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Housing affordability in the renewable energy transition: Evidence from the domestic rooftop solar panel uptake in Sydney, Australia

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ABSTRACT

This study investigates the factors influencing household solar panel uptake in the Sydney metropolitan area from 2013 to 2024, using a panel dataset and postcode-level solar installation data. Employing fixed effects panel regression, along with Poisson and negative binomial models for installation counts and Tobit and ordinary least squares models for system capacity, we find that market factors—such as solar system costs and electricity prices—significantly affect solar adoption and capacity. In contrast, feed-in tariffs have a negligible impact. A notable contribution of our research is the incorporation of housing and rental affordability into the analysis. We show that housing affordability, measured by the price-to-income and price-to-rent ratios, plays a significant role in influencing solar uptake. However, rental affordability, as measured by the rent-to-income ratio, has minimal effect. This study highlights housing affordability as a key barrier to solar adoption for property owners and underscores the structural barriers renters face in the clean energy transition. We recommend the implementation of a "Use It or Lend It" solar program, where the government could install solar panels on the rooftops of suitable buildings where the property owners opt not to do so themselves, offering a more effective policy alternative to traditional rebates in accelerating the clean energy transition.

1. Introduction

Responsible for only 1.3 % of global greenhouse gas emissions but being the highest per capita producer of emissions in the world due to fossil fuel exports [5], Australia is facing a significant challenge in renewable energy transition. Under the Paris Agreement, Australia initially set a reduction target of 26–28 % below the 2005 levels by 2030. In 2022, the Commonwealth Government increased that target by legislation to 43 % (section 10 of the Climate Change Act 2022). If Australia is to meet its emissions reduction target, it will need to generate more than 80 % of its electricity from renewables by 2030 [24]. This will represent a significant increase from the 35 % current electricity generation from renewables in 2023 [6]. Australia is not yet on track to meet its 2030 emissions reduction target [25].

Australia is a world leader in domestic solar adoption, with 3.9 million homes as of September 2024 having solar panels [8,87]. Adoption of solar is facilitated because most houses are detached, semi-detached or townhouses, with only 16 % being apartments [4]. Rooftop solar (including commercial installations) comprises about one-quarter of electricity capacity nationally [87]. The uptake has been driven by eligibility for rebates under the Small-Scale Renewable Energy Scheme (SRES). Additionally, a system for the approval of photovoltaic modules and inverters, and the accreditation of installers and designers has evolved [22,34].

However, despite high domestic solar adoption in recent years, 2.8 million owner-occupied houses remain without solar, and two-thirds of new houses are being built without solar [87]. Fewer than 14 % of houses with solar are supported by battery storage [23]. With clear public support for more rooftop solar [31,45], many interdependent measures have been proposed to increase adoption. Broadly, the measures involve financial assistance, public information and education campaigns, home energy efficiency upgrades, mandating the inclusion of solar on suitable new builds, and free solar for low-income renters in government and community housing. While proposals to increase solar adoption in apartments and rental accommodation vary [64,87], there appears to be wide support for additional government assistance to increase the rate of domestic solar adoption [45].

This paper contributes to the literature by conducting a panel analysis including the time dimension, which is relatively uncommon in studies on solar panel adoption. Using postcode-level solar installation

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data in Sydney, Australia, over the period 2013 to 2024, we apply fixed effects panel regression alongside Poisson and negative binomial models for installation counts, and Tobit and ordinary least squares models for system capacity. Our results indicate that a 10 % increase in installation costs leads to a 6.69 % decrease in installations, while a 10 % rise in electricity prices is associated with a 10.43 % increase in uptake. Similar patterns are observed for system capacity: a 10 % increase in installation costs reduces capacity by 8.5 %, whereas a 10 % rise in electricity prices boosts capacity by 13.5 %. Conversely, feed-in tariffs are found to have an insignificant effect on both uptake and capacity.

A novel contribution of this research is the explicit inclusion of housing affordability metrics—specifically the price-to-income and price-to-rent ratios—as well as a rental affordability metric, the rent-to-income ratio, in the panel analysis. This is supported by a strong theoretical framework that links housing to energy justice, capital constraints, and tenure-based exclusion within broader socio-technical and social processes [37,72]. While previous studies on solar uptake widely focus on household income, wealth and cash assets [2,11,14,15], few studies have incorporated housing and rental affordability into consideration in solar uptake. As housing is the single largest financial asset for many Australian households [70], housing costs (i.e., mortgage or rent payments) play a crucial role in linking household behaviour and technological advancement within socio-technical systems, being an important social justice aspect about the injustices and inequalities of sustainable energy transitions [18,66,73]. Our findings reveal that housing affordability is a critical determinant of solar uptake. A 10 % increase in the price-to-income ratio reduces the number of installations by 8.39 % and installed capacity by 5.35 %. Similarly, a 10 % increase in the price-to-rent ratio results in a 6.91 % decline in installation numbers and a 3.95 % reduction in capacity. In contrast, rental affordability as indicated by the rent-to-income ratio shows no statistically significant effect. This suggests that renters may face structural barriers to solar adoption, as their ability to participate in clean energy transitions is largely determined by landlord decisions rather than their financial capacity or preferences.

Given that housing affordability emerges as a key barrier to household solar adoption—one unlikely to be resolved in the short term—this paper explores practical policy solutions to address it. Even with existing government rebates and financial incentives, many households face financial constraints that limit their ability to cover the upfront costs of solar installation, particularly low-income homeowners [81,82]. Additionally, renters encounter structural barriers, as they lack ownership control over the properties they live in, further hindering their participation in the clean energy transition. To overcome these challenges, we propose a 'Use It or Lend It' solar program. Under this scheme, homeowners and investors would have the option to permit the government to install and maintain solar systems on their rooftops, without bearing any financial or maintenance responsibilities. Our findings provide policymakers with evidence of the long-term affordability challenges facing solar uptake and underscore the need for innovative, targeted interventions to ensure more equitable access to renewable energy.

The paper proceeds as follows. Section 2 provides background on the small-scale solar program, as well as literature on rooftop solar studies. Section 3 presents the research design. Section 4 describes the data. Section 5 discusses the empirical results and explores potential policy implications. Section 6 concludes.

2. Background

2.1. The Small-Scale Renewable Energy Scheme (SRES)

The uptake of domestic rooftop solar panels during the sample period (January 2013 – April 2024) was incentivised by the SRES. The SRES is an economic instrument created by the Renewable Energy (Electricity) Act 2000 (Commonwealth) and administered by the Clean Energy Regulator (CER), a non-corporate Commonwealth entity established by the Australian Government. The legislation established a renewable energy target, which by the time of the sample period had been separated into a large-scale target and the SRES.

Under the SRES, the owners of eligible systems under 100 kW can claim Small-Scale Technology Certificates (STCs). These are usually assigned to a registered installation agent in exchange for a discount on the installation cost. For example, a typical 6.6 kW system may cost $8500, but the consumer only pays approximately $6200. The $2300 difference is the amount that the retailer receives from a registered installation agent for the assignment of the STCs. Note that the discount received by purchasers of rooftop solar systems is not a government subsidy. Rather, the $2300 discount for the installation of the photovoltaic system is the market price for STCs reflecting the amount that competitive retailers are willing to pay to generate the amount of renewable energy required by the legislation. Commonly referred to as a rebate, the SRES created financial incentives for electricity retailers to increase the amount of renewable energy that they sell each year [21,49,58,80].

The renewable energy generation target stated for 2020 in the Renewable Energy (Electricity) Act 2000 was reached a year in advance. A review in 2018 found that the CER was administering the renewable energy target (including the SRES) well [7]. The SRES appears to have achieved its objective, namely of acting as a short-medium-term catalyst for renewables investment until solar becomes the cheapest, longer-term option for those Sydney households able to invest in it [87].

The capacity of the electricity grid to accept middle-of-day exports of electricity to the grid from household rooftops is challenging [50]. Centralised coal generators are gradually being replaced by decentralised renewable energy generators and a distributed grid system [53]. This paper assumes that distributed grid upgrades will continue, such that domestic solar can increase in line with Australia's target of increasing renewables from 35 % to 82 % of electricity generated by 2030.

2.2. Literature review

The adoption of renewable energy, particularly solar power by households is influenced by a myriad of market and demographic factors. For instance, Zhang et al. [83] identified household income, housing type, property value, and population density as key determinants of residential solar uptake in the Netherlands. The positive effects of education and income on adopting energy efficiency measures were also documented in Das et al. [29]. Wilson et al. [76] found that property characteristics such as type and age and household characteristics like size and income are significant influencers of households' decisions to invest in green initiatives in residential properties. Lan et al. [48] provided additional empirical evidence on the impact of household socioeconomic characteristics on solar uptake and spatial distribution. Further to household characteristics, van der Kam et al. [75] noted that older generations are more likely to adopt solar PV systems as part of their retirement planning, while Huijben and Verbong [44] observed increasing solar PV adoption among younger homeowners, who are motivated by the long-term financial benefits. These findings show the growing interest in investment in solar energy systems among young and older generations. Earlier, Nair et al. [56] reiterated the role of household attributes like education, income, age, and energy costs in shaping a household's decisions about adopting renewable energy preferences. The issue of monetary gains versus comfort from installing solar systems was raised by Aravena et al. [3]. They found that households often prioritise economic benefits such as energy savings over comfort, and environmental benefits have little concern when making decisions. The willingness to pay for solar uptake is another crucial issue that Khan et al. [46] raised. Using a survey of 354 potential homebuyers in Pakistan, they found people's willingness to pay for solar systems is positively correlated to demographic variables like age, literacy level, and gender, while negatively related to income and environmental knowledge. These negative correlations, which contrast with findings from other studies [e.g., [71,86]], may be due to the specific socioeconomic conditions in Pakistan and the relatively small survey sample size. Additionally, the upfront costs and related expenses in solar panel investment are the most critical drivers of a household's decision to invest in solar energy [12]. Adding to these costs is the information barrier potential solar adopters face, which also leads to high indirect costs resulting from searching for information [63].

A growing body of research links housing expenses with household energy choices. This strand of literature focuses on assessing housing expenditure concerning renewable energy sign-up, particularly in urban areas where housing affordability is gradually deteriorating. Research by Fry et al. [36] found that for low-income households, a 1 % rise in electricity prices increases energy expenses by 0.44 % and decreases food expenditure by 0.09 %. Wholesale electricity prices have also increased in Australia, mainly due to the rise in natural gas prices, thereby worsening household energy bills [27]. A study from the Australian Housing and Urban Research Institute (AHURI) indicated that 18 % of public renters and 14 % of private renters could not keep sufficiently warm during winter due to rising energy costs [28]. These findings mean energy poverty could reduce the likelihood of owning a home and transitioning from renting to homeownership [55]. This also relates to what Best et al. [15] describe as the wealth effects on household solar-panel uptake, highlighting the growing gap between the lowest and highest household financial quartiles. Additionally, drawing from 167 studies on solar energy adoption, Best et al. [13] elucidated that about 25 % of previous studies explicitly raised the issue of equity, equality, or justice among households. Therefore, it is critical to increase the adoption of solar panels to reduce the average energy bills paid by households. When the electricity price falls, a solar consumer might consume more electricity than before – a solar rebound effect [62]. Agnew et al. [1], therefore, call for the massification of solar uptake and battery adoption to help minimise energy-related housing expenses and ease the growing pressure on the electricity grid partially caused by the solar rebound effect.

Government policies, including subsidies, rebates, and loan programs, also play a crucial role in promoting renewable energy adoption. Studies in various countries, including Germany, the Netherlands, China, Japan, the United Kingdom, the United States, and Australia, demonstrate the effectiveness of financial incentives such as auction systems and solar feed-in tariffs in promoting household solar uptake to meet the government's initial target [35,42,47,52,54,74,82,84]. The role of financial incentives in solar adoption is also echoed by Crago and Chernyakhovskiy [26], who recorded that an additional $1 per watt rebate will increase annual PV capacity by approximately 50 %. Therefore, economic and financial incentives are critical in promoting solar panel uptake among households [65,81]. Carattini et al. [20] pointed out the importance of amending municipal building codes to integrate and promote solar installations in residential construction to achieve the desired outcome in a decentralised political system.

Moving forward, new ideas and strategies are needed to encourage broader solar PV updates, especially given the regressive nature of funding for solar. Government rebates to promote domestic solar uptake tend to benefit owner-occupiers, not renters, who comprise the majority of 'hardship customers' of energy retailers. In order to assist renters, Dodd and Nelson [30] suggest that a not-for-profit could deploy rooftop solar for hardship renters and divide the benefits between the landlord (a $1000 payment) and the renter (who would receive the balance of the solar offset). This could be an additional approach to deal with the regressive nature of current solar PV rebates for panels and batteries. Other approaches include using software to allow solar households to sell excess electricity to non-solar households [51], and community solar banks, that allow low-income households and renters to benefit from a solar farm located elsewhere [43]. However, Zou et al. [87] stop short of solar retrofitting for rental properties and apartment buildings, because of physical, economic and social challenges. Instead, they advocate mandatory inclusion of solar on new and substantially renovated houses and new apartment buildings. Rather than waiting for substantial development applications to trigger conversion from gas hot water and cooking to electric (and by implication, encouraging rooftop solar uptake as well), Wood et al. [77] would legislate long-term end-dates for the sale of gas appliances, grant instant asset write-offs for landlords that replaced gas appliances with electric, provide better information for renters and landlords about energy upgrades, and phase in dates by which rental properties must be all-electric.

In reviewing the literature, the increasing energy demand, and rising climate change concerns, renewable energy systems have become critical in transitioning to low-carbon and sustainable systems [2]. As recently argued by Schuetz [67], there is a research gap in the urban economics literature on the link between housing decisions and climate change, which could inform the timely formulation of policies. Several studies have examined the drivers of solar uptake decisions [29,76,83], the nexus between rising energy bills and the adoption of renewable energy [27,36], and the varying legislations and policies that seek to improve solar and battery adoption [42,47,80]. However, these studies have not examined the interplay between housing affordability and renewable energy adoption. Additionally, existing studies often neglect a comprehensive analysis of a panel context with a time dimension. Our research addresses these gaps by incorporating housing and rental affordability as a central factor, using longitudinal panel data to capture broader trends and behaviours across different postal areas.

3. Empirical estimation strategies

3.1. The models

To examine solar panel uptake, we employ a panel data fixed effects regression model, which accounts for unobserved effects that may correlate with explanatory variables. We analyse the number of solar installations and solar system capacity separately at the postcode level. Since the number of installations is a count variable, we employ count regression models [e.g., [39,65]], specified as follows:

$$INS_{it} = \exp(+\beta_1 Affordability_{it} + X_{it} + \gamma_i + \delta_t) + \mu_{jt}. \tag{1}$$

where INS_{it} denotes the number of small-scale solar panel installations in postcode i at month t. $Affordability_{it}$ represents a set of affordability measures for postcode i at month t, including price-to-income, price-to-rent, and rent-to-income ratios. X_{it} includes a set of key market determinants that may affect solar panel uptake, such as solar installation cost, electricity prices, and feed-in tariffs. γ_i controls for the postcode fixed effect, capturing time-invariant local characteristics; δ_t captures year and seasonal fixed effect, accounting for temporal trends. μ_{jt} is the error term. Standard errors are robust and clustered by postcodes.

The equation is first estimated using a Poisson regression, assuming that INS_{it} follows a Poisson distribution. However, if overdispersion is detected, i.e., the variance of INS_{it} exceeds its mean, the standard Poisson assumption is violated. In such cases, we use Negative Binomial Maximum Loglikelihood (NB ML) and Negative Binomial Quasi-Maximum Loglikelihood (NB QML) models as alternatives to relax the overdispersion restriction and the distributional assumption of INS_{it} in the Poisson regression. To avoid potential multicollinearity among the affordability measures, we include them one at a time in the regression analysis.

For the installed solar system capacity, the distribution of capacity observations piles up at zero, which clearly cannot have a conditional normal distribution. For this reason, we employ a censored regression model specified as follows:

$$\ln(CAP_{it}) = \beta_0 + \beta_1 Affordability_{it} + X_{it} + \gamma_i + \delta_t + \epsilon_{jt}. \tag{2}$$

Where CAP_{it} is the sum of small-scale solar system capacity installed in postcode i at month t, and ϵ_{jt} is the error term assuming following a normal distribution with a mean of zero and constant variance. All other variables are defined as in Eq. (1).

Eq. (2) is estimated using a Tobit model, which is suitable for dealing with censored data. Note that the Tobit model estimates the relationship for the latent $CAP_{it}*$, not the observed CAP_{it}. The Tobit coefficients reflect both the possibility of being uncensored and the expected value of CAP_{it} when uncensored. For comparison purposes, we also estimate a linear Ordinary Least Squares (OLS) model. OLS regressions are applied to both the full sample and a restricted subsample that excludes zero-capacity observations. While OLS regression may produce biased estimates in the presence of censoring, it still might be a good approximation for the marginal effects, especially when censoring is not severe, and covariates are centred around their mean [79].

By employing postcode fixed effects in the panel regression, we aim to produce a consistent estimator by removing unobserved locational amenities, housing types (e.g., freestanding vs. apartments), roof suitability, and demographic factors that remain relatively stable within each postcode over time. Time-fixed effects are included to account for broader economic and environmental conditions, such as inflation, weather patterns, and seasonal variations (e.g., December or January effects). Compared to random effect models, the fixed effect model is preferred, as unobserved postcode characteristics such as locality attributes and demographic factors are likely correlated with affordability measures in our analysis. Unlike studies that include postal socioeconomic or demographic factors in cross-sectional analyses of solar panel diffusion [e.g., [48,85]], we address the time-varying affordability issues using a panel data time series approach, where we rely on postcode fixed effects to account for the slowly evolving demographic characteristics in our analysis. Other influences—such as peer or neighbour effects [38,57], marketing or information campaigns [63], and limits imposed by network companies across suburbs—are generally delineated by postcodes and will be controlled for using postcode fixed effects.

Endogeneity due to reverse causality—where solar adoption may influence housing prices through green premiums—is unlikely to pose a significant concern in this study. This is because it typically takes several months or even years for dwellings with new solar installations to be sold and reflected in market prices. As a result, our housing affordability metrics are implicitly lagged in time relative to the solar PV adoption data observed in the same month, which helps mitigate concerns about reverse causation. Similar considerations have been adopted in prior studies, such as Best et al. [10], which employ explicit lagged variables to address potential endogeneity.

Finally, to account for potential dependence among observations within the same postcode, we cluster the standard errors at the postcode level, allowing for possible serial correlations over time within each postcode. In addition, we employ robust standard errors to further address potential misspecification of the variance and distributional assumptions in the analysis [e.g., [19]].

4. Data

4.1. Data of small-scale solar panel systems and selected sample period

Monthly aggregated postcode data for small-scale solar photovoltaic (PV) systems (<100 kW), including installation numbers and capacity, are sourced from the CER. As the PV postcode data for small-scale installations under 15 kW is not available, this represents a limitation in our study. However, according to the national data from the Australian Photovoltaic Institute, among the total number of small-scale installations between 2007 and 2024, 87 % of installations were under 15 kW [9]. Therefore, we use CER's small-scale installation and capacity data as a proxy for residential rooftop solar systems at the postcode level.[1]

Our sample period spans from January 2013 to April 2024. A State-level feed-in-tariff scheme had been influential on solar uptake before 2013. However, during the sample period, the Australian Government's SRES was the only enduring and broadly based (not means-tested) regulatory incentive for solar uptake applicable in Sydney. The feed-in-tariff was much lower, reflecting the transition of solar uptake from being driven by government subsidy (the pre-2013, legislated, high feed-in-tariff) to uptake driven by market forces [see discussions in [59,60]]. April 2024 represents the most recent data available at the time of this research.

We focus on the Sydney metropolitan area, comprising 30 local government areas (LGAs), excluding the Blue Mountains, Hawkesbury, and Wollondilly, with a population of approximately 5.12 million. As the capital of New South Wales (NSW) and Australia's largest city, Sydney offers a representative context for examining solar uptake driven primarily by market forces rather than government subsidies. More importantly, Sydney's ever-worsening housing affordability makes it an ideal case for studying the interaction between solar adoption and housing affordability. This enables our findings to be generalised to other modern cities worldwide that face similar urban challenges in their clean energy transitions.

In total, the dataset includes 225 postcodes over 136 months, yielding 30,600 panel observations. Fig. 1 illustrates the average number of solar PV installations and their capacity across postcodes in the Sydney metropolitan area. Figure (a) shows the spatial distribution of solar installations, indicating most of the solar adoption occurred in the western suburbs of Sydney, while system capacity was distributed consistently except for a few hotspots across the area. Figure (b) shows a rapid increase in both the number of installations and total capacity from 2013 to 2020, followed by a plateau with significant seasonal fluctuations from 2020 onwards.

4.2. Cost of the solar power systems, feed-in tariffs and electricity prices

Data on the installation costs of typical solar power systems in Sydney are sourced from Solar Choice, which publishes the Solar Price Index (SPI), utilised by both the Australian Government and Bloomberg NEF. The SPI measures the cost of solar systems on a per-watt basis ($/W), factoring in up-front incentives such as STCs. The SPI data are available monthly from August 2012.

Information on solar feed-in tariffs in NSW is obtained from reports by the Independent Pricing and Regulatory Tribunal (IPART). During the study period, NSW had no legislated minimum feed-in tariff, allowing electricity retailers to set their rates. However, IPART provides an annual benchmark for feed-in tariffs, which is used in our analysis.

Electricity price data for NSW is sourced from IPART and Ausgrid. Prior to 2014, IPART regulated electricity prices for government retailers. After 2014, we use the median household electricity bills reported by Ausgrid to estimate electricity prices. The electricity price data are indexed annually from 1999.

The data are interpolated at monthly intervals and matched with the solar PV installation dataset from the CER. Fig. 2 illustrates trends in solar system costs, feed-in tariffs, and electricity prices in Sydney and NSW, showing a continuous decline in solar system costs, a significant rise in electricity prices, and fluctuating feed-in tariffs ranging from 5 to 13 cents per kWh during the study period.

[1] Although the Australian PV Institute (APVI) publishes monthly postcode-level installation data by installation size, system capacities are grouped into broad categories rather than provided as continuous numerical values. As a result, we adopted the CER data in this study.

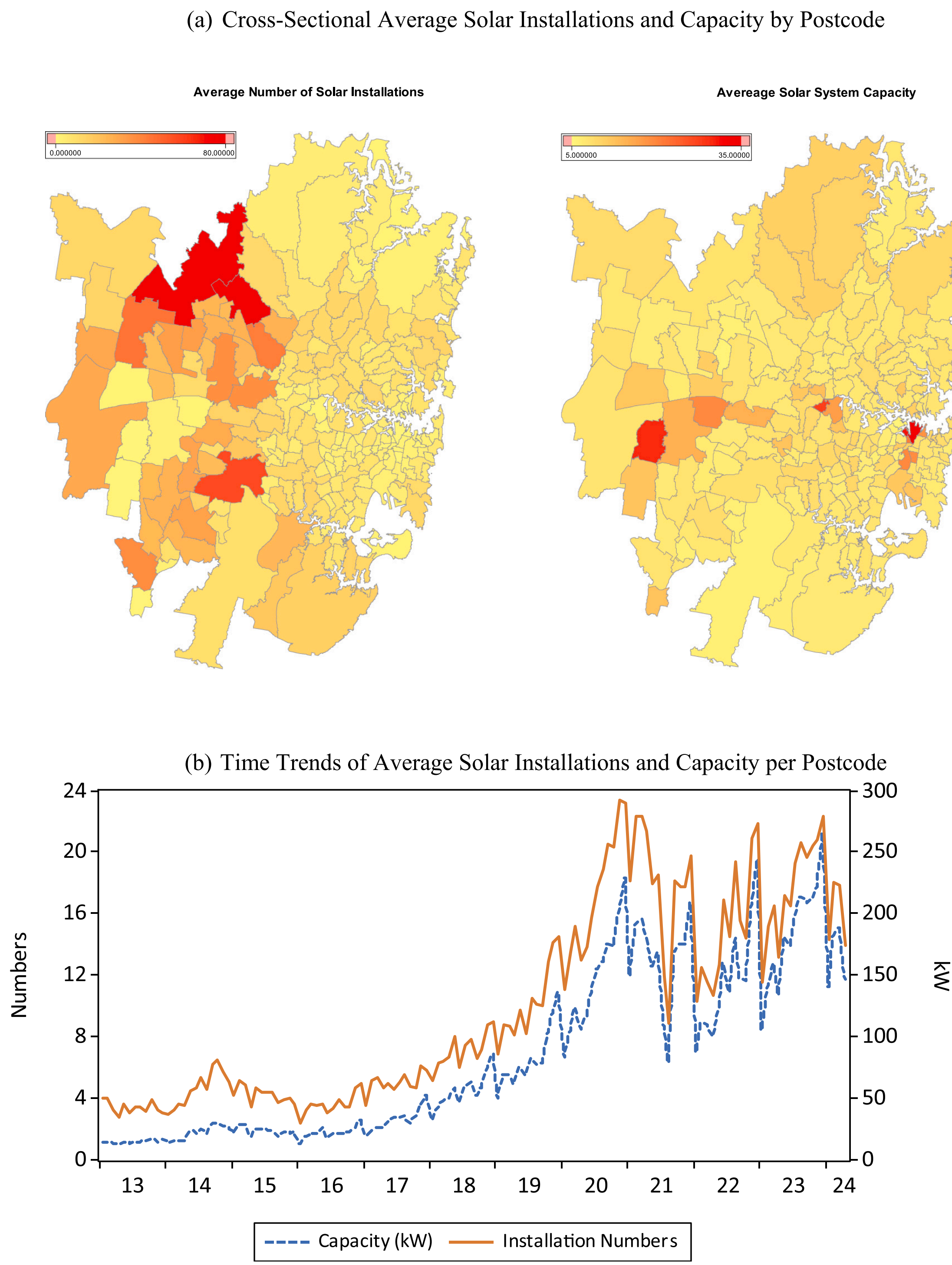

Fig. 1. Solar installations and capacity across Sydney postcodes. This figure displays the monthly average number and capacity of small-scale solar panel installations at the postcode level in the Sydney metropolitan area, shown both cross-sectionally (Fig. 1(a)) and over time (Fig. 1(b)) during the sample period from January 2013 to April 2024.

4.3. Measures of housing and rental affordability

Housing-related affordability is measured at the postcode level using three ratios: 1) price-to-income ratio, calculated as median house prices divided by median annual household income, 2) price-to-rent ratio, measured by median house prices divided by median annual rent, and 3) rent-to-income ratio, derived as median house rents divided by median annual household income. The first two ratios are commonly used to evaluate housing affordability, while the third is typically used to assess rental affordability. Although widely adopted in housing literature, these metrics technically reflect levels of unaffordability.[2]

[2] When these ratios are high, it generally implies that a significant portion of household income is devoted to mortgage or rent payments, which may reduce a household's capacity to invest in rooftop solar. However, we acknowledge that in some higher-income or affluent areas, this interpretation may not necessarily signal housing-related financial hardship.

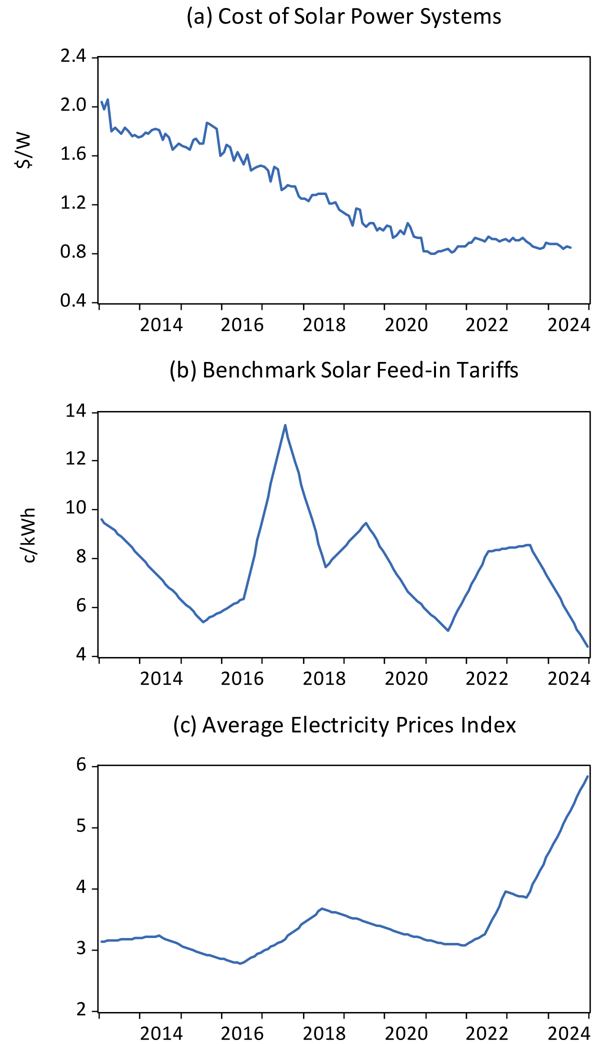

Fig. 2. Market factors affecting the rooftop solar panel uptake. Fig. 2(a) is sourced from Solar Choice Price Index for Sydney, Fig. 2(b) is sourced from the annual IPART reports in NSW, and Fig. 2(c) is sourced from the published IPART electricity prices in NSW.

Postcode-level median house prices and rents are sourced from CoreLogic, while median household incomes are obtained from the 2011, 2016, and 2021 Census data. These census data are interpolated to a monthly frequency and matched with the solar PV installation dataset from the CER. To minimise the influence of outliers, the affordability measures are winsorised at the 1st and 99th percentiles of the dataset.

Fig. 3 illustrates the trends and cross-sectional distributions of housing and rental affordability within the Sydney metropolitan area over the study period. Figure (a) shows that housing affordability remains a significant concern, with the price-to-income ratio at approximately 16.8 and the price-to-rent ratio at 41.8 in 2024. Meanwhile, rental affordability, as measured by the rent-to-income ratio, remained relatively stable before the COVID-19 pandemic at around 0.36, dipped to 0.32 during the pandemic, and has since rebounded sharply, surpassing pre-pandemic levels to reach 0.39 in 2024. Figure (b) presents the spatial distribution of housing and rental affordability, highlighting that affordability challenges are widespread, particularly severe and concentrated in Sydney's coastal and eastern suburbs.

4.4. Summary statistics

Table 1 summarises the key variables used in this research. On average, each postcode records 9.82 installations per month, with a total capacity of 83.31 kW per month over the study period, equating to approximately 8.5 kW per installation. If we calculate the average capacity per installation for each postcode and then take the mean of these averages, the result is 5.6 kW per installation, which aligns with the typical 6.6 kW residential solar system size in the Sydney market. The average cost of a solar power system is $1.28 per watt, the electricity price index stands at 3.33, and the average feed-in tariff is 7.85 cents per kWh. Median house prices are AUD 1.33 million, with median weekly rents at AUD 660, and median weekly household incomes at AUD 2048. The average price-to-income ratio is 13.95, the price-to-rent ratio averages 38.97, and the rent-to-income ratio averages 0.35. There is substantial variation across postcodes, with price-to-income ratios ranging from 5.00 to 35.97, price-to-rent ratios spanning from 19.74 to 88.02, and rent-to-income ratios varying from 0.21 to 0.64, reflecting significant heterogeneity in affordability across the Sydney metropolitan area.

5. Results and discussion

5.1. Key market determinants on solar panel uptake

Table 2 presents the baseline panel regression results for the number of solar panel installations, highlighting the key market factors influencing household decisions on rooftop solar uptake, as specified in Eq. (1). Column (1) reports the results from the Poisson regression, Column (2) shows results from the Negative Binomial Maximum Likelihood (NB ML) model, and Column (3) presents results from the Negative Binomial Quasi-Maximum Likelihood (NB QML) model.

In Column (1), the Poisson regression results indicate that a 10 % increase in solar installation costs reduces the number of installations by 8.84 %, while a 10 % increase in electricity prices increases installations by 8.86 % on average at the postcode level.[3] Feed-in tariffs, however, are statistically insignificant. For the Poisson model to be valid, it requires that both the conditional mean function is correctly specified, and the conditional distribution follows a Poisson process. This implies equality between the conditional mean and variance, an assumption often violated in empirical data. To test for overdispersion, we employ the Wooldridge [78] test, regressing the squared standardised residuals minus one on the predicted number of installations. The resulting coefficient of 0.0752 (standard error = 0.0034) is statistically significant, indicating that the variance exceeds the mean and confirming the presence of overdispersion.

To address this, Column (2) reports results from the NB ML model, which relaxes the restrictive Poisson assumption by allowing the variance to exceed the mean. Here, a 10 % increase in installation costs reduces the number of installations by 6.69 %, while a 10 % increase in electricity prices leads to a 10.43 % increase in installations, on average. Compared to the Poisson model, the NB ML results suggest a slightly lower sensitivity to installation costs but a stronger response to electricity prices.

Column (3) presents the results of the NB QML model, using the fixed overdispersion parameter of 0.0752 identified in the Poisson regression. The advantage of the QML approach is that it yields consistent parameter estimates as long as the conditional mean is correctly specified, even if the distributional assumption is violated. The NB QML results closely align with those of the NB ML model, reinforcing the robustness of the findings and supporting the use of the NB ML model in this context as suggested by San-Martin and Elizalde [65].

Table 3 presents the results for solar system capacity using both Tobit and OLS regression models. The dependent variable is the log of monthly installed solar system capacity at the postcode level. The logarithmic

[3] The proportionate change for an 10 % increase in solar installation costs is calculated as: exp.(−0.9251*0.1)-1 = −0.0884, say −8.84 %; while the proportional change for an 10 % increase in electricity prices is estimated as: exp.(0.8490*0.1)-1 = 0.0886, say 8.86 %.

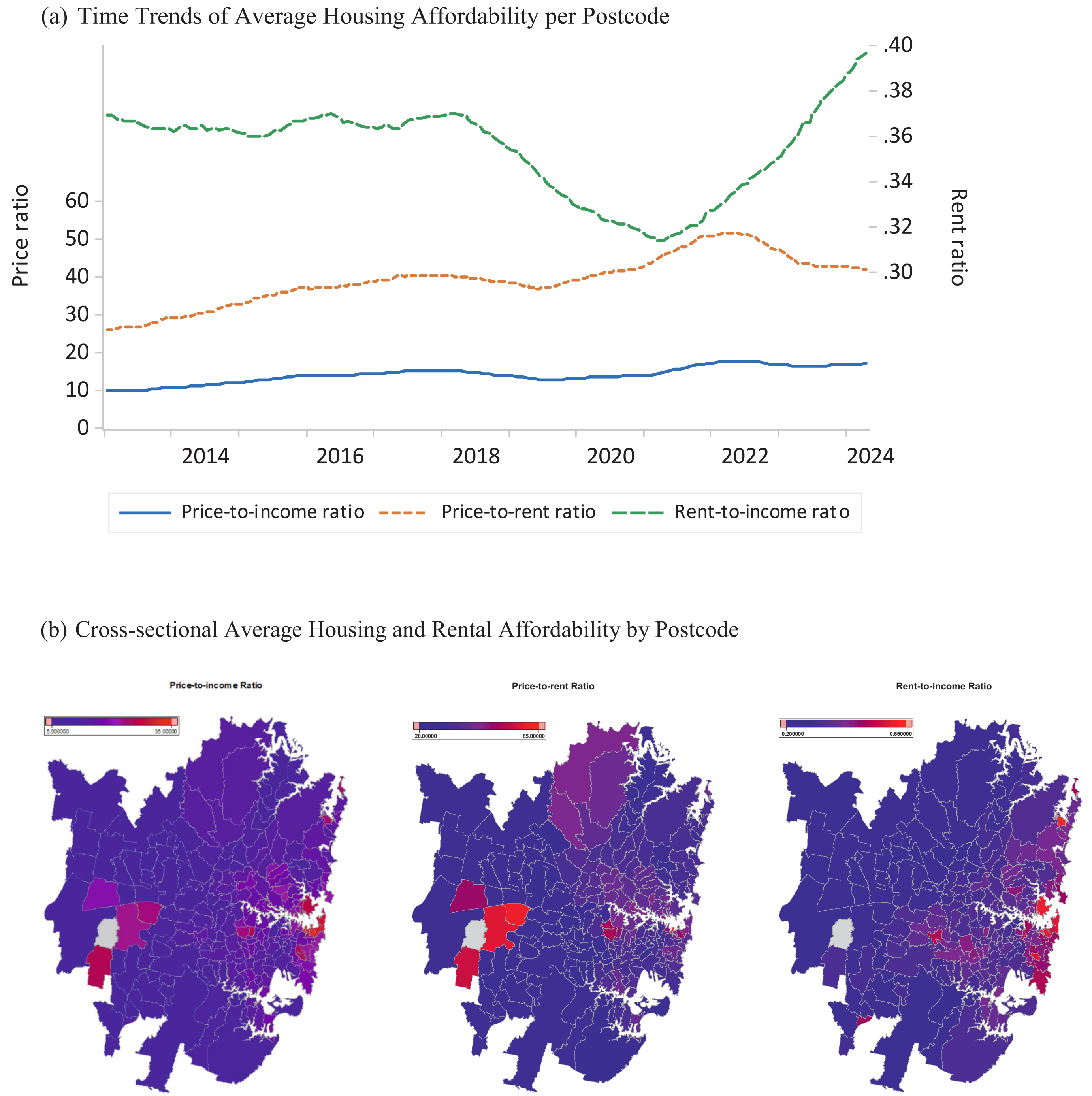

Fig. 3. Housing and rental affordability over the sample period. This figure displays the monthly average housing-related affordability, measured by the price-to-income, price-to-rent, and rent-to-income ratios, at the postcode level in the Sydney metropolitan area during the sample period from January 2013 to April 2024. Fig. 3 (a) shows the trends of average monthly housing affordability over time and Fig. 3 (b) presents the cross-sectional distributions across postcodes.

transformation helps approximate a normal distribution for the dependent variable which is necessary for both the Tobit and OLS models.

Column (1) shows the results from the Tobit regression. We find that solar installation costs are negatively associated with solar system capacity, while electricity prices are positively related to the installation capacity. Both relationships are statistically significant at the 1 % level. Meanwhile, solar feed-in prices are statistically insignificant. Since the estimated coefficients in the Tobit model cannot be interpreted directly as marginal effects, we use the method suggested by Wooldridge [79] to estimate these effects. The results indicate that a 10 % increase in solar installation costs would reduce capacity by approximately 8.5 %, while a 10 % increase in electricity prices would increase capacity by approximately 13.5 %. The marginal effect for feed-in prices is −0.0094, which is negligible.

For comparisons, Column (2) presents the OLS results using the full sample (all observations). The OLS estimates are very similar to the Tobit estimates in Column (1), indicating that the impact of zero-capacity installations is minimal in this study. However, the OLS model underestimates the impact of solar installation costs and more accurately estimates the impact of electricity prices. Column (3) presents

Table 1
Summary statistics.

	Mean	Median	Maximum	Minimum	Std. Dev.	Observations
Installation Numbers	9.82	4.00	286.00	0.00	16.82	30,600
Capacity (kW)	83.31	29.21	3293.35	0.00	157.75	30,600
Cost of the Solar Power Systems ($/W)	1.28	1.22	2.06	0.80	0.38	30,600
IPART Electricity Price Index	3.33	3.20	4.94	2.77	0.42	30,600
IPART Solar Feed-in Prices (c/kWh)	7.85	7.82	13.45	5.05	1.77	30,600
Median House Prices (AUD)	1,550,049	1,335,000	5,345,000	411,000	921,757	30,029
Median Weekly Rents (AUD)	730	660	1698	380	268	30,030
Median Weekly Households Income (AUD)	2074	2048	3481	1024	541	30,464
Price-to-income Ratio	13.95	13.11	35.97	5.00	5.96	29,893
Price-to-rent Ratio	38.97	36.88	88.02	19.74	12.08	29,690
Rent-to-income Ratio	0.35	0.34	0.64	0.21	0.09	29,923

This table presents summary statistics of key variables for the analysis in this study. The panel contains 225 postcodes and 136 months, total 30,600 observations over the sample period from January 2013 to April 2024.

Table 2
Results for the number of installations.

	(1)		(2)		(3)	
	Poisson		NB ML		NB QML	
Log of Solar Installation Cost ($/W)	−0.9251	***	−0.6923	***	−0.7105	***
	(0.0766)		(0.0863)		(0.0846)	
Log of Electricity Prices Index	0.8490	***	0.9918	***	0.9875	***
	(0.0807)		(0.0823)		(0.0819)	
Log of Solar Feed-in Prices (c/kWh)	−0.0587		−0.0349		−0.0369	
	(0.0425)		(0.0409)		(0.0406)	
Constant	−2.4238	***	−2.7605	***	−2.7421	***
	(0.1319)		(0.1242)		(0.1258)	
Adjusted R-squared	0.8756		0.8450		0.8472	
AIC	5.1253		4.7731		4.7768	
Log likelihood	−78,167		−72,778		−72,835	
Panel observations	30,600		30,600		30,600	
Number of Postcodes	225		225		225	
Postcode FE	Yes		Yes		Yes	
Seasonal FE	Yes		Yes		Yes	
Year FE	Yes		Yes		Yes	

This table presents the baseline panel regression results assessing key market determinants influencing the number of small-scale solar PV installations in the Sydney metropolitan area from January 2013 to April 2024. The dependent variable is the number of installations at the postcode level. Column (1) reports results from the Poisson regression, Column (2) from the Negative Binomial Maximum Likelihood (NB ML) model, and Column (3) from the Negative Binomial Quasi-Maximum Likelihood (NB QML) model. Standard errors are shown in parentheses and are robust, clustered by postcode. Significance levels:
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

Table 3
Results for the solar system capacity.

	(1)		(2)		(3)	
	Full sample		Full sample		Capacity >0	
	Tobit		OLS		OLS	
Log of Solar Installation Cost ($/W)	−0.8580	***	−0.7292	***	−0.5519	***
	(0.1555)		(0.1331)		(0.1090)	
Log of Electricity Prices Index	1.3652	***	1.3614	***	1.2539	***
	(0.1615)		(0.1479)		(0.1217)	
Log of Solar Feed-in Prices (c/kWh)	−0.0095		−0.0371		−0.1027	*
	(0.0762)		(0.0672)		(0.0556)	
Sigma (σ)	0.9898	***				
	(0.0308)					
Constant	−2.6063	***	0.4412	**	1.0217	***
	(0.2393)		(0.2109)		(0.1609)	
Adjusted R-squared			0.7364		0.7509	
AIC	2.7399					
Log likelihood	−41,670					
Panel observations	30,600		30,600		26,763	
Number of Postcodes	225		225		225	
Postcode FE	Yes		Yes		Yes	
Seasonal FE	Yes		Yes		Yes	
Year FE	Yes		Yes		Yes	

This table presents the baseline panel regression results assessing key market determinants influencing the capacity of small-scale solar PV installations in the Sydney metropolitan area from January 2013 to April 2024. The dependent variable is the log of installation capacity at the postcode level. Column (1) reports results from the Tobit regression, Column (2) from the OLS model using all observations, and Column (3) from the OLS model excluding zero-capacity observations. Standard errors are shown in parentheses and are robust, clustered by postcode. Significance levels:
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

the OLS results using the subsample, which excludes observations with zero capacity. Compared to both the Tobit and full-sample OLS models, the subsample results substantially underestimate the impact of solar installation costs on capacity, and slightly underestimate the positive impact of electricity prices.

Overall, results from Tables 2 and 3 align with market expectations. Lower solar installation costs lead to higher demand for rooftop solar systems, while higher local electricity prices increase demand for solar installations. Since solar feed-in tariffs in NSW were market-determined during the study period, households may have focused less on maximising electricity generation for sale and more on aligning solar system size with their daytime energy needs. In many cases, the optimal strategy is to optimise self-consumption of solar power rather than rely on feed-in tariffs for additional income. Given this self-consumption approach, feed-in tariffs became less significant in household decision-making. Theoretically, the optimal point for solar installation is reached when the marginal cost of adding extra panels equals the marginal savings in electricity. This helps explain why solar system capacity is more sensitive to changes in costs and electricity prices than the number of installations.

5.2. *Affordability and solar panel uptake*

In addition to market determinants, we explore the influence of housing and rental affordability on household decisions regarding solar panel uptake. Affordability is particularly relevant in the clean energy transition, especially given the high upfront costs associated with installing rooftop solar panels. Property owners must consider both their ability to service their property and invest in it. Renters also play a role in the energy transition, as their demand for solar energy could encourage market responses.

To examine this, we use three affordability ratios. For property owners, we employ the price-to-income and price-to-rent ratios, which reflect both their affordability to service their property (e.g., maintenance, insurance, council rates, mortgage payments), and the influence of investment demand and speculative activities [e.g., [32,33,41,68–70]]. The price-to-rent ratio is also commonly used to assess households' tenure choices between owning and renting, where rent serves as a proxy for a homeowner's user costs of ownership [17,40,61]. Lastly, the rent-to-income ratio measures rental affordability for renters.

Table 4 presents the results of our analysis on the effect of affordability on solar uptake, based on a negative binomial maximum likelihood regression. Column (1) indicates that the price-to-income ratio is statistically significant at the 1 % level and negatively correlated with the number of installations. Specifically, a 10 % increase in the price-to-income ratio leads to an 8.39 % decrease in installations. Column (2) reveals that the price-to-rent ratio is also statistically significant and negatively related to installations, with a 10 % increase resulting in a 6.91 % decrease. In Column (3), the rent-to-income ratio is negatively associated with solar uptake but is statistically insignificant. Since the price-to-income, price-to-rent, and rent-to-income ratios reflect housing unaffordability, these findings suggest that solar panel uptake is positively associated with housing affordability (i.e., when housing is more affordable—such as when the price-to-income ratio is low—solar uptake is higher), while rental affordability has little effect. As housing becomes less affordable, fewer households are likely to adopt rooftop solar panels and engage in clean energy initiatives. Among the price-to-income and price-to-rent ratios, the price-to-income ratio appears to have a stronger influence on homeowners' decisions regarding solar panel adoption.

Table 4
Housing affordability and solar panel uptake.

	*(1)		**(2)		(3)	
	NB ML		NB ML		NB ML	
Log of Solar Installation Cost ($/W)	−0.4270	***	−0.5597	***	−0.6660	***
	(0.1135)		(0.0973)		(0.0939)	
Log of Electricity Prices Index	0.7535	***	0.6084	***	1.0834	***
	(0.1095)		(0.1365)		(0.1059)	
Log of Solar Feed-in Prices (c/kWh)	−0.0094		−0.0151		−0.0351	
	(0.0429)		(0.0415)		(0.0413)	
Log of Price-to-income Ratio	−0.8762	***				
	(0.2336)					
Log of Price-to-rent Ratio			−0.7159	***		
			(0.1878)			
Log of Rent-to-income Ratio					−0.3493	
					(0.3064)	
Constant	1.3130		0.0365		−3.1264	***
	(0.5023)		(0.6670)		(0.3730)	
Adjusted R-squared						
AIC	4.8279		4.8407		4.8220	
Log likelihood	−71,910		−71,609		−71,894	
Panel observations	29,893		29,690		29,923	
Number of Postcodes	223		224		223	
Postcode FE	Yes		Yes		Yes	
Seasonal FE	Yes		Yes		Yes	
Year FE	Yes		Yes		Yes	

This table presents the regression results assessing the influence of housing-related affordability on the number of small-scale solar PV installations in the Sydney metropolitan area from January 2013 to April 2024. The dependent variable is the number of installations at the postcode level. The regression is estimated by the Negative Binomial Maximum Likelihood (NB ML) model. Housing affordability is measured by the price-to-income and price-to-rent ratios, while rental affordability is captured by the rent-to-income ratio. Standard errors are shown in parentheses and are robust, clustered by postcode. Significance levels:
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

Table 5 presents the results of affordability on solar system capacity. Panel A presents the Tobit results based on the full sample, and Panel B presents the OLS results based on the subsample, where capacity is greater than zero. The estimated marginal effect for the price-to-income ratio in Column (1) is −0.535, indicating that a 10 % increase in the price-to-income ratio results in a 5.35 % decrease in installation capacity.[4] The marginal effect for the price-to-rent ratio in Column (2) is −0.395, meaning that a 10 % increase in the price-to-rent ratio leads to a 3.95 % decrease in capacity. Column (3) shows that the rent-to-income ratio has little impact on solar installation capacity. These results are supported by the OLS regression in Panel B, which shows smaller coefficients compared to the Tobit model.

The difference in the magnitudes of affordability coefficients between Table 4 and Table 5 reflects the nature of household decisions: first, whether to adopt solar panels, and second, if so, what size of solar system to install. Our results suggest that housing affordability, plays a significant role in the decision to install solar panels. However, once the decision to adopt solar is made, affordability appears to have less impact on the size of the solar system chosen. Although household wealth has been found positively related with both uptake and size decisions of solar adopters [15,16], it could be that the system size is more influenced by economic and operational factors, such as optimal size, payback period, available roof space, and household-specific energy demand.

5.3. Policy implications

Our empirical findings demonstrate that housing affordability is a key determinant in household decisions regarding rooftop solar uptake, in addition to the cost of solar installations and electricity prices. Specifically, higher price-to-income and price-to-rent ratios are significantly associated with reduced solar adoption, suggesting that affordability constraints serve as a substantial financial barrier. In contrast, rental affordability as measured by the rent-to-income ratio has little impact. This suggests that housing affordability not only limits property owners' ability to invest in solar systems but also exacerbates inequities in access to clean energy, particularly between property owners and renters.

Given that housing affordability challenges are structural in nature and unlikely to be resolved through short-term market adjustments, a targeted policy intervention is warranted. To address this, we propose a 'Use it or Lend it' solar access scheme as a viable strategy to overcome affordability barriers and expand solar participation. The proposal is similar to the 'shared value' model of Dodd and Nelson [30], under which both landlords and tenants benefit financially from rooftop solar installations carried out by a third party (such as a not-for-profit).

Under this scheme, owners of detached and semi-detached houses would have the option to permit the government to install and operate solar panels on their rooftops (opt-out). Owners who opt out would retain full ownership of their property while receiving compensation in the form of financial incentives or annual lease payments for allowing public use of their rooftop space. They would also face no upfront or maintenance costs, as the installation, upkeep, and insurance of the system would be fully managed by the government or accredited third-party providers. Crucially, property owners would retain the flexibility

[4] To calculate the marginal effect in the Tobit model, we followed the Wooldridge [79] (pp. 600) to calculate the adjusted factor.

Table 5
Housing affordability and solar system capacity.

	(1)		(2)		(3)		(4)		(5)		(6)	
	Panel A: Full sample (Torbit)						Panel B: Capacity > 0 (OLS)					
Log of Solar Installation Cost ($/W)	−0.6959	***	−0.8274	***	−0.8598	***	−0.4167	***	−0.4979	***	−0.5341	***
	(0.1663)		(0.1620)		(0.1569)		(0.1231)		(0.1132)		(0.1132)	
Log of Electricity Prices Index	1.1700	***	1.0717	***	1.3503	***	1.1288	***	1.0826	***	1.3137	***
	(0.1652)		(0.1775)		(0.1671)		(0.1358)		(0.1508)		(0.1378)	
Log of Solar Feed-in Prices (c/kWh)	−0.0211		−0.0089		−0.0175		−0.0891		−0.0862		−0.1003	*
	(0.0751)		(0.0759)		(0.0755)		(0.0564)		(0.0562)		(0.0558)	
Log of Price-to-income Ratio	−0.5380	**					−0.4732	**				
	(0.2177)						(0.2122)					
Log of Price-to-rent Ratio			−0.3968	**					−0.3135	**		
			(0.1901)						(0.1512)			
Log of Rent-to-income Ratio					−0.2062						−0.2301	
					(0.2299)						(0.2080)	
Sigma (σ)	0.9702	***	0.9599	***	0.9736	***						
	(0.0289)		(0.0283)		(0.0302)							
Constant	−0.8995		−0.7733		−2.7111	***	2.0849	***	2.1576	***	0.6991	**
	(0.5983)		(0.7186)		(0.3302)		(0.5044)		(0.5790)		(0.3448)	
Adjusted R-squared							0.7539		0.7550		0.7531	
AIC	2.7309		2.7159		2.7304							
Log likelihood	−40,567		−40,067		−40,600							
Panel observations	29,893		29,690		29,923		26,512		26,435		26,460	
Number of Postcodes	223		224		223		223		224		223	
Postcode FE	Yes		Yes		Yes		Yes		Yes		Yes	
Seasonal FE	Yes		Yes		Yes		Yes		Yes		Yes	
Year FE	Yes		Yes		Yes		Yes		Yes		Yes	

This table presents the regression results assessing the influence of housing-related affordability on the capacity of small-scale solar PV installations in the Sydney metropolitan area from January 2013 to April 2024. The dependent variable is the log of solar system capacity at the postcode level. Housing affordability is measured by the price-to-income and price-to-rent ratios, while rental affordability is captured by the rent-to-income ratio. Panel A shows the results from Tobit regression and Panel B presents the OLS results using a subsample excluding zero observation. Standard errors are shown in parentheses and are robust, clustered by postcode. Significance levels:

*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

to opt back in at any time, subject to the cost neutrality principle and pre-agreed terms. The 'use it or lend it' policy could be of particular benefit to hardship customers of energy retailers, who are predominantly renters.

To ensure feasibility and fairness, the program would include statutory safeguards covering roof integrity, property owner indemnity against potential damage, and strict regulation of third-party access. Each property's solar suitability would be assessed by accredited professionals, considering technical viability as well as property owner submissions (for example, planned redevelopment or renovations). Assessment findings would be made transparent via a public register, while privacy protections and access rights would be clearly defined in legislation.

This arrangement provides property owners with clear, risk-free benefits: guaranteed financial compensation without any responsibility for system maintenance or capital outlay, while maintaining full property rights. For the government, the electricity generated from opt-out systems can be allocated to benefit low-income households and renters, groups who face the greatest barriers to direct solar participation. This redistribution of clean energy supports greater equity in the clean energy transition and directly addresses the housing affordability barriers identified in our study.

The 'use it or lend it' approach would be based on rights and obligations set out under legislation, as would mandatory inclusion of solar on new and substantially renovated houses and new apartment buildings [87]. The former has the theoretical advantage of allowing a qualified entity to initiate the change ('lend it') at any time. The latter would force landowners to 'use it' (consistent with other legislated obligations on landowners), but the trigger (seeking development consent for substantial renovation or new dwellings) may be years, if not decades, away. Another trigger could be legislated deadlines [77].

6. Conclusion

This research provides valuable insights into the key market factors influencing household solar panel uptake in Australia. By using panel data over a 12-year period, we offer a more comprehensive analysis compared to studies relying solely on cross-sectional or survey data. Our findings underscore the significant role of solar installation costs and electricity prices in driving solar adoption, both in terms of the number of installations and capacity. However, we also find that feed-in prices have little impact on solar uptake.

Furthermore, we contribute to the existing literature by incorporating housing and rental affordability as critical determinants. Specifically, we show that owners' affordability is positively and statistically significantly associated with solar uptake, whereas renters' affordability has little effect. These results suggest that affordability constraints for property owners are hindering solar adoption, while renters face an additional inequity, with limited access to clean energy solutions.

Given that housing affordability is a complex, long-term issue and market forces alone may not resolve it quickly, we propose a 'Use it or Lend it' system as a potential solution. Under this scheme, owners of detached and semi-detached houses would have the option to allow the government to install solar panels on their rooftops if the property is deemed suitable after a solar assessment by an accredited assessor. This approach would help increase solar uptake, particularly among households or investors unable or unwilling to invest in solar systems themselves.

Future research could benefit from a deeper investigation into the heterogeneity of solar adopters, particularly using individual household-level data at the time of application. Such an approach would ensure that policy recommendations are tailored to meet the specific needs of various household groups. Moreover, future research could explore the relationship between housing affordability and solar PV adoption using a quasi-experimental design to enable more granular analysis—such as comparing high versus low feed-in tariff zones or thresholds—and to assess the effects of declining solar subsidies. This would provide deeper insights into household decision-making in the context of clean energy transitions.

Given the urgency of transitioning to renewable energy and the lost opportunity represented by suitable homes where owners have not adopted solar voluntarily, consideration should also be given to the institutional arrangements necessary for implementing a legislated scheme that grants the government default solar rights on suitable properties.

CRediT authorship contribution statement

Song Shi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mustapha Bangura:** Writing – review & editing, Writing – original draft, Conceptualization. **David Robinson:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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