Energy Policy 110 (2017) 313–324

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Assessing the impact of solar PV on domestic electricity consumption: Exploring the prospect of rebound effects

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ARTICLE INFO

Keywords:
Solar photovoltaics (PV)
Electricity consumption
Rebound effect
Feed-in tariff
Government incentives
Econometric modelling

ABSTRACT

This study examines patterns of electricity use by households in Sydney who have installed solar photovoltaic (PV) technology compared to those who have not in order to assess the impact of government solar incentive schemes, and to identify whether conservation or rebound (increased consumption) effects are associated with rooftop PV. Findings have significance in determining whether a rebound effect needs to be factored into projected energy/carbon savings from solar PV installation. At issue 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. Analysis and modelling was undertaken on billing data for the period 2007–2014 on a representative sample of 4819 households. The sample comprised three groups: households who were early adopters and installed PV under a 60 c/kWh gross feed-in tariff scheme, a group who installed under a 20 c/KWh gross feed-in scheme and a control group with no PV. Econometric modelling undertaken on energy consumption behaviour of households with versus without local renewable energy generation revealed that on a kWh basis, the rebound effect is estimated to erode up to one fifth of the carbon benefit of renewable energy generated by solar PV.

1. Introduction

An energy transition is now a clearly established global goal for the 21st century, with the UNFCCc (2016) in collaboration with 197 nations assembled in Paris for COP21, endorsing a framework agreement within which such a transformation is possible. Within this framework, each sovereign nation creates policies designed to significantly reduce their own greenhouse gas (GHG) emissions over the medium and long term. Regular reporting on emissions and actions taken to meet nationally established targets represent an important part of this agreement. In Australia, energy, emissions and climate policy continues to be a fraught area politically, given the strength of the protective regime that has grown up around the country's major fossil fuel related industries since the mid 20th century: coal mining for export and for local power generation. However, the weight of scientific evidence internationally (IPCC, 2013) and within Australia (BoM, 2016) in relation to the future disruptive impacts of climate change is now clear. Also, recent public opinion surveys suggest that three quarters of Australians believe climate change is occurring, with 60% agreeing that climate change is being driven by human induced industrial and urbanisation-related activities which have been rapidly accelerating over the past 70 years (Climate Institute, 2016; Steffen et al., 2015); and 90% indicate that responsibility for policy and action rests primarily with the federal government.

At the UNFCCC's COP21 Conference, Australia confirmed its emissions reduction target of 28% on 2005 levels by 2030 (DEE, 2016). Many countries are developing 2050 plans to help guide long term planning and decision-making by investors and the community, but in Australia only state governments have committed to longer term targets to date; for example, New South Wales, Victorian and South Australian governments have all committed to net zero emissions by 2050.

Renewable energy has a central role to play in this energy transition in Australia, but currently accounts for less than 6% of national energy supply (DIIS, 2016). In an attempt to stimulate supply of clean energy, the Australian government introduced (in 2009) its renewable energy target (RET) of 20% of national electricity generation by 2020 (www.cleanenergyregulator.gov.au) – a significant increase over the initial target of 2% established in 2001. In January 2011 the RET was split into two parts:

- A large scale RET – focused on incentives to establish solar farms, wind farms and hydro-electric power stations; and
- A small scale RET – with incentives for rooftop solar PV, small scale wind, hydro and solar water heating

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http://dx.doi.org/10.1016/j.enpol.2017.08.035
Received 19 January 2017; Received in revised form 14 August 2017; Accepted 17 August 2017
0301-4215/

Table 1
Representative state government feed-in tariff schemes for domestic small scale solar PV.
Source: www.solarspec.com.au

State	Schemes and dates	FiT rate (cents/kWh)	Duration of scheme
NSW	1/1/2010–31/10/2010	60	31/12/2016
	1/11/2010–28/4/2011	20	31/12/2016
Victoria	1/11/2009–31/12/2011	60	31/12/2024
	1/1/2012–31/12/2012	25	31/12/2016
	1/1/2013–31/12/2015	6.2	31/12/2015
	1/1/2016-	5	Current
Queensland	1/7/2008–9/7/2012	44	1/7/2028
	10/7/2012–30/6/2014	8	From 1/7/2015 succeeded by FiTs offered by retail market

In an attempt to directly stimulate consumer uptake of small scale rooftop solar systems, state governments became active participants in solar incentive schemes directed at households. Here state governments offered purchasers of solar PV units a guaranteed feed-in tariff (FiT) as an incentive payment for electricity fed into the national grid. This marked the emergence of distributed generation as a significant force in the decarbonisation of low density housing in Australian cities (Newton and Newman, 2013).

There was initial uncertainty at what level the FiT should be set. This is illustrated in Table 1, where the initial FiTs in all states were set as mandatory government rates at what could be classed as premium or subsidy levels. The rationale for subsidies in this context has been advanced by Loynes (2014) as:

- Compensating for the higher prices of solar PV that operated at the time
- Growing a local PV industry
- Encouraging electricity consumers to be more energy conserving and reduce carbon emissions
- Promote diversification and decentralisation of energy production

Government reviews after the first 12–18 months of operation of the 'solar bonus' schemes resulted in significant reductions in subsidised FiTs, followed shortly thereafter with shifts of all FiTs for new PV installations to market rates offered by electricity retailers.

The impact of these government incentives for installing rooftop solar were dramatic, as Fig. 1 illustrates.

The most recent report from the Clean Energy Council of Australia (2016) reveals that small scale (< 100 kW) rooftop solar installations rose from 3500 units nationally in 2007 to a peak of over 350,000 in both 2011 and 2012; creating a total installed capacity of over 4000 MW, and representing 16% of total clean energy generated in Australia in 2015.

With a reduction and subsequent removal of government subsidies in this area, annual levels of new PV installation have declined(in the state of New South Wales that includes Sydney, from *a* peak of 80,000 systems in 2011 to 30,000 in 2016; Clean Energy Council, 2017). This is at a stage when governments overseas and in Australia are setting long term (commonly 2050) targets for net zero emissions, in line with UNFCCC objectives. To achieve this level of decarbonisation will require a cocktail of policies ranging from replacement of coal-fired power stations by a mix of gas, wind farms and solar thermal plants, realising significant energy efficiencies in electrical products, buildings, transport and city design, and endeavouring to instill persistent energy conservation behaviours in the general population. Each sector of the economy needs to develop a roadmap for transitioning to net zero emissions that embraces these key elements (ASBEC, 2012; Berry and Davidson, 2015). A roadmap for decarbonising the Australian housing sector has been articulated by Newton and Tucker (2011) and is represented diagrammatically in Fig. 2. The modelling underpinning this study underlines the critical importance of an above average energy efficient building shell (a minimum 5 star rating in the Australian Building Code – below which progression to a zero carbon dwelling was found to be unattainable) and energy efficient built-in appliances in providing the necessary platform for achieving net zero emissions. They are not of themselves sufficient, however. Solar PV represents the second critical contextual element for decarbonised housing. Energy conservation behaviour on the part of dwelling occupants cannot be relied upon in contemporary consumerist high income societies to deliver emissions reductions, given the size of the attitude-action gap that currently exists in the population (Newton and Meyer, 2013, 2016).

With the future trajectory of rooftop solar PV diffusion uncertain, given the removal of what have been considered to be generous direct government incentives to consumers (GSES, 2016), it is important to understand the impact that installation of PV up until 2015 has had on electricity demand as well as in emissions reduction. The take-up and use of solar PV needs to be understood in terms of the behavioural response of households in relation to electricity consumption. 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 (in this case, under government subsidised feed-in tariff schemes).

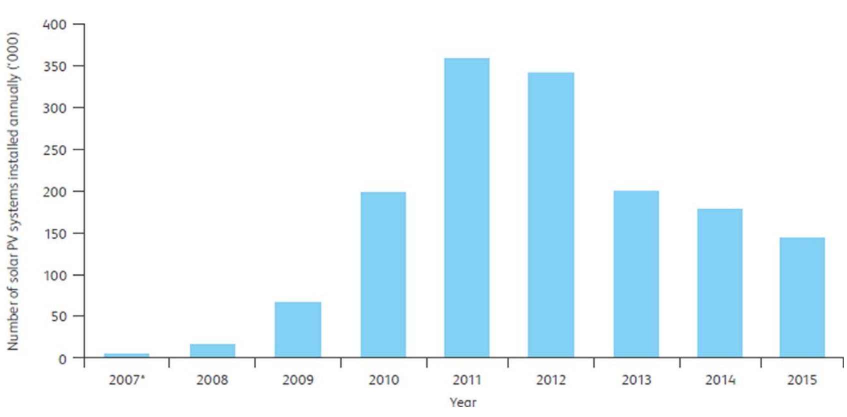

Fig. 1. Annual solar PV installations, Australia 2007–2015; Source: Clean Energy Council of Australia (2016).

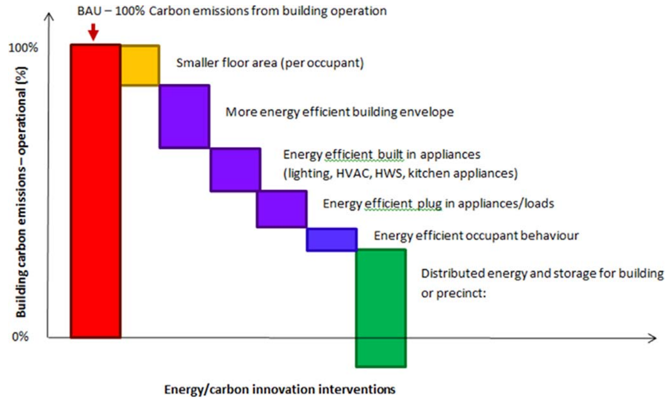

Fig. 2. Staircase of measures to create carbon negative buildings.

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 providing new energy generation products such as 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). By comparison, there are relatively few studies which seek to explore the relationship between installation of solar PV and subsequent electricity consumption.

In one of only two Australian studies 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 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 revealed a rebound effect of 15% for the households that adopted PV. On this finding 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'. Havas et al. (2015) note that installation of solar PV does not require or necessitate conservation–oriented behavioural changes on the part of residents. In a second study that probed the impact of solar PV and feed-in tariffs on electricity generation and use in New South Wales (2010–2012) using data aggregated to Census Area Level 2, Motlagh et al. (2015, 1827) found that: '…high FiT only encourages higher consumption and does not effectively alleviate demand from grid. This in particular applies to GM [gross metering] where FiT profit is more visible. In comparison, under high FiT, GM households tend to consume more electricity than NM [net metered] households, while in general all generating households (whether GM or NM) consume more electricity than non-generating households. This could be further discussed with regards to the rebound effect'.

A similar number of international survey-based studies identified by the authors either had a sample size of PV owners that was too small to shed light on consumption patterns (Caird et al., 2008) or were based on household self-estimates of electricity savings associated with PV (compared to actual use from utility bills) and other confounding domestic energy efficiency measures that suggested savings of 6% in energy use (Keirstead, 2007). A more comparable study (Oliver et al., 2017) identified a rebound effect associated with subsidised PVs, but focus was on net-metered use rather than gross-metered as in the present study.

At present then, there is a major knowledge gap on key topics such as the impact of government incentives for diffusion of a technological innovation such as rooftop solar, forecasting future demand for domestic (grid based) energy in an era of rooftop solar, and policy related to carbon mitigation targets and national carbon offset strategies and measurement:

- carbon mitigation targets. If there is no allowance for rebound effects in projected energy/carbon savings from a range of energy efficiency, low carbon energy generation, and other 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 residential buildings/human settlements/cities (Newton and Newman, 2013), 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 determine payments to households that supplied electricity to the grid. Feed-in tariffs have ranged widely, reflecting the uncertainty surrounding the impact they would have on take-up.

The aim of the research on which this paper is based was to establish the impact that installation of solar PV has had on domestic energy use in Sydney households from mid-2007 until December 2014. In particular, analysis focused on establishing:

- The contribution that rooftop solar PV made to distributed electricity generation
- Whether households with solar PV demonstrated a rebound effect in relation to electricity use
- The environmental benefits associated with solar PV during this initial phase of take-up.

2. Data

Data for this study was supplied by Ausgrid, the utility that supplies electricity to more than 1.7million homes across Sydney and adjacent regions. The data set is now publicly available 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 4819 Sydney households, starting from July-September 2007 to October-December 2014. Data for all solar households in the sample was based on gross feed-in tariffs. Gross metered customers export all their generated PV energy in return for feed-in credits and purchase all 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). For net metered customers (not part of this study), the electricity produced by the PV system partially reduces the energy consumption from the grid so the demand-supply assessments are not clearly separated.

Accelerated uptake of solar panels by Sydney households was evident by June 2010. Among the 4819 households in the sample, 1951 had installed solar panels during the sample period and were receiving feed-in-tariffs. In particular, 1641 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. 310 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 ended on 31 December 2016, so both feed-in-tariffs rates ceased on this date. On the other hand, 2868 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 by Ausgrid to be a representative sample of households in Sydney with a gross metering solar system. The non-solar sample was created by Ausgrid taking an initial random sample of 30,000 detached houses without solar across the whole Ausgrid network area. This sample was then reduced to a 10% sample of those customers by postcode weighting to approximately match the postcode distribution of the solar sample. 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 which does not contain 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. The econometric modelling was undertaken on the full sample of households, covering up to the last quarter of 2014. The modelling also included consideration of other accessible data that has been found to influence electricity use – temperature and income, All parameters used in the econometric modelling are described below.

2.1. TEC: Total Electricity Consumption (kWh)

Total electricity consumption data was based on household quarterly electricity consumption bills irrespective of the time of use (eg, peak, shoulder, etc). Fig. 3 shows average electricity consumption (kWh) per household for each quarter over the sample period (sample average, unless otherwise specified, means the average for the entire sample inclusive of both solar PV and non-solar PV households). It is clear that June and September winter quarters recorded much higher electricity usage due to heating and lighting needs.

2.2. 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). Fig. 4 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.

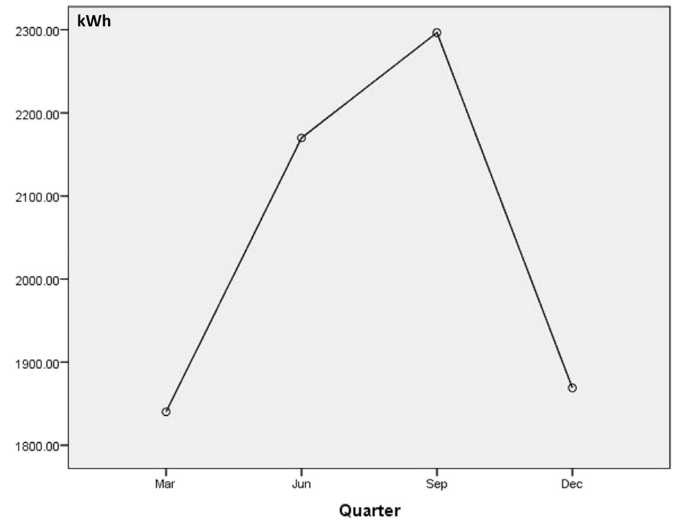

Fig. 3. Sample average quarterly electricity consumption per household (kWh/HH) from 2007 to 2014.

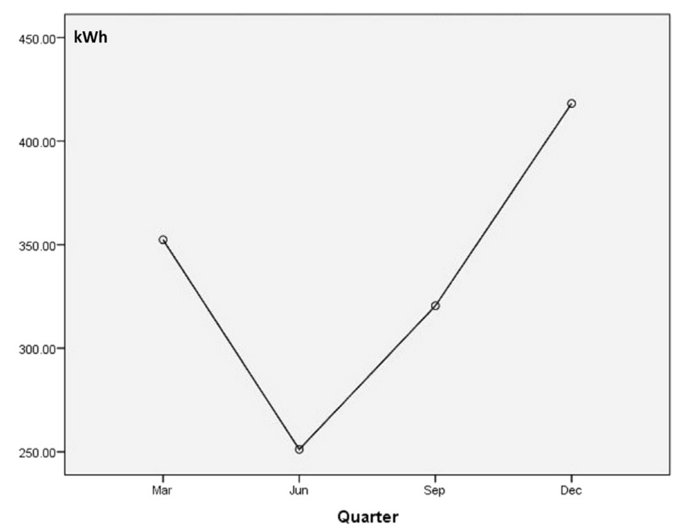

Fig. 4. Sample average quarterly electricity generation per household (kWh/HH) from 2010 to 2014.

2.3. SolarFiT: Solar Feed-in-Tariff ($)

Solar Feed-in-Tariff was calculated simply as:

$$SolarFiT = GEG*Block\,Tariff$$

As previously mentioned, there are two categories of households with solar panels: one on the 60 c/kWh tariff and a second on the 20 c/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 by Ausgrid was only 27.87 c/kWh in NSW (AEMC, 2014). The early adopters would have received a feed-in-tariff (60 c/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, after having paid for the initial installation of the solar PV system, the amount of solar feed-in-tariff received for each kWh generated was equivalent to more than twice of the average cost of purchasing each kWh in the retail market. Even for the later adopters, the feed-in-tariff (20 c/kWh) was still equivalent to more than 70% of what they paid for grid electricity on a per kWh basis on the regular domestic supply tariff. The question to be explored is whether participation in these shemes led to a change in electricity consumption patterns.

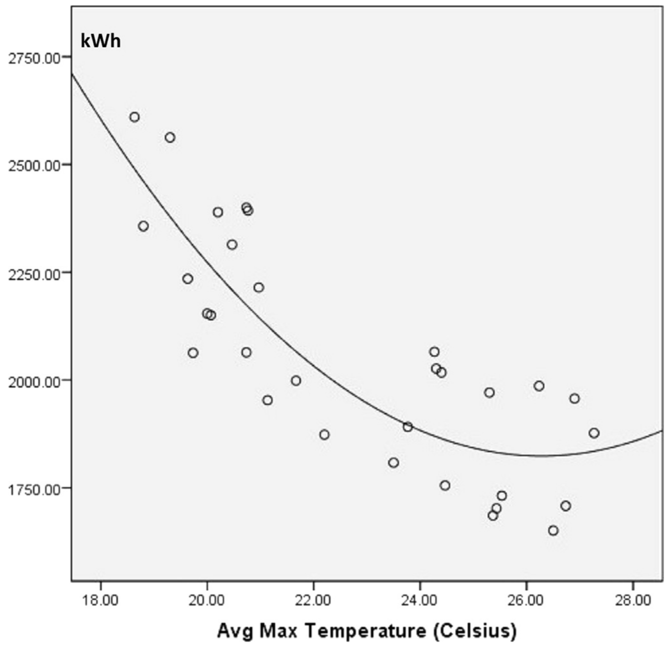

Fig. 5. Sample average quarterly electricity consumption per household (kWh/HH) vs average quarterly maximum temperature (Celsius).

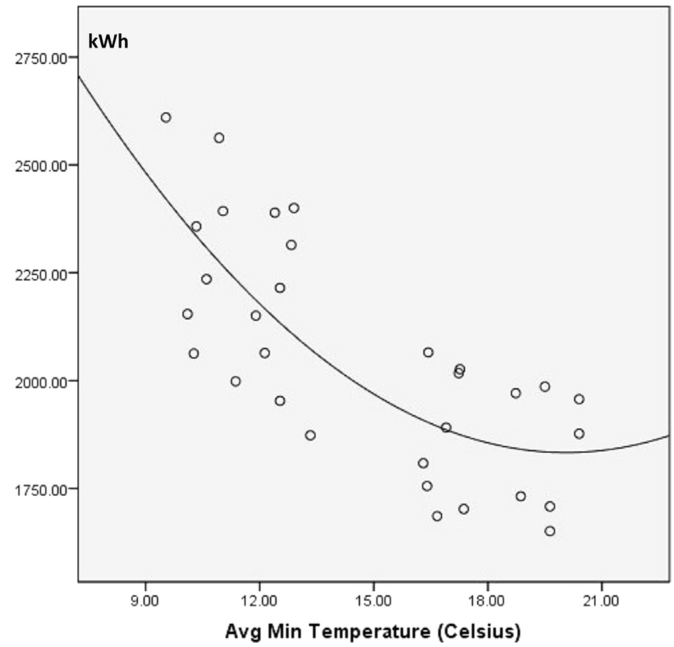

Fig. 6. Sample average quarterly electricity consumption per household (kWh/HH) vs average quarterly minimum temperature (Celsius).

2.4. TMAX: Average Maximum Temperature (°C)

Quarterly average daily maximum temperature in Sydney was obtained from the Bureau of Meteorology website for Sydney City (151.21E/33.87S). Fig. 5 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.

2.5. TMAXSQ: Average Maximum Temperature Squared (°C²)

As shown in Fig. 5, 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 the 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.

2.6. TMIN: Average Minimum Temperature (°C)

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*. Fig. 6 shows a similar pattern as the one observed for *TMAX*.

2.7. TMINSQ: Average Minimum Temperature Squared (°C²)

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

2.8. TaxInc: Personal Taxable Income

Personal taxable income data for each household's corresponding postcode was obtained from the Australian Tax Office (ATO). It was included in the model to capture the possible presence of an income effect on electricity consumption, since there are significant spatial variations in household income across Australian cities (Macleod, 2015). 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.

3. Methodology and results

3.1. Time series overview of electricity consumption and solar electricity generation

We start with a time series overview of the electricity consumption and generation data employing the approach of Hyndman and Khandakar (2008). Fig. 7 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 characteristic of Sydney

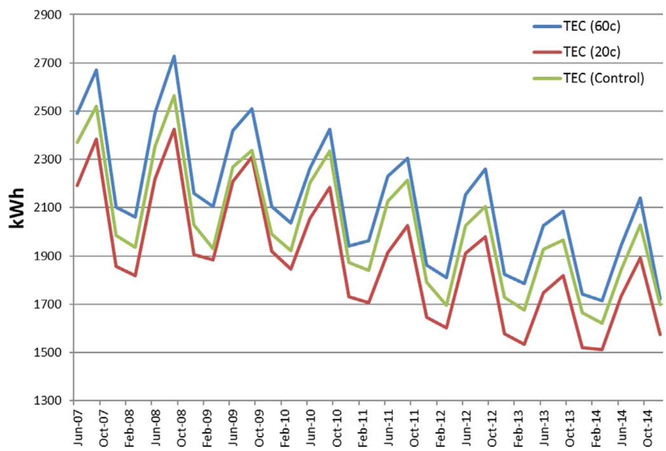

Fig. 7. Sample average quarterly total electricity consumption per household (kWh/HH) from Jun-2007 to Dec-2014 for the 60c group, the 20c group, and the control group.

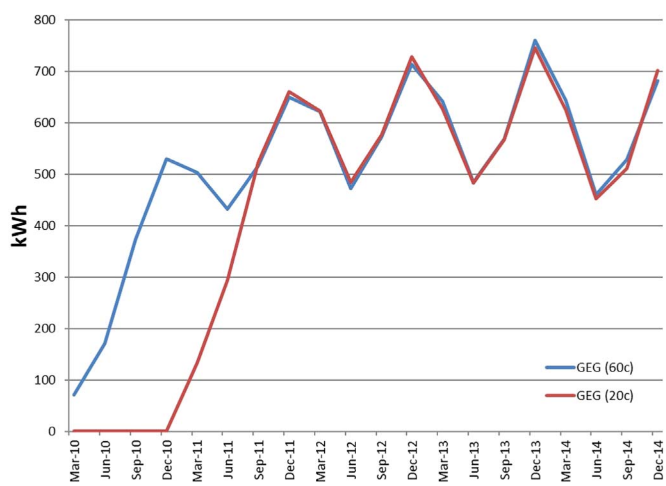

Fig. 8. Sample average quarterly solar electricity generation per household (kWh/HH) from Jun-2010 to Dec-2014 for the 60c group and the 20c group.

households as a whole during the period of study (Brazzale, 2014). This was attributed to improvements in the energy efficiency of household electrical appliances and houses/apartments, and possible conservation behaviours linked to the increase in electricity prices (Swoboda, 2014).

Moving on to a time series overview of solar electricity generation, Fig. 8 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.

For those households with solar PV installed, solar electricity generation as a proportion of their total electricity consumption is depicted in Fig. 9. 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 December 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.

Finally, as an exploratory investigation into the impact of solar PV on household electricity consumption, Table 2 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

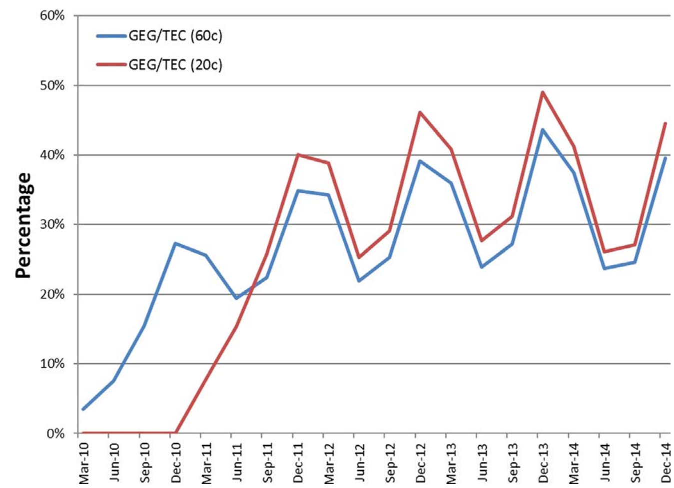

Fig. 9. Sample average quarterly solar electricity generation as a percentage of total electricity consumption for the 60c group and the 20c group.

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 had become a regular component for all households with PV). Year-on-year percentage changes were negative for all three groups, reflecting the general decreasing trend in domestic electricity consumption. However, a closer inspection reveals that for the 60c group the largest negative value (−5.2%) was recorded in 2010, when all 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. This reflects the fact that 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.

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.

3.2. *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). Due to the nature of the sample data, where total electricity consumption (TEC) of a large cross-section of Sydney households was observed over time, a dynamic panel model was chosen for our subsequent analysis. 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:

Table 2
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%

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

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.
- $\{\alpha_{60c,k}, \alpha_{20c,k}, \alpha_{con,k}\}(k = 2008, 2009, ..., 2014)$ 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.

The above dynamic panel data model accounts for: (i) cross-sectional variations between households, such as their varying levels of solar FiT received, personal incomes, etc; (ii) temporal variations facing all households, such as 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 $T \to \infty$, size of the correlation becomes negligible and the bias disappears (Baltagi, 2001; Hsiao, 1986; Nickell, 1981). As the 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.

3.2.1. Consequences of ignoring the impact of solar FiT

Before presenting the complete estimation results from the dynamic panel model, it is instructive to first investigate what would happen if the impact of solar FiT were ignored. Specifically, the equation was first estimated with both $SolarFiT_{60c,t}$ and $SolarFiT_{20c,t}$ removed. Fig. 10 shows the regression residuals (which are obtained by subtracting the fitted consumption values from the actual consumption data), averaged for each quarter for each group (60c, 20c, and control), and separated into Pre Solar PV period and Post Solar PV period.

Pre introduction of solar PV, residuals from all three groups exhibited very similar behaviour, 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

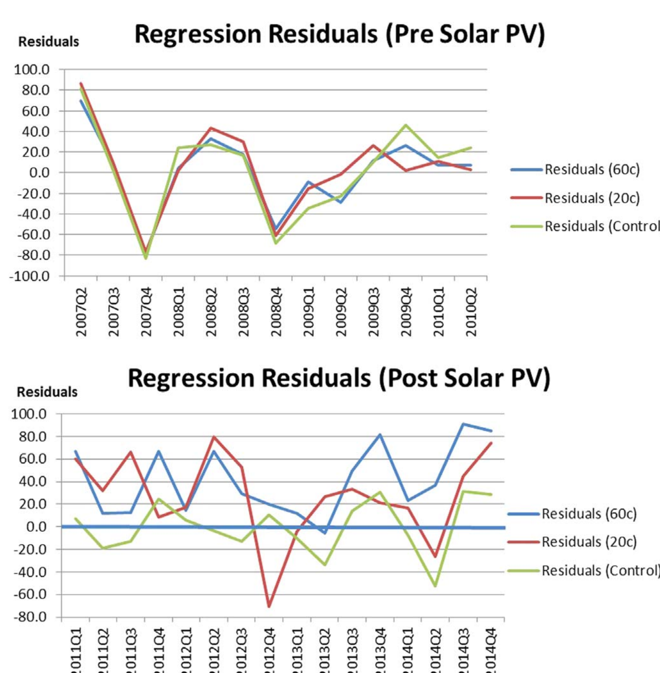

Fig. 10. Residuals from estimation of Eq. (1) with solar FiT variables removed.

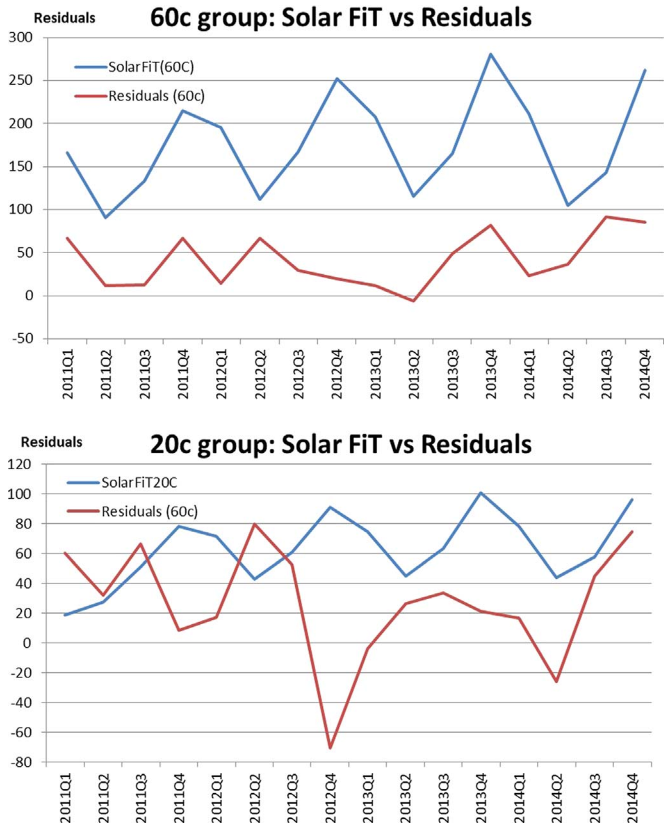

Fig. 11. Residuals from estimation of Eq. (1) with solar FiT variables removed and plotted against time.

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. To further establish the link between the behaviour of the residuals and solar FiT, they are plotted against each other in Fig. 11.

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

In summary, in a model where all significant 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 appeared to be correlated with the presence/absence of solar FiT.

3.3. Dynamic panel model results

Coefficient estimates of the model, together with their corresponding p-values, are presented in Table 3.

The effect of 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, 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, which account for the general trend in household electricity consumption, are shown in Fig. 12. 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 recent reports on widespread decline in domestic electricity consumption, as technological improvements, general energy efficiency gains and rising retail electricity prices have contributed significantly to

Table 3
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.

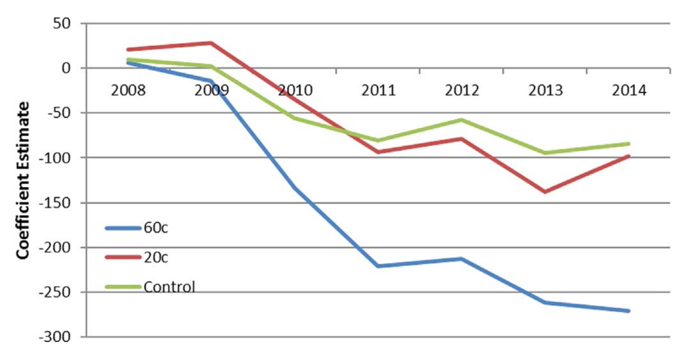

Fig. 12. Estimated year-specific fixed time effects for the three consumer groups.

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 (again, see Fig. 7).

The estimated seasonal effects are shown in Fig. 13. 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.

Temperature fluctuations are also found to be significant determinants of energy consumption. Fig. 14 shows the estimated coefficients for average maximum temperature ($TMAX$) and its squared term

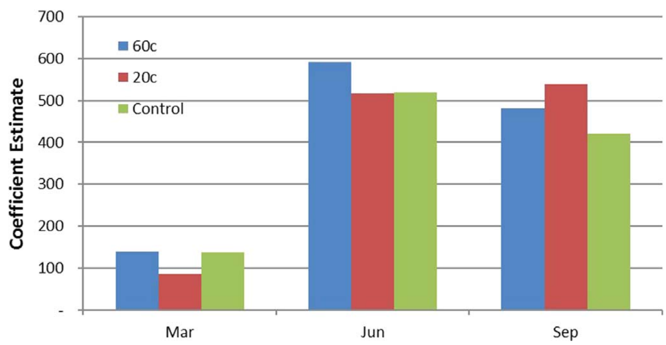

Fig. 13. Estimated seasonal effects for the three consumer groups.

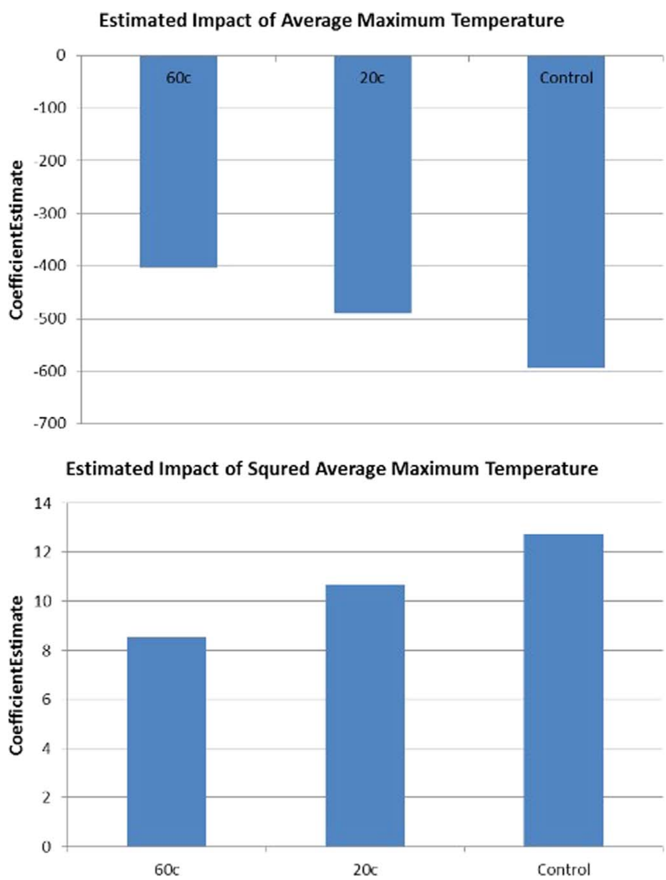

Fig. 14. Estimated coefficients for average maximum temperature (TMAX) and its squared term (TMAXSQ) for the three consumer groups.

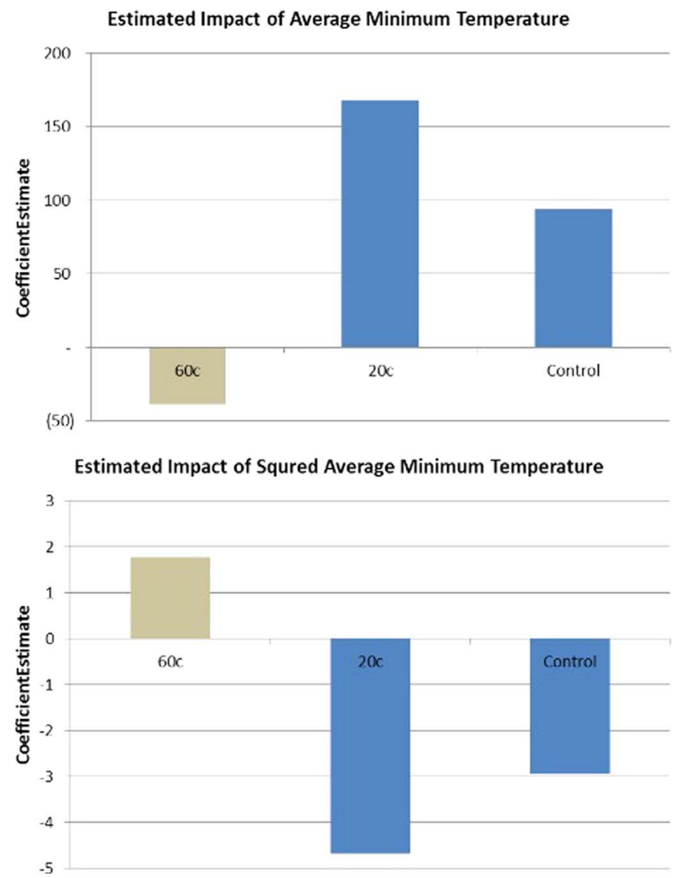

Fig. 15. Estimated coefficients for average minimum temperature (TMIN) and its squared term (TMINSQ) for the three consumer groups.

(*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 thermal comfort needs. Meanwhile, the estimated coefficients are positive and significant for *TMAXSQ* for all three groups, consistent with our observation in Fig. 5 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, Fig. 15 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 thermal comfort needs. Meanwhile, the estimated coefficients are negative and significant for *TMINSQ* for these two groups, consistent with our observation in Fig. 5 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.

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, the effect of $SolarFiT_{i,t}$ 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

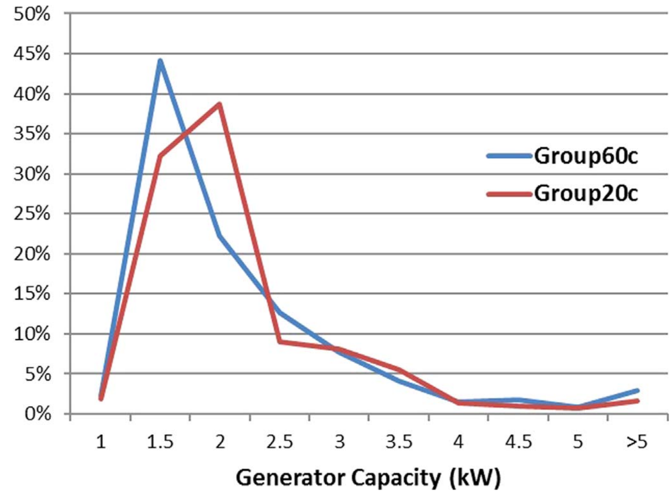

Fig. 16. Distribution of solar generator capacities for the 60c group and the 20c group.

solar generator capacities installed by the 60c group and the 20c group. Fig. 16 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 of increasing capacity PV installations nationally (Clean Energy Council of Australia, 2016) 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 permitted under the Solar Bonus Scheme (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 under the Scheme.

3.4. 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:

$$ReboundEffect_{i,t}(60c) = 0.209{*}GEG_{i,t}(60c)ReboundEffect_{i,t}(20c) = 0.167{*}GEG_{i,t}(20c) \quad (2)$$

Eq. (2) is subsequently evaluated for all households post solar panel installation and averaged across all households for each quarter. Fig. 17 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 Fig. 18. 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 ~5% and ~8% for the 60c group, and between ~4.5% and ~7.5% for the 20c group.

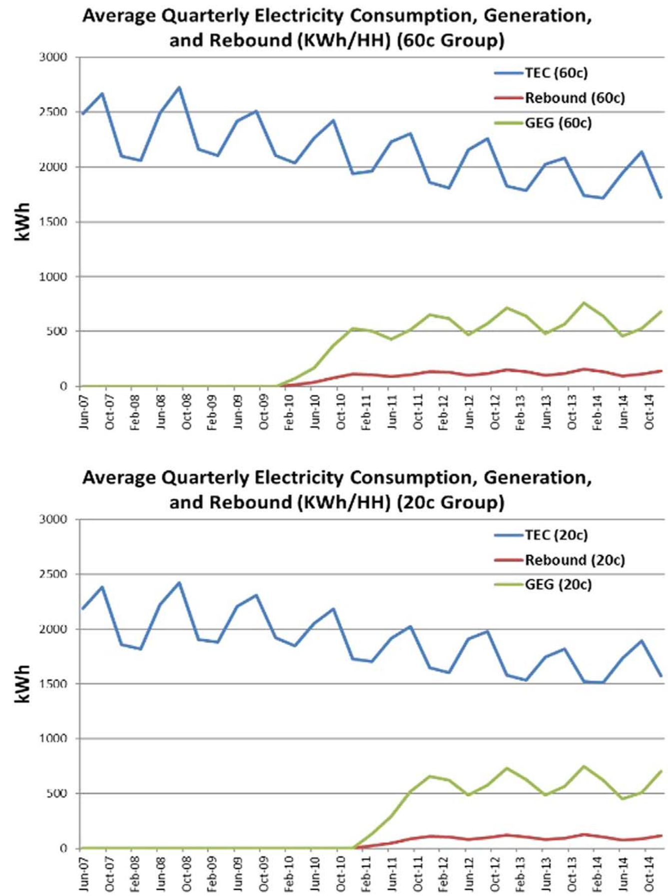

Fig. 17. Average electricity consumption, solar electricity generation, and rebound effect for the 60c group and the 20c group.

4. Conclusions and policy implications

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: 60 c/kWh and 20 c/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, 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 a measurable 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 energy services 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 study period. 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 early adopters of solar PV (compared to the majority of the Australian population) and profit maximisers (in their installation of large PVs to maximize their feed-in-tariff). Their response in relation to elevated electricity consumption compared to the control group with no solar PV confirms that human behaviour will be central in any transition to a low carbon future (see also Gill et al., 2010 and Gram-Hanssen, 2013).

In concert with other studies (Wood and Blowers, 2015), this

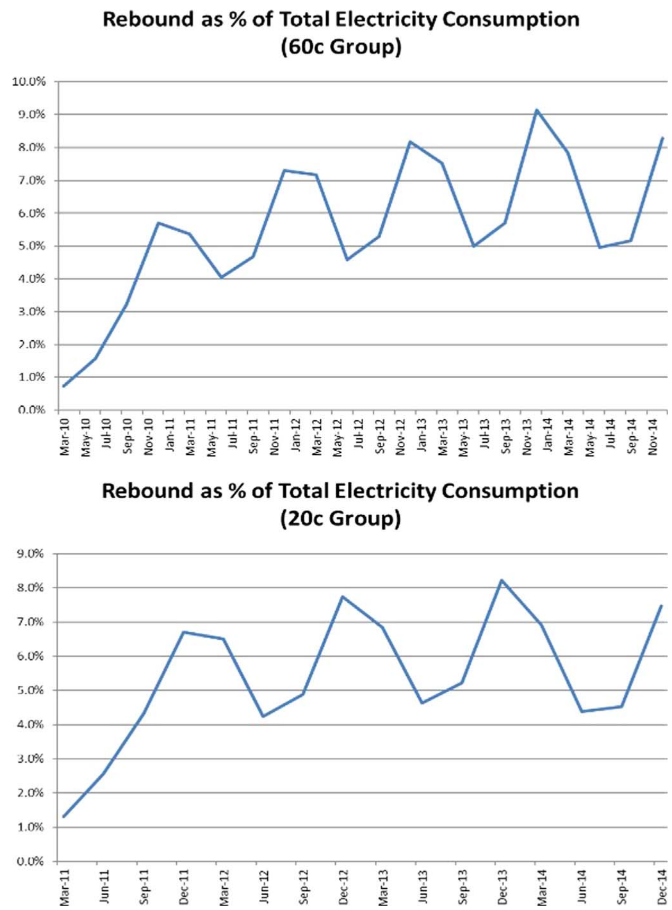

Fig. 18. Rebound effect viewed as a percentage of total electricity consumption for the 60c group and the 20c group.

research affirms the policy rationale stated at the outset of this paper 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% 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 large 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 government inquiries seeking to identify what constitutes an appropriate (market) 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 possible that any rebound effect would diminish as there will be no income windfall for those with PV systems. Without the subsidised feed-in tariffs and with a net meter, the main sources of financial benefit from the PV unit rests with the savings made on electricity bills; ie. using the electricity the PV unit generates in the home at the time of generation, saving electricity purchase from the grid. As the next phase of solar PV diffusion is set to evolve in 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 Fig. 2). It is clear, however, from this and other related studies, that household behaviour remains a significant factor in a transition to low carbon living in an era of distributed renewable energy and storage and an emergence of the 'prosumer'.

Acknowledgements

This work was supported by the Co-Operative Research Centre for Low Carbon Living. The authors also 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).

References

AEMC, 2014. Residential electricity price trends, Final Report, Australian Energy Market Commission, Sydney ⟨http://www.aemc.gov.au/getattachment/ae5d0665-7300-4a0d-b3b2-bd42d82cf737/2014-Residential-Electricity-Price-Trends-report.aspx⟩ (Accessed 6 June 2016).

ASBEC, 2012. Net Zero Emission Homes: An Examination of Leading Practice and Pathways Forward. ⟨http://asbec.asn.au/files/121213_Zero_Emission_Homes_Leading_Practice.pdf⟩ (Accessed 23 December 2016).

Baltagi, B., 2001. Econometrics Analysis of Panel Data, 2nd ed. Wiley, Chichester.

Berkhout, P., Muskens, W., Velthuijsen, J., 2000. Defining the rebound effect. Energy Policy 28, 425–432.

Berry, S., 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.

Caird, S., Roy, R., Herring, H., 2008. Improving the energy performance of UK households: results from surveys of consumer adoption and use of low- and zero carbon technologies. Energy Effic. 1 (2), 149–166.

Chitnis, M., Sorrell, S., 2015. Living up to expectations: estimating direct and indirect rebound effects for UK households. Energy Econ. 52, 100–116.

Clean Energy Council of Australia, 2017. Clean Energy Australia Report for 2016. ⟨https://www.cleanenergycouncil.org.au/policy-advocacy/reports/clean-energy-australia-report.html⟩ (Accessed 25 July 2017).

Climate Institute, 2016. Climate of the Nation 2016. ⟨http://www.climateinstitute.org.au/climate-of-the-nation-2016.html?Gclid=CIf5lurWrtECFVEHvAodIOcIDg⟩ (Accessed 23 December 2016).

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: Int. J. Indoor Air Qual. Clim. 23 (6), 442–461.

Essential Services Commission, 2016. The Energy Value of Distributed Generation. Government of Victoria, Melbourne (Accessed 23 December 2016). ⟨http://www.esc.vic.gov.au/document/energy/36002-distributed-generation-inquiry-final-report-energy-value/⟩.

Giddings, B., Park, M., 2012. Eco-efficiency rebound effects associated with household energy using products. In: Israsena, P., Tangsantikul, J., Durling, D., (Eds.) Proceedings of Design Research Society 2102, 2, Bangkok, pp. 623–639.

Gill, Z., Tierney, M., Pegg, I., Allen, N., 2010. Low energy dwellings: the contribution of behaviour to actual performance. Build. Res. Inf. 38, 491–508.

Gillingham, K., Kotchen, M., Rapson, D., Wagner, G., 2013. The rebound effect is overplayed. Nature 493, 475–476.

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

GSES, 2016. Generous Feed in Tariff Schemes: Their Demise and what Information is Useful for Affected System Owners Global Sustainable Energy Solutions. 〈https://www.gses.com.au/wp-content/uploads/2016/08/GSES_Generous-feed-in-tarrifs-end.pdf〉 (Accessed 25 July 2017).

Havas, L., Ballweg, J., Penna, C., 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 University Press, Cambridge.

Hyndman, R., Khandakar, Y., 2008. Automatic time series forecasting: the forecast package for R. J. Stat. Softw. 26 (3), 1–22.

IPCC, 2013. IPCC Fifth Assessment Report. 〈http://ipcc-wg2.gov/oeAR5/images/uploads/WGIIAR5-Glossary_FGD.pdf〉 (Accessed 23 December 2016).

Keirstead, J., 2007. Behavioural responses to photovoltaic systems in the UK domestic sector. Energy Policy 35 (8), 4128–4141.

Loynes, K., 2014. Overview of Feed-in Tariffs, Parliament of Australia, Canberra. 〈http://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/pubs/rp/rp1314/QG/Tariffs〉. (Accessed 23 December 2016).

Macleod, K., 2015. Mapping Australia: What do People Earn in your Local Area? 〈http://www.sbs.com.au/news/map/regional-variations-in-income〉 (Accessed 25 July 2017).

Maxwell, D., Owen, P., McAndrew L., Muehmel, K., Neubauer, A., 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. 〈http://ec.europa.eu/environment/eussd/pdf/rebound_effect_report.pdf〉 (Accessed 23 December 2016).

Motlagh, O., Grozev, G., Foliente, G., 2015. Impacts of Feed-in Tariff and Metering Types on Electricity Consumption Efficiency in Australia. 21st International Congress on Modelling and Simulation, Gold Coast, Australia, 29 Nov to 4 Dec 2015, pp 1827–1833.

Newton Peter, W., Tucker Selwyn, N., 2011. Pathways to decarbonising the housing sector: a scenario approach. Build. Res. Inf. 39 (1), 34–50.

Newton, P., 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., Meyer, D., 2016. Built environment and human behaviour challenges to sustainable consumption: a gap analysis. In: Shaw, D., Newholm, T., Chatzidakis, A., Carrington, M. (Eds.), Ethics and Morality in Consumption: Interdisciplinary Perspectives. Routledge, London.

Newton, P., Newman, P., 2013. The geography of solar photovoltaics (PV) and a new low carbon urban transition theory. Sustainability 5, 2537–2556.

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

Oliver, M., Moreno-Cruz, J. Toroghi, S., 2017. The solar rebound, household income and subsidization of residential photovoltaic systems, Presentation to 40th IAEE International Festival, Singapore.

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. 〈https://www.thersa.org/discover/publications-and-articles/reports/a-new-agenda-on-climate-change〉 (Accessed 23 December 2016).

Sorrell, S., Dimitropoulos, J., Sommerville, M., 2009. Empirical estimates of the direct rebound effect: a review. Energy Policy 37, 1356–1371.

Steffen, W., Broadgate, L., Deutch, O., Gaffney, Ludwig, C., 2015. The trajectory of the Anthropocene: the great acceleration. Anthr. Rev. 2, 81–98.

Swoboda, K., 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〉. (Accessed 23 December 2016).

UNFCCc, 2016. Paris Agreement. 〈http://unfccc.int/2860.php〉 (Accessed 23 December 2016).

Wood, T., Blowers, D., 2015. Sundown, sunrise. How Australia can finally get solar power right, Grattan Institute, Melbourne. 〈https://grattan.edu.au/wp-content/uploads/2015/05/822-sundown-sunrise4.pdf〉 (Accessed 23 December 2016). 〈www.mssanz.org.au/modsim2015〉.