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Spatial Diffusion of Air Conditioners and Time-Varying Price Tariffs in Residential Housing

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Abstract: In order to plan for the major changes to extra loads and storages on an electricity distribution system with temporally and spatially variable capacity, it is critical to be able to project the magnitude, rate, and location of technology/appliance uptake by consumers at a fine spatial scale. This paper presents an application of a methodology, based on diffusion modelling, for estimating the uptake of air conditioners and time-varying price tariffs from 2013 to 2033, with the case study of housing stock in Townsville Local Government Area (LGA). It integrates technologies in multi-criteria analysis and choice modelling, to better capture the sensitivity of different types of air conditioner and price tariff uptake across a landscape of heterogeneous consumers. Several variables were included in the modelling to characterise consumer preference of different air conditioners and tariffs: upfront cost (purchase price), annual cost (maintenance and running costs), household income, house age, visual appeal, convenience, comfort, familiarity and socio-economic rating. The model makes possible a highly granular geographical and demographic analysis, allowing uptake trends to be assessed for each ABS Statistical Area Level 1 (SA1) spatial unit of approximately 150 households, which Townsville LGA contains 431 residential SA1s. This provides a better understanding of the changes in peak demand across Ergon Energy electricity grid at scale of individual feeder. We show the base case along with sensitivity uptake to various electricity price scenarios.

To set up the diffusion model, ABS 2011 census data was used to formulate a typology of location (SA1) by building type by demographic variables. For the application to air conditioners, the following options were considered, no air conditioner, ducted, 1 split system, 2 split system, 3 split system, 1 box air conditioner, 2 box, 3 box. Townsville is currently a saturated market with 76% of households having three or more air-conditioners (Queensland Household Energy Survey 2011). For the base case scenario there was a significant shift from box air conditioners to split systems and ducted systems from 2013 to 2033. The main changes were about a 53% drop in houses with 3 box air conditioners, with these households mostly moving to either 2 split systems or ducted. When testing the sensitivity of various electricity price scenarios, it had minimal impact on market share of each air conditioner option at 2033, though the high electricity price scenario led to a modest reduction in ducted air conditioners.

For the application to time varying price tariffs, uptake of Tariff 33 increased to 81.7% by the end of 2033, up from 75% in 2013. The uptake of Tariff 12 and Tariff 33+12 was 0.64% and 2.19% respectively at 2033. Low uptake of the Tariff 12 scenarios was not surprising due to their minimal reduction in costs for detached housing and an increased annual electricity cost for semi-detached and apartment dwellings. When testing a scenario where the daily service fee for Tariff 12 was reduced to that of Tariff 11, this reduced the annual costs by $230/yr, and led to the uptake of Tariff 12 and Tariff 12+33 increasing to 0.82% and 2.81% respectively.

Keywords: *Choice Modelling, Multi Criteria Analysis*

1. INTRODUCTION

Wise investment in distribution infrastructure to meet future peak demand in electricity use requires foresight on which substations and feeders will reach critical thresholds and by when. Peak demand increases with geographically expanding and higher density residential housing, along with changes to electricity usage within households. Adoption of new or more efficient appliances, and their time of day usage, has a significant impact on future peak demand (Richardson et al., 2010). To forecast the stock of different types of appliances/technologies at key future dates, Higgins et al (2012 and 2013) developed an integrated modelling methodology for high resolution spatial and temporal projection of uptake, and the subsequent electrical grid impacts from these technologies. To date we have applied this model to forecast the uptake of solar PVs and electric vehicle in partnership with state governments and local energy distributors. Application to air-conditioners is more complicated than solar PVs (Higgins et al., 2013) since: dwellings usually have multiple air-conditioners and a mixture of different types; and adoption of air-conditioners is less driven by financial goals.

The diffusion model combines features of choice modelling, multi-criteria analysis and dynamic systems. Full mathematical detail of the model is contained in Higgins et al (2012). The primary goal of a diffusion model is to forecast the stock of air-conditioners or uptake of different tariffs across dwellings at incremental time intervals (e.g. 3-monthly) through to a target date. The multi-criteria analysis features accommodate the different variables that influence whether a household in a given location will choose a particular technology or tariff option at each time interval. It provides a capability to analyse adoption patterns of the competing options under a range of features that a buyer would consider for a purchase. A flow chart of the diffusion model is contained in Figure 1. The model is dynamic in that it updates the eligible purchasers and choice amongst possible options at each time interval. The number of households eligible to change tariff or purchase or replace an air-conditioner in a given time period, is a statistical function of lifespan of the technology (that they already have) and other variables that may determine whether the consumer purchase(s) sooner. For example, a high income household may replace their air-conditioner sooner than a lower income household. Once the number of households eligible to purchase in a given time period is determined, the next "closely linked" decision is what choice do they make amongst the competing options. This is where the choice modelling component comes in. The probability of choosing an option (e.g. single split system, 2 split systems, one box air conditioner) is a weighted logistic function of the range of variables that a consumer would consider when making a choice. Once the probability of choosing each option is calculated, the model (bottom of Figure 1) updates the stock of each option in the current time interval and then proceeds to the next.

A novelty in this methodology is the probability of product replacement being a function of product failure, as well as a utility sub-function of other drivers of replacement. In the case of tariffs product replacement is the average time to the decision to make a change. When implemented, it accommodates the socio-demographic differences of consumers who are early versus late replacers of the technology, as well as the effects of incentives to reduce the time to replacement. Another feature of this methodology is the improved ability to accommodate the evolution of variables for adoption over the forecasting horizon.

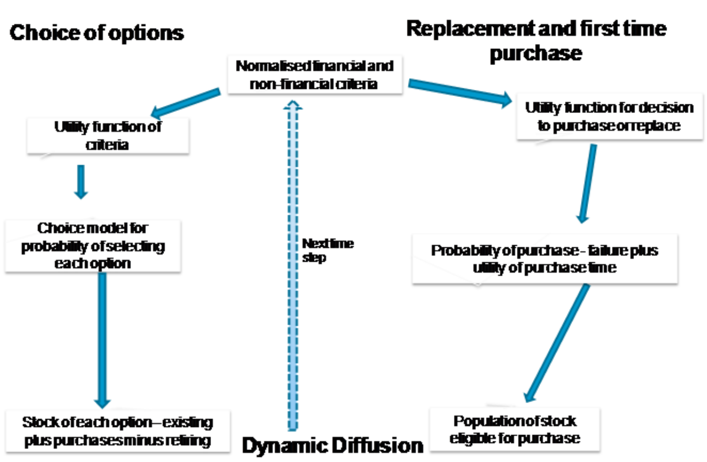

Figure 1. Outline of diffusion model

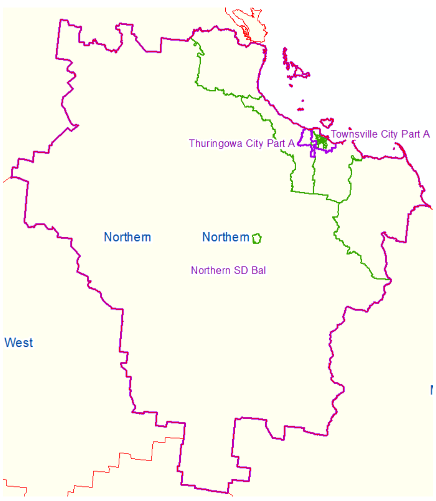

Figure 2. Townsville LGA

Residential housing stock in Townsville was used for the applications in this paper. Townsville LGA, took its present form in 2007 through the amalgamation of the cities of Townsville and Thuringowa, and covers a metropolitan region encompassing a broad range of urban, suburban and semi-rural localities. It has an area of 3,738 km^2 and a population of 185,786 (ABS, 2010). The geographical area for this project comprises Statistical Subdivision (SSD) 34505 Townsville City Part A and 34510 Thuringowa City Part A (Figure 2). These make up the current Townsville LGA, and contain a total of 431 ABS Statistical Area Level 1 (SA1s) with residential housing, based on the 2011 census.

2. APPLICATION TO AIR CONDITIONERS

The variables used in the diffusion model are contained in Table 1. These represent key drivers that consumers would consider for a purchase and installation. Table 2 and 3 contains upfront and annual operating costs for each option, where on average air conditioning accounts for 28.3% of residential electricity consumption in Townsville (Ren et al., 2013). Annual cost is based on all day use of the air-conditioner at a temperature setting of 27 degrees Cesium. Energy consumption was calculated using the AusZEH design tool (Ren et al., 2013; Ren et al., 2012) and converted to cost assuming \$0.25378/kWh. The tool is a physics-based, bottom -up model, which is designed to predict annual electricity consumption with hourly solution by integrating building envelop, equipment and appliances, and human behaviour together for specific year or future using local Typical Meteorological Year (TMY) weather data. The thermal performance (i.e., COP - Coefficient of Performance) of air conditioners is defined by the users, which can be used to evaluate the air conditioning performance in the past, current and future for this project.

Eight options are considered, with a description of any restrictions:

1) No air conditioner
2) Ducted. For Townsville this is assumed to not occur in dwellings before 1992 due to low structural efficiency of installing such an air conditioner.
3) One split system. Assumed to be in the main living area
4) Two split systems. Assumed to be in the main living area and master bedroom
5) Three split systems. Assumed to be in the main living area, master bedroom and second bedroom
6) One box system. Assumed to be in the main living area. Assumed dwellings in post 2006 will not install box air conditioners due to their lack of visual appeal on newer buildings.
7) Two box systems. Assumed to be in the main living area and master bedroom
8) Three box systems. Assumed to be in the main living area, master bedroom and second bedroom

In practice, dwellings often have a mix of split and box systems. These combinations were not considered due to the large number of additional options created and the lack of accurate data for number of dwellings currently containing each option. Portable air conditioners and evaporative coolers were not considered in this analysis.

Table 1. Description of variables used in diffusion model for air conditioners

Model Variable	Description
Familiarity	This parameter accounts for the effects of experience of the air conditioner option. That is, the more houses that have similar types of air conditioners the greater the appeal.
Advantage/ Disadvantage	This is an ABS socio-economic indicator of households within the ABS SA1. It is a value of between 400 and 1200, with a higher value representing a higher socio-economic location
Upfront cost	This is an estimate of the manufacturer's suggested retail price (MSRP) plus the installation cost for 2013.
Annual cost	This represents the annual running costs of the air conditioner option in the dwelling (at 2013), which was simulated using the AusDesign tool (Ren et al, 2013). It is assumed to increase by 3.5% per year in accordance to long term electricity projections.
Household income	The net household income, obtained from ABS data.
Appeal	This represents the visual and noise appeal, and it depends on the age of the dwelling. In Townsville a box air conditioner in a new dwelling would be much less appealing than a split or ducted system.
Comfort	Comfort factor from having the air conditioner option. For example, a ducted air conditioner or three split systems will have a greater level of comfort than a single box air condition in the main living area.

Table 2. Upfront cost ($) for each option

	Option							
Dwelling size	**No air**	**Ducted**	**1 split**	**2 split**	**3 split**	**1 box**	**2 box**	**3 box**
1-2 beds	0	6000	2500	4100	5700	1100	1900	2700
3+ beds	0	10000	2500	4100	5700	1100	1900	2700

Table 3. Annual operating costs assuming 2013 Queensland Tariff 11 of $0.25/kWh and full day usage

		Option							
Dwelling structure	**Age**	**No air**	**Ducted**	**1 split**	**2 split**	**3 split**	**1 box**	**2 box**	**3 box**
Detached	Pre1992	0	1300	502	545	595	570	620	676
Detached	1992-2006	0	1234	549	647	682	591	697	735
Detached	Post2006	0	815	350	433	469	362	447	485
Semi-Detached	Pre1992	0	1300	442	472	524	502	536	595
Semi-Detached	1992-2006	0	740	482	600	661	519	647	712
Semi-Detached	Post2006	0	515	406	428	456	420	443	471
Unit	Pre1992	0	1300	444	496	532	505	564	604
Unit	1992-2006	0	492	349	390	426	376	420	458
Unit	Post2006	0	525	340	370	398	352	383	412

For the diffusion model application to air conditioners, the adopters are households. The key assumptions with respect to adoption are as follows.

(1) A household may only acquire up to 3 air conditioners, but it depends on what they currently have. A house with ducted air conditioning cannot move to the split or box air conditioner options.

(2) The lower appeal of ducted air conditioners on older houses (pre 1992) is aimed to discourage them being installed on such houses. In Townsville they tend to be unsuited to ducted air conditioning due to lack of insulation.

(3) For households installing an additional air conditioner, the upfront cost difference between the options is applied. There is an exception when moving between box and split systems.

(4) A household can reduce the number of air conditioners at no upfront cost.

(5) An average lifespan of 10 years is applied. If replacing an air conditioner with the same type, it is assumed the air conditioner is repaired or re-conditioned at (between 25% and 75%) of the upfront cost.

A major step to setting up the diffusion model was to construct a typology to represent all possible location by demographic categories. To do this, information representing the 2011 census from the Australian Bureau of Statistics (ABS) was available at a granular spatial scale, called Statistical Area Level 1 (SA1) where each SA1 represents about 150 households. Each location was partitioned in accordance with a set of variables that are assumed to influence households' choice of air conditioner adoption: Dwelling structure, home ownership, household income, dwelling age and number of bedrooms. For each combination, the number of households was extracted using the ABS TableBuilder on-line tool. To avoid having an extremely large number of categories and to avoid privacy issues arising from small samples at the ABS data, the following categories were used:

Housing type: Detached house; Semi-detached, Apartment (including low and high rise)

House age : <1992, 1992-2006, >2006. For each SA1, a proportion of housing stock for each age category was estimated using Google Maps

Ownership: Owned (including mortgaged); Rented

Household income: $0-$40,000/yr; $40,000-$100,000/yr; >$100,000/yr

Bedrooms: 1-2 bedrooms; 3+ bedrooms

Ideally, we would prefer additional variables such as construction type and floor area, though these were not available. Also, more variable categories would have provided greater precision. However, this would create too many categories with less than three households, at which ABS Tablebuilder automatically aggregates to other categories to maintain privacy.

A set of discrete time intervals was used, which are 3-monthly from 2012 to 2032, though the time frame can be extended. The model was calibrated using an estimated number of installations at 2011 from the Queensland Household Energy Survey. The model weights for each variable in Table 1 were adjusted until the best correlation between forecast and actual was achieved. That is when forecasting from 2005, the goal was to get as close as possible fit between the actual and model in 2011.

A base case scenario was firstly produced (Figure 3), which represents the uptake projections with baseline forecasts of electricity price. For this analysis, the number of dwellings is assumed unchanged from 2012 to 2032. Figure 3 shows a progressive move away from box air conditioners to split systems and ducted air conditioners. The number of households with no air conditioner dropped from 3.5% in 2012 to 0.7% in 2032. An interesting observation is a significant increase in dwellings with 2 split systems, which is primarily from households shifting from the 3 box air conditioner option. Figure 4 shows that by 2032, the high percentage of dwellings with the 3 Box air conditioner option will be more restricted to the inland and older areas of Townsville whilst the ducted option will be more towards newer and more expensive locations.

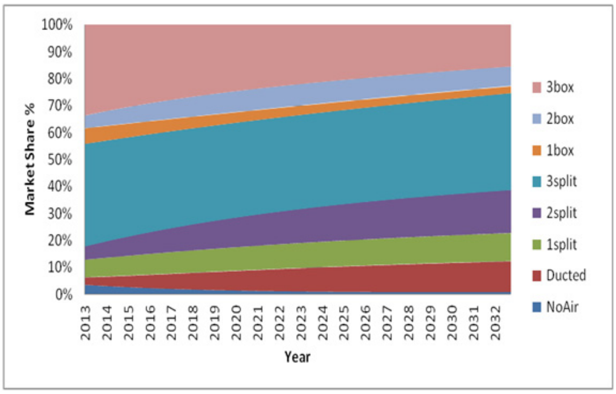

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Figure 3. Baseline uptake of each air conditioner option

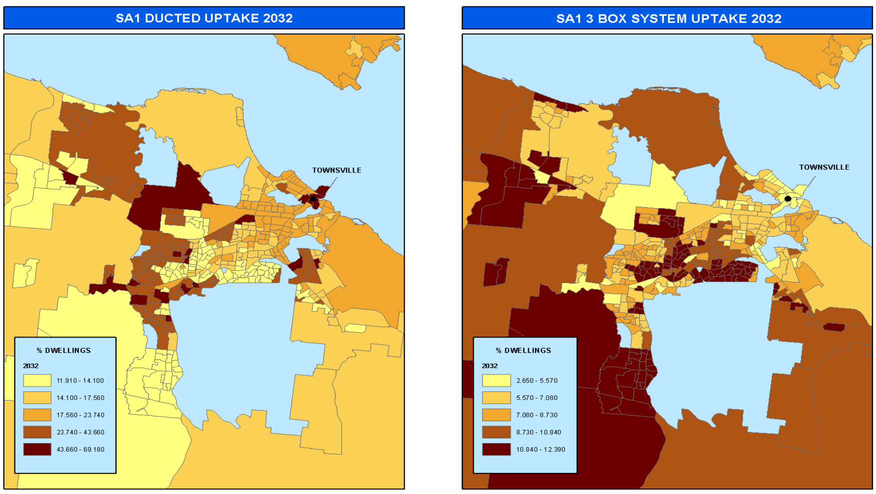

Figure 4. Uptake of the ducted (left) and 3-Box (right) options (%)

3. APPLICATION TO TIME VARYING PRICE TARIFFS

Variables used in the diffusion model for the price tariff study were similar to that of air conditioners, except appeal, comfort and household income were replaced with convenience and house age. Three house age categories were considered: <1992, 1996-2006, >2006, and an estimate was made of proportion of each SA1 in Townsville containing each category. Four options are considered, which are based on 2013 electricity pricing tariffs for Queensland households:

1) Tariff 11 - \$0.25378 per kWh + \$0.28787 per day service fee
2) Tariff 33 - \$0.17155 per kWh for applicable permanently connected appliances
3) Tariff 12 - \$0.18846 per kWh off peak, \$0.23575 per kWh for shoulder, \$0.38415 per kWh for peak, +\$0.86436 per day service fee
4) Tariff 33 + Tariff 12

Table 4 contains annual costs for each option. Annual costs were assumed to increase 3.5% each year in accordance to 2013-2032 electricity price projections. Electricity consumption was calculated using the AusZEH design tool (Ren et al., 2012; Ren et al., 2011) and converted to cost assuming price tariffs and service fees of each tariff option. Detached housing with pools was distinguished with those without pools, due to the cost of running the pump. We assumed 25% of households in Townsville had a pool (Queensland Household Energy Survey 2011).

Table 4. Annual costs (\$/yr based on 2013) including service fee

	Tariff 11	**Tariff 12**	**Tariff 33**	**Tariff 12+33**
Detached 2 person	3291	3125	1818	2732
Detached 4 person	3816	3727	2261	3272
Semidetached 2 person	2155	2514	1735	2333
Semidetached 4 person	2777	3143	2276	2901
Flat 2 person	1908	2264	1575	2070
Flat 4 person	2607	2965	2178	2679
Detached 2 person no pool	2736	2547	1677	2154
Detached 4 person no pool	3261	3149	2120	2694

In April 2013, 75% of households in Townsville had Tariff 33, and 25% had Tariff 11 alone (data supplied by Ergon Energy). There were no households with the Tariff 12 options. Calibration was difficult since past data (e.g. 2009) on households with Tariff 33 were not available. Also, there were no households with Tariff 12. The model weights for each variable were set at values that best represented the relative priority: Familiarity 0.5; ABS advantage/disadvantage 0.25; annual cost 2.2; convenience 1.0; house age 0.5.

For the base scenario Figure 5 shows the uptake projections through to the end of 2032, where Tariff 11 reduces to 15.4%. The uptake of Tariff 12 and Tariff 33+12 was 0.64% and 2.19% respectively. There was a much larger adoption of Tariff 33 for households with pools (89%) versus without pools (79%) at 2032. Uptake of Tariff 12 was slightly higher in households without pools (0.7%). Low uptake of the Tariff 12 scenarios was not surprising due to their minimal reduction in costs for detached housing (Table 4) and an increased annual electricity cost for semi-detached and apartment dwellings. We tested a scenario where the daily service fee for Tariff 12 was reduced to that of Tariff 11. This reduced the annual costs by \$230/yr, and led to the uptake of Tariff 12 and Tariff 12+33 increasing to 0.82% and 2.81% respectively. It is only a small increase due to the favourable cost savings offered by Tariff 33.

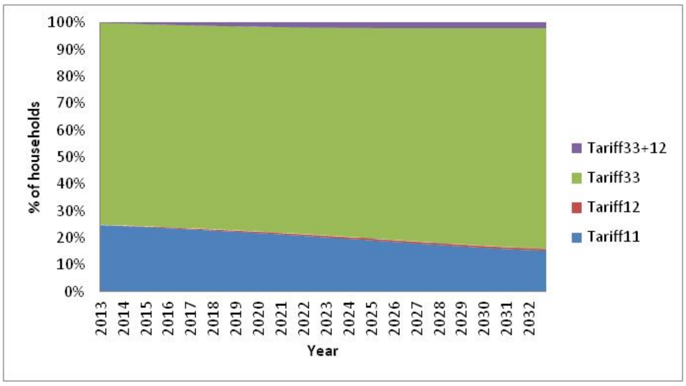

Figure 5. Percentage of households with each tariff

4. CONCLUSIONS AND FURTHER RESEARCH

In this paper we implemented an innovative diffusion model, linking features of multi-criteria analysis and choice modelling, and applied it to estimate the market share of different air conditioner and price tariff options, across a landscape of heterogeneous households. A characteristic of the model was its capacity for a highly granular geographical by demographic analysis, allowing adoption rates of technologies to be assessed at a sub-precinct level. This approach provides an essential capability for energy providers to better understand future capacity constraints across their electricity grid as adoption of technologies increase at different locations. The analysis can be improved with additional information on existing appliances within the building stock at different locations (e.g. the type of hot water system, air conditioners used in each room). An ability to better capture non-financial motivations to adoption, beyond the current demographic variables, would improve uptake projections. This includes circumstances such as: purchasing a low efficiency air conditioner with the same type in an emergency replacement; and increased likelihood of adopting other energy efficiency technologies (e.g. 5 star shower heads, more efficient lighting) to take better advantage of the time of use tariff.

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