2 What was the effect of HEEUP on household electricity and gas consumption?

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Summary of results

The results of overall pre-post intervention comparisons for the daily electricity and gas consumption measures (not including pathways involving a fuel change) indicated a highly significant decrease in electricity and gas consumption. These decreases of 25% (2.09 kWh per day) and 7% (7.63 MJ per day) for electricity and gas respectively are of practical (as well as statistical) significance give an annual reduction of 762 KWh ($213.46) for electricity consumption and 2,787 MJ ($55.64) for gas consumption. That is, in overall terms the intervention was successful in producing energy savings.

The upgrade paths yielding significant decreases in daily *electricity consumption* were electric storage to heat pump (29%), electric storage to gas instantaneous (42%), and electric storage to gas solar (41%).

The significant electricity reductions were associated with financial saving equivalent to $244.14 (electric storage to heat pump), $303.89 (electric storage to gas instantaneous), and $295.65 (electric storage to gas solar).

Increased gas assumption associated with upgrading from electric storage to gas instantaneous and to gas solar, was not statistically significant for either of these pathways.

The upgrade paths yielding significant decreases in daily *gas consumption* were gas storage to gas instantaneous (15%) and gas storage to gas solar (13%). These effects correspond to financial savings of $114.45 and $101.96 respectively.

Introduction

The adoption of energy-saving technologies by households is an important part of achieving energy conservation and greenhouse gas targets in Australia. Despite the opportunity to realise significant energy savings, however, oftentimes homeowners are reluctant to take on cost intensive energy efficiency investments, such as purchasing a more efficient hot water service (Frondel & Vance, 2013). With this in mind, the National Strategy for Energy Efficiency (Council of Australian Governments, 2010) seeks to increase the up-take of low emission hot water services in Australian households through public education, financial incentives and reducing barriers that may hinder households buying and installing these technologies. Steps toward this end are described in the commissioned report entitled *Investigation of Deemed Savings for Residential Activities in a Possible National Energy Savings Initiative* (EnergyConsult, 2012) which details the expected energy savings from a range of technology upgrades. Further, over the last 10 years, the Australian Government has funded the trial and evaluation of energy-saving interventions using a range of approaches including replacing inefficient water heaters with new, energy efficient solar or heat pump models (e.g. Alice Solar City, 2013; Lynch et al., 2013; 2013; Perth Solar City, 2012; Solar City Adelaide, 2013).

One of the barriers to household investments in energy efficiency has been the financial cost of energy saving technologies especially for low-income households. The HEEUP project was designed to address this significant barrier head on by providing households with tailored information and advice on the financial costs and benefits of a hot water upgrade and by providing households with access to funds through a number of financial mechanisms. Therefore, the behaviour change focus of HEEUP was primarily on energy consumers' decisions to purchase and install a new, energy efficient hot water service. From this strategy of persuading householders to upgrade their inefficient water heating systems, energy savings should result from the improved efficiency of new, replacement technology.[2]

Research aims and research questions

The objectives of this section of the report is to assess the magnitude of any change in household energy consumption that is attributable to the hot water service upgrades, and to identify specific types of hot water service upgrades that contribute to energy savings. The following sections describe the evaluation methodology employed to assess the change in energy consumption in HEEUP and the data analysis strategy employed to test for significant decreases in energy consumption over time as a function of the intervention. The results of the data analysis are discussed in the final section of the report. This analysis addresses the following questions:

[2] This report details an evaluation of the effect of the hot water service installations on household energy consumption and not the effectiveness of the program on consumer decision-making regarding the purchase and installation of new, energy efficient water heating technology.

1 What, if any, change in household energy consumption results from the hot water service upgrades?
2 What, if any, change in household energy consumption results from specific types of hot water service upgrades?
3 What variables explain any change from pre-intervention consumption to post-intervention consumption?

Selected previous research

Installing technology upgrades in households to produce energy conservation has been trialled in other contexts (see Abrahamse et al., 2005, for a review of these studies). However, there have not been a large number of experimental trials in the behavioural sciences that evaluate the effectiveness of replacing inefficient hot water services with more efficient technologies. Rather, research employing regression techniques has identified various technologies as more or less consequential for energy demand. For example, one recent study on the drivers of household energy consumption in NSW identified technologies such as pool pumps, moderate to high use of clothes dryers, and the use of ducted air conditioning as significant contributors to average daily electricity demand (Fan, MacGill & Sproul, 2015). Having a gas hot water service, on the other hand, was associated with significantly lower demand for electricity, even after controlling for the presence of a gas connection in the household.

Other examples of research focused on the impact of water heating on consumption and conservation have studied the potential savings that might accrue from energy efficient water heating technologies but without much attention afforded human factors in the use of these innovations (DEDJTR, 2015; EnergyConsult, 2012; Huang & Lee, 2004; Moreland Energy Foundation Limited, 2010; Nekså et al. 1998). These documents tend to identify heat pumps and solar (gas and electric boosted) solutions as the technology producing the biggest energy savings, especially when replacing electric storage units or inefficient gas systems (i.e. below 5 star). These replacement options can save around 30 to 35 MJ per day on average.

The Australian Government has funded a number of energy efficiency trials, some of which included installation of solar hot water systems and/or heat pumps (DERT, 2013; Sayeef et al., 2013). A number of these programs demonstrated significant energy savings. For example, in their report of the Solar Cities program, the CSIRO cites average daily savings of 0.7 (3.2%) and 1.7kWh (7%) following solar water heating installations in Perth and Alice Springs respectively (Sayeefet al., 2013). However, these results seem to ignore the type of existing technology in place.

The Perth Solar City (2012) project installed mostly electric boosted solar hot water systems in 1151 households (having a modal income of between $50,000 and $100,000 per year). In 911 households, solar systems were installed to replace existing water heating devices and the largest percentage of these was gas storage systems (45%). In other households, the existing systems were electric storage (32%), gas instantaneous

(17%), and electric instantaneous (6%). The evaluation for the effect of the solar water heating replacements was conducted on 235 households that had an existing storage or instantaneous electric system. In their report, Perth Solar City (2012) stated that, where an electric storage or instantaneous system was replaced with a solar water heating system (with electric booster), households decreased their electricity consumption by an average of 18.2% per day compared with a comparison group of households.[3] Analyses involving other combinations of existing systems were not reported and therefore it is not possible to know what, if any, statistically significant gas savings were associated with shifting from gas systems to solar hot water.

The Alice Springs Solar City report (Alice Solar City, 2013) installed solar hot water systems (mostly electric boosted) and heat pumps over a four year period. The majority (61.9%) of installations replaced existing solar systems, while electric storage (23.0%), gas storage (10.6%) and gas instantaneous (4.5%) made up the remainder of systems already in place. The authors of the report observed energy savings that varied with the type of existing technology that was replaced by the new solar water heater. There figures (based on a subsample of 504 owner occupiers) suggested an annual saving of 16.7% (4.27kWh/day on average) and 11.1% (3.01 kWh) depending upon whether an electric storage system was replaced or an existing solar system.[4]

Lynch et al. (2013) evaluated the Central Victorian Solar Cities energy efficiency program in which some households were fitted with 1.5kW solar hot water systems while other households received one of a number of alternatives (e.g. a home energy audit, retrofits such as curtains and pelmets, photovoltaics, in-home display). The combination of interventions resulted in a 13% reduction in average daily energy consumption when compared with a matched control. However, the solar water heater replacement intervention involving 65 households resulted in the greatest savings. The researchers reported that shifting to solar decreased electricity consumption by 22% (or 4.84 kWh/day on average) relative to a matched control group. In 77% of these households, the solar systems replaced electric hot water systems.

The brief overview of selected energy efficiency trials in Australia above brings to the fore the conclusion that technology upgrades will not produce the same outcomes for energy efficiency in all applications. The type of existing technology being replaced, the magnitude of pre-intervention daily consumption, how energy is used in households across different regions and population, the type of data management and analysis procedures brought to bear, can all have a bearing on the savings observed. In trials were water heating technology has been used in everyday situations suggest that program induced savings can range from anywhere from between 3% and 18% depending upon a range of study-specific factors.

[3] Levels of statistical significance were not reported.
[4] Levels of statistical significance were not reported.

There are also factors that can limit the optimal performance of water heating technologies. These are described in the following section.

Limits to technology-driven efficiency

Rebound effects

It was reported by the Department of Climate Change and Energy Efficiency that households with a modern solar hot water system generally save 1.5–2 kilowatt-hours (kWh) per day on hot water-related energy costs when compared with traditional hot water systems. However, the preceding discussion illustrates that savings are variable, which may be partly due to the different analyses undertaken by each solar city and the CSIRO.

Furthermore, it turns out that the introduction of energy saving technology into a household can change energy consumption behaviours in unintended ways that serve to limit the potential savings that might be expected from the upgrade. The dependency between the performance of water heating technologies and how they are used in households explains the gap between their performance 'on paper' and their usually less than expected performance in-situ. The reason for this gap is usually attributed to the operation of 'rebound' or 'takeback' effects by which the introduction of energy efficient technologies results in a cost reduction and an associated increase in consumption (Berkhout et al. 2000; Greening, Greene, & Difiglio, 2000). Put another way, individuals 'spend' the savings resulting from the installation of an energy efficient water heater. Rebound effects can take the following form in households:

- Direct rebound effects whereby the use of energy increases as a result of increases in efficiency (e.g. installing an energy efficient hot water service, but using more hot water).
- Indirect rebound effects whereby the decrease in the cost of energy services means that households have more money to spend on other energy consuming goods and services (e.g. installing an energy efficient hot water service, but running space heating at a higher temperature).

Research on the existence and size of rebound effects is contested, but most studies suggest that some degree of takeback is likely to occur. Some researchers have concluded that the size of the effect can constitute up to 30% of the achievable energy savings (Chitnis et al., 2014; Dimitropoulos, 2007). For heating and hot water services, there is evidence that the direct effect may be much larger, especially for households that have electricity as their only source of energy (Gálvez et al., 2015). Furthermore, current evidence indicates that the largest rebound effects are associated with activities undertaken by low-income households (Milne & Boardman, 2000; Chitnis et al., 2014).

Installation, operation and breakdowns

The Alice Solar City project discovered a faulty valve in the Over Temperature Protection system resulting in the over use of the electric booster. The fault was estimated to exist in 230 systems after installation. A faulty electric boost solar hot water system can have similar energy use to an electric storage system. One of the 'transferable lessons' arising from the Alice Springs Solar Cities (2013) project was that 'Pilot installations of new technologies with careful monitoring is therefore worth considering in similar programs, even for modifications to well understood products' (p.54) . (The DCCEE (2010) describe a number of other operating and installation issues that can reduce the efficiency of solar water heating systems.)

The quality of the installation of energy efficiency technologies also influences their performance. According to Sayeef et al. (2013) solar water heating systems have variable performance because they depend upon exposure to sunlight. The installation of energy efficient technologies such as solar water heating systems and heat pumps is critical to their performance. For example, the orientation of the roof of the dwelling determines the direction in which the solar collectors should face. When incorrectly installed the overnight booster will be over-used to compensate for cooler afternoon solar heating.

The correct operation of energy efficiency can also be important to optimal performance. Where solar systems are concerned, hot water is best used in the morning hours so that water can be heated during the day and stored overnight. Inefficiencies occur if water is being used in the late afternoon and evening because the booster will be required to heat the water rather than the sun.

Environmental factors

The context in which new energy efficient technologies operate has an influence on the optimal performance. Heat pumps, solar hot water systems and storage systems are all sensitive to some extent to factors such as climate. For example, the DCCEE (2010) advise that the performance of heat pumps is best when used in areas having suitable climate conditions:

Heat pumps work most efficiently in warm, humid climates. They are not suited for installation outdoors in cold climates and where regular freezing or very cold and dry conditions are experienced. Some heat pumps are manufactured to work more effectively during brief frost conditions but they will cost more to run in these conditions and are not recommended for use in prolonged cold periods. Note that some heat pumps may require an electric booster element if operated in regions where it is cold. The cost of running a heat pump may increase if it is required to boost during the day when electricity tariffs may be high. (DCCEE, 2010, p.198)

The fact that the performance of energy technologies cannot be generalised in a straightforward manner means that evaluations of their effectiveness must take into account where the evaluation was done and during what time of the year. Therefore, generalising energy efficiency results from trials conducted in northern Australia to the south-eastern part of the country may be misleading.

Methodology

Study participants

Selection

The data for this study comes from a sample of participants in the HEEUP. The 339 households in this study were all the participants with data available up to the 31 October 2015. The entire program delivered a total of 792 hot water upgrades.

Participants were selected to participant in HEEUP using an opt-in process whereby concession card households were approached by mail and invited to receive a subsidised hot water system. A number of strategies were employed to recruit participants for a hot water upgrade. For example, AGL Energy mailed out to concession card-holding customers in selected suburbs having adequate proportions of low-income, owner-occupied households. A small number of participants were also recruited from referrals provided by community service organisations operating in selected communities.

The data for this study was collected from 339 households within the postal areas shown on the map in Figure 11. The postal areas were initially selected using socio-economic indicators for low-income regions in Melbourne however this was subsequently expanded to include higher income regions. The numbers on the map show the number of households sampled within each postal area with darker shades indicating larger samples. Participants resided in areas from across the Melbourne region with larger numbers recruited from areas around Frankston, Chelsea and Mornington in the southeast, Sunbury and Craigieburn in the outer north, and near Glenroy, Coburg and Reservoir in the inner north.

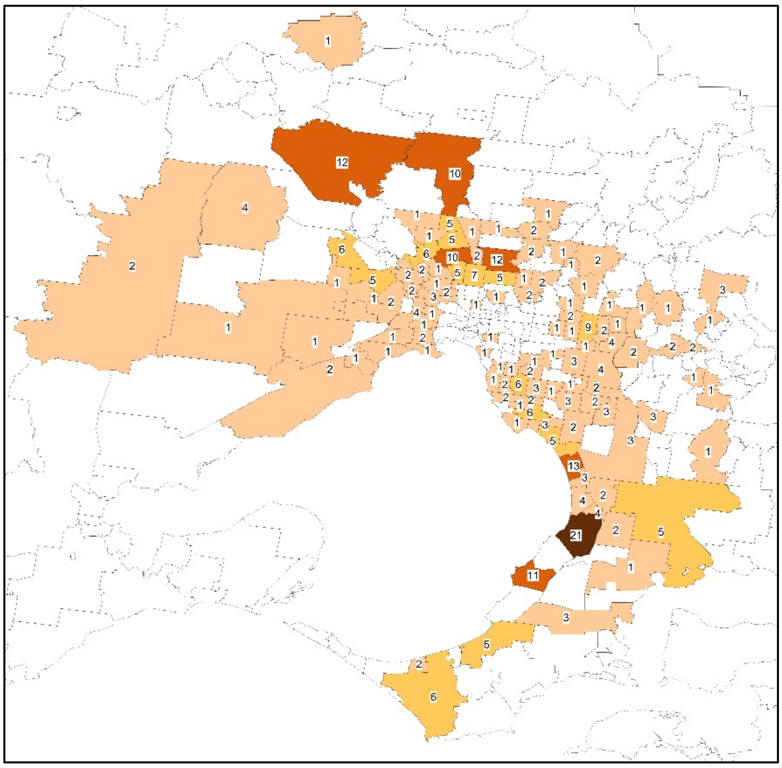

Figure 11: Location and number of intervention households

Household, behavioural, employment and income characteristics

A number of household, appliance, behavioural and demographic variables were collected during the survey stage of the study and these are listed in the tables in Appendix F1 along with their categories, counts and percentages. This data was collected by HEEUP project staff. Behavioural data concerning how hot water is used in the household was collected by the project staff using the hot water tool developed for this project. Not all variables are used in the modelling analysis but they are presented here to more fully characterize the sample profile. A summary of the data relevant to the analyses of 339 households described in this report appears in the following section.

Household characteristics (HHC)

- **Dwelling type (HC_1)**: The majority (75.5%) of dwellings were either detached or semi-detached houses with the remainder being units of varying types. An issue with this factor is that 56% of values are missing which makes it problematic to include in the main analysis as this would severely limit the model's ability to estimate other factor effects.
- **Home ownership (HC_2)**: The majority (95.5%) of homes are owned outright or owned with a mortgage with the remainder being community housing.
- **Home age (HC_3)**: 16.9% of homes were under 20 years old with a significant minority (17.5%) being 60 years or older.

- **Number of residents (HC_4)**: 31.5% of homes were single person households with the majority of homes (90.5%) having 4 or less persons resident.
- **Number of bathrooms (HC_5)**: The majority of households (61.5%) had a single bathroom with the remainder having two or more two bathrooms.
- **Existing household energy source (HC_6):** The great majority (94.5%) of homes were supplied with electricity and natural gas. Only 5% were electricity only households, and a couple of households had LPG gas in addition to electricity and natural gas.
- **Wood energy source (HC_7)**: Only 3.3% of households used wood as an energy source.
- Controlled load electricity (HC_8)

The household component equation for household i is a linear combination of the above items.

$$HHC_i = \sum_{j=1}^{8} h_j HC_{ij}$$

Appliance characteristics (HAC)

- **Existing hot water service tank size (AC_1):** The majority of households (69%) reported a small (160L) tank, 18.6% reported a medium (250L) tank and 12.4% reported having tanks larger than 250L.
- **Age of existing hot water service (AC_2):** Only 10.4% of households reported a HWS less than nine years old with the majority of HWS being much older than this.
- **Washing machine size (AC_3):** Most households (97.7%) have washing machines with capacity of 5kg or more.
- **Rooftop photovoltaics (AC_4)**: 26.5% of dwellings have rooftop PV with the majority (76%) being attached to houses rather than units.

The household component equation for household i is a linear combination of the above items.

$$HAC_i = \sum_{j=1}^{4} a_j AC_{ij}$$

Behavioral characteristics (HBC)

- **Number of weeks unoccupied per year (BC_1)**: Most households (77.8%) reported zero weeks unoccupied with the remainder being typically unoccupied one to four weeks. (No information on when these absences occur)
- **Number of clothes washes per week (BC_2):** Most households (76.3%)) do between 3 and 6 washes per week.

- **Number of showers per week (BC_3):** The most common numbers were 7 (18.7%) and 14 (20.7%) corresponding to one and two person households. I assume households reporting less than 7 shower per week are using alternative bathing regimes. The correlation between number of residents and number of showers is fairly high ($r = 0.7$) which is to be expected.
- **Average shower time (BC_4):** The majority (52.7%) of households reported showers lasting six minutes or less and a significant minority (33.7%) reported showering for between seven and ten minutes. The remaining 13.6% reported showering for ten of more minutes.

The household component equation for household i is a linear combination of the above items.

$$HBC_i = \sum_{j=1}^{4} b_j AC_{ij}$$

Demographic characteristics (HDC)

- **Employment status (DC_1)**: The majority of households (52.4%) answered 'retired' and just 15.9% of households reported at least one employed person.
- **Household income (DC_2)**: The majority of household incomes (68.7%) fall between \$400 and \$999 per week, which places them lower, and in many cases, much lower than the average disposable household income in 2013–14 of \$998 per week reported bythe Australian Bureau of Statistics (2015).
- **Highest education level (DC_3)**: 5.6% of households reported primary, 21.2% reported year 10, 17.1% reported year 12 and the remaining 54.4% reported TAFE or Tertiary as the highest household education level.

The household component equation for household i is a linear combination of the above items.

$$HDC_i = \sum_{j=1}^{4} d_j DC_{ij}$$

Intervention

The home hot water service (HWS) is a major source of household energy consumption. Many households have older inefficient HWS and as such could benefit from upgrading to a more energy efficient appliance. The intervention in this study is some form of HWS upgrade (see later for details of various upgrade paths undertaken).

Project staff engaged with potential participants and, using either the hot water tool or via direct advice, provided participants with tailored information about the financial costs and benefits associated with purchasing and installing a hot water upgrade. The hot water tool, or a survey, enabled the collection of specific information about the participant, the dwelling, the existing hot water service, and how hot water was used in the household. This data was collected by energy engagement officers via personal interview and physical inspection of properties.

Based on the information garnered from the hot water tool, or later in the program from the experience of the EEOs, households were recommended a particular upgrade that best suited their circumstances. However, the upgrade ultimately installed was the option householders preferred irrespective of the output from the hot water tool.

Recruited participants were provided with access to a subsidy to contribute to a proportion of the costs of the hot water upgrade. In addition, participants were offered an interest-free loan through the No Interest Loan Scheme (NILS). These financial services covered the purchase and installation costs of the upgrade they had chosen.

Study design

A stepped wedge design was implemented by which participants are assigned to different intervention times (see the following section for more on this design). In this way, participants who get an intervention later in the study can serve as controls for participants who experienced the intervention earlier. This avoids the need for a separate traditional control group.

Participant data was collected prior to the intervention including variables such as individual resident demographic such as the number of residents (e.g. age, beliefs about energy efficiency) and household variables (e.g. number of residents, age of dwelling). This data was examined to identify individual and household level factors associated with energy consumption over time.

The response data

Gas and electricity energy consumption data was collected at the household level for the period March 2012 to December 2015. The start and finish dates varied somewhat by household but this did not affect the analysis since there was sufficient data pre- and post-intervention for almost all households. Consistent with Rickwood et al. (2012) accumulation energy data obtained from an ongoing meter readings schedule of intervals greater than one month were binned (standardised) to months so as to enable comparisons among households. Smart meter electricity data was also standardised to monthly intervals.

The response data for each household forms a seasonal time series with summer and winter peaks corresponding to changing cooling, heating and lighting requirements of households. As can be seen in the charts in Figure 12 the seasonal variation is quite pronounced during the winter months for gas and electricity. A less obvious feature of the electricity consumption chart is the small summer peaks which are probably due to cooling power usage.

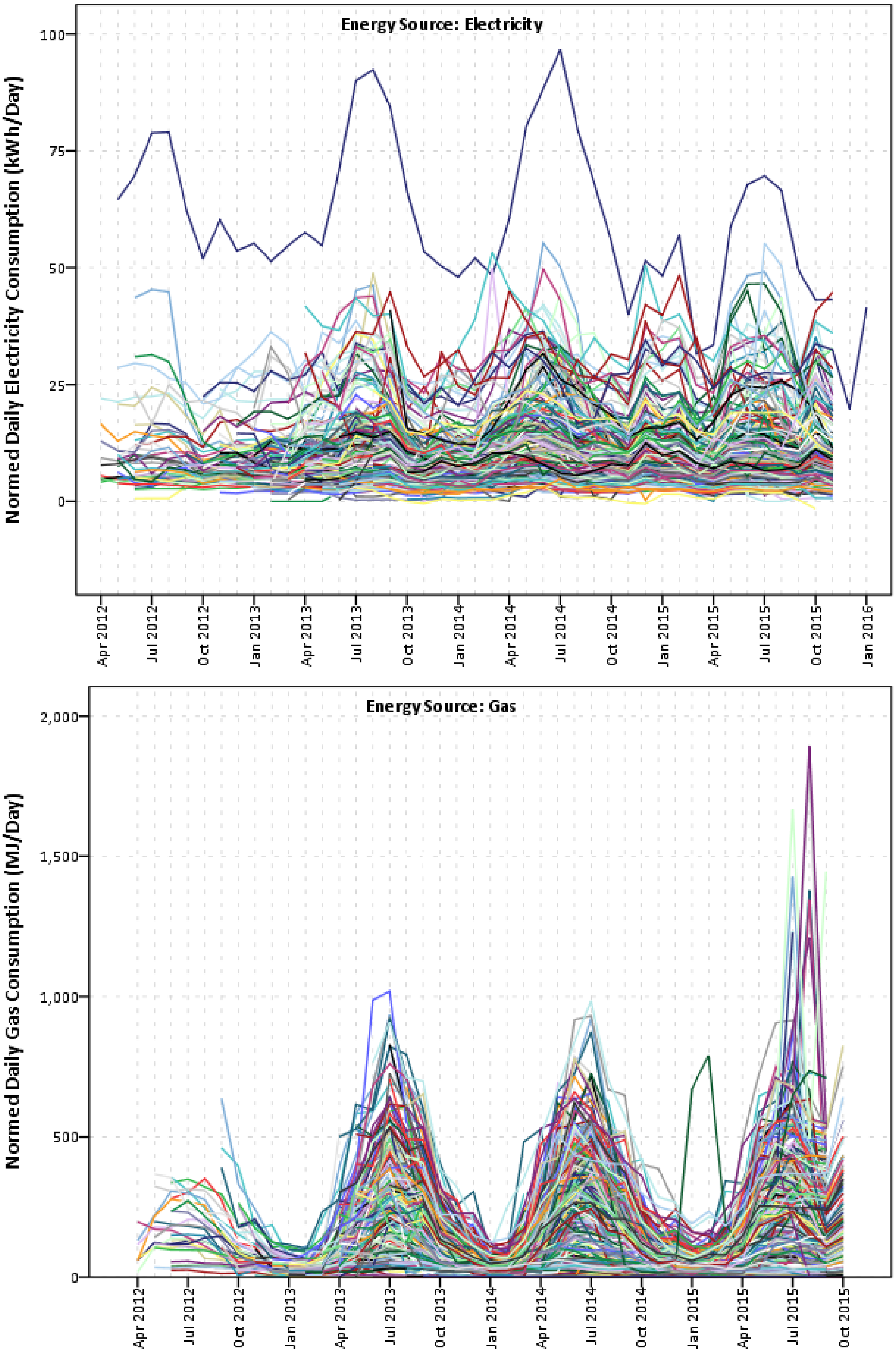

Figure 12 Seasonal variation in energy consumption data

The charts also show some very unusual energy consumption patterns particularly for electricity where a few households consumed well over 50 kWh per day for most of the study period. For gas consumption there are a few unusually large observations during the last winter peak (July 2015). It is unclear why these households have such unusual usage patterns but there are certainly not typical and may bias results and so these households were not included in the analysis.

The stepped wedge design

As it was not feasible to carry out all interventions within a short period (one or two months), and it was difficult to recruit a separate control group[5], a stepped wedge design was used in this study. This design allows for a sequential rollout of the intervention in such a way that households in the pre-intervention stage act as controls for those in the post-intervention stage. The design was first used in the Gambia Hepatitis study (Hall et al., 1987) and is a form of cluster randomized trial design. It has been used with varying levels of success particularly in the health field (see reviews by Mdege, Man, Taylor, and Torgerson, 2011; Brown and Lilford, 2006). Although there a few if any examples in the literature of using a stepped wedge design in household contexts, the Mexican study by Gruber et al. (2013) examined the effect of installing UV-disinfection devices in households on water contamination and its consequences.

	2012	2013	2014												2015											
Cluster	1-12	1-12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
1							4																			
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Post Intervention
Pre Intervention

Figure 13 The stepped wedge design (numbers on diagonal are the number of households in each cluster (cluster size)).

The design is best illustrated by the grid in Figure 13 where rows index clusters and columns index time. Data collection started in early 2012 and continued until December 2015. All households were initially in the pre-intervention control stage. The first

[5] A separate control group would need data on all demographic variables collected for the intervention group not just the energy consumption data.

intervention occurred in May 2014 when the 4 households in Cluster 1 received their upgrades/retrofits. From June 2014, these households were in the post-intervention stage while clusters still in the pre-intervention stage acted as controls for this cluster. This process continued until the two households in Cluster 20 received their upgrades/retrofits. The Cluster 20 households have no controls which is unavoidable and does not prevent analysis of the previous 19 clusters proceeding.

Ideally a stepped wedge design should be balanced with respect to cluster size as this ensures maximum power and efficiency in estimation. It is clear from Figure 13 that balance was not achieved since cluster size varies between 1 and 46 households. However, modern statistical techniques such as the linear mixed models (LMM) or general estimating equations (GEE) can cope with departures from this ideal to some extent.

Upgrade pathways

The principal intervention in this study was a hot water service upgrade and 30 distinct simple pathways are possible as shown in Table 6.

	Installed HWS Type (B)					
Existing HWS Type (A)	Gas instant	Gas storage	Solar (elec. boost)	Solar (gas boost)	Heat pump	Total (A)
Electric Storage	18	2	6	13	27	66
Electric instantaneous	1	1	0	1	0	3
Electric boosted Solar	1	0	0	1	1	3
Elec A –> B Total	20	3	6	15	28	72
Gas Storage	42	40	0	90	10	182
Gas instantaneous	14	2	0	14	0	30
Gas boosted Solar	0	0	0	1	0	1
Gas A -> B Total	56	42	0	105	10	213
Gas & Elec A -> B Total	76	45	6	120	38	285

Table 6: Possible simple upgrade pathways. Numbers give count of households taking indicated upgrade pathway.

For households with an existing electric HWS there are 15 simple pathways and also 15 for those with an existing gas HWS. Not all pathways were actually observed (zero counts) or occurred in numbers too small for estimation of their effect. For those pathways with fewer than 5 households involved no estimation is attempted.

Table 7 contains ten estimable upgrade paths along with the number of households taking each path and the number of pre and post intervention observations available to estimate the intervention effect.

Upgrade path	Households (N)	Observations	
		Pre	Post
Elec Sto to Elec Solar	6	157	73
Elec Sto to Heat Pump	27	688	129
Elec Sto to Gas Inst	18	452	102
Elec Sto to Gas Solar	12	298	93
Gas Sto to Gas Inst	42	1010	303
Gas Sto to Gas Sto	40	970	175
Gas Sto to Gas Solar	89	2211	495
Gas Inst to Gas Inst	14	340	84
Gas Inst to Gas Solar	14	333	88
Gas Sto to Heat Pump	10	211	20
Total	272	6670	1562

Table 7: Estimable hot water service upgrade pathways

Analysis preliminaries

The primary outcome was the average effect of the intervention which was estimated separately for gas and electricity consumption. This effect, if present will be buried in the systematic seasonal variation in the data which must be accounted for in the analysis through some form of seasonal adjustment. Another source of nuisance variation is due to annual climate variations which can be accounted for by weather normalizing the data prior to analysis.

Weather normalization

Weather normalization was carried out using heating and cooling degree day (HDD and CDD) data from weather stations as close as possible to the postal area of each household. In the study area there are 15 weather stations and it was possible to select stations within a few kilometres of each postal area. For the HDD data the base temperature was 18 degrees Celsius and for the CDD data the base temperature was 24 degrees Celsius. The normalization factor was calculated using the formula

$$NF = \frac{\overline{HDD}_i + \overline{CDD}_i}{HDD_{it} + CDD_{it}},$$

where i indexes the postal area and t indexes the time point in months. The averages in the numerator were calculated over 5 years. The raw daily data were then normalized by multiplying by this factor. Normalization allows for month to month comparisons between years but does not remove seasonality in the data.

Seasonal adjustment

Seasonal adjustment allows for within year month-to-month comparisons of the weather normalized data to be made. Several methods of seasonal adjustment were considered (ARIMA X11, Ratio to Moving Average and the ABS Census Method) however all require at least 4 years monthly data for each household and so could not be implemented. One method that does not suffer from this restriction is harmonic regression adjustment which involves fitting the following first (frequency = 1/12) and second (frequency = 2/12 = 1/6) order harmonic model

$$\boldsymbol{H_{it}} = \boldsymbol{\beta_{0i}} + \boldsymbol{\beta_{1i}t} + \boldsymbol{\beta_{2i}}\text{Cos}\left(\frac{\boldsymbol{2\pi t}}{\boldsymbol{12}}\right) + \boldsymbol{\beta_{3i}}\text{Sin}\left(\frac{\boldsymbol{2\pi t}}{\boldsymbol{12}}\right) + \boldsymbol{\beta_{4i}}\text{Cos}\left(\frac{\boldsymbol{2\pi t}}{\boldsymbol{6}}\right) + \boldsymbol{\beta_{5i}}\text{Sin}\left(\frac{\boldsymbol{2\pi t}}{\boldsymbol{6}}\right) \quad (\mathbf{1})$$

where H_{it} is the expected value of household i at time $t = 1,2, \ldots T_i$ and the $\beta's$ are coefficients to be estimated. This model can be fitted to the data for each household and then adding the constant and trend component (i.e. $\beta_0 + \beta_1 t$) to the residual series to form a seasonally adjusted data series. The adjusted series can then be analyzed to examine the effects of the intervention and other factors. Alternatively, the above model components can be included in the main analysis as covariates so that the seasonality is simultaneously estimated with the intervention and other factor parameters. The advantage of the latter approach is that a random coefficients model can be used which not only accounts for the seasonal component but also allows for any differences in the component between households. This can be achieved using a linear mixed model without need of the large number of interaction effects that would be required to estimate a separate model for each household. This approach is adopted in this work and preliminary regression using the above model yielded an overall R^2 value of 96% so the harmonic model does an excellent job of accounting for the seasonal variation observed in Figure 12 (on p. 32).

Demographic factors

The inclusion of demographic factors is governed by availability and their percentage of missing values. Including a factor such as Home Type with nearly 60% missing values greatly reduces the sample size available to estimate the intervention effect which is the main focus of this study. As a compromise, we assess the effect of each demographic factor on the intervention effect separately and then use a multiple comparison adjustment maintain a 5% Type I error rate across the comparisons.

The analysis model

Following Hussey and Hughes (2007) and using the components defined above, the individual level household responses are modelled as

$$Y_{it} = \mu + \alpha_i + HHC_i + HAC_i + HBC_i + HDC_i + H'_{it} + \theta X_{it} + e_{it} \quad (2)$$

where μ is the overall mean, α_i is a random household effect, HHC_i is the household characteristic component for household i, HAC_i is the appliance characteristic component for household i, HBC_i is the behavioral characteristic component for household i, HDC_i is the demographic characteristic component for household i, H'_{it} is the harmonic component for household i minus β_{0i} (since it is absorbed by μ), θ is the intervention effect, X_{it} is an indicator of the treatment mode in household i at time t (0 = control arm, 1 = intervention arm). The term e_{it} is the random error for household i at time t and reflects the fact that energy use of households cannot be modelled perfectly due to many other unknown factors that influence household energy use patterns. These other factors are assumed to operate randomly in their influence on energy use (e.g. relatives come to stay, the HWS breaks down, people go on holidays, etc.). Since we are dealing with repeated measurements over time, e_{it} cannot be assumed to be independent but this can be accommodated by the LMM or GEE procedures.

In traditional analysis the error at time t is assumed to be independent of errors at any other time. We are dealing with repeated measurements on each household which means that measurements (and hence errors) at time t will be correlated with earlier measurements. This correlation is usually short-term and may only extend one or at most two time periods. To account for this correlation we assume the error follows an auto(self)regressive process such as

$$e_{it} = \phi e_{it-1} + \psi_{it}$$

where ϕ is a constant (autocorrelation coefficient) to be estimated and ψ_{it} is an error term that is independent of all other error terms. An unstructured error term is a more general method of handling correlation in repeated measures and allows for a much wider range of correlation structures to be considered when fitting the model.

The LMM procedure was chosen for this analysis at it provides a more a natural fit for individual level data and allows for random covariate coefficients to account for possible between household variance in the seasonal component.

The results of the analysis are given in terms of marginal means from (2) which are therefore directly comparable between control and intervention arm due to the seasonal adjustment terms entering the model as covariates. This negates the need for a month by month analysis as all months are comparable after seasonal adjustment.

Results

The GEE procedure was applied separately to the electricity and gas data for the overall intervention effects and then separately to the subsets of electricity and gas data that are defined by the 10 upgrade pathways.

Overall effect of HWS upgrades

Table 8 shows the results of overall pre-post intervention comparisons for the daily electricity and gas consumption measures for all upgrade pathways not involving a fuel change. In both cases a highly significant ($p \leq 0.003$) decrease in energy consumption was observed. The decreases of 25% and 7% for electricity and gas respectively are of practical (as well as statistical) significance give an annual reduction of 762 KWh ($213.46) for electricity consumption and 2,787 MJ ($55.64) for gas consumption. That is, in overall terms the intervention was successful.[6] Upgrades involving a fuel change are considered in the next section.

Consumption Units	kWh/day	MJ/day
Pre upgrade fuel	Electricity	Gas
Post upgrade fuel	Electricity	Gas
Pathways	1,2	5,6,7,8,9
Households (N)	33	199
Pre upgrade consumption	8.474	103.028
Pre upgrade observations	845	4864
Post upgrade consumption	6.385	95.393
Post upgrade observations	202	1145
Post - Pre consumption	-2.089	-7.635
Percent change	-25%	-7%
p-value[a]	0.000	0.003
Annual Cost change	$ (213.46)	$ (55.74)

a. The p-value is for testing if the post-pre difference in consumption is significantly

Table 8: Overall Intervention effect on daily electricity and gas consumption

Effect of selected upgrade paths

Table 9 displays the pre-post intervention comparisons of daily energy consumption for the four pathways where pre upgrade fuel type was electricity. In these four cases the response variable was electricity consumption in kWh per day. Note that third and fourth upgrade paths involve a change of fuel type post upgrade and so the analysis of these paths was repeated using gas consumption as the response variable in order to calculate the net effect of the intervention on cost savings.

Upgrade paths yielding significance decreases in average daily electricity consumption were electric storage to heat pump ($p < 0.001$) with a 29% reduction in consumption, electric storage to gas instant ($p < 0.001$) with a 42% reduction in consumption and electric storage to gas solar ($p < 0.001$) with a41% reduction in consumption. The non-

[6] The St Vincent de Paul Society's Victorian Tariff Tracking Project (Mauseth Johnston, 2015a, 2015b) data which monitors electricity retailer market offers indicates that, for January 2014, the average market offer for 14 Victorian retailers was $0.28. For market offers concerning seven gas retailers, the data provided for January 2015 indicates an average value 0f $0.02. Applying these figures to the consumption changes provides an estimate of average daily savings or expenditures per annum.

significance of the Electric storage to electric solar ($p = 0.605$) is possibly due to the small number of households (6) involved and the resulting low power of the statistical test. A larger sample of this type of upgrade may well yield a significant result.

Consumption Units	kWh/day	kWh/day	kWh/day	kWh/day	MJ/day	MJ/day
Pre upgrade fuel	Electricity	Electricity	Electricity	Electricity	Electricity	Electricity
Post upgrade fuel	Electricity	Electricity	Gas	Gas	Gas	Gas
Upgrade Pathway	Storage to Solar	Storage to Heatpump	Storage to Instant	Storage to Solar	Storage to Instant	Storage to Solar
Households (N)	6	27	18	12	19	11
Pre upgrade consumption	9.107	8.207	7.106	7.114	46.016	58.733
Pre upgrade observations	157	688	452	298	509	264
Post upgrade consumption	8.758	5.818	4.133	4.221	57.054	67.491
Post upgrade observations	73	129	102	93	83	70
Post - Pre consumption	-0.348	-2.389	-2.973	-2.893	11.038	8.758
Percent change	-4%	-29%	-42%	-41%	24%	15%
p-value[a]	0.605	0.000	0.000	0.000	0.109	0.478
Annual Cost change	$ (35.60)	$ (244.14)	$ (303.89)	$ (295.65)	$ 80.57	$ 63.94
Net annual cost change[b]	-	-	$ (223.31)	$ (231.71)	-	-

a. The p-value is for testing if the post-pre difference in consumption is significantly different from zero.
b. Net annual cost change only calculated for upgrades involving fuel change as - annual cost change in electricity plus annual cost change in gas for the particular upgrade pathway.

Table 9: Intervention upgrade pathway outcomes for electricity consumption

The results involving a fuel change (paths 3 and 4) exhibit 42% and 41% decreases in electricity consumption respectively. This is to be expected since they involve changing the fuel type from electricity to gas. The annual cost change for these paths has been offset by adding the cost change associated with post upgrade gas consumption yielding the net annual cost changes in the table.

Table 10 displays the pre-post intervention comparisons of daily energy consumption for the six pathways where pre upgrade fuel type was gas. In these six cases the response variable was gas consumption in MJ per day. Note that the sixth upgrade path involves a change of fuel type post upgrade and so the analysis of this path was repeated using electricity consumption as the response variable in order to calculate the net effect of the intervention on cost savings.

Upgrade paths yielding significance decreases in average daily gas consumption were gas storage to gas instant ($p < 0.001$) with a 15% reduction in consumption, gas storage to gas storage ($p = 0.011$) with a 16% increase in consumption and gas storage to gas solar ($p = 0.001$) with a 13% reduction in consumption.

The non-significant results for the gas instant to gas instant ($p = 0.923$), gas instant to gas solar ($p = 0.183$) and gas storage to electric heat pump ($p = 0.091$) imply that although these changes are real enough for the sampled households we do not have enough evidence to infer that these result would occur in the target population of households. That is, we cannot generalize beyond the sampled households.

Consumption Units	MJ/day	MJ/day	MJ/day	MJ/day	MJ/day	MJ/day	kWh/day
Pre upgrade fuel	Gas	Gas	Gas	Gas	Gas	Gas	Gas
Post upgrade fuel	Gas	Gas	Gas	Gas	Gas	Electricity	Electricity
Upgrade Pathway	Storage to Instant	Storage to Storage	Storage to Solar	Instant to Instant	Instant to Solar	Storage to Heatpump	Storage to Heatpump
Households (N)	42	40	90	14	14	10	14
Pre upgrade consumption	105.425	101.596	106.911	69.408	122.977	98.988	7.221
Pre upgrade observations	1010	970	2211	340	333	211	366
Post upgrade consumption	89.747	117.801	92.944	70.035	108.310	77.478	7.706
Post upgrade observations	303	175	495	84	88	20	56
Post - Pre consumption	-15.678	16.206	-13.967	0.627	-14.667	-21.510	0.485
Percent change	-15%	16%	-13%	1%	-12%	-22%	7%
p-value[a]	0.000	0.011	0.001	0.923	0.183	0.091	0.275
Annual Cost change	$ (114.45)	$ 118.30	$ (101.96)	$ 4.58	$ (107.07)	$ (157.02)	$ 49.56
Net annual cost change[b]	-	-	-	-	-	$ (107.46)	-

a. The p-value is for testing if the post-pre difference in consumption is significantly different from zero.
b. Net annual cost change only calculated for upgrades involving fuel change as - annual cost change in gas plus annual cost change in electricity for the particular upgrade pathway.

Table 10: Intervention upgrade pathway outcomes for gas consumption

The impact of household, appliance, behavioural and demographic characteristics.

To assess the impact of household and demographic characteristics on the intervention effect, each factor defining the characteristics was entered into model (2), and the interaction between the factor and the intervention factor estimated. This allowed for the pre-post differences for each level of each factor to be estimated and assessed for significance. The results from this process are displayed in Appendix F2 for electricity and gas consumption respectively. The tables contain the number of households (N), the number of observations (Obs) and marginal means from the model pre- and post-intervention, the difference between marginal means, and the *p*-value for testing if the difference is significantly difference from zero (*p*-values < 0.05 are bolded). Also note that some factor levels were collapsed to avoid the numerical estimation problems associated with levels with few observations.

Since there are 60 tests for each energy source, some attention needs to be paid to limiting the Type I error rate to 5%. This may be achieved by choosing a per-comparison significance level of $0.05/60 \approx 0.002$ which is the Bonferroni correction. That is, a pre-difference is only considered significant if its *p*-value is less than 0.002 which is very conservative[7]. A less conservative method is the false discovery rate (FDR) method of Benjamini and Hochberg (1995) which gives an adjusted *p*-value of 0.006 for each

[7] With such a low *p*-value cut-off we would likely miss real significant effects.

comparison. Using this approach we find the significant results listed in Table 11 and Table 12.

Overall, pre and post intervention marginal means were statistically similar for almost all factors and their levels. This is probably not surprising since the household and demographic factors remained constant throughout the trial and although many do affect the level of energy use, it is difficult to see how they could moderate the intervention effect for better or worse. It may be reasonable to assume that some household residents have a more positive attitude to energy conservation and the level of the factor is a proxy indicator of this. For example, it may be that the motivations that might lead residents to install roof top PV are the same motivations that could lead them to make the most out of the intervention, resulting in a reduction for this group that is not present for homes without roof top photovoltaics. However, beyond this speculation, further research is required to test the hypothesis.

Factor	Level	p-value	Post - pre	Interpretation
Age of existing HWS	0-2 years	0.000	-4.044	Homes with a HWS less than 2 years old are associated with a highly significant post intervention reduction in consumption of 4.044 kWh/day
Washing machine size	medium	0.005	-1.534	Home with a medium size washing machine are associated with a very significant post intervention reduction in consumption of 1.534 kWh/day
Employment status	Retired	0.001	-1.419	Homes with retired residents experienced a very significant post intervention reduction in consumption of 1.419 kWh/day

Table 11: Energy source = Electricity. Significant household, appliance, behavioural and demographic factor interpretations.

Factor	Level	p-value	Post - pre	Interpretation
Home ownership	Owned or mortgaged	0.003	-21.39	Homes that are owned outright or mortgaged experienced a very significant post intervention reduction in consumption of 21.39 MJ/day
Home age	10 to 20	0.000	-30.83	Homes between 10 and 20 years old experienced a very significant post intervention reduction in consumption of 30.83 MJ/day
Number of occupants	2	0.006	-19.94	Two person households are associated with a very significant post intervention reduction in consumption of 19.94 MJ/day
	3	0.009	-38.07	Three person households are associated with a very significant post intervention reduction in consumption of 19.94 MJ/day
Number of	2	0.003	-25.71	Homes with two bathroom experienced a very significant post intervention reduction in consumption of 25.71 MJ/day

bathrooms	3	0.000	-42.06	Homes with three bathrooms experienced a highly significant post intervention reduction in consumption of 42.06 MJ/day
	4	0.000	-21.61	Homes with four bathrooms experienced a highly significant post intervention reduction in consumption of 21.61 MJ/day
Existing energy source	Electricity and natural gas	0.008	-18.36	Home with electricity and natural gas are associated with a very significant post intervention reduction in consumption of 18.36 MJ/day
Age of existing HWS	17-20 years	0.000	-45.66	Homes with a HWS between 17 and 20 years old are associated with a very significant post intervention reduction in consumption of 45.66 MJ/day
Rooftop PV	Yes	0.001	-28.54	Homes with rooftop PV are associated with a very significant post intervention reduction in consumption of 28.54 MJ/day
Number of showers/week	8-14 min showers	0.001	-26.38	Homes in which residents shower between 8 and 14 times a week are associated with a very significant post intervention reduction in consumption of 26.38 MJ/day
Average shower time	medium	0.004	-28.09	Homes in which take a medium amount of time (7-12 mins) for a shower are associated with a very significant post intervention reduction in consumption of 26.38 MJ/day
Employment status	Not in workforce	0.008	-27.49	Homes where residents are not in the workforce (not retired) are associated with a very significant post intervention reduction in consumption of 27.49 MJ/day
Education level	Secondary	0.001	-30.32	Home in which the highest education level achieved are associated with a very significant post intervention reduction in consumption of 30.32 MJ/day

Table 12: Energy source = Gas. Significant household, appliance, behavioural and demographic factor interpretations.

Discussion

What change, if any, in household energy consumption results from the hot water service upgrades?

The results of overall pre-post intervention comparisons for the daily electricity and gas consumption measures (not including pathways involving a fuel change) indicated a highly significant decrease in electricity and gas consumption. These decreases of 25% (2.09 kWh per day) and 7% (7.63 MJ per day) for electricity and gas respectively are of practical (as well as statistical) significance give an annual reduction of 762 KWh ($213.46) for electricity consumption and 2,787 MJ ($55.64) for gas consumption. That is, in overall terms the intervention was successful in producing energy savings.

The overall program effects cannot be easily compared with Solar Cities projects because of the different emphasis they place on interventions aimed at reducing energy consumption (in addition to different research designs, data management and analysis procedures, regions, etc.). Nonetheless, the reduction achieved in average daily kWh exceeds the range of 0.7 and 1.7 kWh reported by the CSIRO (2013) for their analysis of electricity interventions in Perth and Alice Springs that championed solar hot water replacements. One might expect to see solar hot water solutions to make the most of sunny conditions more characteristic of Perth and Alice Springs than Melbourne, but this assumption was not met. Note also that shifting from electric storage systems to solar hot water is expected to bring about generous savings relative to alternatives pathways, and that this pathway was much more common in the two solar cities projects (23% of households in Alice Springs and 32% in Perth) than was the case in the HEEUP (5.4% of households).

What change, if any, in household energy consumption results from specific types of hot water service upgrades?

Upgrades affecting electricity consumption

The upgrade paths yielding significant decreases in daily *electricity consumption* were electric storage to heat pump (29%); electric storage to instantaneous gas (42%) and electric storage to gas solar (41%) compared to the stepped wedge control. The latter two pathways reflect the fact that the new technology was gas rather than electric, such that a concomitant decrease in electricity consumption is expected in these instances. In fact, these two pathways were associated with non-significant increases in gas consumption of 11.04 MJ (gas instantaneous) and 8.76 MJ (gas solar) as households make use of their new gas water heating technologies.

Net annual cost savings resulting from shifting from electric storage to gas instantaneous gas from electric storage to gas solar were in excess of $220 in both cases. Of the 19 households opting for this pathway, 85% were on an off-peak tariff and 95% resided in households of two people or fewer. Using the running cost information supplied by Sustainability Victoria (2015) a differential can be estimated based on an off-peak tariff for the electric storage units and based on household residents of one or two. Done this way, the expected net annual saving in running costs are $247, which is consistent with the HEEUP savings estimate.

When the above procedure was applied to the pathway from electric storage to gas solar, the expected running costs amounted to $417 per annum on average. This figure is a good deal larger than the HEEUP estimate of $231.71. However, slightly more than half (53.85%) of these solar systems were installed between March and September 2015 suggesting that the consumption record of these households did not cover the months most important to the technology’s efficiency. Households involved in this pathway had electric storage systems mostly operating on an off-peak tariff (84.6%) and comprised one or two residents (69.3%).

The 29% (2.39kWh) reduction owing to the installation of a heat pump was below the estimate of 23.49 MJ (6.52 kWh) provided by DEDJTR (2015). However, 95.6% of all heat pumps were installed between March and November 2015 such that household consumption did not reflect their operation during the hottest months of the year in Melbourne and surrounds.

The financial savings realised by shifting from electric storage to a heat pump amounted to $244.14 per year on average. The electric storage units in these households operated on an off-peak tariff and the households consisted of one or two residents. Based on estimates of the operating cost of running electric storage and heat pump systems the expected financial saving is in the vicinity of $192 per annum for households of one or two people (Sustainability Victoria, 2015).[8] The estimated saving of $244.14 from the HEEUP data exceeds the expected financial saving assuming that the heat pumps operated on a standard peak tariff. If an off peak tariff is assumed for the heat pumps then the difference in running costs is around $305.

The pathway involving an upgrade to electric-boosted solar was not significant unlike that reported by Lynch et al. (2013). In the Central Victorian Solar City trial, the installation of solar water heating decreased electricity consumption by 22% (or 4.84 kWh/day on average). Similarly, in the Alice Springs Solar City trial, the reduction in energy achieved from upgrading from an electric storage system to an electric-boosted solar system was 16.7% (4.27 kWh).[9] The HEEUP results indicate that the effect in kWh of installing the solar units was not significantly different to zero.

This non-significant effect cannot be easily explained on the basis of an installation time that avoided exposure to the hottest months of the year because most of these installations were completed in the middle of 2014. The consumption records for these households reflected the operation of the solar systems during the summer of 2014/2015. The non-significant effect in this case might instead be attributable to low statistical power owing to a small number of households and observations.

In sum, the reductions in electricity consumption and financial savings estimated on the basis of the HEEUP model results showed some alignment with expectations provided by Sustainability Victoria (2015) and the DEDJTR (2015) although they are not completely consistent with either one of these sources. Rather, deviations from expectations tend to suggest that the HEEUP interventions achieved lower energy reductions. These differences may be due to the sample households and study context having characteristics (e.g. low-income households, older residents, small number of residents, relatively cooler climate, etc.) different to those on which the DEDJTR and Sustainability Victoria estimates have been based.

Upgrades affecting gas consumption

Upgrading from a gas storage unit to either an instantaneous gas system or a gas-boosted solar system reduced gas consumption by 15% and 13% respectively. These

[8] The estimates supplied by Sustainability Victoria (2015) are based on the following tariffs: peak electricity (28 c/kWh), off-peak electricity (18 c/kWh).
[9] The Alice Springs Solar City report does not provide statistical information against which the significance of this point estimate might be assessed.

reductions were equivalent to 15.68 MJ/day and 13.97 MJ/day and $114.45 and $101.96 per annum. However, according to the deemed energy savings data provide by EnergyConsult (2012), the expected reduction might have been 36.05 MJ or $263.16 for solar.[10] Employing alternative figures from DEDJTR (2015) the expected gas reduction was 26.85 MJ or $195.98. The financial data by Sustainability Victoria (2015) offered an estimate of $184 based on a tariff equal to 1.75 c/MJ and assuming a 3-star rated gas storage unit. By all these measures, the HEEUP estimates achieve less gas and financial savings than was expected by the gross data. It is not clear why this should be the case without further investigation.

One curious result arising from the data analysis was the 16% increase in gas consumption associated with upgrading from an existing gas storage unit to a new gas storage system. According to EnergyConsult (2012) the change in hot water service should have brought about a reduction in consumption of 8.88 MJ per day based on their modelling assumptions. Perhaps the replacement storage units were larger allowing some households to use more hot water than they were able to access with their previous smaller system. However, further enquires are needed to determine why the increase in consumption occurred.

Another ‘like-for-like’ upgrade – instantaneous to instantaneous – did not affect consumption to a statistically significant extent. Neither Sustainability Victoria (2015), DEDJTR (2015), nor EnergyConsult (2012) provide data upon which to estimate an expectation for this pathway. Of the 14 households involved, half of them had installation dates between April and October 2015, toward the end of the program. It may be that there was not a long enough record for these 7 households to establish reliable results. Otherwise one might conclude that the new instantaneous systems were not much more energy efficient than the ones they replaced.

Non-significant results were observed for the upgrade from instantaneous to gas solar. The solar water heating systems were installed between June 2014 and October 2015 with 81% of installations completed before July. This suggests that the timing of the installation likely had little impact on the model result. The model estimate implies that the gas solar upgrade did not improve households’ energy consumption to a statistically significant degree.

The final gas pathway included in the analysis can be considered as marginally non-significant given the low participation rate (i.e., 10 households). A decrease in gas consumption was expected because the heat pumps operated on electricity. That said, the electricity consumption of these households did not increase to a statistically significant effect resulting in a net benefit. In fact, the net annual cost saving was estimated to be $107.46 per annum. The heat pumps were installed between April and October 2015 and, therefore, were not operating during the summer months suggesting that the cost savings might be an underestimate of the potential savings.

[10] EnergyConsult (2012) does not provide figures for instantaneous gas.

An estimate of the financial savings from switching from gas storage to a heat pump can be calculated from the Sustainability Victoria (2015) running cost data. Sixty percent of the households involved in this pathway resided in households of 2 or 3 people suggesting a differential equal to $82 (off-peak tariff). The HEEUP estimate of the benefit ($107.46) was about double this figure. Interestingly, the peak tariff estimate based on Sustainability Victoria results in a net cost of $70 assuming a 3-star rated gas storage unit.

To summarise, significant reductions in household gas consumption was achieved by replacing gas storage units with instantaneous and solar systems. There was an increase in consumption on average in households when existing gas storage units were replaced with new ones, but this effect had a lower probability compared with the upgrades to instantaneous and solar. Like the effects observed for reductions in household electricity consumption, the significant reductions in gas consumption tended to fall short of expectations based on available data from a number of government sources. This might simply reflect the different methods of calculating the estimates and the different populations from which they were derived.

What variables explain any change from pre-intervention consumption to post-intervention consumption?

The analysis of household, appliance and demographic variables identified significant predictors of consumption. There were many more significant relationships involving gas consumption than electricity consumption. Where the latter fuel source was concerned, the pattern of associations was not very informative and one result was counterintuitive. That is, households having hot water service less than two years old were associated with a post-intervention reduction in electricity consumption. It may be that the energy saving was likely involve more of these households moving from electric storage to a more efficient alternative.

The only other two significant effects identified households having medium sized washing machines and households with retired residents as experiencing decreased consumption. The former relationship is not very meaningful and the latter may suggest that retirees had a greater commitment to reducing their energy use following the intervention, but this requires further investigation.

For gas consumption, there are relationships involving the number of residence in a household and the number of bathrooms in the dwelling. Reductions in gas consumption were associated with more residents, more bathrooms and more frequent showering. These relationships most likely signal that economies of scale are at play. As more people use the new hot water system the greater the benefit compared to the hot water service that existed prior to the intervention.

Other relationships were unsurprising such as households having electricity and natural gas experiencing post-intervention reduction in gas. This would likely be the case for households that shifted from an existing gas hot water service to an electric appliance, an option that is not open for households with access to only one type of energy source. Likewise, households with photovoltaics might be expected to demonstrate a reduction in their gas consumption if they installed an electric water heating device. In fact, 90 households reported having photovoltaics on the roof. Also, somewhat expected was the association between older existing hot water services and reduced gas consumption following installation of a new appliance.

Limitations and lessons learned

Some of the limitations of the research have been noted in the preceding discussion. These are (i) the non-random assignment of households to time-based clusters required in step-wedged designs resulting in group numbers that varied considerably, (ii) small numbers of households in some of the pathway groups and varying group sizes across pathways, (iii) missing values on some of the participant data. The issues of random assignment to time and the creation of clusters and intervention groups may be difficult to achieve given the need for a flexible, participant-centred recruitment process, but efforts might be made in future programs to minimise missing values especially where data is collected via face-to-face structured interviews.

While the extent of rebound effects is unknown in this study, they are likely to occur to some extent when new technologies are introduced for the purpose of improving energy efficiency in residential households. In order to limit the effect of rebound behaviours and to maximise the potential savings that new technologies promised, there are opportunities to refine the HEEUP technology upgrade intervention by directly addressing the human dimensions of using technology in everyday settings (Giglio et al., 2014; Gill et al., 2015). Tailored and timely feedback about households' energy consumption can help householders learn to adjust their behaviour in ways that achieve targeted savings in line with the reductions expected from the new technology (Delmas et al., 2013; Karlin et al., 2015; Vine et al., 2013). Combining this intervention with information about how best to use the new technology (Gill et al., 2015) and goal setting strategies for attaining commitment from householders to achieve an agreed energy consumption target (Karlin et al., 2015) might be additional activities that work to reduce the inevitable rebound effects that have been shown to operate in similar upgrade interventions.[11]

Rebound effects suggest that the very installation of new technology can change consumption behaviours such that behavioural patterns before the intervention are different to those following it. For example, Gill et al. (2015) studied how solar hot water heating technology is actually used in households and found that the efficiency benefits of solar water heating were not fully realised because householders did not know how to use the technology to maximise savings, even in households committed to reducing their energy consumption. The researchers concluded policy approaches based on

[11] A Spanish study estimated the rebound effect for water heating to be 34%, 36% and 38% for high, medium and low-income households respectively (Gálvez et al., 2015).

implementing so-called 'technological fixes' need to shift toward a position that better appreciates the way newly installed technology becomes integrated with the 'norms, expectations, practices and habits of the household' (p.92). For Gill et al., post-installation 'marks a point at which households might be supported to experiment with combinations of water use timing, booster operation and to develop new habits that incorporate the contingencies of weather, household processes, and SHW system operation' (p.92). Put simply, technological solutions to rising energy consumption may require more than targeted efforts to increase adoption, but also efforts to ensure that the use of this technology is likely to see the expected energy savings realised in practice and in ways that are consistent with the needs of households.

Future evaluation methodologies might include data about householders' experience with using new technologies in their homes (i.e. post installation), and their perceptions of its performance, convenience and acceptability. Understanding how new technologies are used in the home may assist with behavioural programs, technology design and installation procedures that facilitates its operation and helps achieve energy efficiency targets. Installers might also be coded in evaluation data sets so that water heating performance and household energy consumption can be compared in an effort to identify any pervasive installation issues.

Conclusion

The Brotherhood of St Laurence partnered with Monash Sustainability Institute to provide an independent evaluation of the HEEUP trial. This evaluation assessed the effectiveness of the HEEUP program by employing a stepped wedge controlled design and estimating effects directly attributable to the various water heater upgrades. To this end, most of the upgrades (i.e. heat pumps, instantaneous gas, and gas solar) that replaced electric storage units were effective in reducing electricity consumption in low-income households. Similarly, upgrades that replaced gas storage units with instantaneous gas and solar gas units resulted in significantly lower gas consumption in low-income households. These upgrade options and pathways are recognised in publicly available material as options likely to improve water heating efficiency and energy costs in residential households (e.g. DEDJTR, 2015; Sustainability Victoria, 2015).

The evaluation indicated that some of the pathways failed to realise energy and cost savings that might be expected on the basis of publicly available estimates and past energy efficiency trials. This may be attributable to factors such as the study population of low-income households, regional location, and characteristics of the research design and data that most likely differ to the contexts in which other estimates have been derived. Future evaluations of energy efficiency trials in low-income residential contexts similar to those described in this report are required to bring more insights to this important area of policy and research.