Behaviors and adaptation of households living in an off-grid house

Dr Gabriela Zapata-Lancaster	Welsh School of Architecture, Cardiff University	ZapataG@cardiff.ac.uk
Simon Lannon		Lannon@cardiff.ac.uk
Huw Jenkins		JenkinsH@cardiff.ac.uk

Fig 1: Off-grid living

WHICH ARE YOUR ARCHITECTURAL (R)SOLUTIONS TO THE SOCIAL, ENVIRONMENTAL AND ECONOMIC CHALLENGES OF TODAY?

Research summary

In the United Kingdom, the low carbon policy aspirations aim for new domestic buildings to be nearly zero carbon by 2020. In the past, the prevalent approach to low carbon performance has relied on the application of energy-efficient systems and low zero carbon technologies to offset the carbon emissions of buildings. However, research on performance gaps suggests that despite the good intentions of designers, the expected energy performance is rarely achieved during operation. Significant discrepancies have been found between as-designed and in-use performance, some of which may be the result of users' behaviours. Off grid buildings can give an insight into the potential onsite energy generation, storage and demand reduction. This article presents a study that analysed an off-grid house built in 2013 as a working farm house to Code for Sustainable Homes level 3 (level 5 energy). The off grid systems in this case study are analogous to an intermittent future energy supply. The study identified the energy-efficiency behaviours of the households and their adaptation in the off-grid house that has been occupied for over a year. The monitored data of in-use performance has informed the analysis of households' routines and practices that affected the energy and water consumption in the dwelling. The study suggests that the reductions in carbon emissions from the occupants' behaviour were limited in their impact as the parasitic loads of the systems dominate. The findings bring attention to a number of aspects that could affect the success of carbon reduction measures in dwellings.

Keywords: off-grid, occupant behaviour, energy performance, low carbon systems

1. Introduction

There is an increased interest in investigating behavioural aspects related to energy consumption in buildings, especially in the context of energy interventions (Druckman et al, 2011; Peters et al, 2012; Maxwell et al, 2011; Milne and Boardman, 2000; Sanders and Phillipson,2006). It has been found that the users can have a significant impact in the performance of buildings, for example Sunikka-Blank and Galvin (2012) find that houses with the same energy rating can use as much as six times the amount of energy for heating. Heating consumption could vary significantly in identical built houses. Yohanis et al (2008) find a variation of the heating consumption by a factor of 2 on a study of 20 terraced low-energy houses in Sweden, while a study in the UK finds a factor of 3 in terms of variation due to users' factors (Gill et al 2010). Therefore, the consideration of users' factors (behaviours and routines) is relevant in the context of energy efficiency and nearly zero energy buildings in order to understand the linkages between occupants' behaviour and in-use performance.
The purpose of this paper is to present the preliminary findings of an ongoing study that investigates the energy performance and water consumption of an off-grid farm house designed to Code for Sustainable Homes level 3 with an energy performance equivalent to level 5. The study is analysing the users' factors (occupants' routines, behaviours and lifestyle) in relation to the monitored energy and water consumption data. This paper discusses the opinions and the behaviours of the occupants in the off-grid house, informed by energy performance and water consumption data. The paper is structured as follows: the research methodology; findings of users' factors in performance; and, preliminary discussion and further work.

2. Research methodology

The study comprised the monitoring and evaluation of the performance and the analysis of the occupant behaviour to explore aspects related to in-use performance, off-grid living, occupants' interaction with low carbon systems and the operation of the house. Data of environmental and performance parameters and indoor conditions in the house were recorded for a period of a year. The results were analysed in relation to the behavioural study (qualitative and observational methodologies) and the as-designed documentation (document analysis) to study the relationship between occupants' lifestyle, interaction with systems and their effect on the performance of the house and its systems.

2.1. Case study

The case study is an off-grid house in a rural area in the United Kingdom. The house has an area of 107m^2, it has two floors and a basement. The ground floor has a living room, kitchen and dining room, a toilet and a storage area. The first floor has three bedrooms and a toilet. The battery storage, the rainwater harvesting tank, the biomass boiler, the hot water storage tank are located in the basement. The key performance parameters of the house are as follows:

U-values (W/m^{2}K)	
Walls	0.13
Floors	0.10
Windows	1.4
Ceiling	0.16
Airtightness	3.63
Primary energy use (kWh/m^{2}y)	7
Energy consumption (kWh/y)	
Space heating	3839
Water heating	3076
CO2 emissions (Kg/y)	

Space heating	42.7
Water heating	27.05
Pumps and Fans	67.21
Lighting	218.77
PV	-1686.35
Total CO_2	-1330.63
Total CO_2 per m^2	-12.42

Table 1. Summary of the house performance

2.2 Data collection methods

The data collection methods include semi-structured interviews with the occupants; self-reported diaries of daily activities to document activities and routines at home; questionnaires to reveal perceptions, opinions, lifestyles and preferences about off-grid living; physical monitoring of environmental conditions; observation and walkthrough in the house to investigate the day-to-day operation of systems and living routines in the house. The data collected are being compared to the as-designed performance estimations and the as-designed recommendations by the design team about energy-efficient lifestyle (building users' guidance) and the monitored performance data.

In terms of physical monitoring, six electric meters were installed in the house to measure the electricity and lighting used in (kitchen, utility, downstairs, upstairs); six electric meters were installed in the basement to measure the energy used by the boiler, sockets, lights, water purifier, immersion heater. A gas metered was installed to monitor the usage for cooking. In terms of environmental conditions, the air temperature and relative humidity are measured in nine locations in the house: basement, kitchen, lounge, utility room, toilet, bedrooms(x 3) and bathroom. The outdoor air temperature, relative humidity and rainfall levels are also recorded.

2.2 Data analysis

The interviews were transcribed verbatim and analysed in the qualitative analysis software NVivo to explore the interaction between the households and the systems, controls and technologies in the house. The research data was interrogated by a thematical code analysis where the main themes that emerged from the qualitative studies were: understanding of building controls and systems (including low zero carbon technologies); concerns about availability of resources; and, adaptation to off-grid living.

3. Results

3.1. Occupants' opinions and general perceptions

The occupants consider that living in an off-grid house has not resulted in compromises or changes to their habits and lifestyle:

(1) 'People were telling us we will have to change, we'll have to do this and you have questions, what is different... And it's not different, it's not, you turn the tap and the water comes out you know, it's amazing; you switch the light on, like it!'

However, the households reported when they moved in the house, they were cautious about using electrical devices and appliances:

(2) 'I tend to be overly cautious with using things and that's down to me to be honest... I think from the beginning we thought, oh we can't use these together, we can't use that together'

Yet, the research participants reported to be willing to make changes in their lifestyle so as to save energy and water. For example, some domestic appliances are not being used in the house such as the microwave, kettle, dishwasher and tumble dryer.

Domestic activities such as washing and ironing were reported to be done during daytime when the energy supply is 'visible' (sun for electrical use and drylining):

(2) 'I iron in the day rather in the night whereas perhaps[before moving to the off-grid house] I might have done it in the night watching the tele and doing the ironing... and I tend to do it more in the daytime rather than in the evening. I do try get the washing, say, if there is a nice day, say tomorrow there's going to be lovely sunshine, right, we'll get the washing going now right to save the drain on the bad days on the batteries so then we don't have to put the generator on to generate the batteries back-up so I'm a bit more cautious with that…'

The occupants expressed their concerns about the availability of water in the event of drought:

(1) '… we are conscious of our water consumption.. that's the biggest worry, the water, really … if we were short of water, and we get to that stage.. We've got two months drought... but how often do we have two months without rain?'

In terms of water supply, the house uses a rainwater harvesting system stored on a 5500 litre tank.

3.2. Patterns and comfort routines in the house

The monitored data show that approximately 71.6% of the time the indoor temperature recorded in the house was between 18 and 22^{o}C degrees. The temperature was between 22 to 25^{o}C during 10.6% of the monitored period. The temperature was below 18^{o}C on 17% of the monitoring period and was over 25^{o}C for 0.1% of the period.

The research participants expressed their satisfaction with the indoor conditions and that the temperature of the house remained stable throughout the day, at around 19^{o}C in winter and 21^{o}C in summer. No significant variations in the temperature profile between weekdays and weekends were recorded in different seasons. It was reported that in terms of passive measures, windows tend to be opened for fresh air and that the occupants exert adaptation at personal level to achieve comfort (i.e. adding extra layers of clothes to be warm). In terms of active measures, the households felt that the temperature in the house tends to be comfortable and stable. It was also reported that the temperature setting tends to be overridden because the research participants do not have set routines. They tend to be in the house intermittently at variable times of the day/week depending on their work commitments:

(2) 'Our routines aren't set. We haven't had a routine as such. Everything is a little bit... flexible'

3.3. Patterns of consumption as per monitored data

The breakdown of energy annual energy consumption of the dwelling show that the appliance load is significantly lower than the UK average. In the off-grid house, the appliances use 6% of the energy and heating/hot water use 94%. The UK average domestic energy use breakdown is 19% for appliances and 81% for heating and hot water.

The monthly profile of the energy use shows that the heating is the dominant demand, and that it was used for 10 months of the year, reflecting the exposed nature of the site (Figure1). The profiles of the photovoltaic are as expected (Figure 2), however the diesel generation profile in the winter shows that it is switched on during the late afternoon or evening and this reflects the user interaction with the system. The user interaction is shown in Figure 3, the diesel generator is used after poor photovoltaic generation days to protect the battery. The condition of the battery is shown by the voltage line.

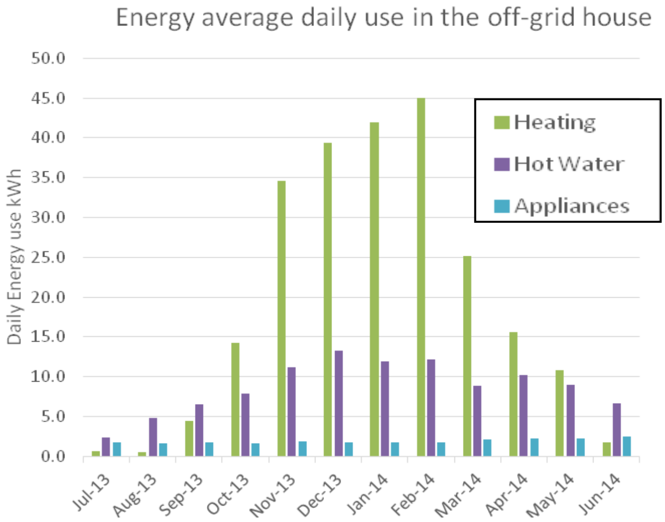

Figure 1 Monthly energy use breakdown

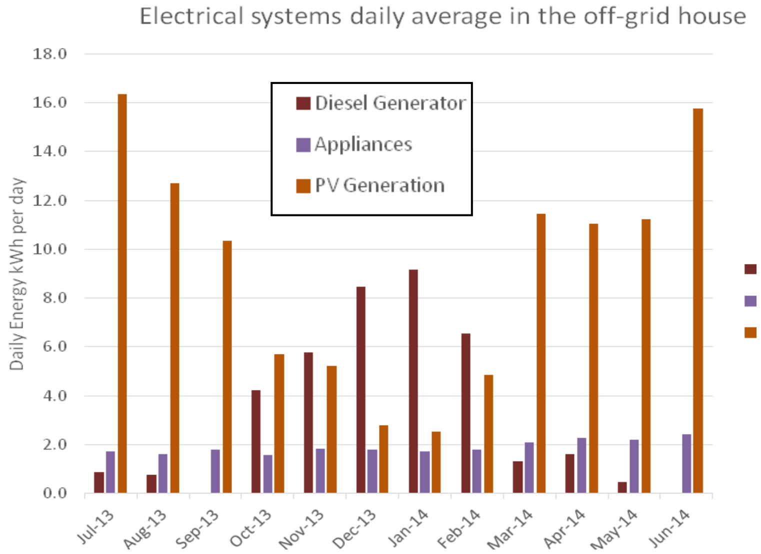

Figure 2 Monthly variation of daily average energy consumption of electric systems

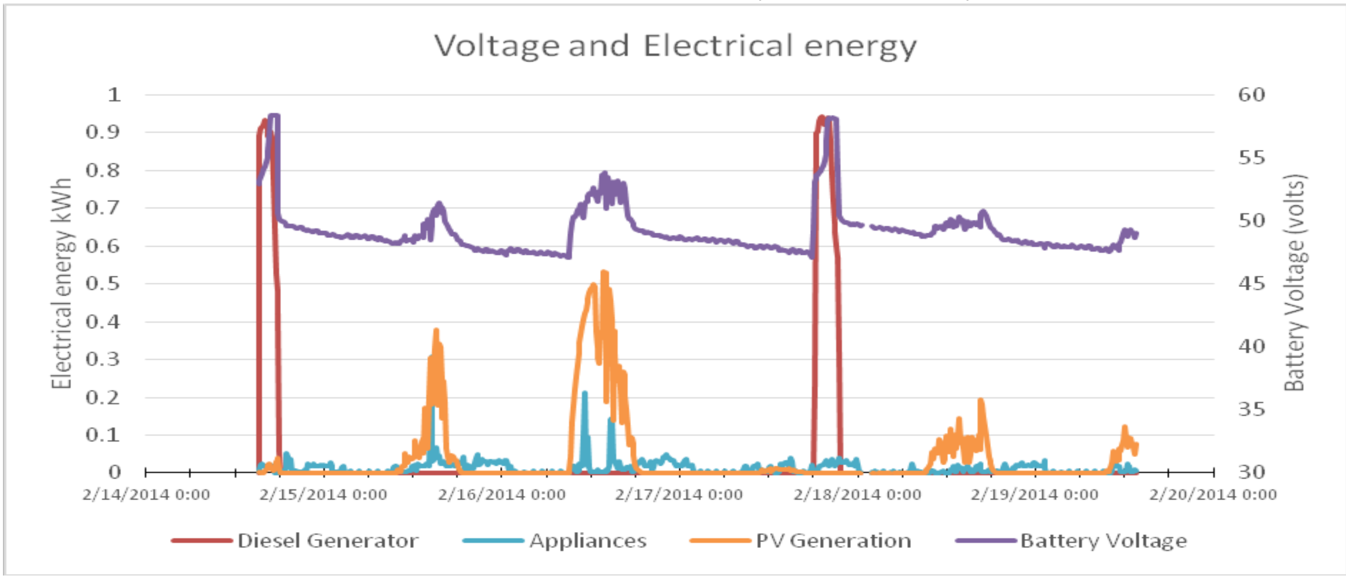

Figure 3 Voltage and electrical energy - sample days in February 2014

The heating demand of the building has been measured for the year using heat meters on the Thermoskirt system. The schedule for the heating in the winter was twice a day, but the occupants would add the fuel into the boiler when required. The daily demand of the system was compared to the temperature difference between outside and inside. The resulting scatter plot (Figure 4) shows a trend that allows the estimation of the daily heat loss for the house of 4.3kWh/day/C.

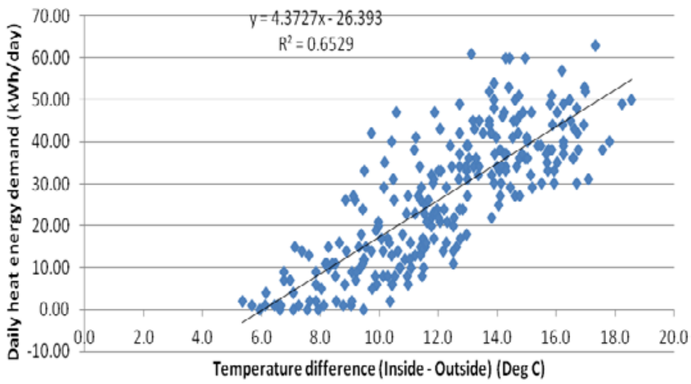

Figure 4 Daily heating energy consumption vs temperature difference

The appliance loads shown in the figures below are based on the monitored kit installed during the construction. These figures do not include the parasitic loads from the services in the basement, the gas cooker and the freezer in the basement. The breakdown of consumption shows that the house's demand due to occupants' activities in the house is nearly a quarter of the demand of the services.

	kWh
Ground floor sockets	1.07
Kitchen ring	0.35
1st floor lights	0.04
Ground floor lights	0.12
Utility sockets	0.03
1st floor sockets	0.09
House	**1.70**
Boiler electric	2.18
Basement sockets	2.22
Basement lights	0.15
Water purifier	2.18
Immersion heater	3.91
Services total	**10.64**

Table 1 Daily electrical energy demand breakdown for April to April 2015

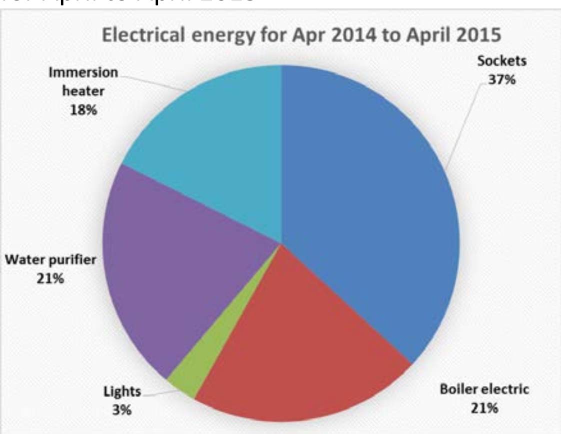

Figure 5 Breakdown of electrical demand in April 2014 and April 2015

From May 2014 the occupants have started to use the excess energy from the photovoltaics to heat the hot water rather than using the biomass boiler. The propane gas used for cooking has been metered on 4.7kWh per day.

4.3. Water usage

The as-designed calculation for water consumption was based on the Water calculator of the Code for Sustainable Homes. The estimation of daily water consumption was 101 lt/person. It has been found that the research participants use an average of 64 lt/person per day.

The water consumption throughout the year remains stable although the consumption was slightly higher in June 2014, possibly as a result of increased occupancy (Figure 6).

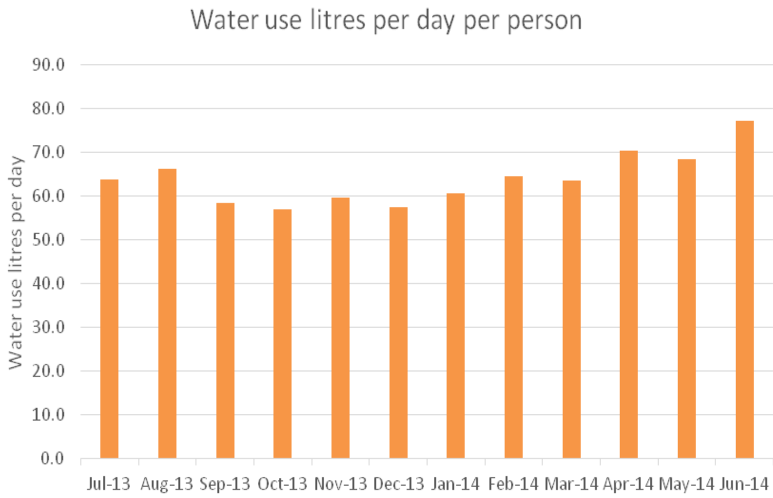

Figure 6 water use litres per day per person

The water system within the property uses a UV lamp to purify the water and a pump to transport the water from the basement. The energy used by the water systems (filter and pump) is shown in Figure 7. The UV lamp and control systems have a base load of 78W and the pump has a load of 1.1Wh/l. In May 2014 the energy consumption related to the water supply used by the pump and UV light was 8.54Wh/l. The average energy required to supply water from the mains in the UK is 0.6 Wh/l.

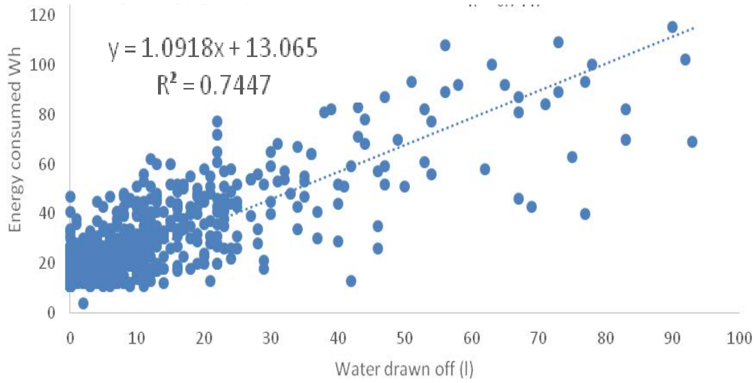

Figure 7 Energy consumption of water purification system and water drawn off.

3.3. Interaction with and operation of low zero carbon technologies

The occupants are in the process of establishing regimes of use, maintenance and routines to manage and operate the house and its systems. The occupants expressed that the weather conditions are the key factor that they considered to operate the systems. They feel confident about their understanding of the systems and their knowledge to operate them. They expressed their interest in controlling and managing the operation of the systems:

(1) 'I think is a thing that you've got to manage, it's not a thing that you could walk away from and say, OK, I'm going to light it at 4 o'clock every day regardless of the weather outside, you know, it's a waste to light it when it doesn't need it…'

In terms of guidance and feedback provided to the households, they expressed their satisfaction with the guidance and support provided to operate the house and its systems. A tablet is used to display the monitored data on energy use. The data has helped the occupatns to identify the householders' energy consumption patterns. They prefer to visualise these patterns in seven days intervals to compare routines and variations between days. The households expressed that they do not need to check the energy use data daily. Conversely, they reported to check regularly the water levels of the rainwater harvesting tank to manage the use of water and anticipate the provision of additional water in case the level runs low during periods of dry weather. The water level measurement device shows the levels using a simple gauge with 9 bars representing a full tank. The households expressed that they were concerned when the water level dropped below 7 bars. To date, the lowest level recorded was 2 bars (approximately 20 per cent of the storage capacity: 1100 lt).

5. Discussion and further work

There are some key aspects to emphasise from this case study, on one side, the occupants have shown that they are willing to change their behaviours and adopt an energy-saving lifestyle. As a result, they have changed their routines in the house, i.e. washing and cooking. In addition, some of the domestic appliances are not being used in the house, for example, tumble dryer, microwave and kettle.

The weather has become part of the rationale that informs the planning of domestic routines and activities in the house. The energy and water supply in the house is linked by the occupants to the weather conditions (sunny day= energy, rain=water). Therefore, the occupants 'visualise' the existing supply to carry the domestic activities. For example, washing is done on sunny days during daytime so as to take advantage of the solar energy collected at the time of the washing (washing machine and dry lining).

The water supply is of concern of the households particularly during dry weather spells. The research participants have bought additional water tanks to increase the waterstorage capacity. The households expressed their interest in managing the operation and control of the technical systems; i.e. turning on/off the diesel generator and managing the use of the batteries for storage of the solar energy. The monitored data show that the water and energy consumption in the house are below the as-designed estimations. The water use is half of the average consumption per person in the UK. The in-use energy consumption due to appliances and devices operated by the households for domestic activities (i.e. lighting, conditioning of spaces) is below the as-designed predictions. However, the parasitic loads of the systems require a higher energy consumption that estimated.

The preliminary results of this ongoing study bring attention to the performance of the systems, the ways that energy and water is supplied and occupants' lifestyles/routines in the context of off-grid living. In the context of limited energy supply and scarcity, there is a need to engage with the occupants for the energy-efficient operation of systems and controls instead of relying only on technology-based solutions to reduce energy use at home. While technology has the potential to increase energy efficiency, inefficient behaviours and routines can cancel out the potential of efficient systems and controls in reducing energy use. Further work will explore the interaction between the households and the systems/controls informed by philosophy of technology and human-computer interaction theories.

6. Acknowledgments

The authors thank the research participants for their contribution to the study.

7. References

Druckman, A., Chitnis, M., Sorrell, S., and Jackson, T. (2011). Missing carbon reductions? Exploring the rebound and backfire effects in UK households. Energy Policy, 39: 3572-3581.

Gill, Z., Tierney, M., Pegg, I. and Allan, N. 2010. Measured energy and water performance of an aspiring low energy carbon affordable site in the UK. Energy and Buildings, 43: 117-125

Maxwell, D., Owen, P., McAndrew. L, Muehmel, K. and Neubauer, A. 2011. Addressing the Rebound Effect, a report for the European Commission DG Environment, 26 April 2011.

Milne, G. and Boardman, B. 2000. Making cold homes warmer: the effect of energy efficiency improvements in low-income homes, A report to the Energy Action Grants Agency Charitable Trust. Energy Policy, 28(6–7): 411-424.

Peters, A., Sonnberger, M., Dütschke, E., and Deuschle, J. 2012. Theoretical perspective on rebound effects from a social science point of view: Working paper to prepare empirical psychological and sociological studies in the REBOUND project. Working paper sustainability and innovation S2/2012 of the Fraunhofer Institute for Systems and Innovation Research (ISI).

Sanders C. and Phillipson M. 2006. Review of differences between measured and theoretical energy savings for insulation measures. Centre for Research on Indoor Climate and Health, Glasgow Caledonian University and the Energy Saving Trust, London. December 2006.

Sunikka-Blank, M. and Galvin, R. 2012. Introducing the prebound effect: the gap between performance and actual energy consumption. Building Research & Information, 40(3): 260-273.

Yohanis, Y., Mondol, J., Wright, A. and Norton, B. 2008. Real-life energy use in the UK: how occupancy and dwelling characteristics affect domestic electricity use. Energy and Buildings, 40: 1053-1059.