Understanding the determinants of rooftop solar installation: evidence from household surveys in Australia[*]

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Australia is a world leader in household uptake of solar photovoltaic systems. In this paper, we use household-level data to identify economic, social, and environmental factors that influence actual uptake and the intention to install. We find that higher net wealth is generally associated with higher likelihood to install. Households that have mortgages, that spend more on electricity, and that pay higher average electricity prices are more likely to intend to install. Environmental preferences and related behaviours, property tenure, and space constraints are associated with both actual uptake and intention to install. We use data from the Survey of Income and Housing of 2015-16 and the Household Energy Consumption Survey of 2012.

Key words: debt preference, electricity price, household survey, net wealth, solar photovoltaic.

1. Introduction

At a global scale, net capacity additions of solar photovoltaic (PV) energy in 2017 exceeded net capacity additions of coal, natural gas, and nuclear power combined (REN21 2018). Rooftop solar helps households to substantially reduce their electricity bills, while also helping to avoid emissions from fossil fuel electricity generation. Uptake rates are increasing both in Australia and overseas. These features motivate study of factors affecting household rooftop solar uptake and intentions concerning future uptake.

Australia's rate of household solar PV uptake is among the highest in the world, with more than 20% of Australian households having rooftop solar PV panels in 2018 (OECD, Organization for Economic Cooperation and Development 2016; Australian PV Institute 2018). The speed of this uptake is evident in Figure 1, with small-scale solar capacity (systems of 6.5 kw and below) increasing from close to zero in 2010 to over five gigawatts in 2018, which is equivalent to approximately two large coal power plants. These
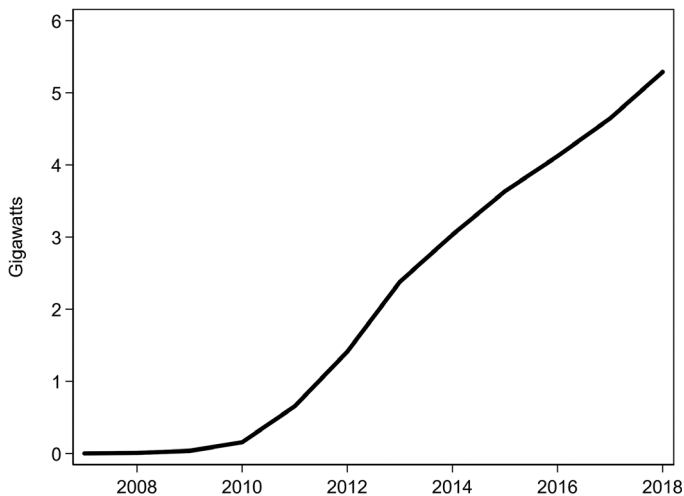

Figure 1 Total capacity of household solar photovoltaic systems of size 6.5 kilowatts and below, March 2007–March 2018. Based on Australian PV Institute (2018) data.

installations accounted for 68% of Australia's total solar PV capacity as of March 2018 (Australian PV Institute 2018). Most of this small-scale capacity has been installed by households.

In this paper, we seek to understand the economic, social, and environmental determinants of solar PV uptake across Australian households. We first focus on the impact of household net wealth. Despite the long history of analysis of wealth effects on total consumption (Cooper and Dynan 2016), the impact of capital constraints on solar uptake has been relatively understudied. Prior studies have focused on house values as a measure of capital, often at the regional level (Kwan 2012; De Groote *et al.* 2016). Kwan (2012) found a positive effect of median home value on solar PV uptake in the United States, while De Groote *et al.* (2016) found mixed results using cadastral income as a proxy for home value in Belgium. Financial capital has also been revealed to be an important determinant of solar use at the national level (Best 2017; Best and Burke 2018). A common challenge for incorporating wealth or capital variables is the availability of suitable household-level datasets.

We contribute to the literature by focusing on the influence of household net wealth on household-level solar panel installations and intentions to install. The net wealth measure encompasses all household assets and liabilities. We use data from two nationally representative household surveys, utilising samples of over 10,000 households. These samples are relatively large compared to previous studies (Balcombe *et al.* 2013). Our use of household-level data complements prior studies that have used data aggregated to the postcode or regional level (Kwan 2012; De Groote *et al.* 2016). Household-level data are advantageous, as the household is the decision-making unit of interest. Household data allow direct assessment of the impact of household

factors, and avoid potential aggregation biases that may emerge when using postcode-data or region-level data.

Another key contribution is that we use data about both actual solar uptake and households' *intention* to install solar PV in the future. Using the intention data allows us to include explanatory variables that would be inappropriate for explaining actual uptake, such as household expenditure on electricity. Household electricity expenditure would be subject to reverse causality if included in a study of factors affecting actual solar installations, because solar systems reduce ongoing electricity bills. This issue does not apply for the intention to install.

Our study includes broad coverage of other factors that may affect solar PV uptake. Environmental preferences may matter, although studies for other countries have found mixed results (Woersdorfer and Kaus 2011; Briguglio and Formosa 2017; Dharshing 2017). Households that adopt energy efficiency measures may also be more likely to install solar panels (Dato 2018). For instance, there could be a positive association between having home insulation or solar hot water systems and the intention to install solar PV. Larger houses that require more electricity, and larger households that consume more electricity may also be more likely to be adopters (De Groote *et al.* 2016; Sommerfeld *et al.* 2017a). In addition, property rights and space factors are likely to influence solar installation choices (Ameli and Brandt 2015; Karakaya and Sriwannawit 2015; Briguglio and Formosa 2017). There are also likely to be environmental effects, including greater solar PV adoption in climate zones that receive more solar irradiation, where more electricity can be generated for any given investment cost (Balta-Ozkan *et al.* 2015).

We also consider novel explanatory variables. These include debt preferences, as proxied by mortgages and the number of credit cards in each household. We also assess the possibility that prior experience with energy poverty affects solar panel installation intentions. Further, we explore the possibility that time constraints reduce solar uptake (Axsen *et al.* 2012), using both a direct survey question on time constraints as well as inferred time constraints based on the number of employed persons and dependent children in the household. We expect that reducing electricity bills is a primary motivator for installing rooftop solar PV, as suggested by survey results from Queensland (Sommerfeld *et al.* 2017b; Bondio *et al.* 2018). We empirically test this expectation using nationally representative surveys.

Our broad coverage of factors affecting variation across households adds to insights from other types of studies, such as analyses of temporal aspects of early adoption in innovation diffusion studies (Islam 2014; Graziano and Gillingham 2015). In contrast to the diffusion of innovation literature (which tends to focus on adoption over time, and on product characteristics), our focus is on socio-economic and environmental determinants leading to cross-sectional variation across households.

Our analysis of solar uptake may be relevant for other technologies. For instance, our results could be useful for understanding likely factors affecting

adoption rates of electric vehicles. The literature on electric vehicle adoption considers socio-economic factors, focusing on income as a measure of economic capability (Sierzchula *et al.* 2014; Hardman *et al.* 2016), similar to the solar literature. Our findings are also of potential use for understanding future patterns in household solar PV adoption in other countries. Australia's position as a world leader in rooftop solar means it is highly relevant for other countries, which are likely to experience increased adoption of small-scale solar panels over time.

2. Method and data

We use the logit model in equation (1) to model uptake and intention to install solar panels:

$$\ln [p/(1 - p)] = \alpha \ln W_h + \beta (\ln W_h)^2 + V_h^{'} \delta^{'} + \varepsilon_h. \qquad (1)$$

The dependent variable is the log of the odds of uptake of solar PV panels. The odds are the probability (p) of solar uptake divided by its complement ($1 - p$). We also use a similar dependent variable for households that *intended* to install solar panels within 12 months after the survey. We do not study factors affecting the size of installed systems. Standard errors use the observed information matrix for the variance-covariance matrix.

W is the net wealth of each household (h). Figure 2 shows the proportion of households with solar panels for each net wealth quintile. The squared net wealth term in equation (1) is useful to assess whether there are different marginal impacts of net wealth at the lower and upper ends of the distribution. It may be that rich households are less motivated by bill stress considerations, so the marginal effect of net wealth on solar uptake may decline as net wealth increases.

The V vector includes our other explanatory variables, which are defined in Appendix S1. Table 1 summarises the data for each of the two household surveys. The proportion of households with solar panels increased from 10% in the 2012 survey to 17% in the 2015–16 survey, as shown in the first row of Table 1. There were also increases in household net wealth and income. Table 1 also includes other variables such as preferences and behavioural tendencies. We use participation in a green power scheme as a measure of environmental preferences. Signing up to a green power scheme requires household action, indicative of 'engaged greens' (Axsen *et al.* 2012).

We include region fixed effects in the V vector to control for unobserved regional heterogeneity. These include state fixed effects to account for differing average electricity prices and feed-in tariffs across states. Figure 3 shows that Queensland (QLD) and South Australia (SA) have the highest small-scale solar uptake among Australian states and territories, including among the two smaller territories not shown. Figure 3 also shows that there are often larger proportions of households with solar panels in areas outside greater capital cities, although this is not the case in Western Australia (WA).
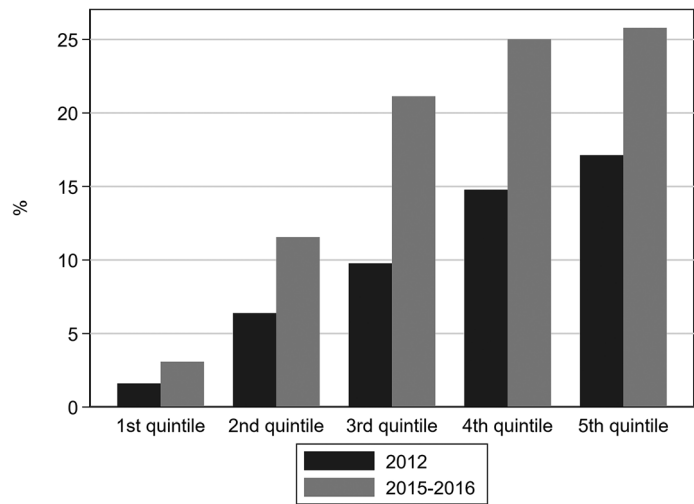
Figure 2 Proportion of households with solar panels in the 2012 Household Energy Consumption (HEC) survey and the 2015-16 Survey of Income and Housing (SIH) by net wealth quintile. The 5th quintile is the highest-wealth households. Based on Australian Bureau of Statistics data (ABS 2013, 2017).

We also control for capital city and state-capital interaction variables. These interaction variables help to control for policy differences across regions[1], as well as factors such as population density (Balta-Ozkan *et al.* 2015), peer effects (Bollinger and Gillingham 2012), and differences in installation costs. The mean of 0.1 for the variable NSW * GCC in Table 1 indicates that 10% of the 2012 survey was households in the greater capital city region (Sydney) within the state of New South Wales.

The two household surveys that we use were conducted by the Australian Bureau of Statistics (ABS 2013, 2017). Both collected detailed information through computer-assisted interview questionnaires on household net wealth, income, energy use, and other characteristics. The first was the Household Energy Consumption (HEC) survey of 2012, which covered 11,978 households. The second, the Survey of Income and Housing (SIH) of 2015-16, is part of a series of similar surveys in previous periods. The 2015-16 survey, which covered 17,768 households, was the first SIH to ask about household solar PV. There is substantial overlap in the variables available from the two surveys.

Advantages of using the HEC survey include the potential to assess factors associated with early uptake (as of 2012) and the availability of additional energy-related questions, such as concerning the intention to install. Use of

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[1] For instance, a national-level policy, the Small-scale Renewable Energy Scheme (SRES), effectively provides an upfront capital subsidy, with higher subsidy rates for areas that receive more solar radiation. For example, households with a value of 1 for the variable NSW * GCC (Sydney households) receive a higher proportional subsidy than households with a value of 1 for the variable VIC * GCC (Melbourne households). GCC = greater capital city.

Table 1 Descriptive statistics for households in each survey

Variable	2012 Household Energy Consumption (HEC) survey Mean	2015–16 Survey of Income and Housing (SIH) Mean
Solar panel uptake, binary	0.10	0.17
Solar panel intention, binary	0.04	n/a
Net wealth ($'000)	721.72	853.61
Income, annual ($'000)	84.30	89.27
Private pension divided by income	0.05	0.06
Long property tenure, binary	0.12	0.16
Rented households, binary	0.30	0.29
Apartment, binary	0.09	0.08
Number of bedrooms	3.09	3.10
Number of persons	2.44	2.35
New South Wales (NSW), binary	0.17	0.18
Victoria (VIC), binary	0.17	0.21
Queensland (QLD), binary	0.14	0.15
South Australia (SA), binary	0.17	0.16
Western Australia (WA), binary	0.15	0.14
Tasmania (TAS), binary	0.11	0.10
Northern Territory, binary	0.03	0.03
Australian Capital Territory, binary	0.06	0.04
Greater capital city (GCC), binary	0.47	0.57
NSW * GCC	0.10	0.12
VIC * GCC	0.09	0.14
QLD * GCC	0.07	0.08
SA * GCC	0.09	0.09
WA * GCC	0.07	0.08
TAS * GCC	0.04	0.04
Employed persons	1.22	1.10
Dependent children under 15 years of age	0.49	0.45
Mortgage, binary	0.36	0.34
Number of credit cards	1.07	1.07
Green power scheme, binary	0.04	n/a
Age of dwelling, categorical	3.95	n/a
Climate zone, categorical	4.16	n/a
Electricity expenditure ($), weekly	29.66	n/a
Insulation, binary	0.74	n/a
Solar hot water system, binary	0.11	n/a
How often could not pay bills, categorical	0.18	n/a
Restrict heating/cooling to save cost, binary	0.10	n/a
Time constraints affecting energy use, binary	0.04	n/a
Electricity price ($ per kilowatt hour)	0.21	n/a
Electricity consumption (kilowatt hours)	126.54	n/a

Notes: The sample sizes are 11,978 for the 2012 Household Energy Consumption (HEC) survey and 17,768 for the 2015–16 Survey of Income and Housing (SIH). The number of observations in the results tables in Section 3 is slightly lower as observations are dropped when taking the log of a negative number, and we also drop households reporting private pension income greater than total income. In the 2012 survey, there were 125 households reporting nonpositive values for income, 9 additional households with private pension income greater than total income and 142 households with nonpositive values for net wealth. In the 2015–16 survey, there were 122 households with nonpositive values for income, 21 additional households with private pension income greater than total income and 191 households with nonpositive values for net wealth. There is one household with a value of 3 for the categorical variable of how often bills could not be paid; our results drop this observation. Electricity consumption is only available for 7,835 households who had their latest energy bill for reference and we calculate electricity consumption price as consumption-expenditure divided by consumption, excluding the top 2% of values that are above $0.59 per kilowatt hour as they seem to suggest inaccurate reporting of electricity expenditure and/or consumption for these households.
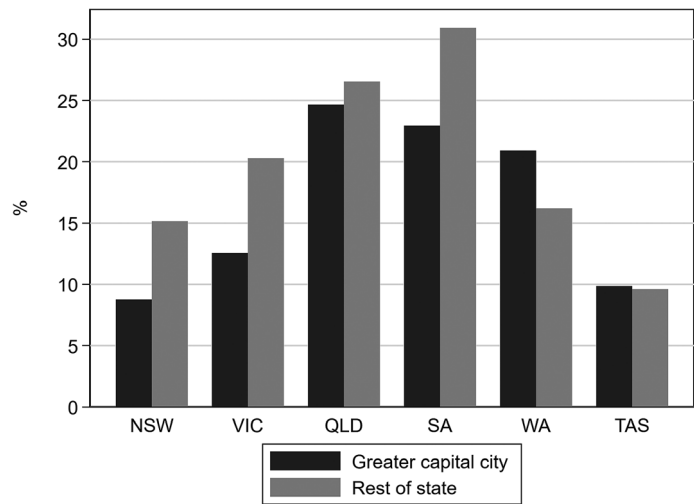
Figure 3 Proportion of households with solar panels in the 2015–16 Survey of Income and Housing (SIH) for each of the six Australian states. NSW = New South Wales; VIC = Victoria; QLD = Queensland; SA = South Australia; WA = Western Australia; TAS = Tasmania. Based on ABS data (ABS, Australian Bureau of Statistics 2017). The Northern Territory and Australian Capital Territory were not split into greater capital city and rest of state categories in the source data.

surveys at different points in time can increase confidence in the robustness of the results. Solar system costs fell by approximately 30% from the time of the first survey to the second (Solar Choice 2018), providing an interesting setting for assessing potentially differential effects.

The sample designs for each survey aimed for reliable coverage of Australia, each state, and each capital city. The 2015–16 survey response rate was 71% of dwellings that were contacted and that met the sampling criteria. Our main results do not use sampling weights. We find similar results using sampling weights [see the online Stata code (Appendix S2), with weights using the inverse of the probability that a household will be selected for the survey by the Australian Bureau of Statistics (ABS) (2013, 2017)]. There is no consensus on use of sampling weights, but unweighted analysis is more efficient (Platt and Harper 2013).

3. Results

3.1 Actual uptake

Table 2 shows results using the 2015-16 Survey of Income and Housing (SIH). Positive coefficients are obtained for log net wealth in explaining solar panel uptake. These are significant at the 1% level in each column. In contrast, there are negative and significant coefficients for the squared terms. The coefficients imply an inverse-U effect, with a turning point at $3.1 million

of net wealth in column 1. This corresponds to the 96th percentile of net wealth in the sample.[2] In column 2, the turning point is at the 93rd percentile. Across all but the very high end of the distribution, there thus appears to be a positive marginal effect of net wealth on the likelihood of actual uptake.

Other dimensions related to wealth in column 1 of Table 2 also have significant coefficients. A variable for the proportion of income from private pensions (including superannuation) has a positive and significant effect on solar uptake, indicative of solar uptake being higher among self-funded retirees. This result holds when including a binary variable for respondents aged 60 and above, as shown in the online Stata code (Appendix S2). The binary 'long property tenure' variable in column 1, which takes a value of one for houses purchased more than 25 years ago, gives an indication of the effect of house age and length of tenure. The negative and significant coefficient for this variable reveals that being in a house for more than 25 years has a negative impact on the likelihood of solar panel uptake. In contrast to the wealth coefficients, it is notable that the income coefficients are insignificant.

Column 2 of Table 2 adds variables related to property rights and space. The negative coefficients for the binary variables for renters and apartment dwellers indicate that these types of households are less likely to have solar panels. The influence of both variables is likely related to property rights and transaction costs, as there are other owners who partly or fully control roof spaces in these contexts. Apartments also have less roof space per household compared to separate or semi-detached houses. There is a positive and significant coefficient for the number of bedrooms, confirming that houses with more rooms and larger roof areas are more likely to have solar panels. This could reflect enhanced siting opportunities, and perhaps also greater incentive to reduce electricity costs for larger houses. Scale impacts are also evident in the coefficient for the number of people; households with more people face higher electricity bills, all else equal, and thus greater incentive for installing solar panels, as well as greater opportunity to spread the fixed cost of panel installation across more people.

Column 3 of Table 2 controls for variables related to geography and jurisdiction. Variables for the state or territory of residence (available in the online code Appendix S2) control for issues such as policy differences and differences in electricity prices, relative to the excluded reference region of the Australian Capital Territory. Relatively high uptake of solar panels in Queensland and South Australia, as shown in Figure 3, is confirmed when controlling for state and other variables in column 3. Being a resident of Queensland increases the log odds of having solar PV by 1.2, while the log odds are higher by 1.4 for residents of South Australia. By exponentiating the coefficients, logit results can also be expressed as ratios of the odds. This implies that the odds of household solar PV uptake for South Australian

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[2] If probability weights and standard errors clustered by state are used, the turning point corresponds to the 94th percentile.

Table 2 Logit results, 2015–16 Survey of Income and Housing (SIH)

	Dependent variable: Solar panel uptake				
	(1)	(2)	(3)	(4)	(5)
Net wealth, log	3.663***	1.507***	1.485***	1.521***	0.201***
	(0.306)	(0.293)	(0.305)	(0.305)	(0.027)
Net wealth, log, squared	−0.123***	−0.052***	−0.048***	−0.050***	
	(0.012)	(0.011)	(0.011)	(0.011)	
Income, log	0.008	−0.014	−0.020	0.002	−0.010
	(0.022)	(0.024)	(0.025)	(0.027)	(0.027)
Private pension div. by income	0.577***	0.737***	0.791***	0.604***	0.570***
	(0.098)	(0.102)	(0.105)	(0.112)	(0.112)
Long property tenure	−0.134**	−0.213***	−0.172***	−0.216***	−0.208***
	(0.055)	(0.056)	(0.057)	(0.059)	(0.059)
Rent		−1.441***	−1.396***	−1.421***	−1.573***
		(0.101)	(0.102)	(0.110)	(0.107)
Apartment		−1.889***	−1.753***	−1.756***	−1.793***
		(0.243)	(0.246)	(0.246)	(0.246)
Bedrooms		0.260***	0.222***	0.220***	0.212***
		(0.029)	(0.030)	(0.030)	(0.030)
Persons		0.044**	0.075***	0.189***	0.192***
		(0.019)	(0.020)	(0.033)	(0.033)
Employed persons				−0.134***	−0.133***
				(0.032)	(0.032)
Dependent children				−0.138***	−0.141***
				(0.041)	(0.041)
Mortgage				−0.038	−0.017
				(0.058)	(0.057)
Credit cards				0.085***	0.082***
				(0.023)	(0.023)
Region fixed effects	No	No	Yes	Yes	Yes
Pseudo R^2	0.070	0.107	0.145	0.148	0.146

Note: ***, **, * show statistical significance at 1, 5, and 10% level, respectively. Standard errors are in brackets below the coefficients. Coefficients for constants are not shown. Region fixed effects include state/territory and capital city variables. There are 17,437 observations for each column.

households are four times higher than for residents of the excluded region, all else equal. The greater capital city binary variable is not significant, but interaction terms between three major Australian states and the greater capital city variable are negative and significant (see the online code Appendix S2). These coefficients indicate that solar uptake is lower in large Australian cities, where population density is higher. This is particularly so for Sydney and Melbourne.

Column 4 of Table 2 includes variables representing time constraints and debt preferences. There are negative coefficients for the number of employed persons and the number of dependent children in a household in explaining solar panel uptake, all else equal. A binary variable for households with a mortgage is not significant, but the number of credit cards possessed by a household is positively related to solar uptake. This suggests that debt preferences may be related to solar uptake. The coefficients for log net wealth

in column 4 are similar to the corresponding coefficients in columns 2–3; they are not highly sensitive to the inclusion of the extra variables.

Column 5 excludes the quadratic term. We find a positive coefficient for log net wealth and an insignificant coefficient for log income. For a 1% increase in net wealth, the odds of solar panel uptake increase by 0.2% on average.

Table 3 shows results based on the 2012 Household Energy Consumption (HEC) survey. Figure 1 indicates solar capacity grew substantially between 2012 and 2015-16, and there were major reductions in the cost of solar installations over this time.

Log net wealth again has a positive and significant effect on solar PV uptake in column 1 of Table 3, with a 1% increase in net wealth being associated with a 0.25% increase in the odds of solar PV uptake. This is similar to the outcome in Table 2. The private pension variable is again positive and significant, with larger coefficients for the 2012 sample compared to the 2015-16 sample in Table 2. It appears that the group of older and wealthy self-funded retirees installed solar panels in an earlier period.

The variables for renters, apartment dwellers, the number of bedrooms, and the number of people in each household have similar coefficients in column 1 of Table 3 as in column 5 of Table 2. Renting has a larger impact for the 2012 sample in Table 3, while the effects of the other three variables were more pronounced in Table 2. These results emphasise that living in apartments or being a renter introduces fundamental constraints to solar uptake, while larger houses and having more people in the household exert positive influences. The odds of solar uptake were over seven times lower for households that rented in 2012 compared to households who own their residence outright (the excluded category), based on the inverse after exponentiating the coefficient of –2. Other aspects related to time constraints and debt preferences appear to be of less importance, based on insignificant coefficients in Table 3.

Table 3 also reveals a positive and significant relationship between participating in a green power scheme and uptake of solar panels: the odds of solar uptake were nearly one and a half times higher for households that participated in the green power scheme compared to those that did not, all else equal. This suggests that environmental preferences have been a motivation for early adoption of solar panels, as expected. This variable is not available in the later SIH survey.

Two additional categorical variables are available from the 2012 HEC survey compared to the later SIH survey. In column 3 of Table 3, there are negative and significant coefficients for the two oldest categories of house age: 20–30 years, and 30 years and over. This confirms that owners of older houses are less likely to install solar panels. New houses may have panels installed on them during construction, and older houses may be less suitable for solar panels for reasons such as lower-quality roof materials, inferior electrical wiring, and the chance of heritage listing. Installing solar panels may also damage old roofs or involve additional capital outlay to repair or

Table 3   Logit results, 2012 Household Energy Consumption survey (HEC)

| | Dependent variable: Solar panel uptake | | | |
	(1)	(2)	(3)	(4)
Net wealth, log	0.251***	0.249***	0.245***	0.243***
	(0.042)	(0.042)	(0.042)	(0.042)
Income, log	0.009	0.007	0.005	0.011
	(0.036)	(0.036)	(0.036)	(0.036)
Private pension div. by income	0.871***	0.870***	0.839***	0.838***
	(0.167)	(0.167)	(0.168)	(0.168)
Long property tenure	−0.315***	−0.313***	−0.125	−0.134
	(0.097)	(0.097)	(0.104)	(0.104)
Rent	−1.985***	−1.996***	−2.004***	−2.009***
	(0.194)	(0.195)	(0.196)	(0.196)
Apartment	−1.630***	−1.630***	−1.698***	−1.696***
	(0.390)	(0.390)	(0.390)	(0.390)
Bedrooms	0.133***	0.135***	0.105*	0.109*
	(0.046)	(0.046)	(0.047)	(0.047)
Persons	0.122*	0.123*	0.122*	0.116*
	(0.051)	(0.051)	(0.052)	(0.052)
Employed persons	−0.020	−0.018	−0.015	−0.012
	(0.048)	(0.048)	(0.049)	(0.049)
Dependent children	−0.107*	−0.111*	−0.106*	−0.103
	(0.063)	(0.063)	(0.063)	(0.063)
Mortgage	−0.100	−0.107	−0.128	−0.131
	(0.083)	(0.083)	(0.084)	(0.085)
Credit cards	0.036	0.033	0.033	0.030
	(0.035)	(0.035)	(0.035)	(0.035)
Green power scheme		0.350*	0.369***	0.375***
		(0.142)	(0.143)	(0.143)
Age of dwelling: 5–10 years			−0.112	−0.110
			(0.144)	(0.145)
Age of dwelling: 10–20 years			−0.176	−0.186
			(0.131)	(0.132)
Age of dwelling: 20–30 years			−0.262*	−0.269*
			(0.135)	(0.136)
Age of dwelling: 30 + years			−0.551***	−0.543***
			(0.123)	(0.124)
Age of dwelling: don't know			−0.340	−0.324
			(0.548)	(0.550)
Climate zone 2: Warm summer				0.191
				(0.294)
Climate zone 3/4: Dry summer				−0.030
				(0.319)
Climate zone 5: Warm temperate				−0.038
				(0.312)
Climate zone 6: Mild temperate				0.188
				(0.324)
Climate zone 7/8: Cool temperate				−0.828*
				(0.421)
Additional region fixed effects	Yes	Yes	Yes	Yes
Pseudo R^2	0.141	0.142	0.146	0.148

Note: ***, **, * show statistical significance at 1, 5, and 10% level, respectively. Standard errors are in brackets below the coefficients. Additional region fixed effects include state/territories and capital city variables. Coefficients for constants are not shown. There are 11,707 observations for each column.

replace roofs. Heritage-listed houses are often not allowed to install solar panels.

The 'long property tenure' variable for residences that were purchased more than 25 years prior to the survey loses significance in column 3 of Table 3 when the categorical age of dwelling variable is added. This suggests that the main effect of this variable is through age rather than continuity of tenure. The categorical climate zone variables are mostly insignificant in column 4. The final category, for the cool temperate and alpine zones, does have a negative and significant coefficient in explaining solar uptake, at the 5% level.

The key results are confirmed in robustness tests with additional variables. The online Stata code (Appendix S2) shows that inclusion of a squared log net wealth variable does not have a material impact on the other key coefficients in Table 3 (with the exception of the log net wealth variable itself). We obtain similar results when controlling for the log average electricity consumption price paid by each household. A binary variable for whether the survey respondent was aged 60 years or more is not significant, and its inclusion has immaterial effects on other coefficients. Using binary variables for wealth quintiles produces negative and significant effects for the lowest three quintiles, but not the fourth, relative to the excluded fifth quintile. This suggests that capital constraints may exist for the bottom 60% of the population by net wealth. A similar result is obtained using the 2015–16 survey. There are also positive and significant coefficients for log net wealth excluding housing. Results are also similar when controlling for a three-way interaction of state, capital city status, and climate zone. This helps to capture regional heterogeneity within cities.[3]

We also produce robustness tests using alternative standard error methodologies and estimation models. The online code (Appendix S2) shows results for four different methods of calculating standard errors, producing negligible differences. We also include results using a probit model, as well as a linear probability model that uses heteroskedasticity-robust standard errors. These models provide similar outcomes to our logit model.

3.2 Intention to install

Table 4 explores factors influencing the *intention* to install solar panels on one's current dwelling within the next 12 months. We exclude households that already had solar panels at the time of the survey, and also renters because the survey did not ask renters about their solar intentions.[4] The negative influence of living in an apartment on solar installation intentions is consistent with the results in previous tables for actual uptake. Many of the

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[3] Sydney, Brisbane and Adelaide areas are each split into two climate zones. Postcode identifiers are not available, so we are not able to control for postcode-level uptake rates.
[4] We thus are not examining intention to expand or replace existing panel arrays.

other coefficients are no longer statistically significant. The insignificance of capital constraints in Table 4 (cf. Tables 2 and 3) is a possible indication of hypothetical response bias.

Some of the results in Table 4 differ to the results for actual uptake. The 'long property tenure' variable is negative and significant, even when controlling for an age-of-house categorical variable (not shown). This suggests that continuity of tenure may influence solar intentions: occupants of households may become comfortable and less likely to intend to make changes after many decades of tenure.

The binary variable for households with mortgages is positive and significant at the 1% level in column 1 of Table 4. This may be explained by factors such as greater potential for bill stress. The result could also reflect the role of debt preferences, similar to the positive relationship for the number of credit cards in Table 2.

The positive and significant coefficients in Table 4 indicate that households with more employed persons are more likely to intend to install solar panels. Corresponding coefficients explaining actual uptake are negative (Table 2). It seems that busy employed people may have less time to organise solar installation.

The forward-looking nature of the dependent variable in Table 4 allows for inclusion of additional explanatory variables, some of which would be subject to the risk of reverse causation if solar installations were the dependent variable. There are positive coefficients for log electricity expenditure, significant at the 1% level, in explaining the intention to install solar panels in the subsequent 12 months. This suggests that avoiding bill stress is a major motivating force for intending to install solar panels. We separately consider consumption and price in column 5, finding that higher electricity prices also drive intentions to install solar panels.

Column 3 of Table 4 includes two additional variables that represent prior energy-related behaviour. There are positive coefficients for binary variables for insulation and solar hot water systems in explaining solar PV intentions, but only the solar hot water variable is significant. There is some evidence that households that have made capital additions related to energy are more likely to add further capital additions such as solar PV.

Column 4 of Table 4 considers the influence of energy poverty on solar intentions. Households that could not pay their bills (including their electricity bill) are more likely to install solar panels, all else equal. There is significance at the 10% level for households who could not pay their bills often, but this is not the case for households who could sometimes not pay their bills. There is a negative coefficient for a binary variable for households that say that they restrict heating and cooling because they cannot afford the extra costs, although this is not significant at the 10% level. These variables are more appropriate for analysing solar intentions than actual installations, since already having solar panels may influence energy poverty outcomes.

Table 4 Results, 2012 Household Energy Consumption survey (HEC), intention to install

	Dependent variable: Intention to install solar panels in the next 12 months				
	(1)	(2)	(3)	(4)	(5)
Net wealth, log	0.102	0.061	0.055	0.063	0.115
	(0.063)	(0.065)	(0.065)	(0.066)	(0.081)
Income, log	0.134**	0.114*	0.115*	0.115*	0.062
	(0.068)	(0.068)	(0.068)	(0.068)	(0.076)
Private pension	0.163	0.239	0.237	0.237	0.446
div. by income	(0.355)	(0.358)	(0.359)	(0.359)	(0.376)
Long property tenure	−0.681***	−0.648***	−0.660***	−0.665***	−0.938***
	(0.194)	(0.195)	(0.195)	(0.195)	(0.237)
Apartment	−1.010**	−0.945**	−0.886*	−0.862*	−0.815
	(0.466)	(0.467)	(0.470)	(0.470)	(0.528)
Bedrooms	0.041	−0.011	−0.018	−0.015	0.001
	(0.068)	(0.070)	(0.070)	(0.071)	(0.082)
Persons	0.163**	0.112	0.106	0.104	0.088
	(0.077)	(0.079)	(0.079)	(0.079)	(0.095)
Employed persons	0.134*	0.141*	0.141*	0.143*	0.172*
	(0.074)	(0.075)	(0.075)	(0.075)	(0.089)
Dependent children	0.027	0.043	0.049	0.044	0.088
	(0.087)	(0.088)	(0.089)	(0.089)	(0.105)
Mortgage	0.337***	0.286**	0.283**	0.280**	0.232
	(0.125)	(0.127)	(0.127)	(0.127)	(0.149)
Credit cards	0.057	0.049	0.047	0.044	0.008
	(0.051)	(0.052)	(0.052)	(0.052)	(0.060)
Green power scheme	0.295	0.316	0.321	0.324	0.346
	(0.211)	(0.212)	(0.212)	(0.212)	(0.239)
Electricity expenditure, log		0.337***	0.336***	0.335***	
		(0.100)	(0.100)	(0.100)	
Insulation			0.114	0.115	0.110
			(0.167)	(0.167)	(0.195)
Solar hot water system			0.277*	0.282*	0.138
			(0.153)	(0.153)	(0.180)
Could not pay bills: sometimes				0.091	0.002
				(0.192)	(0.243)
Could not pay bills: often				0.433*	0.028
				(0.250)	(0.347)
Restrict heating/ cooling to save cost				−0.289	−0.069
				(0.209)	(0.246)
Time constraints				−0.174	−0.263
				(0.256)	(0.325)
Electricity price, log					0.745***
					(0.284)
Electricity consumption, log					0.176
					(0.112)
Region fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	7,153	7,019	7,019	7,018	4.923
Pseudo R^2	0.064	0.068	0.069	0.070	0.069

Note: ***, **, * show statistical significance at 1, 5, and 10% level, respectively. Standard errors are in brackets below the coefficients. Region fixed effects include state/territory and capital city variables and climate zones. Coefficients for constants and age of dwelling are not shown. The sample excludes households that already had installed solar panels and rented households because they were not asked about their solar intentions.

4. Conclusion and policy implications

This paper explored factors influencing household uptake of rooftop solar PV in Australia. In 2015-16, there was an inverse-U effect of log net wealth, with a positive marginal effect of net wealth on solar uptake until very high net wealth levels. There is a positive relationship between the proportion of income from private pensions (including superannuation) and solar uptake, even when controlling for age. Larger houses and households are more likely to install solar panels. Use of green power is a useful predictor of whether households install solar. Key constraints for solar uptake include living in apartments and renting. Households in older homes are less likely to install solar panels, all else equal. Log income was not found to have a significant average effect on actual installations, but there was some evidence of a positive effect on intended uptake.

Our results suggest that many households face capital constraints to installing solar panels. Policy options to address household capital constraints include government provision of capital subsidies or loans. There have been a small number of studies on the effectiveness of rebates to cover part of the upfront costs of solar panels, such as for California (Hughes and Podolefsky 2015) and the north-east of the United States (Crago and Chernyakhovskiy 2017). An argument against government-funded subsidies is that taxpayers pay for them through higher taxes, meaning there is an efficiency cost to the economy.

The means-testing of any subsidies/loans for household-level solar PV installations is worthy of consideration. Australia is top among OECD countries in the use of means-tested welfare payments, based on either income and/or assets (Australian Government 2017). In the case of solar panels, our results suggest that means-testing based on net capital levels would be more relevant than means-testing based on income levels given that net wealth is a more important constraint than income. While our estimates provide useful information on the size of suitable thresholds, the exact calibration of means-tested thresholds depends on program objectives. Recent policy announcements in Australia have featured income-contingent subsidies (ACT Government 2018; Victorian Government 2018).[5]

Developing the market for solar panel leasing is one way to facilitate uptake among resource-constrained households and renters (Rai and Sigrin 2013). Market solutions include approaches via which residential rooftop solar panels are owned by companies and the related net revenues are aggregated, packaged into financial securities and sold to investors. This potentially provides a low-cost financing mechanism (Alafita and Pearce 2014). There is scope for further development of new business models for rooftop solar, with a particular focus on apartment blocks and renters.

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[5] A recent policy announcement from the Victorian Government (2018) does restrict subsidy eligibility to homes valued under 3 million Australian dollars, which is quite a high threshold. The scheme also applies an annual household income test of 180,000 Australian dollars.

Australia's position as a world leader in household solar PV uptake means that the results in this paper are of international relevance, including for predictive purposes for uptake of solar PV in other contexts. The Australian solar PV experience could perhaps also be informative for predicting uptake of related technologies, such as household batteries and electric vehicles.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1 Description of variables at the household level.

Appendix S2 Best_Burke_Nishitateno_Data and code.zip.