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Pathways to the Large-Scale Adoption of Residential Photovoltaics in Saudi Arabia

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Abstract: This survey of predominantly middle–high-income owner-occupier households in the Kingdom of Saudi Arabia (KSA) assessed household perspectives to residential photovoltaics (PVs) (n = 268). Higher-income households were statistically more likely to (i) accept financial payback times of more than 12 months for the CAPEX cost of a PV system, and (ii) be prepared to contribute up to SAR 10,000 (USD 2666) towards the CAPEX cost of a system. A multiple logistic regression analysis indicated that a high household education level and the dwelling tenure (owner) are key variables that positively influence PV acceptability. Median apartment and villa households in this survey had annual electricity demands of 22,969 kWh and 48,356 kWh, respectively. The available roof area per apartment and villa was assessed, considering parapet shading and roof furniture limitations (the presence of AC units, etc.), at 20 m^2 and 75 m^2, respectively. This would accommodate either a 4 kWp apartment system or a 10 kWp villa system mounted horizontally. Time-of-use tariffs or grant subsidies towards the cost of a PV system will be required to enable the surveyed households to meet their stated economic conditions for purchasing a PV system. This indicates that PV policies in KSA will need to be adapted to encourage the uptake of PVs.

Keywords: solar photovoltaics in buildings; household energy surveys; energy in the KSA; energy policy

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Citation: Alshehri, A.; James, P.; Bahaj, A. Pathways to the Large-Scale Adoption of Residential Photovoltaics in Saudi Arabia. *Energies* **2024**, *17*, 3180. https://doi.org/10.3390/en17133180

Academic Editors: Wenting Lin, Xuehui Wang, Jianye Chen and Yuhan Huang

Received: 1 June 2024
Revised: 21 June 2024
Accepted: 22 June 2024
Published: 28 June 2024

1. Introduction

The Kingdom of Saudi Arabia (KSA) is a fossil-fuel-dominated economy; 64.5% of its total energy is supplied by oil and 35.5% is supplied by gas, with all other sources making a negligible contribution (<0.05%). In 2021, 41.3% of its electricity generation came from oil, 58.4% came from gas, and 0.2% came from solar photovoltaics (PVs) [1]. Since 2021, there have been a number of large PV plants commissioned, the first significant-scale project being the Sakaka Solar PV Park, with a 405 MW capacity [2]. Several GW-scale plants are now in the pipeline in the KSA, and it appears that finally a transition towards large-scale solar energy is in progress in this country where the global horizontal irradiation exceeds 6 kWh/m^2 per day. In total, there are currently around 5 GW's worth of PV projects in progress, as part of a wider national ambition [3–5] to deliver 40 GW's worth of large-scale PVs, which in itself poses supply chain challenges for the country [6].

In contrast, the residential sector for PVs remains very challenging in KSA. In KSA, the national GASTAT 2022 survey [7] details the percentage of electricity generated from various sources for different house types. In relation to villas, the only regions where a non-zero percentage of PV electricity is reported are Asir (0.39%) and Al-Baha (0.09%). In relation to apartments, there are seven regions with a non-zero percentage of PV electricity, as follows: Medina (0.13%), Al-Qassim (0.17%), the Eastern Province (0.11%), Asir (0.07%), the Northern Borders (0.04%), Al-Baha (0.29%), and Al-Jowf (0.25%). Together, this represents 0.04% of the total villa and apartment stock in the KSA. An overall PV penetration level of 0.04% can be considered as being very low. For example, in the UK, as of March 2024 [8], there were 1.3 million residential PV systems out of a stock of 30.1 million dwellings [9], corresponding to a penetration level of 4.3%, which is 100 times that observed in the KSA.

There are a number of barriers to the adoption of PV in the KSA. These span economic, technical, cultural, and process/procedure-related barriers. Previous work in the KSA has highlighted many of these issues. Felimban et al. [10] showed that in a Jeddah context, cultural aspects resulted in very high cooling demands due to preferences for low AC temperature setpoints, alongside low levels of satisfaction with current electricity tariffs (~25%), suggesting an ongoing economic barrier for PVs. Clearly, low grid-electricity tariffs have been, and remain, a barrier preventing PV uptake [11]. In terms of grid-connection permission in the KSA for a residential system, this remains a complex and expensive process [10,12,13]. WERA, the Water and Electricity Cogeneration Regulatory Authority, set out the requirements for a grid-connected PV system in their Regulatory Framework for Small-Scale Solar PV Systems, 29/04/1441H, vn2 [12]. These requirements are extensive and include, but are not limited to, (i) staying within aggregated PV capacity limits on the distribution system (3% of the peak load of the power system); (ii) the queuing of connections for approval by the relevant authority; (iii) a maximum aggregated PV capacity of less than 15% of the local transformer capacity; and (iv) the requirement that a feasibility study of the scheme is followed. The financial value of PV export to the utility grid is a developing topic in the KSA: the current rate is 0.02 USD/kWh, compared to an import rate of ~0.055 USD/kWh, far away from net metering [12]. In reality, the level of PV export from a KSA house is likely to be very low due to the good match between PV generation and the dominant high AC load. The lack of net metering may act as a barrier to PV uptake (due to this being perceived as unfair by households), even though the financial cost of adopting this measure may be small in reality. In terms of the climate, the impact of dust on PVs is a concern that will need to be addressed to ensure good long-term system performance [14].

While residential PVs cannot hope to compete with the headline LCOE (Levelised Cost of Energy) of a large-scale PV system, they do offer a number of additional advantages, which means that they have the potential to become a significant electricity source in the KSA. Chief among these is the fact that electricity demand in the KSA is dominated by the residential sector, accounting for 47% of the overall demand (143 TWh), 70% of which is due to the demand for air conditioning (AC) [15]. PV generation is broadly in phase with this demand for AC, which means that generation at the point of use can support the electricity distribution network. The KSA operates a tiered electricity tariff for its residential customers, admittedly for a very low cost per kWh base, as shown in Figure 1. The electricity demand for a "typical household" is very high, at around 35,000 kWh per annum.

Saudi Arabia recognises the importance of addressing both the supply side and the demand side of electricity. New policies include addressing the efficiency of white goods and air conditioners used in homes [16]. The KSA has historically sold electricity at a very low unit price, which poses particular challenges in the residential sector. It is hard, for example, to incentivise energy-efficiency measures in terms of a building or its appliances on the grounds of financial payback time. In addition, low energy prices encourage wasteful behaviour, such as the excessive use of air conditioning in homes, delivering temperatures far below what is required for thermal comfort. These impacts have been in part addressed through changes to the residential electricity tariffs. Figure 1 compares the tariff changes from 2015–2017 to 2018–2023, where the lower tariff blocks were removed. This policy is not without its challenges, however, as its impact on high-electricity users will be marginal, whereas low-electricity users will experience a far higher percentage increase in their monthly bills. A such, the change in the tariff structure can be seen as being somewhat regressive.

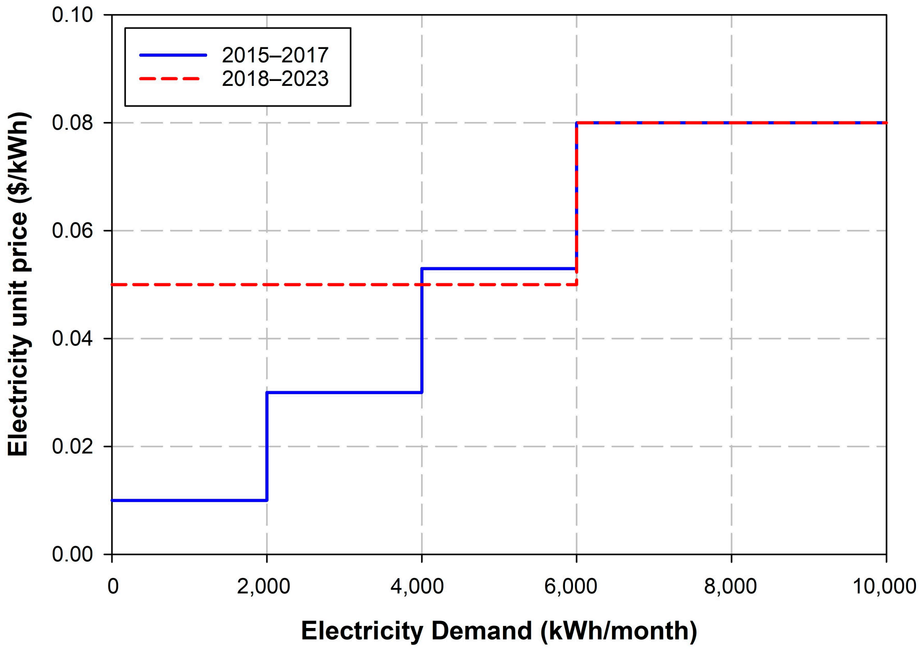

Figure 1. Residential electricity tariffs 2015–2023, KSA [11].

The rise in tariffs does potentially create the conditions under which residential PVs could compete economically with grid power in the KSA. Over the past decade, the cost of PVs has fallen by significantly: the global weighted average LCOE of utility-scale PV plants declined by 89% between 2010 and 2022 from USD 0.445/kWh to USD 0.049/kWh [17]. Clearly, in a KSA context, with its very high irradiance levels, the LCOE of utility-scale plants would be at the lower end of this range.

Khan et al. [18] have assessed the potential of rooftop PVs in the residential sector in the KSA. Their assessment considered the net available roof area for PVs accounting for obstacles like balustrade walls, staircases, water tanks, satellite dish antenna, and air conditioning units as 31.8% of the overall roof area, or 221 million m^2. The overall annual electricity generation from PVs was estimated at 51 TWh with a full deployment of PVs over the available roof area, corresponding to 30% of the annual residential electricity demand. A study by Abdullah Shaher et al. explored the potential of rooftop solar PVs to meet the electricity demand in the urban areas of Abha city, KSA, whilst minimising imports from the grid [19]. Their assessment showed that rooftop solar PVs in residential and commercial areas is sufficient to meet local peak demands, providing smoothing to the grid and the opportunity for localised storage using batteries. Abdelhafez et al. modelled the deployment of PVs at scale in the residential sector of Hail city in the KSA [20]. They estimated the effective area to be 24.4% of the overall roof area, slightly less than the Khan et al. [18] estimate of 31.8%.

According to Al Garni, PV modules in the KSA can experience a decrease in power output of up to 30% due to dust accumulation [21]. Their study also found that the rate of dust accumulation on PV modules is higher during the summer months. Some form of scheduled cleaning regime will therefore be required to ensure a PV system maintains a high level of performance. There are a number of options being developed for large-scale PV farms, such as cleaning robots, which may emerge as a cleaning option for residential systems.

Rising electricity prices alongside dramatic cost reductions for photovoltaics and residential-scale battery storage mean that a financial crossover point will be reached where residential PVs make financial sense in the KSA. It is important to understand the perception of residential PVs from the perspective of middle-income households in the KSA. We believe that middle-income households are the most likely to adopt PVs first. In a KSA context, lower-income households are more likely to be renting from private landlords, which creates additional barriers to PV adoption beyond just financial ones. A household that rents would be unlikely to be able to install a PV system as they would not have the authority to make a physical change to a home they do not own. This is comparable to typical KSA tenancy agreements in [22] "Clause Eight" where no changes to the property are allowed unless they have written permission of the landlord. A typical KSA tenancy agreement can be viewed on the KSA government EJAR and Ministry of Dwellings platform [22] but a user must first register with them to gain access. An example of this issue from the UK is the failed Green Deal initiative, where tenants were not allowed to make energy-efficient changes to their dwellings without the consent of their landlord [23].

In addition, renters are more likely to stay for a shorter period of time (fewer number of years before moving) in a home and so the incentive to install a PV system is much weaker [24]. From a landlord's perspective, there is no real incentive at present to adopt PVs, unless they were either (i) able to charge a higher rent value, or (ii) were obligated to by energy performance legislation. Minimum energy performance standards for a dwelling to be rentable have recently been introduced in the UK: for example, see [25]. Somewhat surprisingly, Ashour et al. [26] showed that dwellings with PVs may actually be perceived as less attractive by tenants (thus command a lower rental price) due to a misunderstanding, in that tenants believe that the electricity supply would be less reliable in such homes. Bouaguel and Alsulimani assessed the factors influencing consumer intention towards solar energy in residential use cases in the KSA using a technology acceptance model [27]. They found that while environmental awareness has positively influenced consumer perceptions, perceived costs have negatively affected consumer perceptions. In an Australian context, Best and Chareunsy [28] assessed solar panel uptake in households and determined that a higher income leads to a lower solar uptake for households with higher levels of wealth. They suggested that income has a non-linear impact, being positive at low incomes but negative at high incomes. High-income households are less likely to be price-sensitive and so the drive to adopt PVs is potentially weaker among these households. In a Ghanaian context, Akrofi et al. showed that the willingness to adopt solar home systems was lower in high-income neighbourhoods [29]. Umit et al [30] showed that across 22 European countries, higher-income households were more likely to buy energy-efficient appliances but less likely to engage in energy-saving behaviour (e.g., reducing appliance usage) as they are not price-sensitive. The middle band of owner-occupier households was therefore chosen as the focus of this study.

2. Materials and Methods

The materials and methods are presented in the following two sections. The sampling and data-collection procedures are discussed in Section 2.1, followed by the data analysis in Section 2.2.

2.1. Sampling and Data-Collection Procedures

To understand the underlying perspective of middle-income households towards PVs, an extensive questionnaire under the title Household PV Potential (KSA-HPVP) was developed, incorporating questions from two previous surveys undertaken in 2021 by the KSA's General Authority for Statistics [31] and in 2020 by Alrashoud and Tokimatsu [24]. This KSA-HPVP survey was approved by the University of Southampton's Ethics Committee (ERGO reference 79322) [32]. The survey instrument is available from the UoS research archive [33]. An abridged dataset with no personal statements is also provided, covering the survey responses relating to this paper, in [33].

The survey consisted of 58 questions, using a tree structure to guide households to questions relevant to their specific circumstances. An initial pilot of the survey (n = 15, 12 responses) was undertaken which led to minor changes to the survey to aid clarity. The survey included questions concerning location, education, income, and dwelling type/household appliances, alongside an assessment of the respondent's perspectives and understanding of PV. The survey was deployed online using the Qualtrics XM platform [34].

The KSA-HPVP survey was released online to 50 households in mid-March 2024. Participants were asked to forward it to friends and relatives to create a snowballing recruitment effect. The snowballing (also known as chain-referral sampling) approach taken was one of exponential, non-discriminative snowball sampling, where the initial 50 households could each create multiple referrals, which could then lead to subsequent referrals. The sample seed used in this study comprised contacts of the researcher, which limited the diversity of the sample [35], and so this surve should not be considered as representative of the entire KSA population. The aim of this study was to specifically look at households living in villas or apartments, and so the seed sample used is considered appropriate.

To assess the roof area available for PVs atop villas and apartments, previous studies in the KSA were used as the basis of the analysis approach [18–20]. These studies assessed the impact of roof parapets, spacing requirements for inclined PV modules, and roof furniture (such as AC units) on the residual roof area for PVs. To assess the economics of PVs applied to villas and apartments in the KSA, HOMER [36], a cost-optimisation tool, was used. The HOMER modelling compared a number of scenario options (grid-only flat tariff; grid + PVs; grid with time-of-use (ToU) tariffs; addition of battery storage). We applied a 5% discount rate and 2% inflation to each scenario, and the cost analysis was run over a 25-year period.

In the case of the apartment, the lead author's family apartment in Jeddah was used. The apartment's electrical demand load profile, which is the basis of the model, was generated from data provided by the Electricity Saudi Company. In the case of the villa, independent electrical monitoring data were available from a previous study, which enabled the profile to be constructed [37,38]. The determined annual demands were linearly scaled to reflect the median annual demand reported in the KSA-HPVP survey.

2.2. Data Analysis

The statistical significance of differences in responses was assessed using a chi-squared test statistic. For 2× contingency tests, the Fisher exact test was used, as this was specifically developed for small sample sizes [39]. Further information regarding these statistical tests can be found here: [40]. We conducted a multiple logistic regression analysis [41] to evaluate the influence of six factors from the HPVP survey on the likelihood of a household adopting PVs using Sigmaplot [42]. Our binary criterion for PV acceptability (dependent variable) was defined by the KSA-HPVP survey question, "What financial payback time would you expect in order for you to seriously consider purchasing such a PV system?". We divided responses into those who stated more or less than 24 months to create our binary YES/NO criterion for PV adoption. The six selected survey questions were converted into independent variables with categorical values. These were as follows: income band, education level, dwelling type, house size, dwelling tenure, and age of head of household.

According to the GASTAT 2019 survey, in relation to Saudi households [43], 44% of households live in apartments. If we consider our dwelling population to be that of Saudi nationals, this is around 3,700,000. For a survey response with a 95% confidence level, with 3,700,000 households, we would need a survey sample of n = 385 for a 5% margin of error. The achieved headline survey response rate of n = 268 represents a margin of error of 6%. This margin of error rises to ~9% (n = 119) in the survey for certain questions where not all respondents chose to answer specific combinations of questions [44]. For example, when this paper compared stated household monthly income and preparedness to contribute up to SAR 10,000 to the capital cost of a PV system, the number of responses was n = 118.

The survey received n = 268 completed responses from the seed of 50 households, which is considered as excellent by the research team for such an extensive survey that took between 30 and 45 min to complete. In the analysis presented in this paper, the number of responses shown is often less than n = 268 survey responses, as respondents sometimes chose "prefer not to say" as a response to certain questions, such as those regarding income.

There were 170 missing observations (not all survey questions were answered for every survey), which resulted in 112 complete household responses (each of which contained all 6 independent variables) for the Multiple Logistic Regression Analysis.

3. Results

The results are presented into two distinct sections: Section 3.1 concerns the KSA-HPVP survey, and Section 3.2 concerns the scenario modelling of PV options. The KSA-HPVP survey discussion illustrates the context of middle-income, owner-occupier households and their perspectives relating to PV. These perspectives are then used to inform Section 3.2, the section on scenario modelling, to establish the conditions (essentially financial) under which PV systems may be taken up by the considered demographic group in the KSA.

3.1. KSA-HPVP Survey

3.1.1. KSA-HPVP Overview

Among the respondents, 98% were Saudi, while 2% were from Yemen, Ghana, and Thailand. A total of 41% of the respondents resided in Riyadh and 26% resided in Mecca (which includes Jeddah City); there were also responses from 11 of the 13 administrative regions of the KSA. Half of the households surveyed had household sizes of more than five, reflective of cultural norms. Regarding age distribution, 8% of the household heads were aged 20–35, while 80% fell between 36 and 64. Moreover, 54% of the participants were living in villas, 35% were living in apartments, and 8% were living in traditional houses. In terms of education, 45% held bachelor's degrees, 22% had master's degrees, and 13% held doctorates. High-school graduates and incomplete high-school graduates made up 18% and 2%, respectively. "Incomplete high school" without the word "graduates" is a translation from the Arabic of the GASTAT survey; Alrashoud [24] uses the term "junior high school" for the same educational level, which refers to people who stopped going to school after the intermediate level.

A comparison of the educational levels of the heads of households with those reported in the 2016 national demographic survey [45] shows clear differences, as shown in Figure 2. The KSA2016 survey responses provided in Table 30-1 of reference [45] was used, which provides a national assessment of educational status with respect to age. A chi-square test between the KSA2016 and KSA-HPVP surveys in terms of the number of respondents with a specific highest education level shows a significant result, with a p-value < 0.00001 (Test 1, Table 1). Note that this test demonstrates associations among variables rather than causal relationships.

The KSA-HPVP survey clearly cannot be considered as representative of the overall KSA population: it represents a sub-sample of well-educated, middle-income households. This is further reinforced when you consider that over 40% of households lived in villas with a useable floor area in excess of 300 m^2, as shown in Figure 3. In terms of monthly household income, 32% of KSA-HPVP respondents stated that this was in excess of SAR 15,000 (~USD 4000). This household income percentage rises to 58% for villa households. As would be expected, there is a strong relationship between having a high monthly income (over SAR 15,000, or approximately USD 4000) and having a preference for larger homes, such as villas or large apartments, according to the KSA-HPVP survey. A Fisher exact test between monthly household income and physical size of home returns a p-value of 0.0005 (result is significant at $p < 0.05$), with n = 180 valid survey responses (Test 2, Table 1).

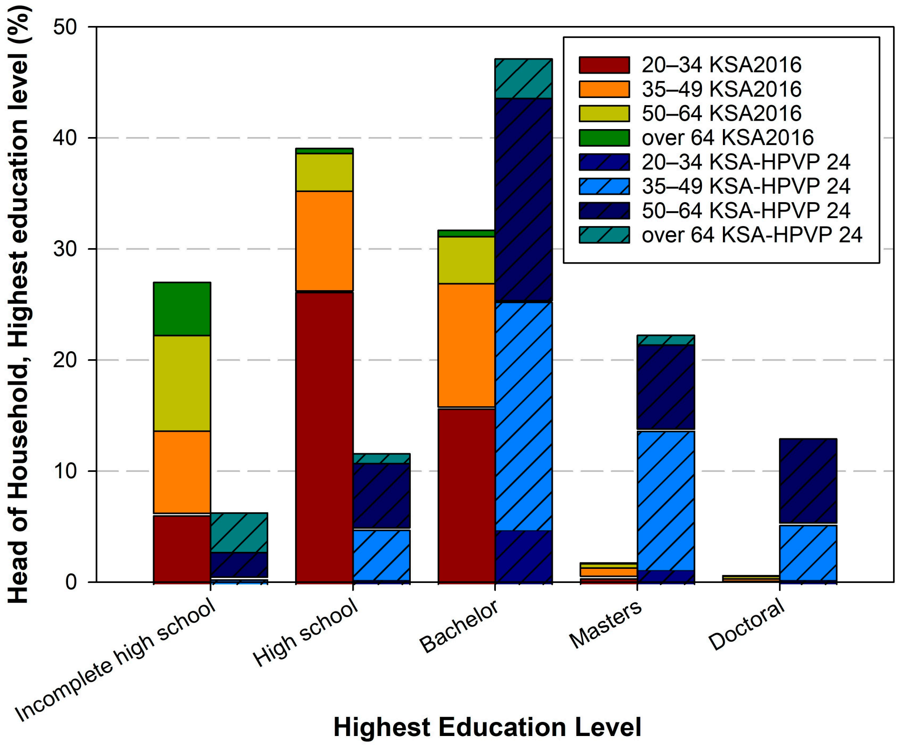

Figure 2. Comparison of the stated highest education level of the head of household, banded by age, comparing the KSA-HPVP survey with the 2016 national KSA survey [45].

Table 1. Chi-square and Fisher exact tests undertaken on the KSA-HPVP survey data.

Test	Statistic Result and Sample Size
Test 1. KSA2016 and KSA-HPVP survey; chi-square test; number of respondents with a specific highest education level.	Chi-square statistic = 1893.51, p-value < 0.00001. n = 11,494,676 for KSA2106; n = 236 for KSA-HPVP. Significant at $p < 0.05$.
Test 2. KSA-HPVP survey; 2×2 comparison between monthly household income (either > SAR 15,000 or ≤SAR 15,000) and home size. Large homes > 250 m^2; smaller homes ≤ 250 m^2.	Fisher exact statistic = 0.0005. n = 180. Significant at $p < 0.05$.
Test 3. KSA-HPVP survey; comparison between households with incomes of SAR 10,000–15,000 per month and households in the > SAR 15,000 monthly income band regarding stated interest in PV; Fisher exact test.	Fisher exact statistic = 0.1039. n = 122. Not significant at $p < 0.05$.
Test 4. KSA-HPVP survey; 2×2 comparison between monthly household income (either > SAR 15,000 or ≤SAR 15,000) and preparedness to contribute up to SAR 10,000 (USD 2666) to the capital cost of a PV system; Fisher exact test.	Fisher exact statistic = 0.0056. n = 164. Significant at $p < 0.05$.
Test 5. KSA-HPVP survey; stated household monthly income (> SAR 15,000 and SAR 10,000–15,000) and acceptability of 12-month payback time for the capital cost of a PV system.	Fisher exact statistic = 0.0488. n = 118. Significant at $p < 0.05$.
Test 6. KSA-HPVP survey; residential ownership and likely consideration of PV systems.	Fisher exact statistic = 0.0435. n = 202. Significant at $p < 0.05$.

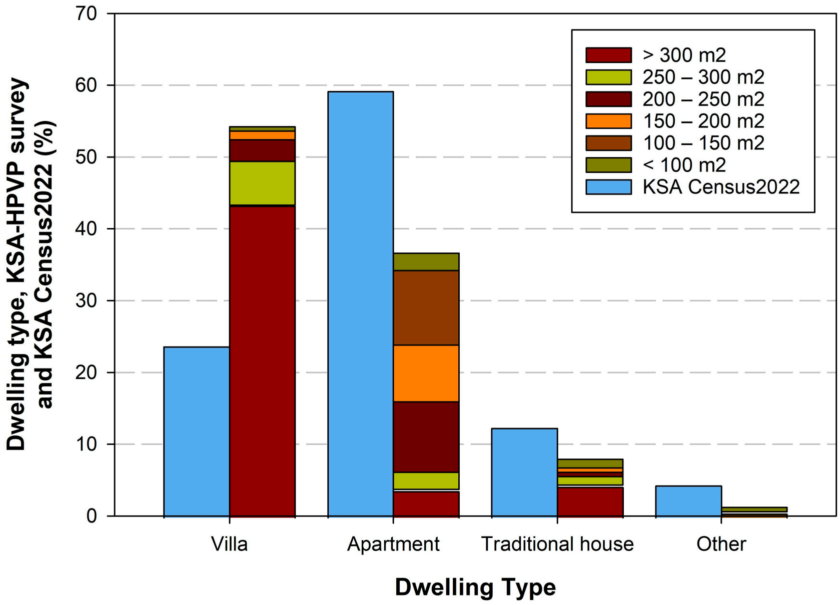

Figure 3. Dwelling type and size, KSA-HPVP survey, n = 268.

The KSA-HPVP survey group in terms of income, property type, and education might therefore be considered as an ideal early-adopter group for PVs in the KSA. This survey explored this issue via a number of open and closed questions to inform an understanding of the conditions under which PVs might be adopted by this group.

3.1.2. KSA-HPVP: Impact of Location on the Perception of PVs in the KSA

We asked households their perception of PVs, and we observed no geographical differences in the responses. A total of 69% of respondents from Riyadh (n = 51 of 74) and Asir (n = 11 of 16) had a positive perception, with 50% from Mecca (n = 25 of 50) and Al Baha (n = 11 of 22) having a positive perception. Across the remaining nine regions (n = 13 of 18), the positive response rate was 72%. When asked what might encourage the installation of PVs in their home, energy cost was ranked the most important consideration (by 79% of respondents), followed by the environment (46%) and reduced dependency on the utility power grid (39%). With regard to concerns and barriers to installing PVs, cost was seen as the dominant issue, followed by the risk that the level of generation would be small, weak financial returns, and poor system lifetime.

3.1.3. KSA-HPVP: Household Sensitivity to Cost and PV Acceptance

In terms of declared household income, we see few regional differences in the responses. Overall, 54% of respondents from Riyadh (n = 97) declared their monthly income to exceed SAR 15,000, compared to 45% from Mecca (n = 60) and 56% for all other regions of the KSA (n = 77). There is no statistical difference observed for stated monthly household income when comparing Riyadh, Mecca, and all "other locations" combined.

We then compared each household's response regarding their interest in adopting PVs (possible answers: yes, no, unsure) in relation to their household income. We found that 65% of respondents who declared their income band stated that they were interested in PVs (n = 92 of 142). For households with a declared income of more than SAR 15,000 per month, the level of interest in PVs was 68% (n = 59 of 86), compared to 53% (n = 19 of 36) for the SAR 10,000–15,000 per month band. This is not, however, a statistically significant difference when tested with the Fisher exact test statistic, with a value of 0.1039 at n = 122 (Test 3, Table 1).

We compared the level of upfront payment (capital contribution) for a PV system that households stated they were prepared to make in order to adopt PVs in their home. This would be for a system that would theoretically meet half of their monthly electricity demand (Figure 4). The Fisher exact test showed that higher-income households (> SAR 15,000 per month) were statistically more likely to be willing to pay up to SAR 10,000 (USD 2666) as a contribution to the capital expenditure (CAPEX) cost of a system. The Fisher exact statistic value is 0.0056. This result is significant at $p < 0.05$ (Test 4, Table 1).

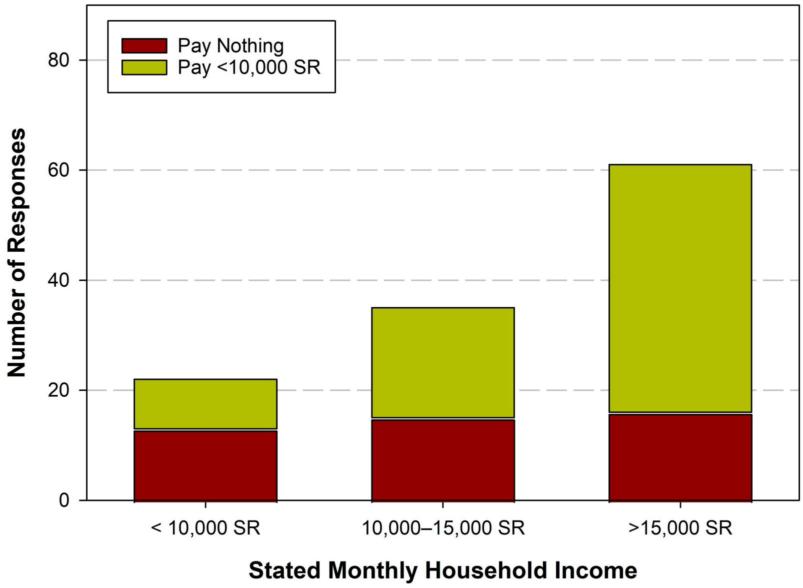

Figure 4. Comparison between stated household monthly income and preparedness to contribute up to SAR 10,000 (USD 2666) to the capital cost of a PV system. KSA-HPVP survey, n = 118.

When considering financial payback time, we compared responses across the monthly household incomes of > SAR 15,000 and SAR 10,000–15,000 (USD 2666 to USD 4000), as shown in Figure 5. If we consider a financial payback time of more or less than 12 months, we find a statistical difference using the Fisher exact test. Higher-income households were statistically more likely to accept financial payback times of more than 12 months for the CAPEX cost of a system. The Fisher exact test statistic is 0.0488, and this result is significant at $p < 0.05$ (Test 5, Table 1).

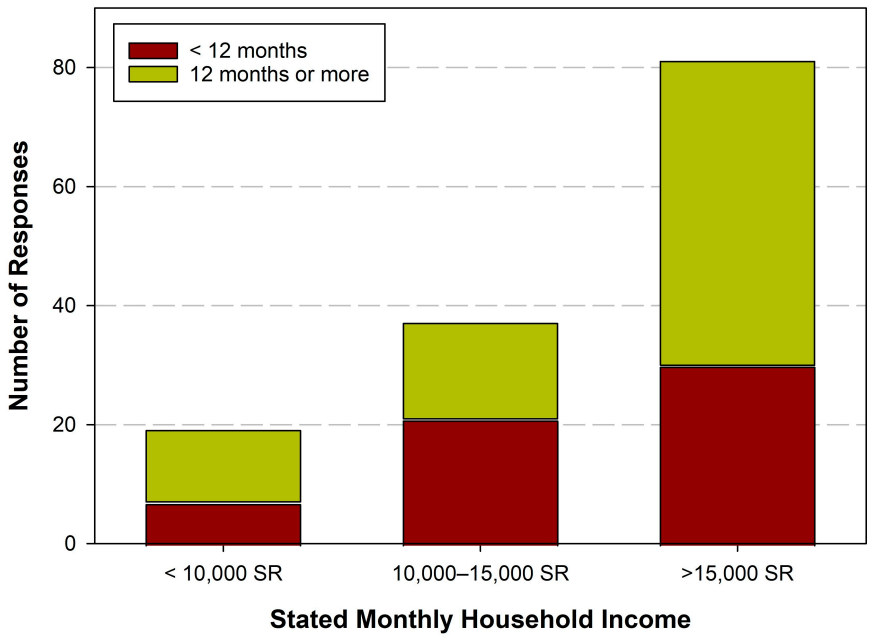

Figure 5. Comparison between stated household monthly income and acceptability of payback time for the capital cost of a PV system. KSA-HPVP survey, n = 137.

3.1.4. KSA-HPVP: Home Ownership's Impact on the Likelihood of Considering PVs

We observed a chi-squared test result with a strong correlation, with a *p*-value of 0.0435, between residential ownership and the likelihood of considering a PV system (Test 6, Table 1). In total, 32% of homeowners across the KSA were more inclined to consider using a PV system, compared to only 17% of renters or those living in housing provided by their employer. Here, we define PV acceptability as a 24-month payback time, as detailed in Section 3.1.5 below.

3.1.5. Multiple Logistic Regression Analysis of the KSA-HPVP Survey

Table 2 shows the six-independent-variable logistic regression model for the KSA-HPVP survey.

Table 2. Multiple logistic regression analysis: KSA-HPVP survey data.

Independent Variable (Categorical Value)	Coefficient	Standard Error	Wald Statistic	*p*-Value	*VIF	Odds Ratio	5% Confidence Lower	5% Confidence Higher
Constant	−3.56	1.884	3.571	0.059		0.0285	0.000709	1.141
Income Band *< SAR 5000/month (1), SAR 5000–1000/month (2), SAR 10,000–15,000/month (3), ≥SAR 15,000/month (4)*	−0.219	0.259	0.71	0.399	1.025	0.804	0.483	1.336
Education Level *Incomplete High School (1), High School (2), Bachelor's (3), Master's (4), PhD (5)*	0.728	0.274	7.042	**0.008**	1.284	2.071	1.21	3.545
Dwelling Type *Apartment (1), Villa (2)*	−0.489	0.665	0.54	0.463	2.397	0.614	0.167	2.259
House Size *1 ≤ 100 m^2 (1), 100–150 m^2 (2), 150–200 m^2 (3), 200–250 m^2 (4), 250–300 m^2 (5), > 300 m^2 (6)*	−0.00513	0.194	0.000701	0.979	2.166	0.995	0.68	1.455
Dwelling Tenure *Provided by Employer (1), Rented (2), Owned (3)*	0.863	0.434	3.953	**0.047**	1.339	2.371	1.012	5.553
Age of Head of Household *≤20 (1), 20–34 (2), 35–49 (3), 50–64 (4), ≥64 (5)*	−0.0569	0.302	0.0356	0.85	1.393	0.945	0.523	1.706

*VIF = Variance Inflation Factor, a value < 5 indicates a low correlation of that variable with other variables.

The developed multiple logistic regression analysis model has the following structure, where Logit P is the log odds ratio:

Logit P = −3.560 − (0.219 × Income Band) + (0.728 × Education Level) − (0.489 × Dwelling Type) − (0.00513 × House Size) + (0.863 × Dwelling Tenure) − (0.0569 × Age of Head of Household).

The Hosmer–Lemeshow *p*-value indicates how well the calculated logistic regression equation fits the measured data. This value compares the predicted number of households (YES or NO) based on the logistic equation with the value from the survey. The obtained Hosmer–Lemeshow statistic of 7.153 (p = 0.520) has a high *p*-value, which indicates a good level of fit to the data. The Pearson chi-square statistic, 112.815 (p = 0.261), similarly indicates a good agreement between the logistic regression equation and the survey data. The *p*-value of the Wald statistic indicates the probability of being wrong in concluding that there is a true association between the independent variable and the dependent variable. We observe that $p < 0.05$ for both the education level and dwelling tenure, which means we can conclude that both of these variables show statistical significance in contributing to predicting the dependant variable (see Table 2). The VIF (Variance Inflation Factor) values are less than 2.5, so we can consider that multi-collinearity is not an issue with this regression model [46]. The odds ratio is the estimate of the increase (or decrease) in the odds if an independent categorical variable value is increased by 1. For example, if the dwelling tenure changes from rented (2) to owner-occupier (3), the odds ratio is 2.371, meaning a household would be more than twice as likely to want to adopt PVs. Similarly, in terms of the education level, a single categorical education level increase (such as from high school to bachelor's) would predict a doubling of the likelihood of adopting PVs.

3.1.6. Key Findings of the KSA-HPVP-24 Survey

The KSA-HPVP survey is not representative of the entire population demographic of the KSA: it represents middle-income, higher-educated, owner-occupier households. The survey responses indicate concerns around system performance and lifetime, but the key issue is the financial concern. The key finding for supporting policy development and the targeting of households for early adoption is that higher-income, owner-occupier households are statistically more likely to both (1) accept longer financial payback times and (2) be willing to make a significant contribution to the cost of a PV system. The multiple logistic regression analysis indicates that the education level (required to be high) and dwelling tenure (owner-occupier) are the key variables that influence the likelihood of a KSA household adopting PVs. Together, these findings thus provide the evidence for targeted interventions with such a cohort of households to kickstart the deployment of household PVs in the KSA. In the next section, we apply these findings to consider under what scenarios PVs may approach financial viability from the household perspective.

3.2. Scenario Modelling of Options for PV Systems

3.2.1. KSA-HPVP: Informed Household Electrical Demand Profiles

In the KSA-HPVP survey, households were asked to state their annual electricity bill (in Saudi Riyal), alongside an estimate of their typical winter and summer monthly bills (in both kWh and Saudi Riyal). This approach enabled us to check the annual electricity usage for consistency across the responses. For example, the estimated annual kWh demand from the seasonal values should be close to the reported annual value entered. Of the n = 124 responses, there were 5 annual kWh responses which were observed to be 10 times too high in comparison to the estimate from the monthly values aggregated for a year. We attributed this to householder input error (the input of an additional zero, e.g., 800,000 kWh instead of the intended 80,000 kWh) and so divided these annual values by 10. There were an additional 15 entries where a monthly electricity value had clearly been entered when the annual value had been requested; we therefore multiplied these values by 12.

Figure 6 shows a box plot distribution for the villas (n = 70) and apartments (n = 54) with the reported data. The villas had an average of 47,588 kWh with a median of 48,356 kWh. The apartments had an average of 24,473 kWh with a median of 22,969 kWh. We chose to use median values for the scenario simulation modelling, as the median value is far less influenced by potential outliers than the average value.

We took half-hourly smart-meter data from (i) a villa [37,38] and (ii) an apartment in Jeddah to enable twelve daily load profiles with an hourly timestep to be generated, one for each month of the year, as shown in Figures 7 and 8. The selected villa had an annual electricity demand of 39,724 kWh from the primarily used living space. The apartment had an annual demand of 37,726 kWh. These profiles were linearly scaled to the median values shown in Figure 6 for the modelling (48,356 kWh for the villa, 22,969 kWh for the apartment).

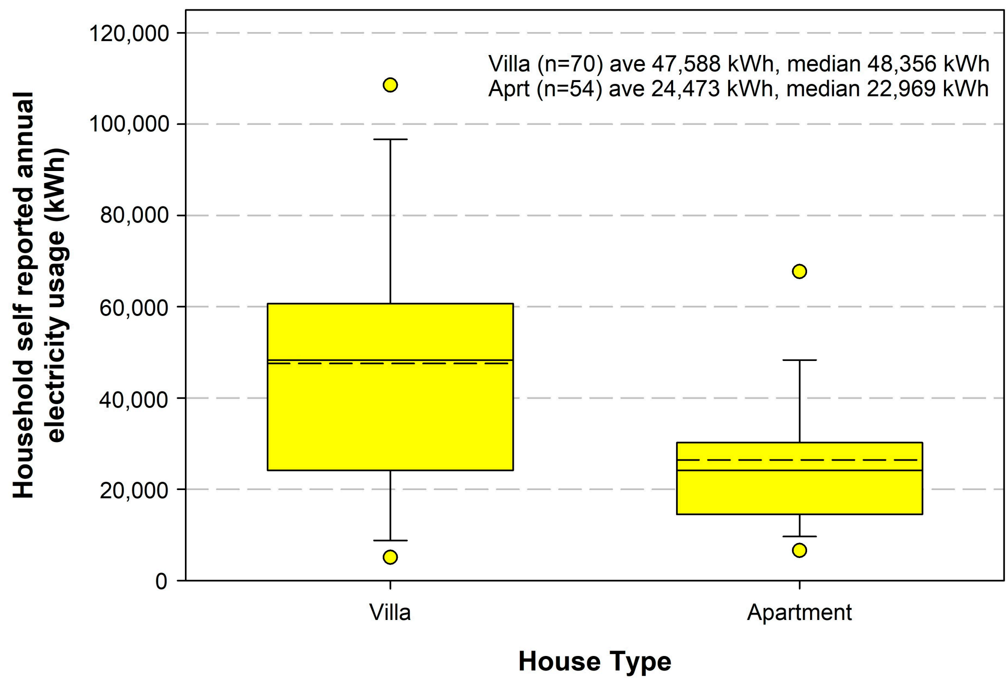

Figure 6. Box plots of household reported annual electricity usage for the villas and apartments. KSA-HPVP survey, n = 124. Box plots show whiskers at the 10th and 90th percentiles, boxes at the 25th and 75th percentiles, and outliers at the 5th and 95th percentiles. Median: solid line; average: dashed line.

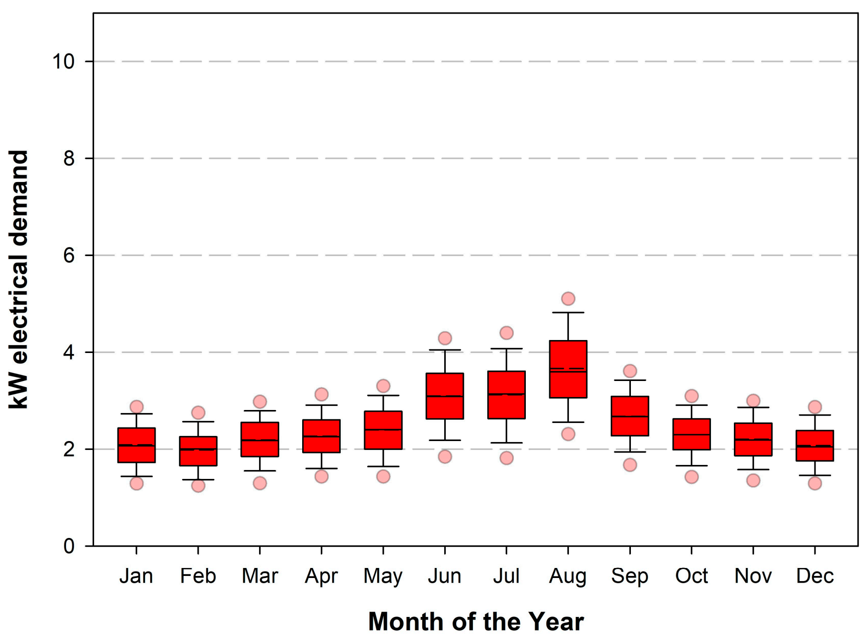

Figure 7. Generated monthly apartment load profiles, scaled to the median KSA-HPVP values. Box plots show whiskers at the 10th and 90th percentiles, boxes at the 25th and 75th percentiles, and outliers at the 5th and 95th percentiles. Median: solid line; average: dashed line. Annual demand: 22,969 kWh.

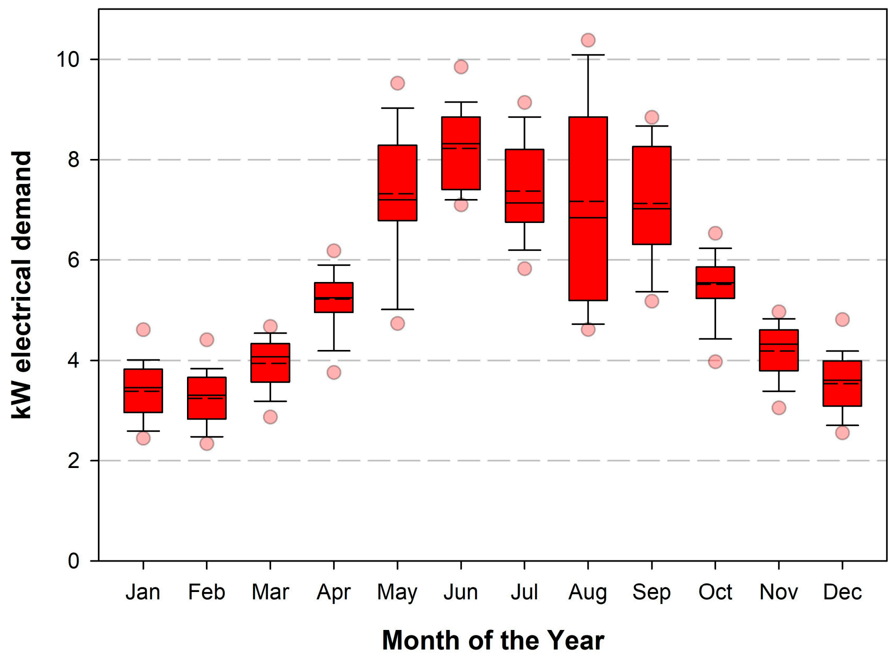

Figure 8. Generated monthly villa load profiles, scaled to the median KSA-HPVP values. Box plots show whiskers at the 10th and 90th percentiles, boxes at the 25th and 75th percentiles, and outliers at the 5th and 95th percentiles. Median: solid line; average: dashed line. Annual demand: 48,356 kWh.

3.2.2. Roof Area Estimates for Household PVs in the KSA

Figure 3 shows that the majority of respondents to the KSA-HPVP survey lived in villas with a floor space area in excess of 300 m^2. To illustrate this sector, we have considered two house types: villa and apartment.

For the villa PV system, we consider a villa as a two-storey structure and the available roof area to therefore be (300/2) x 50% = 75 m^2, as per Abdelhafez et al. [20]. Monocrystalline silicon PV modules have an STC efficiency of around 20% and therefore require approximatively 5 m^2 per kWp, including supporting framing. We therefore consider here either (i) a 10 kWp capacity PV system for a villa on a horizontal surface; or (ii) 9 kWp on a 21-degree slope.

For the apartment PV system, we consider an apartment of 200 m^2, reflecting the median from the KSA-HPVP survey. Typically, an apartment encompasses half of the area of the single storey of a block. However, apartment blocks are typically four-storey structures with a total of eight apartments, and the available roof area per apartment will therefore be (400/8) x 40% = 20 m^2, as per Abdelhafez et al. [20]. We therefore consider here (i) a 4 kWp PV system for an apartment on a horizontal surface; or (ii) 3 kWp on a 21-degree slope.

3.2.3. PV Modelling Scenarios

We used HOMER [36] to undertake an economic comparison of PVs with utility grid connection under a number of different financial scenarios. We compared five scenarios, as outlined in Table 3. S1–S3 are grid-import tariff scenarios, to which we added PVs (S4) and battery storage (S5) with a range of export tariff options. These tariff scenarios were incorporated within the HOMER model, running multiple combinations of tariffs, PV systems, and balance-of-system costs at the same time. Scenarios were ranked in order from the lowest to highest LCOE.

Table 3. HOMER modelling scenarios for villas and apartments with PVs, battery storage, and time-of-use tariffs.

	Scenarios (S1–S5)
S1	*Grid, flat tariff* 0.055 USD/kWh.
S2	*Grid, 2-step time-of-use (ToU) tariff* 0.055 USD/kWh, rising to 0.11 USD/kWh between 12:00 and 19:00 each day.
S3	*Grid, 3-step ToU tariff* 0.055 USD/kWh, rising to 0.11 USD/kWh between 12:00 and 19:00 each day; rising to 0.22 USD/kWh between 12:00 and 19:00 each day in the peak summer period (June, July, August).
S4	*PV with grid tariffs S1, S2, and S3* Villa PV system: 10 kWp, horizontal; apartment PV system: 4 kWp, horizontal.
S5	*PV with tariffs and storage* Addition of battery storage, with a capacity of 5 kWh for an apartment or 10 kWh for a villa; grid and PV charging of the battery is allowed.

We used the LCOE as our cost metric from the HOMER modelling outputs. We consider the additional balance-of-system cost of the PV system as anything in addition to the PV modules, inverter, and battery. This may include installation labour costs, electrical connection permission costs, PV module framing support costs, etc. This combined balance-of-system CAPEX cost is modelled between USD 0 and USD 15,000 in increments of 5000. A CAPEX cost of USD 0 would clearly represent some form of subsidy towards the cost of a system on the part of the KSA government. When comparing a smaller-capacity PV system on a 21-degree slope with a larger horizontal array, the horizontal array always had a lower LCOE. For example, in the case of the apartment with a 3 kWp sloped PV system (S4) with the 3-step ToU tariff applied (S3), the LCOE was 0.0855 USD/kWh, compared to 0.0803 USD/kWh for a 4 kWp flat system and 0.0808 USD/kWh for a grid-only system (balance-of-system cost = USD 5000). We therefore report only the horizontal PV and grid-only cost results from this point.

Scenario S3 represents the most aggressive stepped tariff where the peak summer rate in June, July, and August rises to 0.22 USD/kWh, between 12:00 and 19:00 each day. This is four times the flat tariff rate of 0.055 USD/kWh that is considered in S1. This stepped tariff would be considered a scenario where household battery storage would be expected to have financial viability. When comparing this with the S3 grid option, the LCOE was 0.0828 USD/kWh; the addition of a 5 kWh battery (installed system CAPEX: USD 2750) did not reduce the LCOE despite the large differential in tariff price during the day. The relatively short life of the battery in this case (replacement every 5 years due to cycling) means that the LCOE rises to 0.0893 USD/kWh. This suggests that the addition of battery storage to PVs in a KSA residential context where PV grid export is small will likely be limited.

Figure 9 compares an apartment with three possible tariff scenarios (S1, S2, S3) applied to an apartment with the median KSA-HPVP demand. The lowest LCOE is an approximation of the current tariff in the KSA, at 0.055 USD/kWh. As would be expected, the application of steps in the tariff raises the LCOE, especially since the peak tariff period coincides with the high AC demand. Three crossover points (a, b, and c) are shown where the LCOE of a PV system (S4) becomes cheaper than a pure grid-only option. This is determined by the balance-of-system cost (CAPEX cost in addition to PV module, inverter, and battery costs). The LCOE crossover points with the balance-of-system cost are (a) ~USD 800 for the flat grid tariff S1, (b) ~USD 3800 for the ToU tariff S1, and (c) ~USD 5300 for the ToU tariff S2. In the case of the apartment, the PV system generated 6073 kWh, of which 110 kWh was exported due to the generation exceeding demand (less than 0.5% of the annual demand of 22,969 kWh). The PV generation represents 26% of the annual demand of this apartment.

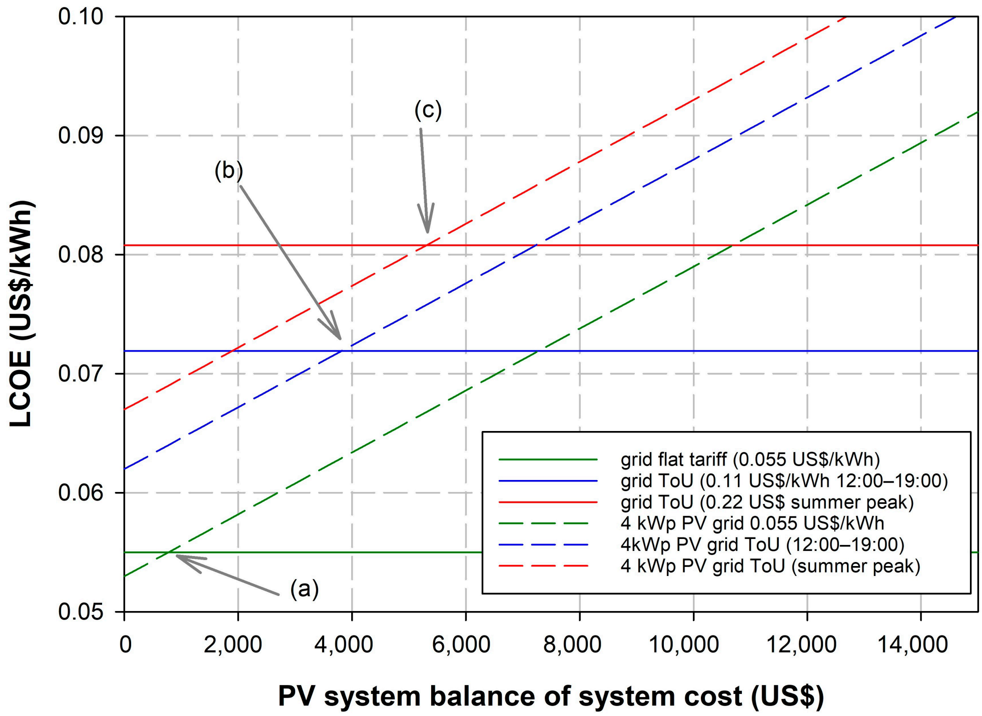

Figure 9. Apartment LCOE comparison of (i) three grid tariff scenarios (S1, S2, S3) applied to the apartment with the median KSA-HPVP demand and (ii) combined with 4 kWp PVs (S4). Annual demand: 22,969 kWh. LCOE crossover points with the balance-of-system cost: (a) ~USD 800, flat grid tariff S1; (b) ~USD 3800, ToU S2; (c) ~USD 5300, ToU S3.

Similarly, Figure 10 compares a villa with three possible tariff scenarios (S1, S2, S3) applied to a villa with the median KSA-HPVP demand. The lowest LCOE is an approximation of the current tariff in the KSA, at 0.055 USD/kWh. Three crossover points (a, b, and c) are shown where the LCOE of a PV system becomes cheaper than a pure grid-only option. This is determined by the balance-of-system cost (CAPEX cost in addition to PV module, inverter, and battery costs). The LCOE crossover points with the balance-of-system cost are (a) ~USD 4600 for the flat grid tariff S1, (b) ~USD 12,600 for the ToU tariff S2, and (c) ~USD 14,600 for the ToU tariff S3. In the case of the villa, the PV system generated 15,182 kWh, of which 414 kWh was exported due to the generation exceeding demand (2.7% of the annual demand of 48,356 kWh). The PV generation represents 31% of the annual demand of this villa.

At present, the residential PV sector in the KSA is very small, which means that the balance-of-system cost will be comparatively high. As the market develops, this cost will clearly reduce through competition and economies of scale. Today, the balance-of-system cost for an apartment is probably of the order of USD 10,000, which would break financial viability rules from the perspective of KSA-HPVP survey respondents. It should be noted that we assessed financial acceptability of PVs in the KSA-HPVP survey on the basis of a maximum upfront payment that would meet half of the monthly electricity demand. In our case studies, the apartment PV would meet 26% of the electricity demand, and this percentage would be 31% for the villa. Therefore, we would expect the actual balance-of-system threshold acceptance cost to be slightly lower than that stated here. If time-of-use tariffs were introduced as per S3, as shown by (c) in Figure 9, the apartment crossover cost would drop to ~USD 5300. The KSA-HPVP survey showed that SAR 10,000 (USD 2700) was within the acceptable range for higher-income households as a financial contribution to the cost of a system. This suggests that to incentivise these households beyond the impact of an S3 grid tariff, a grant subsidy of ~USD 2600 would be required. A range of subsidy options could be considered here depending on economic circumstances: beyond traditional style grants to, for example, reverse auctions, where PV installers would bid to offer their services to households.

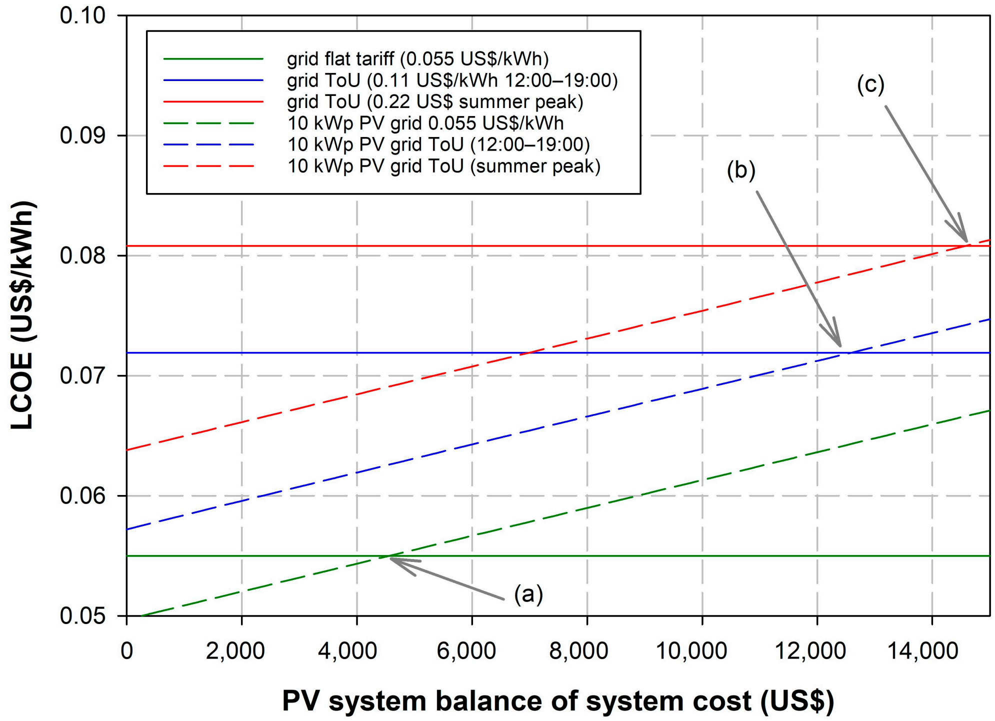

Figure 10. Villa LCOE comparison of (i) three grid tariff scenarios (S1, S2, S3) applied to the apartment with the median KSA-HPVP demand and (ii) combined with 10 kWp PVs (S4). Annual demand: 48,356 kWh. LCOE crossover points with the balance-of-system cost: (a) ~USD 4600, flat grid tariff S1; (b) ~USD 12,600, ToU S2; (c) ~USD 14,600, ToU S3.

Export tariffs will have a very limited effect as the level of mismatch between PV generation and the general high level of demand in the home is very small (less than 110 kWh per annum in the assessed scenarios for the apartment, for example). In the context of villas, the installed PV capacity is much higher than that in apartments (10 kWp compared to 4 kWp), which enhances the economics of these scenarios. For both of the time-of-use tariffs considered (S2, S3), the balance-of-system crossover cost is in excess of USD 10,000, which suggests that this sector should be able to encourage uptake without additional subsidies if a time-of-use tariff is introduced. The current grid price (S1) has a balance-of-system cost of USD 4600, which is less than our estimated cost of USD 10,000, which means that an additional grant subsidy or a low-interest loan would be needed if the tariff does not change.

4. Discussion and Conclusions

This study provides insights into the views of middle-income, well-educated, owner-occupier households regarding residential PVs. Our scenario modelling of PV systems has shown that the economics of such systems have marginal financial benefits at present (weak economic case), far less than the householder-stated conditions that would encourage the studied demographic to adopt this technology. The modelling showed that significant changes in grid tariffs (time-of-use tariffs in particular) will be required to create the financial conditions for PVs to be seen as an attractive technology for households in the KSA.

Consider a 5 kWh battery that operates to utilise the difference between ToU tariffs, such as in S3. Here, the tariff doubles between 12:00 and 19:00 from September to May, increasing by a further two times during June, July, and August. The battery could achieve a maximum of one charge–discharge cycle per day to utilise the tariff differential. Per year, there are a potential 92 cycles at four times the cost differential, and a further 273 cycles at two times the cost differential. This would correspond to 1921 kWh of electricity import for battery charging to deliver 1825 kWh (365 days at 5 kWh/day), assuming a lithium-ion battery has a round-trip charging efficiency of around 95% [47]. In the context of the KSA-HPVP apartment, this storage represents ~8% of the annual demand. Moreover, 1921 kWh at 0.055 USD/kWh indicates a charging cost of USD 106; this avoids 460 kWh at the four-times rate (avoided cost: USD 101) and 1365 kWh at the two-times rate (avoided cost: USD 150). The simple financial saving would be USD 145 per year for a 5 kWh battery, or 29 USD/kWh storage per year. The battery would need to be replaced every four years with such a high level of cycling (current CAPEX storage cost: ~150 USD/kWh), which makes storage unattractive even with the S3 time-of-use prices. This is in contrast to countries such as the UK, where PV export without storage can be around 55% for a 2.9 kWp PV system [48]. In our KSA case studies, the level of PV export without storage is negligible (less than 3%).

In summary, this study has shown that PVs in the context of medium–high-income, owner-occupier households have the potential to become attractive if certain market conditions are established. This could be in the form of either (i) time-of-use tariffs or (ii) the provision of grants to contribute towards the capital cost. With the current tariff structure in the KSA, a grant of ~USD 5000 would appear to be a suitable incentive. Our multiple logistic regression analysis indicates that when the education level of a household is high and the household is an owner-occupier household, this enhances the likelihood of that household adopting PVs. The economics of PVs are enhanced by maximising the installed capacity on a roof (and therefore the kWh generation) rather than optimising the yield per kWp. Battery storage, even with a time-of-use tariff, is not really justified here, as the high electrical demand and good match with PV generation mean that its benefit is limited.

Author Contributions: The authors' contributions to this article were as follows: conceptualisation, A.A., A.B. and P.J.; methodology, A.A., A.B. and P.J.; validation, A.A. and P.J.; formal analysis, A.A. and P.J.; investigation, A.A.; data curation, A.A.; writing—original draft preparation, A.A. and P.J.; writing—review and editing, A.A., A.B. and P.J.; visualisation, P.J.; supervision, A.B. and P.J.; project administration, A.B. All authors have read and agreed to the published version of the manuscript.

Funding: The lead researcher of this study, A. Alshehri, was funded by the King Salman Scholarship programme of Saudi Arabia.

Data Availability Statement: The survey instrument used in this study has been made available: see [18]. A subset of the survey that encompasses the data required for the analysis presented in this paper is available from the University of Southampton data repository [18].

Acknowledgments: This work is part of the activities of the Energy and Climate Change Division and the Sustainable Energy Research Group (www.energy.soton.ac.uk) (accessed on 31 May 2024), within the Faculty of Engineering and Applied Sciences at the University of Southampton, UK. This research is also part of a PhD programme sponsored by the King Salman Scholarship programme of the Kingdom of Saudi Arabia.

Conflicts of Interest: The authors declare no conflicts of interest.

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