LOW CARBON LIVING CRC

RP3028: Final Report:

Mapping the adoption processes of energy efficient products in the residential sector

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Disclaimer

Peer Review Statement

The CRCLCL recognises the value of knowledge exchange and the importance of objective peer review. It is committed to encouraging and supporting its research teams in this regard.

The author(s) confirm(s) that this document has been reviewed and approved by the project's steering committee and by its program leader. These reviewers evaluated it's:

- originality
- methodology
- rigour
- compliance with ethical guidelines
- conclusions against results
- conformity with the principles of the Australian Code for the Responsible Conduct of Research (NHMRC 2007),

and provided constructive feedback which was considered and addressed by the author(s).

Supplementary materials

At a request from Magnus Moglia (magnus.moglia@csiro.au), the following can be provided:

- A case study (38pp) and a user guide (44pp) for the original commercial buildings adoption ABM.
- A social media report (34pp).
- A document on the Solar Hot Water System Case Study Parameterisation (5pp).
- A brief user guide for residential sector ABM (6pp)
- A prototype residential sector ABM description (28pp).

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Executive Summary

This report provides a summary of the research activities in the research project *RP3028: A Virtual Market for Analysing the Uptake of Energy Efficiency Measures in Residential and Commercial Sectors*.

In Australia, as of the first quarter of 2017, electricity generation accounts for 35% of greenhouse gas emissions and energy use accounts for 79% of emissions (Department of Environment and Energy 2017). The residential sector (i.e. households) account for approximately 11% of Australian energy use (Department of Industry Innovation and Science 2016). This leaves the residential sector energy use currently responsible for approximately 9% of Australia's greenhouse gas emissions.

Because of the possibility of achieving reductions in greenhouse gases by promoting energy efficient technologies, there is a growing interest from governments around the world. As an Australian example, the New South Wales Energy Efficiency Action Plan is a government plan to promote residential energy efficiency (State of New South Wales and Office of Environment and Heritage 2013).

To enable the development of policy programs to increase adoption of energy-efficient products, there is a need to develop a knowledge base from which it is possible to understand the likely success of policy interventions.

The required knowledge will be based on a combination of data and observations from which to develop either a mental or a computational model. These models, in turn, will guide the policy design, implementation and evaluation process.

The effort to increase energy efficiency in the residential sector, depends to a large extent on the consumer behaviour of residents, and in this report, we provide a summary of the complexities of consumer choice, including the need to consider:

- Cognitive biases: it is important to incorporate the latest and most relevant aspects of behavioural science.
- Social comparisons: the choice is often based on a social process which involves normative pressures.
- Imitation: decisions are often based on heuristics and perhaps the most common one is imitation of peers
- The role of media: decisions are influenced by perceptions which in modern society is strongly influenced by media.
- Limited bandwidth and strict budgets: people will make decisions in contexts with competing demands for time, effort and money.
- Non-monetary priorities: there are many aspects that people will consider, some of which are non-monetary and often also non-quantitative such as lifestyle or comfort factors.
- Decision triggers: decisions are made only at certain times, and it may be useful to consciously trigger additional decisions in order to speed up the transitions process.
- Heterogeneity: people have their own priorities and biases and whilst socially influenced people do not act consistently as groups, but rather in response to individual circumstances and priorities.
- Decision points: choices architectures and information provided at decision points are critically important for the outcome.

These aspects of consumer choice have been embedded into an Agent-Based Model of household energy efficiency adoption, and this model is described in this report.

Furthermore, the described model embeds not only household agent decision making but in fact three types of actors, based on mapping of the adoption processes in this project, i.e. the:

- Households, who make decisions on product purchases;
- Sales agents, who proactively sell products; and
- Information agents, i.e. those that provide recommendations indirectly or directly.

As the model describes these three types of agents in interaction, the model is able to explore where in the supply chain it is most cost-effective to nudge or incentivise decision making in order to promote the adoption of energy-efficient products.

Within a case study on how to increase the adoption of solar hot water systems, the model has shown that in the circumstances being modelled:

- It is more cost effective to provide a subsidy to households rather than to incentivise sales agents via energy savings certificates.
- It is, even more, cost-effective to engage plumbers to recommend solar hot water systems.

This shows the importance of providing the right information at the right time to households. In the case of solar hot water systems, plumbers have the opportunity to provide such information to householders at the time when they are making a decision.

The model explorations also show that when modelling adoption, it is critical to understand the mechanics of the process. Embedding insights from behavioural science as much as possible allows for fine-tuning parameters in the delivery of interventions.

We believe this modelling approach has potential to support plans to increase resource efficiency in society.

The approach is adaptable to many types of situations (water conservation, green infrastructure, etc.) but will require some effort to update the models.

Introduction

This report provides a summary of the research activities in the research project *RP3028: A Virtual Market for Analysing the Uptake of Energy Efficiency Measures in Residential and Commercial Sectors*. The project flows on naturally from the project RP3002, which had a focus on modelling the adoption of energy efficient products in the commercial buildings sector.

The study's goal was to '*model the uptake of low carbon and energy efficient technologies and practices by households and under different interventions*'. Specifically, aiming to represent non-financial drivers of behaviour such as through the influence of social networks. The study was also undertaken in close collaboration with the key stakeholder who is expected to use the modelling capability, i.e. the Office of Environment and Heritage which is part of the New South Wales (NSW) State Government.

The reasons for reducing householder energy use is because there are serious impacts from human activity on the planet (Zalasiewicz, Williams et al. 2010). It's widely agreed that there is an urgent need to decrease global greenhouse gas emissions (IPCC 2014).

In most countries, the largest contributor to greenhouse gas emissions is the energy sector (Höhne, Blum et al. 2011). Within the energy sector, globally, the residential sector represents nearly a third of all energy use (Swan and Ugursal 2009).

In Australia, as of the first quarter of 2017, electricity generation accounted for 35% of greenhouse gas emissions and energy use accounted for 79% of emissions (Department of Environment and Energy 2017). The residential sector (i.e. households) account for approximately 11% of Australian energy use (Department of Industry Innovation and Science 2016). This leaves the residential sector energy use currently responsible for approximately 9% of Australia's greenhouse gas emissions.

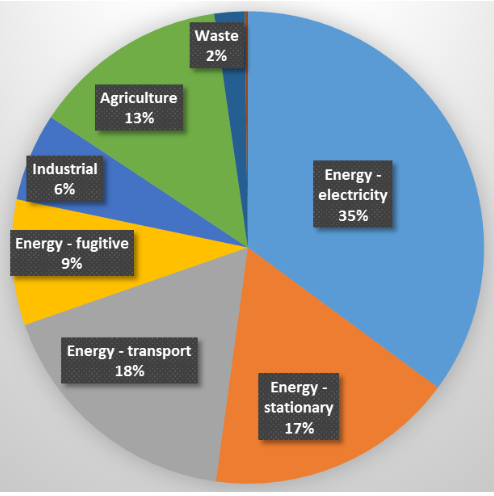

Figure 1: Proportion of emissions attributable to sources in Australia. Source: Department of Environment and Energy 2017.

The main approaches for reducing the CO_2-e emissions from the residential sector are: firstly to reduce energy use through greater energy efficiency and secondly to use cleaner energy through the increased use of renewable energy technologies.

Globally, there has been a tendency towards greater energy efficiency in the residential sector through technological advancements in lighting, space heating and cooling, cooking, refrigeration, and water heating (Fan, MacGill et al. 2015). A number of products help reduce residential energy use:

- Energy efficient Heating, Ventilation and Cooling (HVAC) systems (Chua, Chou et al. 2013; Noonan, Hsieh et al. 2013; Wilson, Crane et al. 2015).
- Energy efficient appliances such as dishwashers, washing machines, fridges, etc. (State of New South Wales and Office of Environment and Heritage 2013),
- Solar hot water systems (Ferrari, Guthrie et al. 2012; Sweeney, Pate et al. 2016),
- Energy efficient lighting, such as LED (Aman, Jasmon et al. 2013),

In the Australian context, the estimated contribution of each of these end uses to the overall average household energy use is shown in Table 1.

Table 1: Proportions of household energy use. **Source**: Australian Government (2013).

End-use category	Percentage of energy use
HVAC systems	40%
Household appliances [a]	33%
Water heating	21%
Lighting	6%

[a] **Note**: Includes refrigeration, laundry, washing and cooking.

Because of the possibility of achieving reductions in greenhouse gases by promoting energy efficient technologies, there is a growing interest to do this from governments around the world. As an Australian example, the New South Wales Energy Efficiency Action Plan is a government plan to promote residential energy efficiency (State of New South Wales and Office of Environment and Heritage 2013).

To enable the development of policy programs to increase adoption of energy-efficient products, there is a need to develop a knowledge base from which it is possible to understand the likely success of policy interventions.

The required knowledge will be based on a combination of data and observations from which to develop either a mental or a computational model. These models, in turn, will guide the policy design, implementation and evaluation process.

Project context

This project builds on previous studies by the CSIRO and the LCL CRC to model the innovation diffusion of energy efficient products amongst households and commercial building owners, using traditional methods, i.e. by means of the Bass equation (Higgins, Foliente et al. 2011; Higgins, Paevere et al. 2012; Higgins, Syme et al. 2014).

These previous efforts to describe innovation diffusion processes were based on the innovation diffusion theory first introduced by Rogers (1962). The term diffusion refers to the process in physics whereby heat is transferred between objects which are in contact with each other. Rogers (1962) focused on how the process of adoption of behaviours or products is transmitted across a social system, with a particular focus on communication as a key part of the process.

Computationally, traditional innovation diffusion models use equations that describe S-curves of increasing adoption rates as shown in Figure 2.

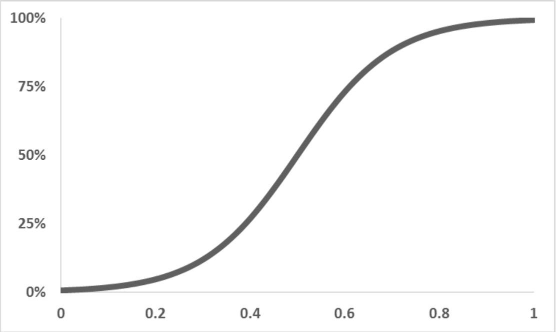

Figure 2: S-Curve describing an innovation diffusion process

Whilst the previous efforts achieved good results, it was also recognised that there were some limitations in the traditional approaches to modelling innovation diffusion processes. The difficulties include the description of:

- Human behaviour including cognitive biases and rule-based decision making.
- Heterogeneity, i.e. variability, in the population.
- The explicit rather than implicit role of communication between households as well as
- Individual householders seeking recommendations from sources other than other householders to inform technology choices.
- The chain of decisions along a supply chain, including how these interact toward the point of technology adoption.

Consequently, it was thought that for the traditional equation-based models, whilst they can be calibrated to provide close correlation with past adoption patterns; they are not particularly useful for ex-ante analysis of policy (estimating the expected outcomes before the implementation of a policy), where bottom-up information can feed the empirical basis for modelling rather than after the fact types of calibration datasets.

Thus, the project team embarked on developing an Agent-Based Model (ABM) for a ‘virtual market’ that can describe the adoption of energy-efficient products in the residential market.

This occurred through a series of activities:

1. Close collaboration with the industry partner (NSW OEH) to identify available data sets, and suitable case studies to apply the modelling capability to. This also involved qualitative mapping of interventions.
2. Social research into the role of media in adoption processes and the socio-cultural context within which a household will make an energy efficient adoption decision.
3. Mapping the interventions and empirical data available on which an ABM can be built.
4. Building an ABM to be trialled and tested by the industry partner.
5. It was also agreed that further work would be undertaken on an existing ABM for exploring the adoption of energy efficient products in the commercial buildings model sector. Thus

This report will not describe these activities in detail, but instead, the focus will firstly be on providing a review of the complexities of a household choosing to adopt an energy efficient product. Secondly, the report on the ABM that has been developed, and to showcase this model by means of a couple of a case study.

The complexities of consumer choice

The first point of call in order to describe the choice of households to adopt energy efficient technology is to move beyond previous relatively simplistic models of human behaviour and attempt to describe a broader range of complexities. Therefore, we have reviewed five different lenses on consumer choice:

1. Behavioural science
2. Social practice
3. Media and communications
4. Household priorities and perceptions
5. Technology attributes

None of these perspectives holds the full answer to describing household decision making yet jointly we think that they provide a useful starting point, and provide design principles for the ABM that we need to develop.

The reason for the multi-perspective approach is the recognition of the high degree of complexity of human decision making, as illustrated by the widely known analogue of the 'blind men and the elephant picture' as seen in Figure 3.

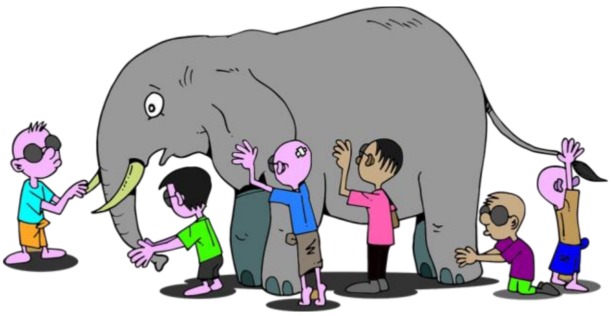

Figure 3: Human decision making: blind men and the elephant kind of problem. This image is free for commercial use[1].

To summarise, in advance, the factors that need to be considered in modelling adoption processes in relation to household energy efficiency are shown in Table 2.

Table 2: Factors that need to be considered within our ABM

Issue	Description
Cognitive Biases	It is important to incorporate the latest and most relevant aspects of behavioural science.
Social comparisons	Choices are often based on social processes which involve normative pressures.
Imitation	Decisions are often based on heuristics and perhaps the most common one is imitation of peers
The role of media	Decisions are influenced by perceptions which in modern society is strongly influenced by media.
Limited bandwidth and strict budgets	People will make decisions in contexts with competing demands for time, effort and money.
Non-monetary priorities	There are many aspects that people will consider of which are non-monetary and often also non-quantitative such as lifestyle or comfort factors.
Decision triggers	Decisions are made only at certain times, and it may be useful to consciously trigger additional decisions in order to speed up the transitions process.
Heterogeneity	People make decisions based on individual circumstances and priorities, which vary considerably across a population.
Decision points	The way that choices are presented, and when they are presented, to consumers is critically important for the outcome.

1 https://pixabay.com/en/ancient-blind-boys-brain-cartoon-2026111/

Lessons from Behavioural Science

Recent advances in the behavioural sciences are highly relevant when trying to understand the adoption of energy-efficient products. To illustrate the relevance, take a couple of examples from Nobel Prize-winning economist Richard Thaler's theories; i.e. those about mental accounting (Thaler 2008) or the human tendency to go with the 'default option' (Thaler and Sunstein 2008).

Behavioural science has been made accessible to the general public through popular science books such as *Thinking Fast and Slow* (Kahneman 2011), *Predictably Irrational* (Ariely 2008) and *Nudge* (Thaler and Sunstein 2008), which are all highly recommended for anyone considering how to incorporate behavioural science into their work.

A first relevant issue identified through behavioural science is that of ***prospect theory***, which describes that the way that humans respond to losses and gains in relation to a reference point. Thus the perceived value is in relation to a reference point and is relative rather than an objective assessment of value. Furthermore, it is argued that losses hurt more than gains feel good, thus humans have a tendency to be risk averse in attempting to avoid losses (Tversky and Kahneman 1986; Kahneman 1992).

The notion of ***mental accounting*** refers to the tendency of humans to mentally account for money in 'different categories' (Thaler 2008). This means that when a windfall occurs, such as by obtaining a discount for a product that the consumer intended to purchase anyway, the consumer will value this not in a strict 'financially rational' manner but rather in a complex way that depends on the framing of the discount and the personal circumstances (Liu 2013; Liu and Chiu 2015).

The ***status quo bias*** is the emotional tendency to prefer whatever is the current state of affairs, i.e. the baseline, and to give the status quo option weight over an alternative on the basis of no other objective benefit other than it means not having to change (Samuelson and Zeckhauser 1988). This emotional effect is in addition to taking into account the issue of the 'extra work' or hassle involved in changing. The status quo is also in interaction with other known biases, such as the endowment effect, i.e. people ascribe more value to things they own (Strahilevitz and Loewenstein 1998), and the loss aversion bias, i.e. the tendency to prefer avoiding losses over making gains (Tversky and Kahneman 1992).

Furthermore, Thaler and Sunstein (2008) have shown that humans are generally lazy when they make decisions and will respond to what is called to "choice architecture" which is to say that there is a tendency to go with the path of least resistance. For example, when starting a new company employees have a tendency to go with the default superannuation savings options, rather than to shop around for the best alternative. It is easy to see that a similar type of issue may be that householders will go with the 'easy option' of adopting whatever their plumber suggests when their hot water system breaks down. Here, this can be referred to as the ***default bias***, although this is not an official terminology.

It is also known that people tend to try and satisfy a small set of criteria rather than to optimise their choice against all relevant criteria (Frederiks, Stenner et al. 2015). This is referred to as ***satisficing*** to "*choose not necessarily the best option or solution to a problem, but rather the first available option or solution that suffices or satisfies the minimum requirements*" (Frederiks, Stenner et al. 2015).

There are further cognitive mechanisms that relate to how people will be influenced by information and others (Tversky and Kahneman 1973; Feldman 1984; Janssen and Viek 2001; Jager and Janssen 2012; Frederiks, Stenner et al. 2015):

- ***Availability bias***: this states that people will tend to draw on knowledge and information that is easily accessible when making decisions.
- ***Trust***: People nonetheless tend to seek information and judgments from those that they trust, "*with an entity's trustworthiness resting on apparent expertise and experience (i.e., competence-based trust), as well as perceived openness, honesty, and concern for others (i.e., integrity-based trust)*".
- ***Social comparison***: people tend are influenced by social comparisons within decision making, i.e. to attempt to conform to social norms, in terms of following the implicit or explicit expectations on what is normal or desirable.
- ***Bounded rationality***: there is a cognitive effort involved in making decisions, and people will sometimes tend to use simple decision rules rather than rigorous analysis to make a choice.

Thus, there is a large body of literature that explores human decision making, which will somehow need to be represented in an ABM describing adoption processes. There is one framework that stands out as potentially taking much of these types of socio-psychological issues into account in the modelling, i.e. the Consumat meta-model of human behaviour (Janssen and Viek 2001; Jager and Janssen 2012). In fact, the Consumat framework has been applied to related issues (Sopha, Klöckner et al. 2013; Sopha, Klöckner et al. 2017).

The Consumat approach has four modes of decision making, Inquire, Imitate, Repeat or Optimise as per the Consumat theory. These are based on an evaluated social needs satisfaction and existential needs satisfaction. The existential needs refer to perceived fitness of options against a range of factors (see household priorities and perceptions below), whilst the social needs satisfaction relates to social comparisons. The choice of mode is dependent on the evaluation of social and existential needs as well as the uncertainty. This is based on the notion that people tend to consider social comparisons when they are uncertain (Festinger 1954). The four modes of decision making are:

- ***Inquiry***, i.e. reasoned social processing, i.e. deliberating with peers and others about what the best option may be.
- ***Imitation***, i.e. copying the behaviour of others – especially similar others.
- ***Repetition***, i.e. automatically stick with previous choices.
- ***Optimisation***, i.e. individually deliberate to find the best alternative.

Energy Efficiency as Social Practice

Multidisciplinary empirical studies of householder consumption have proliferated over the last two decades, based on voluntary environmental action typically focused on cultural norms and individual responsibility. However, the results of these campaigns have been quite limited, and academics argue that these interventions have failed to acknowledge the wider systems (social, cultural) and infrastructure capabilities at play (Shove 2003; Barnett, Cloke et al. 2011; Warde 2014).

Consumption as a term has become essential to those householders who feel a personal responsibility to resolve environmental problems, and who therefore see consumption as inherently bad for society and for the planet. Due to this, the perceived moral obligations of sustainable consumption are influencing some householders' purchasing decisions. Giddens argues that sustainable consumption raises moral issues that are affecting individuals when they attempt to help solve large-scale environmental problems (1991). Some consumers now feel that they can and need to address world problems from an individual perspective, which may bring a sense of liberating empowerment (Micheletti 2003; Spaargaren and Oosterveer 2010; Lewis and Potter 2011) as well as an overwhelming feeling on individual responsibility and pressure to make the 'right choice' (Sandilands 1993; DeBurgh-Woodman and King 2013; Warde 2014).

There is an emerging body of research looking at household consumption from the perspective of social practices. Originating in the work of Bourdieu (1977) and subsequently Giddens (1991) practice theory and provides a contrast to the theoretical models of individual choice and behaviour.

Theories of practice have helped the development of issues of structure and agency of materials and objects (human and non-human) in the conceptualisation of consumption. Warde argues that consumption is not in itself a practice, but an element of a wide range of diverse practices, 'paths of dependency' within specific contexts (2014). A key advantage of a practice perspective is in developing empirical research on the impact of everyday mundane activities (particularly within the home) against environmental impacts (washing bodies and clothes (Shove 2003): heating and cooling (Shove 2003; Lane and Gorman-Murray 2011; Strengers and Maller 2011): More recent work in practice theory has paid increasing attention to human and non-human objects, materials (Shove and Spurling 2013) and actor-network relationships (Nicolini 2012). These accounts play on the borderline between these everyday activities and their connection to self on display to a wider social context, highlighting in the connection between consumption practices of the individual and collective social networks.

Using a practice theory perspective can be highly useful as it allows the organization of the practice and the moments of consumption within it, allowing the social actors to confront moments of consumption outside of the widely proliferated binary notion of consumers being either "sovereign choice-makers" or "marketing dupes" (Warde 2014). Contemporary consumption theory now recognises a larger range of agents and networks involved in the production, purchasing, and use of goods (Lane and Gorman-Murray 2011).

Consumption is now seen to go beyond the limits of the economics of the individual and into the realm of the social collective. Zelizer argues that in fact (Zelizer 2013);

> *"Consumption, like production and distribution, does crucial social work, not only sustaining human lives and social institutions but also shaping interpersonal relations.*"

Therefore, framing consumption as a means of social improvement and towards an essential social construct which can be directed towards social improvement (Warde 2014).

To provide an example, as individuals, it has been argued that women have borne the brunt of the labour of consumption for the household and as a result, garnered the attention of marketers and advertisers as key decision makers in the home (Cook 2013). Cook argues that 'the place of mothers and motherhood in commercial life represents one of the great under-told stories of consumer culture' (2013).

It has been argued that in striving to become the 'good mother', a woman will sometimes negate her own identity, and in the case of sustainable consumption, her environmental impact, for the sake for her child (Atkinson 2014). This indicates the trade-offs that are associated with making consumption choices.

Cultural norms set expectations for mothers (or parents) to defer some measure of personal gratification to their children's needs (or at least wants), both at home and in the marketplace. It is in the regular handling of children's desires that the sorting of priorities takes place at an everyday level (Cook 2013). Indeed, mothers are encouraged to consume in a way that combines concern for the child with concern for the environment regardless of the increase in domestic labour such purchases entail (Sandilands 1993; Ray 2011).

In the case of brands that promote sustainable products to mothers, it is essential to note that while on one hand, they bring the mother a sense of empowerment over her choices for the betterment of her child, on the other hand, many sustainable mothering practices are also labour-intensive, child-centred and more time-consuming than their less-sustainable counterparts i.e. using cloth nappies over disposable nappies (Atkinson 2014).

This shows that sustainable consumption may have unintended consequences, for example some argue that they reinforce gender inequalities. This shows that complex trade-offs are made when making consumption choices and that when consumers are engaged in sustainable consumption practices, it is ideal if they do so in a way that does not exacerbate social pressure or involve additional time, or labour costs.

Media and Communications

The study team undertook an exploratory investigation into the role that social media and social networks play in public conversations related to home-making, home renovations and sustainability in Australia. This offers an alternative to the approaches which simply consider lack of information is as the main barrier to the greater integration of energy efficient products and solutions in the residential sector. Instead, the study's media research focused on the ways that people engage with each other and with a range of the selected intermediaries. The main findings in the study can be found in the supplementary materials.

Prior research on media and home renovations has found the mainstream commercial media has a significant influence on shaping the renovation practices of renovators (Phillips, Jones et al. 2014; Mackay and Perkins 2017). This study confirms a strong social media activity and engagement with renovation and/or sustainability issues by the accounts associated with the established media outlets and popular TV shows.

While representing different TV genres (competition reality versus lifestyle programming, i.e. The Block vs. Grand Designs), popular TV shows confer the ongoing relevance of television as a popular medium, with social networking tactics used to help spread their messages and reach larger audiences.

However, it is clear that different intermediaries deploy different communication strategies. For example, some people or organisations prefer Facebook over Twitter as their primary social media engagement platform. There is also a great deal of cross-referencing between multiple social media platforms and web-based content (examples provided in the supplementary materials).

The Facebook page analysis indicates that leading sample FB pages with links and visual communication with photos and videos tend to foster high engagement, with posts containing URLs attracting a particularly high number of comments. It was also found that cross-promotion is a general trend on social media platforms, especially those associated with popular TV programs. Generally, the use of @mentions, retweets and specific hashtags helps support the visibility of accounts and reach larger audiences. The social media activity in the environmental not-for-profit category demonstrates an active use of retweets and links as a means to distribute information, and to connect to content from similar environmental orgs.

Another finding comes from the analysis of government organisations. Research has captured the challenges and barriers encountered by, for example, local councils in using social media for public engagement (Omar, Scheepers et al. 2012). This study demonstrates a comparatively low level of engagement by government organisations, with the exception of some very high profile organisations.

Interestingly, the most 'liked' individual message in the sample was posted on the City of Melbourne page representing a local government jurisdiction, with over 50k likes (it was a congratulatory message for the 2016 C40 Cities Awards night). Building on these insights, there are several implications for the agencies attempting to promote energy efficiency through media and communication strategy with a view to reaching a larger audience around sustainable/energy efficient home renovations:

1. **Link with existing online communities and social networks**: explore the potential to connect with highly active social networks/communities. Above all, create cross-platform promotion opportunities, especially around related environmental topics such as on dealing with heatwaves, dealing with the wildlife and ecology; or networks associated with home renovations.

2. **Carefully consider content and messaging**: for example organising media and communication campaigns around events – with opportunities to disseminate messages in the lead-up to the event, actual event and post-event interaction.

3. **Provide tailored information**: local councils have been encouraged to use social media to distribute 'accurate information' pertaining to 'local conditions' in times of emergency, such as flooding (Purser 2012) or heat waves. The focus on local information is relevant for energy efficiency programs in the residential sector, given differences between the states' jurisdiction and renovators' information-seeking and consumption patterns. (Podkalicka, Milne et al. 2016). There may be room for formal communicators and organisations promoting energy efficient products, to complement existing informal, peer-to-peer conversations with information tailored to the local context

4. **Creative ways of talking about cost**: while there is a great deal of information sharing amongst home renovators, one aspect that was considered uncomfortable was sharing the actual cost of products and services used during home renovations (Hulse, Podkalicka et al. 2015). Some popular TV shows have attempted to do this in entertaining ways, for example, featuring a broadcast segment whereby items/materials used in home renovations were showed with their price tags.

5. **Inclusivity**: consider embedding content /messages about energy efficient home renovations as part of the broader range of everyday practices such as cooking, gardening, crafting, socialising; and values such as comfort – rather than treating energy efficiency as an exclusively technical and confined domain of daily life. This insight draws from the literature on the relevance of social practices and cultural values in home-making (see above), and has fuelled industry initiatives such as 'The 17 Things' framework (https://liveability.com.au/). Accurate information (including cost) is valuable, but in promoting energy efficient products and services it is important to situate the benefits of sustainable homes as meaningful, permeating everyday life, and being shared socially as such.

In conclusion, increased energy efficiency hinges on appreciation and awareness of energy efficient products and program; and it is important to be tactical so as to ensure that use of social media and media are effective.

Household Priorities and Perceptions

When a household decision maker chooses between purchasing an energy efficient product vs. purchasing a non-energy efficient product, what are the factors that they consider? Through a review of the literature we have identified a number of these factors.

Financial factors: Whilst it is widely acknowledged that households are not well described as rational economic actors, people still tend to be influenced by monetary factors. However, many of the financial indicators are difficult for household decision makers to estimate, requiring cognitive effort. Furthermore, behavioural economics tells us that the initial cost is likely to weigh more heavily for many people. The importance of these issues is affected by socio-economic factors (Hall, Romanach et al. 2013). Specifically, the upfront price of a product is particularly important because energy efficient technologies tend to come at a higher initial cost, and therefore access to capital can be a limiting factor in the adoption process (Wilson, Crane et al. 2015). The financial factors generally considered to be important for household decision makers are: upfront price, return on investment, and the ongoing cost.

Aesthetics and taste anxiety as identity creation and as a kind of residential ethics is a driver for home renovation or upgrade decisions (Rosenberg 2011). The impact of aesthetics depends on the type of energy efficient product. For lighting, aesthetics relates to the capacity to produce natural colours, and the degree of illumination (Aman, Jasmon et al. 2013). Perceived light quality based on hearsay and past experience, is often as important as the in-practice light quality.

Comfort: Energy efficient products are often linked with greater perceived comfort in the home and this is a key selling point (Chua, Chou et al. 2013; Wilson, Crane et al. 2015)

Resale value of the property: energy efficient products can be important features of a home, and thus could make the property more attractive on the real estate market. This would lead to higher property resale values (Noonan, Hsieh et al. 2013).

Electricity use: Whilst not everyone is motivated by achieving reduced electricity use and/or environmental benefits, some people consider this to be important. This is expected to be a function of environmental attitudes and awareness (Hall, Romanach et al. 2013; Liu, Chang et al. 2013; Newton and Meyer 2013).

Other environmental issues: clearly there are environmental impacts beyond greenhouse gas emissions. For example, in the case of lighting products, some of these emit low levels of mercury (Hg) and have been banned in some countries, yet in some localities, these products are still available for purchase (Aman, Jasmon et al. 2013).

Social influence: household decision makers are known to be influenced via social comparison and through recommendations from peers. To explain in more detail, when peers adopt a technology this means a householder often experiences some level of peer pressure to imitate behaviour (Rosenberg 2011; Hall, Romanach et al. 2013; Noonan, Hsieh et al. 2013; Hicks, Theis et al. 2015). Furthermore, household decision makers social communication, and in recent times, social media, play an important role in shaping the perception of technology attributes (Wilson, Crane et al. 2015).

Access to finance: especially if a household decisions maker has limited access to capital, access to affordable loans could be an important factor in the decision-making process (Wilson, Crane et al. 2015).

Decision trigger points: there are two types of events that will lead a household decision maker to consider purchasing a product:

- The first trigger is when an existing product breaks down or is at the end of its life (i.e. performing poorly). This will trigger the household decision maker to explore options for upgrades.
- The second trigger relates to the household decision maker being approached by a sales agent trying to sell an upgrade. In this case, the household decision maker may or may not find it pertinent to consider the offer.
- The third trigger is when a home is being built or renovated at which time a household decision maker will consider whether or not to purchase an energy efficient product.

Split incentives: When those who pay the energy bills are not those who would need to invest in energy-efficient technology. For example, renters may pay energy bills whilst it is the property owner who purchases the HVAC technology.

Survey of household priorities: based on a survey from NSW OEH (2014), the project established a database of respondents' priorities. Using the responses to survey questions, a set of weights associated with each of the performance criteria was established. This can be used in equations that describe the householder decision makers' needs satisfaction of options, i.e. the utility function. Based on the survey it was possible to estimate the top priorities for different survey respondents, as shown in Table 3. However, it should be noted that the sample is not necessarily entirely representative of the population and there is considerable variability between household categories.

Table 3: Top priorities of survey respondents.

Priority area	Percentage of respondents
Return on investments	26%
Price	22%
Resale value of house	18%
Comfort	15%
Ongoing costs	10%
Electricity use	6%
Aesthetics	2%
Environmental issues	0%

Technology attributes

Beyond the above considerations, there are a number of product-specific attributes that are evaluated by householders when making a decision whether to adopt or not adopt it, as shown in Table 4 to Table 6.

Table 4: Relevant technology attributes for lighting technologies, adapted from Moglia et al. (2017).

Purchasing consideration	Description
Light qualities	This relates to the ability to render colours naturally, and the level of illumination. The perception of light quality, based on hearsay and past experience, is likely to be as important as the actual and current light quality.
Expected useful life	The useful life of a lighting product varies considerably and impact on the environmental impact as well as the lifecycle costs of the product. There is also a nuisance element related to products that break down more often. The lifetime of lighting equipment is typically measured in hours, as the expected time until the amount of light (lumens) has dropped to about 50% of initial values. LED lighting typically has longer lifetime compared to incandescent, fluorescent, or halide lamps.
Toxicity of materials	Some lighting types emit levels of mercury (Hg) which have been banned in some countries, but the sale of these persist in other locations.
Overall environmental impacts	Probably not generally considered by laypeople, this includes consideration of the lifecycle impacts of different options, and, modern options (such as LED) vastly outperform more traditional options such as incandescent lights, in all environmental dimensions, i.e. soil, water, air and resource impacts.
Total Harmonic Distortion	A measure of the amount of electrical distortion created by the equipment and this aspect is mostly a concern for electrical engineers or electricians rather than residential users of lighting products.
Temperature emission	Some lights emit less heat than others, which is considered a selling point in some cases.

Table 5: Relevant technology attributes for HVAC systems, adapted from Moglia et al. (2017).

Purchasing consideration	Description
Thermal comfort	A comfortable home is a key consideration for the investment in HVAC systems, especially if this comfort can come with less guilt of using energy and emitting greenhouse gases, plus different systems perform differently in this respect
The inconvenience of making the change	Installing HVAC systems can lead to significant inconvenience and this, in turn, may be a deterring factor when choosing to upgrade.
Potential to increase in the resale price of a property	The HVAC system is a significant part of the infrastructure of a home, and an upgrade is likely to make the property more attractive and thus quite likely create higher resale values.
Sound	Some HVAC systems are associated with noises and sounds that may be unappealing to potential customers.

Table 6: Relevant technology attributes for household appliances, adapted from Moglia et al. (2017).

Purchasing consideration	Description
Energy star rating	Consumers have been shown to be willing to pay extra for a higher energy star rating of appliances and/or fridges.
Functionality of the fridge/appliance	Particular design features of appliances or fridges play a key role in decision making. For example, the purchase of a fridge is considerably dependent on the volume of the food compartments, as well as the freezer compartment volume.
Water and/or other resource use	Residents may be concerned not only about conserving energy but also about conserving water or other resources.
Size of the household appliance	Especially the presence of children influences the demand for larger appliances, such as washing machines.

The Agent-Based Model

Here we describe an overview of the model, with a complete description of the model provided in an associated journal article (Moglia, Podkalicka et al. 2018). The standardised protocol for describing ABMs is the Overview-Design concepts-Details (ODD) protocol (Grimm, Berger et al. 2006; Grimm, Berger et al. 2010) which suggests describing the: 1) Purpose, 2) State variables and scales, 3) Process overview and schedule, 4) Design concepts, 5) Initialisation, 6) Input and 7) Sub-models.

Purpose

The purpose of the model is to describe '*the uptake of low carbon and energy efficient technologies and practices by households and under different policy/program interventions*'. Furthermore, the ABM sets out to achieve this in a way that describes more of the detail of the adoption process and the complete ecosystem of actors, in line with insights from the review of complexities of consumer choice previously described. In addition, the purpose of the model is in line with ex-ante explorations of proposed interventions to increase adoption rates of energy-efficient products.

State variables and scales

There are three types of agents in the model:

- ***Households***: representing the main decision point in the model of whether to adopt energy-efficient products.
- ***Sales agents***: representing the promotion of energy efficient products by commercial entities.
- ***Information agents***: representing the ecosystem of agents that provide recommendations to households on which product to purchase and thus represents diverse agents such as retailers (as they provide recommendations), tradespeople and media.

In ABMs, agents have attributes which are properties and descriptions which provide input into how determining how they will behave and act in the model. Agent attributes are summarised in Table 7 to Table 9.

Table 7: Summary of household agent attributes

Attribute	Description
Dwelling type	Type of house that the household resides in: detached house, apartment/unit/townhouse, semi-detached or terrace, or other
Household type	As per household typology (see supplementary materials).
Financial vulnerability	Whether the household is financially vulnerable, i.e. whether they would be struggling to purchase an energy efficient product without financial support.
Preferences	Normalised weights on priorities for each of the priority areas shown in Table 3.
Peers	Social network connections.
Information profile	Describing the information agents that the household agent will consult and/or trust.
Technology ownership	Whether the household owns an energy efficient product, the age of it and whether it is broken.
Decision-making profile	Parameters that describe the household decision-making process.

Table 8: Summary of sales agent attributes.

Attribute	Description
Records of sales success and failure	Track record in selling energy-efficient products.
Expenses	Expenses from purchasing and selling products.
Income	Income from selling products.
Sales price	The price at which the sales agent will sell the product.
Administration cost factor	The cost of administering the subsidy scheme.
Cost of sales attempt	The cost of one attempt to sell the product.
Purchasing discount	The discount that the sales agent receives when purchasing a product. They first buy the product before they sell it.

Table 9: Summary of information agent attributes.

Attribute	Description
Preferences	A set of weights for each of the priority areas shown in Table 3
Recommendation	Yes / No, in terms of the recommendation of an energy efficient product. Decided dynamically.

Process overview and scheduling

An ABM is an engine for simulating the actions and interactions of agents within their environment. A simulation needs a schedule for the events and actions along the timeline. For the ABM described here, this schedule is illustrated in Figure 5.

It is noted that there are two decision points for households:

1. ***The product is at the end of its life***. When a product breaks down, a household agent will look for a new product to replace the old one. At this point, the household will consider whether to purchase an energy efficient product.
2. ***The household is being approached by a sales agent***. In each time step, a sales agent will contact a number of household agents, who will at this point decide to what extent they want to engage with the question of whether to purchase an energy efficient product. This will happen when 1) the price is competitive, i.e. not significantly higher than the market price, 2) the consumer is not already satisfied and certain, and 3) the household agent's current product is relatively near the end of its life (i.e. past the 35% survival rate).

In each time step, household agents will need to be assigned to decision modes, as per the Consumat theory which is based on social psychology. This is done according to the evaluation of satisfaction and uncertainty, as per Figure 4.

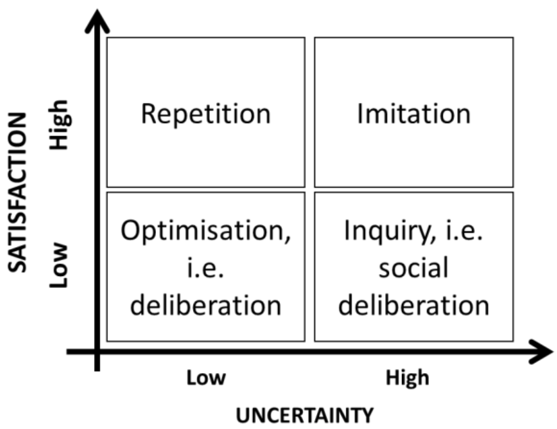

Figure 4: Consumat decision theory matrix

Thus, a household agent will need to evaluate the level of satisfaction and uncertainty as high or low. This, in turn, is based on three criteria, existential needs satisfaction (see the equation 1), social needs satisfaction (see equation 3) and primary focus satisfaction (i.e. performance > 0.5).

$$Existential\ Needs\ Satisfaction(i) = \left(\sum_{j=1}^{8} w_{i,j} \cdot p_j\right) + Behaviour - adjustment \quad (1)$$

$$Behaviour - adjustment = \Delta(hassle) + \Delta(discount) + \Delta(free) + \Delta(word\ of\ mouth) + \Delta(status\ quo\ bias) \quad (2)$$

$$Social\ Needs\ Satisfaction(i) = (\alpha_i \cdot u) + (1-u) \cdot (1-\alpha_i) \quad (3)$$

Here,

- i refers to household number i,
- w(i,j) refers to the preference weight of household i regarding performance factor j. The weights add up to 1.
- p_j refers to the performance of the energy efficient product against factor j. This is a normalised number between 0 and 1.
- α_i refers to the personality value of household i
- u refers to the adoption rate of energy efficient products

The behaviour-adjustment factors are as described in Table 10.

Table 10: Behaviour adjustment factors

Δ-Factor	Description – link with behavioural science
Hassle	The Simplifying the process of adoption is important, as often the perceived hassle of shifting is a major hurdle. This factor represents the 'hassle' involved with taking part in a policy program.
Discount	Due to mental accounting (Thaler 2008; Thaler 2011), there is an irregular response to monetary incentives in that people would tend to give it greater weight to incentives such as subsidies (due to constrained budgets, etc.) than otherwise would be warranted. To simplify things, in the model the effect is proportional to the discount given. If the product is given away for free there is, in turn, an additional factor added (Shampanier, Mazar et al. 2007).
Zero-price effect	
Word of mouth	People's perception of a technology is influenced by its reputation, i.e. experiences amongst friends.
Status quo bias	It is known that people have a tendency to keep doing what they are doing, or sticking with a decision that they already have made (Samuelson and Zeckhauser 1988). This factor represents the emotional inertia of changing the type of product.

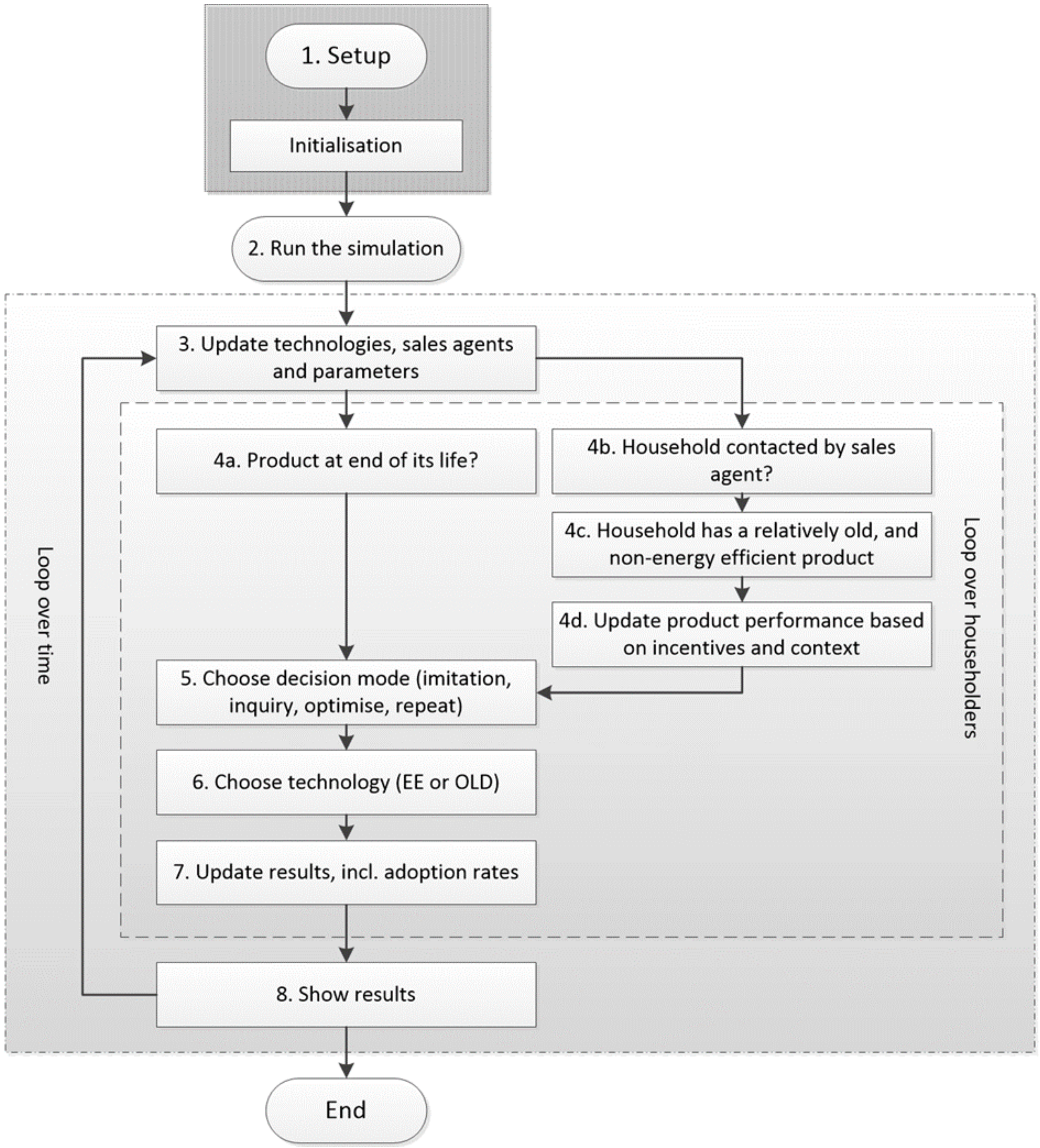

Figure 5: Scheduling of simulation process

The modes, in turn, are carried out according to the following instructions.

Repetition: Satisfied and certain. The repetition decision mode involves repeating the behaviour of the past, i.e. if a household agent already has an energy efficient (EE) product, the household agent will then also upgrade with an EE product, and vice versa if the household agent has a non-energy-efficient product (OLD) product.

Imitation: Satisfied and uncertain. The imitation decision process involves copying the behaviour of a friend in the household agent's connections within the social network. Only friends that are "satisfied" are considered (i.e. the attribute satisfaction = 1). If the household has no satisfied friends, then the household will consider the adoption rate in the broader community, i.e. if the uptake of EE is 25% then the likelihood that a household will adopt EE is 25% and vice versa.

Optimisation: Unsatisfied and certain. The optimisation decision mode is very simple, i.e. it chooses the product that is associated with the highest overall performance, i.e. the highest personalised value of the performance calculated as the weighted sum of product performance and individual priority weights, as well as incorporating a range of behavioural factors.

Inquiry: Unsatisfied and uncertain. The inquiry decision mode involves exploring recommendations from the information sources that the household agent will consider (i.e. based on the information preference attributes) and seek recommendations from each of these. Each of the recommendation sources is associated with a 'weight of recommendations' (assigned in an input file). Based on the number of the weight of recommendations for EE and the weight of recommendations for OLD, a probability p is calculated as the weight of recommendations for EE divided by the weight of recommendations for EE and OLD. The probability of adopting EE given the recommendation weights is equal to p.

Information agent decision making: Information agents provide recommendations to households (i.e. '*you should buy an energy efficient product*', etc.) when households are in the 'inquiry' decision mode. In the default model, there are nine types of information sources, i.e. family and friends, TV home improvement programs (based on expert opinion, two different types of shows are included due to their current dominant position in the Australian market, i.e. Grand Designs and The Block), retailers (two included), tradespeople, online forums, builders, government information sources; these are chosen and parameterised based on information in industry reports (Office of Environment and Heritage NSW 2014; Office of Environment and Heritage NSW 2014) and academic papers (Rosenberg 2011; Podkalicka 2018). To determine which recommendation to provide, information agents have the same type of attributes as households regarding prioritising the performances for each of the technology options to calculate the probability of recommending an EE product based on a discrete choice logit model:

$$P(recommendation = EE) = \frac{e^{(k \cdot \mu)}}{e^{(k \cdot \mu)} + e^{(k \cdot (1-\mu))}} \quad (4)$$

Here, μ is the weighted performance of the EE products, and where the weights are the information agents' priorities provided in an input file. I.e. there are different values for each of information agents.

k is a weighting factor which should ideally be fitted based on choice experiment data; however in the absence of this data the parameter has been set to 5 so that the equation reproduces what is considered realistic behaviour.

Sales agent decision making: Sales agents represent actors who will contact households directly to attempt to get them to upgrade to an energy efficient type of product. In the context of the Energy Savings Scheme in New South Wales, these may be what are called the 'aggregators' who create energy saving certificates on behalf of clients, and who thus can claim the financial reward of doing so (each certificate can be claimed at a price which is adjusted on an ongoing basis). However, sales agents do not necessarily need a subsidy from the government, but may also simply be able to create a financially viable business by purchasing discounted products and having an acceptable level of success in their sales activities. In each time step, sales agents contact a certain number of households and attempt to sell an energy efficient product. In the model, a household will make a decision based on the following rules:

- If the household does not already own an energy efficient product, and if the existing not very energy efficient product is past its half-life (when half of all products would already have been expected to have been replaced), the household will consider purchasing an energy efficient product (i.e. initiate a decision making process).
- In this context, the household will only consider purchasing an EE products if it is sold either at or below current market price.
- Then, if the household escalates to the decision making process, the eventual decision will be on the basis of the *Optimise* decision mode, i.e. on the basis of the existential needs satisfaction (Eq. 1), but with adjustment for the price provided by the sales agent, and with the usual behaviour-adjustments.

In each time step, each sales agent will update their attributes and decision rules on the basis of the assumption that they will act as financial rational actors and maximise their profits (which is consistent with indications from qualitative research in the project, on medium-sized to large businesses; but not appropriate for smaller companies):

- Calculating the *success rate*, the number of successful calls divided by the total number of calls.
- Calculating the *return on investments* by dividing the *profit* with *costs*.
- Adjusting the *outreach* (the number of calls made in each time step).

Design concepts

Model design concepts are described in Table 11.

Table 11: Model design concepts

Issue	Design feature
Method for agent adaptation	Households make decisions based on the Consumat theory (Janssen and Jager 1999; Janssen and Viek 2001; Jager and Janssen 2012).
Emergence	The Consumat model allows for decision rules, two of which enable a degree of emergent behaviour due to the interaction with other agents.
Fitness	Households calculate the fitness of adopting a technology as per above.
Interaction	Households interact with each other households through imitation (enabled through social networks) and social needs. Social needs evaluations are dependent on the behaviour of other households. In addition, households are influenced by information agents in the inquiry decision mode and sales agents trigger household decision points.
Level of social influence	In the user interface, the user can provide input through a 'slider' to decide whether the level of social influence is at, with a parameter between 0 and 1 to indicate anything in between. I.e. the adoption rate for the purposes of social influence is calculated as a weighted sum of the mesoscale and macro-scale adoption rates. The default is set to the mesoscale.
Social network typology	A social network is assigned to household agents. The user can choose between friends' network based on a small world network, random network, or a spatially based network (i.e. neighbours).
Consumer heterogeneity and collectives	A household survey is used to describe heterogeneity in 1) priorities; 2) level of financial vulnerability; 3) types of household as per typology [a]; 4) preferred information sources used

[a] **Note**: The typology depends on the type of product. In the case of solar hot water systems: family with younger kids, family with older kids, double income no kids, single household, retired, unemployed, investor.

Initialisation

The initialisation of the model involves creating the agents of the model (householders, sales agents and information agents), the technology performance attributes, the social network between household agents. Household agents are based on an input file which specifies the number of households within each category (for each combination of dwelling type and household type, as per typologies). When a household agent is created, it receives its attributes copied from one of the household survey responses, as per Figure 6. There are input files to specify attributes of the information and sales agents.

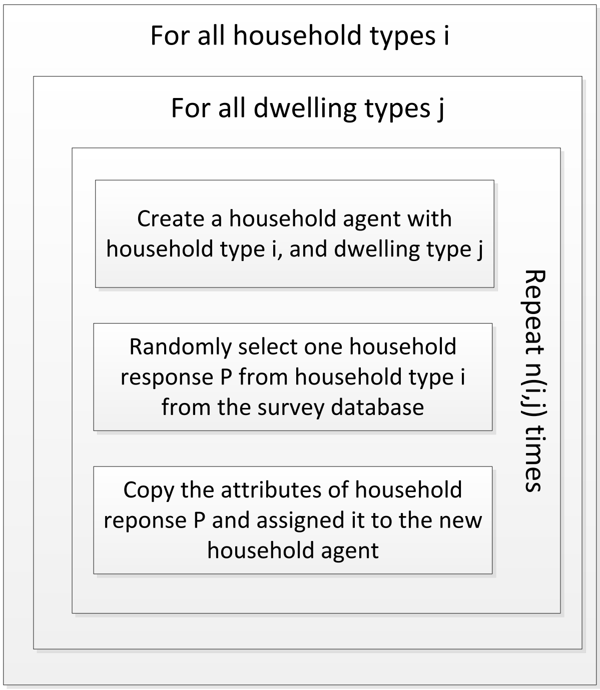

Figure 6: Initialisation of household agents. n(i,j) is the number of households of household type i, and dwelling type j as per input file.

Sub-model

There is a need for carbon accounting component, which estimates the reduced carbon emissions based on the adoption of new products. For solar hot water systems, assumptions used to calculate emissions reductions are shown in Table 12.

Table 12: Carbon accounting parameters

Parameter	Explanation
Proportion of household energy use	Hot water is assumed to account for 21% of the household energy use (NSW Government 2016).
Reduction in energy use	A solar hot water system is assumed to reduce energy use for hot water by 60% (Moore, Urmee et al. 2017).
Household energy use	An average household is assumed to use approximately 5,920kWh per year.
Emissions factor	For New South Wales the emissions factor is set to 0.86 kg CO2-e/kWh (Department of Environment 2014).
Emissions factor gradient	It is assumed that with the gradual installation of renewable energy and other cleaner energy sources, the emissions factor will continually drop at a rate of 0.01 per annum.

Interventions to explore

Here we describe the interventions that we have identified and explored, as options to evaluate using the ABM. These have been identified on the basis of engagement with the collaborators at NSW OEH. Similarly the mapping of the mechanisms by which these work has been achieved through this engagement. The categorisation of leverage points in the adoption process is shown in Figure 7. It is noted that information agents provide recommendations, but sales agents proactively sell energy efficient products only. Thus, for example, retailers are information agents rather than sales agents.

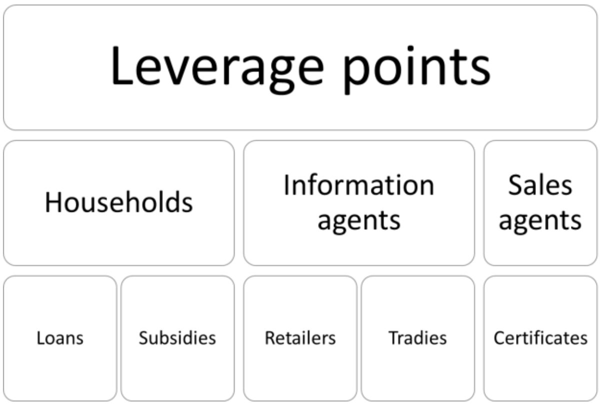

Figure 7: Classification of leverage points

Activating sales agents

The Energy Savings Scheme[2] adopted by the New South Wales state government in Australia, by which so-called aggregators apply for energy savings certificates achieved by installing, improving or replacing energy savings equipment.

The aggregators may pass on none, some or all of this money to the household or business implementing the action. A lever to increase adoption is the price of the energy savings certificates.

So if an action to improve energy efficiency in a household is estimated to save a certain amount of energy, this translates to a number of certificates and an amount of money, depending on the current price of the certificates.

Key methods to intervene, to increase the effectiveness of the scheme, include:

- Increase the price of the Energy Savings Certificates.
- Reduce the perceived hassle associated with being part of the scheme.
- Provide additional incentives for sales agent (i.e. aggregators) to engage in sales activities.

Providing a subsidy

Providing a subsidy to households when they purchase an energy efficient product is one of the simplest approaches, yet often argued to be costly. The subsidy would be universally available to all energy efficient products. The main setting of the subsidy is:

- The percentage discount provided to households.
- The choice of which products that qualify for the discount.

Working with retailers and plumbers

Retailers and tradespeople have the enviable role of communicating with households at the time of purchase, i.e. when they are making a decision. We know from the behavioural science of course that this is important.

There are programs, such as by NSW OEH, with training provided to retailers to ensure that the right information is given to customers at the time of purchase and to make sure both retailers and customers have access to and are aware of energy efficient options and their benefits.

A special case involves the solar hot water systems. As the main decision point at which households will choose to purchase a solar hot water system is when the old one breaks down, with significant urgency for getting a new system.

Thus having plumbers ready to provide adequate information and services to support an upgrade to a solar hot water system is very important and potentially a very effective strategy for promoting energy efficiency.

The main lever here is:

- Incentivising and helping retailers to suggest and support the purchase of energy-efficient products.
- Incentivising and helping tradespeople to suggest and support the purchase of energy-efficient products.

Cheap loans to vulnerable households

Financially vulnerable households, i.e. those with debt and/or low incomes, are often in a position where they can’t afford energy efficient products. They are also households which would benefit from reductions in ongoing cost and overall being cost effective. In those cases, the upfront cost may be a significant hurdle that can be overcome by providing targeted cheap loans, for the purchase of energy-efficient products.

[2] http://www.ess.nsw.gov.au/Home

Case study: Solar Hot Water Systems

Solar hot water systems are known to provide significant reductions in greenhouse house emissions due to reduced energy requirements.

Solar hot water systems operate by pumping a liquid, such as water, through a sun-facing heat collector. This collects heat which can be used to heat up water. This helps provide a household with a good source of hot water, as it has been estimated in the context of Australia to provide a 60% reduction in energy use related to heating water (Moore, Urmee et al. 2017). Heating water represents on average of 21% of household energy use in Australia (NSW Government 2016).

Adoption of solar hot water systems could reduce average household energy use by nearly 13%, or about 746 kWh per year, which at an electricity price of 28 cents per kWh would equate to a household monetary saving of nearly $210 per annum. The upfront purchase price of a solar hot water system, according to www.choice.com.au, is in the range of $3,000 to $7,000. An instant electric hot water system, on the other hand, has a price in the range of $600 - $1,300. The estimated average life of a water heater is in the range of 8 – 12 years. With these numbers, the per annum cost of hot water is still higher for solar hot water systems at an average of $660 per annum, compared to an average $447 per annum for an electric instant hot water system (both numbers exclude estimates for maintenance costs). However, at the cheaper end of the price ranges solar hot water systems have a lower per annum cost whilst at the top end of the price ranges, electric instant systems have a lower per annum cost. This raises a couple of points:

- People tend to put greater emphasis on upfront cost rather than the long run expected cost.
- The return on investments calculations are relatively finely balanced between the two types of systems and can, therefore, be swayed towards solar hot water systems, with a relatively minor 'nudge'.

Parameterisation

To set up a set of interventions to explore how to increase the adoption rate of solar hot water systems, we parameterise the model, which is shown in the supplementary material A. This shows the technology performance attributes, general model settings, information agent parameters, and household input file.

Baseline

Running the model multiple times with a baseline scenario, i.e. with no intervention, helps to explore whether the model provides repeatable results. With a range of stochastic aspects of the model, it would be plausible that different simulation runs would provide significantly different results but this does not seem to be the case.

The result of 20 simulation runs times four different types of social network, is shown in Figure 8 which shows only limited variability between runs. There are some systematic differences depending on the underlying social network structure however with slightly higher rates of adoption in the scale-free social networks.

Other observations from the simulations, i.e. the sales agent never gets activated in this baseline scenario because the return on investment never gets above the critical threshold as the certificate price is $0 so the sales agent struggles to generate profit. Furthermore, the adoption rate curve seems to follow what will have to be assumed the 'middle part' of an S-curve (standard in innovation diffusion), which is consistent with starting at a starting adoption rate of 21% and not reaching a plateau during the simulation time frame.

It is unfortunate that there is no accessible longitudinal data on uptake of solar hot water systems available in Australia in order to validate the model against. In terms of validation, only limited comparison with historical data is possible but a paper by Ferrari et al (2012) with data on sales of solar hot water systems shows that the 35% of hot water systems sold in 2010 in New South Wales were solar hot water systems. This is consistent with the linear trend in the sales rate (i.e. the percentage of new products being solar hot water systems) extracted from the model when the trend in the sales rate is extended back in time (see Figure 9). This is promising, considering none of the parameters in the model was calibrated to fit with historical data.

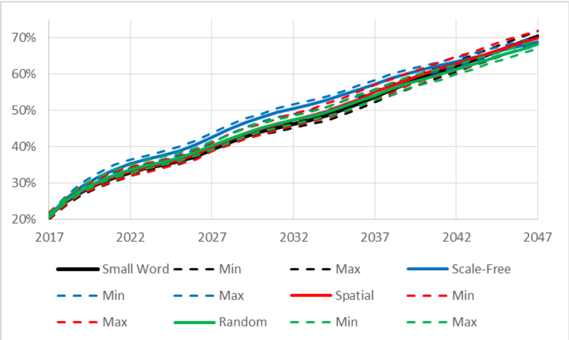

Figure 8: Average, minimum and maximum adoption rates from 20 simulation runs for each social network setting, with the baseline case of no interventions in the case of using a Small-world, Scale-free, Spatial and Random social network. X-axis: years. Y-axis: Adoption rates of solar hot water systems, as a proportion of all hot water systems.

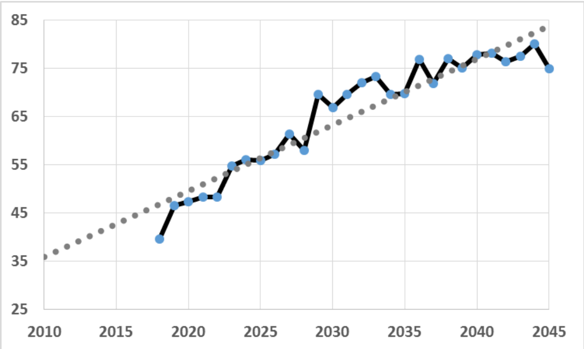

Figure 9: Sales rate (proportion of all sales being solar hot water) as a function of time. X-axis: years; and Y-axis: the proportion of hot water systems being solar hot water systems. A trend line has also been added to illustrate projected sales rates, going backwards in time.

Evaluating interventions

The types of interventions that the model could explore are shown in the previous section. Specifically, to illustrate the use of the model, here we describe a couple of interventions to promote the adoption of hot water systems, including the:

- Energy Savings Scheme[3]. We explore three settings for energy savings certificates, i.e. $0, $20, and $30.
- Influencing plumbers to recommend solar hot water systems. This may occur through training, information or possibly even a commission for sold systems if considered appropriate.
- Providing a 20% subsidy to households.

The results of these simulations explored with the model are shown in Figure 10. It is clear that here, the monetary incentive through the Energy Savings Scheme is less efficient in terms of increasing adoption rates when compared to the option of promoting the recommendations of plumbers, and also less effective than providing a 20% subsidy.

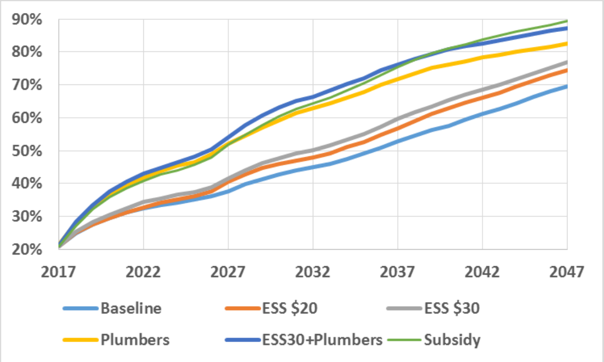

Figure 10: Exploring the result of a set of possible interventions. X-axis: years. Y-axis: Adoption rates of solar hot water systems, as a proportion of all hot water systems.

Table 13: Summary of scenario results

	CO2-e red. per hh [a]	Cost per hh per year (C)	Adop. rate 2047 (%)	Extra reduction (Δ) [b]
Baseline	3.81	$0	68.6	-
ESS - $20	4.39	$19	75.5	0.58
ESS - $30	4.54	$29	76.5	0.73
Influencing plumbers	5.93	Unavailable	81.5	2.12
20 % subsidy	6.32	$17	88.9	2.51

Notes. [a]: the unit is tonnes of CO2-e over a 30 year time period. [b] Calculated as the reduction per household above the baseline scenario.

It is noted that the model does not necessarily specify the amount of money spent by the government on these schemes. It can do so when associated with subsidies or certificates, but any additional information on the cost of schemes (such as if influencing information providers) will have to provide by users.

[3] http://www.ess.nsw.gov.au/Home

Reflections

The scenario analysis clearly demonstrates that running model simulations with different scenarios provide insights beyond what is accessible to human cognition. The model is able to explore wherein a complex supply chain it is most cost-effective to incentivise decision making in order to promote adoption of energy-efficient products. Furthermore, the model is able to explore less tangible issues like common human biases in decision making, such as status quo bias, and the catalysing impact of making adoption easier and less of a hassle.

In terms of the specific results from the scenario analysis, we have shown that for solar hot water systems, and with this type of population (as represented in the survey), it is more cost effective to provide a subsidy to households rather than to incentivise sales agents via energy savings certificates. This is despite the fact that sales agents generate decision points that otherwise would not occur. This is somewhat counter-intuitive because otherwise subsidies only get activated when a product reaches the end of its life. Thus without marketing activities from sales agents, the maximum rate of the upgrade is dependent on the ageing of products and is inevitably limited.

To validate this finding, regarding the effectiveness of providing a subsidy to households vs. incentivising sales agents, it will be necessary to collect better data on the model parameter, the 'discount-effect', which relates to the behavioural biases of mental accounting (Thaler 2008).

Nonetheless, scenario analysis has also shown that it is an effective to promote plumbers to recommend solar hot water systems, and whilst the cost effectiveness hasn't been evaluated costs are likely to be competitive. This shows the importance of providing the right information at the right time to households. In the case of solar hot water systems, plumbers are at this point in the decision-making process.

The model explorations also show that when modelling adoption processes, it is critical to understand the mechanics of the process as it were, which can vary significantly depending on the type of intervention. Embedding insights from behavioural science allow for fine-tuning some key parameters in the delivery of interventions.

Regarding the viability of the modelling approach for policy analysis, we believe it has considerable potential to support plans to increase resource efficiency in society. The approach is adaptable to many types of situations but will require some effort to update the models.

To adapt the model to new types of products and interventions, the primary task is to collect the appropriate data, including surveys of households and other key actors. Actors that need to be surveyed are sales agents, information agents and supply chain actors. The coding of the model is relatively straightforward, yet requires familiarity with the model itself, as well as some training in Agent-Based Modelling.

The modelling capability described in this paper has here been applied to residential energy efficiency but adjustments of the model are being built to allow the analysis of interventions to increase household water conservation as well as shifting suburban commuter travel modes to low carbon alternatives.

Ongoing activities: where to next?

This project has explored, from a technical perspective, the approach for using ABM to explore the adoption processes of energy efficiency products. This has been shown to be a useful approach, however, there are remaining questions to be answered:

- How can this approach be embedded in practice into ex-ante intervention analysis by policymakers?
- How can this approach be viably supported through an integrated framework that involves data collection, stakeholder engagement and regulation?
- How can this approach be financially viable for those who provide the technical assistance to support it?

Furthermore, there are other areas which can benefit from the use of similar tools, such as for example exploration of interventions to:

- Increase water conservation behaviours in the community.
- Increase the energy efficiency of the commercial building stock.
- Increase the adoption of low carbon transport modes amongst urban commuters.
- Increase community engagement in the circular economy.
- Increase the adoption of green infrastructure.

Related projects

These topics are explored in related projects with the Low Carbon Living CRC, i.e. RP2021 (Greening Suburban Transport), RP3002 (A Framework for Low Carbon Living Community Policy & Program Development), RP3035 (Modelling the Uptake of Water Conservation and Efficiency Measures in Sydney), and SP0018 (Framework for Utilisation of Integrated Adoption Diffusion Modelling).

The last of these projects, i.e. SP0018, specifically explores the questions of how these tools can be used to increase their impact and to provide a financially viable business model to allow for their maintenance.

Conclusions

This project has shown that there is considerable potential in using ABM to explore the complex ecosystem of agents which contribute to the increased adoption of energy-efficient products.

We argue that ABM is particularly useful for ex-ante type analysis, because of its ability to embed from-the-ground-up understanding of processes and actor decision making profiles, rather than to rely on macro-level aggregate data for calibration of model parameters. We have also shown how such a model can be empirically parameterised using surveys. Further work is required, however, to provide a firm empirical basis for all the parameters in the model. Work is currently underway to achieve this.

The ABM also supports a considerable ***capacity for users to relatively easily explore the model results' sensitivity to parameters***. ***In other words, it is not a black box***. This is important, both for supporting users of modelling tools to develop an understanding of cause and effect relationships within complex processes, as well as to explore under what circumstances interventions work, and when they don't work.

The ABM has also ***confirmed its capacity to embed insights from behavioural science***, but this was no surprise as this fact is already well-established based on an extensive body of research.

In terms of providing specific guidance beyond what is previously available, ***the tool allows the capacity to evaluate which type of actors to incentivise in order to get the greatest impact on adoption rates***.

For example, through the case study on solar hot water systems, we explored whether it is more effective to incentivise householders, sales agents or plumbers.

We found that it is more effective to engage plumbers due to their potential to provide information at the right time when households make decisions. We also found that it is more effective to incentivise households rather than sales agents.

We believe that the tool we have developed is highly novel in comparison to existing tools on the market, and will provide policymakers with another important tool in the toolbox.

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