argue that this is reasonable as there have not been any changes reported in occupancy or usage (i.e., temperature setpoints, heat sources) of rooms in 2019 compared to 2021 onward.

2.2. Household Survey

Seven further households were selected via a non-probability method through (i) Contact with potential clients of a PV installation contractor, who had previously expressed interest in installing a PV array on their roof, but did not proceed due to the cost. The contractor staff contacted the clients and explained that the system could be installed free of charge by participating in this research project. (ii) Snowball method through contacts. The sample was purposive in that a range of villa sizes were required to provide insights into possible links between PV array and total floor area on techno-economic performance. Questionnaire-based face-to-face surveys were conducted in eight selected villas in Jeddah, including the initial study villa (Villa 1), using the Fulcrum [61] data collection tool. Data regarding occupancy, total floor area, electricity consumption, uses of air conditioning, preferred indoor temperature, and energy efficiency aspects were collected. Ethical approval was obtained through the University of Southampton with reference 65403.

2.3. PV Installation and Monitoring

Initial sizing of the PV arrays was carried out using criteria of minimum cost of energy, assuming (a) export would be possible and (b) all floors of the house could consume power from the array (see [30] for details). In practice, neither of these conditions has been achieved yet (see later in this Section). The primary constraint was the available roof area.

Multiple firms were initially identified and contacted from the SERA's list of accredited and qualified solar PV installers [62] in Jeddah to obtain quotations and project proposals for the installation of concrete-base roof-mounted PV systems.

A suitable PV installer was selected based on criteria: (i) quoted cost for supply and installation of PV systems, (ii) lead time for acquiring required permits and installation, and (iii) reputation in the market. The villa owners (referred to as 'consumers' by the regulator) registered online with the Saudi Electricity Company (SEC) for the small-scale PV installation process, where the installer submitted all required documents and designs in collaboration with the consumers.

The process of obtaining approval from the SEC to become 'prosumers' (i.e., feeding-in to the network) is not straightforward and at the time of writing is still pending 3 years post-installation. Barriers include the following:

1. Approval required at the municipal level, requiring inspections that potentially raise issues not directly related to PV installation (e.g., unrelated planning matters).
2. Significant consultancy fees of SAR 7000 (approx. USD 1900) for structural and planning investigations.
3. The list of approved PV balance-of-system equipment is limited, and some major manufacturers have chosen not to obtain (or renew in the case of the inverters used in this project) approved status due to the present small market size.

The installer completed and tested the PV systems in Villa 1 and 2 in June 2022 (see Figure 1 for images and Figure 2 for a schematic of the installation) and connected the inverters to the dedicated electricity meters assigned to the highest consuming floor of each villa. The 1st floor in each villa accounts for the highest electricity usage. Both systems were connected to the low-voltage (LV) utility grid at 127/220 V (three-phase). In Villa 1, the total A/C capacity for the first floor alone was 39 kW.

The grid-tie inverters used in this project were manufactured by Fronius International GmbH (Wels, Austria). The model of inverter was Symo 15 kW three phase, and each installation was equipped with a smart meter (model 50kA-3) and weather station (IG Data Logger with ambient temperature, plane-of-array irradiance, wind speed and ambient and PV module temperature sensors) from the same manufacturer [63]. This was to enable PV system performance data collection to be related to ambient conditions, with data pushed to cloud-based Fronius SolarWeb platform.

2.4. Ambient Temperature and Cooling Degree Days

Prior to the installation of weather stations on Villa 1 and 2 in June 2022, weather data were taken from a station at King Abdulaziz University [64]. The two datasets overlap for 221 days in 2022–2023, allowing a direct intercomparison of the sources. Over this period, the temperatures were linearly related with a high $R^2 = 1.000$ (see Table 1). A zero-intercept model was fitted due to a marginally lower Bayesian Information Criterion (BIC) than including an intercept. This was used to create a composite time series of ambient temperature, with data points prior to installation adjusted using the fitted coefficient (Figure 3).

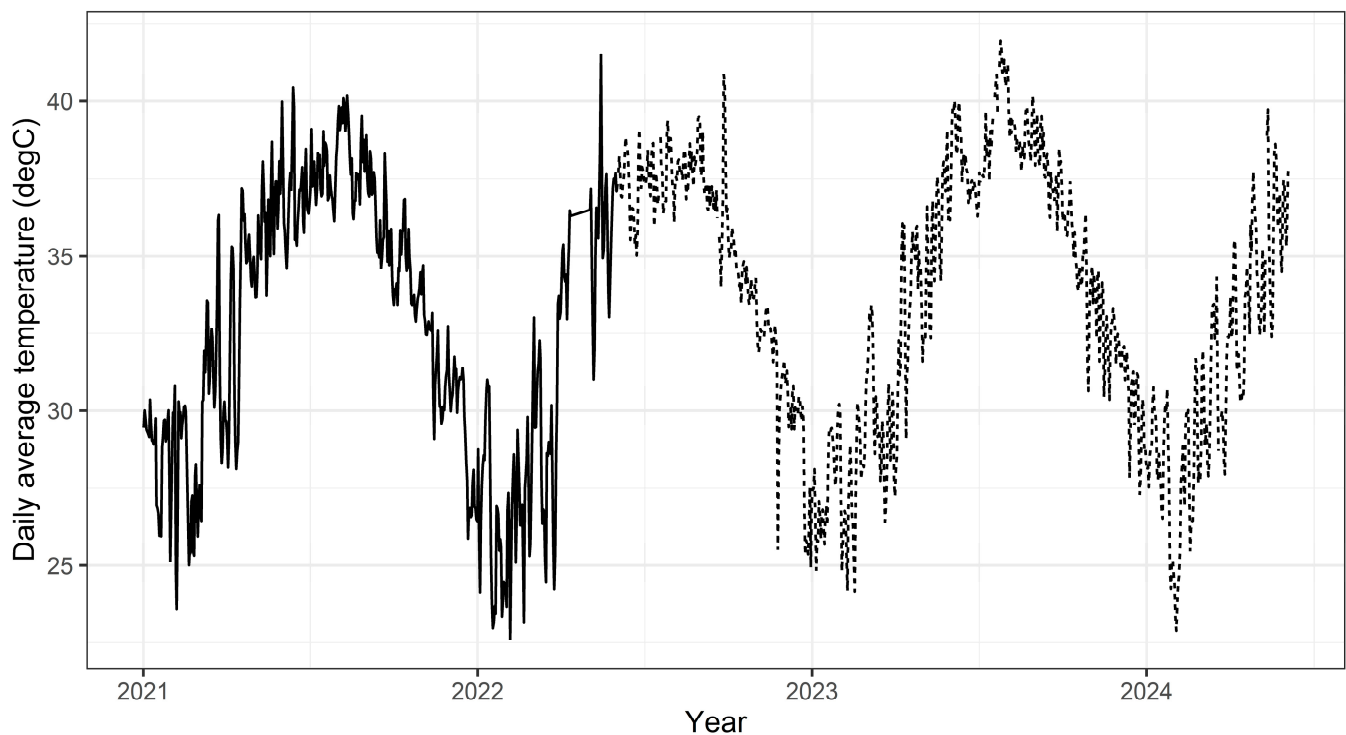


Figure 3. Composite daily average external ambient temperature dataset. The solid line represents temperature measured at the King Abdulaziz University solar PV installation weather station [64], adjusted using the fit parameters in Table 1. The dotted line is the temperature measured by the PV installation weather station.

Table 1. Linear model fit parameters between the two temperature datasets for the overlap period (subscript ‘r’ refers to the rooftop weather station, ‘u’ refers to the university weather station).

Dependent Variable:	
$T_{a,r}$	$T_{a,u}$
CI_{95}	0.923 *** (0.921, 0.925)

Table 1. Cont.

	Dependent Variable:
Observations	221
R^2	1.000
Adjusted R^2	1.000
Residual Std. Error	0.596 (df = 220)
F Statistic	626,731.000 *** (df = 1; 220)

Note: *** $p < 0.01$.

Given that electrical demand is dominated by cooling [18], in order to compare energy demand across multiple years, it was necessary to allow for the effect of varying ambient temperatures. The approach of using Cooling Degree Days (CDD) was used [65]. This assumes that, above a threshold ambient temperature, energy demand is proportional to the difference between the threshold and the ambient temperature. CDD were calculated using the Saudi standard base temperature of 18.0 °C [66] using Equation (1). The base temperature allows for internal gains within a building due to windows, appliances, and people, and represents the ambient temperature at which cooling starts to be required to maintain a comfortable indoor temperature

$$CDD = \bar{T}_a - 18.0, \quad (\bar{T}_a > 18.0 \text{ } ^\circ\text{C})$$

$$CDD = 0 \quad (\bar{T}_a \leq 18.0 \text{ } ^\circ\text{C}) \quad (1)$$

where $\bar{T}_a$ is the daily mean ambient temperature and CDD are the cooling degree-days. $\bar{T}_a$ was calculated from 5 min sampled data for accuracy, although the mean difference between $\bar{T}_a$ and the more common $(T_{\max} - T_{\min})/2$ was + 0.5 °C (standard deviation also 0.5 °C).

2.5. Financial Analysis Methodology

Calculation of net present value (NPV) and internal rate of return (IRR) for the PV arrays was carried out using the FinancialMath library (version 0.1.1) in R statistical language (version 4.2.3) [67]. The NPV V was calculated from the relation in Equation (2):

$$V = Q_0 - \sum_{k=1}^n \frac{Q_k}{(1 + \alpha)^{t_k}} \quad (2)$$

where Q_k represents positive cashflows into the project at elapsed year t_k . Q_0 is the installed cost including all components, labour, and relevant tax (see Section 3.3 for more details). The discount rate α considered for the analysis (15%) was chosen as a plausible rate within the range found in previous studies of consumer behaviour relating to energy efficiency investments [68–71]. Although the range of implicit discount rates found in these studies is large and varies strongly with methodology (from 10% up to several hundred percent), a consistent finding was that consumer implicit discount rates are higher than those used in commercial investment decisions. The number of years n for the NPV calculation was chosen as 7, as a value in the range of other studies [69,72]. The IRR α_0 was solved from the polynomial roots of Equation (3) and represents the discount rate that results in zero NPV at t_n .

$$Q_0 - \sum_{k=1}^n \frac{Q_k}{(1 + \alpha_0)^{t_k}} = 0 \quad (3)$$

The parameters in Table 2 were used in conjunction with the results of the performance monitoring given in Section 3.4 (taking the mean of the two villas). As mentioned above, the export of power was not implemented with the configuration of inverters used in the system

due to the difficulty and delays involved in obtaining approval from the municipality and network operator. Therefore, for the purposes of the financial analysis, potential export was calculated using the measured daily plane-of-array insolation, scaled by the peak daily output measured over the two-year period. One of the options considered in the financial analysis was the effect of implementing tariff thresholds at the building level, rather than the individual meter level. This presented a difficulty as data for meters on all floors were only available for 2019 (later data were only for the 1st floor). In this case, the consumption over the tariff threshold was taken from the 2019 monthly consumption, and the monthly potential generation from the average insolation measured in 2022–2023 was subtracted to calculate the additional avoided cost.

Table 2. Parameters used in financial analysis.

Parameter	Value
Exchange rate (SAR/USD, November 2024)	3.75
Residential tariff (SAR)	0.18 (0–6000 kWh/month) 0.3 (>6000 kWh/month)
Existing net billing feed-in tariff * (SAR) [41]	0.07
Discount rate (%)	15
Number of years for NPV	7
Installed cost (USD/kWp)	1250
Annual maintenance cost (USD)	150 (for 15 kWp PV system)

* Export not yet implemented in this installation.

3. Results and Discussion

3.1. Baseline Electricity Consumption Data from Villa 1

As mentioned in Section 3, electrical consumption data for all four meters in Villa 1 were available for 2019 only. Daily and monthly average electricity consumption, and hourly average peak load values for Villa 1, at different months, are presented in Table 3. Hourly average electricity load profiles for different months for the whole year are presented in Figure 4. The highest daily average consumption occurs in the month of July (267 kWh/d or 8.2 MWh/month), and the lowest daily average consumption occurs in December (109 kWh/d or 3.4 MWh/month). Hotter months between April and October have significant daytime loads compared to the evenings, which can be linked to cooling. It is worth noting that peak electrical demands occur during the daytime between 8 am and 4 pm, and there is, therefore, little incentive for incorporating energy storage with PV systems. In the case of the study Villa 1, it corresponds to the fact that most loads come from the floor, which has the highest number of air conditioning units.

Table 3. Daily average electricity consumption at different months for Villa 1.

Consumption	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Daily avg. (kWh)	112	120	140	199	212	233	267	247	234	189	120	109
Daily peak (kW)	7.8	7.3	10.4	13.3	14.4	16.2	18.5	16.4	15.7	13.3	8.8	7.5
Monthly total (MWh)	3.5	3.4	4.3	6.0	6.6	7.0	8.2	7.7	7.0	5.9	3.6	3.4

3.2. Survey of Selected Villas for PV System Deployment

The results of the survey are presented in Table 4. All selected intervention sites are single-family owner-occupied villas with three floors. Total floor area (TFA) ranges from 360 m² to 864 m². Each villa is fitted with multiple independent electricity meters connected to the utility grid. All villas, except Villa 3 and 4, have multiple building energy efficiency

measures with the exterior wall insulation and double-glazed windows in common. Older villas (3 and 4), which were built between 1980 and 2000, have fewer energy efficiency measures in place, either roof or exterior wall insulation. Average monthly electricity consumption in summer (June–September) is much higher than the rest of the year, which is related to cooling demands. Among the samples, high electricity consumption during summer and the rest of the year does not correspond to building total floor space and number of occupants. For instance, although Villa 1 and Villa 2 have exactly the same floor area (789 m²) and number of occupants, electricity consumption varies significantly. Villa 1 uses 5.5 MWh/month in summer and 4.5 MWh/month during the rest of the year. Whereas Villa 2 consumes 8.2 MWh/month in summer and 6.1 MWh/month during the rest of the year. Similarly, Villa 4, with almost half of the floor space compared to Villa 1, presents higher electricity consumption (7.22 MWh/month in summer and 4.7 MWh/month rest of the year). Each villa has a dedicated floor with most of the bedrooms and family living areas, which uses almost half or more than the total electricity consumed by the building. However, as all villas have multiple electricity meters billed separately, only Villa 3, 5, and 6 had meters where consumption reached the higher bracket of the electricity tariff (SAR 0.3/kWh) for the units exceeding the 6 MWh/month limit, especially in the summer. The use of split air conditioning units is common across the samples. Two villas use window-mounted (Villa 3 and 4) and central (Villa 5 and 6) air conditioning units. Villa 1, 5, and 6 use air conditioning setpoints of 23–25 °C, and the rest of the villas report 20–22 °C. Out of five villas using 20–22 °C as preferred indoor temperature (Villa 2, 3, 4, 7, and 8), only two (Villa 2 and 3) are willing to increase it.

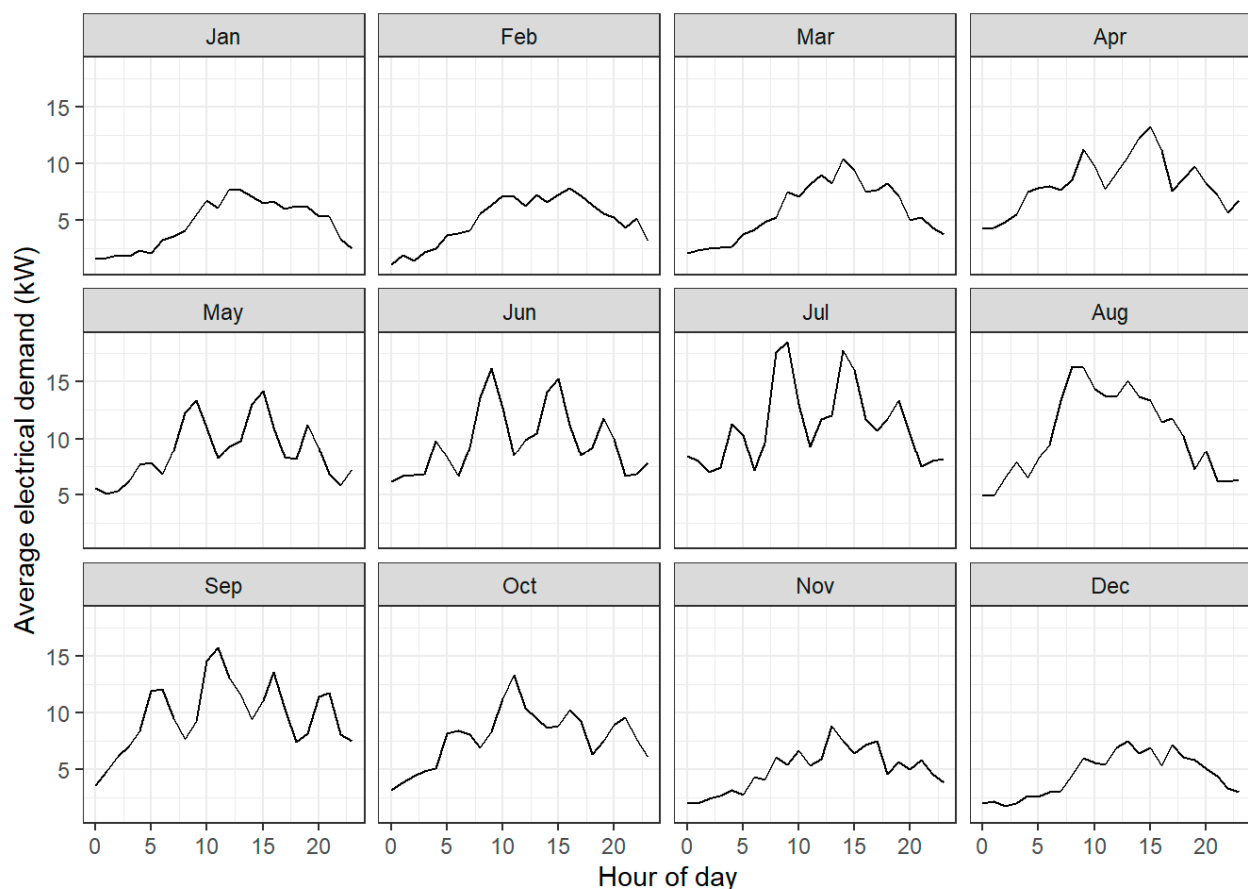


Figure 4. Monitored hourly average electrical load profiles for different months for the whole study, Villa 1, which includes three different floors and an annex with air conditioned room, pump, and swimming pool.

Table 4. Survey data from eight proposed intervention villas.

Variable	Villa 1 *	Villa 2 *	Villa 3	Villa 4	Villa 5	Villa 6	Villa 7	Villa 8
Number of floors	3	3	3	3	3	3	3	3
Occupancy type (O = Owner occupier, R = Renting)	O	O	O	O	O	O	O	O
Construction year	2001-'15	2001-'15	1980-'00	1980-'00	2001-'15	2001-'15	2001-'15	2001-'15
Total floor space of the villa (m ²)	789	789	864	693	520	615	491	491
Total space for the highest electricity-consuming floor (m ²)	287	287	522	252	274	292	292	292
Adults	4	6	6	5	8	5	4	4
Children	2	0	4	2	4	0	1	1
Total number of electric meters installed	4	3	5	2	2	2	2	2
Separate billing for each meter?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Applicable tariffs (SAR/kWh): 0.18 (0–6 MWh/month); 0.3 (>6 MWh/month)	0.18	0.18	0.18, 0.30	0.18	0.18, 0.30	0.18, 0.30	0.18	0.18
Monthly average electricity consumption for whole villa in summer (MWh/month)	5.5	8.22	11	7.22	11.8	8.3	4.4	4
Monthly average electricity consumption for whole villa in other seasons (MWh/month)	4.5	6.1	5.6	4.7	7.4	5.3	2.5	2
Monthly average electricity consumption of the most used floor in Summer (MWh/month)	3.9	4.8	7.2	3.7	6.4	6	No data	No data
AC temperature range (°C) used in main living areas and bedrooms of the villa	23–25	20–22	20–22	20–22	23–25	23–25	20–22	20–22
Willingness to adopt higher AC temperature setpoints?	Not sure	Yes	Yes	Not sure	No	No	No	Not sure
Willingness to install rooftop PV?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reason for interest in PV installation (F = Financial, E = Environmental, S = Social recognition)	F, E	F, E	F, E, S	F, E	F, E, S	F, E	F	F, E
Cooking fuel type (G = gas, E = Electric)	G, E	G, E	G, E	G, E	E	G, E	G, E	G, E
Type of AC units (C = Central, S = Split, W = Window)	S	S	S, W	S, W	C, S	C, S	S	S
Energy efficiency measures in place (W = wall insulation, R = roof insulation, DG = double glaze, S = shading)	W, R, DG	W, R, DG	R	W	W, R, DG, S	W, DG, S	W, R, DG	W, R, DG

* A floor plan and list of electrical loads for these villas are included in [59].

3.3. PV System Costs

The cost of the 15.12 kWp PV system for each of the two villas, including installation and commissioning provided by the selected installer, is presented in Table 5. Each system costs USD 1250/kWp fully installed. For comparison, an installation cost of USD 1200/kWp rooftop PVs in Bahrain was reported by [73], and the UK residential median installed cost per kWp for 2021–2022 was approximately USD 1900/kWp [74]. The costs of smart meters and the weather stations deployed to collect data for the purpose of this study in both installations were excluded from the PV system cost estimation presented in Table 5.

Table 5. Cost of system components for each 15 kWp system installation (currency conversion used: USD 1 = SAR 3.75).

Item	Description	Unit Price (USD)	Quantity	Total Price (USD)
PV module	540 Wp, Monocrystalline [75]	247.00	28	5684
Ground (roof) mount structure module	Double portrait, 2272 × 1134 × 35 mm, 12 frames, 25° tilt	668.00	3	2005
Ground blocks	Concrete, 20 × 40 × 80 cm	32.30	16	516
Inverter	15 kW Fronius (Wels, Austria) Symo-220 V	4060.00	1	4060
DC cable	4 mm ² (1500 VDC)	1.30	80 m	101
Accessories	Sets of MC4 connectors, labels, cable ties, double cable glands (IP68), etc.	252.00	1	252
DC protection	15 A fuses and surge protection	239.60	1	240
AC cable	Cu-XLPE/PVC-4 × 16 mm ²	5.00	40 m	202
AC protection	Four pole 50 A miniature circuit breaker	101.00	1	101
Interface protection	ABB (Zurich, Switzerland) grid feeding monitoring relay CM-UFD.M22M	1210.50	1	1210
Installation	Delivery, installation, commissioning, and warranty	2143.50	1	2144
			Sub total	16,515
			VAT (15%)	2477
			Total	18,992

3.4. Performance Monitoring and Analysis of Installed PV Systems

Prior to the installation of PV arrays on Villa 1 and 2, the only source of electrical energy consumption data was monthly billing data, apart from in 2019 when energy monitors were used to record consumption on all floors of Villa 1. Post installation, monitoring data from the PV installation were also available at 1 min resolution for the first floor. A comparison of grid imports, as measured by the PV system (aggregated to monthly) with the billing data for June 2022–June 2024, indicates a very small residual error over the period (see Figure 5). Therefore, the import and use of electrical energy on the first floor of Villa 1 and 2 can be directly compared before and after PV installation, as shown in Figure 6.

It is expected that electrical loads are strongly dependent on ambient temperature due to the dominance of air conditioning in the hot climate. This is, in fact, the case, as both Villa 1 and 2 displayed a similar positive association between consumption and cooling degree-days (CDD) (see Figure 7). Linear fit slopes were significant at the 1% level, albeit with considerable scatter (R^2 of 0.52 and 0.35, respectively). Note that there were no days with zero CDD in the measurement period. Villa 2 indicated a higher y-intercept at zero CDD, which can be explained by a lower temperature set point in Villa 2 (see Table 4). No significant change in consumption per degree-day was observed after the installation of PVs in either villa; this was expected as there were no reported changes in thermostat set point or occupancy pattern during the two-year period. It is hypothesized that the low import tariff and high standard of living mean that a rebound effect (increase in electricity demand due to perception of reduced cost) is unlikely.

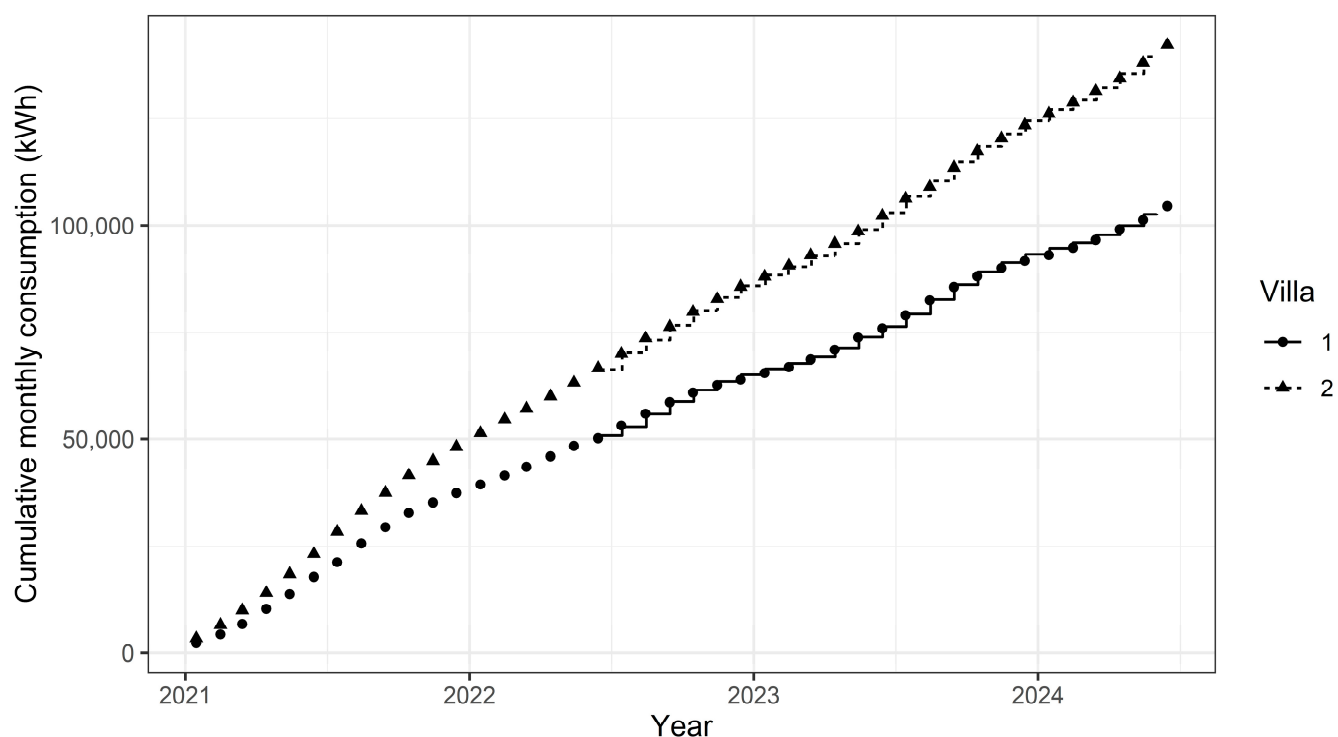


Figure 5. Cumulative electrical consumption for the 1st floor meter for Villa 1 and 2 with base-line at 1 Jan 2021. Symbols represent billing data, and stepped lines indicate monitored electrical consumption from the PV smart meter system (from 1 June 2022 onward).

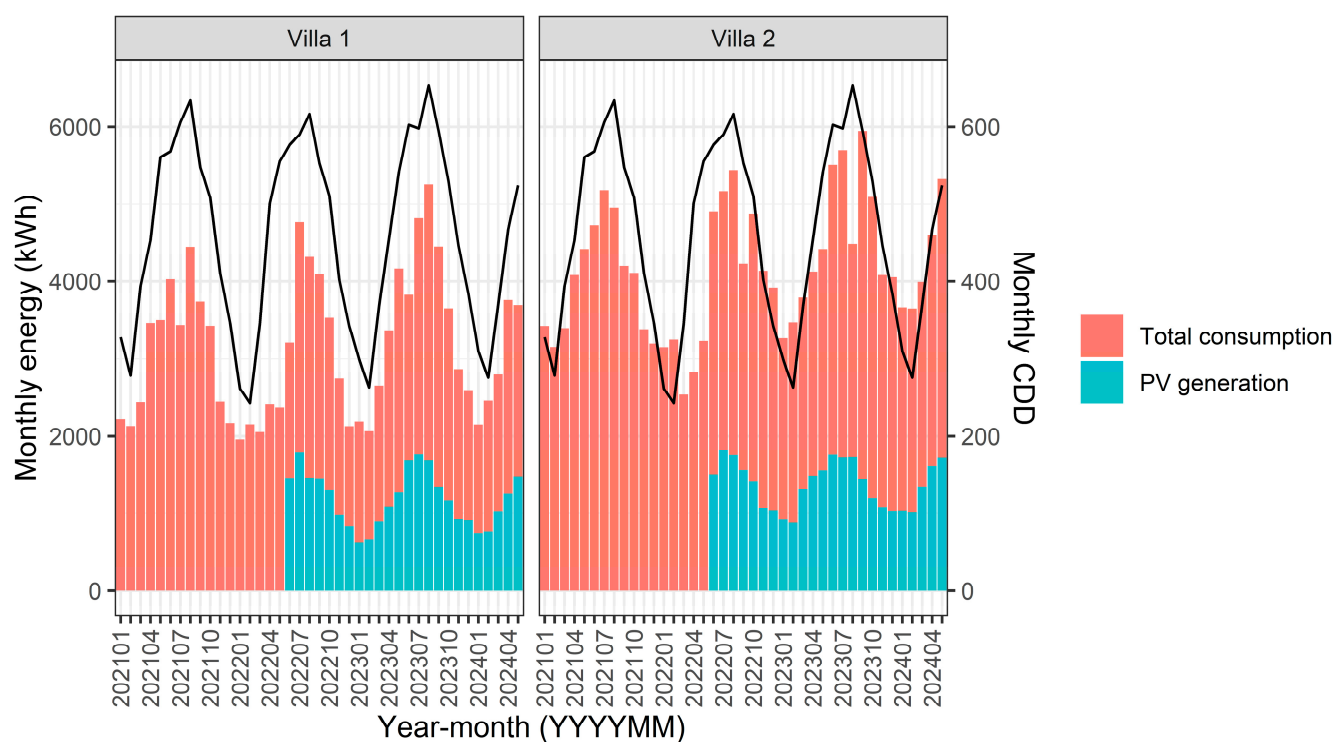


Figure 6. Stacked bar plot of monthly PV generation, consumption (floor 1 only) for Villa 1 and 2 (left y-axis) with overlaid monthly cooling degree days (CDD) (line plot, right y-axis).

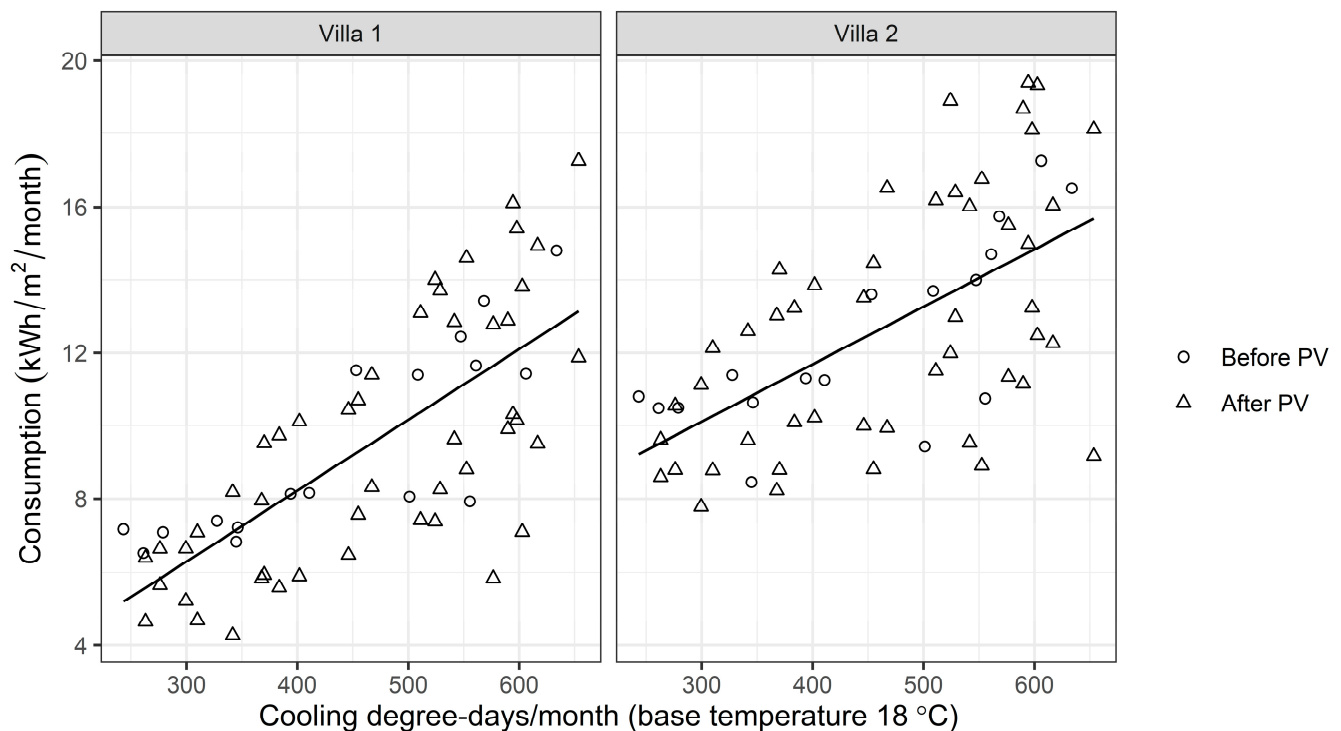


Figure 7. Variation in electrical consumption per floor area of the first floor of Villa 1 and 2 with cooling degree days (CDD). For fit parameters, please see Table 6.

Table 6. Model fit parameters for the consumption best fit lines in Figure 7.

	Dependent Variable:	
	Consumption (kWh/m ² /month) (Villa 1)	(Villa 2)
Cooling degree-days	0.019 ***	0.016 ***
CI ₉₅	(0.015, 0.024)	(0.011, 0.021)
Constant	0.655	5.530 ***
	(−1.465, 2.774)	(3.089, 7.971)
Observations	65	65
R ²	0.529	0.359
Adjusted R ²	0.522	0.349
Residual Std. Error (df = 63)	2.231	2.570
F Statistic (df = 1; 63)	70.762 ***	35.271 ***

Note: *** $p < 0.01$.

3.5. Comparison of First- and Second-Year PV Performance

Comparison of the first and second years of monitoring data did not indicate any significant change in the performance of the PV array, as measured by the daily generation divided by the daily plane-of-array insolation (see Figure 8). A Wilcoxon paired two-sided signed rank test gave $p = 0.16$, supporting the null hypothesis of no change between the two years. It is possible that some degradation occurred but was masked by the curtailment of generation due to the constraint of zero export to the grid. In addition, the array modules were cleaned monthly to remove dust buildup, and this may have led to more variation than any long-term trend in performance (a previous study by the authors indicated a 20% drop in performance for a non-cleaned versus cleaned PV array in Jeddah [64]). Therefore, PV module performance degradation was not included in the financial modelling in Section 3.6 as a separate term; measured values of array performance were used instead.

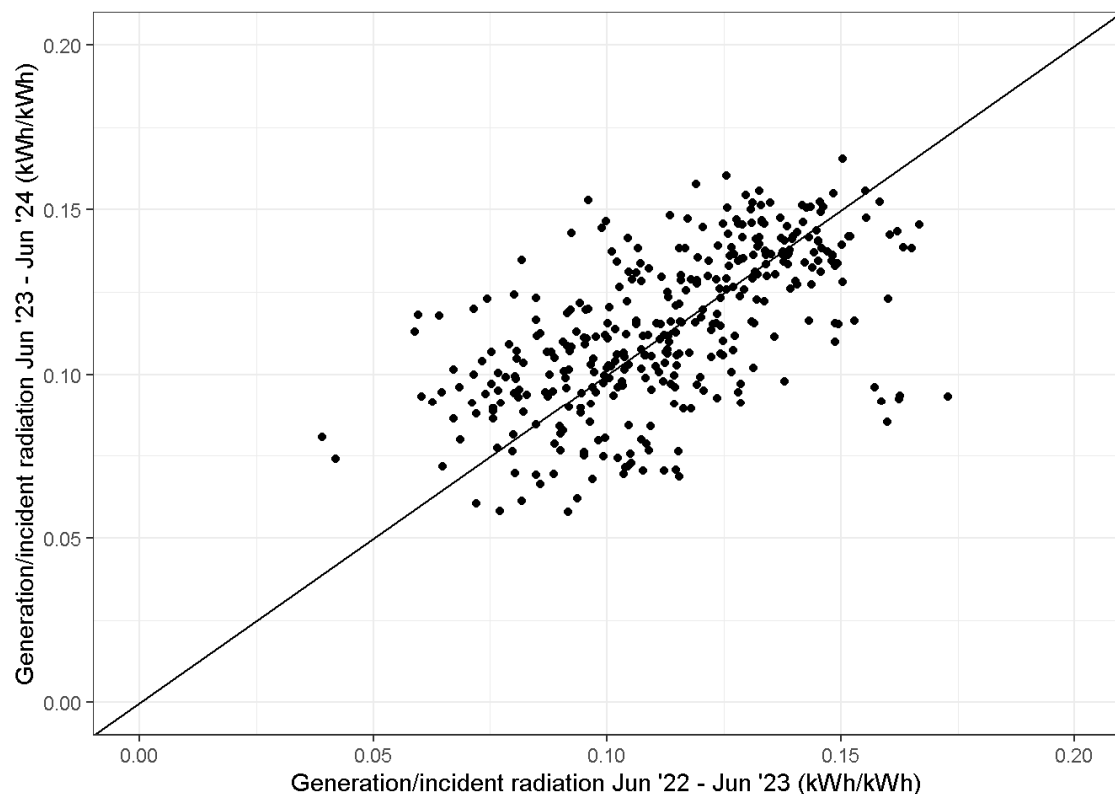


Figure 8. Daily PV array performance for June 2022–June 2023 compared with June 2023–June 2024. 1:1 line plotted for reference.

3.6. Financial Analysis

The aim of this work was to evaluate in practice the potential for rooftop PV generation, and this is in the end an economic question, which this Section aims to address, based on the quantitative (and also qualitative) evidence of the technical performance highlighted in the previous Sections, along with the experience of installation. Challenges to the growth of residential building-mounted PVs in Saudi Arabia include low tariffs by global standards (despite high consumption, Saudi households spend a lower proportion of household income on energy than 12 of the 17 largest economies, including Germany, UK, France, China, India, and Brazil [76]), and a lack of an economic feed-in tariff for microgeneration. To overcome these challenges and encourage the take-up of PV, increased feed-in tariffs are required, and this can also be supported by changes in the application of tariffs to higher-consuming households. For the case study villas, in order to achieve a positive NPV after seven years (at a 15% discount rate), combinations of the following measures were considered (note: these are hypothetical and do not imply recommendation by the authors):

1. Net billing feed-in tariff increased from current level of 0.07 SAR.
2. Meters in one property aggregated as one for tariff calculation purposes (triggering a higher tariff rate in hotter months). Another option would be to increase the meter service (standing) charge for the second and subsequent meters, as it is currently a negligible amount (USD 4/month or less than 1 day of electricity in December), but this is not considered further here as it would disproportionately impact lower consumers.
3. Decrease in the higher tariff threshold from the present value of 6000 kWh/month.
4. Decrease in installed cost/kWp of PV (through increase in volume and improved learning within the supply chain [77]).

The key performance parameters needed for the financial analysis were taken as the average of Villa 1 and Villa 2 and are indicated in Table 7. Six combinations of the measures

above, in addition to ‘business as usual’, were analysed in the cases described in Table 8. As indicated in Table 9, only case VI (including all measures 1–4) resulted in a positive NPV after seven years of operation. The business-as-usual NPV, with no export and income purely from avoided import, was USD (−16,300) after 7 years.

Table 7. Key results used in financial analysis (annual average of Villa 1 and 2).

Parameter	Value
Annual import from grid 1st floor meter (MWh)	32.6
Annual PV generation (MWh)	15.5
Peak measured daily average performance (generation/incident radiation)	17.3%
Annual PV curtailment/potential export (MWh)	9.9
Total villa avoided import over threshold (MWh) *	6.5 (>6000 kWh/month); 18.4 (>3000 kWh/month)

* Total villa electrical consumption data estimated from 2019 data.

Table 8. Cases considered in net present value (NPV) analysis.

Measure	BAU	I	II	Case III	IV	V	VI
Feed-in tariff (0.07 SAR [41])		•					
Feed-in tariff (0.18 SAR)			•				
Feed-in tariff (0.3 SAR)				•			
Feed-in tariff (1.0 SAR)					•	•	•
Installed cost decrease by 20%			•	•	•	•	•
Total villa tariff threshold (6000 kWh)						•	
Total villa tariff threshold (3000 kWh)							•

Table 9. Financial analysis results for 7-year cashflow.

Case	NPV (USD)	IRR
BAU	(−16,290)	-
I	(−15,530)	-
II	(−10,580)	-
III	(−9280)	-
IV	(−1680)	11.2%
V	(−810)	13.2%
VI	770	16.7%

Needless to say, measures (2) and (4) (tariff threshold reduction and all household meters counting toward the threshold) would not be popular with residential consumers. In addition, savings in PV installed cost might not materialize. To achieve a positive NPV after seven years, with only the avoided imports at the current rate and export of power, would require a net billing feed-in tariff of 1.5 SAR/kWh (0.40 USD/kWh). This is higher than the value reported by [69] in a 2024 theoretical study of a 15 kWp system in Saudi Arabia (0.25 USD/kWh for a 7-year period). With a FiT at this level compared to the import tariff, it is likely that the annual meter net bill would be negative. Therefore, there would need to be payments to consumers in order for the scheme to be workable, rather than simply deducting from the customer balance at the end of a billing period. The value of exports could be capped at the value of imports to prevent this from occurring, but for the case study villas, the NPV would then be USD (−12,800). If the cap was applied at a household (as opposed to meter) level, then the NPV would improve to USD (−9150).

4. Conclusions

The objective of this study was to evaluate the potential for, and challenges of, installing residential rooftop solar power generation through a field deployment in Saudi Arabia. In contrast to previous studies [59,69], the results are based on measured performance in the field, rather than simulation. The deployment of rooftop PV arrays installed and monitored as part of this work led to a decrease of 20–30% in the import of electrical energy from the grid to the respective villas (as a proportion of the demand of all floors). When appropriately scaled up, this could substantially reduce loads on the electrical distribution network and reduce carbon dioxide emissions from the residential sector (as close to 100% of electrical generation is from fossil fuels). However, significant scaling up of rooftop PVs requires consideration of the stability of the distribution network.

The practical experience of installing the PV arrays highlighted the challenges involved, including multiple utility meters per villa and difficulty in obtaining permission to export to the grid. Fundamentally, the combination of real system costs and real system performance implied a feed-in tariff higher than that of previous simulation-based studies in order to make the investment viable.

The significance of these results is that, in order to realize the benefits of residential rooftop PVs more widely for Saudi Arabia, significant changes need to be made to the policy framework for FiTs. The present level of net billing feed-in tariff is not sufficient to support the growth of residential-scale PVs through early adopters. In addition, the permitting process for residential PVs is presently bureaucratic, complex, long, and costly. The system should be streamlined to reduce the period between application and attaining ‘prosumer’ status and remove the need for onerous municipal inspections. Delays in this process could act as a deterrent for property owners considering investing in PV systems for their roof, due to lost income from not being able to export to the grid.

The limitations of this study are the currently small sample size and lack of grid stability considerations. Future work will extend the long-term performance monitoring to all of the six villas in Table 4 in order to improve the estimates of financial viability provided here.

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Abbreviations

The following abbreviations are used in this manuscript:

A/C	Air conditioning
CDD	Cooling degree-days
FiT	Feed-in tariff
KAPSARC	King Abdullah Petroleum Studies and Research Center
PoA	Plane-of-array
PVs	Photovoltaics
SAR	Saudi Riyal
SEC	Saudi Electricity Company
SERA	Saudi Electricity Regulatory Authority

Appendix A

Table A1. Summary of datasets used in the analysis (per villa, for Villa 1 and Villa 2).

Variable	Start Date	End Date	Sampling Rate	Total Readings	Completeness
Ambient temperature (King Abdulaziz University)	2021-01-01	2023-03-27	2 min	504,870	96.2%
Ambient temperature and PoA irradiance (rooftop PV array)	2022-06-03	2024-06-03	5 min	210,816	99.96%
Electricity billing data	2021-01-15	2024-06-15	Monthly	42	100%
Electricity consumption (2019, all floors)	2019-02-04	2019-12-09	~20 s	3,546,401	67%
Electricity generation and consumption (post installation of PV, floor 1 m) aggregated daily	2022-06-03	2024-06-02	1 day	1462	100%

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