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Densification, what does it mean for fuel poverty and energy justice? An empirical analysis

Lavinia Poruschi[a,b,*], Christopher L. Ambrey[c]

[a] CSIRO Land & Water, Ecosciences Precinct, 41 Boggo Road, Dutton Park, QLD 4102, Australia
[b] Cities Research Institute, Sir Samuel Griffith Centre (N78_3.28), Nathan Campus, Griffith University, 170 Kessels Road, Brisbane, Queensland 4111, Australia
[c] Institute for Social Science Research, Cycad Building (1018), Long Pocket Precinct, 80 Meiers Rd, Indooroopilly, Queensland 4068, Australia

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ABSTRACT

Energy is increasingly at the forefront of the global political agenda. While there is a longstanding literature relating to fuel poverty and increasingly energy justice, there remains little evidence which explores its link with the urban form. Specifically, the purpose of this study is to explore the relationship between the urban consolidation hypothesis and the cultivation of energy justice in Australia. This study uses data from the Household, Income and Labour Dynamics in Australia (HILDA) survey (years 2007–2014), a national probability sample and indefinite life panel. The substantive findings of this study demonstrate that for low income and renting households greater urban density corresponds to a higher likelihood of experiencing fuel poverty. Further, for households with a dwelling type described as an apartment (two or three storeys) there is a separate and quite generalisable indication that this type of dwelling is associated with a lower likelihood of experiencing fuel poverty. This study connects the debate regarding urban consolidation and energy consumption to the fuel poverty and energy justice literature. Alongside this contribution, this study also provides policymakers and planners with new evidence to inform remediation policies that are directed at supporting the fuel poor.

1. Introduction

Energy is increasingly at the forefront of the global political agenda. A growing awareness of poverty, inequality, climate change and energy security have drawn attention to the energy-social justice nexus. Urban socio-technical transformations of key infrastructure, such as energy systems, need to occur at the intersection of sustainability and liveability with their performance monitored and evaluated against measures of social equity, environmental sustainability and liveability (Newton, 2012). Throughout the world millions of households suffer from "fuel poverty", generally regarded as spending 10% or more of household income on energy (Liddell, 2012a, b; Liddell et al., 2012). Having the capacity to heat or cool and maintain thermal comfort is inextricably linked to human health and wellbeing (Wilkinson et al., 2007), particularly for the very young, the handicapped and older residents. In this regard, the World Health Organization recommends that indoor air temperatures in the home should range between 18 and 24 °C to protect human health (Ormandy and Ezratty, 2012). As explained by Boardman (2012b), thermal comfort, freedom from intense anxiety about paying for energy needs, the affordability of adequate hot water and light are part of our human rights enshrined in the UN's Declaration:

> "Everyone has the right to a standard of living adequate for the health and well-being of himself and of his family, including food, clothing, housing and medical care." (United Nations, 1948, article 25(1))

Nevertheless, fuel poverty is a growing concern in many countries, driven primarily by higher fuel prices that are not offset by energy efficiency improvements in the homes of the fuel poor (Boardman, 2012b). Since 2007 household energy prices have risen significantly across Australia (Azpitarte et al., 2015). This has been attributed to electricity sector liberalisation, over-investment in grid development and other factors (Chester and Morris, 2011; Graham et al., 2015; Nelson, 2015; Parkinson, 2014; Simshauser et al., 2011a, b; Smith, 2013).[1] Notably a driving factor of gas and energy prices overall is the

* Correspondence to: CSIRO Land & Water, Ecosciences Precinct, GPO Box 2583, Brisbane, Queensland 4001, Australia.
E-mail addresses: lavinia.poruschi@csiro.au (L. Poruschi), c.ambrey@uq.edu.au (C.L. Ambrey).

[1] Initially, the rise in prices was attributed to a rapid growth in peak demand for electricity, the need for greater capacity attendant cost pressures across the electricity production chain (cf. Simshauser et al., 2011a, b). However subsequent peer-reviewed and gray literature show a reduction in peak demand (Nelson, 2015; Smith, 2013). The energy market appears to show a confluence of factors leading to a reduction in total annual energy consumption, with opposing pressures on peak demand leaving a series of questions to be answered with regard to what the future of the grid and energy prices will be (Australian Energy Regulator, 2017; Graham et al., 2015).

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set-up of extensive operations which divert gas from the domestic market to export, without a legal requirement to ensure affordable supply to the local market (Australian Competitor and Consumer Commission, 2016; Queensland Government, 2010). No study has yet to consider how urban consolidation, through gains in energy efficiency and changes to household level energy consumption behaviour, may mitigate the risk of experiencing fuel poverty.

Urban consolidation or densification is often heralded as the pathway to sustainability (Glaeser, 2012; Morikawa, 2012; Neuman, 2005; Newman, 1992). It is argued that dense cities offer economies of scale in terms of public infrastructure; reduced transmission and reduced distribution losses of energy supply, compact housing with reduced heating/cooling needs all of which are thought to lead to decreased energy consumption (Burton, 2000; Capello and Camagni, 2000; Gaigné et al., 2012; Poumanyvong and Kaneko, 2010). Nonetheless, urban development focused on higher-density living intended to reduce energy consumption and enhance energy savings can lead to higher energy use behaviours (e.g. higher reliance on air-conditioning), less opportunity to save or switch to alternative sources and in turn greater entrenched disadvantage (Farbotko and Waitt, 2011; Gray and Gleeson, 2007; Newton and Newman, 2013; Poruschi and Ambrey, 2016; Steemers, 2003; Poruschi et al., 2018). To the extent that a more dense urban form contributes to lower energy consumption (cf. Holden and Norland, 2005), it is conceivable that it may also mitigate the risk of suffering from fuel poverty. In this sense, the compactness of development may be advocated as a means of redressing energy injustice.

The purpose of this study is to investigate empirically the role of a denser urban form, as it has unfolded in Australia, in mitigating the risk of fuel poverty. Density induced household level energy consumption behaviour is reasoned to underlie this empirical link. To the extent of the knowledge of the authors, this is the first study to explicitly test this link. In doing so, this study makes a distinct contribution to the fuel poverty and energy justice literature. Alongside this contribution, this study also provides policymakers and planners with new evidence to inform remediation policies directed at supporting the fuel poor.

Other work has analysed consumer behaviour related to switching energy providers and what factors influence how quickly the switch is made (e.g. Kleit et al., 2012; McDaniel and Groothuis, 2012), preferences for sources to access renewable energy and willingness to pay for this access (e.g. Yang et al., 2016), controlling consumption behaviour through technology (e.g. Diaz-Mendez et al., 2018). With the goal of informing the urban planning community and energy policymakers, this study departs from studying modification in consumer behaviour and focuses on whether there is an association between changes in the density of the urban form and changes in the risk of fuel poverty.

In this study, it is maintained that fuel poverty can be understood as an expression of energy injustice. It involves the diminished capacity to access energy services and thereby to secure a healthy living environment (Walker and Day, 2012). Situated within the emerging broader energy justice literature fuel poverty may be conceived of as a manifestation of the different dimensions of energy justice; energy production (e.g. different forms of technology), consumption; and related to environmental justice research, the issues of distributive and procedural justice (Fuller and McCauley, 2016).

In detail, the aim of this study is to investigate a number of specific research questions.

(1) What is the extent to which low income households and households in denser areas are more likely to experience fuel poverty, other things held constant? This question is important to establish the presence of; magnitude and the generalisability, on average, of any such link between: low income and fuel poverty; and density and fuel poverty. Low income is defined as 50% of the median income, a *de facto* poverty line (Australian Council of Social Service, 2014, 2016; Headey, 2006). This measure differs from the poverty rate measure used by (Kleit et al., 2012) which refers to the proportion of people in a customer's zip code below the poverty line.

It should be acknowledged that encapsulated within the broader low income grouping used in this study is a diverse range of households. It is possible that the group-specific (e.g. low income seniors) experiences' diverge in some way from the average experience of a low income household.

(2) What is the degree to which any link between density and fuel poverty depends on the having a low income, other things held constant? This research question moves beyond revealing an average link to examine the potential heterogeneity in the link between density and fuel poverty. In particular, the degree to which it may depend on financial disadvantage. This is integral to identify whether or not (and to what degree) for disadvantaged households greater density corresponds to a greater likelihood of experiencing fuel poverty.

(3) What is the magnitude to which any link between a household's dwelling type and fuel poverty depends on low income, other things held constant? This research question goes further still, substituting density with a household's dwelling type, which it is reasonable to expect are positively correlated and possibly indistinguishable from one another. Therefore, it is important to show, at least naively, whether or not (and to what magnitude) for low income households dwelling types correspond to a greater likelihood of experiencing fuel poverty.

(4) To what extent are these differences distinguishable? This research question dispenses with the naïve characterisation of the potential heterogeneity in the link between density and fuel poverty. It aims to uncover whether or not (and by how much) for low income households there is a link between a household's dwelling types and fuel poverty; and density and fuel poverty can be distinguished from one another. This is crucial for the identification of the link between, for low income households, a denser urban form and fuel poverty.

(5) Do other vulnerable groups, in denser areas, face a potentially heightened risk of fuel poverty, other things held constant? This research question examines whether or not (and by what amount) other vulnerable groups may also be at disproportionate risk of fuel poverty.

In all, it is envisaged that the insights gleaned by addressing these research questions will prove valuable to decision makers seeking to assist the fuel poor. In what follows, the remainder of Section 1 reports on the broader relevant evidence. Section 2 discusses the data and method, while Section 3 reports the results of the analysis. Finally, Section 4 discusses the findings and concludes offering insights for future research.

1.1. Urban consolidation as a means to cultivate energy justice?

Fuel poverty can be understood as an expression of energy injustice (Walker and Day, 2012). Relatedly, fuel poverty may be framed as a climate injustice, whereby households suffer disproportionately from climate change (or even adaptation and mitigation measures, such as Pigouvian taxation mechanisms) which risk further ingraining inequalities and the vulnerability of groups who already possess a limited capacity to adapt to anthropocentric climate change (Byrne et al., 2016; Callan et al., 2009; Poruschi and Ambrey, 2016; Roberts, 2008).

Fuel poverty specifically though, depends to an extent on fuel prices and incomes, but more fundamentally it depends on the energy inefficiency of the home and capital equipment. These contributors to fuel poverty highlight the importance of capital expenditure, which the fuel poor, by definition, do not have the means to undertake. Exacerbating the plight of those experiencing fuel poverty is the absence of legal rights and responsibilities for enhancing the energy efficiency of the building in which they reside (Boardman, 2012b). Renters represent a case in point. The confluence of; (1) landlords' incentives to maximise (minimise) the present value of investment profits (losses); and (2) renters' limited capacity to control the fixtures and to some extent the appliances used; means that renters potentially face being burdened by higher energy costs (compared to home owners) for the purposes of heating and cooling (Davis, 2012; Rehdanz, 2007). This is one example of where policies to address fuel poverty do not necessarily need to be targeted at low income groups specifically. Rather, policies need to consider the more nuanced aspects of poverty (Bennett et al., 2002).

An underappreciated consequence of urban planning and design policies that advocate urban consolidation is what these policies imply for fuel poverty, through energy consumption. Urban form may impact energy consumption in two significant ways: (a) at a network level, through system efficiencies due to expected lower line and distribution losses; and (b) at a household level, through building energy system impacts (e.g. reduced opportunities for direct solar gain, reduced opportunities for cross-ventilation, reduced heat losses from conduction due to common walls and floors/ceilings) and related household level energy consumption behaviour.

However, critics argue that increasingly dense urban areas instead cause traffic congestion, overcrowding and air pollution which outweigh these benefits; increasing energy consumption and emissions (Burton, 2000; Capello and Camagni, 2000; Gaigné et al., 2012; Poumanyvong and Kaneko, 2010). There could be a mismatch between economic activity and consolidation planning (Forster, 2006), which in turn can lead to energy gains in efficiency being offset by socio-economic changes (Echenique et al., 2012). In addition, the more energy-efficient lifestyle of carefully designed medium-density communities can come under threat when further densification occurs (Carrick and Osborne, 2017). If the protagonists of urban consolidation are correct, a question which remains perhaps the most fundamental question facing urban researchers (cf. Randolph, 2004), then such policies would be expected to mitigate fuel poverty.

According to the prevailing narrative, densification might be useful for reducing energy consumption in transport and there several examples of well-designed dense dwellings which can bring about energy savings (e.g. the Christie Walk development in Adelaide, Crabtree, 2005). It is likely though, that negative consequences such as reduced living space and a lack of affordable housing will follow (Burton, 2000; Karathodorou et al., 2010). Increased noise, increased air pollution, a lack of natural light, ventilation and greenery brought about by densification may lead to greater use of heating and air-conditioning and hence higher energy consumption, potentially offsetting decreases in energy use reduction (Byrne et al., 2016; Steemers, 2003).

As noted by an anonymous reviewer, it is plausible that between these opposing perspectives a more tempered and moderate perspective exists. In this regard, it may be, as found for the United Kingdom, that for densities of 30–50 semi-detached buildings (e.g. townhouses and terrace houses) per hectare could realise improved use of passive solar energy (Owens, 1986). Moreover, in tropical environments, adding an internal courtyard improves thermal condition of other neighbouring spaces (Sadafi et al., 2011). Further, much like how attached dwellings can 'share' heating (cf. Tirado Herrero and Ürge-Vorsatz, 2012) it is also plausible that to some extent they may 'share' cooling (Owens, 1986).

However, there is evidence to suggest that multi-storey units (Malo, 2016) and semi-detached dwellings (Stephan et al., 2013) respectively do not allow natural ventilation and are not overall superior to other residential forms. Ideally, the whole life-cycle of the building and its use would be considered in building design (Myors et al., 2005; Perkins et al., 2009). Unless careful consideration is given to energy efficiency inner high-rise buildings may be no more (or even less) energy efficient than detached or semi-detached buildings.[2] To date, research efforts have tended to be orientated around the connection between vulnerability and direct energy consumption for transport in cities (cf. Dodson and Sipe, 2007, 2008); or general vulnerability to natural hazards (Cutter and Finch, 2008). However, there is a paucity of evidence on links between urban consolidation and fuel poverty specifically.

There is however some, albeit unclear evidence, on the connection between residential energy demand and densification in Australia (Gray and Gleeson, 2007; Rickwood et al., 2008). It is maintained by some that, "dispersed, incremental urban consolidation [in line with market forces] is unlikely to reduce household energy demand." (Gray and Gleeson, 2007). The problem has been characterised as: "…not a problem of optimal city size, but of efficient size. […] Economies of scale exist, ceteris paribus, but turn into diseconomies after a certain urban dimension" (Capello and Camagni, 2000). Notwithstanding these alternative conceptions of the problem, to the extent of the knowledge of the authors no study has yet to empirically investigate what densification may mean for fuel poverty.

2. Data and method

This section details the data employed in the study and the estimation strategy used.

2.1. Household, Income and Labour Dynamics in Australia (HILDA) survey

In terms of the socio-economic data on households this is obtained from waves 7–14 (for years 2007–2014) of the Household, Income and Labour Dynamics in Australia (HILDA) survey. These waves (years) of the HILDA survey are employed as these are the periods for which all variables available in the sample. The Household, Income and Labour Dynamics in Australia (HILDA) Survey is a household panel survey which is funded by the Australian Government, administered by the Melbourne Institute of Applied Economic and Social Research with the fieldwork currently being undertaken by Roy Morgan Research.

The sampling design of the HILDA survey involves the selection of households into the sample by a multi-stage process. To begin with, a random sample of 488 Census Collection Districts (CDs) based on the 1996 census boundaries was selected from across Australia, stratified by State, and within the five largest States in terms of population, by metropolitan and non-metropolitan regions, each CD consisting of approximately 200–250 households. The CDs were sampled with probability proportional to their size as measured by the number of dwellings (unoccupied and occupied) recorded in the 1996 Census with some adjustments for population growth since the Census. Within each of these CDs, all dwellings were fully enumerated and a sample of 22–34 dwellings randomly sampled based on the expected response and occupancy rates within each area (Watson and Wooden, 2002). The data collection for each wave occurs from August of the current year or wave until February (or March) of next year. Usually interviews were carried out within one month of the anniversary of the previous interview (Summerfield et al., 2015).

The unit of analysis is the household. The HILDA survey defines a household as, "…a group of people who usually reside and eat together" (Watson and Wooden, 2002). While the household units in the sample are identified according to this definition no time-invariant definition is provided. Longhi (2015) has addressed a similar difficulty with Understanding Society, The United Kingdom's Longitudinal Study by linking the household to their local area and focusing only on those households that did not move over time. Diverging from Longhi (2015) this study defines a household through the members a household (originally defined) and involves following these groups of individuals over time.[3]

[2] Benefits from increasing residential density can exist, however it is likely they require changes in the way it is designed and implemented, perhaps even as a "social and ecological phenomena" (Crabtree, 2005).

[3] The way households are originally defined by the HILDA team is very similar to that used by the Australian Bureau of Statistics. It is "a group of people who usually reside and eat together" (Shields et al., 2009; Watson and Wooden, 2002). For this study, a household is followed through time by assigning to the household an unique identifier for a given individual within that household that is observed most regularly over time. This means new household members can come into the household (e.g. a new child is born) and old household members can leave the household (e.g. a household member moves out). In brief, this unique household identifier remains constant over time and while the individual remains in the household, the unique household identifier remains unchanged.

The dependent variable employed in this study to measure fuel poverty is a dichotomous variable. It takes a value 1 if the household is experiencing fuel poverty and 0 otherwise. It is important to note that fuel poverty is defined as (in real 2000 $AUD terms) spending 10% or more of disposable equivalised household income on direct residential energy, where energy expenditure is average household energy expenditure and includes electricity, gas and other heating fuel. The equivalisation is based on the Australian Bureau of Statistics method (the 'modified OECD')[4] (Australian Bureau of Statistics, 2015). As noted by Azpitarte et al. (2015) the incidence of fuel poverty may be underestimated as there is evidence respondents tend to the survey tend to underreport their annual expenditure on energy bills by between 13 and 20 per cent (Wilkins and Sun, 2010). While this study has used one definition of fuel poverty, alternative definitions have also been proposed elsewhere (Boardman, 2012b; Hills, 2011; Legendre and Ricci, 2015; Moore, 2012; Waddams Price et al., 2012; Watson and Maitre, 2015). Azpitarte and colleagues (2015), also use the HILDA survey and show using sequential stochastic dominance analysis of: the 10% ratio; the twice the median; the simple self-report of fuel poverty (whether or not one can afford to heat their home and pay their energy bills on time) definition; and the low income – high cost definition (cf. Hills, 2012); that no one definition is superior to all of the others. Further, another Australian study comparing various definitions of fuel poverty arrives at much the same conclusion (Nance, 2013).

Additionally, an alternative definition not explored here is the minimal comfortable level of energy use. Notably, this definition of minimal (comfortable) level of energy use is proposed in the context of achieving energy equity (Boardman, 2012a; Higgins and Lutzenhiser, 1995). While operationalisation of the definition can be difficult in large survey samples, it can be argued that ideally the best definition would be rooted in the main cause fuel poverty, based on energy efficiency improvements *relative* to average efficiency levels or simply needed energy (for any purpose) (Boardman, 2012a, 2012b; Moore, 2012). Due to paucity of data on dwelling size to model energy needs (Watson and Maitre, 2015), this definition remains infeasible for this particular study. All variables are described in Table 1.

2.2. Density

Fig. 1 shows for Australia's most populated and densely populated city, Sydney how the central areas of high density can also exhibit high levels of overall disadvantage (as measured by the Socio-Economic Indexes for Areas' (SEIFA) Index of Relative Socio-economic Disadvantage (IRSD) (Australian Bureau of Statistics, 2013b).[5] It also shows that relatively non-disadvantaged areas can be adjacent to relatively disadvantaged areas. The supplementary material provides an illustration for Australia's three most populated and densely populated cities (people/km^2) all of which are projected to roughly double in size (from 2012 levels) by 2061 (Australian Bureau of Statistics, 2013a, 2014; Commonwealth of Australia, 2015). Note that the buffer lines are concentric lines at 5 km, 10 km and 30 km from the suburb considered central to the metropolitan area. In Fig. 1, the areas for which no value of the IRSD index was recorded are hashed with black continuous lines.

[4] The total equivalence factor is calculated based on summing 1 point for the first adult in the household, 0.5 points for each additional adult and 0.3 points for each child under the age of 15.

[5] The IRSD ranks all areas in Australia (at various spatial levels) on a scale from the most to the least disadvantage (where least disadvantage receives the highest score). The index is composed of a series of variables included in the index based on a factor loading (weight). Out of the 16 contributing factors which are expressed as percentages, the factors which load most heavily in decreasing order of weight are: the percentage of people on low incomes, the percentage of families with children under 15 years where parents are jobless, the percentage of occupied private dwellings with no Internet connection and the percentage employed people working as labourers. Other factors considered include educational attainment, unemployment, paying low rent, the presence of disability, the ownership of private vehicles and English language skills.

Note that population density is calculated based on the 2001 Census Collection District (CD) boundaries (the most detailed spatial unit available) to match the HILDA dataset and is sourced in non-census years from the National Regional Profiles of Australia (Australian Bureau of Statistics, 2013a).

2.3. The estimation strategy

This study systematically approaches research questions 1–5 in turn. This study employs a conditional logit model abstracting from time-invariant household-specific factors and concurrently appreciating the binary nature of the dependent variable.

The first research question is: What is the extent to which low income households and households living in denser areas are more likely to experience fuel poverty, other things held constant? Research question 1 is investigated using Eq. (1) for household h, at time t:

$$\begin{aligned}\text{Fuel poverty}_{h,t} &= \alpha_0 + \alpha_1\text{Lowincome}_{h,t} + \sum\nolimits_{i=1}^{j} \alpha_{2i}\text{Characteristics}_{i_{h,t}} \\ &\quad + \sum\nolimits_{k=1}^{m} \alpha_{3k}\text{Dwellingtype}_{k_{h,t}} + \alpha_4 log_2\text{Density}_{h,t} \\ &\quad + \sum\nolimits_{n=1}^{p} \alpha_{5n}\text{D}_{n_{h,t}} + \mu_h + \varepsilon_{1h,t}\end{aligned} \tag{1}$$

Where *Fuel poverty*$_{h,t}$ takes 1 as a value if the household is experiencing fuel poverty and 0 otherwise. *Lowincome*$_{h,t}$ takes 1 as a value if the real disposable equivalised household income is less than half of the median real household income (of the sample) and 0 otherwise. 'Low income' is preferred to 'poor' as the government of Australia has not adopted an official poverty line, but in practice, researchers do use the 50% (or the more relaxed threshold of 60%) of the median income as a *de facto* poverty line (Australian Council of Social Service, 2014, 2016; Headey, 2006). The percentage of observations in each year (wave) of households who are in fuel poverty ranges from 3% to 10%, and, the percentage of low income households ranges from 3% to 15% (see Fig. 2).

Characteristics$_{i_{h,t}}$ captures other household characteristic variables, $i \ldots j$, such as the housing tenure and whether or not the household is a sole person household or characterised as a lone parent household. *Dwellingtype*$_{k_{h,t}}$ represents dwelling characteristic variables, $k \ldots m$, including the dwelling type and the number of bedrooms. $log_2 Density_{h,t}$ represents the logarithm (with a base of 2) of the population density for location of household h at time t measured at the Census Collection District level. $D_{n_{h,t}}$ denotes dummy variables, $n \ldots p$. The dummy variables include the Socio-Economic Indexes for Areas (SEIFA), Index of Relative Socio-Economic Disadvantage deciles[6] and the year-specific fixed effects. Year specific fixed effects capture impact from changes that occur in time besides the model variables, such as annual changes to the Australian National Construction Code or possible effects from the global financial crisis – a recession period which Australia largely escaped (Board, 2016; Edey, 2014; Hill et al., 2008; Junankar, 2013). μ_h is the household-specific fixed effect which capture other factors that may have an impact, but which are time-invariant such as the year a dwelling was built. Finally, $\varepsilon_{1h,t}$ is the error term.

The second research question is: What is the degree to which any link between density and fuel poverty depends on low income, other things held constant? Research question 2 is investigated using Eq. (2) for household h, at time t:

$$\begin{aligned}\text{Fuel poverty}_{h,t} &= \alpha_0 + \alpha_1\text{Lowincome}_{h,t} + \sum\nolimits_{i=1}^{j} \alpha_{2i}\text{Characteristics}_{i_{h,t}} \\ &\quad + \sum\nolimits_{k=1}^{m} \alpha_{3k}\text{Dwellingtype}_{k_{h,t}} + \alpha_4 log_2\text{Density}_{h,t} \\ &\quad + \alpha_5 log_2\text{Density}_{h,t}\text{Lowincome}_{h,t} + \sum\nolimits_{n=1}^{p} \alpha_{6n}\text{D}_{n_{h,t}} + \mu_h \\ &\quad + \varepsilon_{2h,t}\end{aligned} \tag{2}$$

Where all terms are defined as in Eq. (1) and an interaction term

[6] Based on the deciles of the index, dummy variables were created with the value 1 if a household is in a particular decile and 0 otherwise.

Table 1
Descriptive statistics.

Variable name	Definition	Mean (std. dev.)	%
Dependent variable			
Fuel poverty	Household is spending (in real 2000 $AUD terms) 10% or more of real disposable equivalised household income on direct residential energy, where energy expenditure includes electricity, gas and other heating fuel		26.9%
Independent variables			
Low income	Household has real equivalised household income that is less than half of the sample median real household income		18.2%
Sole person	Household contains one member		41.6%
Age (65 or greater)	Household contains a resident who is 65 years of age or greater		37.4%
Lone parent	Household contains lone parent with children less than 15 years of age without others		11.6%
Renter	Household is rented		33.3%
Rent free	Household is rent free		4.0%
Semi-detached house (one storey)	Household dwelling is a semi-detached house (one storey)		5.1%
Semi-detached house (two or more storeys)	Household dwelling is a semi-detached house (two or more storeys)		2.6%
Flat/Unit/Apartment (one storey)	Household dwelling is a Flat/Unit/Apartment (one storey)		6.5%
Flat/Unit/Apartment (two or three storeys)	Household dwelling is a Flat/Unit/Apartment (two or three storeys)		5.4%
Flat/Unit/Apartment (four or more storeys)	Household dwelling is a Flat/Unit/Apartment (four or more storeys)		1.1%
Other dwelling	Household dwelling is another dwelling type (e.g. a non-private dwelling, a dwelling attached to a house or office or a caravan, tent, cabin or houseboat)		3.0%
Density	Number of people per square kilometre in household's Census Collection District (CD)	1261.63 (1517.51)	

Variables not reported in Table 1 include: Socio-Economic Indexes for Areas (SEIFA), Index of Relative Socio-economic Disadvantage decile dummy variables and wave dummy variables.

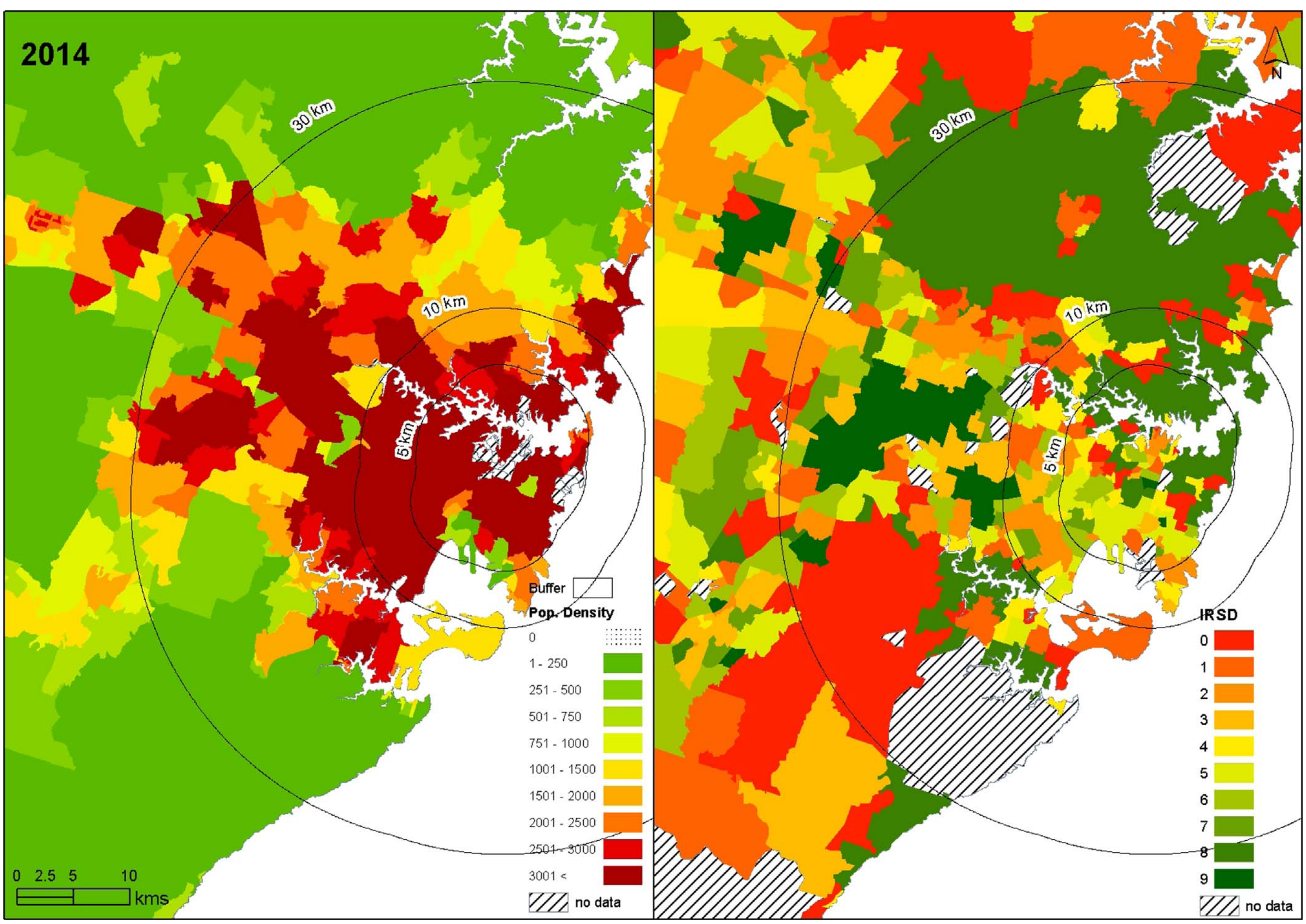

Fig. 1. Sydney broader metropolitan area population density (left) and presence of disadvantage (Index of Relative Socio-economic Disadvantage, right), state suburb level. Derived from data provided by the Australian Bureau of Statistics (2013a, b).

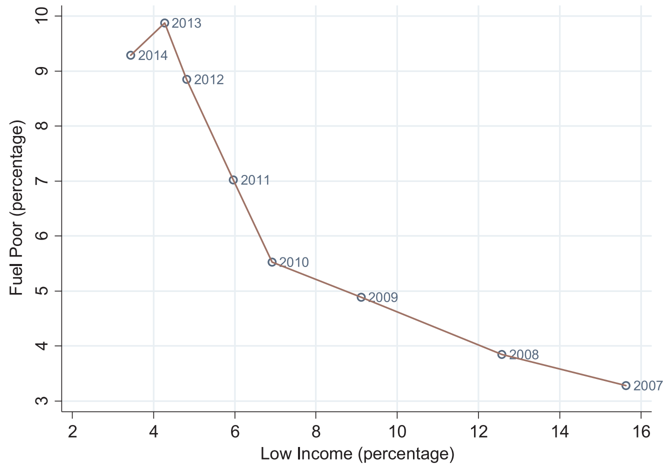

Fig. 2. Percentage of fuel poor versus low income households (observations) for each year (wave) of data.
Derived from the Household, Income and Labour Dynamics in Australia survey data.

between density and low income (e.g. $log_2Density_{h,t} \times Lowincome_{h,t}$) is included in the model.

The third research question is: What is the magnitude to which any link between a household's dwelling type and fuel poverty depends on low income, other things held constant? Research question 3 is investigated using Eq. (3) for household h, at time t:

$$\text{Fuel poverty}_{h,t} = \alpha_0 + \alpha_1\text{Lowincome}_{h,t} + \sum\nolimits_{i=1}^{j} \alpha_{2i}\text{Characteristics}_{i_{h,t}} + \sum\nolimits_{k=1}^{m} \alpha_{3k}\text{Dwellingtype}_{k_{h,t}} + \alpha_4 log_2\text{Density}_{h,t} + \sum\nolimits_{n=1}^{p} \alpha_{5n}\text{Dwellingtype}_{n_{h,t}}\text{Lowincome}_{h,t} + \sum\nolimits_{q=1}^{r} \alpha_{6q}\text{D}_{q_{h,t}} + \mu_h + \varepsilon_{3h,t} \tag{3}$$

Where all terms are defined as in Eq. (1). Additionally, interaction terms between dwelling type and low income (e.g. $Semi-detached\ house(one\ storey)_{h,t} \times Lowincome_{h,t}$) are included in the model.

The fourth research question is: To what extent are these differences distinguishable? Research question 4 is investigated using Eq. (4) for household h, at time t:

$$\text{Fuel poverty}_{h,t} = \alpha_0 + \alpha_1\text{Lowincome}_{h,t} + \sum\nolimits_{i=1}^{j} \alpha_{2i}\text{Characteristics}_{i_{h,t}} + \sum\nolimits_{k=1}^{m} \alpha_{3k}\text{Dwellingtype}_{k_{h,t}} + \alpha_4 log_2\text{Density}_{h,t} + \alpha_5 log_2\text{Density}_{h,t}\text{Lowincome}_{h,t} + \sum\nolimits_{n=1}^{p} \alpha_{6n}\text{Dwellingtype}_{n_{h,t}}\text{Lowincome}_{h,t} + \sum\nolimits_{q=1}^{r} \alpha_{7q}\text{D}_{q_{h,t}} + \mu_h + \varepsilon_{4h,t} \tag{4}$$

Where all terms are defined as in Eq. (1). However, interaction terms used in Eqs. (2) and (3) are included together.

The fifth research question is: Do other vulnerable groups, in denser areas, face a potentially heightened risk of fuel poverty, other things held constant? Research question 5 is investigated using Eq. (5) for household h, at time t:

$$\text{Fuel poverty}_{h,t} = \alpha_0 + \alpha_1\text{Lowincome}_{h,t} + \sum\nolimits_{i=1}^{j} \alpha_{2i}\text{Characteristics}_{i_{h,t}} + \sum\nolimits_{k=1}^{m} \alpha_{3k}\text{Dwellingtype}_{k_{h,t}} + \alpha_4 log_2\text{Density}_{h,t} + \alpha_5 log_2\text{Density}_{h,t}\text{Lowincome}_{h,t} + \sum\nolimits_{n=1}^{p} \alpha_{6n} log_2\text{Density}_{h,t}\text{Characteristics}_{n_{h,t}} + \sum\nolimits_{q=1}^{r} \alpha_{7q}\text{D}_{q_{h,t}} + \mu_h + \varepsilon_{5h,t} \tag{5}$$

Where all terms are defined as in Eq. (2). This more parsimonious model also includes interaction terms between density and other vulnerable groups' non-financial disadvantage (e.g.$log_2Density_{h,t} \times Lone\ parent_{h,t}$).

3. Results

The model estimates for Eqs. (1)–(5) are reported in Table 2.

To begin with, variance inflation factors indicate that Eq. (1) does not suffer from severe or worrisome multicollinearity. Specifically, the highest variance inflation factor is 2.04 and the mean variance inflation factor is 1.58. With regards to the first research question: What is the extent to which low income (financially disadvantaged) households and households living in denser areas are more likely to experience fuel poverty, other things held constant? Table 2 column 1 indicates that low income households are far more likely (odds-ratio = 11.75, p-value = 0.00) to experience fuel poverty, other things held constant. The odds-ratios are the probability obtained by exponentiation of the coefficient in the model and can be read as a household with low income is 11.75 times more likely to be in fuel poverty. A result that is statistically significant at the 1% level. Further, the results in Table 2 column 1 also point to sole person (odds-ratio = 4.87, p-value = 0.00) and lone parent (odds-ratio = 1.95, p-value = 0.00) households are more likely to suffer from fuel poverty. While households situated in apartments of two or three storeys (odds-ratio = 0.69, p-value = 0.03) are less likely to be in fuel poverty. Density is not found to be statistically significantly linked to fuel poverty in a linear (not reported in Table 2) or log functional form.

In terms of the second research question: What is the degree to which any link between density and fuel poverty depends on low income, other things held constant? Table 2 column 2 indicates that the link between density and fuel poverty does depend on low income (odds-ratio = 1.05, p-value = 0.04), other things held constant. Low income households in denser areas are more likely to experience fuel poverty. Specifically, for a low income household, a two-fold increase in density is associated with a much greater likelihood of experiencing fuel poverty ($8.69 \times 1.04 = 9.0376 \cong 9.04$ times greater likelihood of experiencing fuel poverty). In addition, sole person (odds-ratio = 4.86, p-value = 0.00) and lone parent (odds-ratio = 1.93, p-value = 0.00) households are correspondingly more likely to suffer from fuel poverty. The odds-ratios of other regressors do not change significantly.

For the third research question: What is the magnitude to which any link between a household's dwelling type and fuel poverty depends on low income, other things held constant? Table 2 column 3 provides some evidence that the link between dwelling type and fuel poverty depends on having a low income, other things held constant. In particular, having a low income and residing in an apartment (two or three storeys) (odds-ratio = 1.74, p-value = 0.05) is associated with a greater probability of experiencing fuel poverty. The odds-ratios of other regressors do not change significantly.

With respect to the fourth research question, 'To what extent are these differences distinguishable?', Table 2 column 4 reveals that when the moderating role of low income for density and dwelling type are considered jointly, only density (odds-ratio = 1.05, p-value = 0.04) is statistically significant, other things held constant. The odds-ratios of other regressors do not change significantly.

As regards the fifth research question, 'Do other vulnerable groups, in denser areas, face a potentially heightened risk of fuel poverty, other things held constant?', Table 2 column 5 indicates that households which live in higher density areas that also rent their homes are marginally less likely to experience fuel poverty. However, this result is only statistically significant at the 10% level. Specifically, a two-fold increase in density is associated with a marginally lower likelihood of experiencing fuel poverty ($0.94 \times 1.06 = 0.9964$). No other statistically significant differences are found for other vulnerable groups in higher density areas.

Table 2
Model estimates.

Variable name	(1) Odds-ratio (Standard error)	(2) Odds-ratio (Standard error)	(3) Odds-ratio (Standard error)	(4) Odds-ratio (Standard error)	(5) Odds-ratio (Standard error)
Low income	11.75***	8.69***	11.75***	8.90***	8.43***
	(0.88)	(1.37)	(0.99)	(1.41)	(1.31)
Sole person	4.87***	4.86***	4.85***	4.86***	4.68***
	(0.61)	(0.60)	(0.61)	(0.60)	(1.27)
Age (65 or greater)	1.00	1.00	1.00	1.00	0.65
	(0.14)	(0.14)	(0.14)	(0.14)	(0.20)
Lone parent	1.95***	1.93***	1.93***	1.92***	1.21
	(0.29)	(0.29)	(0.29)	(0.28)	(0.46)
Renter	0.88	0.88	0.89	0.88	0.56**
	(0.11)	(0.11)	(0.11)	(0.11)	(0.15)
Rent free	0.84	0.85	0.84	0.85	0.96
	(0.15)	(0.15)	(0.15)	(0.15)	(0.40)
Semi-detached house (one storey)	0.94	0.94	0.99	1.01	0.93
	(0.13)	(0.13)	(0.15)	(0.15)	(0.13)
Semi-detached house (two or more storeys)	1.08	1.09	1.08	1.12	1.09
	(0.22)	(0.22)	(0.23)	(0.24)	(0.22)
Flat/Unit/Apartment (one storey)	0.87	0.87	0.93	0.95	0.87
	(0.12)	(0.12)	(0.15)	(0.15)	(0.13)
Flat/Unit/Apartment (two or three storeys)	0.69**	0.69**	0.58***	0.60***	0.69**
	(0.12)	(0.12)	(0.11)	(0.11)	(0.12)
Flat/Unit/Apartment (four or more)	0.97	0.97	1.00	1.03	0.96
	(0.30)	(0.31)	(0.34)	(0.35)	(0.31)
Other dwelling	0.78	0.78	0.77	0.77	0.79
	(0.15)	(0.15)	(0.16)	(0.17)	(0.15)
Number of bedrooms	0.96	0.96	0.96	0.96	0.97
	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)
Log_2Density	1.00	0.99	1.00	0.99	0.94*
	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)
Log_2Density × Low income		1.04**		1.04**	1.04**
		(0.02)		(0.02)	(0.02)
Semi-detached house (one storey) × Low income			0.85	0.78	
			(0.19)	(0.18)	
Semi-detached house (two or more storeys) × Low income			0.98	0.88	
			(0.41)	(0.37)	
Flat/Unit/Apartment (one storey) × Low income			0.79	0.76	
			(0.18)	(0.17)	
Flat/Unit/Apartment (two or three storeys) × Low income			1.74**	1.55	
			(0.48)	(0.43)	
Flat/Unit/Apartment (four or more) × Low income			0.90	0.77	
			(0.65)	(0.56)	
Other dwelling × Low income			1.06	1.03	
			(0.36)	(0.35)	
Log_2Density × Sole person					1.01
					(0.03)
Log_2Density × Age (65 or greater)					1.05
					(0.03)
Log_2Density × Lone parent					1.06
					(0.04)
Log_2Density × Renter					1.06*
					(0.03)
Log_2Density × Rent free					0.99
					(0.05)
Summary statistics					
Observations	17490	17490	17490	17490	17490
Wald test statistic	Wald(χ^2) = 1563.86	Wald(χ^2) = 1570.89	Wald(χ^2) = 1568.80	Wald(χ^2) = 1575.56	Wald(χ^2) = 1578.81
Prob $> \chi^2$	0.00	0.00	0.00	0.00	0.00
Pseudo R^2	0.24	0.24	0.24	0.24	0.24

Standard errors in parentheses adjusted for clustering at the household level.
Variables not reported in Table 1 include: Socio-Economic Indexes for Areas (SEIFA), Index of Relative Socio-economic Disadvantage decile dummy variables and wave dummy variables.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

4. Conclusions and policy implications

This study set out to investigate empirically the role of a denser urban form, as it has unfolded in Australia, in mitigating the risk of fuel poverty. Density induced household level energy consumption behaviour is reasoned to underlie this empirical link. To the extent of the knowledge of the authors, this is the first study to explicitly test this link.

To begin with the results point to more low income households being significantly more likely to experience fuel poverty (statistically significant at the 1% level); while for density (whether characterised as a log or linear functional form) these results suggest that, distinct from low income, density is not linked to fuel poverty (Research question 1). With regards to low income households specifically though, the results paint a very different picture. For low income households greater density is found to correspond to a greater likelihood of experiencing fuel poverty, statistically significant at the 5% level (Research question 2). Similarly, a household's dwelling type and fuel poverty depends on having a low income in a broadly consistent direction with having a low income and residing in an apartment (two or three storeys) being associated with a higher likelihood of suffering from fuel poverty, statistically significant at the 5% level (Research question 3). These results for low income-specific links appear to be explained away by the broader density of the urban form (Research question 4). Moreover, there is evidence to indicate that the negative link between density and fuel poverty is attenuated for renters, although this is only statistically significant at the 10% level (Research question 5). One quite strong and resilient finding to emerge from addressing the research questions applies generally to households. That is, for households with a dwelling type described as an apartment (in a two or three storey building) are consistently found to be noticeably less likely to experience full poverty, statistically significant at least at the 5% level.

Not unlike earlier studies, the findings presented here are not without their limitations. This study uniquely accounts for time-invariant household-specific factors (e.g. the building's year of construction (and hence building age and what efficiency implications this may have)) and other potential confounders. The extent to which the results are confounded by other factors is mitigated by a number of other controls. Most notably, time-invariant household-specific factors, including but not limited to, house size. House size is the biggest difference between old and new homes in Australia; with the size of having more than doubled over the last 60 years (Stephan and Crawford, 2016). This work considered weather although found the results to be little changed when including the heating and cooling degree days variables. There is room for further research effort in future studies to attribute more granular measures in space and time to a household energy consumption behaviour. In addition to this potential limitation, it should be acknowledged that expenditure on energy is likely understated (cf. Wilkins and Sun, 2010). This could lead to an understatement of the incidence of fuel poverty. Additionally, while this study has used one definition of fuel poverty, alternative definitions also exist (Boardman, 2012b; Hills, 2011; Legendre and Ricci, 2015; Moore, 2012; Waddams Price et al., 2012; Watson and Maitre, 2015). While this study treats year-specific effects as a nuisance, future studies with more disaggregated data may wish to interrogate this variation in order to isolate the impact of broader structural economic changes on fuel poverty.

In all, the substantive findings of this study describe a quite nuanced narrative. They demonstrate contrary to dominant urban consolidation narrative (cf. Glaeser, 2012; Newman, 2006) that for low income households greater urban density through an interaction effect correspond with a an increase in the likelihood (odds-ratio) of experiencing fuel poverty. This is in contrast to what might be expected given the often celebrated economies of scale in terms of direct energy consumption, that are thought to be offered by densification (Burton, 2000; Capello and Camagni, 2000; Gaigné et al., 2012; Poumanyvong and Kaneko, 2010). The findings appear to reflect the more vulnerable position of low income households in higher density environments. Contrary to *a priori* expectations, renting (distinct from being a low income household) seems to reduce marginally the positive link between density and fuel poverty. This is despite renters' suffering from a disparity in opportunity to shape their own energy consumption. This inequality of opportunity could lead to difficulties ensuring an appropriate level of heating and cooling (Davis, 2012; Rehdanz, 2007). This result is also at odds with the ubiquitous Strata Title ownership structure within which apartment buildings are managed in Australia. This ownership framework is not designed to deal with long-term issues of building renovations – including lifting the energy efficiency standards – and long-term falling resale value (Randolph, 2006; Seeling et al., 2009). Moreover, high-rise based housing development in metropolitan areas is driven increasingly by investors than by owner-occupiers (Australian Bureau of Statistics, 2017; Randolph, 2006). This provides a mechanism which could plausibly further polarise the opportunities of renters and owners. One explanation for renting mitigating the link between density and fuel poverty (a result which is statistically significant at the 10% level) is that, renting is reasonably likely to be related to households accessing state or territory energy hardship schemes (e.g. The Queensland Government's Home Energy Emergency Assistance Scheme). However, future research could explore the impact of such schemes on fuel poverty and also what it may mean for renters in denser areas.

For policymakers and urban planners the implications of these findings are that, for low income households, the physical structure of a city (e.g. density design) may matter for the socio-economic structures of a city (e.g. fuel poverty). However, more research effort is needed to understand precisely what specific attributes of a city and what processes within that city (cf. Neuman, 2005) may cultivate energy efficiency. Within the literature on socio-technical transformations related to energy supply and consumption systems, a number of interconnected complex relationships involving the: regulatory; socio-economic; behavioural; technical; and physical structure aspects of cities remain underexplored (Bartiaux et al., 2006; Daniel et al., 2015; Dodson, 2013; Moloney et al., 2010; Sovacool, 2009).[7] As the findings stand though, they imply that the answer to the most profound research question facing urban researchers, "Does urban consolidation achieve its stated goals?" (Randolph, 2004), is, for low income residents already at risk of fuel poverty, "Not necessarily".

For policymakers and urban planners another insight to be gleaned from the results presented in this study is that residing in an apartment (two or three storeys) is found to be quite consistently and generally linked to a lower likelihood of experiencing fuel poverty. This finding accords with earlier and more provisional evidence that townhouses in Sydney are associated with lower levels of energy consumption and greenhouse gas emissions (Myors et al., 2005).

Fuel poverty represents a clear form of energy injustice. It is crucially important that decision makers remain cognisant of the distributional, recognition and procedural justice foundations of instances of energy injustice (cf. Jenkins et al., 2016). Fundamentally, as Walker and Day (2012) explain, fuel poverty is emblematic of a lack of recognition and a lack of procedural justice which are wrong in themselves and are interconnected and ultimately perpetuate the production of distributional inequalities. In order to disrupt ingrained disadvantage and fuel poverty energy policy needs to address aspects of energy justice whether they be entrenched in the form: (1) distribution; (2) the recognition of impacted groups; or (3) the procedures for remediation (Jenkins et al., 2016). This inevitably needs to be reconciled with the potential trade offs between groups and their goals (Chakravarty and Tavoni, 2013). Ultimately though, whether undertaken by the government or the civil society, there remains a real need to develop and implement practical interventions to effect change for households experiencing fuel poverty.

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[7] Small scale developments (e.g. some blending energy efficient building design with community-oriented lifestyles) offer one tractable means for impact assessment (Burke, 2004; Charlesworth and Adams, 2011; Crabtree, 2005).

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2018.03.003.

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