Modelling the Uptake of Energy Efficient Technologies in the Residential Sector

L. Marquez[a], A. Higgins[b], C. McNamara[c], C. Xu[d] and G. Foliente[c]

[a] *CSIRO Computational Informatics, Clayton, VIC, Australia 3168*
Email: leorey.marquez@csiro.au
[b] *CSIRO Ecosystem Sciences, Dutton Park, QLD, Australia 4102*
[c] *CSIRO Ecosystem Sciences, Highett, VIC, Australia 3195*
[d] *NSW Office of Environment and Heritage, Sydney, NSW, Australia 1232*

Abstract: The growing demand from government planners and policy makers has led to the development of specialised decision support tools to assist in evaluating the myriad of options, policies, strategies and programs aimed at reducing energy consumption and the associated greenhouse gas emissions in every sector of the economy. The residential sector continues to be a major focus for sustainability and reduction efforts in Australia with its significant share of energy consumption. This paper presents the basic capabilities of a decision support tool aimed at creating future scenario projections based on known population and housing trends in NSW initially, and applied to other Australian states eventually. Codenamed TERENCE (Tool for the Evaluation of Residential ENergy Consumption and Emissions), the tool allows planners, researchers and policy makers to assess the relative impact of assumptions about future technology and policy using a defined baseline (or "business as usual" scenario) for comparison. TERENCE combines a highly graphical and visual presentation with geographical granularity only limited by the availability of data. This paper describes the application of TERENCE in evaluating different rebate scenarios aimed at estimating the uptake of various water heater options by 2030.

Keywords: *Energy modeling, simulation modelling, technology diffusion, multicriteria analysis*

1. INTRODUCTION

Governments employ various intervention schemes, in the form of policy and fiscal instruments, rebates or other incentives, to stimulate or accelerate adoption of technologies or measures towards meeting national or state environmental performance targets. In Australia, consumer rebates have been successful at increasing the adoption of private health insurance, water tanks, and solar photovoltaic (PV) panels. Rebates are usually part of the suite of government initiatives aimed at achieving energy consumption targets through improved supply or demand management. The Australian Government has committed to the long-term goal of reducing Australia's GHG emissions by 60% of 2000 levels by 2050, and has set a medium-term target of a reduction in greenhouse gas emissions by 2020 of between 5% and 15% less of the level they were in 2000 (Australian Government, 2008).

One of the biggest challenges for government and industry to reduce resource use and GHG emissions in the residential sector is the selection of the most cost-effective intervention schemes. Any regulatory measure, having legal authority and compliance requirements, can be expected to have widespread impact. But the environmental impact and effectiveness of any voluntary schemes, relying on industry and/or consumer adoption, are very difficult to evaluate and project into future scenarios. Despite large budgets for government intervention schemes, methods and tools are lagging to systematically evaluate the likely success and effectiveness of alternative voluntary schemes amongst consumers. Thus, there is a clear need for a modelling approach that can take into account:

- The diffusion process of consumer adoption over different time steps by spatial scales and location, and by demographics, family size, income, debt levels, etc;
- Likely ceiling levels of adoption; and
- The dynamics of introducing different intervention schemes at different time steps, and interactions between options, potentially including the ability to optimise the timing and size of the intervention options.

To address this need, the Australian Zero Emissions Home (AusZEH) project from 2009 to 2011 developed the scenario evaluation tool TERENCE (Tool for the Evaluation of Residential ENergy Consumption and Emissions) for analysing the energy consumption and GHG emissions across housing stock, in the presence of intervention schemes, technology changes, population growth and demographic changes. TERENCE combines features of simulation, choice modelling, multicriteria analysis (MCA) and diffusion modeling in a framework that provides a capability to analyse adoption patterns of competing technology options (e.g. different Solar PV sizes, or water heater options) under a range of intervention scenarios. This paper describes the components of TERENCE and presents the results of a case study where TERENCE was applied. This paper was adapted from a detailed report on the case study presented by Higgins et. al (2012).

2. MULTICRITERIA FORMULATION

In the generic model, the total stock of all residential housing is known over the planning horizon along with the stock of energy efficient technologies on offer. For example, technology options for water heaters can include LPG, heat pump, solar gas boost, solar-electric boost, natural gas, and electric. A household will purchase a water heater amongst the competing options available, when they are ready to replace their existing heater.

Table 1. Water heater options and base upfront and annual costs

Water Heater Option	Upfront cost	Annual cost (small home)	Annual cost (large home)
LPG	A$1700	A$489	A$889
Heat pump	A$3500	A$153	A$254
Solar gas boost	A$5786	A$232	A$281
Solar electric boost	A$4750	A$165	A$244
Natural Gas	A$1664	A$334	A$528
Electric	A$1600	A$520	A$835

The proposed model uses a multicriteria analysis (MCA) approach to estimate, for each time period, the proportion of the housing stock that have adopted each technology option, either through a new purchase or continuing 'optimal' maintenance of current installations. Assuming one household per dwelling, each household is tasked with obtaining two main decisions:

1) Time of replacement- This decision refers to the period when the household decides to replace the existing water heater. It is a function of the failure rate for the water heater as well as a utility function for a household to replace it sooner. If there are benefits or incentives for replacing the water heater with an alternative option, the household will replace the water heater prior to failure.

2) Choice of water heater replacement -. The selection of technology for replacement is based on a utility function combining financial and non-financial criteria.

Inputs to the model include data which represent the following:

- The set of categories $d \epsilon D$ of residential buildings by location and demographics.
- The set of competing water heater options $o \epsilon O$ and their attributes (e.g. cost, lifespan, etc.). Sample parameters for the upfront costs and annual costs of the six available water heater options are presented in Table 1, based on the NSW Office of Environment and Heritage (OEH) spreadsheet on life costs of water heater options.
- The set of decision criteria $j \epsilon J$ used to evaluate each option. Table 2 show some of the criteria used to compare the water heater options, and the weights given to each criteria. Each option receives a performance rating between the best and worst possible values for a given criteria. The individual ratings from all criteria are then weighted and aggregated into a single benefits index for the option. The benefits indices are then compared to identify the 'best' option.
- The set of discrete time periods $t \epsilon T$. Periods are 6-monthly from 2007 to 2030.
- The total market share of stock of each water heater option in each demographic by location category at the beginning of the planning horizon.

Table 2. Criteria parameters for option selection

Criterion	Weight	Best value	Worst value
Annual Cost	2.0	0	A$1200
Upfront Cost	2.0	0	A$6000
Familiarity	2.22	1	0
% of Green Voters	4.31	30%	0%

If we let the benefit index $B_d^{o,t}$ be the weighted aggregation of the financial and non-financial criteria that impact consumer choice, then $B_d^{o,t}$ is calculated from

$$B_d^{o,t} = \sum_{j \in J} w_j * (y_{d,j}^{o,t} - 0.5) \qquad (1)$$

where w_j is the weight for criterion $j \epsilon J$ that is relevant to technology option $o \epsilon O$,

and $y_{d,j}^{o,t}$ is the distance of the value of criterion $j \epsilon J$ from the best and worst values of technology option $o \epsilon O$ by category $d \epsilon D$ at time $t \epsilon T$.

If we let $x_{d,j}^{o,t}$ be the value of each criterion $j \epsilon J$ for technology option $o \epsilon O$ by category $d \epsilon D$ at time $t \epsilon T$, then this distance value can be computed in two ways - under complete dependence on market share or under partial dependence. In the case of complete dependence, we use the normalised score as a function of market share of water heater stock in the previous time period giving us

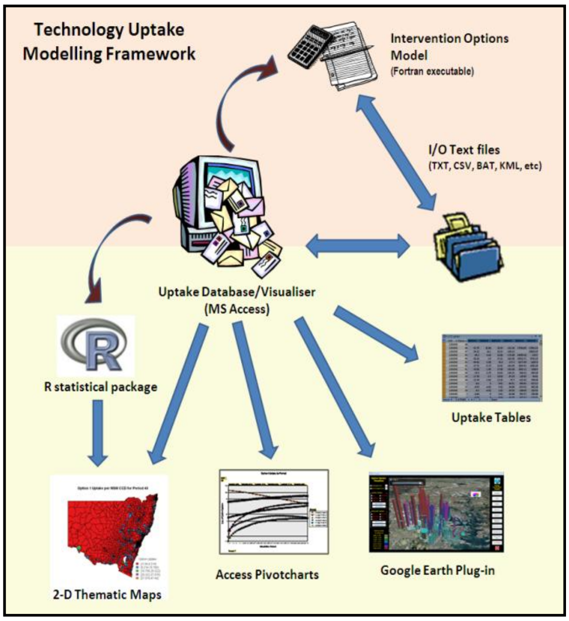

Figure 1. Components of the TERENCE technology uptake modeling framework

$$y_{d,j}^{o,t} = A_d^o(t-1) / \sum_{o' \in O} A_d^{o'}(t-1) \quad (2)$$

where $A_d^o(t)$ represents the level of stock of technology option $o \epsilon O$ for category $d \epsilon D$ at time $t \epsilon T$. In the case of partial dependence, we can use a linear price function:

$$y_{d,j}^{o,t} = \alpha * \left(\frac{f_{d,j}^{o,t,-} - x_{d,j}^{o,t}}{f_{d,j}^{o,t,-} - f_{d,j}^{o,t,+}} \right) + \beta * A_d^o(t-1) / \sum_{o' \in O} A_d^{o'}(t-1) \qquad (3)$$

where $f_{d,j}^{o,t,+}$ and $f_{d,j}^{o,t,-}$ are the best and worst points, respectively, of option $o \epsilon O$ for criteria $j \epsilon J$, and $\alpha + \beta = 1$.

When equation 2 is used, the criterion partly resembles the imitation component of the Bass diffusion model. Imitation captures the reduced risk or hassle when a larger portion of the market has adopted.

To obtain the timing of replacement, let $p_d^o(t,t')$ be the probability of replacing technology option $o \in O$ for category $d \in D$ at time $t \in T$ when it was purchased in period $t' \in T$. We calculate $p_d^o(t,t')$ using Weibull distribution, which is commonly used to represent appliance reliability:

$$p_d^o(t,t') = k * \left(\frac{B_d^{o,t} * (t-t')}{b^0}\right)^{k-1} * e^{-\left(\frac{B_d^{o,t} * (t-t')}{b^0}\right)^k} \tag{4}$$

where b^o is the expected lifespan of technology option $o \in O$, and k controls the shape of the distribution.

The probability that a household from category $d \in D$ will choose technology option $o \in O$ amongst the competing options during time period $t \in T$ is given by

$$S_d^o(t) = \frac{e^{B_d^{o,t}}}{\sum e^{B_d^{o,t}}} \tag{5}$$

where

$B_d^{o,t}$ is the benefits index of choosing technology option $o \in O$ for category $d \in D$ at time $t \in T$.

3. TERENCE MODELLING FRAMEWORK

A scenario analysis tool, codenamed TERENCE (Tool for the Evaluation of Residential ENergy Consumption and Emissions), has been developed that provides a user interface to the intervention options model as well as tabular and graphical display to the input data and modelling output. TERENCE combines a highly graphical and visual presentation with geographical granularity only limited by the availability of data. The current prototype performs data analysis at the CCD level with appropriate data. Recent results from client interactions/presentations has shown that there is a high demand for modelling and policy analysis to feature a high level of geographical granularity. Presentations of energy consumption modelling and electric vehicle adoption projections at ABS CCD scale attracted major interest when shown for the whole state (NSW and Victoria) but with the capability to zoom in to street level.

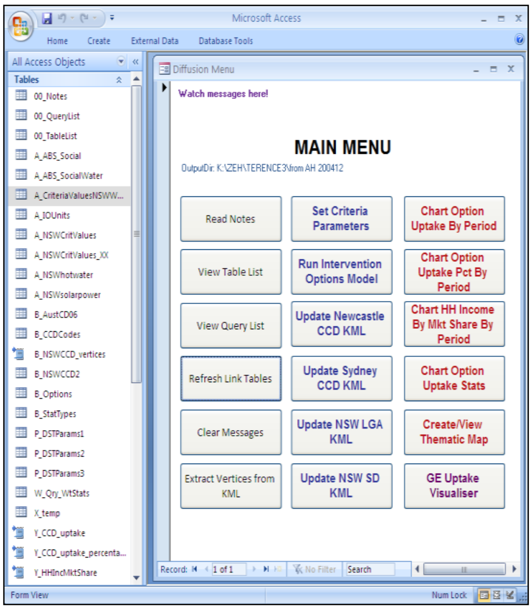

Figure 2. Main window of TERENCE database showing the main menu and navigation panel

Figure 1 illustrates the components of the TERENCE technology uptake modelling framework. An MS Access database provides the front-end to this framework resulting in the integration of the intervention options model with database management, scenario definition and evaluation, and statistical and graphical analysis. This framework allows the user to view and edit input data to define scenarios for the intervention model, run the intervention model, and then display and analyse the modelling results using a number of statistical and graphical methods.

There are five principal components in the framework, and these are described as follows.

3.1. Database

This is the Microsoft Access database file that provides the main interface to the modelling framework. The Database contains or provides links to the demographic, housing, technology options, energy consumption, intervention programs and other related data required by the simulator. It also stores the results of the simulations which are then accessed by other data analysis platforms such as Excel, R or GIS for visualization or additional examination. Figure 2 presents the main window of the TERENCE Database featuring the navigation panel on the left and the main menu on the right.

The navigation panel lists the contents of the database in terms of tables, queries, forms and modules. The tables are of two types: linked and unlinked (or local). Linked tables are connected to an external data source (such as a text file, a spreadsheet, or tables from another Access file) where the actual data is stored. Unlinked or local tables have their data stored in the database file.

The centre column in the main menu provides facilities for defining intervention scenarios, running the intervention options model, and analysing the impact of the scenarios on technology uptake. Scenario modelling is accomplished primarily by using two middle-column options in the main menu:

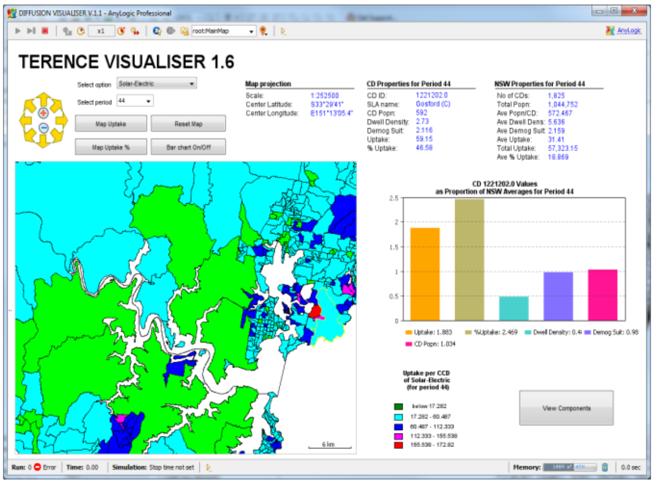

Figure 3. Simulation output for solar-electric water heaters in Sydney region using Anylogic 6.7

- **Set Criteria Parameters:** This option presents a dialog where values for costs and benefits of options representing different scenarios can be set and written into an input file to be used by the intervention options model.
- **Run Intervention Options Model:** This option runs the intervention options simulator.

3.2. Intervention Options Simulator

The simulator implements the multicriteria decision model in one of three forms: (1) as a Fortran-compiled executable, (2) as a Java-based simulation model in Anylogic 6.7, or (3) as a Visual Basic Application (VBA) module in Microsoft Access. Figure 3 shows a map of the distribution of solar-electric water heaters in Sydney CCDs for 2030 using Anylogic 6.7. Among the three, the Fortran executable version performs the fastest. The Fortran-executable simulator is called by the Database from a batch file to perform the diffusion modelling calculations and produce the uptake estimates for each time inteval. The steps performed in each simulation run are summarised as follows:

1. For each building type, assign the initial uptake levels of each option.
2. For each iteration, determine the replacement status of each option for each building type for the next time period.
3. If replacement status is TRUE or remaining life is zero then perform the option selection procedure.
4. Move to the next time period and copy the next option uptake status as the current option uptake status.
5. Update aggregated uptake counts for CCDs, building types, and options.

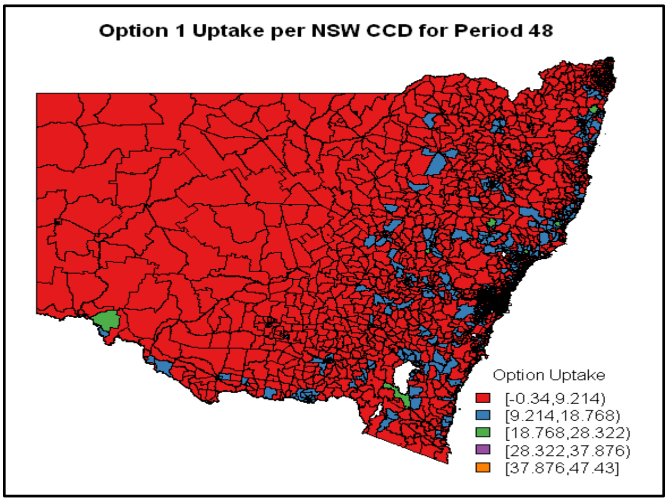

Figure 4. Distribution of uptake for Option 1 (LPG) among NSW CCDs in period 48

3.3. Input/Output Files

Spreadsheets (.xls), other databases (.mdb, .accdb) and text files (.csv, .txt) are used by TERENCE to create linked tables of data for the simulator. Queries are then used to combine data from separate tables into the format required by the analysis. Other text files (*.csv, *.txt, *.kml, *.html, *.R, *.bat) are used to store output from the simulator and database, and encode calls and instructions to operate other components.

3.4. Pivotcharts/Thematic maps

The detailed uptake estimates (by building type, option, location, period) produced by the intervention options model are saved in CSV files and accessed using linked tables. With around 570,000 records, uptake results (and similar large output files) contain such a huge amount of information that is difficult to display in table format. Various graphical formats are provided in TERENCE to present and analyse information from these large data files.

Pivotcharts provide a flexible way of presenting, selecting and grouping uptake data across different dimensions. A large range of chart types are available in Microsoft Access including bar, column, lines, pie XY, stock and area charts. For some of the chart types, the option to use a 3-D version may also be available. Pivotcharts also provide various filters and aggregation functions that can change the display of data in series. The main menu provides several ready made options to view pivot charts of the uptake results.

CRAN R (version 13.0 or later) is also called by TERENCE to execute R code to produce two-dimensional thematic maps of the distribution of the uptake estimates, as shown in Figure 4. R is called by the Database via a batch file to produce a map image file by merging data produced by a query with NSW CCD boundaries from a shapefile.

3.5. Google Earth Plug-in

Google Earth is used to provide visualisations of uptake over time and space by embedding 2-D and 3-D charts of uptake statistics with geographic and temporal attributes. The display data for Google Earth are written into KML-formatted (Keyhole Markup Language) files produced by the Database and displayed in the plug-in screen using Javascript code. Figure 5 shows a 3D bar chart of the uptake of solar-gas heaters in Sydney CCDs using Google Earth. The height and color of the hexagonal bars represent the value of the uptake in the CCD for the given time period. The radius of the hexagon is proportional to the area of the CCD. The legend for this bar chart is shown at the lower portion of the left panel. The slider control at the upper left corner of the screen allows the user to animate the changes in the size and colours of the bars for the entire simulation period.

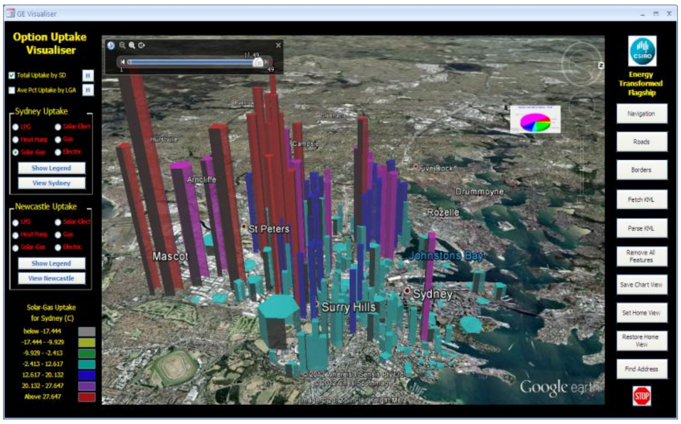

Figure 5. 3-D hexagonal bar chart showing uptake of Solar-Gas option for 2030 for the CCDs of Sydney

4. CASE STUDY

A case study (Higgins et. al, 2012) was conducted to investigate the impact of different rebate scenarios on the phasing out of electric hot water systems in New South Wales (NSW), Australia. The objective was to analyse the adoption patterns of six water heater options (LPG, heat pump, solar gas boost, solar electric boost, natural gas, and electric) from 2007 to 2032 across NSW. Forecasting was conducted at census collection district (CCD) level using demographic data from the Australian Bureau of Statistics (ABS). Household categories were created based on combinations of dwelling structure (3 levels), home ownership (2 levels), household income (3 levels), number of bedrooms (2 levels) and CCD location (11,811). Although not all combinations were available, 119835 household categories were still considered.

Seven criteria were used to evaluate the attractiveness of an option to a household category in a given time period. Three of the criteria (annual energy cost savings from option; upfront cost of option; market share of option) represent expected values or performance levels for the options. Market share is used to indicate familiarity and a reduced level of risk in adopting the option. The remaining four criteria (household income; ABS index of relative socio-economic advantage and disadvantage; ABS index of relative economic resource; Green Party support) represent characteristics of the household and its location. The ABS indices represent socio-economic characteristics of the CCD. Green Party support pertains to the proportion of voters in the CCD that voted for the Green Party in the 2011 state election and is used as a psychographic proxy for attitude favoring the adoption of more expensive options such as solar electric and gas boost water heaters.

4.1. Base Case

The base case represents water heater uptake levels from 2007 to 2030 where financial incentives were in effect from 2007 to 2011, and none after 2011. Figure 5 show the distribution of the uptake of the solar-gas option in 2030 using Google Earth. Locations accessible to the Jemena gas network show a very high market share of natural gas heaters by 2030 due to their low cost. Solar gas boost heaters had low adoption due to their high upfront cost relative to the competing natural gas option. Adoption of solar heaters was more restricted to wealthier parts of Sydney and coastal regions were also conducive to adopting energy reduction technologies (i.e. large % of Green voters). Heat pumps had a significant uptake in the parts of Sydney not serviced by the Jemena gas network as well as coastal regions with higher household incomes. This result highlights the need for increased incentives for low income households.

A major advantage of forecasting uptake of water heaters at such high geographical granularity is the ability to analyse impacts on the electricity/gas grid, particularly at the scale of substations and individual feeders. This is an important capability for energy distributers to plan for future network capacity expenditure. When linked with a simulation model for residential energy, such as the AusZEH Design Tool (Ren et al 2011), peak energy demands can be estimated from the outputs.

4.2. Rebate Scenarios

Federal and state government policy, in the form of financial rebates, has been a major strategy to accelerate the phasing out of electric water heaters in NSW and across Australia. In order to assess the effectiveness and efficiency of different incentives when implemented between 2011 and 2030, a sensitivity analysis was conducted on the size of the rebate for natural gas, heat pump and solar heaters, when introduced from 2011 though to 2030. Instead of a flat dollar rebate, as per those previously offered, a % discount to the upfront cost is offered. Rebates are only offered to households replacing electric water heaters, rather than replacing other water heater types. A range of rebate programs were simulated and the results showed that by limiting the rebate to lower income households, assuming high income households will replace their water heaters without a rebate, the efficiency of the rebate (cost per unit) increased by about 15%. This means testing substantially reduced total cost to government, but the effect on phasing out electric heater stock was also reduced. Terminating the rebate at 2020 and 2025 had a worse effect than restricting the rebate to lower household incomes due to the significant reduction in efficiency. By implementing a smaller fixed rebate for the heat pump of $300 versus the solar option ($900), the efficiency was less than a fixed rebate of $600 for both.

5. CONCLUSION

This paper described the capabilities of TERENCE as an analysis tool for planners and policymakers looking to evaluate the impact of programs and strategies aimed at increasing the adoption of energy efficient technologies in the residential sector. The framework features an intervention options model, which employs simulation and multi-criteria analysis (MCA) in estimating the adoption rates of competing technologies over a period of time based on a range of socio-economic criteria. TERENCE combines a highly graphical and visual presentation with geographical granularity only limited by the availability of data. TERENCE was applied in a case study investigating a set of rebate scenarios aimed at reducing the market share of electric water heaters by 2030. The results showed the flexibility and efficiency of the TERENCE framework in defining criteria, setting up scenarios and analysing output along spatial and temporal dimensions. Future work extensions being considered include specification of additional scenarios involving taxes/fees for purchasing electric water heaters, as well as introducing non-financial incentives for adopting energy efficient technologies.

REFERENCES

Australian Government. (2008) Carbon pollution reduction scheme: Australia's low pollution future, Department of Climate Change. www.climatechange.gov.au.

Higgins, A., C. McNamara, C. Xu, L. Marquez, G. Foliente (2012). Modelling for Energy Efficiency in NSW Residential Sector. Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Ren, Z., G. Foliente, W. Chan, D. Chen and M. Syme (2011). AusZEH Design: Software for low-emission and zero-emission house design in Australia. Proceedings of the Building Simulation 2011 Conference, In press.