LOW CARBON LIVING CRC

Asesssing the Impact of Solar PV on Domestic Electricity Consumption in Sydney:

Exploring the Prospect of Rebound Effects

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Title	Assessing the Impact of Solar PV on Domestic Electricity Consumption in Sydney: Exploring the Prospect of Rebound Effects
ISBN	
Format	
Keywords	Solar pv, renewable energy, feed-in tariff incentives, rebound effect, dynamic panel modelling
Editor	
Publisher	
Series	
ISSN	
Preferred citation	

Australian Government
Department of Industry, Innovation and Science

Business
Cooperative Research Centres Programme

Acknowledgements

This research is funded by the CRC for Low Carbon Living Ltd supported by the Cooperative Research Centres program, an Australian Government initiative.The authors wish to acknowledge the contribution made to this study by Ausgrid in supplying the data on which this study is based. It can be sourced from the Ausgrid website (http://www.ausgrid.com.au/Common/About-us/Corporate-information/Data-to-share/Solar-household-data.aspx ; last accessed 3 March 2016).

The authors also wish to thank the members of the Steering Committee on this project for their valuable feedback at various stages of this project leading up to the production of the Final Report:

Gene McGlynn, Department of Industry, Canberra

Ghulam Amur, Department of Environment NSW, Sydney

Robert Enker, Victorian Building Authority, Melbourne

Robert Simpson, Ausgrid, Sydney

Deo Prasad, CRC for Low Carbon Living, Sydney

Disclaimer

The modelling undertaken in this study is based on data provided from the sample of household data provided from Ausgrid billing records.

Peer Review Statement

This report has been reviewed by the Steering Committee. The responsibility for what appears in this report, however, rests with the authors.

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Executive Summary

This study examines patterns of electricity use by Sydney households who have installed solar PV technology compared to those who have not in order to identify whether conservation or rebound effects are associated with domestic photovoltaics. A rebound effect exists when expected energy (and carbon) savings stimulate greater energy use. Currently this is an area where knowledge is lacking, compared to a larger body of studies which have measured the rebound effect from energy efficiency programs targeting buildings and appliances. Findings from this research have significance in determining whether a rebound effect needs to be factored into projected energy/carbon savings from solar PV installation. In scope here is the robustness of carbon mitigation estimates included in future rounds of international climate change agreements as well as local forecasts of future electricity demand affecting the national grid and its associated infrastructures. Analysis and modelling was undertaken on billing data for the period 2007-2014 provided by Ausgrid on a representative sample of households living in detached housing in Sydney. The sample comprised three groups: households who were early adopters and installed PV under a 60c/KWh feed-in tariff scheme, a group who installed under a 20c/KWh scheme and a control group with no PV. Econometric modelling undertaken for this study on energy consumption behaviour of households with *vs* without local renewable energy generation revealed that on a KWh basis, the rebound effect is estimated to erode up to one fifth of the benefit of renewable energy generated by solar PV.

Key Findings

1. All household groups exhibited a significant downward trend in electricity consumption over the period from 2007 to 2014.
2. Solar households as a group were found to generate over 40% of their total electricity consumption from renewable sources during the peak summer quarters and approximately 25% during the winter quarters.
3. Households who were early adopters of solar panels demonstrated higher levels of electricity consumption relative to the control group that had no PV. The early adopters received a feed-in-tariff (60c/KWh), which was more than double of what they paid for electricity from the grid (27.87c/KWh was Ausgrid's retail price). Even for the late adopters, the feed-in-tariff (20c/KWh) was still be equivalent to more than 70% of what they paid for grid electricity.
4. Analysis of change in electricity consumption for the period when household behaviour among the solar households could be expected to have 'stabilised' (ie circa 2012), both the 60c group and the 20c group experienced a lower year-on-year percentage decrease in electricity use relative to the Control group. In other words, the introduction of solar PV appeared to have slowed down the general decreasing trend for the 'green' households.
5. Installation of solar PV (with feed-in tariff) has created a significant rebound effect among those Sydney households that subscribed to the NSW Solar Bonus Scheme. It was estimated that on a per KWh basis, the rebound effect is estimated to erode about 20.9% of the benefit of renewable energy generated by solar PV for the 60c group, and 16.7% for the 20c group.

Introduction

There are multiple drivers behind a transition to small scale renewable energy from roof top solar PV. From a consumer's perspective, there is greater energy independence and an insulation from rising prices in the national electricity market, and for an increasing segment of the population, satisfaction from being an ethical consumer (Newton and Meyer 2016). From a government's perspective, a reduction in end-user demand for new ('centralised') electricity generation capacity and distribution flows through to a reduction in future capital budgets, as well as making a positive contribution to achieving national carbon mitigation targets. From an industry perspective, new business opportunities flow from linking into an emerging green economy (Newton and Newman 2015).

For this study, focus is on the critical connection required to transition to net positive energy/carbon negative housing: an energy efficient building (and appliances) *plus* distributed generation (DG) that creates sufficient energy on site over the course of a year to meet all requirements of the occupants *plus* a surplus of green energy that can be supplied to the grid (Berry and Davidson 2015). The concept of a stairway of innovations capable of delivering carbon negative buildings is illustrated in Figure 1 and includes: an eco-efficient use of floor space, energy efficient shell, energy efficient built-in appliances, energy efficient plug-in appliances and local energy generation (Newton and Tucker 2011). To be effective in achieving energy *from* the built environment, however, requires that all technological and design innovation needs to be operated in a manner that delivers optimal outcomes. Behaviour of occupants is now recognized as a critical factor in achieving low/zero carbon outcomes (Newton and Meyer 2013). The take-up and use of solar PV (as well as a range of energy efficiency interventions) therefore needs to be understood in the context of a socio-technical innovation. Rebound has been found to be associated with all energy efficiency innovations to date, and the question that this study explores is whether a rebound effect is associated with households that install solar PV (under current feed-in tariff schemes). This constitutes a major knowledge gap of relevance to key topics such as the impact of government incentives for diffusion of a technological innovation, forecasting future demand for (grid based) energy and climate change policy:

- climate change policy - if there is no allowance for rebound effects in projected energy/carbon savings from a range of energy efficiency, low carbon energy generation, and carbon mitigation interventions then there is likelihood of an over-estimation of the effects of such initiatives in government carbon abatement calculations (Rowson 2013). The scale and speed with which solar PV has penetrated Australia's built environment has confirmed it as a significant potential force in shrinking the carbon footprint of our residential buildings/human settlements/cities, but a rebound effect could diminish this impact.

- energy demand forecasting – for governments and utilities, results from this study can contribute to reduction in uncertainty in forecasting future domestic electricity demand and the associated supply side decisions that flow from these forecasts.

- incentive schemes – incentives represent one of several instruments available to governments attempting to influence demand and/or supply side behaviours among consumers and producers. In the case of solar PV, incentives have involved establishing feed-in tariffs that would determine payments to households that supplied electricity to the grid. Feed-in tariffs have ranged widely, reflecting the uncertainty surrounding the levels at which they initially needed to be set.

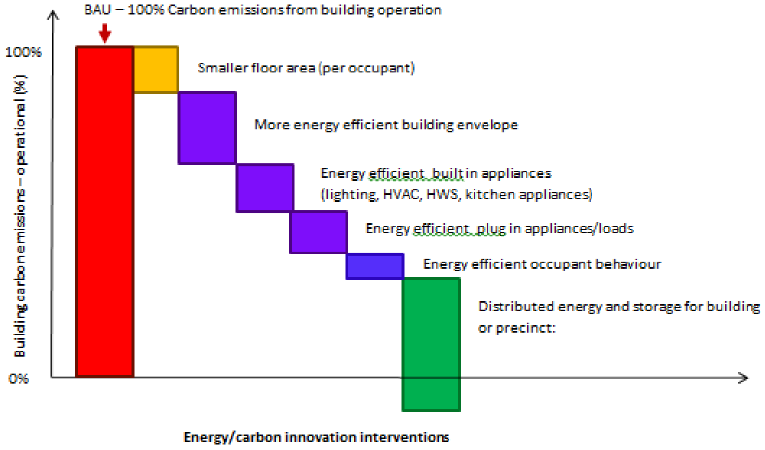
The aim of this project is to establish the impact that installation of solar PV has been having on domestic energy use in Sydney households from mid-2007 until December 2014.

The remainder of this report is structured as follows:

- a brief outline of the context in which solar PV has been operating in Australia
- an overview of the rebound effect literature, including selected studies which have attempted to estimate its magnitude
- a description of data and methods used in the analysis of PV take-up and use in Sydney

- results of a time series overview of electricity consumption and generation
- results of a dynamic panel model of electricity generation and consumption, and an estimation of the rebound effect for Sydney residents with installed PV under different feed-in tariffs.

Figure 1 Staircase of measures to create carbon negative buildings



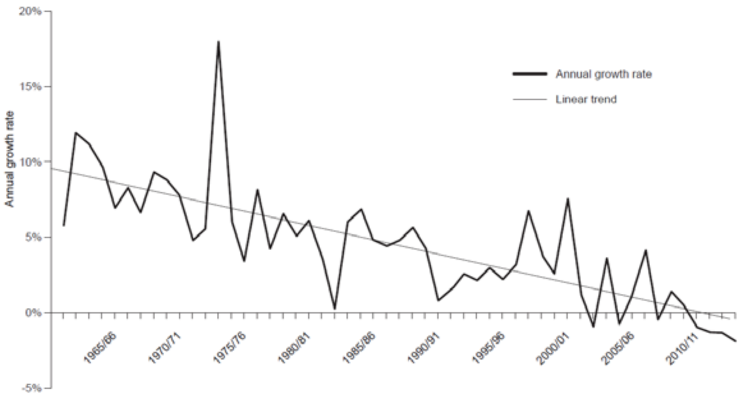
The macro context of this study

This study models electricity use by a large sample of Sydney households over the period June 2007 to December 2014, with particular focus on the influence installed solar PV has on levels of consumption.

During this period, several key trends have been occurring in relation to electricity demand and supply generally and more particularly in relation to renewable energy generation and PV of relevance to this study:

1. Annual electricity growth rates have been falling (consistently since the mid-1960s; Figure 2) due to the combination of a number of factors: fuel switching (from electricity to gas), impact of government supported energy efficiency programs, growth in DG (especially residential solar), reduction in large industrial loads due to structural shifts in energy intensive industry (eg. closure of smelters, manufacturing plant, oil refineries) and consumer response to electricity price rises (AEMC, 2011; Brazzale 2014)

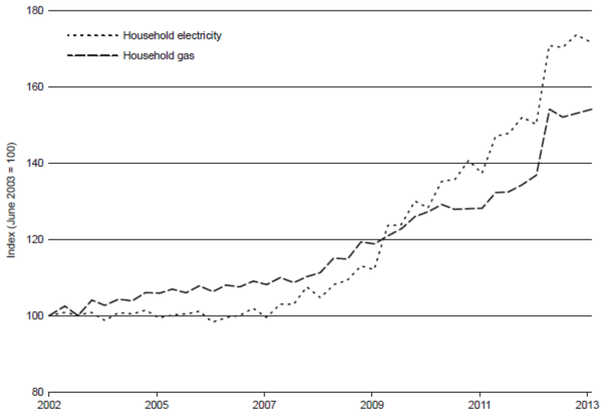
Figure 2 Annual energy consumption growth rate for the NEM jurisdictions



Source: Australian Energy Market Commission (2014)

2. In real terms, prices for domestic electricity increased on average by 72% nationally between 2003 and 2013 (Figure 3; Swobode 2014; Department of Industry and Science 2015, p9). Sydney experienced the highest percentage increase over this period at 107%, although recent forecasts suggest that rates of price rise are expected to moderate or decline slightly (AEMC 2014). Three quarters of electricity costs have been attributed to the cost of transporting energy plus wholesale costs – areas where DG can be expected to deliver significant eco-efficiency benefits.

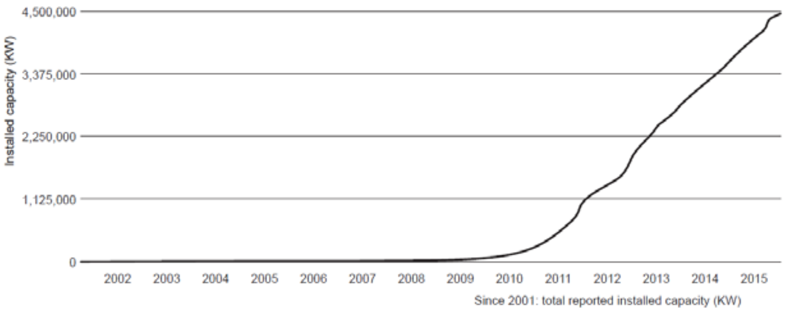
Figure 3 Real electricity and gas price increases, 2003 to 2013



Source: Kai Swoboda (2014) Energy prices—the story behind rising costs, Parliament of Australia , Canberra http://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/pubs/BriefingBook44p/EnergyPrices

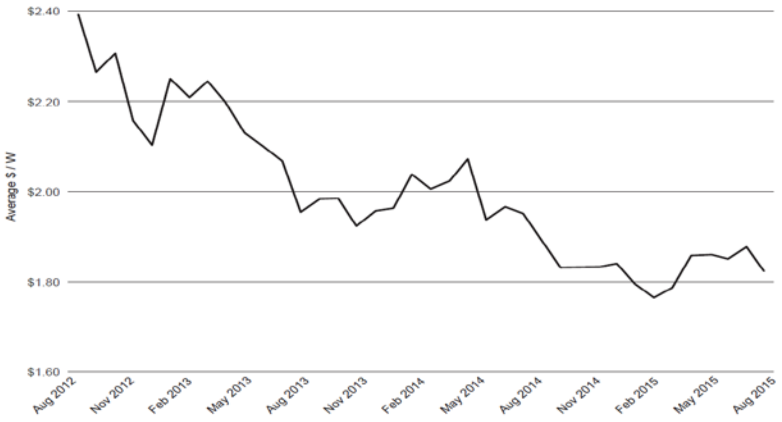
3. The period since 2010 has seen rapid growth in domestic solar PV installations (Figure 4; Australian PV Institute 2015). This phenomenon has been widespread across Australia’s cities and regions (Newton and Newman 2013), attributed to a significant decline in the cost of solar PV (Figure 5; Solar Choice 2015) combined with attractive government incentives linked to feed-in tariffs. Larger PV systems are also being installed (Figure 6).
4. Governments in Australia (federal and state) have been encouraging investment in renewable energy through the federal Renewable Energy Target (RET), directed towards ensuring 20% of the nation’s electricity demand in 2020 will be supplied from both small and large scale renewable technologies. At state level, governments have introduced schemes to encourage the installation of solar PV by domestic consumers by offering attractive feed-in tariffs that provide payment for electricity that is fed back into the grid (considered by some commentators as too generous; Wood and Blowers 2015). In NSW the Solar Bonus Scheme had an initial 60c feed in tariff, which was wound back to 20c at the beginning of 2011 and will cease at the end of 2016

Figure 4 Growth in PV installations in Australia



Source: Australian PV Institute (2015)

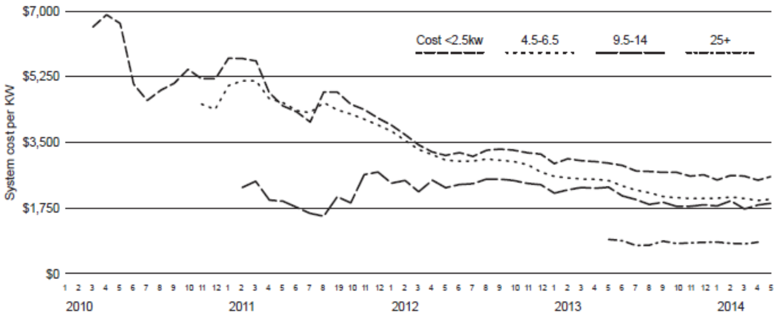
Figure 5 Average solar PV system prices, 2012-2015



Source: Solar Choice (sept 2015); http://www.solarchoice.net.au/blog/residential-solar-system-prices-september-2015

Note: The chart illustrates solar PV system pricing trends since September 2012. Data points are the average of average $/W for each system size (1.5kW-5kW until Nov 2013, then also including 10kW from Dec 2013).

Figure 6 System cost per kW by installation size



Source: Australian PV Institute (2015)

Overview of the Rebound Effect and its Estimation

According to Berkhout et al (2000), Sorrell et al (2009), Giddings and Park (2012), Chitnis and Sorrell (2015) and others, the rebound effect centres on the proposition that by making energy-consuming services cheaper to consumers either through more efficient use of that energy (eg. more fuel efficient cars, energy efficient lighting, whitegoods etc) or by harnessing the sun for local energy generation via solar PV, greater consumption of energy is encouraged. Direct rebound effects refer to the increased use of a product that embodies improved energy efficiency compared to an earlier vintage ; for example with energy efficient cars—drive more; with energy efficient lighting—install more, leave lights on; with energy efficient airtight buildings—leave air-conditioning running; with 'free' solar energy—use more. Indirect rebound effects refer to monetary savings from energy efficiency gains that are re-allocated to the purchase of other products whose production and operation involves energy use and greenhouse gas emissions; for example, savings on domestic energy bills spent on air travel, more electric appliances etc. In this study, the focus is on estimating *direct* rebound effects of installing solar PV.

There are numerous studies which have sought to measure rebound effects associated with a broad spectrum of energy efficiency initiatives. The two most comprehensive reviews identified to date (Sorrell et al 2009; Maxwell et al 2011) reveal a range of estimates for direct rebound effects relating to automobile transport, space heating and cooling (including dwelling energy efficiency), and other domestic appliances – demonstrating that rebound effects are end-use and context specific, as well as being reflective of different estimation methods. Most estimates of rebound effect for energy efficiency range between 10 and 30%, with some outliers, but few examples of 'backfire' (where intended energy/carbon savings are entirely negated by consumer behaviour). For total rebound effects, the estimates are considerably higher (Chitnis and Sorrell 2015).

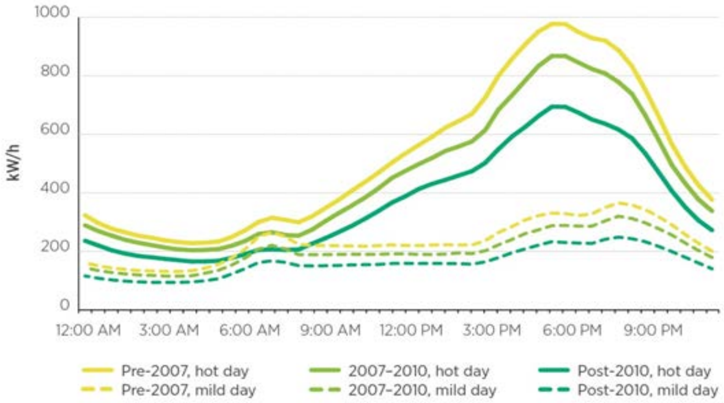
Below are summaries of key findings from the small number of Australian studies that have addressed the issue of energy rebound. They all reveal significant interplays between technology, design and *behaviour*.

Building energy efficiency and rebound

The *as designed* vs. *as operated* gap in relation to buildings has been subject to several studies revealing that the technical assumptions inherent in building design, especially those related to 'average' expected occupant behaviour, can diverge significantly from those observed in reality; for example: there are different perspectives among a population concerning thermal comfort and associated temperature settings; lighting preferences; frequency of clothes washing, bathing, dish-washing; number of hours spent at home etc (deDear et al 2013). Indeed, there are an increasing number of studies demonstrating considerable variability in energy consumption by occupants of similar *types* of housing (Gill et. al., 2010; Gramm-Hanssen, 2013) as well those with *identical energy performance ratings* (Sunnikka-Blank and Galvin 2012). While not technically a rebound study, this research in Germany and in several other west European countries challenges prevailing policy views 'that large, deep cuts in energy consumption can be achieved by focusing on the technical aspects of thermal retrofits and by demanding extremely high thermal standards. The gap identified between performance and the measured consumption suggests that 'there could be less potential for economically feasible savings than assumed [from] policy' (Sunnikka-Blank and Galvin 2012, p270).

The first Australian study that has investigated whether new housing designed to attain a 5-star energy efficiency standard actually performed better than lower rated (3.5 and 4-star) housing – as occupied -- CSIRO (Ambrose et al, 2013) undertook detailed analysis of over 400 houses in Brisbane, Melbourne and Adelaide during 2012 and 2013. Each house had its design professionally re-rated for energy efficiency, had its inside and outside temperatures monitored over summer and winter periods and undertook a survey of household occupants (including information on their energy bills). The results indicated that greenhouse gas emissions were reduced by 7% for the higher rated houses over a year, but during the summer, energy use and carbon emissions increased in the higher rated houses in all cities. A subsequent study (Ambrose and James, 2014) concluded that many households were relying on their mechanical air conditioning systems to maintain comfort rather than taking advantage of natural ventilation. A larger but less detailed analysis of data in Melbourne showed that more modern households built under more stringent building standards do in fact reduce energy consumption by around 30% (BREE 2014; see Figure 7). The whole area of 'as designed' vs. 'as built' vs. 'as operated' is now focus for more robust study, given the 'gaps' that have been identified in energy performance between each link in the chain (Pitt and Sherry, 2014; Newton and Meyer, 2016).

Figure 7 Effects of more energy efficient houses and appliances on electricity use



Source: BREE 2014a

Household appliances and rebound

In the domestic sector it is in the growth of electrical appliances where energy demand is forecast to grow most (Newton et al 2012; Newton and Tucker 2011). Despite energy efficiency improvements in many of the products in this category, there are other forces at work that are at the heart of the rebound effect considered to be operating in this area, with the result that full energy savings are not being realised. A recent desktop study by Giddings and Park (2012) assessed the potential rebound factors operating on the following list of household appliances as follows:

- TV: rebound considered likely due to increases in the size of units, standby power (now beginning to be addressed in newer products), use of peripheral devices for recording, gaming etc; increased viewing/use time; multiple units in household)
- Washing machines: rebound probable due to increase in frequency of wash cycles; partial loads, and the fact that some models of front loading machines do not provide options of cold wash
- Dishwashers: despite enhanced energy efficiency of units, the number of dishwashers in dwellings has doubled over the past 20 years and most wash cycles are on partially filled contents – rebound possible
- Refrigerators: there has been an increase in fridge size (especially freezer capacity) and most are over-filled; numbers of second fridges per dwelling have increased; rebound probable.

‘Rebound’ effects here could be confounded by other than energy efficiency dividends being ‘re-invested’ in either more products or more use. For example, overall cost of these electrical products have declined significantly over the past decade, which enables trade-up to more efficient products, but also makes them more affordable and accessible to more households than previously. This period has also witnessed an increase in affluence among the Australian population that has been reflected in increased household consumption (Hamilton and Denniss 2005; Newton 2011).

Rebound from solar PV

In the only other Australian study known to date that has attempted to estimate whether a rebound effect is associated with the installation of solar PV, Havas et al (2015) analysed data generated from a survey of 378 households located in Alice Springs as part of the federal Solar Cities Program (http://www.alicesolarcity.com.au/about/ago). The results indicated a rebound effect of 15% for the households that adopted PV. The authors commented that adoption of solar PV ‘…can confound consumer behaviour, such as when a rebound effect occurs as households increase electricity usage due to the electricity savings made from adopting renewable energy technologies—which have been promoted to reduce household electricity consumption’. The authors note that installation of solar PV does not require or necessitate conservation–oriented behavioural changes on the part of residents.

Data

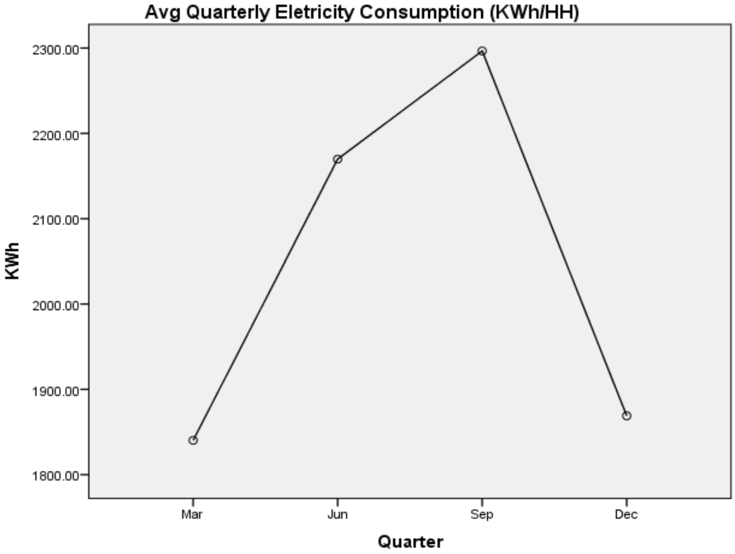
Data for this study was sourced from the Ausgrid website (http://www.ausgrid.com.au/Common/About-us/Corporate-information/Data-to-share/Solar-household-data.aspx). It consisted of a representative sample of quarterly observations of electricity usage and solar panel electricity generation of 4,889 Sydney households, starting from Jun-2007 to Dec-2014. Household data was based on gross feed-in tariffs for all solar households in the sample. Gross metered customers export all their generated PV energy in return for feed-in credits and purchase their electricity at prevailing retail rates. Gross metering has been seen as a good way to encourage households to invest in solar because the payments received from supplying electricity to the grid are very obvious to the '*prosumer*' (ie those households who both produce and consume electricity).

Accelerated uptake of solar panels by Sydney households was evident by June 2010. Among the 4,819 households in our sample, 1,951 had installed solar panels during the sample period and were receiving feed-in-tariffs. In particular, 1,641 of these households installed solar panels before the end of October 2010 and were considered early adopters of the technology. They were on 60c/KWh solar feed-in tariff. 240 of these households installed solar panels after 31 October 2010 and they were on 20c/KWh solar feed-in tariff. The NSW Solar Bonus Scheme ends on 31 December 2016, so both feed-in-tariffs rates cease on this date. On the other hand, 2,868 households had never installed solar panels and served as the control group for this study. The data covered 162 unique postcodes in Sydney and was considered to be a representative sample of households in Sydney with a gross metering solar system. The control group was sampled from non-solar separate(detached) houses from the same postcodes. The number of households in each Sydney postcode for the 60c, 20c and Control group is found in Appendix 1.The key variables used in the analysis are defined below. They are restricted to those data fields used in customer billing by the energy utility and as such do not have information related to the household (eg. size, income etc) or dwelling (eg. age, type), attributes that would have proven useful in exploring patters of domestic energy consumption more deeply. The billing data does, however, contain the information critical to an examination of the rebound effect associated with installation of solar PV. The exploratory data analysis in this study was undertaken on annual data, comparing year on year percentage change in average quarterly electricity consumption for the two 'solar' groups covering the year after PVs were installed (Table 1). The econometric modelling was undertaken on the full sample of households, covering up to the last quarter of 2014 (Table 2).

TEC: Total Electricity Consumption (KWh)

Total electricity consumption data was based on quarterly electricity consumption on various network bill rate codes and were combined irrespective of the time of use (eg, peak, shoulder, etc). Figure 8 shows average electricity consumption (KWh) per household for each quarter over the sample period. It is clear that June and September winter quarters recorded much higher electricity usage due to heating and lighting needs.

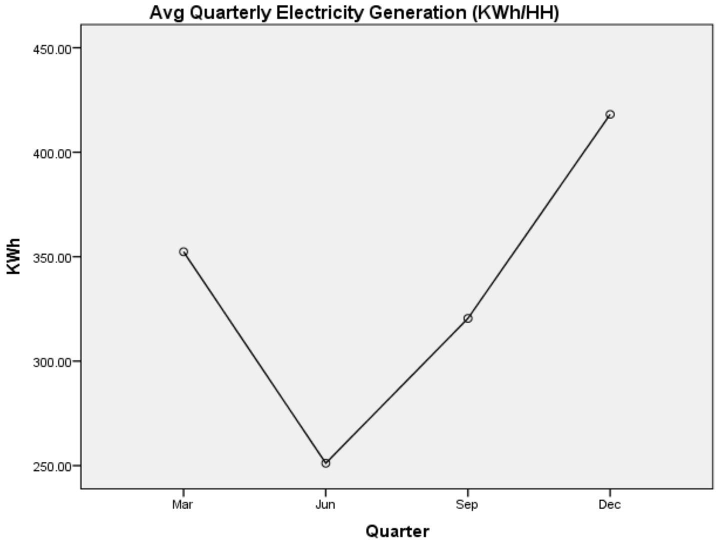
Figure 8 Sample average quarterly electricity consumption per household (KWh/HH) from 2007 to 2014.



GEG: Gross Electricity Generation (KWh)

Gross electricity generation was calculated as the total amount of solar-generated electricity exported back into the grid (irrespective of the tariff scheme the household was on). Figure 9 shows average quarterly electricity generation (KWh) per household post Jun-2010. As expected, a significantly higher amount of solar electricity was generated during December and March summer quarters.

Figure 9 Sample average quarterly electricity generation per household (KWh/HH) from 2010 to 2014.



SolarFiT: Solar Feed-in-Tariff ($)

Solar Feed-in-Tariff (also termed ‘Solar Bonus’ by the NSW government) was calculated simply as:

$$SolarFiT = GEG * Block\ Tariff$$

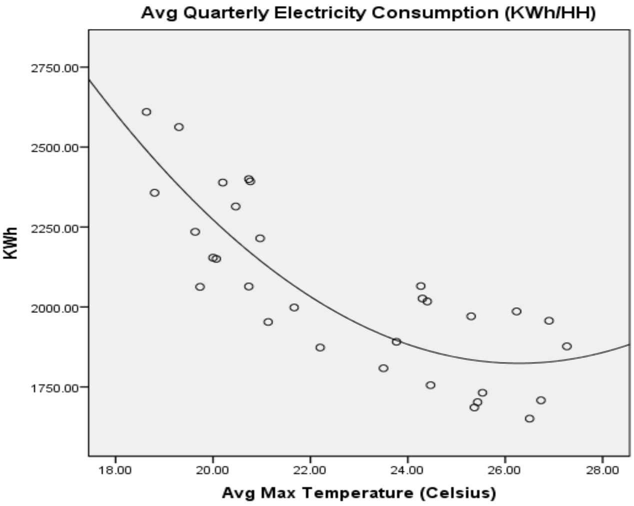
As previously mentioned, there are two types of households with solar panels, and generally speaking the early adopters of the technology were on the 60c/KWh tariff and the later adopters were on the 20c/KWh tariff.

To put it in context, according to the latest report by Australian Energy Market Commission on residential electricity price trends in 2014, the representative retail offer for Ausgrid was only 27.87c/KWh in NSW. The early adopters would have received a feed-in-tariff (60c/KWh), that was more than double of what they would have paid for electricity from the grid on a per KWh basis. To put it differently, every KWh of solar electricity generated would be equivalent to consuming more than two KWh’s of electricity for free. Even for the late adopters, the feed-in-tariff (20c/KWh) was still equivalent to more than 70% of what they paid for grid electricity on a per KWh basis. It could be expected that such a generous scheme would lead to a change in electricity consumption patterns.

TMAX: Average Maximum Temperature (°C)

Quarterly average maximum temperature in Sydney was obtained from the Bureau of Meteorology website for Sydney City (151.21E/33.87S). Figure 10 shows the relationship between average quarterly electricity consumption and average quarterly maximum temperature. It is clear that as the maximum average temperature decreased the amount of electricity consumed increased (*heating* for comfort effect). It is also apparent that as average temperatures increase above 26° there is also a rise in electricity consumption (*cooling* for comfort effect). This relationship appears to be nonlinear and is indicative of the conclusions now being made by international research panels (de Dear et al 2013) that humans are the final arbiters of thermal comfort, not instrumental settings on thermostats.

Figure 10 Sample average quarterly electricity consumption per household (KWh/HH) vs average quarterly maximum temperature (Celsius).



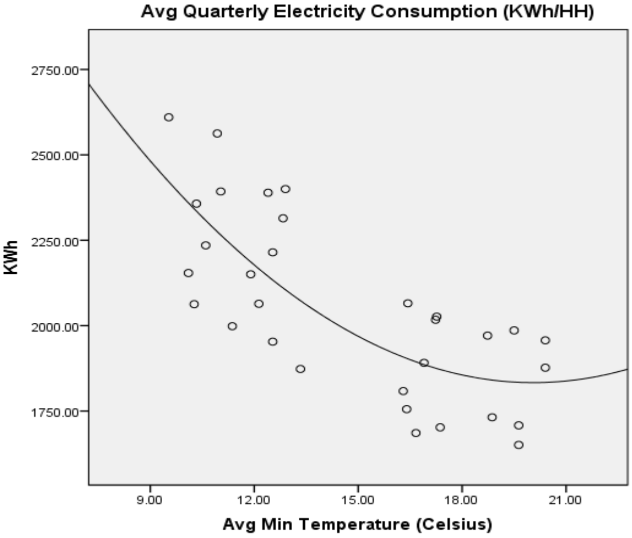
TMAXSQ: Average Maximum Temperature Squared (℃^{2})

As shown in Figure 10, the relationship between average electricity consumption and average maximum temperature follows an inverted U-shape, the relationship between the two variables is nonlinear and a quadratic term is also included in our subsequent regression analysis. In general, the lower the maximum temperatures, the winter heating effect dominates: the lower the temperature the higher the electricity consumption. On the other hand, with higher maximum temperatures, the summer cooling effect dominates: the higher the temperature the higher the electricity consumption. The inclusion of both *TMAX* and *TMAXSQ* would capture both the winter effect and the summer effect.

TMIN: Average Minimum Temperature (℃)

Quarterly average minimum temperature in Sydney was obtained from the Bureau of Meteorology and was included in the model for the same reason as *TMAX*. Figure 11 shows a similar pattern as the one observed for *TMAX*.

Figure 11 Sample average quarterly electricity consumption per household (KWh/HH) vs average quarterly minimum temperature (Celsius)



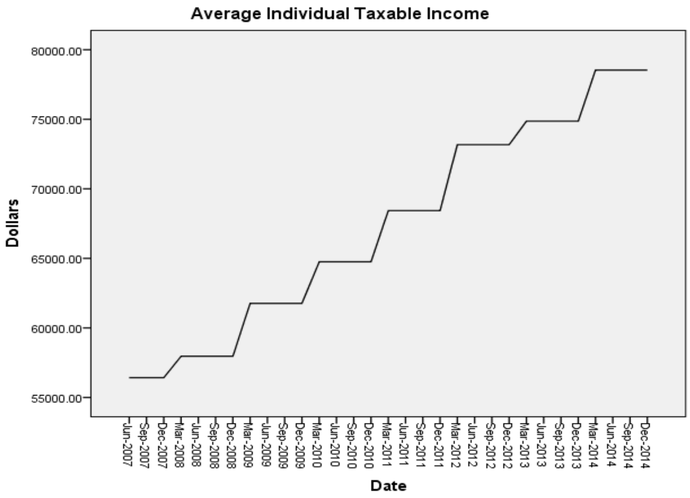
TMINSQ: Average Minimum Temperature Squared (℃^{2})

The squared minimum temperature was included for a similar reason as *TMAXSQ*

TaxInc: Personal Taxable Income

Personal taxable income data for each household's corresponding postcode was obtained from the Australian Tax Office (ATO). Figure 12 shows the increasing trend in personal taxable income in Sydney over time, and it was included in our model to capture the possible presence of an income effect on electricity consumption. It is a crude measure and subsequent modelling results need to be viewed in this light. It was also not possible to assemble any indicators of electricity pricing at household level for this project since Ausgrid is an electricity wholesaler and does not control the prices that electricity retailers offer to individual customers in Sydney (highly variable and dynamic). Nor is there a Consumer Price Index value for electricity at postcode level.

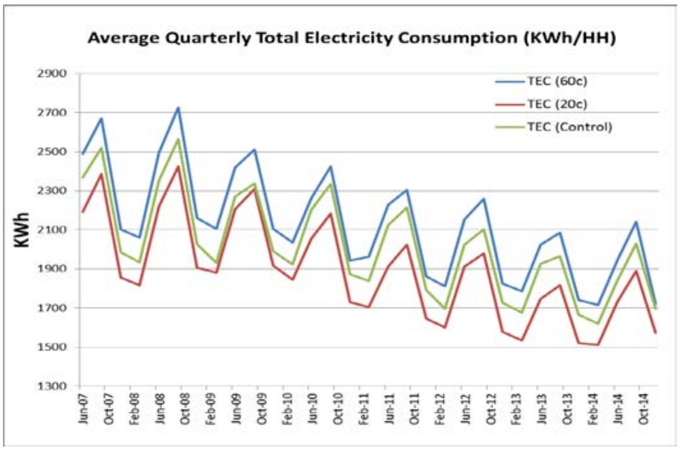
Figure 12 Sample average individual taxable income (dollars) from Jun-2007 to Dec-2014



Time Series Overview of Electricity Consumption and Solar Electricity Generation

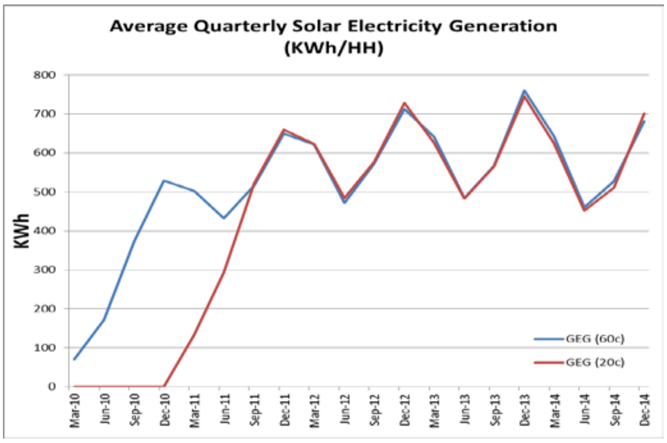
We start with a time series overview of the electricity consumption and generation data. Figure 13 shows the time series plot of quarterly electricity consumption per household from the 60c solar FiT group, the 20c solar FiT group, and the control group respectively. Throughout the sample period, the 60c group consumed the highest amount of electricity on average, with the 20c group consuming the least, and the control group being somewhere in between. It is likely that these are three distinct socio-demographic groups, but the billing data provided by Ausgrid provides no additional socio-demographic data. All groups exhibited significant seasonal fluctuations, as well as a significant downward trend over time, which was most likely due to improvements in energy efficiency level of household electrical appliances and houses/apartments (as previously referenced) and possible conservation behaviours linked to the increase in electricity prices.

Figure 13 Sample average quarterly total electricity consumption per household (KWh/HH) from Jun-2007 to Dec-2014 for the 60c group, the 20c group, and the control group



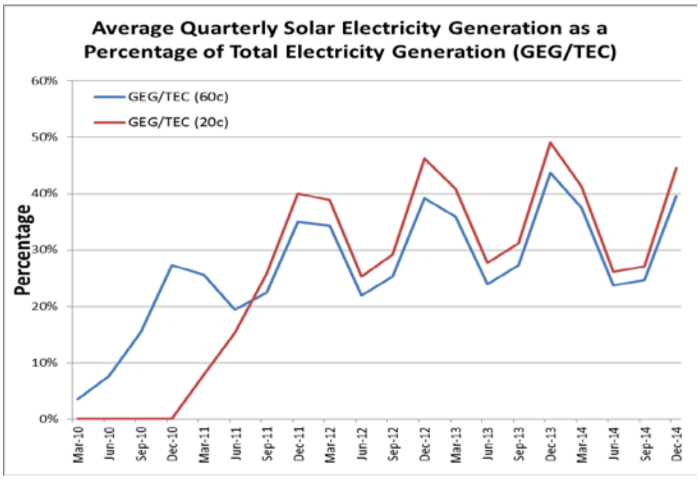
Moving on to a time series overview of solar electricity generation, Figure 14 shows the time series plot of quarterly solar electricity generation per household for the 60c and 20c groups. It is clear that once the adoption of solar panels stabilized for each group, average solar electricity generation per household was very similar between the two groups. There were significant seasonal fluctuations, and the time series showed a slight increasing trend over time.

Figure 14 Sample average quarterly solar electricity generation per household (KWh/HH) from Jun-2010 to Dec-2014 for the 60c group and the 20c group



For those households with solar PV installed, solar electricity generation as a proportion of their total electricity consumption is depicted in Figure 15. This percentage increased over time and exhibited significant seasonal fluctuations. As of 2014, this percentage was 40% for the 60c group and 45% for the 20c group respectively during the Dec summer quarter, when solar electricity generation reached its maximum. Even during the June winter quarter, when solar electricity generation was significantly lower due to reduced sunlight, this percentage still reached a significant 24% for the 60c group and 26% for the 20c group.

Figure 15 Sample average quarterly solar electricity generation as a percentage of total electricity consumption for the 60c group and the 20c group



Finally, as an exploratory investigation into the impact of solar PV on household electricity consumption, Table 1 compares the year-on-year percentage change of average quarterly consumption for the following years: 2010 (when all early adopters (60c group) and some of the late adopters (20c group) completed their solar PV installation); 2011 (when the remaining late adopters (20c group) completed their solar PV installation); and 2012 (when solar PV had become a regular component for all green households). Year-on-year percentage changes were negative for all three groups, which was as expected due to the general decreasing trend in electricity consumption. However, a closer inspection reveals that for the 60c group the largest negative value (-5.2%) was recorded in 2010, when 60c households had completed their solar PV installation. For the 20c group, the two largest negative values (-6.1% and -6.7%) were recorded in 2010 and 2011 respectively, when some 20c households had completed their solar PV installation in 2010 and some later in 2011. More tellingly, when the difference in the year-on-year percentage change is compared between the two solar groups and the Control group, during the years when solar PV was introduced into both 60c and 20c households, on average they consumed *less* electricity than the Control group. This was consistent with economic expectations, as solar PV was a big expense item and electricity expenditure could have been reduced to pay for some of that cost. However, in the year(s) *after* the introduction of solar PV when household behaviour could be expected to have 'stabilised' (ie circa 2012), both the 60c group and the 20c group experienced a *lower* year-on-year percentage decrease relative to the Control group. In other words, the introduction of solar PV appeared to have slowed down the general decreasing trend in electricity consumption for the solar households.

Table 1 Comparison of year-on-year percentage change of average quarterly electricity consumption of the three groups for year 2010, 2011 and 2012

	Average Quarterly Consumption (KWh) by Group			**Year on Year % Change by Group**			**Difference in Year on Year % Change relative to the Control Group**	
Year	**60c**	**20c**	**Control**	**60c**	**20c**	**Control**	**60c**	**20c**
2010	2166	1953	2083	***-5.2%***	***-6.1%***	-2.3%	***-2.9%***	***-3.8%***
2011	2090	1823	1993	-3.5%	***-6.7%***	-4.3%	0.8%	***-2.3%***
2012	2012	1768	1888	-3.7%	-3.0%	-5.3%	1.5%	2.3%

From the point of view of achieving a low carbon society, both the reduction of total electricity consumption and the increase in green energy production are good news. However, as will be demonstrated in subsequent econometric analysis, presence of a rebound effect could undermine a significant percentage of this gain.

A Dynamic Panel Model

The most common method for estimating rebound effects is by econometric analysis of data of the type assembled for this study (Sorrell et al 2009). To fully understand the impact of solar PV on Sydney household electricity consumption, while having systematically controlled for seasonal, weather, and income effects, a dynamic panel model with the following econometric specification was estimated:

$$\begin{aligned}
TEC_{i,t} = {} & \alpha_i + \rho TEC_{i,t-1} + \sum_{k=2008}^{2014} \alpha_{60c,k} Year_{k,t} + \sum_{k=2008}^{2014} \alpha_{20c,k} Year_{k,t} + \sum_{k=2008}^{2014} \alpha_{con,k} Year_{k,t} \\
& + \sum_{k=Mar}^{Sep} \gamma_{60c,k} Qtr_{60c,k,t} + \sum_{k=Mar}^{Sep} \gamma_{20c,k} Qtr_{20c,k,t} + \sum_{k=Mar}^{Sep} \gamma_{con,k} Qtr_{con,k,t} \\
& + \beta_{60c,1} TMAX_{60c,t} + \beta_{60c,2} TMAXSQ_{60c,t} + \beta_{60c,3} TMIN_{60c,t} + \beta_{60c,4} TMINSQ_{60c,t} \\
& + \beta_{20c,1} TMAX_{20c,t} + \beta_{20c,2} TMAXSQ_{20c,t} + \beta_{60c,3} TMIN_{20c,t} + \beta_{60c,4} TMINSQ_{20c,t} \\
& + \beta_{con,1} TMAX_{con,t} + \beta_{con,2} TMAXSQ_{con,t} + \beta_{con,3} TMIN_{con,t} + \beta_{con,4} TMINSQ_{con,t} \\
& + \theta_{60c} TaxInc_{60c,t} + \theta_{20c} TaxInc_{20c,t} + \theta_{con} TaxInc_{con,t} \\
& + \gamma_{60c} SolarFiT_{60c,t} + \gamma_{20c} SolarFiT_{20c,t} + \varepsilon_{i,t}
\end{aligned} \tag{eq2}$$

Where:

- *TEC* is total quarterly electricity consumption for the household on various network bill rate codes and are combined irrespective of the time of use (eg, peak, shoulder, etc).
- i is the unique household indicator and t is the time period (Qrt-Year) indicator.
- α_i captures the household-specific individual fixed effects. They are not directly interpretable and are removed during the estimation process through mean-deviation.
- ρ captures the temporal dependence in the data, as household electricity consumption is likely to be serially correlated and current consumption level is likely to be similar to consumption levels of previous quarters, even after controlling for seasonal variations. For instance, across a large sample household size tends to change gradually, electrical appliances accumulate over time, household financial situations tend not to change suddenly, etc.
- $\{\alpha_{60c,k}, \alpha_{20c,k}, \alpha_{con,k}\}$ $(k = 2008, 2009, \ldots, 2014)$ account for year-specific time fixed effects and they account for the general trend in average household electricity consumption. They are separately estimated for each of the three groups.
- $\{\gamma_{60c,k}, \gamma_{20c,k}, \gamma_{con,k}\}$ $(k = Mar, Jun, Sep)$ account for the seasonal effects (with the Dec quarter used as a reference quarter) and are estimated separately for each of the three groups.
- $\{\beta_{60c}, \beta_{20c}, \beta_{con}\}$ account for the effect of temperature variations on electricity usage and are estimated separately for the three groups.
- $\{\theta_{60c}, \theta_{20c}, \theta_{con}\}$ account for the income effect on electricity usage and are estimated separately for the three groups. Lastly and most importantly for this study,
- $\{\gamma_{60c}, \gamma_{20c}\}$ systematically measure the extent to which solar feed-in-tariffs affected household electricity usage and are estimated separately for the 60c group and the 20c group.

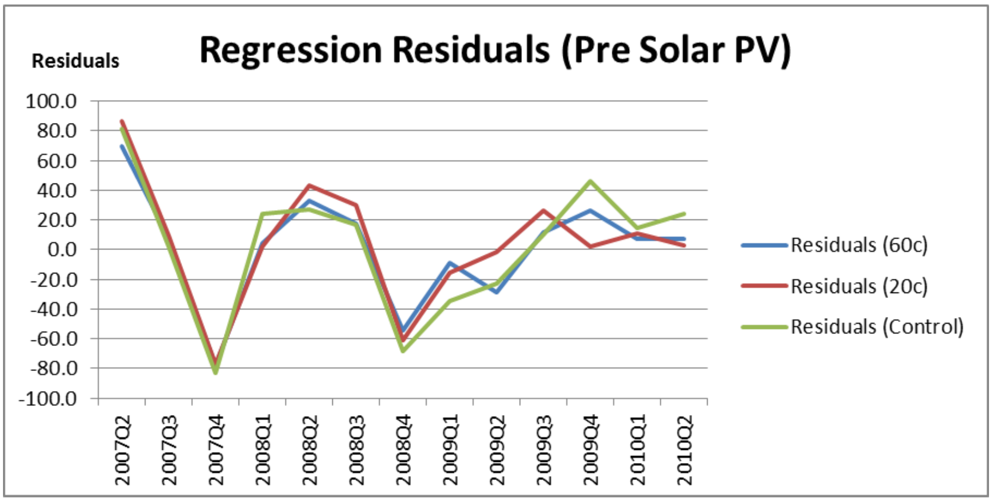
A dynamic panel data model accounts for: (i) cross-sectional variations between households, such as their varying levels of solar FiT received, personal taxable incomes, etc; (ii) temporal variations facing all households, such as time trends, seasonal temperature fluctuations, etc; (iii) temporal dependence in the data, as household electricity consumption is likely to exhibit significant inertia and is expected to change slowly over time for a large sample as is the case in this study.

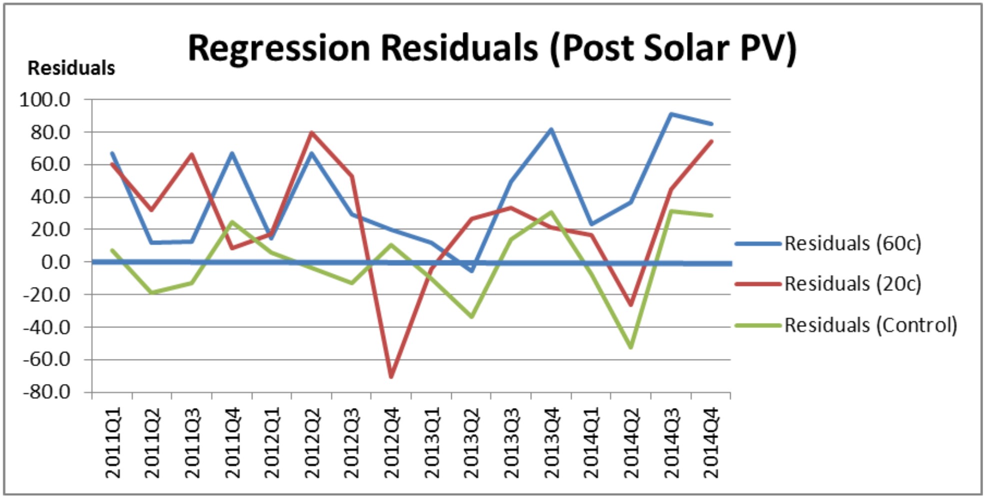
The standard estimator for a fixed effects panel data model is the LSDV (least squares dummy variable) estimator, which mean-deviates the equation to eliminate the time invariant fixed effects. Specifically, as the mean of the variables has been removed from both sides of the equation, household-specific individual fixed effects (i.e, α_i) are systematically eliminated as they are time-invariant for each individual household. When applied to a dynamic panel model, the presence of the lagged dependent variable can become problematic, as the demeaned lagged dependent variable and the demeaned error term are correlated of order $(1/T)$, where T is the sample size in the temporal dimension. Fortunately, as $T \rightarrow \infty$, size of the correlation becomes negligible and the bias disappears (Baltagi, 2001; Hsiao, 1986; Nickell, 1981). As our data consists of quarterly observations over the course of 8 years, we argue that the biasing effects are negligible and proceed to estimate our model using the LSDV estimator.

Consequences of Ignoring the Impact of Solar FiT

Before presenting the complete estimation results from equation (2), it is instructive to first investigate what would happen if the impact of solar FiT were ignored. Specifically, equation (2) was first estimated with both $SolarFiT_{60c,t}$ and $SolarFiT_{20c,t}$ removed. Figure 16 shows the regression residuals, averaged for each quarter for each group (60c, 20c, and control), and separated into Pre Solar PV period and Post Solar PV period.

Figure 16 Residuals from estimation of equation (2) with solar FiT variables removed.

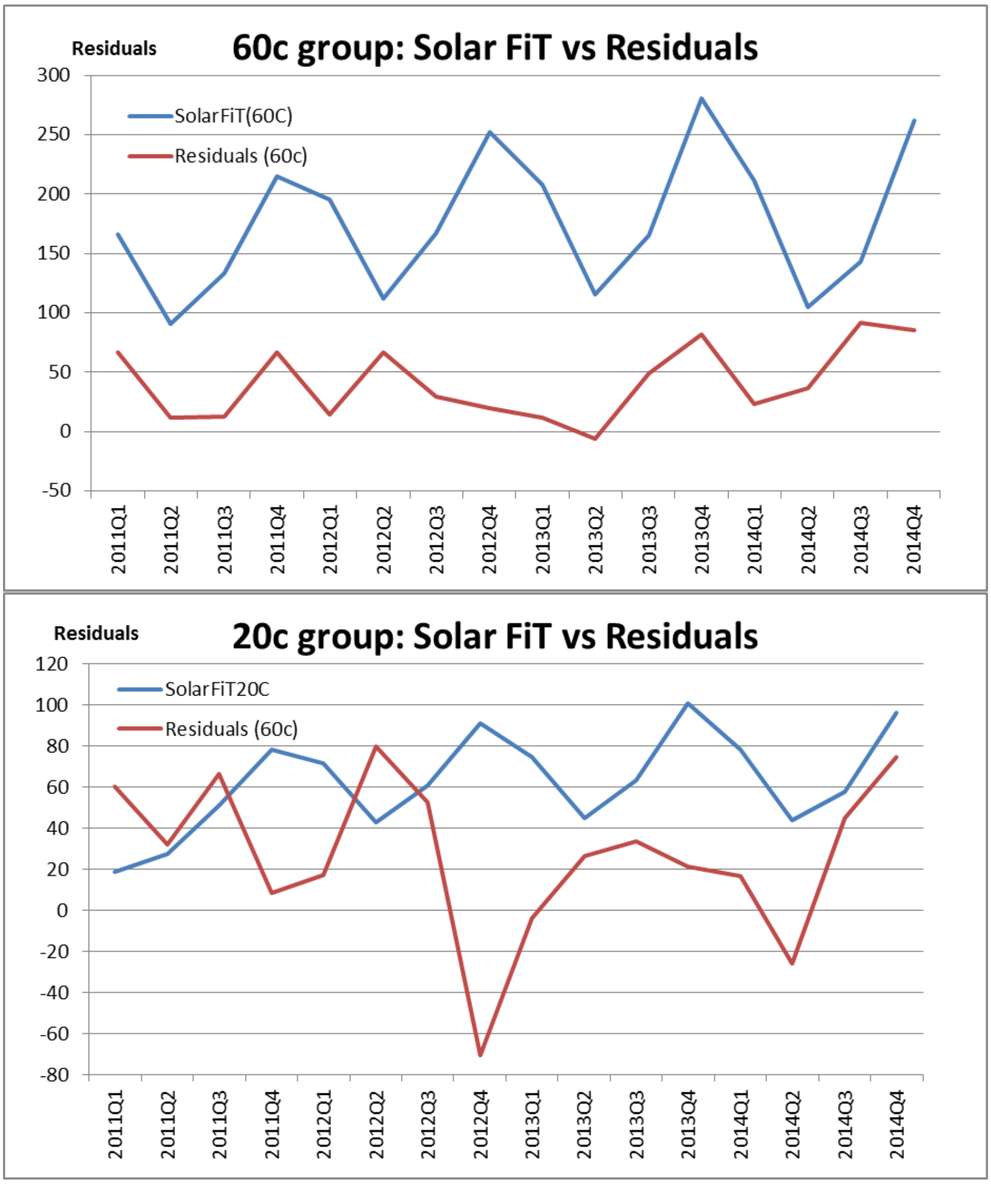




Pre introduction of solar PV, residuals from all three groups exhibited very similar behavior, fluctuating above and below zero, which is exactly what one would expect. However, post introduction of solar PV, while the Control group still retained constant fluctuation above and below zero, both the 60c and 20c group had residuals that stayed above zero for most quarters. A positive residual means that the actual total electricity consumption exceeded the predicted amount, which is exactly what one would expect in this case, as solar FiT has been removed from the model.

To further establish the link between the behavior of the residuals and solar FiT, they are plotted against each other in Figure 17:

Figure 17 Residuals from estimation of equation (2) with solar FiT variables removed and plotted against solar FiT.



For the 60c group, it can be seen that there is a strong correlation between the two series, both in terms of their overall increaseing trajectory and their seasonal fluctuations. While the 20c group had a much smaller sample size (240), similarities between the two series are still evident.

In summary, in a model where all signfiicant factors had been accounted for except for solar FiT, the residuals behaved differently between the Control group and the two solar PV groups. The differences in the residuals were highly correlated with the presence/absence of solar FiT.

Dynamic Panel Model Results

Coefficient estimates of the model, together with their corresponding p-values, are presented in Table 2.

Table 2 Dynamic Panel Model Results

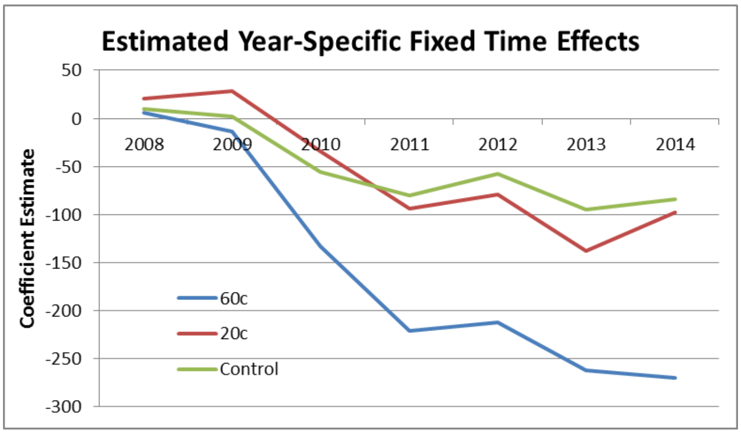
Variable	Estimate	P-value	Variable	Estimate	P-value
$TEC_{i,t-1}$	0.593	0.000***	$TMAX_t(60c)$	- 402.700	0.000***
$Y2008\ (60c)$	5.844	0.701	$TMAXSQ_t(60c)$	8.533	0.000***
$Y2009\ (60c)$	- 14.130	0.299	$TMIN_t(60c)$	- 38.880	0.309
$Y2010\ (60c)$	- 133.200	0.000***	$TMINSQ_t(60c)$	1.761	0.150
$Y2011\ (60c)$	- 220.800	0.000***	$TMAX_t(20c)$	- 490.200	0.000***
$Y2012\ (60c)$	- 212.300	0.000***	$TMAXSQ_t(20c)$	10.670	0.000***
$Y2013\ (60c)$	- 261.800	0.000***	$TMIN_t(20c)$	168.000	0.057*
$Y2014\ (60c)$	- 270.300	0.000***	$TMINSQ_t(20c)$	- 4.678	0.099*
$Y2008\ (20c)$	20.490	0.564	$TMAX_t(con)$	- 593.900	0.000***
$Y2009\ (20c)$	28.410	0.391	$TMAXSQ_t(con)$	12.730	0.000***
$Y2010\ (20c)$	- 34.400	0.364	$TMIN_t(con)$	93.650	0.001***
$Y2011\ (20c)$	- 93.900	0.056*	$TMINSQ_t(con)$	- 2.945	0.001***
$Y2012\ (20c)$	- 79.200	0.235	$TaxInc_t(60c)$	- 0.001	0.250
$Y2013\ (20c)$	- 138.100	0.050**	$TaxInc_t(20c)$	- 0.004	0.171
$Y2014\ (20c)$	- 98.100	0.205	$TaxInc_t(con)$	- 0.003	0.001***
$Y2008\ (con)$	9.854	0.386	$SolarFiT_t(60c)$	0.349	0.000***
$Y2009\ (con)$	2.111	0.836	$SolarFiT_t(20c)$	0.837	0.000***
$Y2010\ (con)$	- 55.530	0.000***			
$Y2011\ (con)$	- 80.290	0.000***			
$Y2012\ (con)$	- 57.730	0.003***			
$Y2013\ (con)$	- 94.520	0.000***			
$Y2014\ (con)$	- 84.350	0.000***			
$Qtr1_t(60c)$	140.100	0.000***			
$Qtr2_t(60c)$	591.900	0.000***			
$Qtr3_t(60c)$	481.000	0.000***			
$Qtr1_t(20c)$	87.100	0.207			
$Qtr2_t(20c)$	517.200	0.000***			
$Qtr3_t(20c)$	538.900	0.000***			
$Qtr1_t(con)$	136.600	0.000***			
$Qtr2_t(con)$	519.400	0.000***			

Note: *** indicates significance at 1% level; ** indicates significance at 5% level; * indicates significance at 10% level.

The lagged dependent variable $TEC_{i,t-1}$ is found to be positive (0.593) and highly significant $(P = 0.000)$. This is consistent with literature and our expectations, as household electricity demand typically exhibits significant inertia; i.e., a similarity in levels of consumption by households for consecutive quarters.

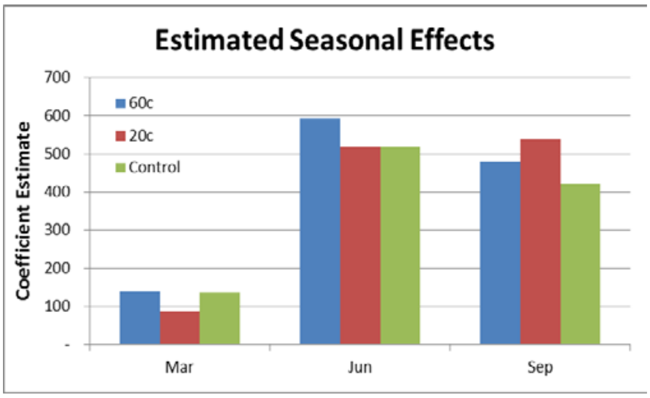
The estimated year-specific fixed time effects are shown in Figure 18. Although their values are not directly interpretable (as the equation was estimated in its mean-deviated form), they are significant and decreasing over time for all three groups. This is consistent with our expectation, as technological improvements and general energy efficiency gains have contributed significantly to reduction in average energy use by households. Moreover, after controlling for effects of other explanatory variables, it appears that the year-on-year reductions of electricity consumption of the 60c group were in general the greatest, while the 20c group and the control group were on par with each other and slightly lower. This is consistent with the assumption that the 60c group were early adopters of solar technology and were possibly early adopters of green technologies in general. But they consumed the most electricity (see Figure 13).

Figure 18 Estimated year-specific fixed time effects for the three consumer groups



The estimated seasonal effects are shown in Figure 19. As seasonal and temperature variations jointly create the weather component, these seasonal effects cannot be interpreted in the same way as the observed seasonal variations in electricity consumption. Nonetheless, consistent with our expectations, seasonal effect was estimated to be the highest for June and September quarters. Moreover, these estimates were found to be similar in magnitude amongst the three groups.

Figure 19 Estimated seasonal effects for the three consumer groups



Temperature fluctuations are also found to be significant determinants of energy consumption. Figure 20 shows the estimated coefficients for average maximum temperature ($TMAX$) and its squared term ($TMAXSQ$) for the three groups respectively. The estimated coefficients are negative and significant for $TMAX$ for all three groups, consistent with the expectation that the higher (lower) the average maximum temperature the lower (higher) the electricity consumption due to heating needs. Meanwhile, the estimated coefficients are positive and significant for $TMAXSQ$ for all three groups, consistent with our observation in Figure 10 that this relationship is nonlinear, and at the higher end of maximum temperature the summer cooling effect dominates and the relationship between temperature and electricity consumption is positive. Interestingly, the magnitude of these estimated coefficients is the smallest for the 60c group, followed by the 20c group, with the control group being the largest. This suggests that the 60c group is least affected by temperature variations. When faced with a warm winter the 60c group is least likely to reduce their heating consumption, and when faced with a cool summer the 60c group is least likely to reduce their cooling consumption. On the other hand, Figure 21 shows the estimated coefficients for average minimum temperature ($TMIN$) and its squared term ($TMINSQ$) for the three groups respectively. The estimated coefficients are positive and significant for $TMIN$ for the 20c group and the control group, consistent with the expectation that the higher (lower) the average minimum temperature the higher (lower) the electricity consumption due to cooling needs. Meanwhile, the estimated coefficients are negative and significant for $TMINSQ$ for these two groups, consistent with our observation in Figure 10 that this relationship is nonlinear. These estimates again confirm that the 60c group is least affected by temperature variations in both summer and winter. Clearly, residents in high income societies are 'comfort seekers'. There is a band of temperatures above and below which most households will seek artificial heating and cooling - with an attendant impact on energy use.

Figure 20 Estimated coefficients for average maximum temperature (TMAX) and its squared term (TMAXSQ) for the three consumer groups.

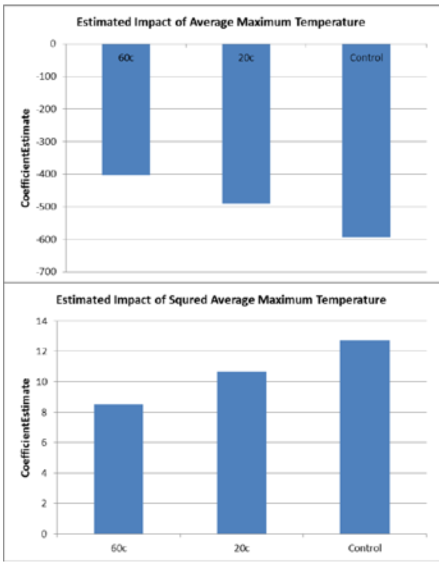
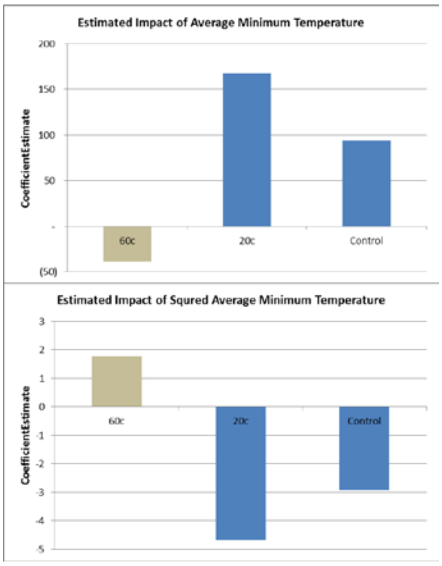


Figure 21 Estimated coefficients for average minimum temperature (TMIN) and its squared term (TMINSQ) for the three consumer groups

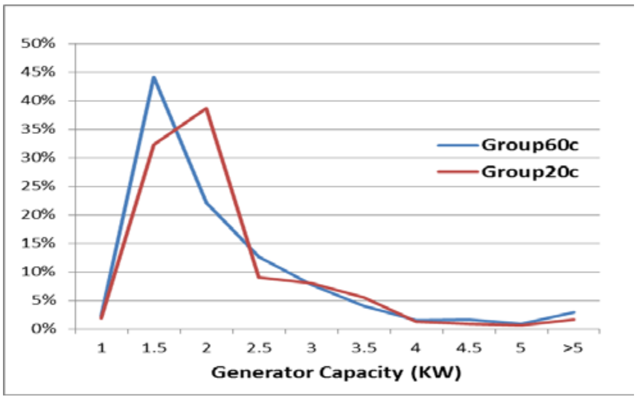


The income effect ($TaxInc_t$) is found to be negative (- 0.003) and significant ($P = 0.001$) only for the Control group. It may be a reflection of the fact that both the 60c group and the 20c group received financial incentives through solar FiT and such an income effect was not likely to be present. Newton and Newman (2013) also found that levels of PV installation were lowest in low income neighbourhoods as well as in the highest income suburbs; with highest rates of take-up in the middle income suburbs. The socio-economics in this fast changing area require deeper analysis than is possible here.

Finally, $SolarFiT_{i,t}$ is found to be positive and highly significant for both the 60c group and the 20c group, confirming that the solar feed-in-tariffs created a significant rebound effect amongst Sydney households. Specifically, for the 60c group, it is estimated that every $1 of solar feed-in-tariff paid to Sydney households resulted in 0.349 KWh increase each quarter, and for the 20c group the increase is estimated to be 0.837 KWh.

It is interesting to look at a comparison between the size of average solar generator capacities installed by the 60c group and the 20c group. Figure 22 compares the distributions of PV electricity generation capacities between the two groups. It is clear that the 20c group tended to have slightly larger generation units installed compared to the 60c group, consistent with the trend towards larger capacity PV installations nationally (see Figure 6) and the hypothesis that this group were trying to “cash in” as much as they could before the solar feed-in-tariff is eventually phased out. Interestingly, at the maximum range of the legal limit of generator capacity (10 KW), there appears to be more 60c group households than 20c households. This suggests that, while on average the late adopters had larger solar PV systems, a small number of early adopters took full advantage of the system and installed the largest generation capacity allowed to receive the NSW Solar Bonus Scheme feed-in tariff.

Figure 22 Distribution of solar generator capacities for the 60c group and the 20c group



Rebound Effect Calculation

To further analyse the size of the rebound effect, we utilize the fact that every \$1 of solar feed-in-tariff translates to $\frac{\$1}{\$0.6/KWh} = 1.667$ KWh and $\frac{\$1}{\$0.2/KWh} = 5$ KWh of solar electricity generated for the 60c group and the 20c group respectively. This means that every 1 KWH of energy generated from solar panels lead to an estimated $\frac{0.349}{1.667} = \ 0.209$ KWh and $\frac{0.837}{5} = 0.167$ KWh increase in electricity consumption respectively. In other words, on a per KWh basis, the rebound effect is estimated to erode about 20.9% of the benefit of renewable energy generated by solar PV for the 60c group, and 16.7% for the 20c group.

More specifically, for each household i at time t the rebound effect is calculated as:

$$ReboundEffect_{i,t}(60c) = 0.209 * GEG_{i,t}(60c)$$
$$ReboundEffect_{i,t}(20c) = 0.167 * GEG_{i,t}(20c)$$

(eq3)

Equation (3) is subsequently evaluated for all households post solar panel installation and averaged across all households for each quarter. Figure 23 compares average electricity consumption, average solar electricity generation, and average rebound effect for both the 60c group and the 20c group. It is clear that while average electricity consumption exhibited an overall decreasing trend, average rebound effect did not. When the rebound effect is viewed as a percentage of total electricity consumption for the two groups, the result is shown in Figure 24. For both the 60c group and the 20c group, this percentage is found to be seasonally fluctuating and increasing over time. In the latest year of 2014, this percentage fluctuated between $\sim 5\%$ and $\sim 8\%$ for the 60c group, and between $\sim 4.5\%$ and $\sim 7.5\%$ for the 20c group.

Figure 23 Average electricity consumption, solar electricity generation, and rebound effect for the 60c group and the 20c group

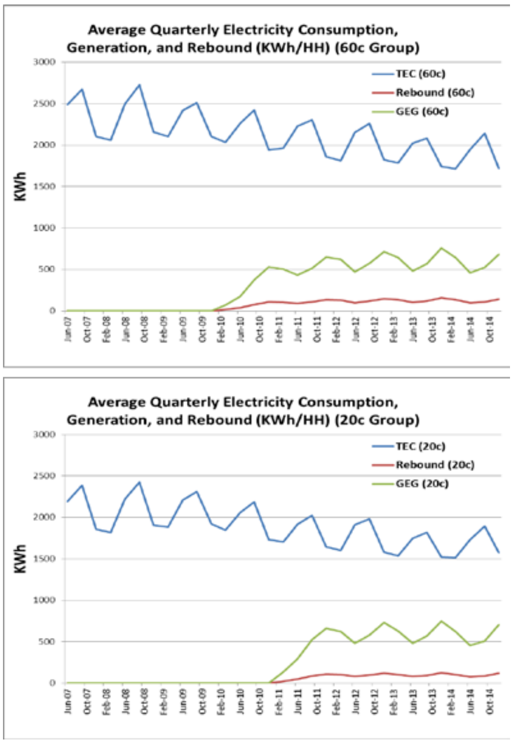
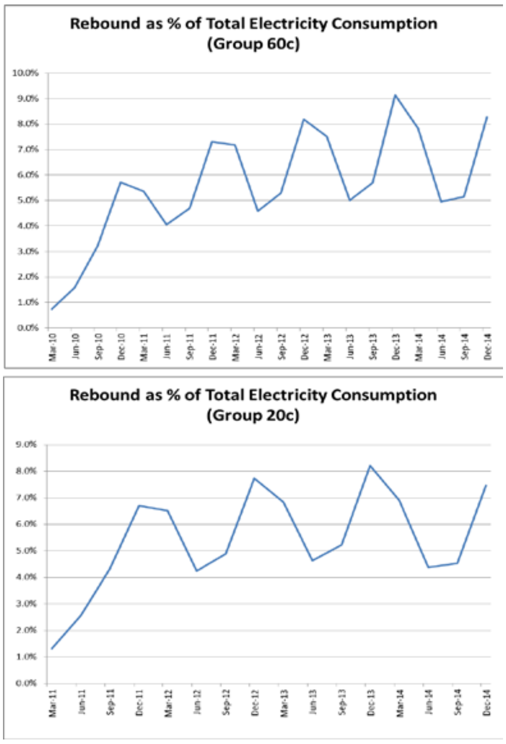


Figure 24 Rebound effect viewed as a percentage of total electricity consumption for the 60c group and the 20c group



Conclusions

It is clear that the rebound effect related to installation of domestic solar PV that includes a solar feed in tariff is real in the context of households that have taken up this technology as part of the NSW government Solar Bonus Scheme. Under this scheme two different feed-in tariffs have operated: 60c/kWh and 20c/kWh. Households responded to the initial feed-in tariff more enthusiastically than state governments had anticipated with a consequence that a second and lower feed-in tariff was instituted for the remainder of the scheme that is scheduled to finish on 31 December 2016. Installation of solar PV, while potentially replacing anywhere between 25% to over 40% of total domestic electricity consumption, also clearly triggered significant increase in electricity consumption as shown by the estimated rebound effect.

For the 60c group, rebound was found to be eroding approximately 20.9% of the benefit of renewable energy generated by PV. For the 20c group, the rebound effect was of the order of 16.7% on average during the period 2007-2014. Since the modelling was undertaken on billing data, one can only speculate on other factors that may explain the level of rebound effect found for the two groups of Sydney ‘solar’ households. Both the 60c group and the 20c group could be equally labelled as green pioneers (in their early adoption of PVs compared to the majority of the Australian population), profit maximisers (in their installation of large PVs to maximize their feed-in-tariff) and possibly green hypocrites (in the significant presence of rebound effects found in both groups; see Newton, 2013 for a further exploration of this type of behaviour), given the type of analyses presented in this study. In concert with other studies (Wood and Blowers 2015), this report affirms the policy rationale stated at the outset of this report in relation to the value of small scale solar PV: its contribution to a reduction in the amount of (fossil fuel based) electricity that needs to be produced for the grid and the associated mitigation of greenhouse gas emissions. Indeed, solar households in Sydney were found to generate between 25 and 40 percent of their total electricity consumption from renewables over the space of a year. Their impact, however, is less than what may have been estimated ---due to the operation of a clear rebound effect. Significant net energy and carbon savings still accrue, however. A rebound effect of this scale and in this context (ie where significant feed-in incentives were involved) should not be viewed as sufficient to derail small scale renewable energy policies (also see Gillingham et al, 2013), but needs to be taken into account when estimating the levels of supply of renewable energy required to meet future demand and the level of feed-in tariff that needs to be established. Indeed, this study is important to current inquiries seeking to identify what constitutes an appropriate feed-in tariff in an era when decarbonisation of the economy is assuming an ever-increasing political significance, Here attempts are being made to ‘*explore different opportunities through which a redesigned FiT can signal to investors, and potential investors, the ‘true value’ of the electricity they may have available for export into the electricity system…..[that is] how investors in distributed generation can be renumerated for the environmental and social benefits arising by virtue of that investment….the scale of those benefits and how they might be attributed to distributed generation. [viz.] the value of the emission avoided when distributed generation of low emissions intensity displaces centrally dispatched electricity’* (Essential Services Commission, 2016 p.ii).

This study does not necessarily provide a clear picture of the behaviour pathway associated with *future* rebound effects from roof top solar PV. As the generous feed-in tariffs studied here disappear, it is likely that any rebound effect would diminish as there will be no income windfall for those with PV systems. As the next phase of solar PV diffusion is set to evolve at the beginning of 2017 after the removal of government funded feed-in tariffs and the market takes over one can only speculate on likely trajectories of take-up and rebound. Indeed, there may be a drop-off in the attractiveness of roof-top solar to Australian households.However, the continued rate of decline in cost of solar PV as its performance continues to increase, plus the emergence of lower cost and higher performance battery storage technology suggests that the decarbonisation of Australia’s housing stock will continue. There are now multiple pathways along which this can occur as the staircase of measures designed to achieve carbon negative buildings illustrates (again, see Figure 1). It is clear, however, from this and other related studies, that household (occupant) behaviour remains a significant factor in a transition to low carbon living.

References

AEMC (2014) Residential electricity price trends, Final Report, Australian Energy Market Commission, Sydney

Australian Photovoltaic Institute (2015) Australian PV market (http://apvi.org.au/)

Baltagi, B. H. (2001). Econometrics analysis of panel data (2nd ed.). Chichester, England: Wiley.

Berkhout, P Muskens, W and Velthuijsen, J (2000) Defining the rebound effect, Energy Policy, 28, 425-432.

Berry S and Davidson K. (2015) Zero energy houses – are they economically viable ? Energy Policy , 43, 12-21

Brazzale R. (2014) A fifth year of declining power consumption, Climate Spectator, 10 January.

BREE 2014 (2014) Energy in Australia 2014, Bureau of Resources and Energy Economics, Canberra

Chitnis, M and Sorrell S (2015) Living up to expectations: estimating direct and indirect rebound effects for UK households, Energy Economics (accepted; accessed 3 Nov 2015)

de Dear, R., Akimoto, T., Arens, E., Brager, G., Candido, C., Cheong, D., Li, B., Nishihara, N., Sekhar, C., Tanabe, S., et al (2013). Progress in thermal comfort research over the last twenty years. Indoor Air: international journal of indoor air quality and climate, 23(6), 442-461

Department of Industry and Science (2014) Energy white paper, Australian Government, Canberra

Essential Services Commission (2016) The energy value of distributed generation, Government of Victoria, Melbourne

Giddings, B and Park M (2012) Eco-efficiency rebound effects associated with household energy using products, in P Israsena , J Tangsantikul and D Durling (eds) Proceedings of Design Research Society 2102, Vol 2, Bangkok, 623-639

Gill, Z., Tierney, M., Pegg, I., and Allen, N. (2010) 'Low energy dwellings: the contribution of behaviour to actual performance', Building Research and Information, 38: 491-508.

Gillingham K. Kotchen, M Rapson D and Wagner, G.(2013) The rebound effect is overplayed, Nature, Vol. 493, 475-6

Gram-Hanssen, K. (2013) 'Efficient technologies or user behaviour:which is more important when reducing household's energy consumption?' Energy Efficiency, 6(3): 447-457

Hamilton, C. and Denniss, R. (2005) Affluenza. When too much is not enough, Allen and Unwin, Sydney

Havas, L. Ballweg, J. Penna, C and race, D. (2015) Power to change: analysis of household participation in a renewable energy and energy efficiency program in Central Australia, Energy Policy, 87, 325-333.

Hsiao, C. (1986). Analysis of panel data. Cambridge: Cambridge University Press.

Hyndman, R. and Khandakar, Y. (2008). Automatic time series forecasting: theforecast package for R. Journal of Statistical Software, 26(3), 1-22.

Maxwell,D.et al (2011) Addressing the rebound effect, A project under the Framework contract ENV.G.4/FRA/2008/0112, Final Report 26 April, European Commission DG Environment.

Newton, P. and Meyer, D. (2016) Built Environment and Human Behaviour Challenges to Sustainable Consumption: a Gap Analysis, In Ethics and Morality in Consumption: Interdisciplinary Perspectives, edited by Deirdre Shaw, Terry Newholm , Andreas Chatzidakis and Michal Carrington , Routledge, London

Newton, P. and Newman, P.(2015) Critical Connections: The role of the built environment sector in delivering green cities and a green economy, Sustainability,7 (7), 9417-9443

Newton, P. and Newman, P. (2013) The Geography of Solar Photovoltaics (PV) and a New Low Carbon Urban Transition Theory, Sustainability, 5, 2537-2556

Newton, P. (2013) Green Hypocrites? Behaviour Change in a Consumerist Society, The Conversation, 19 April

Newton Peter W. and Tucker Selwyn N. (2011) Pathways to Decarbonising the Housing Sector: A Scenario Approach, Building Research and Information, 39(1), 34-50

Newton, P and Meyer, D. (2013) Exploring the Attitudes-Action Gap in Household Resource Consumption: Does ‘Environmental Lifestyle’ Segmentation Align with Consumer Behaviour?, Sustainability, 5, 1211-1233

Newton, P. Pears, A. Whiteman, J. and Astle, R. (2012) The Energy and Carbon Footprints of Urban Housing and Transport: Current Trends and Future Prospects, in R. Tomlinson (ed.) The Unintended City, CSIRO Publishing, Melbourne

Newton, P. (ed.) (2011) Urban Consumption, CSIRO Publishing, Melbourne

Nickell, S. (1981). Biases in dynamic models with fixed effects. Econometrica, 49, 1417-1426.

Pitt & Sherry and Swinburne University (2014) National energy efficient building project, report prepared for The Department of State Development, Adelaide.

Rowson J. (2013) A new agenda on climate change. Facing up to stealth denial and winding down on fossil fuels, Action and Research Centre, London.

Sorrell S, Dimitropoulos, J and Sommerville M (2009) Empirical estimates of the direct rebound effect: a review, Energy Policy, 37, 1356-1371

Sunikka-Blank, M. and Galvin, R. (2012) Introducing the prebound effect: the gap between performance and actual energy consumption, Building Research and Information, 40(2) 260-273

Swoboda, K (2014) Energy prices – the story behind rising costs, Parliament of Australia, Canberra

Wood, T and Blowers, D (2015) Sundown, sunrise. How Australia can finally get solar power right, Grattan Institute, Melbourne.

Appendix 1 Number of 60c, 20c and Control group households by Sydney postcodes

Postcode	60c Group	20c Group	Control Group	Postcode	60c Group	20c Group	Control Group
2008	1	0	1	2111	3	3	12
2010	2	0	3	2112	23	2	45
2015	2	0	3	2113	15	2	27
2016	1	1	4	2114	12	2	25
2018	6	3	13	2118	3	2	9
2019	3	2	8	2119	13	1	23
2020	2	1	5	2120	19	2	36
2021	2	0	3	2121	17	4	35
2022	1	0	3	2122	18	2	23
2023	3	0	8	2125	2	0	3
2024	4	0	2	2126	33	2	65
2025	0	0	2	2128	0	1	1
2026	6	1	14	2130	6	0	8
2029	2	0	1	2131	6	1	11
2030	3	0	4	2132	2	0	4
2031	9	1	15	2133	8	2	15
2032	3	1	9	2134	8	0	16
2033	2	2	6	2135	7	2	20
2034	9	2	13	2136	2	2	0
2035	12	2	24	2137	11	3	22
2036	7	2	17	2138	6	0	11
2037	5	2	10	2140	6	0	10
2038	6	0	8	2141	22	5	46
2039	6	1	11	2143	5	2	11
2040	3	2	7	2144	10	5	21
2041	7	1	7	2154	8	0	13
2042	5	0	9	2158	4	0	7
2043	4	1	5	2159	9	0	14
2044	7	0	9	2162	13	4	27
2045	1	0	1	2190	11	3	22
2046	10	4	21	2191	4	0	6
2047	2	0	3	2192	1	2	4
2048	2	2	6	2193	5	1	13
2049	5	0	8	2194	5	2	10
2050	1	0	0	2195	3	1	4
2060	2	0	2	2196	10	3	20
2062	4	0	5	2197	3	1	6
2063	5	0	7	2198	7	1	16
2064	3	0	7	2199	6	1	11
2065	9	0	16	2200	9	5	16
2066	13	2	28	2203	9	1	14
2067	13	1	26	2204	12	2	23
2068	11	0	15	2205	9	1	17
2069	9	1	19	2206	3	3	12
2070	12	0	20	2207	16	6	37
2071	8	0	14	2208	9	4	24
2072	2	0	2	2209	5	4	16
2073	6	0	9	2210	28	4	51
2074	19	2	34	2211	8	3	19
2075	10	0	17	2212	8	2	15
2076	13	2	22	2213	12	1	21
2077	31	2	50	2214	6	1	12
2079	5	2	14	2216	7	2	16
2080	1	0	1	2217	5	1	10
2081	7	0	10	2218	11	4	24
2082	8	2	17	2219	2	1	5
2083	3	0	5	2220	14	5	29
2084	2	0	3	2221	9	2	15
2085	6	2	15	2222	2	1	5
2086	11	1	20	2223	17	2	31
2087	17	2	27	2224	9	1	17
2088	8	1	17	2225	4	1	8
2089	1	0	2	2226	12	2	21
2090	1	2	3	2227	9	1	14
2092	10	0	14	2228	9	0	15
2093	20	2	38	2229	17	0	31
2094	4	0	6	2230	13	1	23
2095	3	1	7	2231	2	0	4
2096	11	2	22	2232	15	4	31
2097	9	1	16	2233	30	5	56
2099	29	1	50	2234	24	6	47
2100	19	2	35	2250	91	7	136
2101	16	1	25	2251	39	7	61
2102	7	0	13	2256	8	2	16
2103	8	1	16	2257	31	3	43
2104	2	1	4	2258	4	0	8
2105	2	1	7	2259	80	4	116
2106	2	0	4	2260	35	1	55
2107	10	0	13	2261	66	3	100
2108	2	1	3	2262	33	2	55
2110	4	0	7	2263	21	4	27

Source: http://www.ausgrid.com.au/Common/About-us/Corporate-information/Data-to-share/Solar-