

Household Solar Adoption in Kathmandu Valley, Nepal: Affordability, Energy Security and Policy Pathways for Sustainable Development in South Asia

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Abstract

Nepal's scattered settlements, difficult topography and fuel-import dependence make a strong case for decentralized household solar energy, but adoption depends on affordability, operational performance and policy support. This study examines the financial viability of household solar systems in Kathmandu Valley and their implications for rural energy access and sustainable development. A mixed-method design combined a structured survey of 110 households across Kathmandu, Bhaktapur and Lalitpur, open-ended interviews with 10 energy-sector experts, and a review of relevant policy and literature. Internal consistency of the 12-item instrument was high (Cronbach's $\alpha = 0.941$). Most respondents reported annual solar generation of 2,001–4,000 kWh, system efficiency of 60–80%, expected lifespan of 10–20 years and annual energy cost savings of NPR 10,001–20,000. Annual savings were positively associated with annual generation ($r = 0.533$), energy efficiency ($r = 0.573$), reliability ($r = 0.642$), maintenance-interval coding ($r = 0.727$) and expected operational lifespan ($r = 0.714$), all $p < 0.001$. An exploratory regression using the composite financial variable to predict financial feasibility yielded $R = 0.489$, $R^2 = 0.239$, $F(1, 108) = 33.984$, $p < 0.001$, explaining approximately 23.9% of the variance in financial feasibility. Expert evidence identified cost, awareness, storage and policy barriers, while targeted finance, subsidies, installer standards, monitoring and grid improvements were key to strengthening adoption and energy security. A regional comparison situates these findings within the wider South Asian household-solar transition, suggesting the financing, storage and institutional barriers identified are transferable to neighbouring countries with comparable resource and policy conditions.

Keywords: household solar energy; financial feasibility; rural energy; Kathmandu Valley; energy security; sustainable development; South Asia; net metering

1. INTRODUCTION

Renewable energy is now key to energy security, climate mitigation and long-term economic development as it can diversify supply and reduce exposure to fossil-fuel price volatility [1,2]. These

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advantages are especially relevant for Nepal where mountainous terrain, scattered settlements and a long tradition of biomass and the use of imported petroleum products have limited access to reliable and affordable energy [3,4]. Nepal has substantial hydropower potential, but the cost and engineering challenges in extending centralized infrastructure to remote settlements justify a complementary role for decentralized renewable energy systems.

Household photovoltaic systems are one of the most mature, decentralized options for rural and peri-urban electrification [5]. Previous studies in Nepal indicate that solar photovoltaic systems can deliver basic domestic services in locations where extending the grid is costly, and that decentralized systems can contribute to rural livelihoods, education, communications and productive activity [6–10]. The Kathmandu Valley is not uniformly rural and includes dense urban centres, peri-urban development and neighboring communities with different levels of infrastructure and income. Thus, it offers a valuable context for studying the interactions of household financial conditions, system performance and policy support.

It is to be noted that Nepal receives approximately 6.8 hours of sunshine per day and average solar insolation near 4.7 kWh/m²/day [11]. For Kathmandu Valley, the reported mean resource is approximately 4.66 kWh/m²/day, with GIS-based estimates ranging from 504,032 to 2,110,665 Wh/m²/year across the study area [12,13]. Solar resources are therefore technically promising, but resource availability alone does not establish household-level feasibility. Financial feasibility also depends on capital cost, subsidy access, household income, energy demand, system reliability, maintenance, storage, and expected useful life.

Figure 1 shows spatial distribution of annual solar radiation in Kathmandu Valley [14,15]. For households, solar investments are characterized by high initial cost and relatively low operating costs. Subsequent adoption is influenced by access to credit, anticipated bill savings, equipment quality, battery replacement costs, and confidence in installation and maintenance services. Such studies on renewable energy adoption consistently identify financing constraints, policy uncertainty, information deficits, social acceptance and institutional capacity as major barriers [16–21]. These constraints tend to be more binding on lower-income and rural households who have more limited liquidity, fewer financing options and higher service-delivery costs.

The rural-development implications are wider than electricity expenditure. Reliable household energy can reduce dependence on traditional biomass, lower the time burden of fuel collection, and improve indoor environmental quality, support education and income-generating activities [22–25]. Solar energy can also contribute to local energy security by reducing reliance on imported fuels and diversifying supply [26–28]. But the economic case needs to be demonstrated from household data, not merely extrapolated from national resource potential.

Study on the adoption of solar energy, household financial feasibility, and sustainable economic development in Nepal has been already reported in literature [5,15,29]. A recent systematic review published in this journal reports that empirical evidence on residential photovoltaic adoption remains concentrated in regions with greater institutional, financial and infrastructural capacity, leaving a persistent gap for lower-income and lower-middle-income countries where solar energy could be transformative for household welfare [30]. To the authors' knowledge, no prior Nepal-focused study has combined household-level reliability and correlation analysis, exploratory regression of financial feasibility, and structured expert interviews within a single mixed-method framework for Kathmandu Valley. The present analysis addresses this gap by synthesizing the frequency distributions of the 110 households, reliability analysis, correlation matrix, regression results and expert evidence in a rural-development context, thereby making explicit an empirical basis, limitations and policy implications that earlier, more narrowly focused Nepal studies have not jointly established.

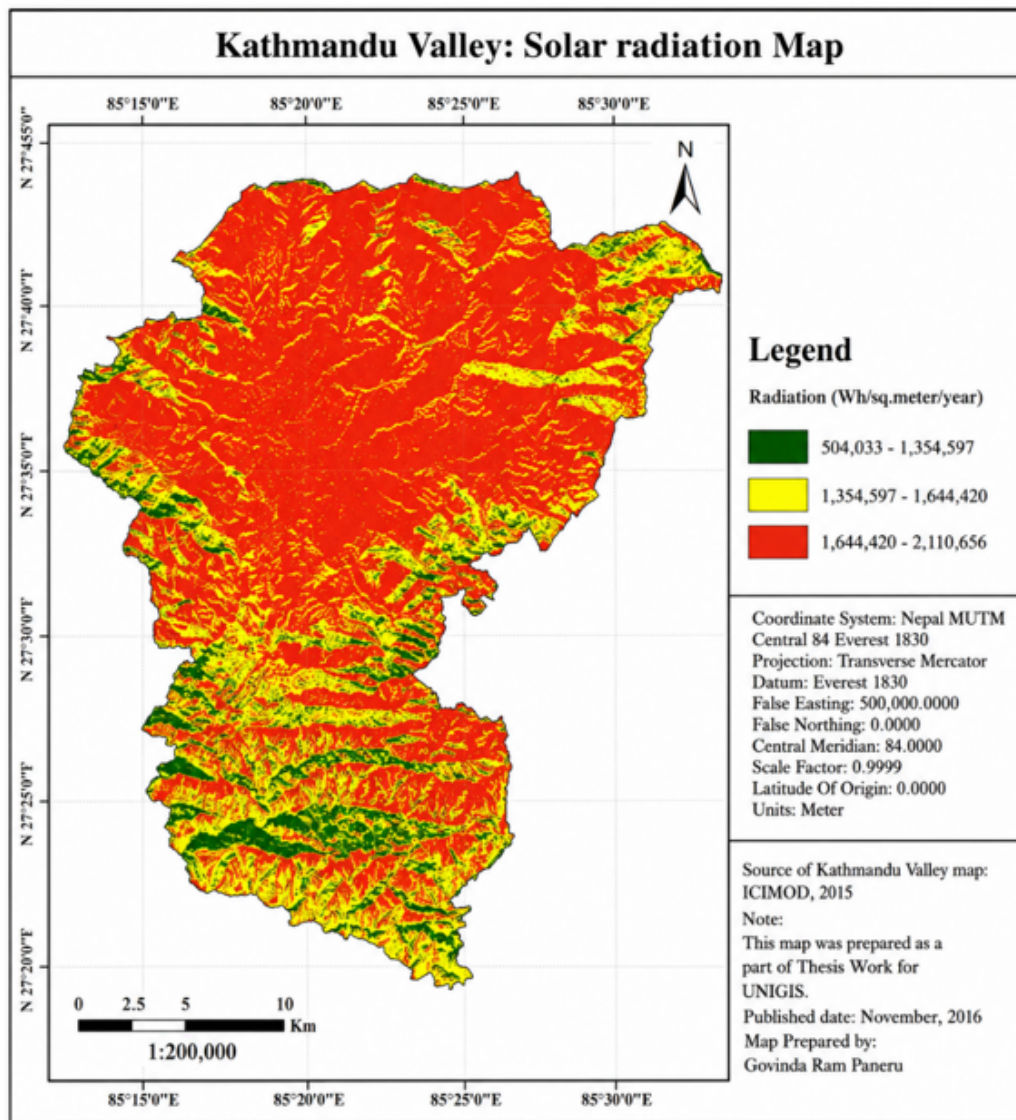


Figure 1: Spatial distribution of annual solar radiation in Kathmandu Valley [14]

The study has four objectives: (1) to analyse the financial feasibility of household solar energy in rural and urban areas; (2) to study the broader feasibility of solar-energy implementation in Nepal; (3) to assess uses and implementation requirements across sectors; and (4) to explain the contribution of solar energy to sustainable economic development. These objectives are operationalized for a research-article focus on terms of household financial and operational indicators, statistical associations with annual savings, and enabling conditions and barriers identified by experts.

Nepal's experience also illustrates a wider regional pattern. As Lo [31] frames it in the inaugural issue of this journal, Asia has largely met its rapidly rising energy demand through conventional fossil-fuel pathways, but energy security, local pollution and global climate change now require Asian countries to pursue more sustainable, often decentralized, energy strategies. Household solar adoption in a mountainous, grid-constrained South Asian setting such as Kathmandu Valley

is therefore not only a Nepal-specific policy question but one instance of this broader Asian energy transition; Section 4 returns to this regional framing when comparing Nepal's household-solar experience with other South Asian countries.

2. MATERIALS AND METHODS

Figure 2 shows the national and local spatial context of Kathmandu Valley, where the study was conducted. The upper panel of the figure shows the location of the valley in Nepal while the enlarged lower panel shows the three constituent districts, Kathmandu, Lalitpur and Bhaktapur that define the study area. The figure also shows the spatial relationship of these districts with Kathmandu being the main urban core, Lalitpur mainly extending to the south and Bhaktapur to the eastern part of the valley.

Kathmandu Valley is a bowl-shaped area in the mid-hills, encircled by mountain ranges. The pattern and density of settlement have been strongly influenced by this geographical setting. The valley is an interesting case to study household solar adoption in particular because it has fast population growth, dense urbanization, the growth of peri-urban settlements and rising residential energy demand all within a relatively small geographic space.

At the same time, there is considerable variation in land use, housing patterns, settlement density and household characteristics across the three districts shown in Figure 2. This urban-peri-urban heterogeneity is a good setting for assessing the impact of geographical and socio-economic conditions on household decisions about distributed solar energy technologies.

These characteristics, along with the availability of solar resources and the continued interest in decentralized and supplementary power solutions, make Kathmandu Valley a suitable study area for investigating patterns and determinants of household solar adoption [32,33].

The convergent mixed-method research design of the study and the integration of the different sources of evidence in a common analytical framework are illustrated in Figure 3. The overall mixed-method design of the research was influenced by the research objectives and carried out in the study area of the Kathmandu Valley through three complementary components: a household survey, expert interviews and a review of relevant policy and academic literature.

The quantitative data were collected from 110 respondents from Kathmandu, Lalitpur and Bhaktapur using a structured household questionnaire administered by applying the simple random-sampling procedure. Of these respondents, 60 (54.55%) were from rural areas and 50 (45.45%) were from urban areas, thus the study was able to collect information from different settlement contexts of the valley. The household survey data were then analyzed through descriptive, correlation, and regression analyses as illustrated in Figure 3 to identify the relationships and patterns associated with the household solar adoption.

For the qualitative component, 10 knowledgeable informants from the energy sector and relevant public institutions were selected by judgmental sampling. We used qualitative content analysis to code their open-ended responses to interview questions in an effort to identify common themes, institutional perspectives and context that could not be adequately captured by the household survey alone. Secondary evidence was collected in parallel from policy documents, institutional reports and academic literature to provide a broader policy and sectoral context for the interpretation of the primary data. The final stage of the framework in Figure 3 was triangulated interpretation, in which the results of the quantitative analysis, qualitative interviews and documentary evidence were examined holistically. The integration enabled the study to compare and corroborate evidence from multiple sources and develop a more comprehensive interpretation of the factors influencing household solar-energy adoption in Kathmandu Valley.

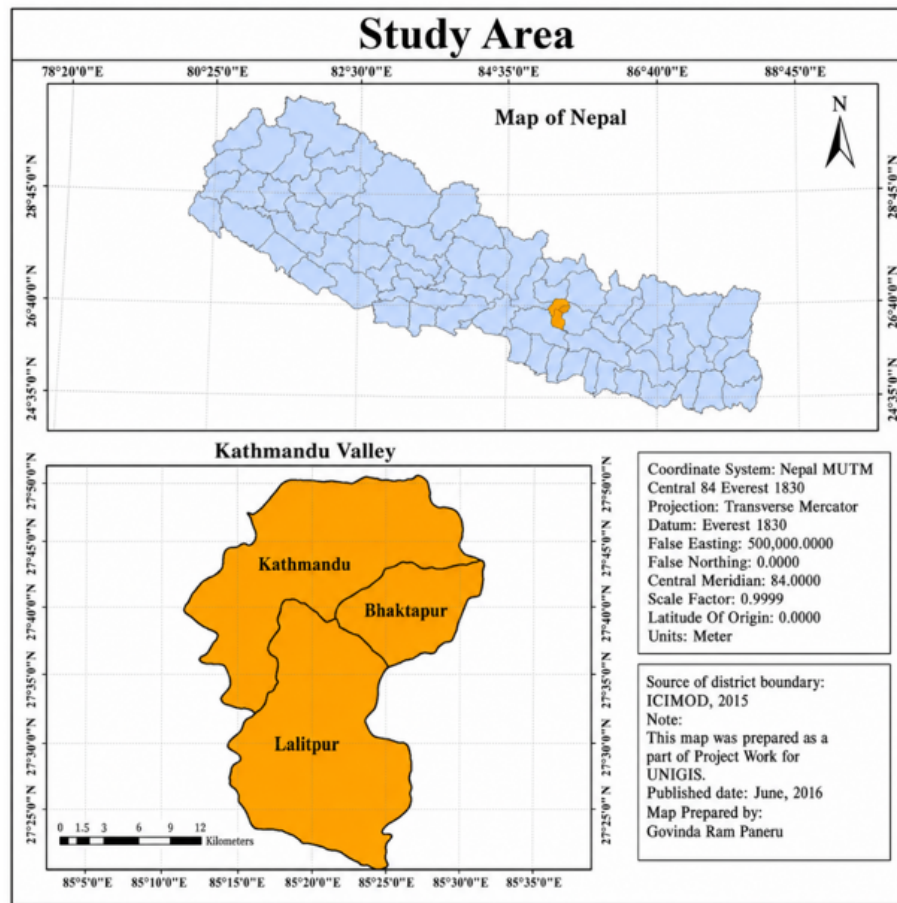


Figure 2: Study area covering Kathmandu, Lalitpur, and Bhaktapur districts [14]

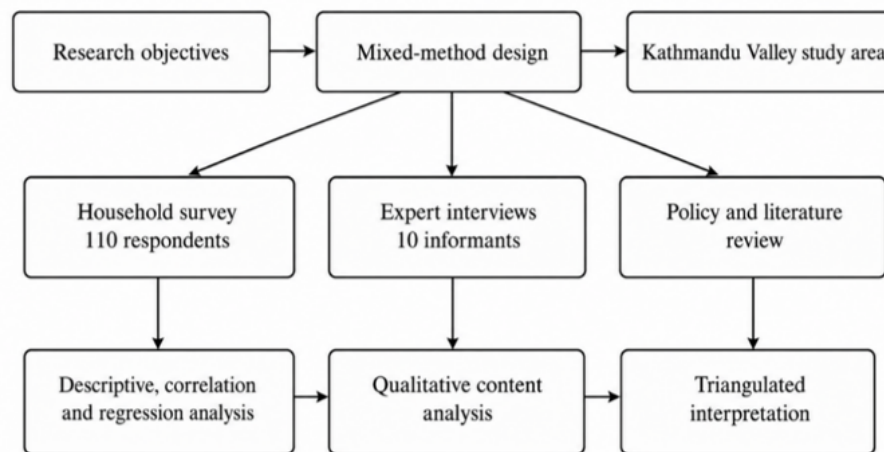


Figure 3: Mixed-method research design integrating household survey data, expert interviews, and policy and literature review for triangulated analysis of solar-energy adoption in Kathmandu Valley

Table 1 shows the study variables and operationalization of each variable in the household questionnaire. The structure of the household questionnaire and the topics covered in the expert interviews are provided in Appendix A. Four main areas of analysis were defined for the variables: Financial, Socioeconomic, Operational, and Financial Feasibility. The financial domain included the initial cost of solar system (Fin A), government incentives or subsidy (Fin B) and average monthly income of the household (Fin C) which were used to capture the economic conditions affecting the adoption of solar by households.

The socioeconomic domain comprises household size (Soc-E D), average daily energy consumption (Soc-E E), annual solar power generation (Soc-E F) and number of electrical appliances owned by the household (Soc-E G). These variables represent household characteristics and patterns of energy demand and use. The variables, Ope H measured system efficiency, Ope I measured perceived system reliability, Ope J measured maintenance frequency, and Ope K measured expected operational lifespan provide information on the household experience with the technical performance and the long-term operation of solar systems.

The main outcome variable to evaluate the benefit of household solar adoption was the annual energy-cost savings (Fin-Fs L), representing the financial feasibility. All variables were captured with ordered categories as indicated in the questionnaire so that the responses can be systematically compared among households. An open-ended expert interview instrument was also used to collect qualitative evidence on perceived benefits, system lifespan, wider economic impacts, and barriers to adoption, government measures, sustainable sector growth, and the role of night-time energy storage, in addition to the household survey.

These quantitative and qualitative measures collectively provided a structured basis to examine the financial, socioeconomic, operational, and feasibility dimensions of household solar-energy adoption presented in Table 1.

Table 1: Study variables and operational measures

Domain	Variable/code	Measurement
Financial	Fin A	Initial solar-system cost category
Financial	Fin B	Government incentive or subsidy category
Financial	Fin C	Average monthly household-income category
Socioeconomic	Soc-E D	Household-size category
Socioeconomic	Soc-E E	Average daily energy-consumption category
Socioeconomic	Soc-E F	Annual solar power-generation category
Socioeconomic	Soc-E G	Number of electrical appliances category
Operational	Ope H	Reported system-efficiency category
Operational	Ope I	Perceived system-reliability category
Operational	Ope J	Maintenance-frequency category
Operational	Ope K	Expected operational-lifespan category
Outcome	Fin-Fs L	Annual energy-cost savings category

Internal consistency was tested by Cronbach's alpha. The 12-item instrument had an alpha of 0.941, indicating high internal consistency of the coded instrument. Quantitative analysis used descriptive statistics, Pearson correlation, and exploratory ordinary least-squares regression. The regression model used a composite financial predictor (MEAN_Fin) and the financial-feasibility outcome. Microsoft Excel was used for recording data and the figures reported in this article were regenerated from the reported tables and statistical output. Qualitative responses were reviewed using content-based thematic synthesis. Repeated ideas were grouped into economic

benefits, environmental and energy-security benefits, adoption barriers, government and financing requirements, maintenance and quality, and energy-storage needs. Quantitative and qualitative findings were then triangulated. SPSS Statistics was used to conduct analysis, which included descriptive statistics, reliability testing, Pearson correlation, and exploratory ordinary least squares regression.

3. RESULTS

The demographic profile of the 110 respondents is summarized in Table 2 and Figure 4. As shown in Figure 4 (a), the respondents were relatively evenly distributed across the three districts of Kathmandu Valley, with the largest share in Kathmandu at 36.36% (n=40), followed by Bhaktapur and Lalitpur at 31.82% (n=35) each. As indicated in Figure 4 (b), the sample was slightly dominated by rural respondents, 54.55% (n = 60), compared to 45.45% (n = 50) being urban respondents. This distribution contained representatives from rural and urban residential areas of the valley.

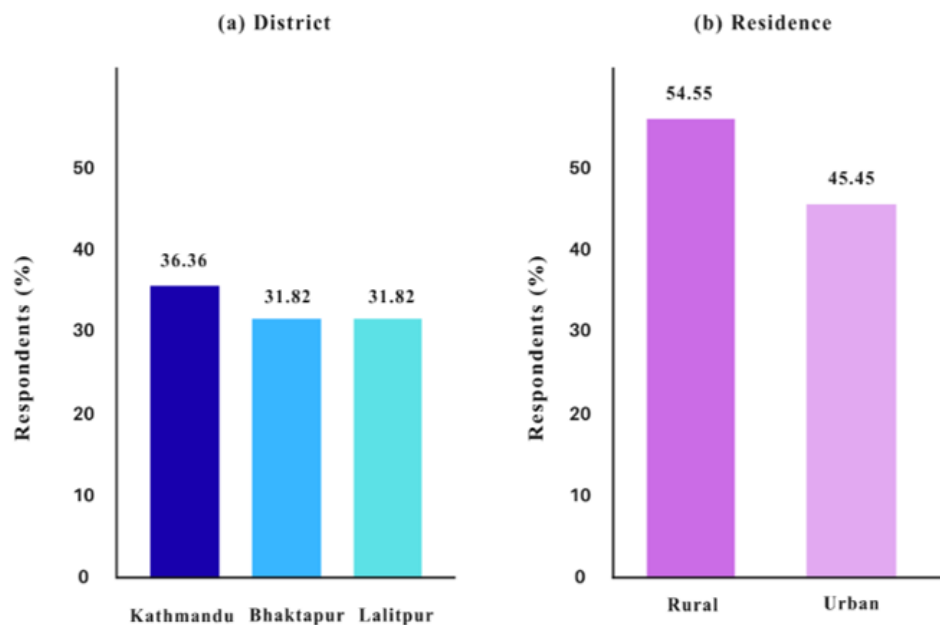


Figure 4: Distribution of respondents by district and rural/urban residence (n = 110)

Further details of the demographic characteristics of the respondents are given in Table 2. Respondents' age was in a wide range. The two largest groups of respondents were 20–30 years old and 31–40 years old (27.27% each of the sample). The respondents aged 41–50 years were 22.73%, those over 50 years were 18.18% and 4.55% were under 20 years of age.

The gender of the respondents was mostly men (54.55%), women (40.91%) and others (4.55%). The respondents had different educational backgrounds, with the highest percentage being those with a bachelor's degree (45.45%), while 27.27% had a high-school education or lower and 27.27% had a master's degree or higher. Participants had varied employment status, where 45.45% were working, 18.18% self-employed, 18.18% students, 9.09% unemployed and 9.09% retired.

Figure 4 and Table 2 show that the sample was drawn from a wide range of districts, residential settings, age groups, education levels, gender, and employment categories, thus providing a broad

demographic base for investigating household solar-energy adoption in Kathmandu Valley. Surveyed households' financial and socioeconomic characteristics suggest a relatively high household energy demand and use of solar systems. The most frequently reported household income group was NPR 60,001–80,000 (52.73% of participants, $n = 58$) as summarized in Table 3. The household size was also relatively large, with the most common category being 7-8 members (44.55% of households, $n = 49$).

Table 2: Demographic characteristics of respondents ($n = 110$)

Characteristic	Category	n	%
District	Kathmandu	40	36.36
District	Bhaktapur	35	31.82
District	Lalitpur	35	31.82
Age	Under 20	5	4.55
Age	20–30	30	27.27
Age	31–40	30	27.27
Age	41–50	25	22.73
Age	Over 50	20	18.18
Gender	Male	60	54.55
Gender	Female	45	40.91
Gender	Other	5	4.55
Education	High school or below	30	27.27
Education	Bachelor's degree	50	45.45
Education	Master's degree or above	30	27.27
Employment	Employed	50	45.45
Employment	Self-employed	20	18.18
Employment	Unemployed	10	9.09
Employment	Student	20	18.18
Employment	Retired	10	9.09
Residence	Rural	60	54.55
Residence	Urban	50	45.45

In line with these household characteristics, 53.64% of respondents ($n = 59$) reported an average daily electricity consumption of 15–20 kWh. The most common report of annual solar-energy generation was in the 2,001–3,000 kWh range, with 44.55% of the full sample ($n=49$) reporting in this range and the broader distribution also had substantial representation in the 3,001–4,000 kWh range. Household electricity demand is also expressed in terms of appliance ownership. The highest proportion of households (48.18%, $n = 53$) indicated that their homes have seven to nine electrical appliances. The complete frequency distributions for all household survey variables are provided in Appendix B.

Most respondents reported receiving some form of government financial support. The largest subsidy category was NPR 20,001–30,000, received by 48.18% of households ($n=53$), and 42.73% reported subsidies of NPR 30,001–40,000. Only 6.36% of respondents reported no subsidy received. These results suggest that government incentives were a key factor in the household solar financing landscape reported here and may have mitigated some of the initial financial burden associated with system adoption. However, the initial solar-system cost data should be interpreted separately due to incomplete responses. The most common category of initial costs in the data is NPR 100,001–150,000, with 39 households coded in that range (see Table 3). This is 35.45% of the total

sample of 110 households.

Figure 5 presents the modal categories of selected financial, energy-use, operational, and financial-savings indicators and provides an overview of the most common household solar system characteristics. The operational results indicated that the reported system efficiency was mainly found in 60-70% and 70-80%, which represent 45.45% and 42.73% of the respondents, respectively, with modal category being 60–70%. These results suggest that most respondents felt their systems were operating in the middle to upper efficiency categories of the questionnaire rather than at the extreme of the response scale.

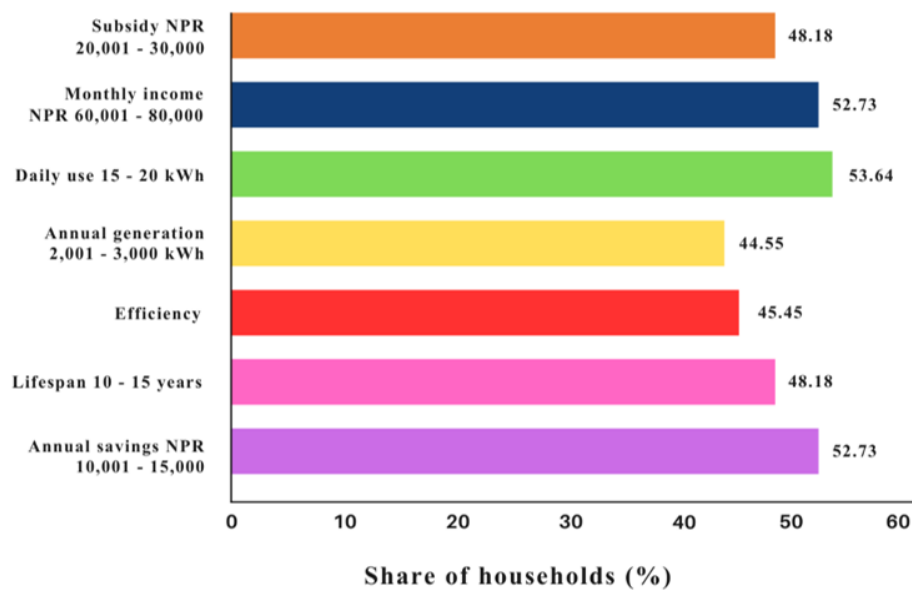


Figure 5: Modal categories for selected financial, energy-use, operational, and savings indicators.

Perceptions of dependability of system were more cautious. 51.82% ($n = 57$) of the respondents selected the neutral category, while 42.73% rated their systems as reliable. Thus, although strongly negative reliability perceptions were relatively infrequent, respondents did not describe their systems as highly reliable to a large extent. Maintenance practices were relatively regular with 49.09% of respondents ($n = 54$) reporting maintenance every six months and 41.82% reporting maintenance yearly. The expected operational life span was also biased into two categories, with 48.18% ($n = 53$) of respondents expecting their systems to operate for 10-15 years and 42.73% expecting a life span of 15-20 years. Overall, the operational indicators imply that, on average, respondents linked household solar systems to periodic maintenance requirements and a lifespan exceeding 10 years.

Figure 6 shows the distribution of reported annual household energy-cost savings. The savings were highly concentrated in the range of NPR 10,001 to NPR 20,000 per annum. The largest group (52.73%, $n = 58$) reported annual savings between NPR 10,001–15,000 and another 39.09% reported savings between NPR 15,001–20,000. However, only 6.37% reported annual savings of less than NPR 10,001 and 1.82% reported savings of more than NPR 20,000. Consequently, more than 90 per cent of the households surveyed reported annual savings of NPR 10,001-20,000.

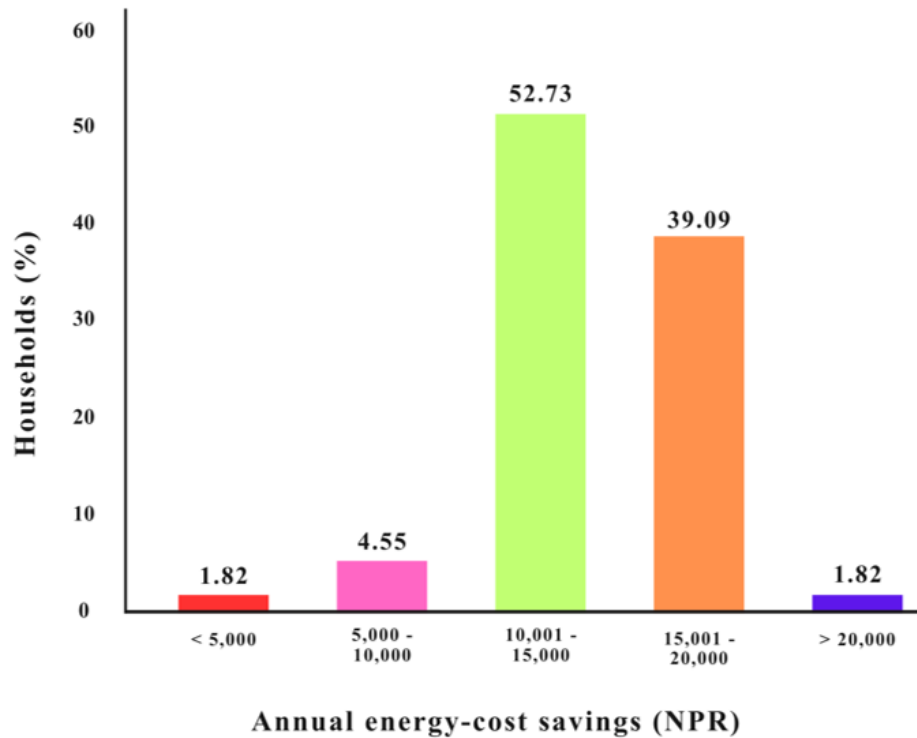


Figure 6: Distribution of reported annual energy-cost savings ($n = 110$)

The results are summarized in Table 3, which shows the category most frequently reported for each major financial, socioeconomic, operational and financial feasibility indicator. The table shows that the representative profile is a household of 7-8 members with an electricity consumption of 15-20 kWh/day and a solar electricity generation of 2001-3000 kWh/year. The household has 7-9 electrical appliances and a monthly income of NPR 60,001-80,000. Operationally, the modal household reported 60–70% system efficiency, neutral reliability, maintenance every six months, 10–15 years lifespan and annual energy-cost savings of NPR 10,001–15,000. This profile is useful for describing the dominant characteristics of the surveyed households, but the modal categories should not be interpreted as meaning that they are representative of every household in the sample.

The annual savings distribution offers descriptive evidence that respondents perceived a direct household-level economic benefit following solar adoption. But annual savings alone are not enough to prove the overall investment profitable. A full financial-feasibility study should also consider initial capital investment, subsidies, maintenance and replacement costs, deterioration of the system, financing terms, expected life span and time value of money. The reported savings therefore are consistent with the existence of recurring energy-cost benefits but, by themselves, do not demonstrate discounted payback, a positive net present value or life-cycle profitability.

Table 3: Representative household solar-system profile

Indicator	Most frequent category	<i>n</i>	% of full sample
Initial cost	NPR 100,001–150,000	39	35.45
Government subsidy	NPR 20,001–30,000	53	48.18
Monthly income	NPR 60,001–80,000	58	52.73
Household size	7–8 members	49	44.55
Daily consumption	15–20 kWh	59	53.64
Annual generation	2,001–3,000 kWh	49	44.55
Electrical appliances	7–9 appliances	53	48.18
System efficiency	60–70%	50	45.45
System reliability	Neutral	57	51.82
Maintenance	Every 6 months	54	49.09
Expected lifespan	10–15 years	53	48.18
Annual savings	NPR 10,001–15,000	58	52.73

Table 4 shows a brief statistical summary of the concentration of household responses across the study variables and complements the frequency distributions reported in the previous sections. All variables were measured on a five-category ordered scale from 1 to 5. Thus, the means and standard deviations reported are not in physical or monetary units but rather indicate the relative position and spread of the respondents across the coded categories.

The variable with the highest mean category score was initial solar-system cost (Fin A) at 3.63 (SD = 0.689) of the variables presented, followed by average daily energy consumption (Soc-E E) at 3.60 (SD = 0.693), household size (Soc-E D) at 3.58 (SD = 0.783), and monthly household income (Fin C) at 3.55 (SD = 0.749). Government subsidy (Fin B) had a mean score of 3.51 (SD = 0.714).

The reported system efficiency (Ope H) had a mean of 3.47 (SD = 0.775). System reliability (Ope I) had a mean score of 3.44 (SD = 0.657). Appliance ownership (Soc-E G) and expected system lifespan (Ope K) followed with mean scores of 3.43. The lowest mean category score was for annual energy-cost savings (Fin-Fs L), with a mean of 3.35 (SD = 0.683). The mean for annual solar generation (Soc-E F) was 3.42 (SD = 0.759), and for maintenance frequency (Ope J) it was 3.39 (SD = 0.705).

Overall, mean scores varied from 3.35 to 3.63, indicating that responses for most variables were focused around the middle-to-upper regions of their corresponding five-category scales. However, these differences should be interpreted with caution as the numerical codes represent ordered response categories, rather than continuous measurements. For example, a mean score of 3.60 for daily energy use is not 3.60 kWh, and a mean of 3.35 for annual savings is not a monetary amount. Rather, these values are the average coded category occupied by respondents.

The standard deviations were from 0.657 to 0.783 representing a relatively moderate spread from the category means. Household size had the most variability (SD = 0.783), followed closely by system efficiency (SD = 0.775) and annual solar generation (SD = 0.759). Conversely, system reliability had the smallest variability (SD = 0.657), meaning the responses were relatively more clustered around its central categories. The variation in annual savings (SD = 0.683) and initial cost (SD = 0.689) was relatively small.

Table 4: Descriptive statistics for coded study variables ($n = 110$)

Variable	Minimum	Maximum	Mean	SD
Fin A: initial cost	1	5	3.63	0.689
Fin B: subsidy	1	5	3.51	0.714
Fin C: monthly income	1	5	3.55	0.749
Soc-E D: household size	1	5	3.58	0.783
Soc-E E: daily consumption	1	5	3.60	0.693
Soc-E F: annual generation	1	5	3.42	0.759
Soc-E G: appliances	1	5	3.43	0.748
Ope H: efficiency	1	5	3.47	0.775
Ope I: reliability	1	5	3.44	0.657
Ope J: maintenance	1	5	3.39	0.705
Ope K: lifespan	1	5	3.43	0.710
Fin-Fs L: annual savings	1	5	3.35	0.683

The Pearson correlation matrix for the coded financial, socioeconomic, operational, and annual-savings variables is presented in Figure 7. The pairwise coefficients were positive and statistically significant ($p < 0.001$), showing that higher coded values of the study variables generally correlated with higher coded categories of annual energy-cost savings. However, the variables were measured on ordered categorical scales, so the coefficients represent associations between the numerical category codes rather than direct relationships between physical quantities like NPR, kWh, efficiency percentages, or years of system operation.

The highest correlations with annual energy-cost savings (Fin-Fs L), as summarized in Table 5, were for maintenance coding (Ope J, $r = 0.727$) and expected system lifespan (Ope K, $r = 0.714$). Reliability (Ope I) was also relatively strongly positively correlated with annual savings ($r = 0.642$), followed by system efficiency (Ope H, $r = 0.573$), annual solar generation (Soc-E F, $r = 0.533$) and number of electrical appliances (Soc-E G, $r = 0.499$). Moderate positive correlations were found between average daily energy consumption (Soc-E E) and annual savings ($r = 0.469$). Household size (Soc-E D) was reported to have the weakest relationship with savings ($r = 0.341$). Taken together, these findings indicate that operational and energy-use characteristics were more highly related to reported savings than most of the coded financial and demographic variables.

Care must be taken in interpreting the positive association between maintenance coding and annual savings. Maintenance scale was coded from more frequent maintenance (monthly servicing) toward less frequent or no maintenance at the upper end of the scale. Thus, the positive coefficient ($r = 0.727$) indicates that households with higher maintenance-category codes also tended to report higher savings categories. It should not be interpreted as evidence that maintenance reduction or avoidance leads to greater financial savings. The relationship may instead be due to differences in system condition, system age, technology quality, maintenance requirements, or other household and system characteristics that were not separated in the bivariate correlation analysis.

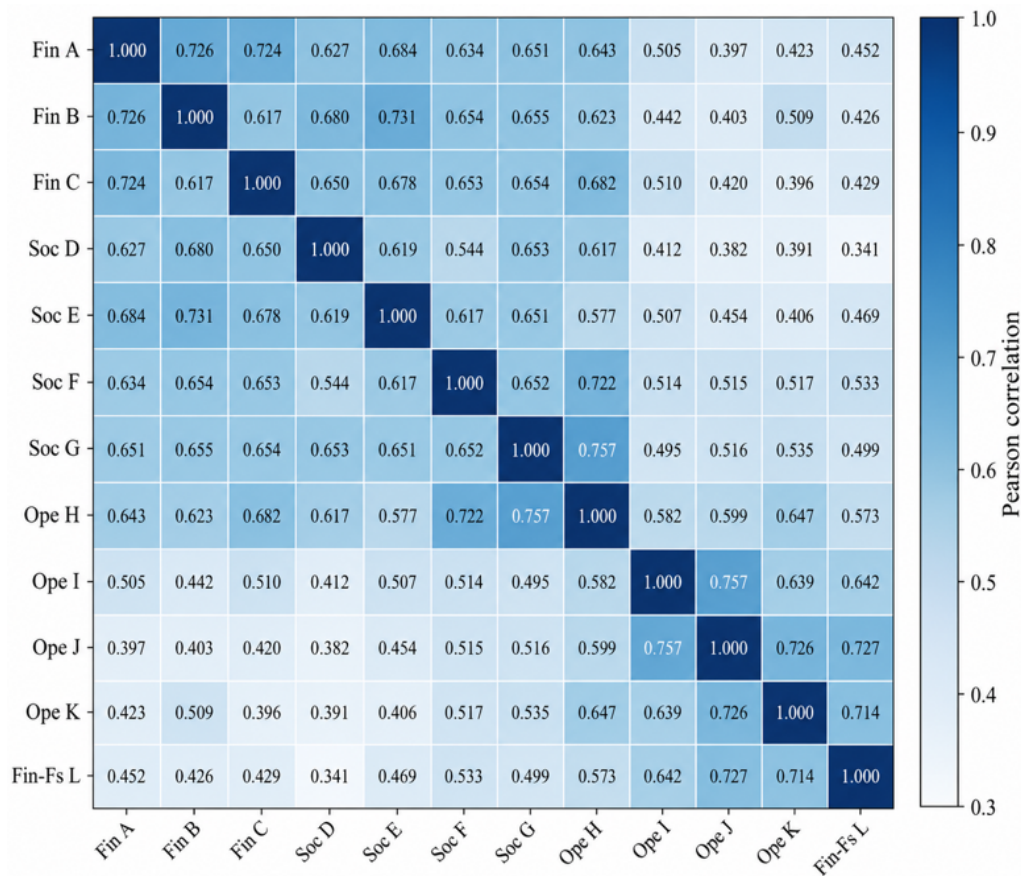


Figure 7: Pearson correlation matrix for the coded study variables. Reported off-diagonal correlations were statistically significant at $p < 0.001$; sample size varies where responses were missing

Financial variables had relatively moderate associations with annual savings. Savings were positively correlated with the initial solar system cost (Fin A) ($r = 0.452$) and monthly household income (Fin C) ($r = 0.429$). Subsidy-category coding (Fin B) was also positively correlated with annual savings ($r = 0.426$). However, the subsidy coefficient should not be interpreted to mean that progressively larger subsidies necessarily brought progressively larger savings since the source coding assigned “no subsidy” to the highest end of the categorical scale. Hence, the numerical ordering of this variable does not reflect a monotonically increasing monetary subsidy amount and therefore does not allow for a straightforward monotonic interpretation of its Pearson coefficient.

Figure 7 also shows that several predictor variables themselves have substantial correlations among them. For example, initial cost was strongly correlated with subsidy-category coding ($r = 0.726$) and system efficiency with appliance count ($r = 0.757$). Such interrelationships suggest that many of the household and system characteristics may be interrelated. If these predictors are subsequently entered together into a multivariable regression or related predictive model, this correlation structure could lead to potential multicollinearity and should be assessed using appropriate diagnostics (e.g., variance inflation factors, tolerance statistics).

Table 5: *Correlations with annual energy-cost savings (Fin-Fs L).*

Predictor	r	p
Initial cost (Fin A)	0.452	< 0.001
Subsidy category (Fin B)	0.426	< 0.001
Monthly income (Fin C)	0.429	< 0.001
Household size (Soc-E D)	0.341	< 0.001
Daily consumption (Soc-E E)	0.469	< 0.001
Annual generation (Soc-E F)	0.533	< 0.001
Appliances (Soc-E G)	0.499	< 0.001
Efficiency (Ope H)	0.573	< 0.001
Reliability (Ope I)	0.642	< 0.001
Maintenance coding (Ope J)	0.727	< 0.001
Expected lifespan (Ope K)	0.714	< 0.001

Overall, the results in Table 5 suggest that the operational characteristics of maintenance coding, expected lifespan, reliability and efficiency were most strongly associated with the annual energy-cost savings, whereas financial and socioeconomic variables generally indicated weaker-to-moderate associations. These results point to variables that are statistically correlated with household savings in the survey data, but the associations are descriptive and associative rather than causal. They therefore provide a basis for the detection of relevant relationships and for the direction of subsequent multivariable analysis but not for demonstrating that changes in any single factor directly result in changes in household financial savings.

The exploratory regression analysis of the relationship between the composite financial predictor and annual energy-cost savings, used as a measure of financial feasibility, is presented in Table 6. The model yielded a multiple correlation coefficient of $R = 0.489$, suggesting a moderate positive association between the composite financial score and the coded annual-savings outcome. The coefficient of determination was found to be $R^2 = 0.239$ and the adjusted R^2 was 0.232. Thus, about 23.9% of the variation in the coded financial-feasibility outcome was statistically associated with variation in the composite financial predictor, whereas the remaining 76.1% was due to factors not represented in this single-predictor model and to unexplained variation.

The overall regression model was statistically significant, $F(1,108) = 33.984$, $p < 0.001$, suggesting that the model with the financial composite fit the observed annual-savings scores significantly better than an intercept-only model. The standard error of the estimate was 0.599. It represents the magnitude of the prediction error on the coded financial-feasibility scale.

The financial composite had a statistically significant positive regression coefficient ($B = 0.524$, $SE = 0.090$, $t = 5.830$, $p < 0.001$). Thus, a one-unit increase in the composite coded financial score was estimated to be associated with a 0.524-unit increase in the coded annual-savings score. The standardized coefficient was $\beta = 0.489$, indicating a moderate positive relationship between the predictor and outcome when both were on standardized scales. The intercept was also statistically significant ($B = 1.479$, $SE = 0.325$, $t = 4.548$, $p < 0.001$). The intercept represents the financial-feasibility score predicted by the model when the composite financial predictor is zero. However, since zero is not in the range of the reported 1–5 coding, the intercept does not have much substantive meaning; it is primarily a mathematical construct defining the regression equation.

As a whole, Table 6 reveals significant associations of the financial characteristics captured by the composite measure with annual household energy-cost savings. But the exploratory statistical model explained less than a quarter of the variance in financial feasibility, indicating that financial

factors alone did not account for most of the variation in reported savings across households. This is consistent with the correlation analysis conducted previously, where operational and energy-related parameters such as maintenance coding, expected lifetime, reliability, efficiency and annual generation showed relatively strong correlation with annual savings. A more comprehensive multivariable model that includes these factors could therefore provide a more complete explanation of household-level financial feasibility, as long as multicollinearity and sample-size concerns are properly addressed.

It is also important to interpret the regression results in an exploratory, and not causal, way. Both the financial composite and the annual-savings outcome were based on ordered categorical responses, and the analysis does not imply that changes in the financial composite directly cause changes in household savings. Also, the findings do not give a comprehensive analysis of the investment feasibility because the regression did not consider the discounted payback period, the net present value, the financing costs, the maintenance expenditure, the component replacement and the system deterioration. The findings, thus, suggest a statistically significant association between the coded financial conditions and the self-reported annual savings in the households surveyed, but do not prove long-term economic profitability.

Table 6: *Exploratory regression predicting financial feasibility*

Model component	Value
R	0.489
R ²	0.239
Adjusted R ²	0.232
Standard error of estimate	0.599
F(df = 1, 108)	33.984
Model p	< 0.001
Intercept B (SE)	1.479 (0.325)
Intercept t; p	4.548; < 0.001
Financial composite B (SE)	0.524 (0.090)
Standardized beta	0.489
Financial composite t; p	5.830; < 0.001

The expert interviews highlighted that solar energy could lower energy costs for households and businesses, strengthen energy security, and reduce dependence on imported fuels. They also highlighted environmental benefits, including lower carbon emissions, and emphasized the suitability of solar energy for remote and off-grid communities, as summarized in Table 7. Four enabler themes were found. First, respondents wanted subsidies, low interest loans and dependable policy support. Second, they stressed public awareness and education to tackle the lack of knowledge in households. Thirdly, they stressed quality materials, proper installation, cleaning and periodic inspection for the longevity of the system. Fourth, they said that research and investment are needed in batteries for storage at night. The main barriers to adoption were high upfront costs, low awareness, lack of government support, and storage limitations.

Table 7 summarizes the principal themes emerging from the expert interviews and links the evidence reported to its practical implications. Thus, the benefits of solar energy are closely related to savings, energy security and environmental improvements, while wider adoption depends on adequate financing, government support, system quality, maintenance and improved energy-storage technologies. The condensed informant-level responses supporting this thematic synthesis are provided in Appendix C.

Table 7: *Thematic synthesis of expert evidence*

Theme	Evidence summarized from expert responses	Implication
Financial benefits	Lower electricity and operating costs; savings can be redirected to other uses	Supports household and firm competitiveness
Energy security	Reduced dependence on imported fuels; reliable power for remote areas	Strengthens decentralized rural supply
Environmental benefits	Reduced carbon emissions and pollution	Supports climate and sustainability objectives
Adoption barriers	High initial cost and limited awareness	Requires targeted finance and outreach
Government role	Subsidies, concessional loans, favourable policy, grid support	Public policy remains a central adoption driver
System longevity	Quality components, proper installation, cleaning, inspection	Installer standards and maintenance networks are needed
Storage	Improved battery technology and research investment	Storage remains a constraint on evening service

4. DISCUSSION

4.1. Household Financial Feasibility

The household results support the conclusion that solar energy can generate meaningful recurring savings in Kathmandu Valley. More than nine in ten respondents reported annual savings between NPR 10,001 and NPR 20,000, while the most common expected lifespan was 10–15 years and the second most common was 15–20 years.

Taken together, these patterns are consistent with a long-lived asset that can offset household energy expenditure. They are also consistent with literature describing solar photovoltaics as a viable decentralized option in Nepal and other rural-electrification settings [6–10,24]. It should be noted that the current study uses financial feasibility in the empirical sense of reported annual savings and positive statistical associations, not as a complete net-present-value or levelized-cost calculation.

4.2. Affordability, Subsidies, and Rural Inclusion

Subsidies were common in the sample and were repeatedly identified by experts as necessary for wider adoption. This aligns with evidence that renewable-energy diffusion in developing economies is strongly shaped by public finance, institutional support, and credit access [18–21]. A recent cross-regional review in this journal similarly identifies high upfront costs and limited access to inclusive financing mechanisms as leading economic barriers to renewable-energy adoption across Asia and other developing regions [34]. For rural households, the relevant policy problem is not only whether the technology produces lifetime savings, but whether the household can

meet the initial payment and absorb replacement or repair costs. A system can be economically attractive over 15 years and still be unaffordable at the point of purchase.

The result that the highest monthly-income category in the sample was not dominant, while the modal income was NPR 60,001–80,000, suggests that the observed adopters may not represent the poorest households. The sample was also drawn from Kathmandu Valley rather than Nepal's most remote mountain districts. Accordingly, the findings demonstrate feasibility among existing adopters but should not be interpreted as proof of universal affordability. Rural finance should combine targeted grants for vulnerable households, low-interest loans for creditworthy households, and performance and quality safeguards for suppliers.

4.3. Operational Quality, Maintenance, and Storage

Operational indicators were strongly associated with reported savings. Reliability, efficiency, expected life, and maintenance coding all correlated with financial feasibility. This is conceptually plausible: systems that generate more energy, operate reliably, and remain in service longer should produce more cumulative value. Solar-technology reviews likewise emphasize equipment quality, system design, and enabling technologies as determinants of performance [35–37].

The maintenance correlation requires nuanced interpretation because the coding assigns larger values to less frequent maintenance. Longer intervals may indicate systems that are newer, better installed, or less failure-prone, but may also reflect under-maintenance. The expert interviews resolve part of this ambiguity by explicitly recommending regular cleaning, inspection, correct installation, and high-quality components. Future data collection should record actual maintenance expenditure, fault events, downtime, battery replacement, and measured output rather than only interval categories.

Storage was one of the clearest technical constraints in the expert evidence. Household solar value is reduced when generation and demand occur at different times and when battery systems are costly or short-lived. Policy support should therefore evaluate total system performance including storage, charge control, and after-sales service, rather than subsidizing panel capacity alone.

A recent multi-location techno-economic comparison of lead-acid and lithium-ion residential battery storage published in this journal similarly finds that storage performance and payback are strongly market- and location-dependent, reinforcing the case for evaluating battery-storage choice explicitly rather than treating storage as a secondary add-on [38].

4.4. Sustainable Development and Energy Security

The benefit of solar energy in Nepal is not limited to cost savings on private bills. Decentralized supply can reduce dependence on imported fuels, allow the provision of essential services and increase resilience in settlements that are expensive to serve with conventional expansion. These functions are vital for the broader concepts of energy security and sustainable energy development [26–28,39,40]. The study also points to applications in agriculture, food processing, buildings, water pumping, lighting, education and small enterprises. Such uses can turn household energy access into livelihood and productivity benefits.

Therefore, rural development policy must consider household solar systems as infrastructure rather than as a separate consumer good. Effective programs require coordinated finance, technical standards, local service networks, consumer protection and data systems that track quality of installation and realized energy output. This systems perspective is in line with the broader

literature on renewable energy markets and the institutional barriers that influence technology diffusion [19–21,41,42].

4.5. Regional Context: Household Solar Adoption Across South Asia

To situate the Kathmandu Valley findings within the wider Asian energy transition discussed above [30], Table 8 compares Nepal’s household and rooftop solar experience with four other South Asian countries. The comparison should be read with an important caveat: Nepal’s reported uptake has historically been dominated by off-grid solar home systems serving areas the centralized grid does not economically reach, whereas India, Pakistan and Sri Lanka have shifted toward grid-tied, net-metered rooftop solar as a mainstream household strategy even where grid access already exists. These are not directly equivalent adoption regimes, and the numerical values in Table 8 should not be read as a single ranked league table.

Table 8: *Comparative Household and Rooftop Solar-Adoption Context across South Asia*

Country	Household / rooftop solar status	Primary adoption driver	Net-metering policy	Source
Nepal	~1.1 million off-grid solar home systems installed nationally (~30 MWp); grid-tied rooftop net metering introduced but later suspended by the utility	Off-grid access in areas the centralized grid does not reach economically	Introduced 2018; suspended 2022, reconnection contested	[13,43,44]
India	Rooftop capacity grew from ~11 GW (2.6% of the energy mix) in 2023 to ~18 GW (3.9%) by May 2025	Government-led subsidy programme (PM Surya Ghar; ~USD 9 billion target for 30 GW / 10 million homes)	Since 2012 (state level)	[45]
Pakistan	Rapid recent rooftop-solar growth driven by consumer economics rather than a single national programme	Market-driven: steep tariff increases combined with falling panel prices and import-duty exemptions	Since 2009 (first in South Asia)	[45]
Sri Lanka	Rooftop capacity more than doubled, from 516 MW (2022) to 1,347 MW (2024), ~23% of national capacity	Government-facilitated financing support with multilateral-agency assistance	Since 2011	[45]
Bangladesh	Rooftop capacity limited to ~245 MW, below 1% of energy supply; described as still at a nascent stage	Constrained by financing access and import duties on system components	Since 2018 (most recent adopter)	[45]

Read this way, Nepal’s position is distinctive rather than simply lagging. Its net-metering framework was introduced later than Pakistan’s, India’s and Sri Lanka’s, and was subsequently suspended, which helps explain why household adoption in Kathmandu Valley remains grant- and subsidy-dependent rather than tariff-arbitrage-driven as in Pakistan, or programme-driven at national scale as in India. The affordability, storage and institutional barriers identified in Sections 4.2 and 4.3 are therefore not unique to Nepal; comparable barriers have constrained Bangladesh’s

rooftop-solar sector, while Sri Lanka's experience suggests that resolving financing barriers, rather than resource availability, can unlock rapid household-level uptake even in a small South Asian economy. This regional comparison indicates that the financing, storage and institutional findings reported here for Kathmandu Valley are likely to be transferable, with appropriate local calibration, to other South Asian settings that share Nepal's combination of strong solar resource, constrained grid infrastructure and nascent net-metering policy.

5. CONCLUSION

Household solar energy in the Kathmandu Valley was associated with substantial reported annual savings, moderate-to-high operating performance and expected service lives of 10-20 years. According to the statistical results, the financial feasibility is not only related to the household financial conditions, but also related to the generation, efficiency, reliability, maintenance patterns and system lifespan. Expert evidence confirms a need for subsidies or concessional finance, public awareness, quality of installers, maintenance services and better storage. The main finding is that household solar energy can contribute positively to household welfare and sustainable rural development, but capital subsidy alone should not be used to promote adoption. Good policy needs to address front-end affordability, technical quality, after-sales service, storage, grid integration and transparent monitoring. As the current evidence is based on coded cross-sectional responses, future research should employ measured generation, validated costs, cash-flow analysis, and longitudinal system-performance data.

The findings suggest that future solar-energy regulations should be more focused considering household financial capacity, technical quality, and long-term system performance. Grants should be used for low-income and distant households and concessional credit with fair eligibility requirements can be used to support households with repayment capacity. To improve the quality and durability of the system, public subsidies should be linked to certified components, qualified installers, commissioning requirements, warranties and reliable after-sales services. Also, rural maintenance networks should be reinforced by training local technicians, availability of spare parts and reasonable inspection and cleaning services. More attention should be paid to the life-cycle costs of batteries, the financing of replacement, the safe disposal, and the storage performance under the actual conditions of household demand. Standardized monitoring of system size, solar irradiance, power generation, downtime, maintenance, battery replacement and household savings would improve evidence-based policy planning. Future studies should include nationally representative stratified samples, rural and urban distinctions, validated coding schemes, verified cash-flow data, and longitudinal follow-up to examine the long-term financial and operational effectiveness of residential solar systems.

Data Availability Statement

The aggregated data and statistical outputs were used in this article.

Ethics Statement

No personally identifiable information was collected or reported in this study.

Prior Dissemination

This manuscript is derived from the first author's doctoral thesis. Related shorter publications are cited in the Introduction. The present manuscript consolidates extensive household mixed-

method evidence, detailed statistical outputs, data-integrity limitations, and rural-development implications.

AI Use Statement

During the preparation of this work, the first author used ChatGPT in order to check the order, spelling, and grammar. No AI tools were used for data analysis, interpretation, or generation of scientific content. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

APPENDIX

Appendix A

Household Questionnaire Structure	
Section	Content
A. Demographic Information	District; age; gender; educational background; employment status; rural or urban location.
B. Financial Variables	Initial system cost; government incentive or subsidy; average monthly household income.
C. Socioeconomic Variables	Household size; average daily energy consumption; annual solar generation; number of electrical appliances.
D. Operational Variables	Energy efficiency; reliability; maintenance frequency; expected operational lifespan.
E. Financial Feasibility	Annual savings on household energy costs are attributable to solar-energy use.
F. Expert Interview Topics	Merits of solar energy; system-lifespan improvement; relationship between feasibility and economic impact; effects on small and large firms; adoption barriers; sustainable growth; government actions; night-storage improvement.

Appendix B

Complete Frequency Distributions (Continued)			
Variable	Category	<i>n</i>	% (<i>n</i> =110)
Initial cost	< NPR 50,000	2	1.82
Initial cost	NPR 50,000–100,000	1	0.91
Initial cost	NPR 100,001–150,000	39	35.45
Initial cost	NPR 150,001–200,000	2	1.82
Initial cost	> NPR 200,000	6	5.45
Initial cost	Unreported/uncoded	60	54.55
Subsidy	< NPR 10,000	2	1.82
Subsidy	NPR 10,000–20,000	1	0.91
Subsidy	NPR 20,001–30,000	53	48.18
Subsidy	NPR 30,001–40,000	47	42.73
Subsidy	No subsidy	7	6.36
Monthly income	< NPR 20,000	2	1.82

Complete Frequency Distributions (Continued)			
Variable	Category	<i>n</i>	% (<i>n</i> =110)
Monthly income	NPR 20,000–40,000	5	4.55
Monthly income	NPR 40,001–60,000	39	35.45
Monthly income	NPR 60,001–80,000	58	52.73
Monthly income	> NPR 80,000	6	5.45
Household size	1–2 members	2	1.82
Household size	3–4 members	3	2.73
Household size	5–6 members	45	40.91
Household size	7–8 members	49	44.55
Household size	> 8 members	11	10.00
Daily consumption	< 5 kWh	2	1.82
Daily consumption	5–10 kWh	1	0.91
Daily consumption	10–15 kWh	42	38.18
Daily consumption	15–20 kWh	59	53.64
Daily consumption	> 20 kWh	6	5.45
Annual generation	< 1,000 kWh	3	2.73
Annual generation	1,000–2,000 kWh	5	4.55
Annual generation	2,001–3,000 kWh	49	44.55
Annual generation	3,001–4,000 kWh	49	44.55
Annual generation	> 4,000 kWh	4	3.64
Appliances	1–3	2	1.82
Appliances	4–6	5	4.55
Appliances	7–9	53	48.18
Appliances	10–12	44	40.00
Appliances	> 12	6	5.45
Efficiency	< 50%	3	2.73
Efficiency	50–60%	3	2.73
Efficiency	60–70%	50	45.45
Efficiency	70–80%	47	42.73
Efficiency	> 80%	7	6.36
Reliability	Very unreliable	2	1.82
Reliability	Unreliable	1	0.91
Reliability	Neutral	57	51.82
Reliability	Reliable	47	42.73
Reliability	Very reliable	3	2.73
Maintenance	Monthly	2	1.82
Maintenance	Every 3 months	5	4.55
Maintenance	Every 6 months	54	49.09
Maintenance	Annually	46	41.82
Maintenance	Rarely/never	3	2.73
Lifespan	< 5 years	2	1.82
Lifespan	5–10 years	4	3.64
Lifespan	10–15 years	53	48.18
Lifespan	15–20 years	47	42.73
Lifespan	> 20 years	4	3.64
Annual savings	< NPR 5,000	2	1.82
Annual savings	NPR 5,000–10,000	5	4.55
Annual savings	NPR 10,001–15,000	58	52.73
Annual savings	NPR 15,001–20,000	43	39.09

Complete Frequency Distributions (Continued)			
Variable	Category	<i>n</i>	% (<i>n</i> =110)
Annual savings	> NPR 20,000	2	1.82

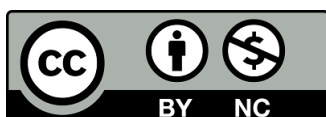
Appendix C

Expert Response Matrix (Continued)		
Informant	Topic	Condensed response
Expert 1	Benefits	Cost savings, lower emissions, and reliable power for remote areas.
Expert 1	Firm impacts	Lower operating costs and improved competitiveness for small and large firms.
Expert 1	Government action	Subsidies, low-interest loans, and district-level installation policies.
Expert 2	System life	Regular maintenance, cleaning, and high-quality materials.
Expert 2	Economic relationship	Lower costs increase savings and investment in other sectors.
Expert 2	Storage	Better battery technology and research investment.
Expert 3	Benefits	Renewable supply reduces dependence on imported fuels.
Expert 3	Adoption barriers	High upfront cost and limited awareness.
Expert 3	Sustainable growth	Lower and more stable energy costs improve energy independence.
Expert 4	Economic relationship	Lower costs, reduced fuel-import deficit, and renewable-energy jobs.
Expert 4	Firm impacts	Improved financial health and competitiveness.
Expert 5	Benefits	Reduced emissions, lower bills, and reduced fuel dependence.
Expert 5	Government action	Subsidies, favourable policies, and grid infrastructure.
Expert 6	System life	Quality components, correct installation, and inspection.
Expert 6	Adoption barriers	Upfront cost and insufficient government support.
Expert 7	Sustainable growth	Stable low-cost energy and reduced fossil-fuel dependence.
Expert 7	Storage	Battery advancement and government investment.
Expert 8	Economic relationship	Operational savings can be redirected into economic activity.
Expert 8	Firm impacts	Cost reductions improve viability and profitability.
Expert 9	Benefits	Lower carbon footprint and reliable off-grid power.
Expert 9	Government action	Incentives, streamlined regulation, awareness, and education.
Expert 10	System life	Maintenance, quality materials, and correct installation.
Expert 10	Sustainable growth	Renewable low-cost energy, reduced imports, and green jobs.

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