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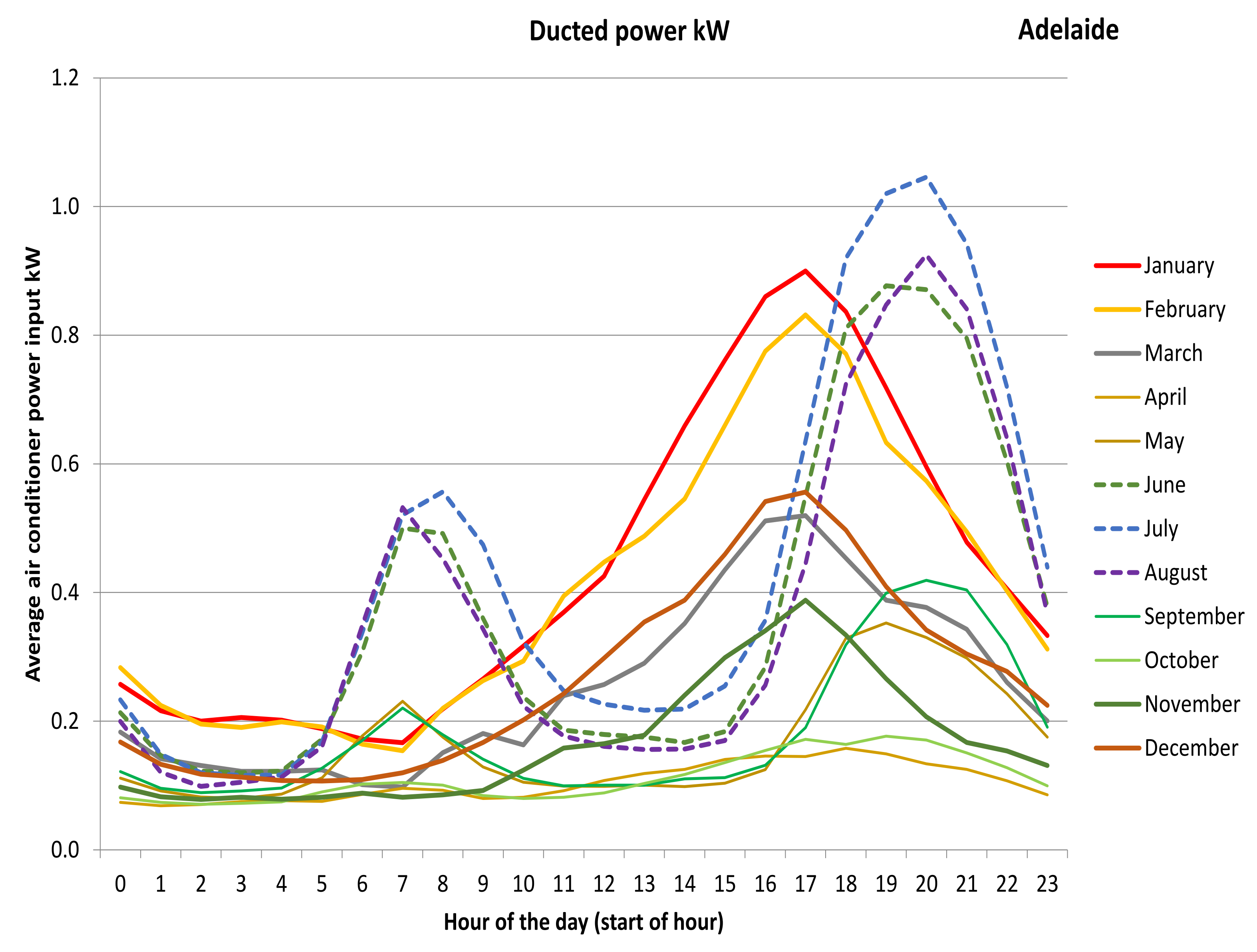
Final Report

Prepared for:

AEMO

Single Phase Induction Motor Loads on the NEM from Refrigeration and Air Conditioners



Prepared by Energy Efficient Strategies

Single Phase Induction Motor Loads on the NEM

Report prepared for:
Australian Energy Market Operator

Report Authors:
Dr Lloyd Harrington, Energy Efficient Strategies
Robert Foster, Energy Efficient Strategies

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Energy Efficient Strategies,
PO Box 515, Warragul VIC 3820
Telephone: +61 (03) 5626 6333
www.energyefficient.com.au

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Executive Summary

Project background

AEMO is seeking information on the typical load type by region in order to model the behaviour of the grid during power system disturbances. The main focus of this study is to quantify typical loads from the so called “Motor D” category, which is made up of single-phase induction motors, primarily used in air conditioners and small refrigeration systems. Quantification of so called “Electronic Loads”, which are made up of power electronic (inverter-based or electronically coupled) motor driven load components, was also requested.

This report provides estimates of specified loads on the National Electricity Market (NEM) interconnected grid system split into NEM sub-regions as defined by AEMO. The main objective of the report is to estimate the load on the NEM interconnected system for different times of the year that is generated by Motor D systems. Three phase motor loads are specifically excluded. The end uses that are specifically investigated and documented include single phase air conditioners of all types, household refrigeration systems (virtually all are single phase) and single phase commercial refrigeration systems (including refrigerated display cabinets and professional storage systems).

AEMO provided 30 min operational load data for each of the nominated sub-regions from 1 July 2012 to 30 June 2019. As instructed by AEMO, the operational demand was converted to underlying demand (intended to represent customer demand) by subtracting transmission and distribution losses and then adding estimated photovoltaic generation.

Single phase induction motors vs inverters

When a single phase induction motor is stationary when it starts, or if it stalls in response to low voltage, the “locked-rotor” current generated is many times greater than the normal operating current (typically 3 to 7 times more). If the rotor is free and connected to a load of low inertia, this locked-rotor current flows for a very short time. If the rotor is ‘locked’, then the locked rotor current will flow indefinitely, but with magnitude gradually falling due to the rise in stator winding resistance due to increasing temperature. Thermal safety protection to protect the motor is usually embedded into the windings (usually in the form of a simple bi-metal strip) and this pulls the motor electrically off-line after a short period under locked-rotor conditions. In order to more accurately quantify the behaviour of stalled motors and thermal overload protection, measurements were conducted by EES on over 40 household and commercial refrigeration products. The results of these measurements are summarised in this report, with details contained in a separate report and series of associated spreadsheets.

Inverter systems appear to be much more resilient to low voltage conditions. Based on test data, inverter controls in refrigerators tested appear to operate without issue down to a supply voltage of around 50V AC without any obvious issues. None of the inverters measured showed any periods of high load or thermal overload currents that are present in single phase induction motors when they stall. Many (but not all) digital controllers, commonly used on newer commercial refrigeration units, have sensors and smart controls to sense low voltage and pull the compressor off-line before it stalls under low voltage conditions. Single phase inverter driven compressor are not used to any extent in commercial refrigeration systems at this stage. But many of the more sophisticated controllers will pull the motor off-line before it stalls on low voltage, thus avoiding thermal overload.

Air conditioners

The residential sector accounts for the vast majority of single phase air conditioners installed in Australia. However, a significant minority are installed in small and medium-sized offices. Detailed analysis estimated the stock in each of the NEM sub-regions over the period from 2012 to 2020. This showed that over 95% of new ducted and split system air conditioners are inverter driven in

Australia, with the remainder driven by Motor D. Window wall systems virtually all use Motor D driven compressors and these make up a very small and declining market share over time.

Air conditioners presented a significant challenge for this project. In the residential sector, the usage and average power profiles are strongly driven by weather, most notably dry bulb temperature. The relationship between air conditioner demand and weather itself is quite complicated, as demand for air conditioning can increase over subsequent days during a heat wave event, even where the peak temperature may remain at similar levels from day to day as buildings gradually heat up. Warm overnight temperatures can also exacerbate air conditioning demand on the subsequent day. Good data on load profiles in the residential sector has been obtained from monitoring data from CSIRO and their contribution of this data is gratefully acknowledged. A novel bottom-up model to predict average air conditioner demand by time-of-day and month by NEM sub-region was developed for this project. Different approaches, based on analysis of end use measurement data, were used to generate weather corrections for air conditioner loads. For household systems, this was driven primarily from the additional system load, over and above a reference minimum base load in each NEM sub-region, while for commercial systems, a weather adjustment was developed based on the ratio of actual hourly system load over the average reference load for the NEM sub-region. This approach allowed hourly data to be generated for all of the main air conditioner types across the whole period of interest from July 2012 to June 2019.

Household refrigerators and freezers

Household refrigerators and freezers have been an essential household appliance since they became readily available and affordable from the 1950s. There has since been very good data collected by the Australian Bureau of Statistics (ABS) from a range of surveys on the stock of household refrigerators and, providing an accurate assessment of the total stock now and into the near future. Currently over 99% of households have at least one refrigerator. The average ownership increased gradually to a peak of about 1.35 refrigerators per house in 2010 and is now falling very slowly. This is due to larger refrigerators and declining household sizes. In contrast, freezer penetration peaked at about 50% of households in the mid-1980s. Since 1990, freezer penetration and ownership has been slowly declining.

It is well documented that the energy consumption of refrigerators and freezers is driven by a range of factors, but primarily by the room temperature in which the appliance operates. Given that the NEM sub-regions vary from tropical in the north to cool temperate in the south, it was important that the energy model for household refrigeration takes into account the indoor ambient temperature. A model of average indoor ambient temperatures in homes for each of the NEM sub-regions was adapted from previous work. This was based on the indoor temperature in Australian homes using data from 300 sites from Melbourne to Cairns and corroborated with data from 736 sites measured by CSIRO in Brisbane, Adelaide and Melbourne.

The approach selected for this project was to use long term end use measurements on some 250 refrigerators and freezers located from Melbourne to Cairns as a basis for developing a robust tool to develop energy estimates for both refrigerators and freezers. Individual daily records of energy and indoor temperature at each site were analysed for all available sites (representing 62,000 days of data) and these were then tagged with the climate zone and its average measured temperature for each month. This allowed a single function of indoor temperature versus average refrigerator power to be developed for all sites to provide a sound basis for developing an energy model for refrigerators. Note that this energy data includes the aggregated impact of ambient temperature, user interactions and defrosting. A separate model was developed for separate freezers. Seasonal and daily use profiles and sensitivity to weather were also based on measured end use data.

Inverter driven compressors in household refrigerators are a relatively recent advent, but their market share is increasing quickly. A detailed survey of major suppliers in Australia mapped the likely share of inverter driven compressors in household refrigerators and freezers and projected this out to 2030. This type of research has not been undertaken previously in Australia.

Commercial refrigeration systems

Commercial refrigeration includes a wide range of equipment used in the commercial sector, primarily for the storage of food at suitable temperatures prior to use or sale. Both refrigerated display and storage cabinets are important in the food sector. They are widely used by a range of companies, from small owner-operated businesses to large companies such as supermarket chains. This study also examines small cool rooms used in the retail sector (as storage for perishable items) as these also often use single phase induction motors. These are not currently regulated for energy efficiency.

At this stage there are virtually no models of commercial refrigeration on the Australian market with single phase inverter driven compressors. It appears that the market drivers that are present in the air conditioner and household refrigerator market are not yet present in commercial refrigeration. There are inverter driven compressors on larger commercial refrigeration systems (e.g. industrial cool rooms), but at this stage, these are exclusively three phase and outside the scope of this project. Given the developments in household refrigeration, single phase inverter driven compressors are likely to appear in smaller commercial refrigeration systems over the coming years, but the timing is currently unclear. The project brief suggested that some digital controllers on commercial refrigeration systems may be able to provide protection and shut the system down during low voltage events. This was confirmed with the test results conducted on 27 commercial refrigeration units; 60% had digital controllers that shut the compressor down before it stalled under low voltage conditions and a further 10% of models did not stall under low voltage conditions. However, 30% of new units tested had a digital controller that did allow the compressor to stall on low voltage, so this characteristic is by no means universal for digital controllers.

Similar to household refrigeration, a model of indoor temperatures in commercial premises was developed that was able to cover each NEM sub-region. This was split into conditioned sites and unconditioned sites. A model of energy versus temperature based on end use measurements was developed to make bottom-up estimates of commercial refrigeration and to develop daily and seasonal load profiles. Top-down energy estimates from the recent regulatory impact statement were used as the primary data source for total energy consumption.

Key results

Based on the bottom-up analysis of data for air conditioners, household refrigeration and commercial refrigeration, hourly load data was generated from 1 July 2012 to 30 June 2019. Stock levels for each product were adjusted for each year of analysis. All times have been corrected back to Eastern Standard Time (without daylight saving), which is used throughout the NEM. Weather corrections were then applied to all data together with key attributes on the share of inverter driven systems and digital controllers. A spreadsheet for each of the seven financial years 2012-13 to 2018-19 has been provided to AEMO with a breakdown of data by end use by hour as part of the project outputs.

The average share of load for the end uses examined for the project, split into Motor D and inverter/digital controllers, is shown in Table ES1 for the year 2018-19.

Table ES1: Average share of Motor D by end use and NEM sub-region in 2018-19

NEM sub-region → End use category ↓	NSW +ACT	SA	TAS	VIC	QLD NORTH	QLD CENTRAL	QLD SOUTH
Air conditioners Motor D	0.9%	1.8%	0.5%	1.5%	0.9%	0.2%	0.8%
Air conditioners inverter	5.5%	6.0%	2.5%	7.0%	4.7%	1.0%	4.8%
Total air conditioners	6.4%	7.8%	3.0%	8.5%	5.6%	1.2%	5.5%
Household refrigeration Motor D	3.7%	4.5%	1.7%	4.3%	4.9%	1.2%	4.0%
Household refrigeration inverter	0.9%	1.0%	0.4%	1.0%	1.1%	0.3%	0.9%
Total household refrigeration	4.5%	5.5%	2.0%	5.3%	6.0%	1.5%	5.0%
Commercial refrigeration Motor D	0.7%	0.7%	0.3%	0.8%	0.7%	0.2%	0.7%
Commercial refrigeration digital cont	1.0%	1.0%	0.4%	1.1%	1.0%	0.2%	0.9%
Total commercial refrigeration	1.6%	1.8%	0.6%	1.9%	1.7%	0.4%	1.6%
Total all end uses Motor D	5.2%	7.1%	2.5%	6.6%	6.5%	1.6%	5.5%
Total all end uses inverter/digital	7.3%	8.0%	3.2%	9.2%	6.7%	1.5%	6.7%
Total all end uses	12.6%	15.1%	5.7%	15.7%	13.2%	3.1%	12.1%

Preliminary analysis shows that the share of Motor D in the underlying system load has decreased over the analysis period 2012 to 2019 and is likely to continue to decrease significantly over the next decade, primarily through changes in the household refrigeration market. Small decreases in Motor D share are also likely to come from air conditioners and commercial refrigeration.

For air conditioners, most systems installed are now of the split and ducted type and these already have a very high share of inverter driven products (over 95%) and little change to this is expected over the coming decade. The share of window wall systems, which continue to use Motor D driven compressors, is now only a few percent of the market and this share is in long term decline. For household refrigerators, the advent of inverter driven compressors is relatively new and these are making substantial inroads into the current market. Large increases in the stock share of inverter driven refrigerators, and to a lesser extent, freezers, are expected over the coming decade, which leads to a corresponding significant reduction in Motor D driven household refrigeration. For commercial refrigeration systems, while there are some uncertainties about the charge in stock share of digital controllers with motor protection over time, it is apparent that most new products have these features, so a gradual long term decline in Motor D share for this sector is expected (digital controller growth more than offsets overall load growth for this product). The total Motor D share has been projected for all NEM sub-regions as illustrated in Figure ES1. This provides a ***qualitative*** assessment of the likely trends in Motor D share out to 2030 for these three major end uses. It is clear that the long term decline in Motor D share for all NEM sub-regions is primarily driven by changes in household refrigeration, with only small contributions from air conditioning and commercial refrigeration, although the absolute contribution does vary somewhat by NEM sub-region. It is important to note that these are average annual values only and there is always significant variation in Motor D share across seasons, by day of the week and hour by hour, especially during more extreme weather events.

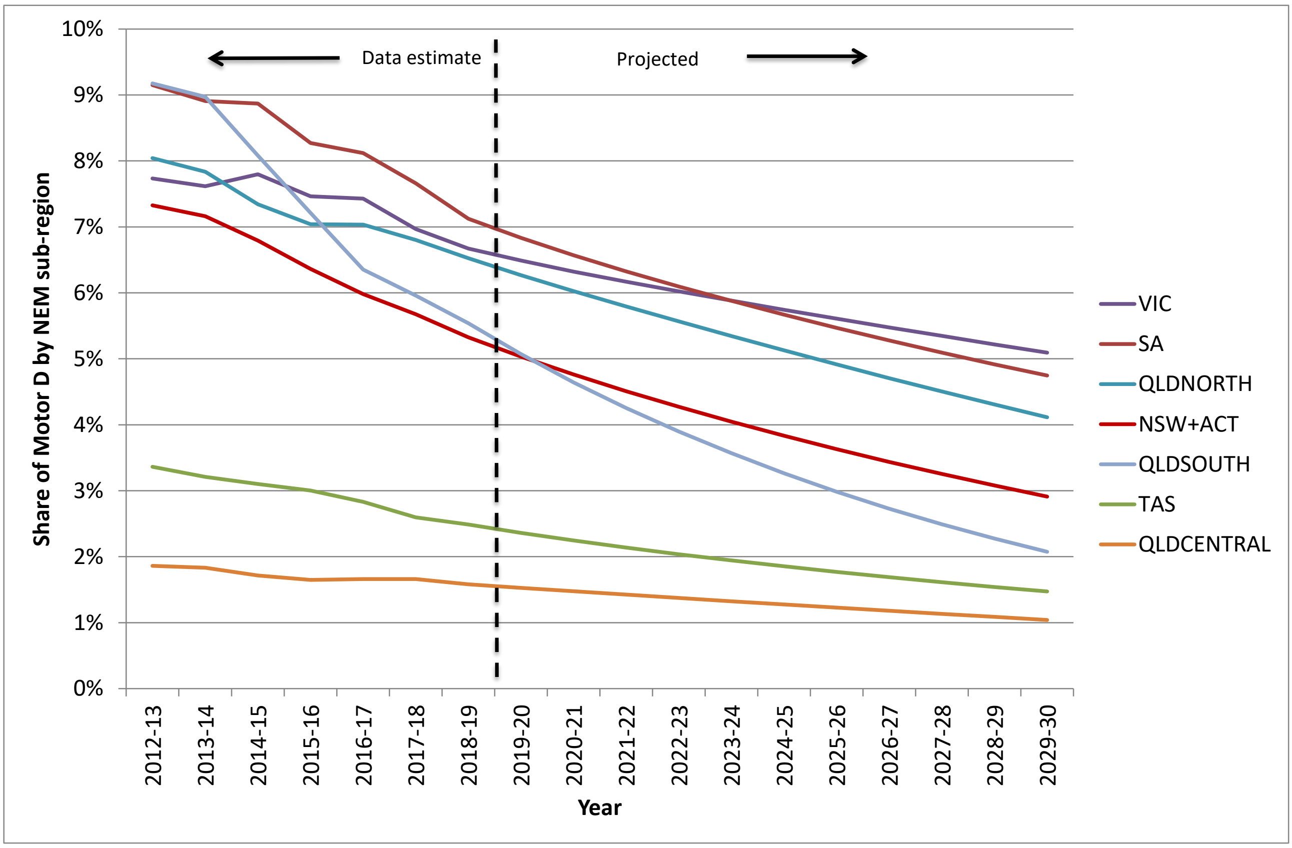

Figure ES1: Projected share of Motor D of underlying system load by NEM sub-region

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Abbreviations

ABS	Australian Bureau of Statistics (federal)
AC	Alternating Current (main power supply, nominally 50Hz)
ACDB	Australian Climate Database
AEMO	Australian Energy Market Operator
BCA	Building Code of Australia (now NCC)
CEC	Comparative Energy Consumption (energy on an energy label)
COAG	Council of Australian Governments (state, federal and NZ)
CSIRO	Commonwealth Scientific & Industrial Research Organisation
DC	Direct Current
DEE	Department of the Environment and Energy (federal)
E3	Equipment Energy Efficiency program (state, federal and NZ)
EE	Energy Efficiency
EES	Energy Efficient Strategies (consultants)
EST	Eastern Standard Time (Australia) without daylight saving (Brisbane time)
FCAS	Frequency Control and Ancillary Services
GEMS	Greenhouse and Energy Minimum Standards (federal law)
GWh	Gigawatt hour (10^9 Wh)
HVAC	Heating, ventilation and air conditioning (equipment)
IEC	International Electrotechnical Commission, Geneva
kWh	kilowatt hour (10^3 Wh)
LED	Light emitting diode used for illumination
MEPS	Minimum Energy Performance Standards (regulated efficiency levels)
Motor D	Single phase induction motor
MV	Mains Voltage (nominally 230 V AC)
MW	Megawatt (10^6 W) (unit of power)
NCC	National Construction Code (Australian Building Codes Board)
NEM	National Electricity Market (interconnected east coast grid of Australia)
OEM	Original Equipment Manufacturer (third party supplier)
PSCAD	Power Systems Computer Aided Design
PSSE	Power System Simulation for Engineering
RIS	Regulatory Impact Statement
S&L	Standards and Labelling
W	watt (unit of power)

1 Project Background

1.1 Request for proposals and scope

A Request for Proposal was received from the Australian Energy Market Operator (AEMO) via the Vendor Panel website in September 2019. The project title was *Air Conditioner Load Composition*.

Specifically, the brief stated:

The proposal must provide an estimate of the proportion of load in the National Electricity Market (NEM) in the Motor D category (single phase induction motors). It is also helpful (but not essential) to provide an estimate of the total quantity of load related to air conditioning of all types, for cross comparison with other datasets. The proportion should be provided as a function of time-of-day, day of week, season, and geographical climate zone (e.g. NEM regions, or sub-regions).

This report sets out the data, assumptions and methodology to estimate the load on the NEM from different types of refrigeration and air conditioner systems, as set out in the project proposal.

A contract to undertake this work was issued to EES on 15 November 2019.

1.2 Project overview

AEMO is updating their dynamic models of load and distributed energy resources (DER) in their PSSE and PSCAD simulation packages[1]. These models underpin many of AEMO's critical functions and are used to understand the way the power system behaves during disturbances and to inform AEMO's operations. In particular, AEMO is seeking information on the typical load type by region in order to model the behaviour of the grid during power system disturbances. The main focus of this study is to quantify typical loads from the so called "Motor D" category, which is made up of single-phase induction motors[2], primarily used in air conditioners and small refrigeration systems. Quantification of so called "Electronic Loads" is also desirable, which are made up of power electronic (inverter-based or electronically coupled) motor driven load components.

Single phase induction motors are widely used for several applications in the residential and commercial sectors. However, the majority of the load and energy consumption will be attributable to smaller air conditioning systems and smaller refrigeration systems. As specified in the request for proposals, this proposal focuses mainly on these two end uses. Each of these end uses by sector is briefly discussed.

Traditionally, smaller air conditioners and household/small commercial refrigerators used a single speed compressor and overwhelmingly these used single phase power. A single speed compressor is effectively an induction motor that is coupled to a refrigerant gas pump (compressor), which is configured as a heat pump using the vapour compression cycle to move heat energy from one space to another. As the maximum rating of the compressor output is always

[1] Power System Simulation for Engineering (PSSE) and Power Systems Computer Aided Design (PSCAD).

[2] Single phase compressors used in refrigeration and air conditioners traditionally were induction motors with "resistance start, induction run" (RSIR motors). To improve efficiency this shifted over time to a hybrid arrangement with an added capacitor. The industry is now moving towards permanent magnet electronically commutated motors, which are more efficient for single speed systems or inverter driven compressors. Shaded pole motors are very inefficient and generally used only for very small motors, like fans, so are not within the scope of this project. Split phase induction motors have a single cage rotor, and its stator has two windings known as main winding and starting winding. Both the windings are displaced 90 degrees in space. The main winding has very low resistance and a high inductive reactance whereas the starting winding has high resistance and low inductive reactance. These types of motors are not used in refrigeration or air conditioning systems to any significant extent so are outside the scope of this study.

somewhat larger than the typical load that it has to service, control of the heat flow is regulated by means of a thermostat or other temperature control device that cycles the compressor on and off as required to maintain the temperature with defined set points (hysteresis cut-offs). The speed of an induction motor is, by definition, fixed by the frequency of the grid and the number of poles on the motor, with a small amount of slip that varies with the loading on the motor.

For the past decade, in the case of air conditioners, inverter driven compressors have become very common and now dominate the single phase air conditioner market. Of the 2,234 single phase air conditioner models currently approved for sale in Australia in late 2019, 87% are inverter driven. The sales share of inverter driven air conditioners is somewhat higher than this model share.

Essentially an inverter rectifies the Alternating Current (AC) supply (typically to 300V Direct Current (DC)) and then uses an inverter to generate a variable frequency three phase output to drive an AC compressor motor at different speeds. While in theory an inverter could generate a wide range of frequencies, in practice, most inverter driven compressors are designed to operate from as few as two speeds to as many as six speeds. In the past, household refrigerators and freezers have overwhelmingly used single speed compressors. Some larger and higher end products now use inverter driven compressors, but these are still a minority of total sales. However, the share of inverters in household refrigeration is increasing rapidly and will be the dominant technology in household refrigerators in the coming years. To some extent this will be further driven by the forthcoming changes in regulation and test method (E3 2017a).

Air conditioners are now a ubiquitous appliance in the residential sector, with an ownership of over 0.75 nationally (Australian Bureau of Statistics 2014). Based on the latest total stock estimates for Australia, there are around 10.6 million single phase air conditioners that are connected to the NEM. This includes a significant number of smaller single phase air conditioners installed in the commercial sector, estimated to be 2.1 million units connected to the NEM. Over 85% of these installed air conditioner units will be driven by an inverter, suggesting that the stock of Motor D systems is around 1.5 million units in the case of air conditioners.

Refrigerators have a high level of ownership in the residential sector, with ownership of 1.3 nationally. Separate freezers make up an additional 0.4 appliances per household (Australian Bureau of Statistics 2014). This puts the total stock of household refrigerators and freezers at around 15 million units. In addition, there are an additional 1.5 million household style units that are used in workplaces and offices for essentially domestic purposes (storing lunches, milk, drinks etc.). In addition, there are a significant number of refrigerated display cabinets installed in shops and retail outlets around Australia, with estimates putting the stock at around 0.7 million units (E3 2017b). The vast majority of all refrigeration systems already installed (~95%) will be powered by single phase induction motors. This illustrates that the stock of Motor D systems is more than 16 million units in the case of residential and commercial refrigeration.

Of course the load profile for air conditioners and refrigeration systems is very different. Residential air conditioners are highly variable in their use and their operation is dictated by weather and occupancy profiles (whether people are at home when it is hot during the day). Small commercial sector air conditioners have a more consistent pattern of use (which tend to more closely mirror office hours), but their output to some extent is impacted by the weather. In contrast, household and commercial refrigeration is a consistent load that is always present. Energy consumption is primarily driven by indoor operating conditions, which typically has a seasonal pattern for residential refrigeration (typically double the average power in summer compared to winter)(Harrington, Aye & Fuller 2018a), but with lower seasonal effects in the commercial sector due to the higher prevalence of space conditioning.

Despite the much larger stock of refrigeration systems connected to the grid and their likely much larger average energy consumption, the power consumed by air conditioners can be very large during more extreme weather events (Energy Efficient Strategies 2004; Strategy.Policy.Research 2019). During mild weather, air conditioner loads are typically very low, while in hot weather they can almost double the total demand on the NEM in some regions. There is a weather sensitive component associated with refrigeration, but this tends to be relatively modest in comparison to air conditioners (refrigerators may experience up to 15% increase in energy during hot weather). Specific cases have been modelled as set out below.

1.3 Defining the data requirements for this project

In order to satisfy the requirements set out in the RFP for this project, the following parameters were estimated:

- Population and households in the NEM regions defined for this study
- Stock of single phase residential air conditioners
- Share of single phase residential air conditioners that are inverter driven
- Stock of single phase commercial air conditioners
- Share of single phase commercial air conditioners that are inverter driven
- Stock of single phase residential refrigerators
- Share of single phase residential refrigerators that are inverter driven
- Stock of single phase residential style refrigerators used in the commercial sector
- Share of single phase residential style refrigerators used in the commercial sector that are inverter driven
- Stock of single phase commercial refrigeration systems
- Share of single phase commercial refrigeration systems that are inverter driven (or use a digital controller to protect the compressor)
- Typical load profiles for air conditioners (seasonal and peak days)
- Typical load profiles for refrigeration systems (seasonal and peak days).

This data has been compiled and was used to generate a stock model and an estimate of the load on the NEM at a regional level for all Motor D systems as well as for Electronic Loads (inverter driven systems) for a range of seasons and for specific weather events for air conditioners and refrigeration systems. For this study, AEMO wanted the share of Motor D loads. As the load on the NEM changes, a weather sensitive component needed to be developed. This was very complex for household air conditioners in particular. The following sections set out our approach to the compilation of the relevant data for this analysis and any associated issues.

1.4 Methodology and report structure

The analysis for this report was primarily undertaken by Dr Lloyd Harrington of Energy Efficient Strategies. No sub-contractors were used. In broad terms, the methodology used and the key assumptions made are generally the same as set out in the EES proposal to AEMO. These are documented and elaborated in detail in this report.

The report structure is as follows:

- Chapter 2 sets out the project scope, input data, key assumptions and some initial analysis of the NEM sub-region load data that was required for this project.
- Chapter 3 provides some background on Motor D systems (single phase induction motors) and inverter driven motors.
- Chapter 4 provides detailed data on air conditioner stock and loads.
- Chapter 5 provides detailed data on household refrigeration stock and loads.
- Chapter 6 provides detailed data on commercial refrigeration stock and loads.
- Chapter 7 provides a more detailed analysis of the results and addresses the requirements of the RFQ.
- Chapter 8 includes the list of references used in this report.

The work involved the compilation and collation of a range of end use data, ownership and stock data and models of total energy consumption for each of the NEM sub-regions. Given there is incomplete data in some areas, some reasonable assumptions were necessary in places, but these should not unduly impact on the accuracy of the results. All assumptions are documented in the report.

Data is split into seven NEM sub-regions as defined by AEMO for this project. These are described in detail in Chapter 2. AEMO provided data on the operational demand (30 min data) for each sub-region from mid-2012 to mid-2019. Under instructions from AEMO, this was converted to underlying demand (operational demand less transmission and distribution losses plus photovoltaic (PV) generation), which was subsequently used for all analysis. This was then converted to hourly demand for analysis in this report.

As instructed by AEMO, all times are defined as the period ending in the time stamp. For example, hourly data for 7 July 01:00 is from the hour commencing 0:00 (midnight) until 1:00 (1am). All times were eventually converted to Eastern Standard Time (EST) in the final analysis (NEM time, which is based on Brisbane time all year without any adjustments for daylight saving). Some of the end use measurement data (particularly for air conditioners) was recorded in local time, so the initial data analysis was conducted in local time (as noted in the relevant section) but converted to EST in the final results. To reduce the complexity of analysis, the time-of-day labels used were generally 1 (1am) to 24 (12 midnight). Software packages (like Excel) and AEMO data load record midnight as 0:00 on the date of the next day, which is effectively the same as 24:00 on the day in question. This has purely been done to more clearly communicate the results (and also simplifies some of the analysis).

The approach used was generally a bottom-up analysis of estimated energy consumption per piece of equipment, scaled up for the known stock in each NEM sub-zone. Data on seasonal profiles and time-of-day profiles by month were used to generate detailed hourly data for every end use over a nominal year together with overall climate corrections. The “sample” year used was the latest AEMO data, running from 1 July 2018 to 30 June 2019, but a subsequent request from AEMO resulted in detailed data files being prepared for each of the seven year from July 2013 to June 2019. Hourly load data for each of the equipment sub-types were estimated for each year and then compiled for analysis against the AEMO underlying load. Various corrections for weather variability were applied as set out in the relevant chapters. The equipment subtypes modelled were effectively:

- 14 types of air conditioners covering the residential and small commercial sector, which were further split into Motor D and inverter driven loads.
- 4 types of household style refrigeration products, which were further split into Motor D and inverter driven loads.
- 8 types of commercial refrigeration system, all of which were Motor D, but were split into products with and without digital controllers that were able to protect the compressor from stalling during a low voltage event.

1.5 Acknowledgements

The following individuals provided guidance during this study. Their contributions are gratefully acknowledged:

- Dr Jenny Riesz, Principal, Operational Analysis, Australian Energy Market Operator who was the project manager and provided guidance and feedback throughout the project.
- Filip Brnadic, Engineer, Operational Analysis and Engineering, Australian Energy Market Operator provided detailed comments and input on the draft report and made a range of helpful suggestions to improve data presentation.
- Joanne Roberts of Australian Energy Market Operator, who managed contractual issues and provided load data from AEMO.

Ian McGill, a design engineer at Fisher & Paykel Appliances in New Zealand, provided some useful information on refrigeration design and the physics of motor stalling and protection systems. Andrew Baghurst of CalTest Laboratory also provided advice on the operation of single phase motors under adverse conditions. Klaus Neuschler of Choice assisted with advice on the operation of the measurement equipment for field measurements.

Aggregated hourly end use measurement data for air conditioners in three cities for several years was provided by the Energy Division of CSIRO for use in this project. This valuable data contribution is gratefully acknowledged.

Ian Boer Refrigeration in Warragul, Victoria provided access to measure low voltage stall characteristics of a wide range of commercial refrigeration products and their cooperation during this project is gratefully acknowledged. A number of private householders also allowed access to their appliances to allow low voltage stall to be undertaken and their cooperation is also acknowledged.

2 Key input parameters and background

2.1 Scope

This report provides estimates of specified loads on the National Electricity Market (NEM) interconnected grid system split into defined NEM sub-regions. The main objective of the report is to estimate the load in the NEM interconnected system for different times of the year that is generated by single phase induction motors, so called Motor D systems. In addition, loads that are generated by single phase Electronic Loads (inverter driven systems) are also estimated. Three phase motor loads are specifically excluded. The end uses that are specifically investigated and documented include single phase air conditioners of all types, household refrigeration systems (virtually all are single phase) and single phase commercial refrigeration systems (including refrigerated display cabinets and professional storage systems).

There are likely to be a number of other loads in the NEM interconnected grid that fall in the definition of Motor D systems such as small pumps (transfer and pressure pumps) and fans. While water and liquid pumping energy is significant at a national level, most large liquid pumps will be three phase and out of scope (e.g. most pumps in the commercial sector are associated with large air conditioning systems such as chillers). Similarly, large air handling systems in the commercial sector will almost always be three phase. Smaller single phase transfer and pressure pumps operate infrequently and the load on the NEM is likely to be small at any given point in time. Pool pumps in a household setting typically use single phase induction motors, but increasingly, these are being replaced by variable speed or inverter driven systems. Pool pumps have not been quantified for this report but some data is available in the recent regulatory impact statement (E3 2016, 2017c). Pool pumps are being targeted for demand response systems to enable them to be disconnected during system peaks.

2.2 Population and households by NEM sub-region

The AEMO brief for this study defined the following sub-regions, which are to be separately modelled:

- Queensland North (QLDNORTH)
- Queensland Central (QLDCENTRAL)
- Queensland South (QLDSOUTH)
- New South Wales (including ACT) (NSW)
- Victoria (VIC)
- South Australia (SA)
- Tasmania (TAS).

AEMO provided a concise definition of each region covered by this study as set out in Table 1.

Table 1: NEM Regions defined by AEMO

No	NEM Region	Postcode range
1	Queensland North	4703 – 4999
2	Queensland Central	4601 – 4702
3	Queensland South	4000 – 4600
4	New South Wales (incl. ACT)	2000 – 2999
5	Victoria	3000 – 3999
6	South Australia	5000 – 5999
7	Tasmania	7000 – 7999

AEMO provided a map of Queensland to show the regional split as shown in Figure 1.

Figure 1: Map of Queensland showing approximate NEM sub-regions

AEMO also provided a series of postcode exclusions from the above NEM regions that cover areas that are not connected to the NEM, as set out in Table 2. Data from the 2016 Census was used to establish the population, families and the number of dwellings in each of the excluded postcode areas. This was then compared to the census total population for the state (or the sub-regions in Queensland) to establish the share of population that is excluded in each state.

Table 2: Postcodes to be excluded from NEM regions with 2016 census data

Postcode	Name	Population	Families	Dwellings	Region, notes
2898	LORD HOWE ISLAND	382	87	202	NSW
2899	NORFOLK ISLAND	1748	491	1080	Not counted in NSW
3921	FRENCH ISLAND	119	29	101	VIC
4025	BULWER	368	26	359	Qld South
4474	ADAVALE	93	19	41	Qld South
4475	CHEEPIE	0	0	0	Qld South
4479	COOLADDI	16	3	11	Qld South
4481	FARRARS CREEK	121	26	100	Qld South
4482	BIRDSVILLE	140	27	134	Qld South
4488	BOLLON	250	71	159	Qld South
4491	EULO	95	27	57	Qld South
4493	HUNGERFORD	23	3	18	Qld South
4731	ISISFORD	218	56	185	Qld North
4732	MUTTABURRA	134	29	90	Qld North
4733	CORFIELD	183	48	140	Qld North
4736	JUNDAH	106	24	90	Qld North
4801	HAYMAN ISLAND	264	0	0	Qld North
4803	HAMILTON ISLAND	1867	60	242	Qld North
4825	ALEXANDRIA/Mt Isa	19246	4537	8599	Qld North
4828	CAMOOWEAL	208	33	260	Qld North
4829	AMAROO	465	94	284	Qld North
4830	BURKETOWN	1714	350	505	Qld North

Postcode	Name	Population	Families	Dwellings	Region, notes
4874	EVANS LANDING (Cape York)	5240	1204	2149	Qld North
4875	BADU ISLAND (Torres Straight)	8101	1637	2304	Qld North
4876	BAMAGA (Cape York)	2827	605	1056	Qld North
5722	ANDAMOOKA	316	67	596	SA
5723	COOBER PEDY	2059	359	1414	SA
5724	MARLA	433	76	242	SA
5734	OODNADATTA	167	29	97	SA
7255	BLUE ROCKS (FLINDERS IS)	833	232	593	TAS
7256	BUNGAREE (KING ISLAND)	1585	384	842	TAS

Source: Postcode list provided by AEMO, population data from 2016 Census (Australian Bureau of Statistics 2017).

The ABS provides projected estimates of households and population by state on a regular basis to assist regions with planning in their catalogue data set ABS3236.0 *Household and Family Projections, Australia, 2016 to 2041* (Australian Bureau of Statistics 2019). This data set provides state and territory estimates of households and population and also provides a split of capital city and the balance of state. The Queensland ABS statistical regions are of little relevance for this study as they do not correlate at all with the three sub-regions defined by AEMO. A summary of ABS3236.0 population and household projections in 2020 by state and territory is shown in Table 3 together with adjustments made to account for exclusions for this study.

Table 3: ABS3236.0 projections of population and households in 2020

State/Territory	Population	Households	Included	NEM Population	NEM Households
New South Wales	8,275,674	3,113,750	99.99%	8,275,251	3,113,591
Victoria	6,760,752	2,572,338	100.00%	6,760,616	2,572,286
Queensland	5,188,076	1,968,069	99.11%	5,142,100	1,950,628
South Australia	1,760,207	724,168	99.82%	1,757,084	722,883
Western Australia	2,655,657	1,019,611	0%	0	0
Tasmania	535,855	229,926	99.53%	533,314	228,836
Northern Territory	254,322	81,553	0%	0	0
ACT	438,275	171,424	100%	438,275	171,424
Other Territories	4,662	1,574	0%	0	0
Australia	25,873,480	9,882,413	88.53%	22,906,640	8,759,648

Notes: Data based on Series I projection (Australian Bureau of Statistics 2019).

In order to split Queensland into the sub-regions required by AEMO, analysis was done on census data at a postcode level in order to quantify the population and families in Queensland Central and Queensland North sub-regions to provide a more accurate way of splitting Queensland. The final split for Queensland is included in Table 4. Note that Queensland South accounts for over 75% of the total Queensland load.

Table 4: Queensland sub-region split for this study, 2020

Sub-Region	Share	Population	Households
Queensland North	15.69%	814,139	308,839
Queensland Central	8.24%	427,432	162,144
Queensland South	75.18%	3,900,528	1,479,645
Qld Excluded	0.89%	45,976	17,441

These state and NEM sub-regional splits are used throughout this report.

2.3 Analysis of NEM load data

2.3.1 Calculation of underlying load

AEMO provided 30 min operational load data for each of the nominated sub-regions from 1 July 2012 to 30 June 2019. AEMO define operational demand as:

"Operational demand in a region is demand that is met by local scheduled generation, semi-scheduled generation and non-scheduled wind/solar generation of aggregate capacity ≥30 MW, and by generation imports to the region, excluding the demand of local scheduled loads." (AEMO 2019a)

As instructed by AEMO, the operational demand was converted to underlying demand (intended to represent customer demand) by subtracting transmission and distribution losses and then adding estimated photovoltaic generation as follows:

$$Demand_{underlying} = Demand_{operational} \times (1 - T_{loss}) \times (1 - D_{loss}) + PV$$

Where PV generation was separately provided for residential and business PV systems (generally less than 100kW) as well as larger PV non-scheduled generation (PVNSG in the range 100kW-30MW) and T_{loss} and D_{loss} are as specified by state as set out in Table 5. Note that the operational demand for each NEM sub-region was provided in MW (30 min) while the PV data was provided in MWh, so was converted to MW.

Table 5: Assumed transmission and distribution losses

State	Distribution losses (D_{loss})	Transmission losses (T_{loss})
NSW	4.6312%	2.2900%
QLD	4.8037%	2.5780%
SA	6.5743%	2.6182%
TAS	5.3100%	2.4300%
VIC	5.1212%	2.6166%

Notes: Data provided by AEMO. Transmission and distribution losses were estimated in line with AEMO's current methodology (AEMO 2019b).

The calculated 30 min NEM underlying data (in MW) was then converted to hourly data from 1 July 2012 to 30 June 2019. This was done by averaging the relevant two half hour values and recording this as hourly. For example data for 1 July 0:30 and 1:00 were averaged and recorded as 1:00 (hour ending at 1am).

2.3.2 High level analysis of NEM data by sub-region

Firstly, it is useful to look at the monthly average demand for each NEM sub-region over the 7 year period where data was provided. This is illustrated in Figure 2. The first observation is that most of the sub-regions exhibit a strong seasonal consumption pattern, except for Queensland Central. There is also significant variation from month to month in NSW, Victoria, Queensland South and South Australia. All sub-regions appear to have a steady pattern of demand over the years, except for Victoria, which is declining over time and Queensland South, which is increasing over time. There was an obvious step change in consumption in Queensland Central in March 2017.

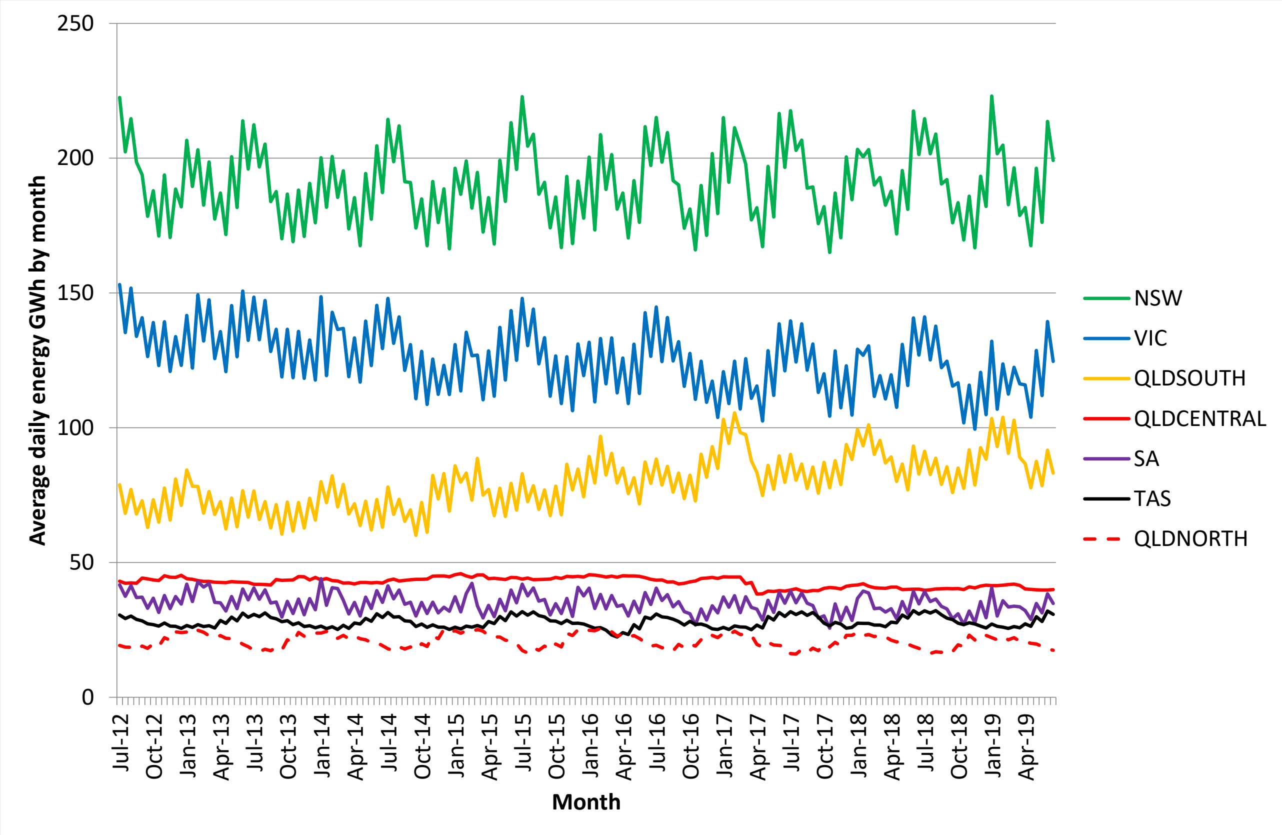

Figure 2: Average daily energy consumption by month for the seven NEM sub-regions (7 years)

This seasonal pattern is illustrated more clearly in Figure 3 for weekdays.

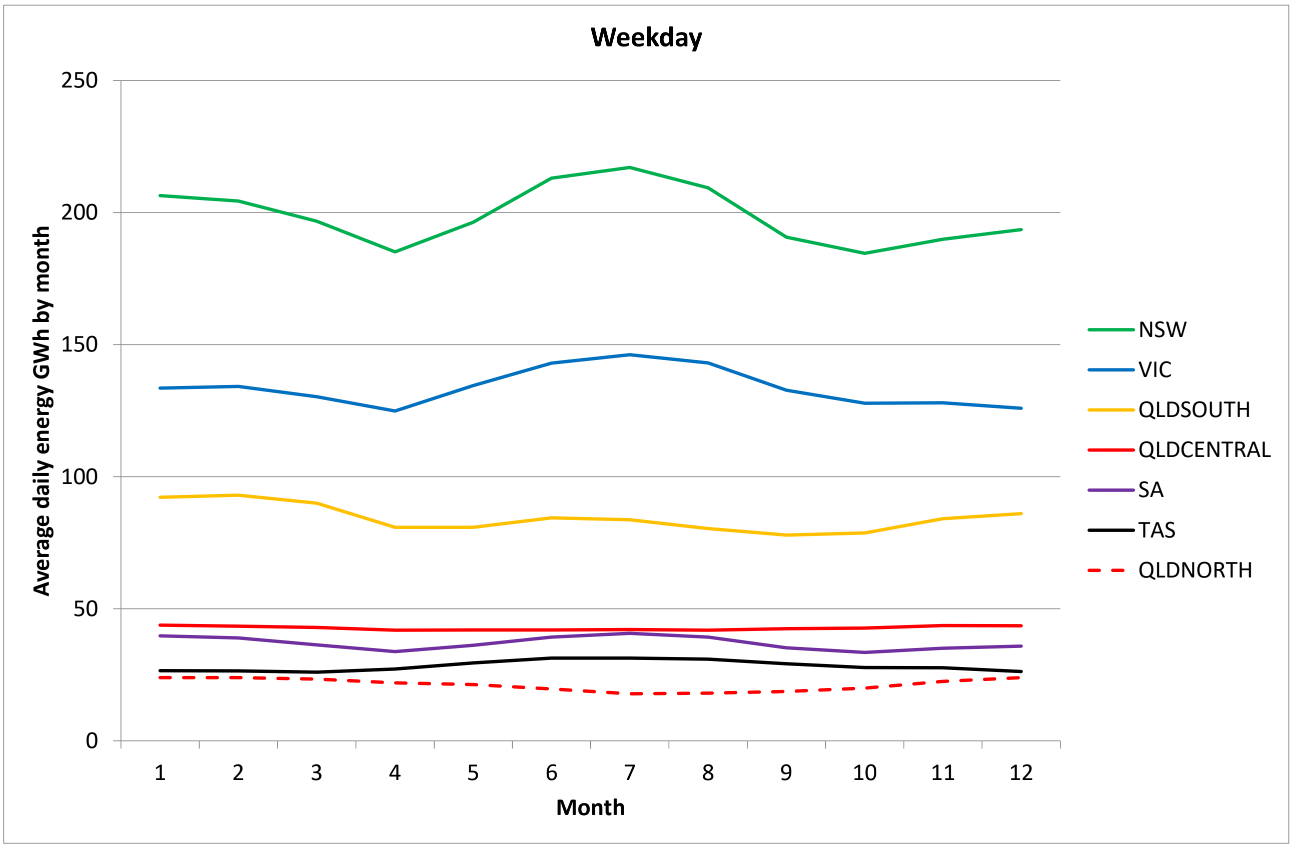

Figure 3: Average daily energy consumption by month for the seven NEM sub-regions (weekdays)

Figure 3 illustrates that there is some winter heating in NSW, Victoria, South Australia, Tasmania and to some extent Queensland South. Increased summer cooling is obvious in NSW, South Australia and Queensland North, and to a lesser extent, in Victoria and Queensland Central. Similar data is shown for weekends in Figure 4. There are significant differences in weekend energy consumption in NSW, Victoria, Queensland South and South Australia (typically 10% to 15% lower). There is only a small difference in weekend consumption in Tasmania and Queensland North (3% to 5% lower) and no difference between weekdays and weekends in Queensland Central.

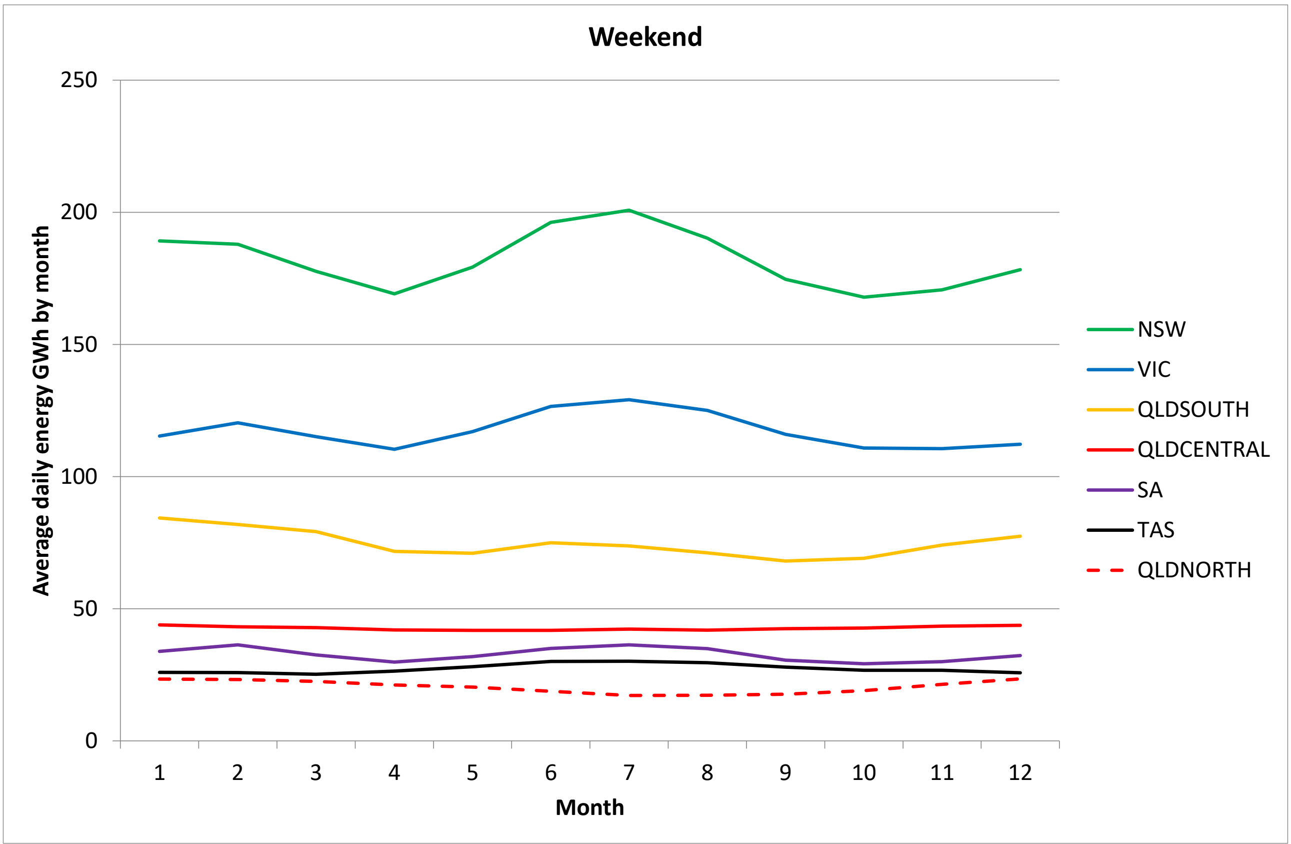

Figure 4: Average daily energy consumption by month for the seven NEM sub-regions (weekends)

To enable more detailed analysis to be undertaken later in this report, the energy data by AEMO sub-region was examined to determine a range of parameters. Firstly, for each month of data for each sub-region, the average, maximum and minimum days were identified (based on total daily energy consumption in GWh). The load shapes for an average day, a maximum day and a minimum day were then compared. This process was undertaken for each month across all seven years of data to provide a more typical impression of how volatile demand is by season by NEM sub-region. The following figures illustrate some of this data for 3 NEM sub-regions in summer (January) and in winter (July). It is obvious that there are differences in behaviour between weekdays and weekends in most sub-regions.

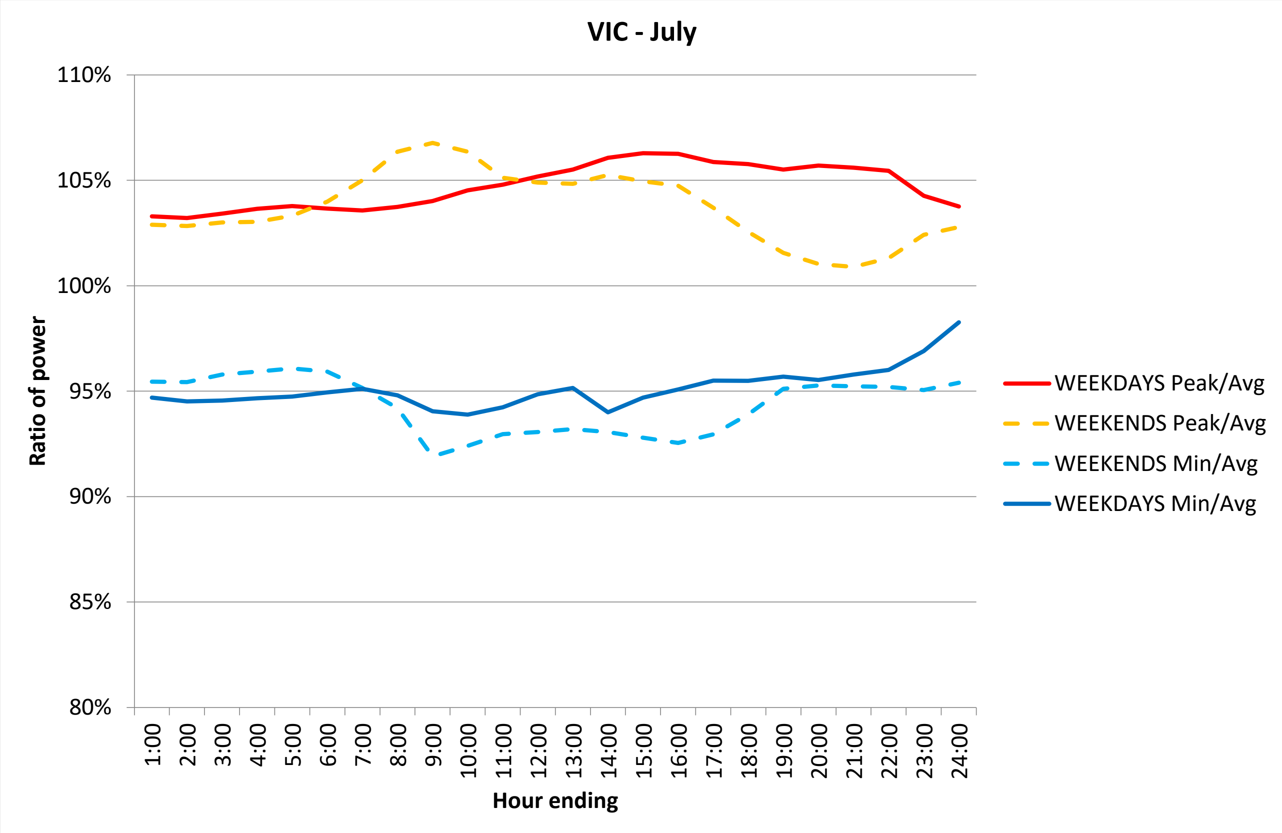

Figure 5: Peak energy day and minimum energy day to an average day, Victoria, July

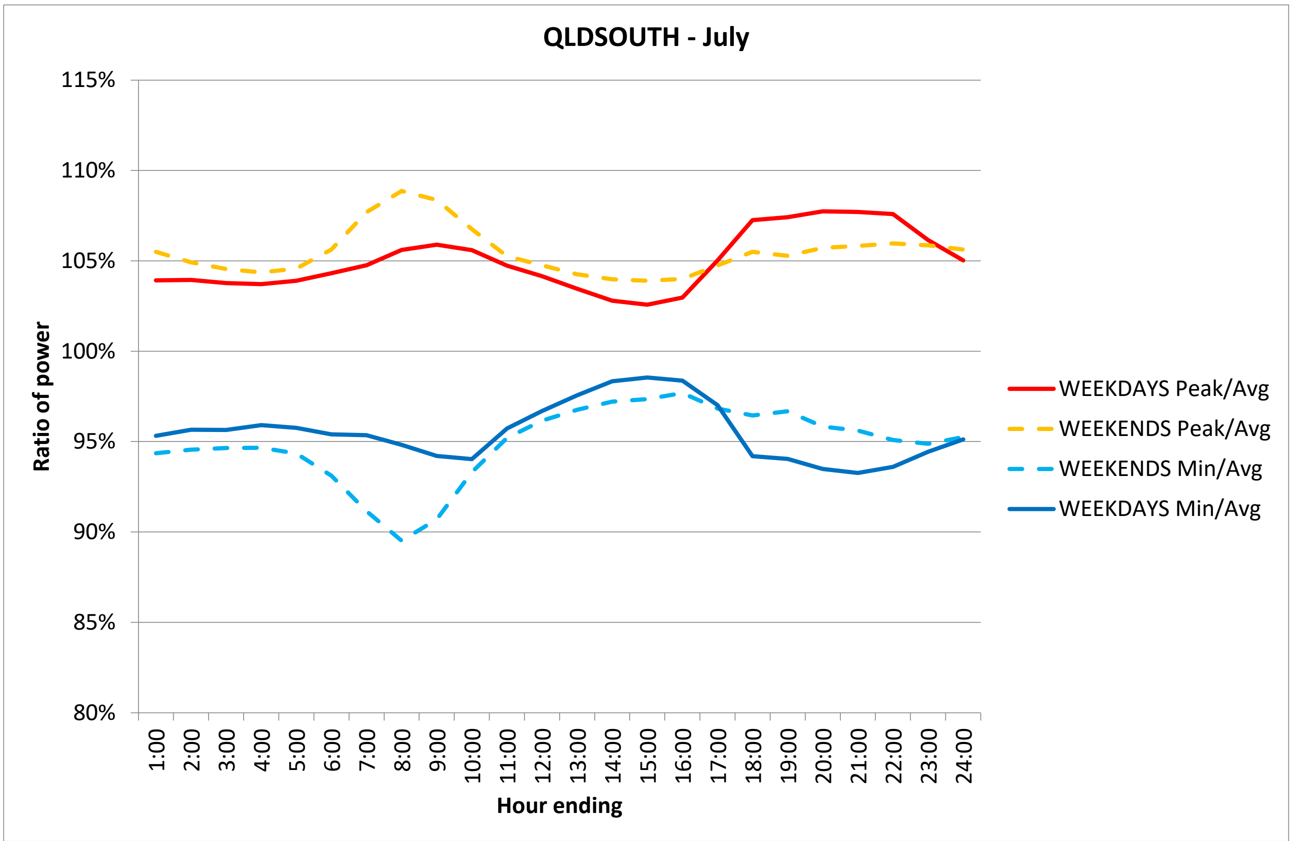

Figure 6: Peak energy day and minimum energy day to an average day, QLD South, July

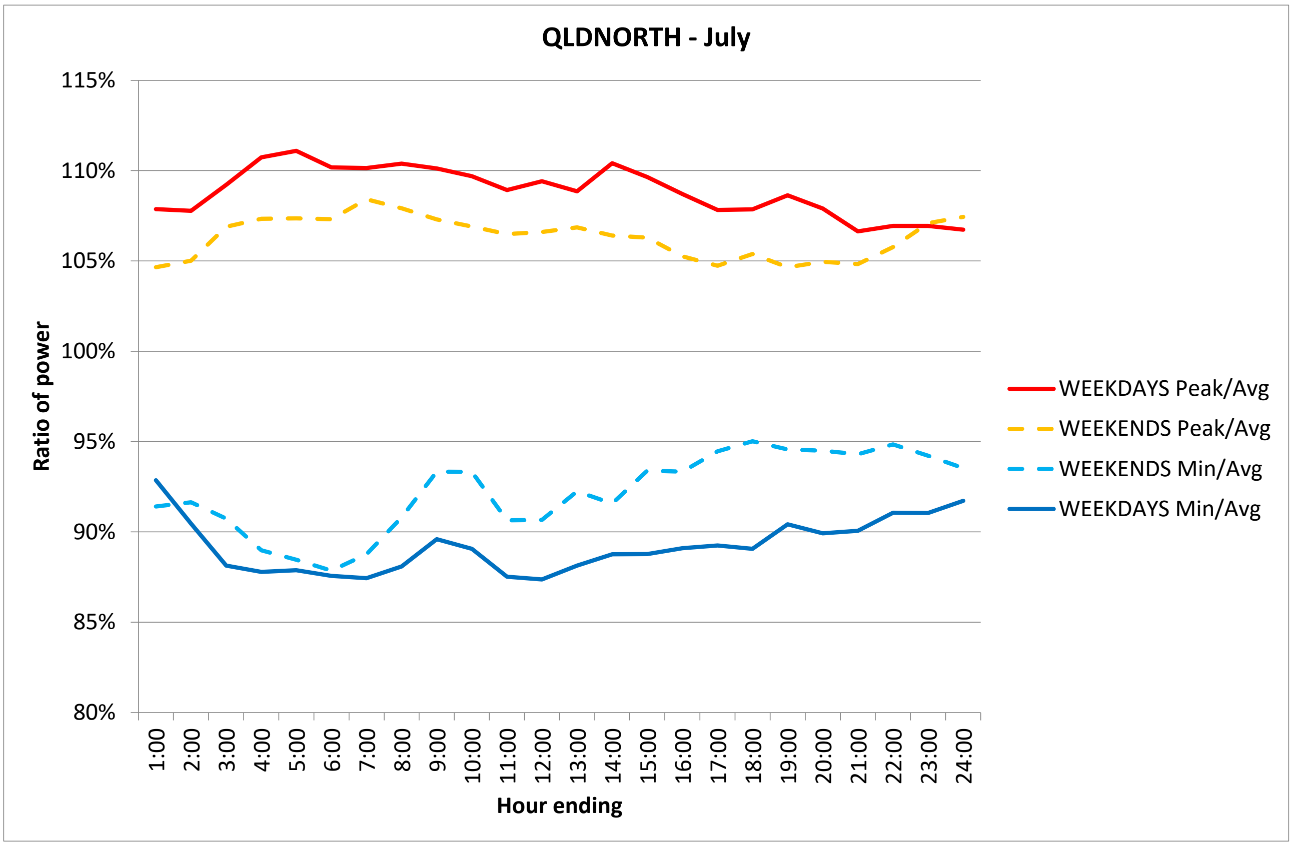

Figure 7: Peak energy day and minimum energy day to an average day, QLD North, July

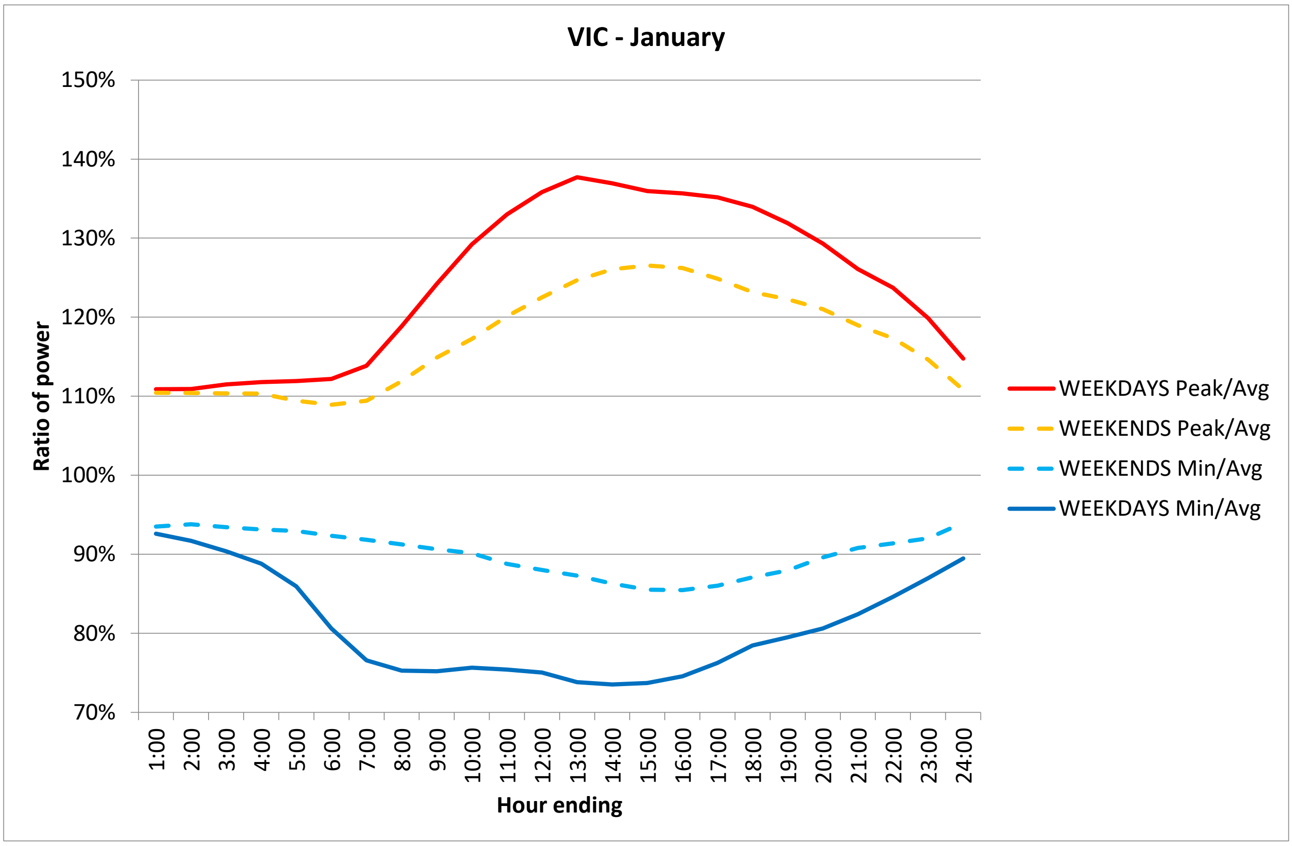

Figure 8: Peak energy day and minimum energy day to an average day, Victoria, January

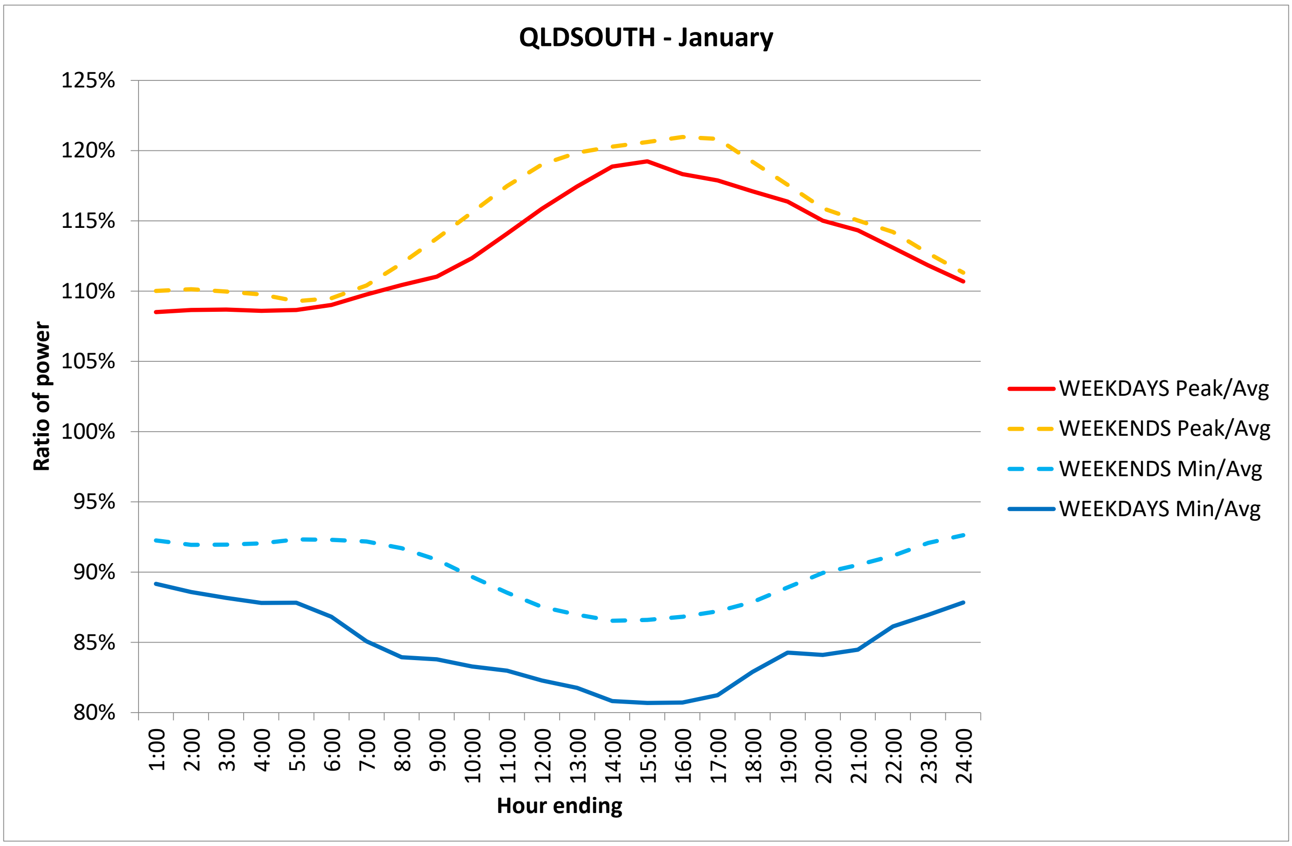

Figure 9: Peak energy day and minimum energy day to an average day, QLD South, January

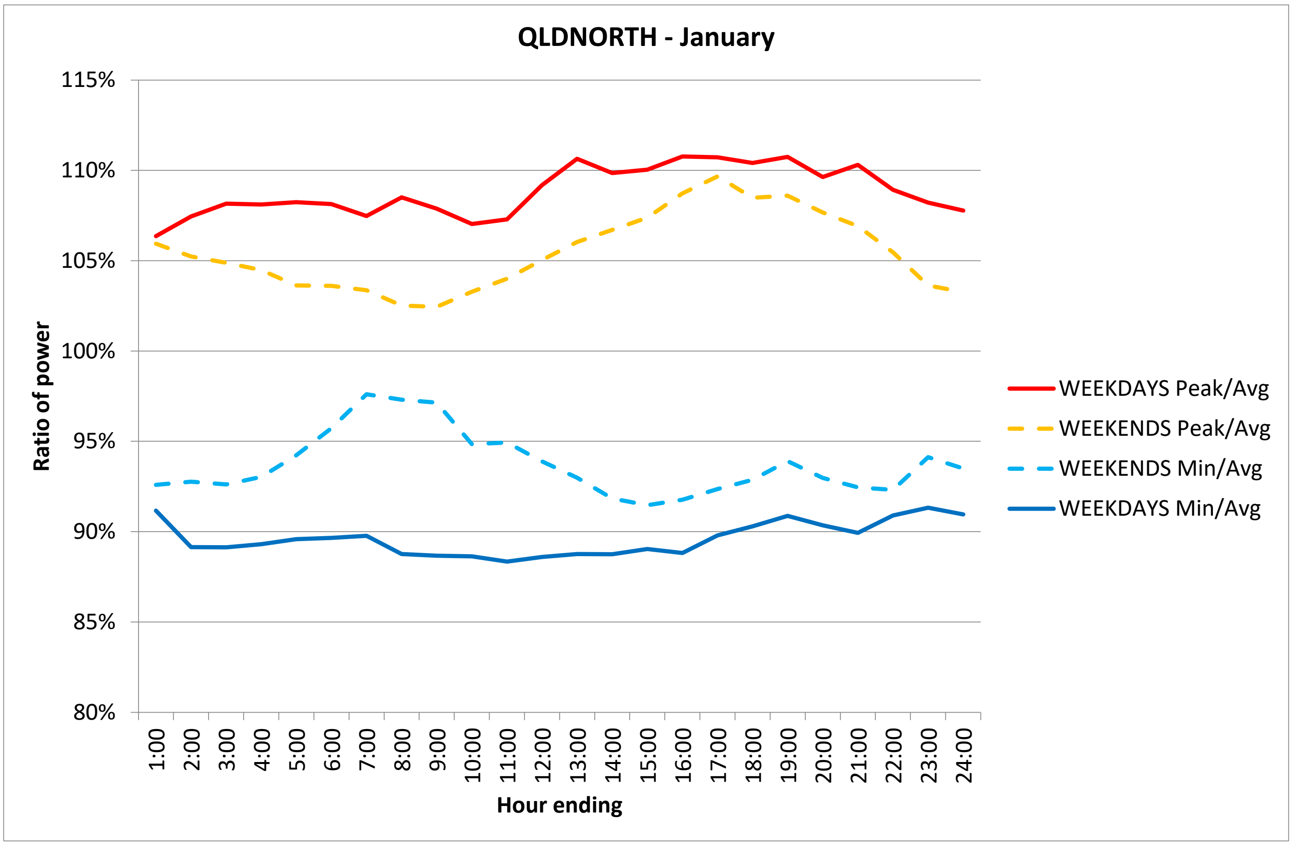

Figure 10: Peak energy day and minimum energy day to an average day, QLD North, January

This type of analysis allowed hourly and daily data to be examined in a more coherent manner to identify temperature driven events on the NEM. As an example, the week of data for Victoria in early January 2019 shown in Figure 11 illustrates the reference weekday and weekend (in blue) and the actual load profile (in red). It is obvious that there are weather driven increases in hourly load (despite the lack of temperature data for this period for this analysis). This also illustrates that weekend energy consumption is lower than during a reference weekday, which is usually the case for most NEM sub-regions.

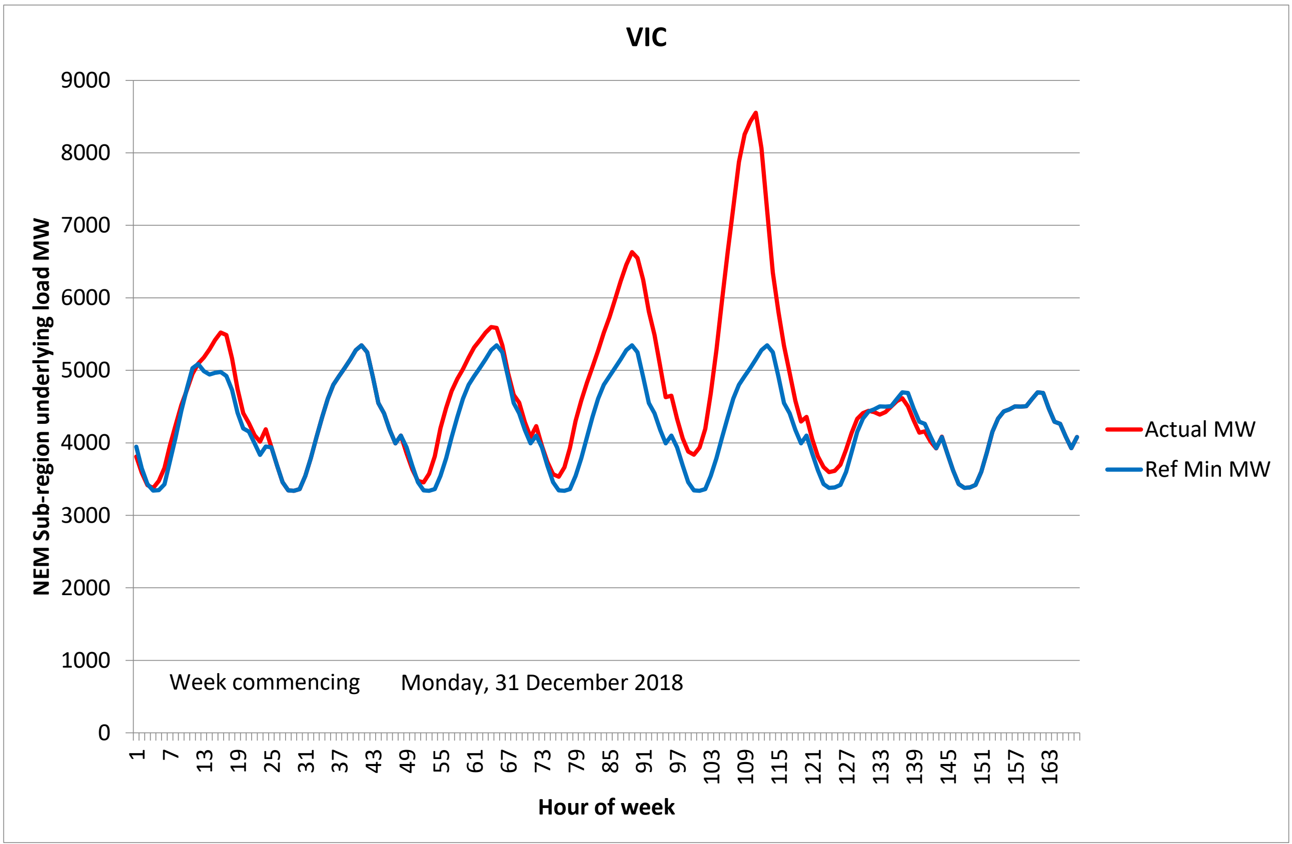

Figure 11: Illustration of reference minimum to actual load, Victoria, January 2019

Examining the data for all NEM sub-regions showed that the day to day volatility was generally quite low for all states, typically within ±10% for most of the time (relative to the average monthly value). The exceptions were NSW, Victoria, South Australia and Queensland South in the summer months, which exhibited more volatile day to day energy, most likely driven by air conditioner loads and weather. Examples of daily energy volatility are shown for all NEM sub-regions in the following figures in the year 2016 as an illustration. Note that the Y axis scale varies between figures.

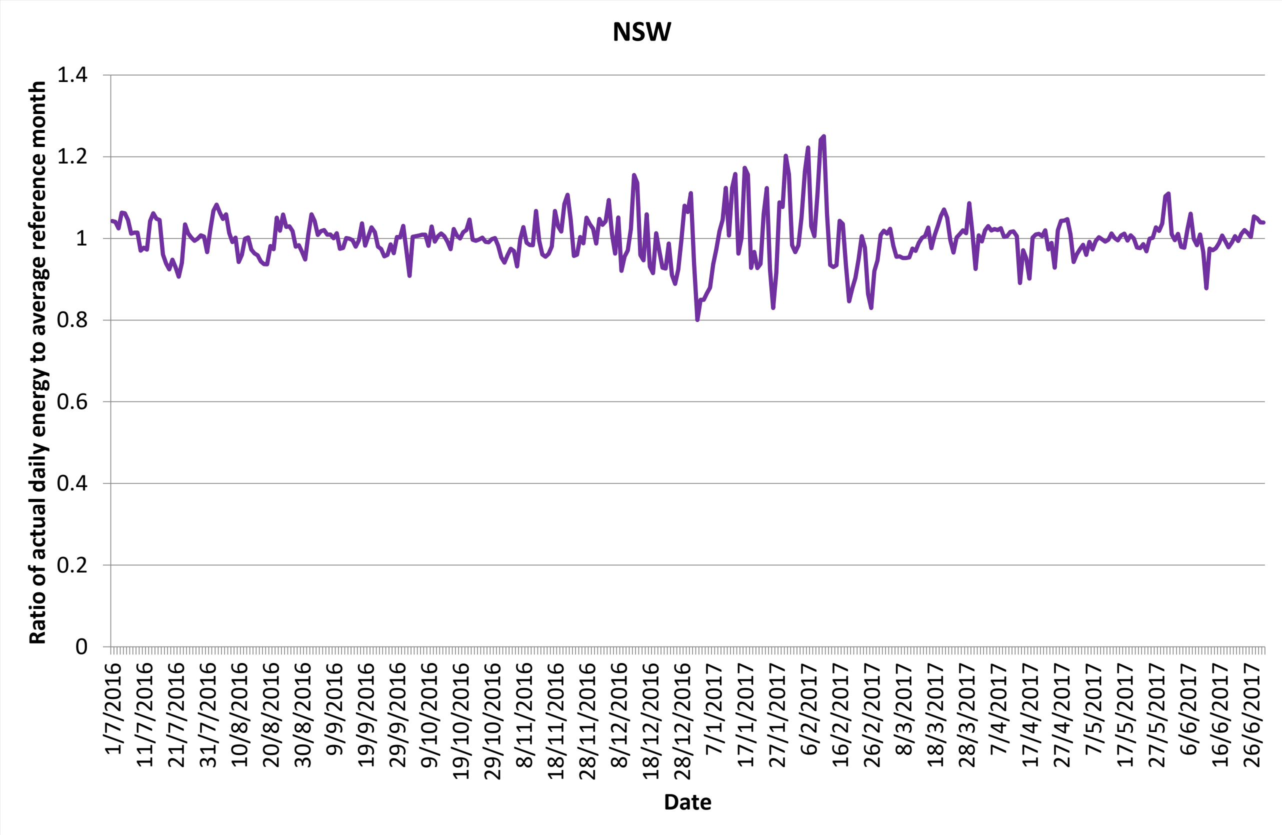

Figure 12: Volatility of daily energy values for NSW (2016)

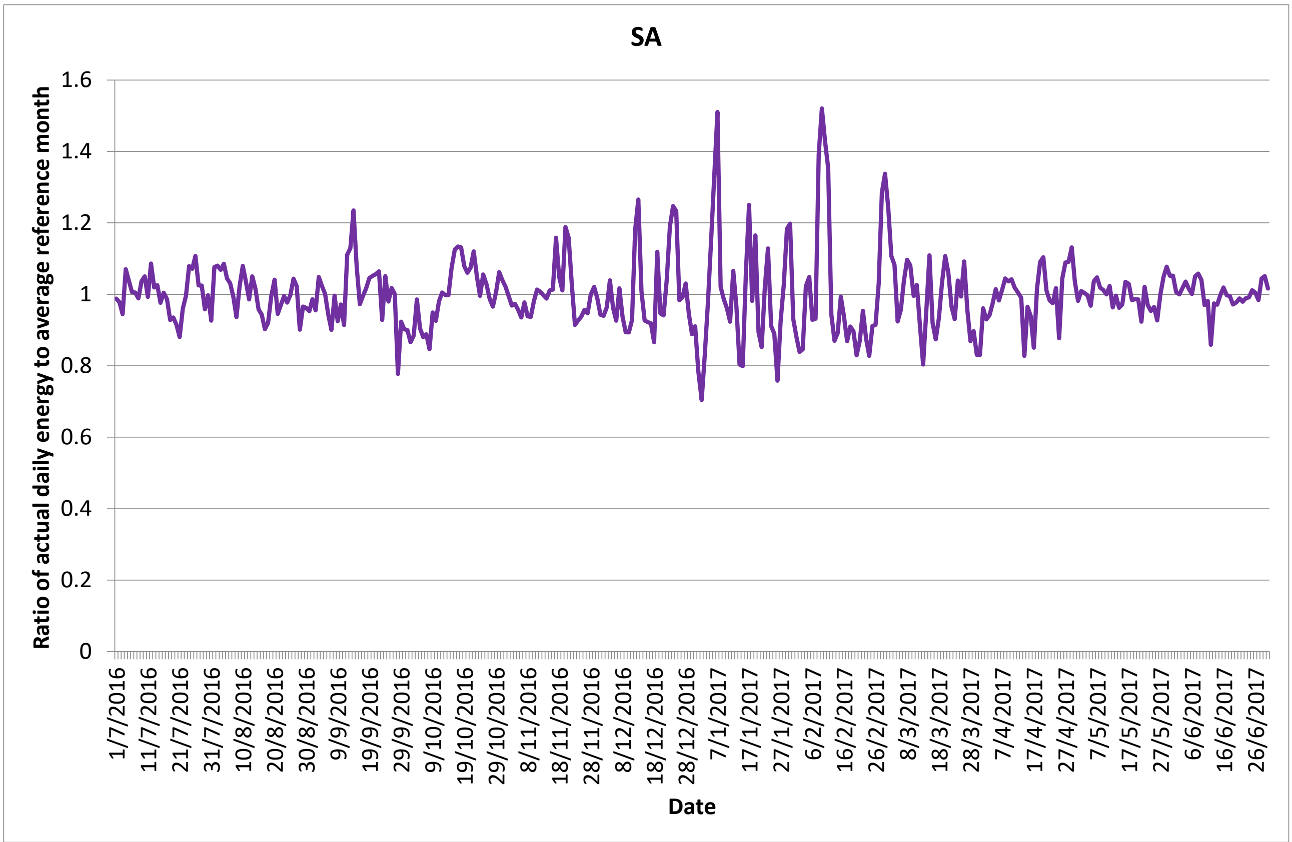

Figure 13: Volatility of daily energy values for South Australia (2016)

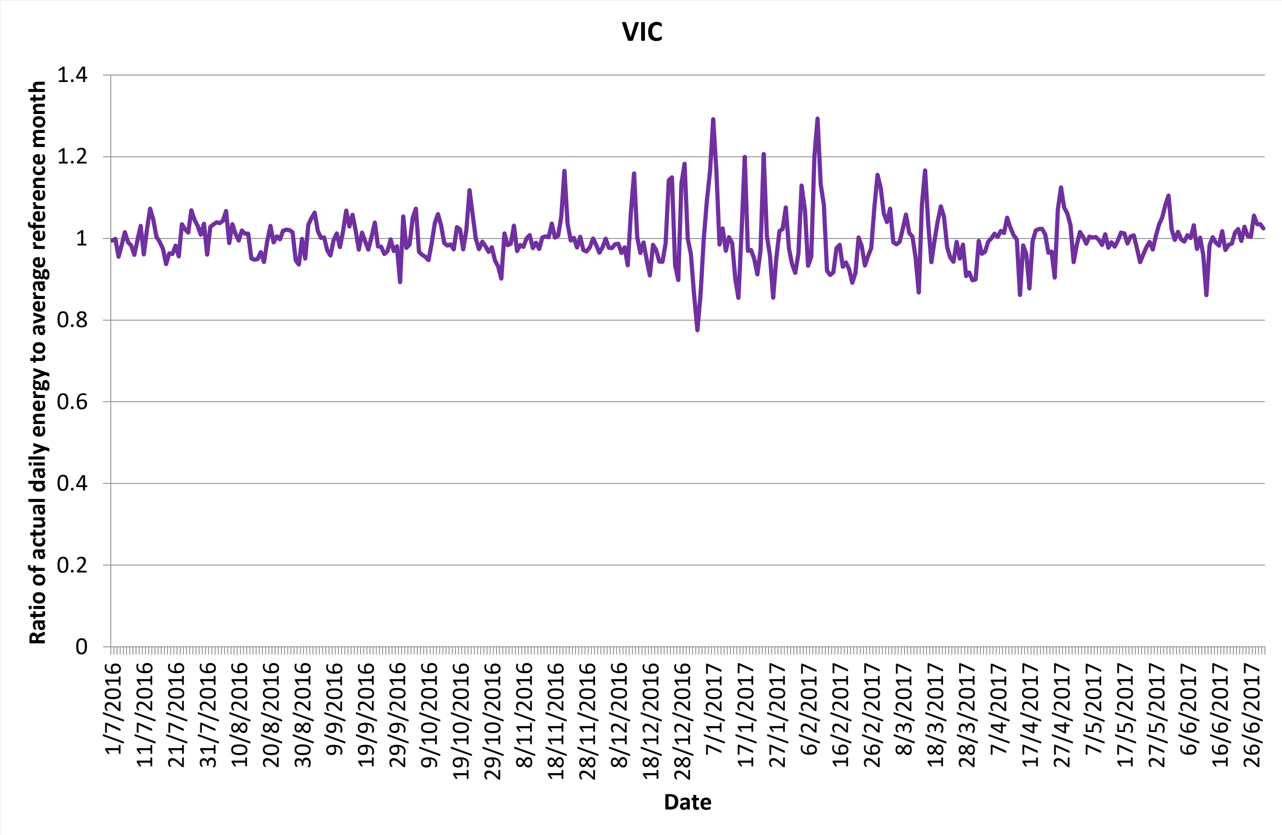

Figure 14: Volatility of daily energy values for Victoria (2016)

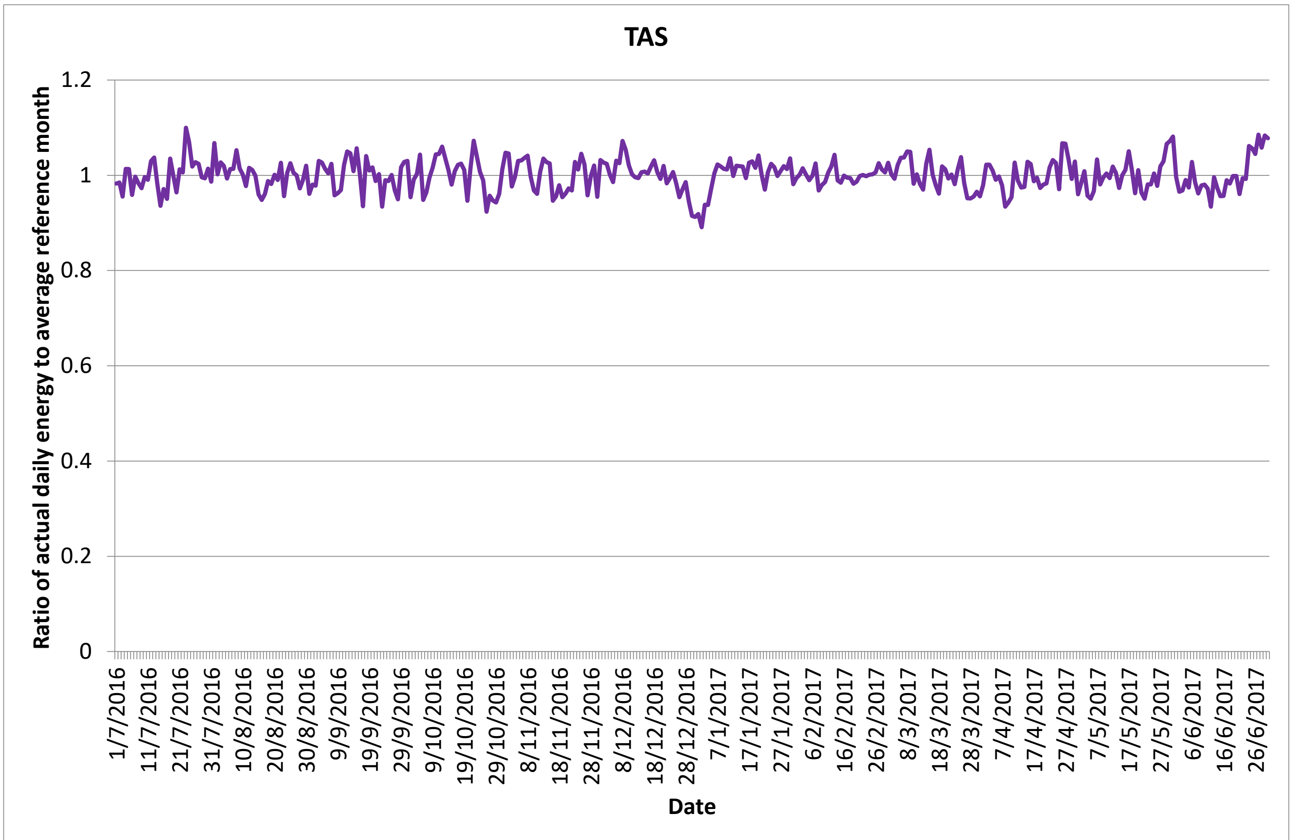

Figure 15: Volatility of daily energy values for Tasmania (2016)

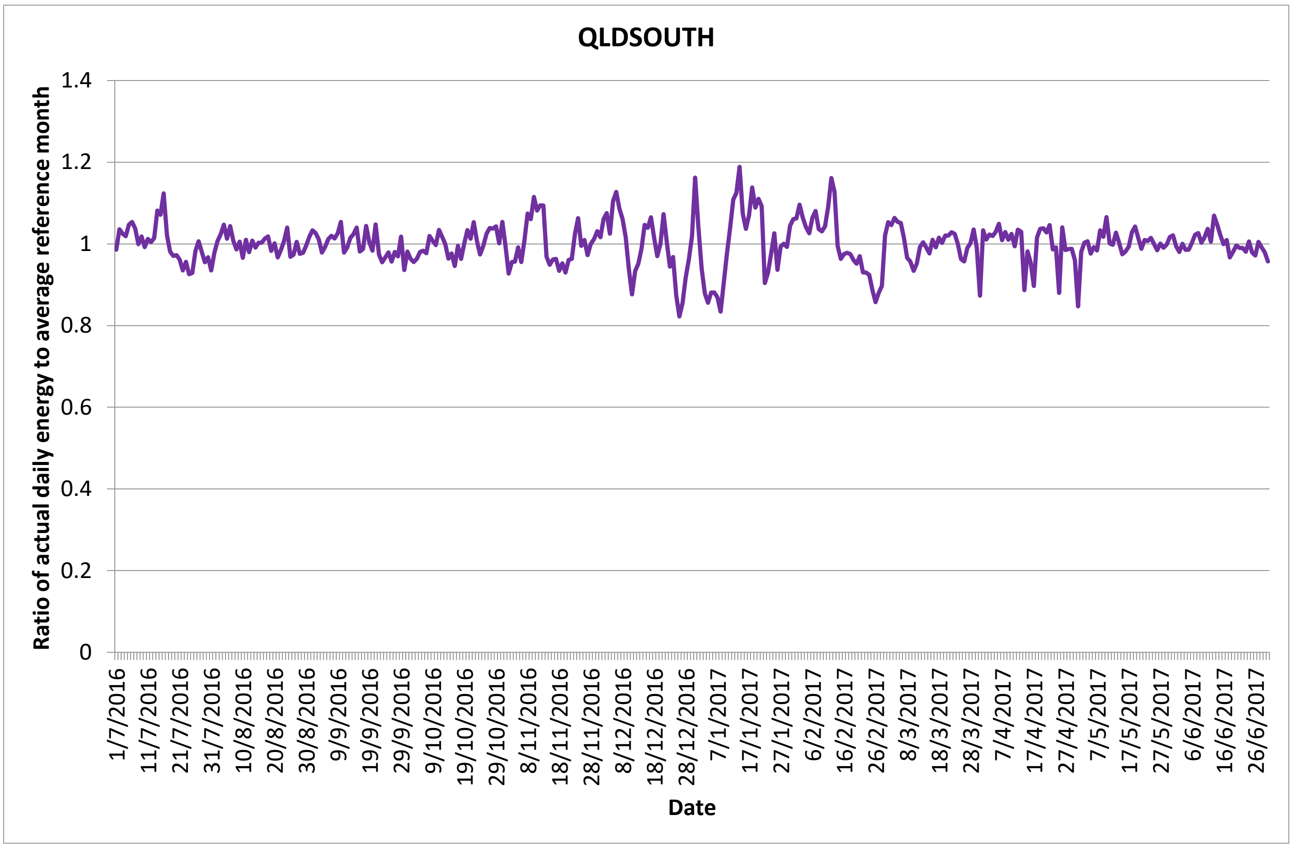

Figure 16: Volatility of daily energy values for QLD South (2016)

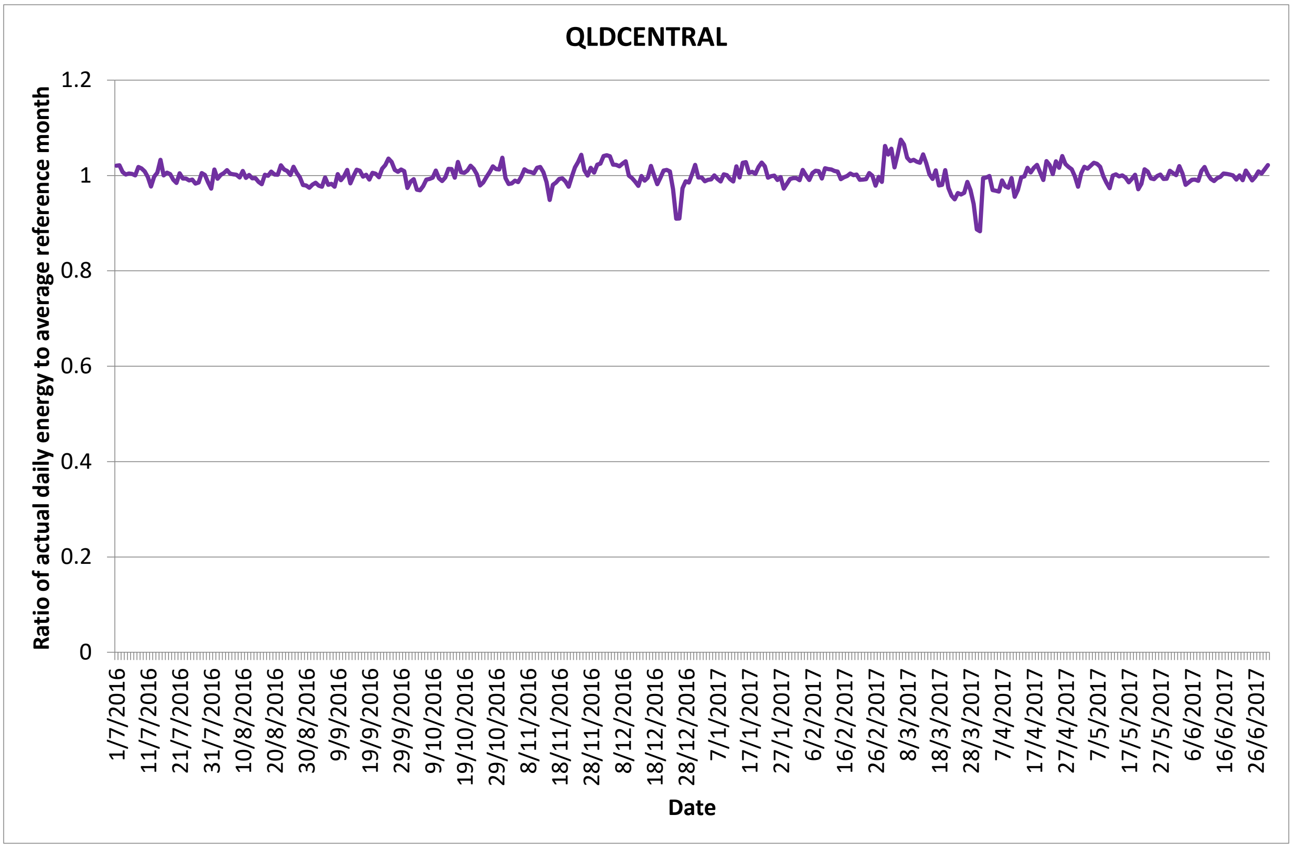

Figure 17: Volatility of daily energy values for QLD Central (2016)

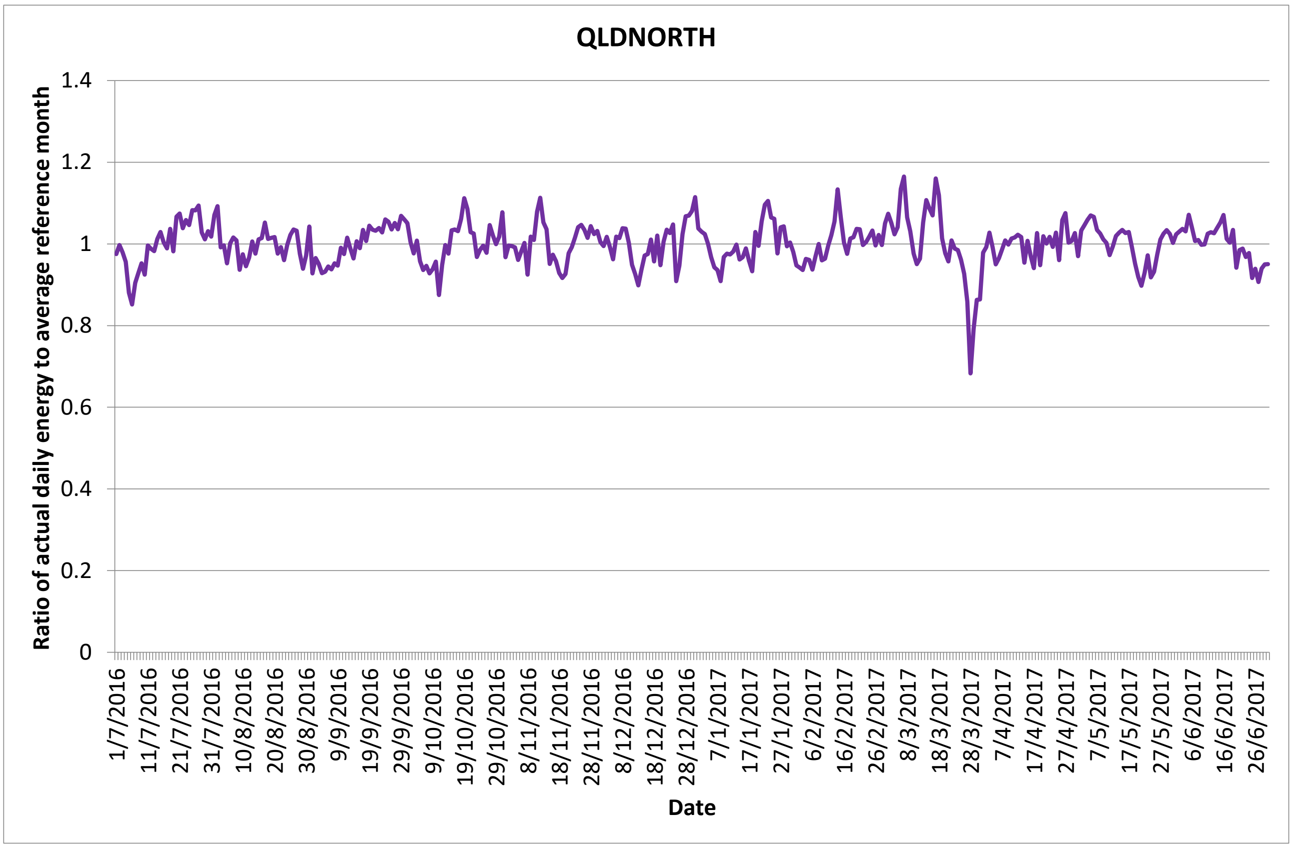

Figure 18: Volatility of daily energy values for QLD North (2016)

3 Motor D and inverter driven motors

3.1 Background on inverters

Inverter driven motors are common on air conditioner and refrigerator compressors. Single phase inverter driven systems typically use a single phase supply (230V/50Hz) and convert this to around 300V DC. An electronic inverter then takes this DC supply and generates a variable frequency three phase output that drives a small dedicated three phase motor, which in turn drives the compressor. In theory, inverter driven systems can operate at any frequency (or speed), but in practice, compressor frequencies are limited to specific fixed frequencies to avoid noise, vibration and resonance issues that can occur at specific frequencies. Most inverter driven compressors allow four or five different pre-set speeds of operation.

Inverters have several operating advantages: they are soft start and electronically controlled, the system can vary to the speed to match the cooling requirement and they tend to be quieter (which is one of their main attractions for consumers). Inverters can be more efficient at part load conditions (in which they tend to spend most of their operating life) as the flow of refrigerant can be reduced, which reduces temperature gradients across the evaporator and condenser. It also means that on-off cycling (which occurs in single speed systems under most conditions) is reduced or eliminated, thus reducing compressor start-up losses. Compressor start-up losses occur as the refrigerant continues to migrate around the vapour-compression system after the compressor stops and it takes some minutes to get back into equilibrium on starting (with low efficiency)(Harrington 2018). It is important to note that inverter systems and single speed systems may have similar efficiency at full load (no cycling of the compressor) – there is a divergence in overall operating efficiency as cooling (or heating) requirements reduce.

Inverter driven systems are of interest for this study as they are thought to disconnect from the grid on low voltage without going into thermal overload (electronic protection) before the motor stalls. Based on limited testing, they also appear to be much more resilient to fluctuations in supply voltage. So it is important to differentiate the share of traditional single speed compressor systems (that use a single phase induction motor with thermal overload protection) and inverter driven systems.

Inverter driven compressors are common in air conditioners. Single phase air conditioners tend to have a power input in the range 500W to 2000W. Inverter driven compressors are less common in household refrigeration systems. Household refrigerators tend to have a power input in the range 50W to 150W. However, the prevalence of inverter driven refrigerators is increasing fairly quickly. There are several factors driving this trend. One is that many of the world's major compressor suppliers are focusing much of their research and development efforts on smaller inverter systems, so suppliers that want to make high efficiency refrigeration products will usually find inverter driven compressors to be the best option. Increases in sales volume of these units is generating price reductions, making them more attractive for use in mainstream products.

Another important factor is that test methods and regulatory requirements for air conditioners and refrigerators have been recently modified to provide some reward to inverter driven systems. For air conditioners, regulations allowed compliance with Minimum Energy Performance Standards (MEPS[3]) at part load in 2010, which recognised that these systems are generally more efficient under normal operating conditions (E3 2009). From 2019, a new climate based labelling scheme is being introduced for air conditioners, based on a seasonal rating (E3 2018). This type of approach rewards systems that are more efficient under part load conditions. Many countries now have seasonal energy efficiency rating for air conditioners (e.g. USA, Europe, Japan), so this provides

[3] MEPS are minimum efficiency levels that are mandated through government regulation such as the federal Greenhouse and Energy Minimum Standards Act (GEMS).

strong incentives for inverter driven systems for mainstream products. The new zoned energy rating label and the old label are shown in Figure 19.

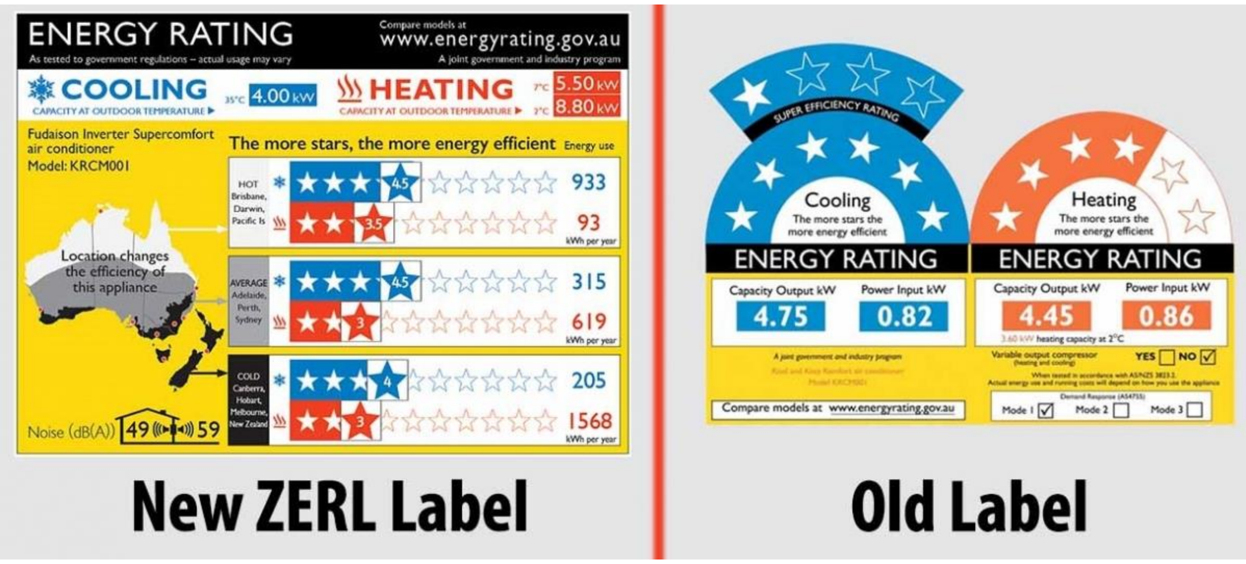

Figure 19: New zoned energy rating label and existing air conditioner rating label

For refrigerators, the current test method AS/NZS4474.1 measures energy consumption of the appliance in a hot room (32°C ambient) without any user interaction (AS/NZS4474. 1 2007). This represents a fairly heavy heat load on the appliance, so refrigerators have to work fairly hard to maintain compartment temperatures in these conditions. From 2019, a new regulatory approach is being introduced, which includes testing at both warmer and cooler conditions (32°C and 16°C ambient) and the inclusion of some user induced energy consumption (proxy for warm foods and door openings)(AS/NZS4474 2018; Department of the Environment and Energy 2019). This testing regime, and the more realistic weighting of cooler operating conditions to reflect normal use in the home, will mean that refrigerators with inverter driven compressors will achieve lower energy consumption and therefore higher star ratings on the energy label (better reflecting their performance in the home). This is expected to more rapidly drive the refrigerator market towards inverter driven compressors over the next five years.

3.2 Response of motors to low voltage conditions

3.2.1 Single phase induction motors (Motor D)

When a single phase induction motor is stationary when it starts or if it stalls in response to low voltage, the "locked-rotor" current generated is many times greater than the normal operating current (typically 3 to 7 times more). If the rotor is free and connected to a load of low inertia, this locked-rotor current flows for a very short time, and may not reach its full value if shaft speed is gained very rapidly. If the rotor is 'locked' (this could be because it is mechanically jammed, deliberately restrained for test purposes or from overload due to low voltage) then the locked rotor current will flow indefinitely, but with a gradually falling magnitude as the stator winding resistance rises from increasing temperature. As long as the locked-rotor current flows, the motor winding(s) heat rapidly[4].

Thermal safety protection to protect the motor is usually embedded into the windings (usually in the form of a simple bi-metal strip) and this pulls the motor electrically off-line after a short period under locked-rotor conditions, typically around 10 sec to 40 sec, but the time varies by the design of the

[4] Older single-phase so-called 'split-phase' machines have a separate relatively high resistance 'starting winding', which is normally switched off by either a thermal or centrifugally operated switch once the motor is at speed. Such windings in a stalled motor will 'burn out' in a very short time if unprotected. These motors are no longer used in refrigeration or air conditioners to any extent.

protection device and the stall current of the motor. The motor will stay disconnected until the bi-metal strip cools and automatically reconnects[5] (this is a mechanical process so the actual time varies, but is often of the order of a minute or two). There do not appear to be any published values for the time in overload once the motor stalls before protection is activated or the disconnection time until reconnection of the motor occurs. However, detailed measurements on 43 products do give some hard data for AEMO fault modelling software. These are fully documented in an associated report (Energy Efficient Strategies 2020).

Safety protection will activate on both high current and/or high temperature. Therefore the thermal trip protection becomes more sensitive in hotter ambient temperatures and under heavier loads. The thermal protection device will attempt to restart once the bi-metal strip cools. If the voltage is still low, the unit will be unable to start and will draw overload current until the thermal protection is reactivated. For self-resetting overload protection a design requirement is that, in the event of a motor stall (either by bearing failure or low supply voltage, for example), the over-temperature/current device must operate so that an indefinite number of energise/de-energise cycles will, at the very least, not lead to a fire.

3.2.2 Response of inverter driven motors to low voltage conditions

Inverter systems appear to be much more resilient to low voltage conditions. Based on test data, inverter controls in refrigerators tested appear to operate down to a supply voltage of around 50V AC without any obvious issues. Some disconnect the motor for a few seconds once the supply voltage dropped below 30V AC. None of the inverters measured showed any periods of high load or thermal overload currents that are present in single phase induction motors when they stall.

3.2.3 Response of digital controllers to low voltage

Many (but not all) digital controllers, commonly used on newer commercial refrigeration units, have sensors and smart controls to sense low voltage and pull the compressor off-line before it stalls under low voltage conditions. Most small single phase commercial refrigeration systems of interest for this study (with single phase induction motors) will still have thermal overload protection on the motor (as a backup). But it appears that many of the more sophisticated controllers will pull the motor off-line before it stalls on low voltage. This appears to be particularly true for larger compressors where stalling would generate very large overload currents and create electrical problems such as tripping circuit breakers. Field measurements on 28 separate commercial refrigeration products provided some insight into the operation and prevalence of these controllers.

3.3 Results of stall measurements on Motor D and inverter systems

To provide a deeper insight into product behaviour under low voltage conditions, AEMO commissioned EES to undertake some additional field measurements on a range of products to ascertain their behaviour under low voltage conditions. The main sources of products measured were:

- Household refrigerators and freezers in private households (13), including 5 inverter driven appliances
- Household freezers in commercial premises (1)
- Commercial refrigerators and freezers in several commercial food operations (6)
- Commercial refrigerators and freezers on display in a commercial kitchen showroom (22)(mix of new and second hand products)
- One inverter driven pool pump in a private household

[5] There are several approaches to protection, the most common being self-resetting (e.g. bimetal strips), which are commonly used in small single phase induction motors found in refrigeration compressors. Some motors have a manual reset protection and some have a thermal fuse, which requires replacement if activated. However, manual reset and thermal fuse protection are not usually used in small single phase induction motors used in refrigeration and air conditioners.

- One additional commercial refrigerator in a commercial food operation was measured but a valid result regarding motor protection could not be obtained due to electrical overload.

While these tests were not conducted in a laboratory setting, high quality measurement equipment was used. Energy measurements were recorded on a Yokogawa WT200 digital power analyser, which was connected to a laptop. Data was recorded at 0.5 sec intervals. A single phase variac was used to vary the supply voltage to the equipment during testing. Changes in supply voltage to the appliance only were recorded by the Yokogawa instrument. Full technical details of the measurements as well as raw data are set out in a separate report and associated spreadsheets (Energy Efficient Strategies 2020). An example of the type of data collected is illustrated in Figure 20. Note the high power when the compressor starts. The power increases only marginally once the motor stalls, but this increases by a factor of five or more once the supply voltage reverts back to nominal. Note the different power factor when stalled. As predicted by theory, the power when stalled reduces over time as the windings heat up and resistance increases.

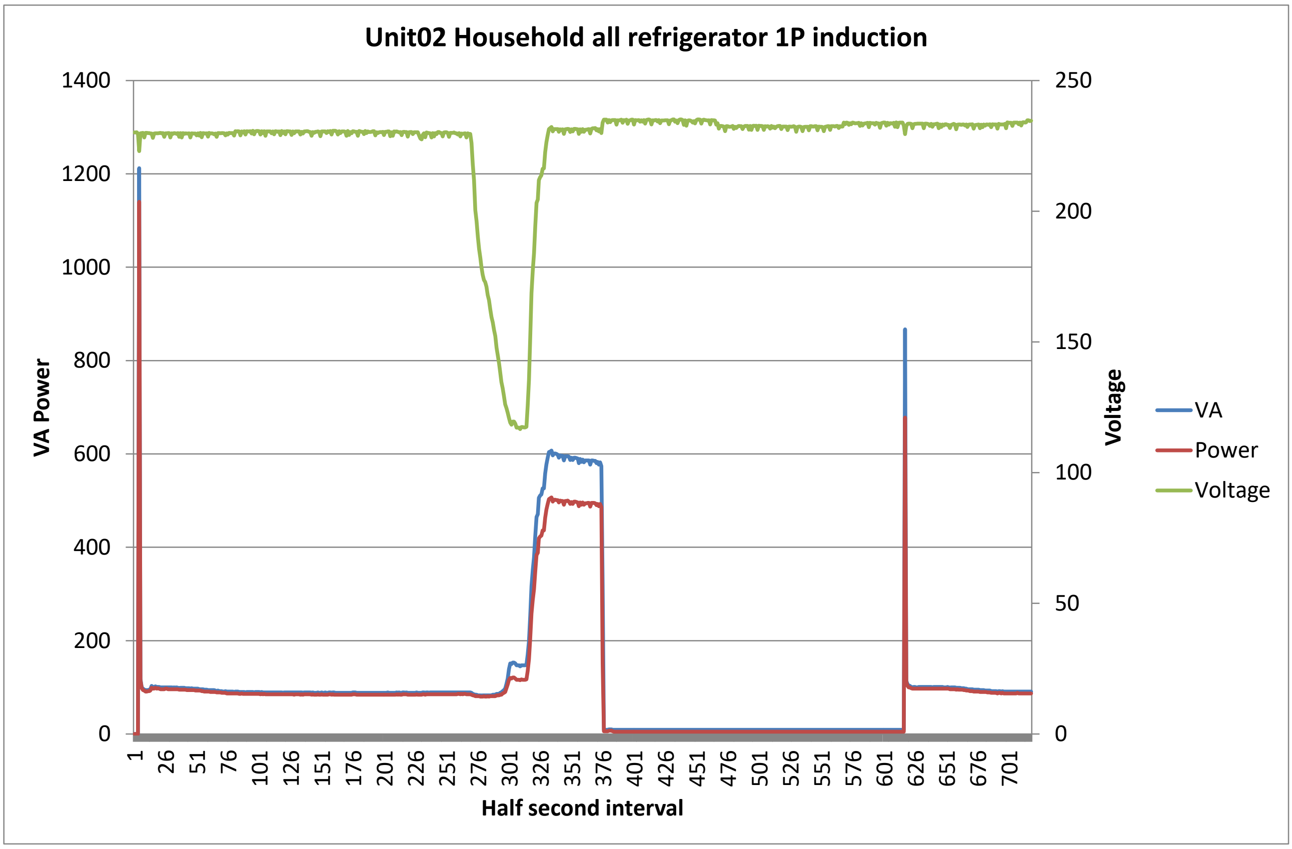

Figure 20: Example of low voltage stall data for a household refrigerator

A summary of the key results by product type and protection type are included in Table 6.

Table 6: Overview of average results of single phase motors subjected to low voltage conditions

Sector	Count	On power W	On Power Factor	Stall/ disconnect V	Protection	Stall Power at 230V	Stall Power Factor	Stall time sec	Off time to restart sec	Ratio Stall P to Operating Power
Household	9	98.4	0.80	112.1	Thermal	796.2	0.84	23.9	106.3	8.2
Household	5	117.2	0.76	18.2	No stall	#N/A	#N/A	#N/A	#N/A	#N/A
Household	1*	152.0	0.64	155.0	Disconnect	#N/A	#N/A	#N/A	11.0	#N/A
Commercial	8	304.1	0.62	113.1	Thermal	1736.6	0.88	15.4	60.6	7.3
Commercial	3	460.0	0.77	25.3	No stall	#N/A	#N/A	#N/A	#N/A	#N/A
Commercial	16	445.0	0.66	102.6	Disconnect	#N/A	#N/A	#N/A	112.6	#N/A

Notes: Measurements by the author, supply voltage to the appliance adjusted via a variac; power, voltage and power factor measured using a Yokogawa WT200. **Household/Thermal** were typically refrigerators with single speed compressors. **Household/No Stall** were inverter driven household refrigerators. Household unit marked * is an inverter driven pool pump. **Commercial/Thermal** were typically refrigeration units with single speed compressors. **Commercial/Disconnect** were typically commercial refrigerators with single speed compressors where the digital controller disconnected the compressor in low voltage conditions. **Commercial/No Stall** were units that appeared to be able to operate through very low voltage conditions without stalling. It is unclear how this was achieved. Where the motor stalled, the stall power was typically found to be 7 to 8 times the normal operating power when operating at the nominal supply voltage (equivalent to the motor start in-rush current)(varied from 2 to 13 times). Refer to the main report and associated spreadsheets for details (Energy Efficient Strategies 2020).

3.4 Discussion of low voltage motor test results

The testing approach for these additional measurements was agreed with AEMO to reflect a more typical supply fault scenario of a short duration voltage drop for a second or two (sufficient for the motor to stall) and then reversion to the normal supply voltage (nominally 230V). Common historic disturbances analysed by AEMO’s DER team include short duration single-phase-ground faults resulting in an under-voltage event, which may or may not cause the motor D type equipment to stall.

These test results were commissioned as a variation to the original project brief to provide insights to single phase induction motor behaviour under low voltage conditions. Firstly, the behaviour of household refrigeration systems was as expected. Most single speed compressors have thermal overload protection when the motor stalls and typically these motors stall when the supply voltage drops to around 110V AC. Once stalled at low voltage, however, the power consumed by the motor is similar to the operating power, but when the voltage reverts back to nominal, the power consumed by the stalled motor is typically seven to eight times the normal operating power. Note for several household and commercial refrigeration systems that went into thermal overload, the motor did not restart normally after the first thermal trip once the supply voltage was back to normal. Of the 17 models that activated thermal overload protection once the motor had stalled, three entered overload protection twice before the motor started normally and three entered overload protection three times before the motor started normally (i.e. about one third experienced multiple thermal overloads before resuming normal operation). When a compressor stops, there is significant refrigerant gas back-pressure from the condenser that takes some minutes to dissipate. If a single phase induction motor attempts to start too quickly after any sort of interruption, the motor load may be too large to allow a normal start. This obviously depends on a number of factors such as the motor starting characteristics, the time between motor stalling and the attempted restart as well as the refrigeration system characteristics.

Five inverter driven household refrigerators were tested. These were all remarkably robust and the compressor motor did not stall or the controller disconnect, even when the supply voltage was reduced to 50V AC. The input power was generally in proportion to the supply voltage, but the unit immediately reverted to normal operation once the voltage was returned to normal. There was no increase in consumption under a very low voltage condition or during any transition.

An inverter driven pool pump was tested. This kept a constant input power with reduced voltage and the controller pulled the motor off-line once the voltage dropped to around 155V. The unit commenced operation again once the voltage resumed to >220V. There were no surges or increases in power at any time under a low voltage condition. It was not possible to test inverter driven air conditioners as these are almost always hard wired at the switchboard. However, it is expected that they will behave in a similar manner to the inverter driven refrigerators (the unit will operate through many low voltage conditions at reduced power and the controller will pull the motor off-line once a critical low voltage is reached with no power surges).

The commercial refrigeration examples were very revealing. Around 30% of the models tested had single speed induction motors (Motor D) that stalled at low voltage. The thermal protection on these units disconnected the compressor after a short period. Around 60% of units tested had single speed induction motors (Motor D) with digital controllers that protected the motor. Under low voltage conditions, the digital controller disconnected the compressor before it stalled, so there was no surge current. The digital controller then restarted the compressor again after a short period that varied considerably across units. A further 10% of units did not appear to stall under even very low voltage conditions and did not exhibit any surge in power. Given the configuration and vintage of these particular units, this appears to be a fortunate combination of product configuration, voltage profile and operating state at the time of the test that allowed this to happen, rather than any specific design attribute or control equipment.

While most small commercial refrigeration units still use single speed induction motors (Motor D), it would appear that most digital controllers are able to protect the compressor under low voltage conditions by disconnecting it without any surge currents. If the sample of 27 units tested is representative of the market, this suggests that the majority of newer commercial refrigeration products will have these features that avoid motor stalling and thermal overload, but with a significant minority of products still using thermal overload protection in low voltage conditions. Some of the suppliers interviewed are aware of these features in at least some digital controllers, but they were unsure whether the specific configuration of the controller is required for each model to allow it to disconnect the compressor before the motor stalls. Based on the measured data, changes in the stock share of commercial refrigeration with thermal overload protection and with digital controllers that disconnect the motor has been estimated, noting that most of the units measured in this sample were new or fairly new. This is included in Chapter 6.

3.5 Power factor

The power factor for small induction motors in refrigerators is typically in the range 0.3 to 0.95 (based on a check of around 20 models tested in a laboratory, plus the additional 14 units test for this report). While most refrigerators have start capacitors, it would appear that many do not have run capacitors to improve power factor. From the data reviewed, there was no clear pattern regarding power factor with respect to refrigerators – power factor could be high or low for both new and old units and single speed or inverter driven units. As set out in Table 6, the average power factor when stalled for household refrigerators was around 0.84 and this appeared to be very consistent and independent of the operating power factor. Similarly, the average power factor when stalled for commercial refrigerators, was around 0.88. While this was slightly more variable than for household refrigerators, it was quite consistent and appeared unrelated to the operating power factor.

In contrast to refrigeration systems, air conditioners generally have a high power factor, as there has been a regulatory requirement for a minimum power factor of 0.85 since 2011 in AS/NZS3823.2[6]. Many models have an operating power factor of well above 0.9. This applies to both inverter driven models and single speed models.

[6] The requirement of AS/NZS3823.2 is effectively a minimum power factor of 0.85 for air conditioners up to 15kW input power. Small units less than 850W input power can have a lower power factor but cannot exceed 1000VA. Larger units above 20kW input must have a power factor of at least 0.80 – these will all be three phase.

4 Air Conditioners

4.1 Stock of single phase air conditioners in the residential sector

The residential sector accounts for the vast majority of single phase air conditioners installed in Australia. However, a significant minority are installed in small and medium sized offices, which is examined later. This section documents data on the residential sector. The split between single phase induction driven systems (Motor D) and inverter driven systems (electronic load) is examined in a later section.

The first piece of data to consider is the penetration of air conditioners at a state level over time. This is illustrated in Figure 21.

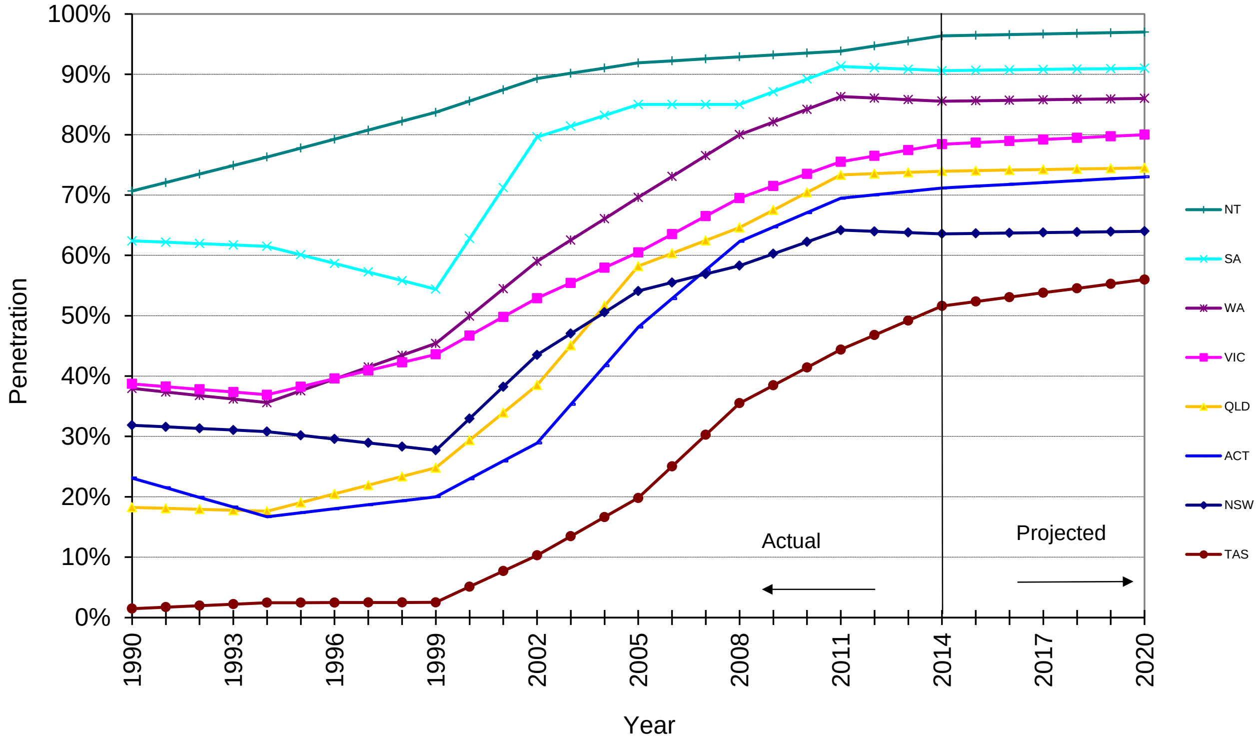

Figure 21: Estimated air conditioner penetration for all states and territories

Source: EES analysis of ABS data (Australian Bureau of Statistics 2014).

Importantly, this data shows that the rate of penetration has slowed considerably since 2010 and it is expected that only small changes will continue to 2020 and beyond. Note that 1 minus the penetration is the proportion of households that have no air conditioner. This data defines the stock of installed appliances at a state level. The adjusted households by region and sub-region with penetration provide a direct way of estimating the households with air conditioners for each NEM sub-region as required for this study. The estimated stock of main air conditioners by NEM sub-region is shown in Table 7.

Table 7: Estimated main air conditioners in 2020 by NEM sub-region

State/sub-region	Penetration	Households with ACs	Households with ACs in NEM
New South Wales	0.641	1,995,914	1,995,812
Victoria	0.802	2,063,015	2,062,973
Queensland	0.745	1,466,211	
Queensland North	0.745		230,085
Queensland Central	0.745		120,797
Queensland South	0.745		1,102,336
South Australia	0.908	657,545	656,378
Western Australia	0.863	879,924	0
Tasmania	0.562	129,218	128,606
Northern Territory	0.974	79,433	0
ACT	0.732	125,482	125,482
Total		**7,396,742**	**6,422,469**

The data in Table 7 gives an estimate of the number of households with at least one air conditioner (and a main air conditioner). ABS collect data on multiple air conditioners in the one house and this shows that, on average, there are around 1.25 air conditioners per house in Australia (this is called saturation and this is somewhat higher in Western Australia and the Northern Territory, which are of less interest for this study). Queensland has more than 1.5 air conditioners per house (for those houses that have an air conditioner). Multiple air conditioners tend to be split systems or window/wall units. There is some evidence that multiple units are used to cool different parts of the house (e.g. living area and bedrooms) and therefore they are not normally used in parallel (or only to a limited extent). Houses with central ducted systems are assumed to have only one system per household. On the basis that households with central and ducted air conditioners only have a single unit per household, it is possible to calculate an adjusted saturation estimate for each state and then separate these into main air conditioners and secondary air conditioners. The available power profiles are primarily for main air conditioners, so a supplementary load profile for secondary air conditioners needed to be developed.

For the purposes of this report, single phase air conditioners are split into 7 general categories of product as follows:

- Split systems reverse cycle (heating and cooling functions)
- Split systems cooling only
- Window wall systems reverse cycle
- Window wall systems cooling only
- Ducted systems reverse cycle
- Ducted systems cooling only
- Evaporative (mostly central, some portable).

These categories have been selected as the electrical characteristics and usage patterns of each is quite distinct in terms of estimating the load on the NEM throughout the year (most notably some heating load in winter for reverse cycle units only) and their penetration varies by state and region. The most comprehensive long term data set for air conditioner ownership in the residential sector is from the series of ABS surveys from 1994 to 2014 ABS4602.0 *Environmental Issues: Energy Use and Conservation* (Australian Bureau of Statistics 2014). Prior to 1994, ABS conducted several surveys in the 1980s, which allows the establishment of long term ownership trends (Australian Bureau of Statistics 1987). EES has undertaken detailed analysis of this data for many years and has also obtained detailed private cross tabs to provide a more detailed picture of air conditioner data at a state level. Projected stock share in 2020 has been estimated by EES based on historical trend data. When combined with data from Table 7, these figures provide an estimate of air conditioners by type by state and NEM sub-region.

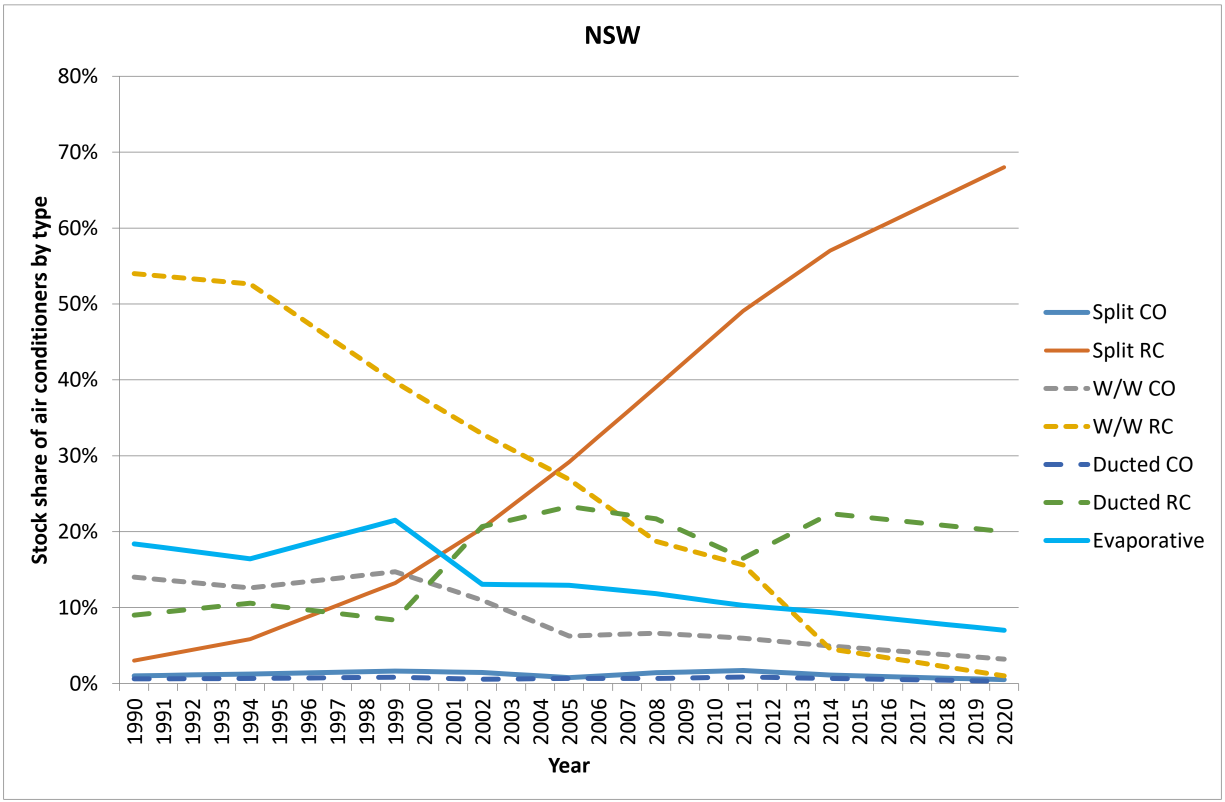

Figure 22: Historical trends in stock share by air conditioner type, NSW

Source: EES analysis of ABS data (Australian Bureau of Statistics 2014)

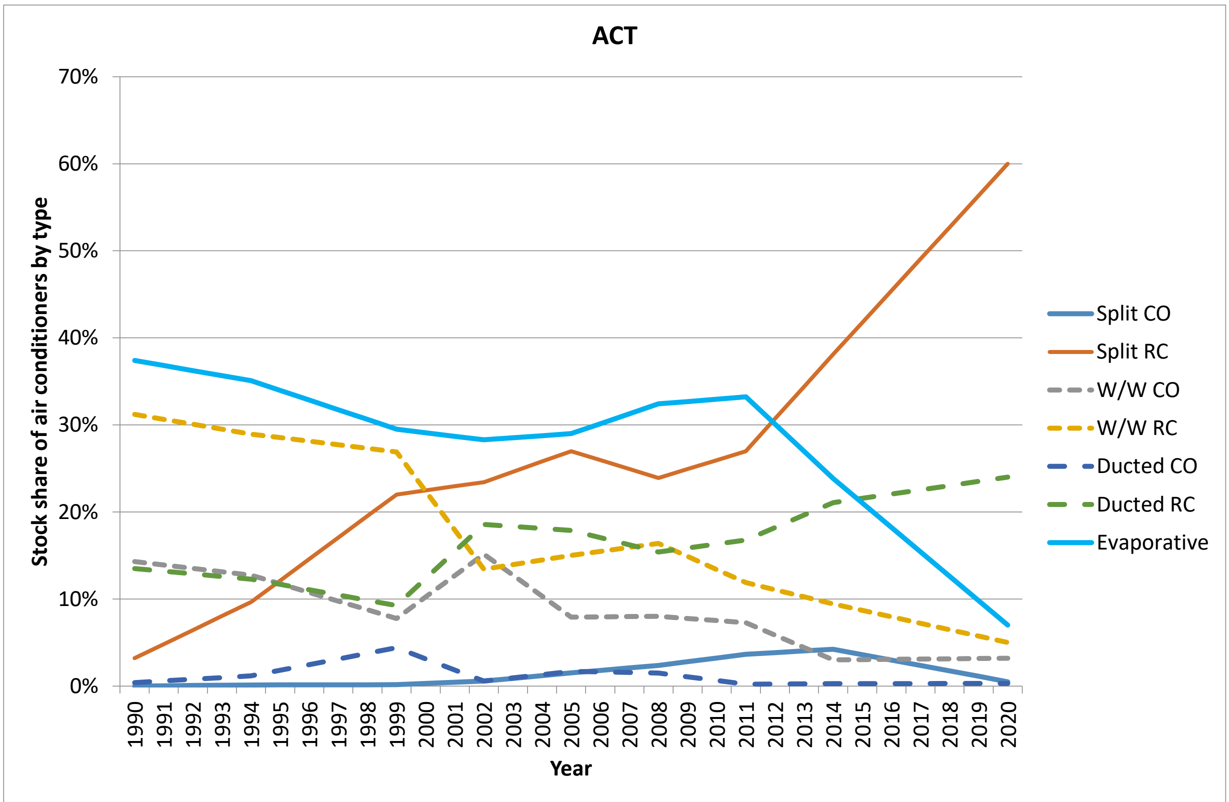

Figure 23: Historical trends in stock share by air conditioner type, ACT

Source: EES analysis of ABS data (Australian Bureau of Statistics 2014)

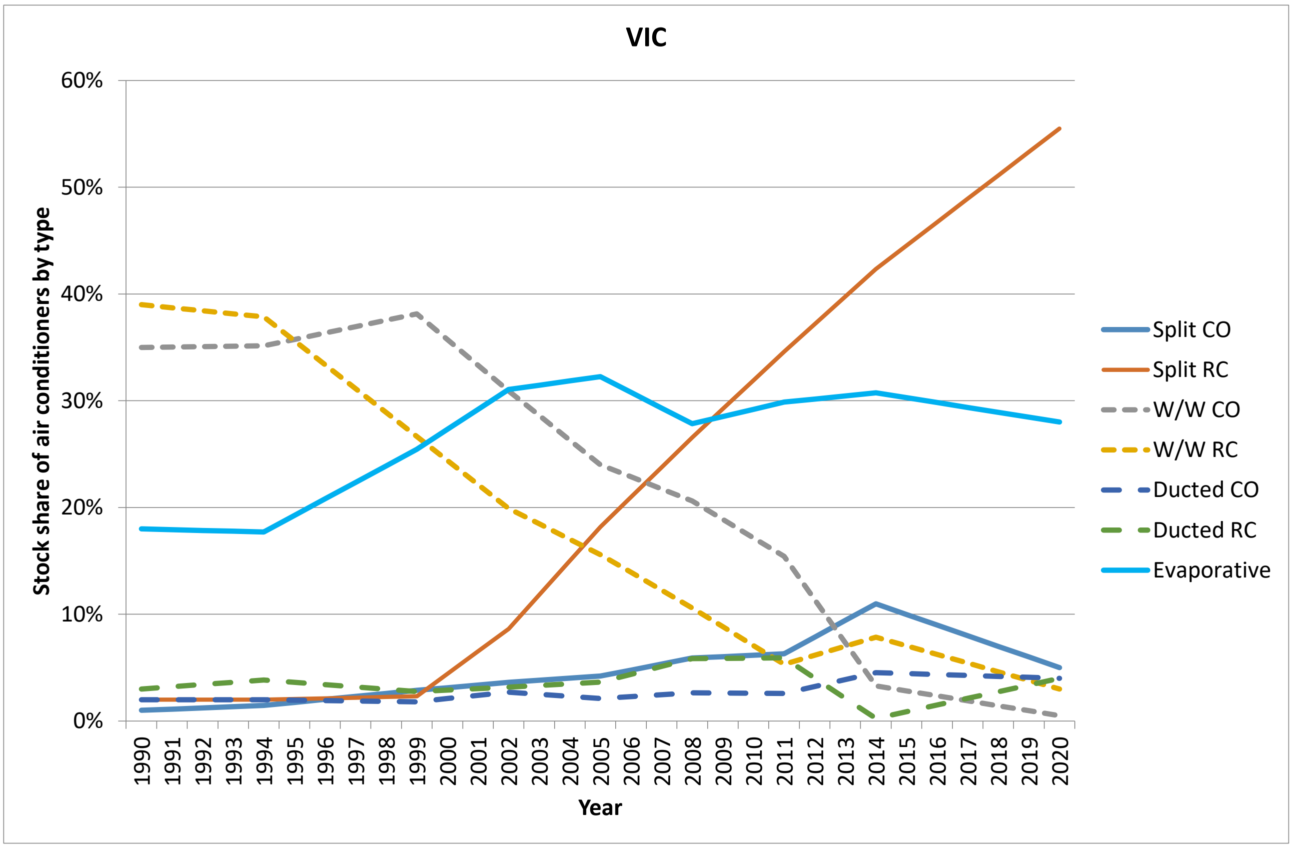

Figure 24: Historical trends in stock share by air conditioner type, Victoria

Source: EES analysis of ABS data (Australian Bureau of Statistics 2014)

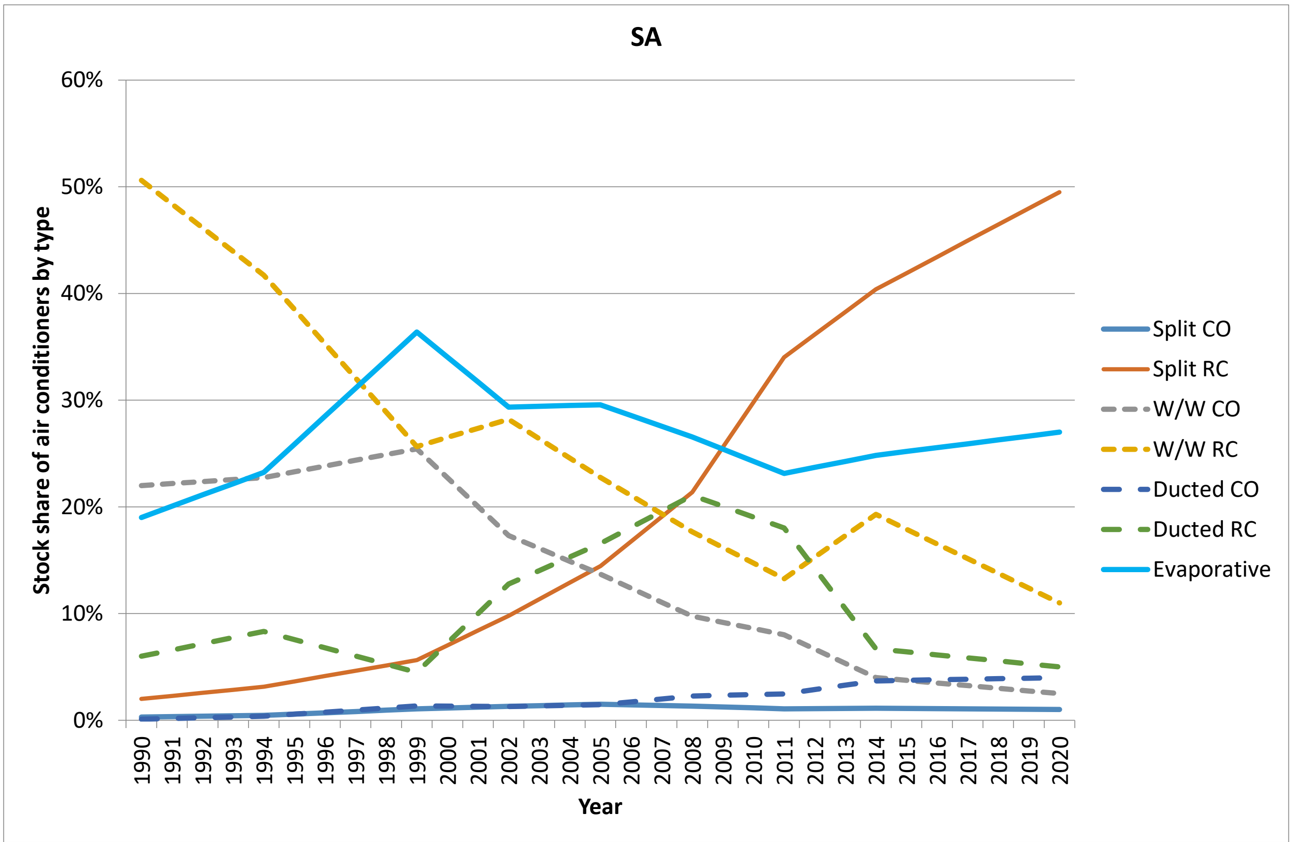

Figure 25: Historical trends in stock share by air conditioner type, South Australia

Source: EES analysis of ABS data (Australian Bureau of Statistics 2014)

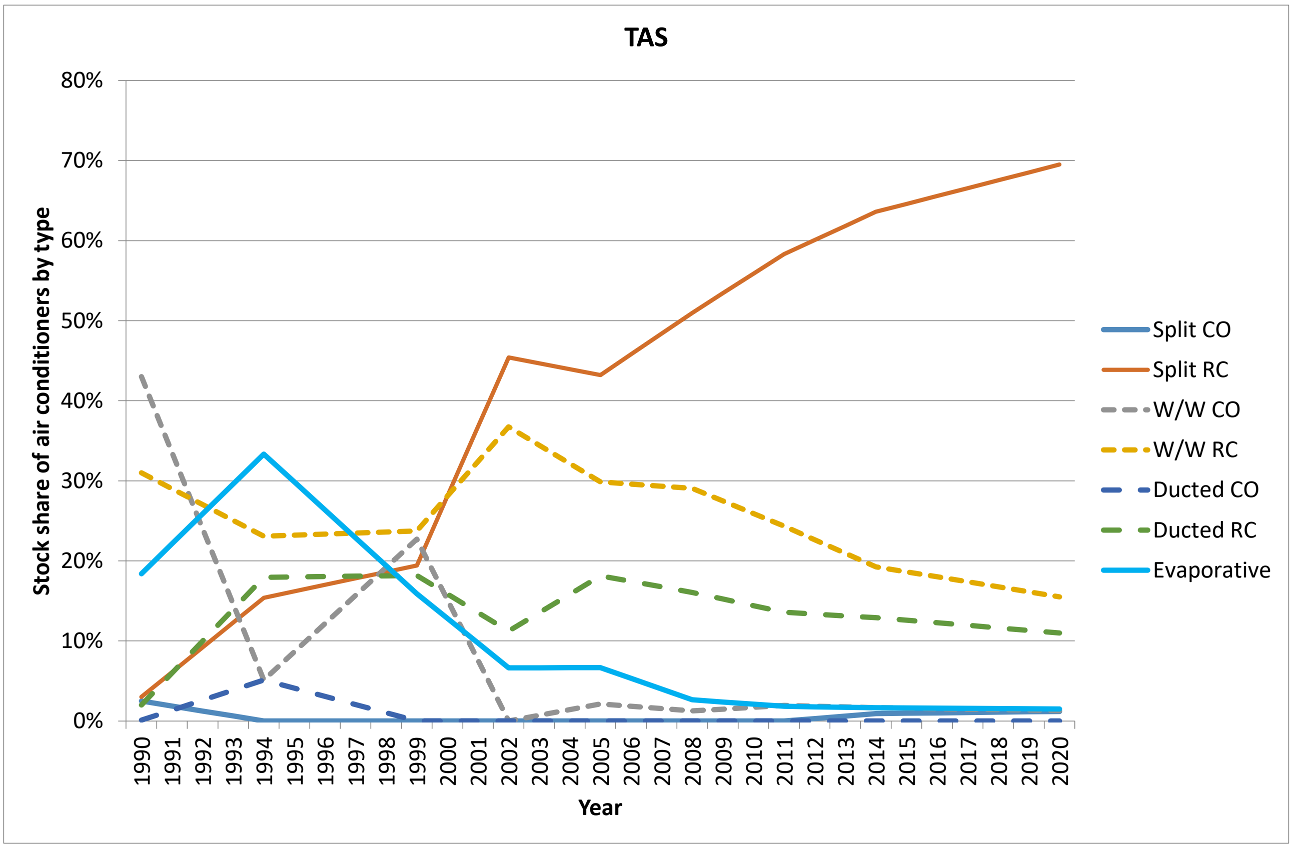

Figure 26: Historical trends in stock share by air conditioner type, Tasmania

Source: EES analysis of ABS data (Australian Bureau of Statistics 2014)

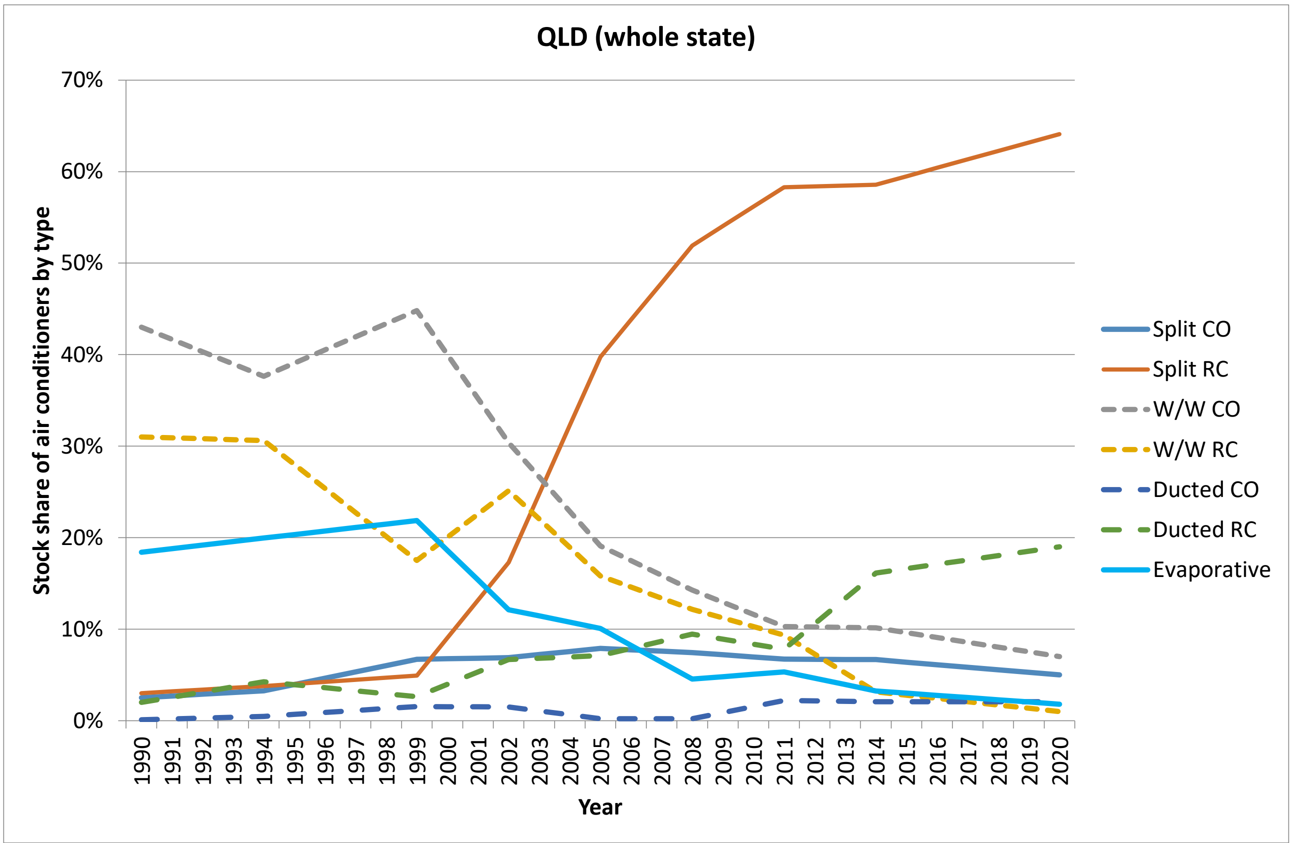

Figure 27: Historical trends in stock share by air conditioner type, Queensland (whole state)

Source: EES analysis of ABS data (Australian Bureau of Statistics 2014)

Queensland was split into three regions (called NEM sub-regions) for this study. There is only limited data on the differences in ownership between the capital city (nominally Brisbane for Queensland) and the balance of the state. However, in the 2014 survey, ABS published some data on the regional split for all states and territories (except the ACT) (Australian Bureau of Statistics 2014). The data for Brisbane is assumed to be representative for all of NEM Queensland South as Brisbane, the Gold Coast and the Sunshine Coast are all likely to have similar climate, demographics and ownership. Given that the ABS balance of state ownership data includes Gold Coast and the Sunshine Coast, it may understate the differences between south east Queensland and the NEM Queensland Central and NEM Queensland North sub-regions, but there is no way to directly quantify this difference given the available data.

The main differences between Brisbane and the “rest of Queensland” as defined by ABS are:

- Higher share of reverse cycle systems in Brisbane
- A corresponding lower share of cooling only systems in Brisbane
- Slightly lower share of evaporative cooling in Brisbane (but both are very low at around 2% or less, which is unsurprising in Queensland)
- Very similar share of houses with no air conditioning (both at around 26%).

Importantly, this illustrates that there is little difference in the penetration of air conditioners between Brisbane and the “rest of Queensland”, so the same overall penetration data can be used for all Queensland sub-regions. Further, separate stock share profiles were developed for Brisbane, which applies to NEM Queensland South and the balance of state, which applies to NEM Queensland Central and NEM Queensland North in order to split up the stock of air conditioners into different types. These are set out in Figure 28 and Figure 29.

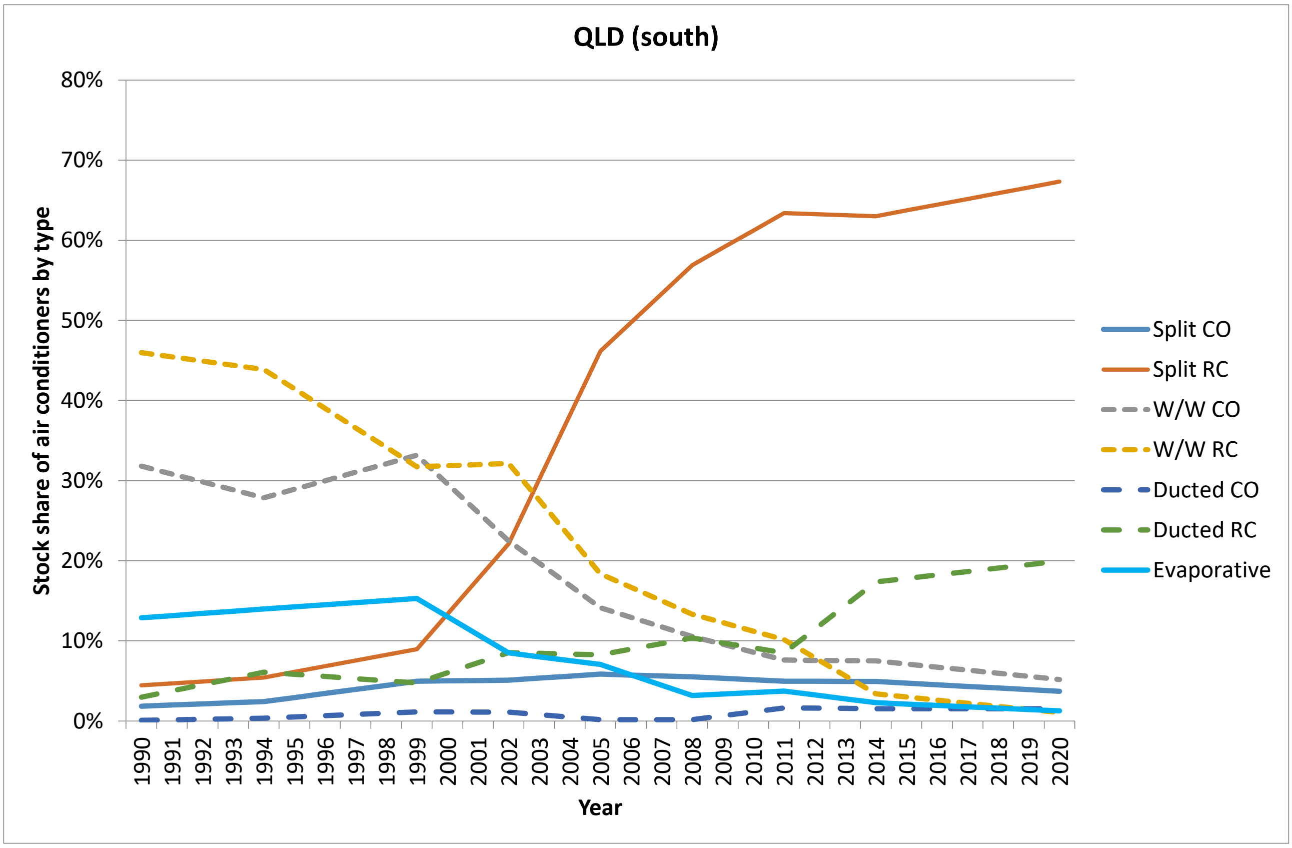

Figure 28: Historical trends in stock share by air conditioner type, Queensland (South)

Source: EES analysis of ABS data (Australian Bureau of Statistics 2014)

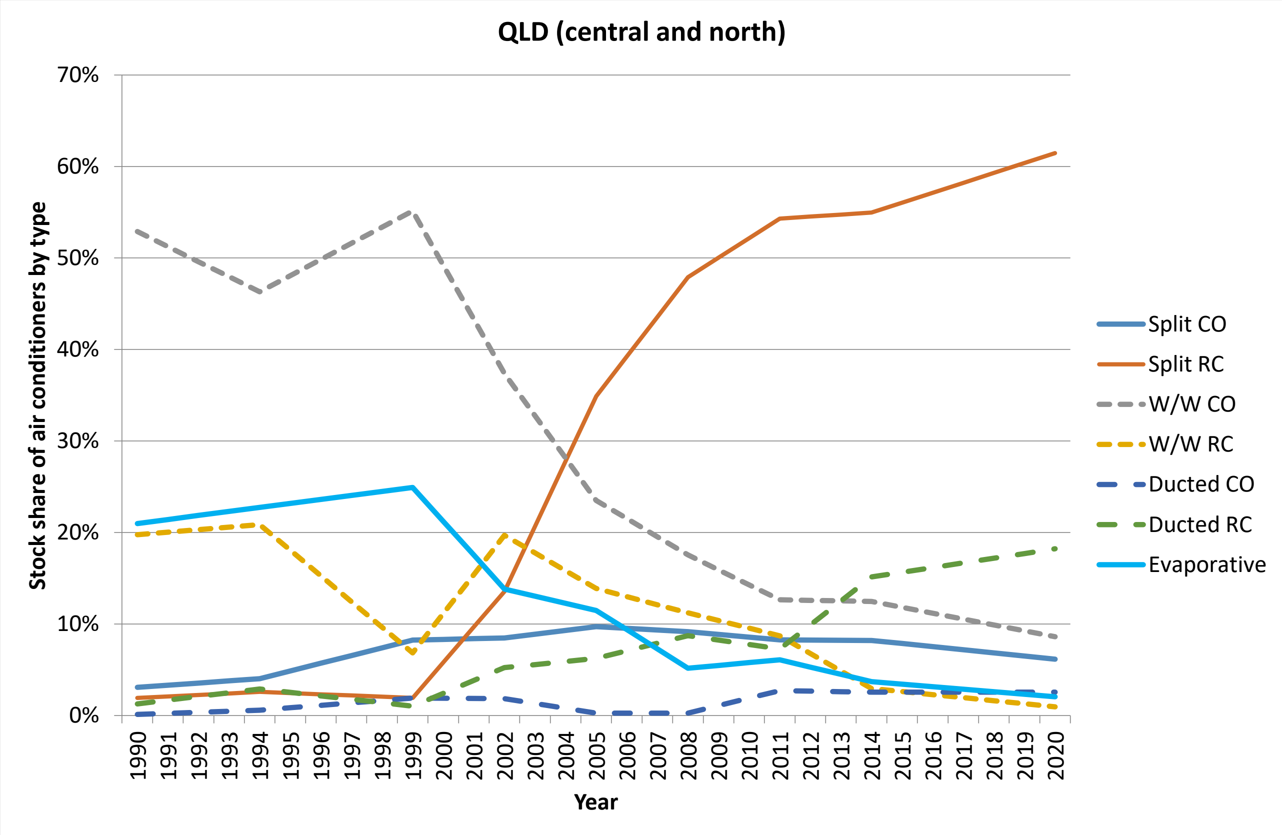

Figure 29: Historical trends in stock share by air conditioner type, Queensland (Central and North)

Source: EES analysis of ABS data (Australian Bureau of Statistics 2014)

In order to make estimates of the commercial stock of air conditioners (see Section 4.2), it is necessary to estimate the stock of all air conditioners in the residential sector throughout Australia. This uses data from ABS on the penetration (households with one or more of the appliance) and the saturation (average number of appliances per household for those household with the appliance) in order to estimate the ownership or stock of appliances installed (Australian Bureau of Statistics 2014). Table 8 shows the key data for each state and territory.

Table 8: Key data for estimating the stock of household air conditioners in Australia in 2020

State/ Territory	Population	Households	Penetration	Ownership	Saturation	Non-ducted Saturation
New South Wales	8,275,674	3,113,750	0.64	0.8064	1.26	1.356
Victoria	6,760,752	2,572,338	0.8	1.001	1.25	1.427
Queensland	5,188,076	1,968,069	0.745	1.28885	1.73	1.811
South Australia	1,760,207	724,168	0.91	1.092	1.2	1.408
Western Australia	2,655,657	1,019,611	0.86	1.204	1.4	1.661
Tasmania	535,855	229,926	0.56	0.6608	1.18	1.208
Northern Territory	254,322	81,553	0.97	2.328	2.4	2.556
ACT	438,275	171,424	0.73	0.7884	1.08	1.133
Other Territories	4,662	1,574	0.75	0.800	1.067	1.112
Australia	25,873,480	9,882,413				

Notes: Saturation is the average number of appliances per home for all types of air conditioners in those households that have an air conditioner. Non-ducted saturation is calculated on the basis that only one central or ducted system per home will be present, therefore giving a better estimate of saturation for non-ducted systems.

Detailed analysis shown above and also from other studies gives an estimate of the share of each type of air conditioner by state and territory as follows.

Table 9: Estimated share of household air conditioner types by state in 2020

State/ Territory	Split cooling only	Split reverse cycle	Window wall cooling only	Window wall reverse cycle	Ducted cooling only	Ducted reverse cycle	Evaporative (all types)
New South Wales	0.5%	68.0%	3.2%	1.0%	0.3%	20.0%	7.0%
Victoria	5.0%	55.5%	0.5%	3.0%	4.0%	4.0%	28.0%
Queensland	5.0%	64.1%	7.0%	1.0%	2.1%	19.0%	1.8%
South Australia	1.0%	49.5%	2.5%	11.0%	4.0%	5.0%	27.0%
Western Australia	1.1%	51.7%	2.6%	5.1%	2.5%	12.0%	25.0%
Tasmania	1.2%	69.5%	1.3%	15.5%	0.0%	11.0%	1.5%
Northern Territory	34.4%	54.5%	1.1%	0.0%	2.0%	1.0%	7.0%
ACT	0.5%	60.0%	3.2%	5.0%	0.3%	24.0%	7.0%
Other territories	0.5%	68.0%	3.2%	1.0%	0.3%	20.0%	7.0%

Data in Table 9 allows the stock of air conditioners by type to be estimated as follows.

Table 10: Estimated national stock of household air conditioner types by state in 2020

State/ Territory	Split cooling only	Split reverse cycle	Window wall cooling only	Window wall reverse cycle	Ducted cooling only	Ducted reverse cycle	Evaporative (all types)
New South Wales	13,534	1,840,615	86,617	27,068	5,988	399,183	139,714
Victoria	147,232	1,634,278	14,723	88,339	82,521	82,521	577,644
Queensland	132,774	1,702,157	185,883	26,555	30,440	278,580	26,743
South Australia	9,259	458,335	23,148	101,852	26,302	32,877	177,537
Western Australia	16,225	755,520	37,858	74,722	21,998	105,591	219,981
Tasmania	1,873	108,495	2,029	24,197	0	14,214	1,938
Northern Territory	69,901	110,632	2,162	0	1,589	794	5,560
ACT	711	85,295	4,549	7,108	376	30,116	8,784
Other territories	6	833	39	12	3	220	77
Total by type	**391,515**	**6,696,160**	**357,008**	**349,853**	**169,217**	**944,096**	**1,157,978**

Notes: Assumes a saturation of 1.0 applied to ducted and evaporative systems, with the non-ducted saturation applied to split systems and window wall systems.

Based on the above penetration trends by NEM sub-region, it is possible to estimate the stock of main air conditioners by type in 2020 as set out in Table 11, and secondary air conditioners as set out in Table 12.

Table 11: Estimated stock of main residential air conditioners in 2020 by NEM sub-region

NEM sub-region	Split cooling only	Split reverse cycle	Window wall cooling only	Window wall reverse cycle	Ducted cooling only	Ducted reverse cycle	Evaporative (all types)
New South Wales	9,979	1,357,152	63,866	19,958	5,987	399,162	139,707
Victoria	103,149	1,144,950	10,315	61,889	82,519	82,519	577,632
Queensland North	14,150	141,407	19,810	2,206	5,875	41,915	4,721
Queensland Central	7,429	74,240	10,401	1,158	3,085	22,006	2,479
Queensland South	40,786	742,084	57,101	11,577	16,935	219,963	13,889
South Australia	6,564	324,907	16,409	72,202	26,255	32,819	177,222
Tasmania	1,543	89,381	1,672	19,934	0	14,147	1,929
ACT	627	75,289	4,015	6,274	376	30,116	8,784
Connected to the NEM	**184,227**	**3,949,410**	**183,589**	**195,198**	**141,032**	**842,647**	**926,363**

Notes: Assumes a saturation of 1.0 for main appliances. Includes three phase.

Table 12: Estimated stock of secondary residential air conditioners in 2020 by NEM sub-region

NEM sub-region	Split cooling only	Split reverse cycle	Window wall cooling only	Window wall reverse cycle
New South Wales	3,554	483,369	22,747	7,108
Victoria	44,081	489,295	4,408	26,448
Queensland North	9,905	98,985	13,867	1,544
Queensland Central	5,200	51,968	7,280	811
Queensland South	34,668	630,772	48,536	9,840
South Australia	2,679	132,615	6,698	29,470
Tasmania	321	18,600	348	4,148
ACT	83	10,005	534	834
Connected to the NEM	**100,491**	**1,915,609**	**104,418**	**80,203**

Notes: Assumes a saturation of 1 minus the non-ducted saturation in Table 8 for each NEM sub-region.

For the purposes of modelling for this report, a detailed stock model was used to generate an estimate of each air conditioner type set out in the tables above for each year from FY 2012-13 to 2018-19 inclusive.

4.2 Commercial air conditioner stock

There is relatively poor data on the stock of single phase non-residential air conditioners in Australia. The commercial sector uses a mixture of single phase and three phase products and most stock and building data do not differentiate these products. Suffice to say that the majority of the air conditioning load in the commercial sector will be provided by three phase products. Much of the air conditioning for larger high rise offices and commercial buildings is provided by chillers, which are typically 100kW and above. The most reliable approach to estimating the single phase stock is to examine total sales over a long period to estimate the stock indirectly, assuming a given lifetime and retirement function. From the over overall stock estimates, an estimate of the commercial air conditioner stock can be developed after the removal of the residential air conditioner stock, which is well documented (as shown in Section 4.1).

A range of sources have been used to provide a reliable data set on sales of single phase air conditioners by type over the period 1990 to 2018 as illustrated in Figure 30. Note that the annual sales of air conditioners are quite volatile and depends on a range of factors such as weather, economic conditions and building activity.

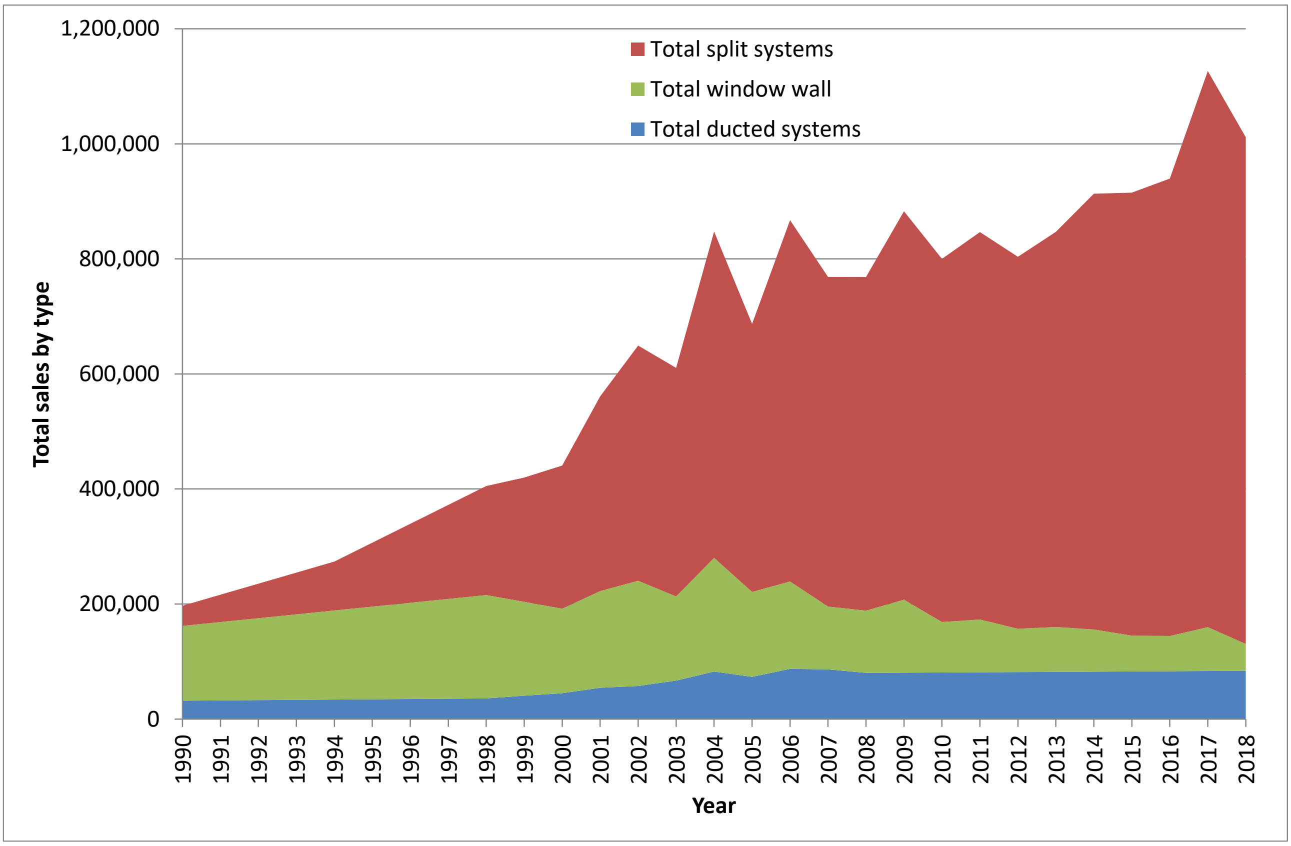

Figure 30: Total single phase air conditioner sales by type, 1998 to 2018

Notes: Single phase air conditioner sales stream compiled from a range of sources, including internal industry sources (George Wilkenfeld and Associates 1993, 2001; E3 2009, 2018; BIS Shrapnel 1988, 2006, 2010; Informark 2008). This figure does not include multi-head split systems. No sales on evaporative air conditioners was available, but good data in residential stock is available.

Figure 30 illustrates that single split system sales were less than half of the market in 1998, with window wall sales almost equal to split systems. Over the past 20 years, sales of split systems have increased substantially and now account for 85% of single phase air conditioner sales. Window wall systems have been in continuous decline for 30 years and now represent about 4% of the single phase air conditioner market. Ducted systems have remained at a fairly constant 8% of the total single phase air conditioner market (noting that many ducted systems are three phase and are excluded from this analysis).The remaining 3% to 5% of the market is multi-head split systems (including VRF systems), which are not shown in Figure 30. The sales of multi-head systems have grown in line with single split systems. Multi-split systems have been regulated for energy efficiency since 2014 (AS/NZS3823.2 2013). Most larger systems are three phase, so are out of scope for this study. There has been little direct sales data available in the past four years, but the assumed sales share in the stock model is an increase from 3% in 2016 to 6% in 2020.

The detailed market data also showed that the share of reverse cycle systems as a share of the total was highly consistent for all years at about 90% of split systems and over 95% of ducted systems (BIS Shrapnel 1988, 2006, 2010; Informark 2008). In contrast the share of reverse cycle window wall system was consistently lower at about 40% over the whole period. These trends are reflected in all the major data sources used to compile the sales stream.

Once this sales stream has been put through a stock model, an estimate of the total stock installed in Australia by air conditioner type can be generated. For this report, an assumed lifetime of 12 years has been used with a standard normal distribution retirement function as set out in Figure 31.

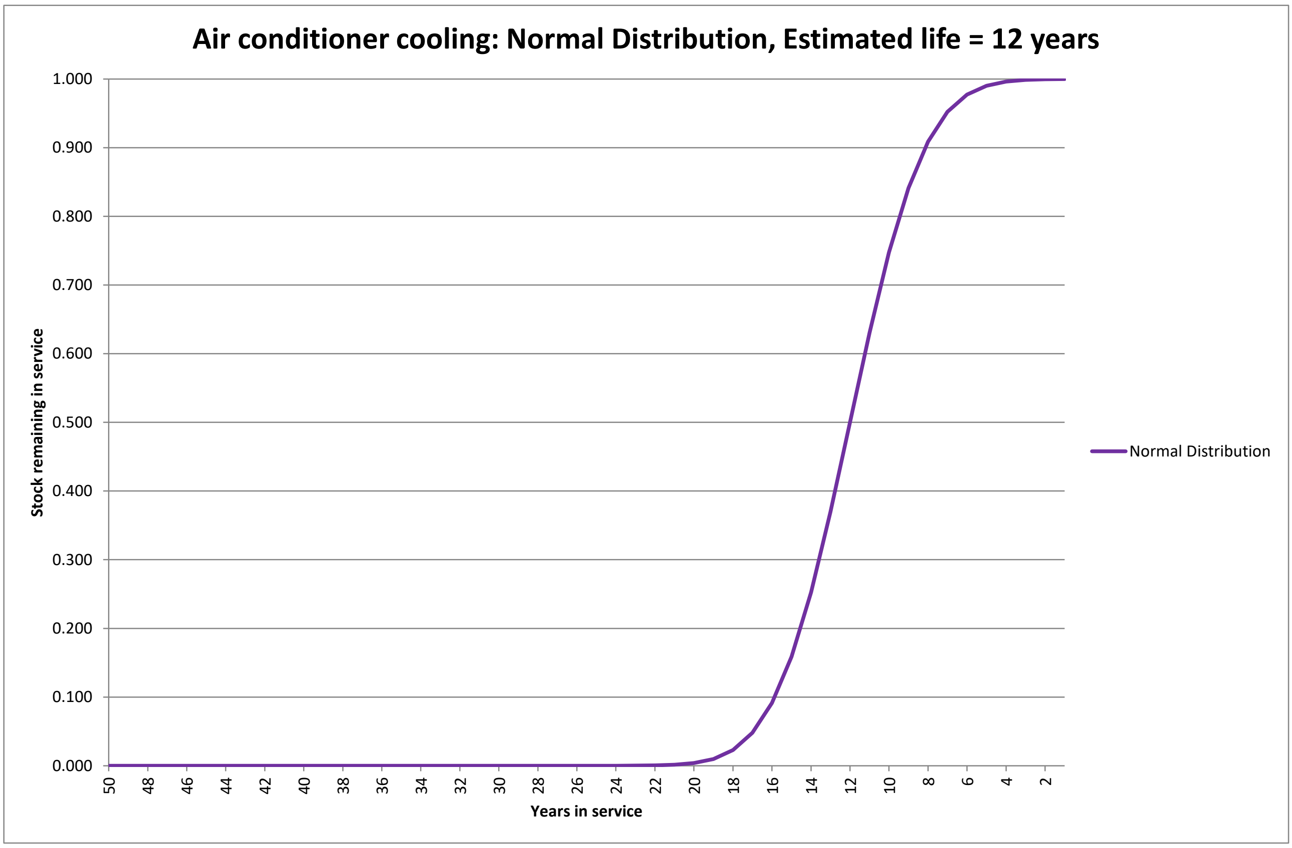

Figure 31: Retirement function (stock remaining) for air conditioner stock model

Once the sales stream for each of the four main air conditioner types has been put through the stock model, the estimated national stock of single phase air conditioners in 2020 can be generated, as shown in Table 13.

Table 13: Estimate of total and commercial stock of single phase air conditioners by type

Air conditioner type	Split cooling only	Split reverse cycle	Window wall cooling only	Window wall reverse cycle
National stock from sales stock model	889,585	8,397,828	540,427	360,971
Residential stock – national	391,515	6,696,160	357,008	349,853
Commercial stock – national	498,070	1,701,668	183,419	11,118
Commercial share of national stock	56.0%	20.3%	33.9%	3.1%

Notes: Derivation of residential stock is shown in Table 10.

The total stock of single phase ducted systems generated by the stock model (992,801 units in 2020) was slightly smaller than the stock of residential ducted air conditioners estimated from ownership data (which covers single and three phase stock = 1,113,313). This suggests that the vast majority of ducted systems are installed in residential households and almost all residential non-ducted stock is single phase (E3 2009; Energy Efficient Strategies 2008; E3 2018). On the basis of this data, an adjustment factor of 0.8917 has been applied to the residential stock for ducted systems in Table 11 to provide an estimate of single phase ducted units. This gives an estimated stock of single phase units of 877,200 units in 2020 within all NEM sub-regions.

The stock model also suggested a much lower proportion of cooling only ducted units when compared to the ownership data (Australian Bureau of Statistics 2014). This suggests that there may be some misreporting in the ABS surveys, along the lines that reverse cycle units are more commonly installed, but owners do not know that they can both heat and cool (or chose not to use the heating function). For the purposes of this report, it is assumed that the share of cooling only and reverse cycle ducted systems installed in the residential sector is as reported by ABS, as this is more reflective of normal consumer use (even though industry sales data is likely to be more accurate).

There is little data on evaporative systems, except for the residential sector. For this report it is assumed that evaporative systems are only installed in the residential sector, which should be a reasonable assumption. Most evaporative systems will use Motor D for fans and water pumping. The share of air conditioners that are evaporative in Victoria and South Australia is about 25%, while in NSW and ACT it is around 7%. Evaporative coolers make up a very small share in other NEM sub-regions (2% or less). Evaporative coolers offer a very different energy service to refrigerative air conditioners and their use is generally restricted to warm, dry climates. There is almost no end use metering data available, so making an adjustment to the total air conditioner load to account for evaporatives is based on very limited engineering estimates only. Evaporative systems are difficult to equate to conventional air conditioners as their use may tend to be more binary in nature (on or off) and there are limited adjustments with respect to capacity once operating. Their use also requires gaps in the building shell to allow externally cooled air that is pumped into the building to exit (typically through open windows or vents, resulting in high air exchange rates). Based on an examination of the existing data sets, it is estimated that evaporative systems will behave most like a cooling only split system in terms of use patterns and coincident demand, except with around 30% of the power input on average. On this basis, subsequent energy values for cooling only split systems (times a factor of 0.3) have been used to develop annual energy profiles based on relative ownership for evaporative systems in all states. These are most significant in Victoria, South Australia, NSW and ACT with negligible impacts in other NEM sub-regions.

The commercial stock of single phase air conditioners can then be broken down into NEM sub-region on a population basis as shown in Table 14.

Table 14: Estimated stock of commercial air conditioners in 2020 by NEM sub-region

NEM sub-region	Split cooling only	Split reverse cycle	Window wall cooling only	Window wall reverse cycle
New South Wales	159,300	544,253	58,664	3,556
Victoria	130,143	444,638	47,927	2,905
Queensland North	15,672	53,545	5,771	350
Queensland Central	8,228	28,112	3,030	184
Queensland South	75,086	256,533	27,651	1,676
South Australia	33,824	115,561	12,456	755
Tasmania	10,266	35,075	3,781	229
ACT	8,437	28,825	3,107	188
Connected to the NEM	**440,956**	**1,506,542**	**162,387**	**9,843**

As for residential air conditioners, for the purposes of modelling for this report, a detailed stock model was used to generate an estimate of each type of air conditioner type set out in the tables above for each year from FY 2012-13 to 2018-19 inclusive.

4.3 Share of single phase inverter driven air conditioners

Inverter driven air conditioners appeared on the market in Australia in the 1990s, primarily in products originating from Japan. Industry statistics have documented the share of inverter driven split systems sales since the late 1990s, which provides useful long term trends (Informark 2008). This data was provided to the federal government on a confidential basis to assist in the regulation of inverter driven systems. The registration system, which is used to track regulated air conditioners, recorded whether the compressor is inverter driven (or not) since 2008 (Energy Rating 2020). This data is necessary as MEPS compliance can be at full load or at part load for inverter driven systems (between 50% and 85% of rated capacity) and the presence of an inverter affects its regulatory compliance (E3 2009, 2018; AS/NZS3823.2 2013). While the regulatory data does not record sales share by model, it appears to provide a good overall indication of the market trends over time as shown in Figure 32. It appears that the sales share of inverter driven models is higher than the share of models registered with inverters in any particular year, with a lag time of around four years. This is likely to be because the highest selling and most popular brands have adopted inverter driven products more quickly than the full mix of models on the market. In practical terms, there is little difference in the share of inverter model numbers registered by air conditioner type and year since 2008 – all types are on the same approximate trajectory. For this report, it is assumed that the blue market line (Informark data plus author extrapolations) is applied to all relevant air conditioner sales by year in order to estimate the stock of air conditioner models installed in any particular year. Note that window wall units are not shown in Figure 32. This is because registration data shows that virtually all window wall systems use single speed compressors driven by a single phase induction motor (Motor D). Since 2008, only 11 window wall models claim to use an inverter (it is unclear whether this is correct), from a total of 420 window wall registrations over that period. So for the purposes of this report, it is assumed that no window wall systems use an inverter.

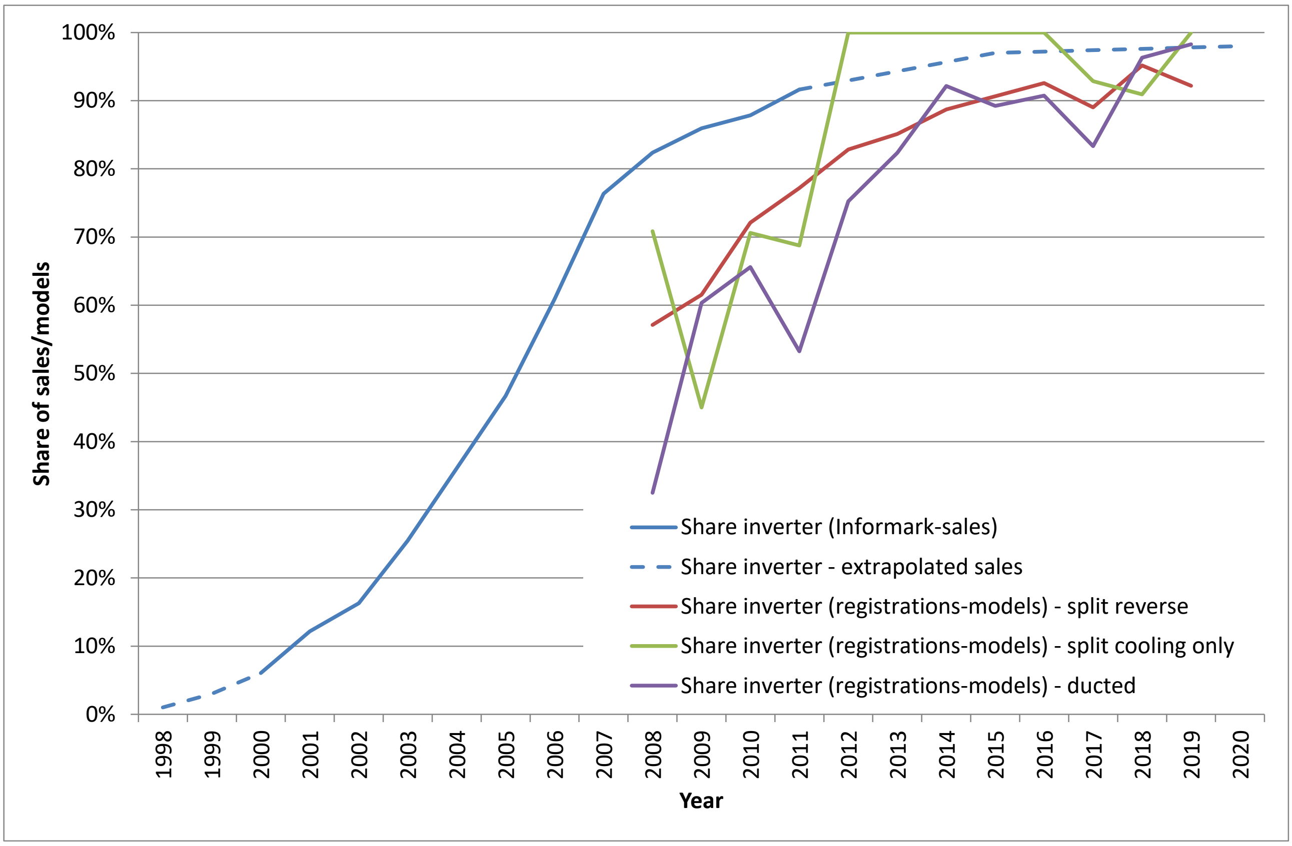

Figure 32: Share of inverter driven air conditioners by type – various sources

Notes: Market share of inverters from industry sources tracks single split system sales (Informark 2008). Registration data tracks models registered by year and type and is publicly available (Energy Rating 2020). Extrapolated sales share from author estimates.

The data shown in Figure 32 is the share of inverters sold into the market in Australia. In order to estimate the stock of inverters installed, it is necessary to put this share through the same stock model that was used to estimate the stock of commercial air conditioners in the previous section (see Figure 31). This generates an estimate of the share of inverter driven air conditioners installed in Australia as shown in Figure 33. For single split systems (both reverse cycle and cooling only) and single phase ducted systems, the share of the stock that is inverter driven is estimated to be 93% in 2020. Around 98% of new single phase air conditioners now sold each year (in 2020) (split and ducted systems) are estimated to be inverter driven. Based on these trends, the stock share of inverter driven air conditioners is likely to rise from 93% in 2020 to 97% by 2025. As noted previously, for this report it is assumed that none of the window wall units installed have inverter driven compressors. Note that the market share and absolute sales of window wall units has been declining gradually for over 20 years.

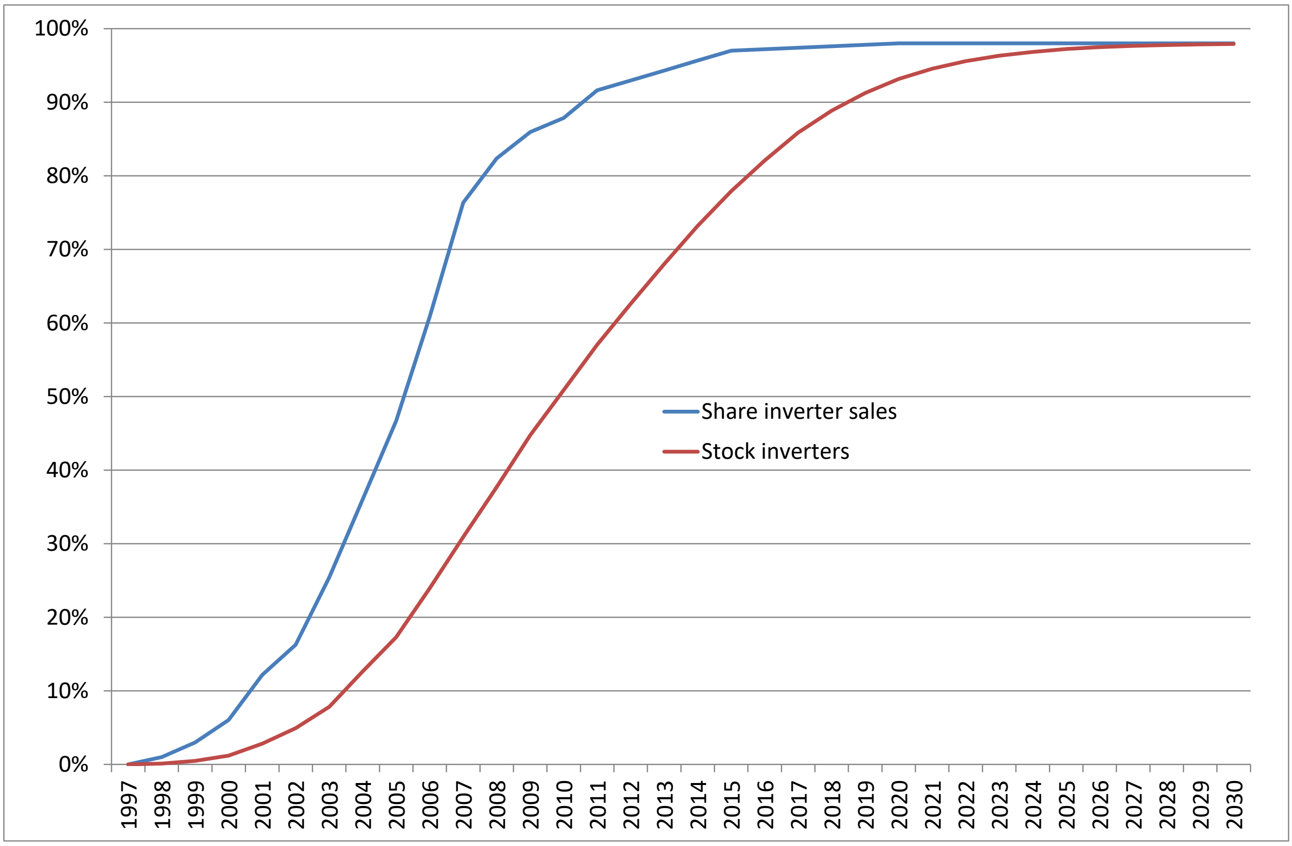

Figure 33: Estimated stock of inverter driven air conditioners in Australia by year

4.4 Energy consumption and load profiles for air conditioners

Air conditioners present a significant challenge for this project. In the residential sector, the usage and average power profiles are strongly driven by weather, most notably dry bulb temperature. However, other weather related factors can also impact such as solar radiation levels, humidity and wind speed. The relationship between air conditioner demand and weather itself is quite complicated, as demand for air conditioning can increase over subsequent days during a heat wave event, even where the peak temperature may remain at similar levels from day to day as buildings gradually heat up. Warm overnight temperatures can also exacerbate air conditioning demand on the subsequent day.

Analysis in Section 4.2 showed that commercial air conditioners made up around 20% of split system reverse cycle air conditioners (with the balance being residential). Commercial systems make up a larger share of cooling only systems (both split systems and window wall) but in absolute numbers, these still only constitute a relatively small share of the total air conditioner market. It is estimated that all commercial sector single phase air conditioners make up about 21% of the total single phase air conditioner stock.

Good data on load profiles in the residential sector has been obtained from monitoring data from CSIRO and their contribution of this data to this project is gratefully acknowledged (Ambrose 2019). Comprehensive air conditioner load profiles for commercial premises that use single phase air conditioners are not readily available, so data has been generated from a couple of sites and from imputed load profiles generated by climate data.

4.4.1 Daily load profiles for household air conditioners

CSIRO have been monitoring a series of households in Brisbane, Melbourne and Adelaide since 2012. This data covers air conditioning in around 50 households from 2012 to 2017 inclusive so is the most comprehensive data source available. This data was used initially to evaluate the impact of 5 star homes on energy consumption (Ambrose et al. 2013), but monitoring has continued as a self-funded research project since 2013. The data is divided into ducted systems and split systems. No window wall systems were monitored in the sample, but a scaled down load shape has been assumed based on the typical difference in rated capacity between these systems. Window wall systems are usually installed to condition small spaces such as a single room. Over the past 5 years the average capacity of window wall systems has been 65% of the average capacity of split systems and this has been fairly consistent since 2002. However, split systems on average are 10% to 12% more efficient than window wall systems, so the expected energy ratio for a capacity ratio of 65% is 71%.

In many ways, air conditioners are a very difficult end use to estimate a typical or average power profile, because they are so variable from day to day. Of course, an average profile can be generated based on the available data. But the expected load on any particular day is unlikely to match this average profile. Based on the available 6 years of CSIRO data, it was possible to generate a seasonal energy profile for each of the three cities as shown in Figure 34 to Figure 36.

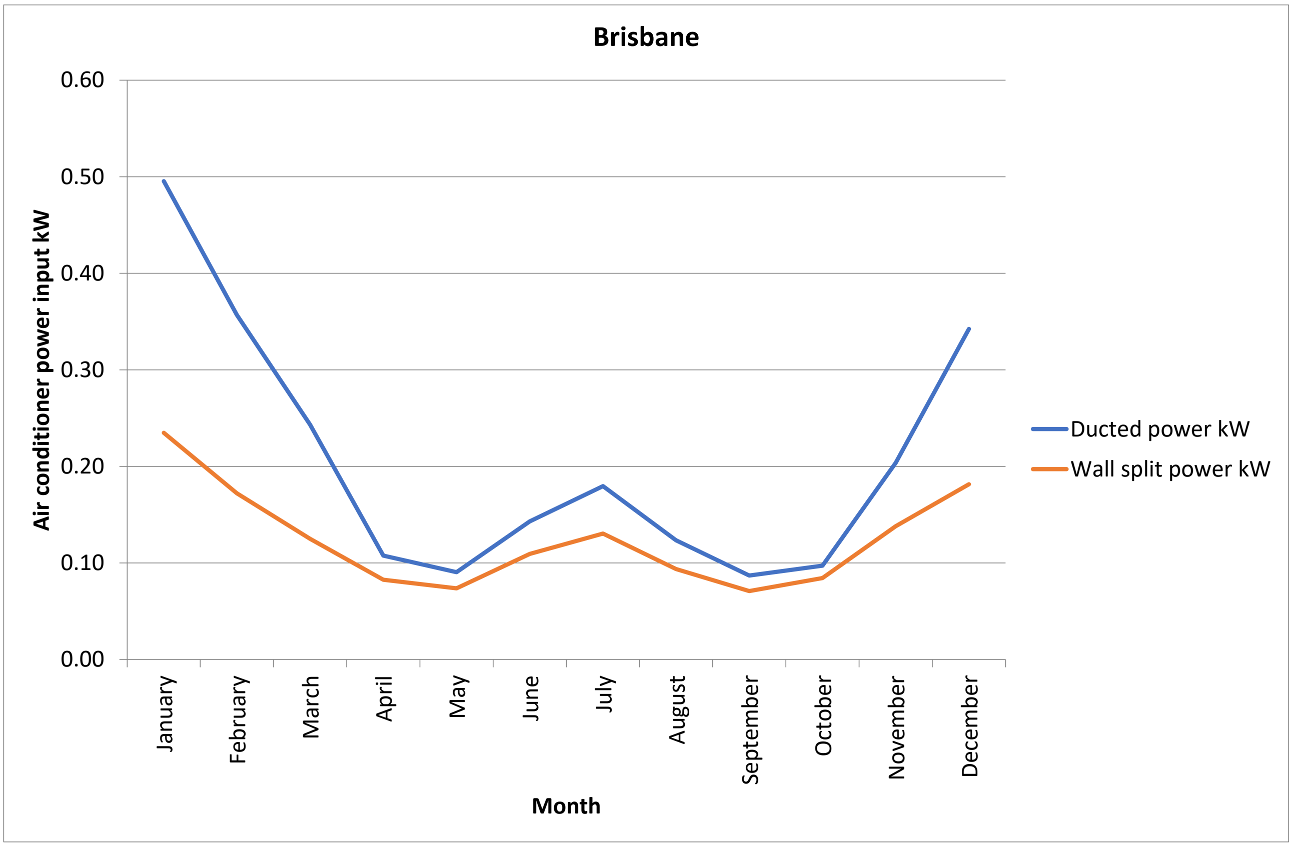

Figure 34: Seasonal power profile for ducted and split systems, Brisbane

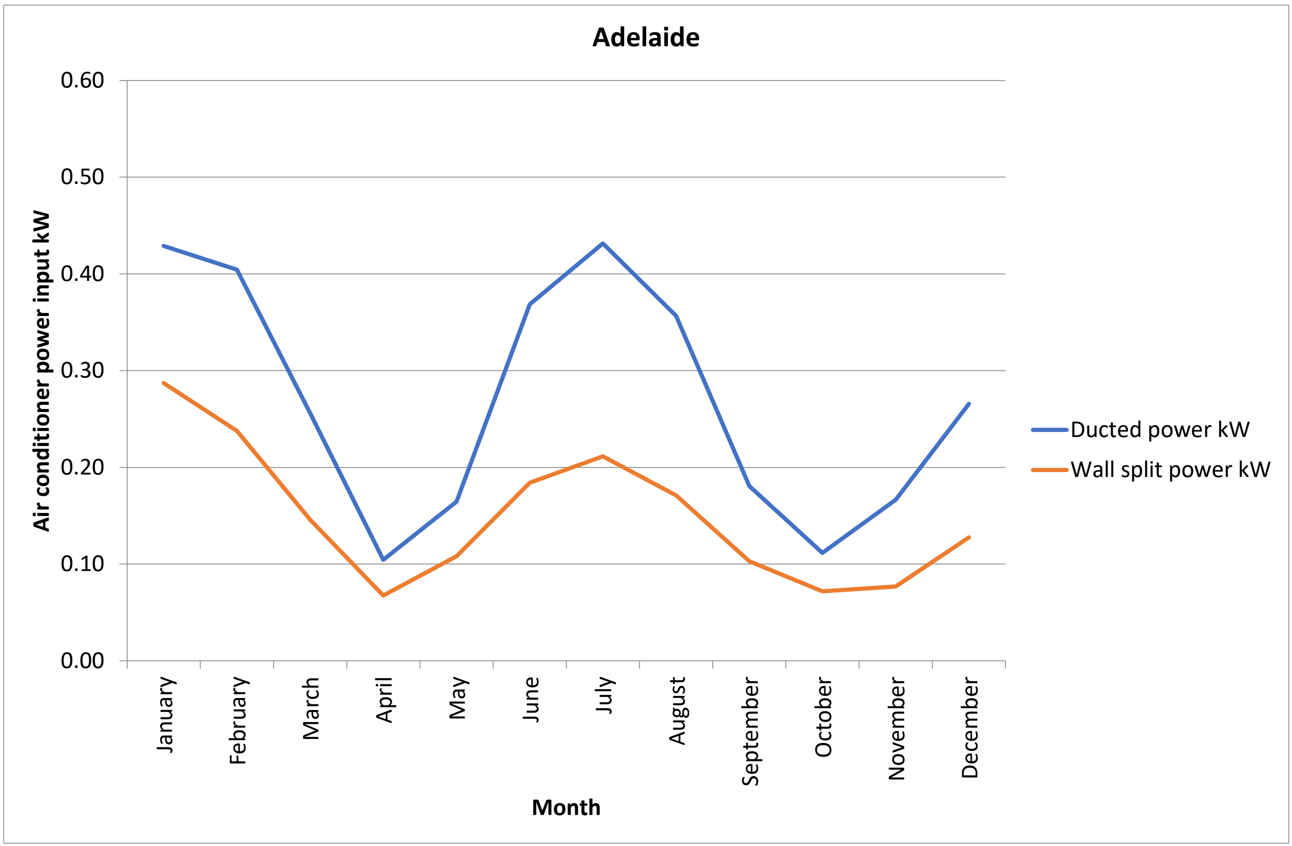

Figure 35: Seasonal power profile for ducted and split systems, Adelaide

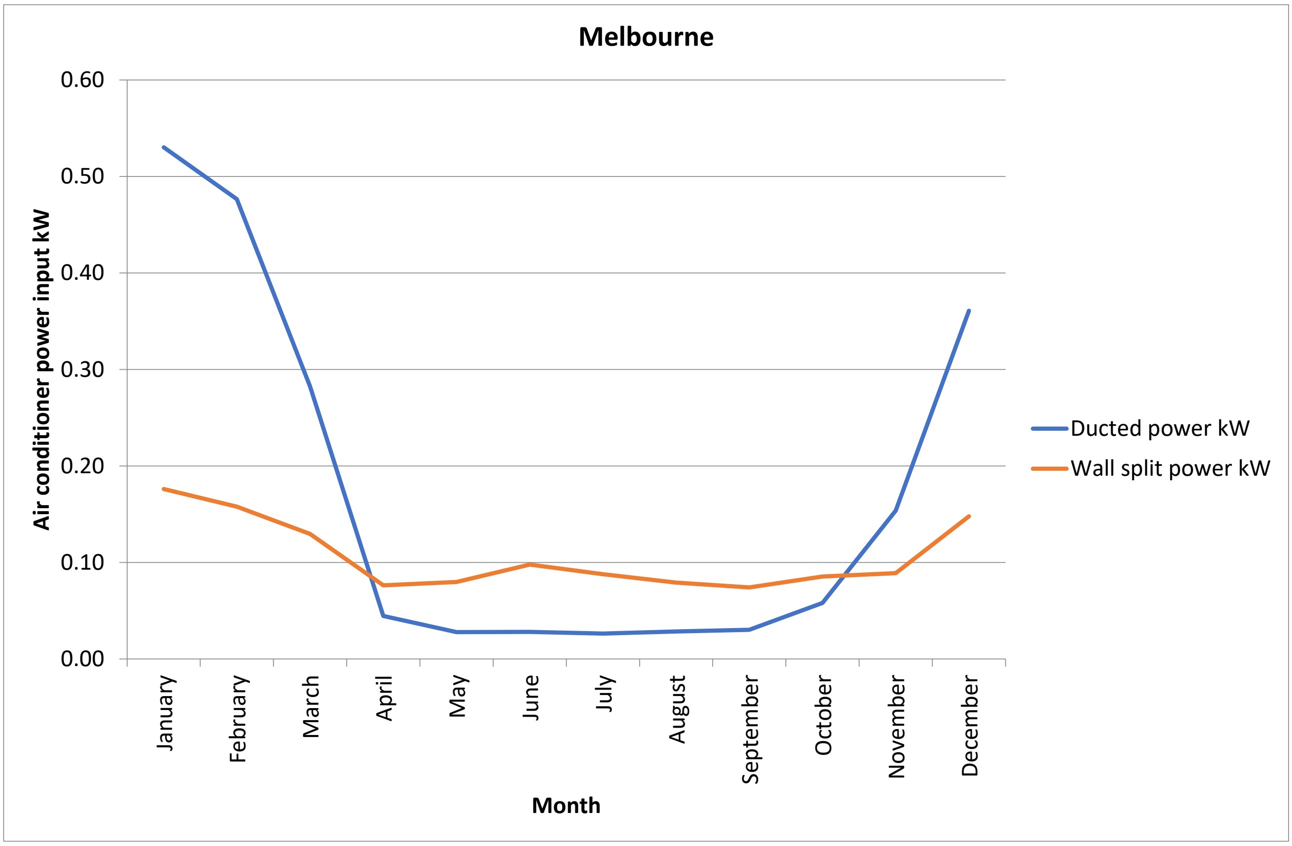

Figure 36: Seasonal power profile for ducted and split systems, Melbourne

There are several interesting observations from these figures. Firstly, the summer cooling load for ducted systems is quite similar across the three cities – around 0.5kW power input in January. The summer cooling load for split systems is also remarkably consistent at around 0.25kW power input in January. Brisbane exhibits only a modest amount of heating in winter, which is reflective of the climate, despite there being little gas heating available in Brisbane. Adelaide shows a significant heating load in winter as reverse cycle systems are very popular for heating in South Australia, despite the availability of gas. Melbourne shows only a small winter heating load for split systems and no winter heating load for ducted systems. This is likely due to the high penetration of central gas ducted heating in Melbourne and the relatively low use of air conditioners for heating, even though many households have reverse cycle systems installed. In many ways this is somewhat misleading, as the availability of gas is much lower outside of Melbourne metropolitan area, so a higher use of reverse cycle heating could be expected in the balance of the state. There may also be some sampling issues from the specific houses selected in Melbourne for this study. Market data does show an increase in reverse cycle heating and a decline in gas heating in Victoria in recent years. So these trends need to be considered.

The next step is to consider the time-of-day usage of air conditioners in each city. This is split by month and by type of system due to the different capacities as shown in the following figures. The legend has been formatted as follows:

- Summer months (December, January, February) have been allocated warm colours with heavy lines to show cooling loads more clearly
- November and March have been allocated more neutral colours with heavy lines as they also generate some cooling load in all three cities
- Winter months (June, July, August) are shown as heavy dotted lines to show heating loads
- The remaining months (September, October, April, May) are shown as thin lines and are generally neutral in terms of heating and cooling, although there is some cooling during April and October in Brisbane and some heating load in May and September in Adelaide and Melbourne.

Note that the data from CSIRO is configured such that the hour shown is local time (corrected for daylight saving where applicable, which applies in Adelaide and Melbourne from mid-October to early April). The data has been configured so that the nominal hour label on the X axis is the hour at the start of the data period[7]. For example, data labelled as 17:00 means the hour starting at 17:00 and finishing at 18:00 local time. In later analysis, the time of use for all NEM sub-regions has been corrected to Eastern Standard Time for all NEM sub-regions.

[7] This is different to the time configuration shown for other products in this report, which are generally on local time all year (no daylight saving adjustments) and also record the average power or energy at the end of the hour. For example, 17:00 means data for the hour starting at 16:00 and ending at 17:00. The CSIRO air conditioner data is later corrected to Eastern Standard Time for all cities.

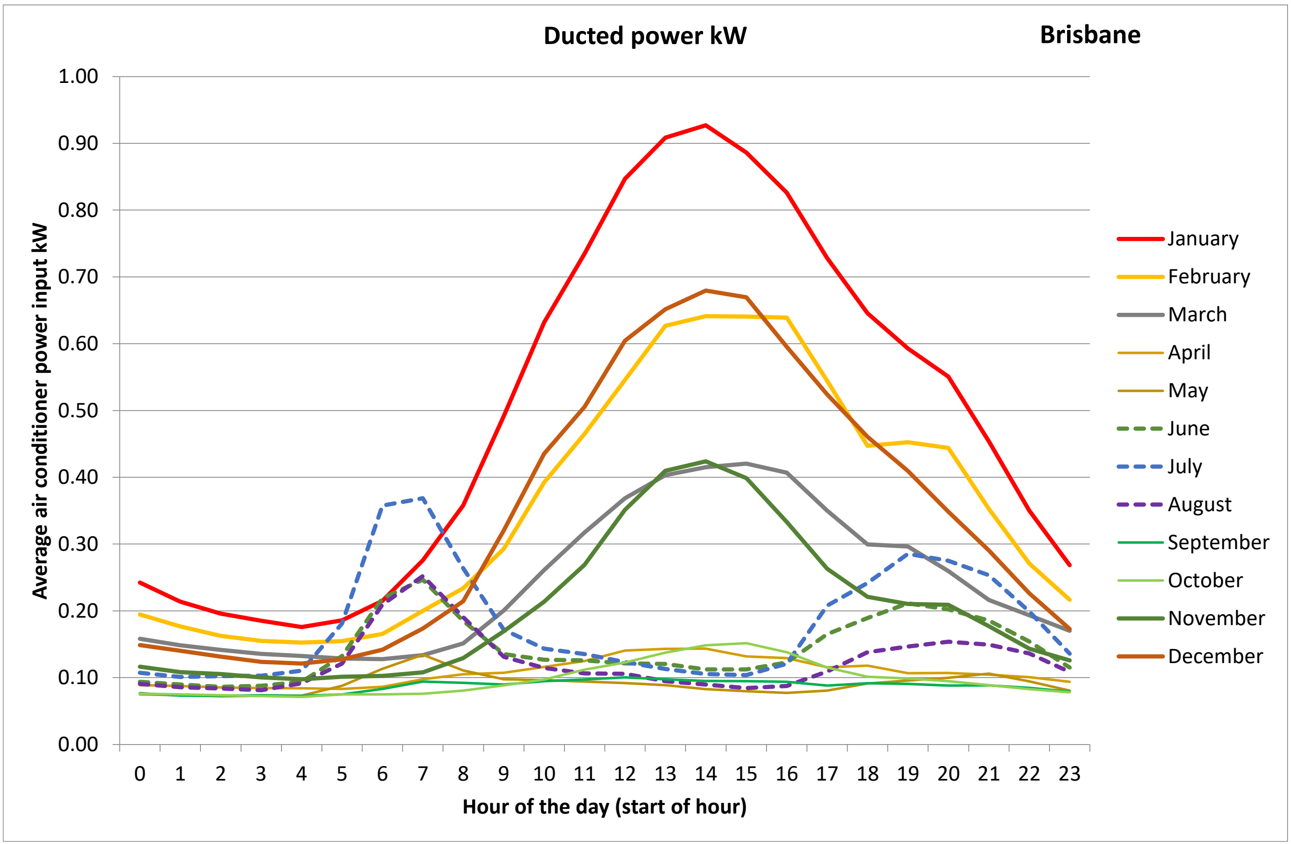

Figure 37: Time-of-day usage for ducted air conditioners by month, Brisbane

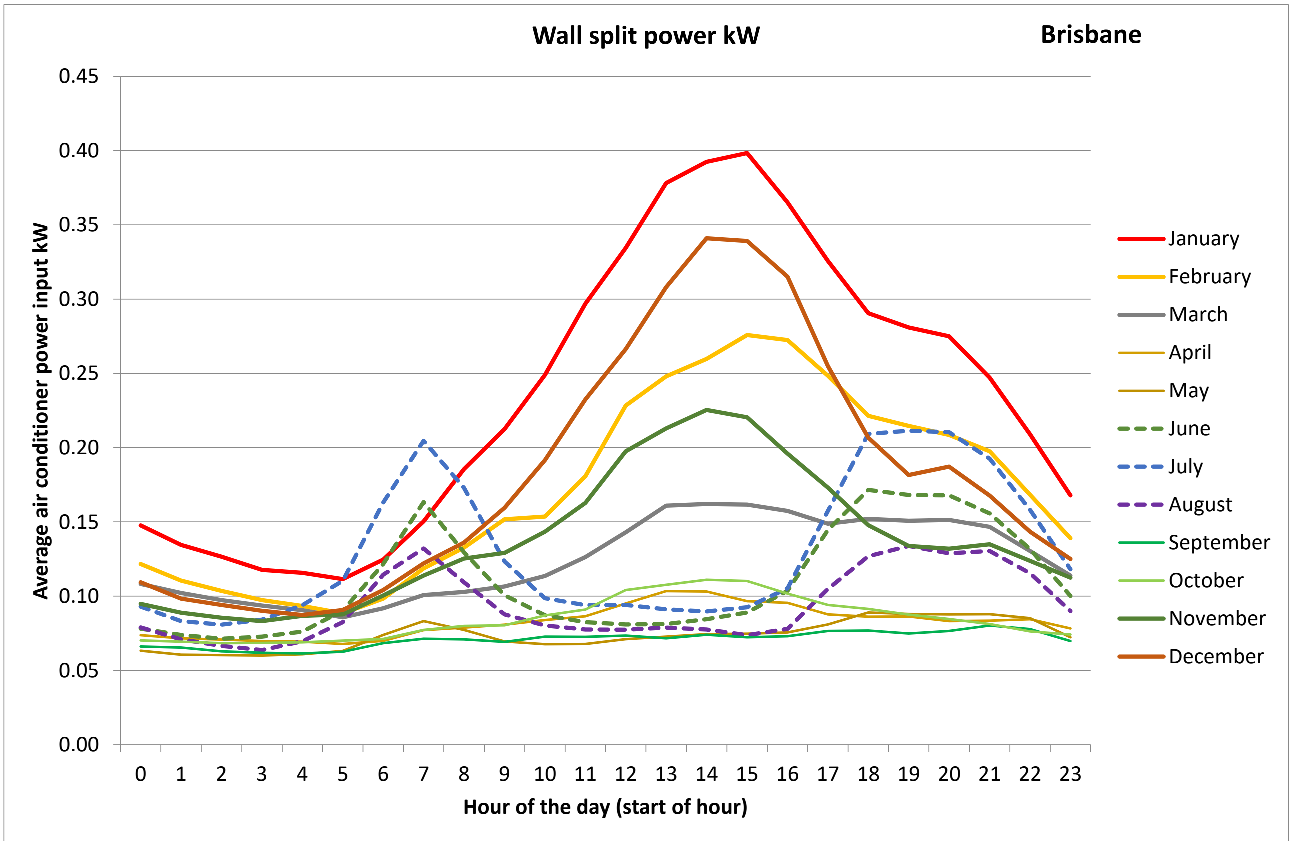

Figure 38: Time-of-day usage for split system air conditioners by month, Brisbane

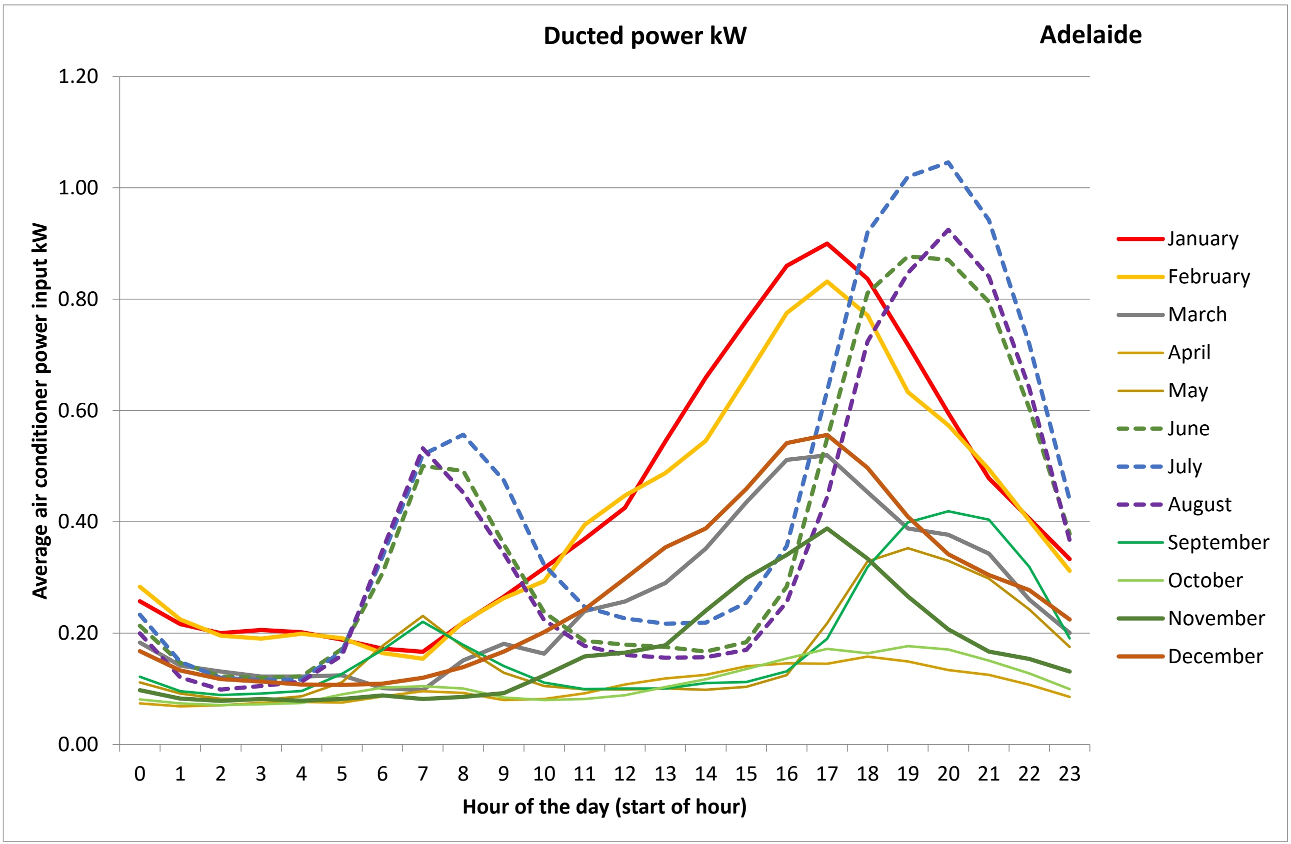

Figure 39: Time-of-day usage for ducted air conditioners by month, Adelaide

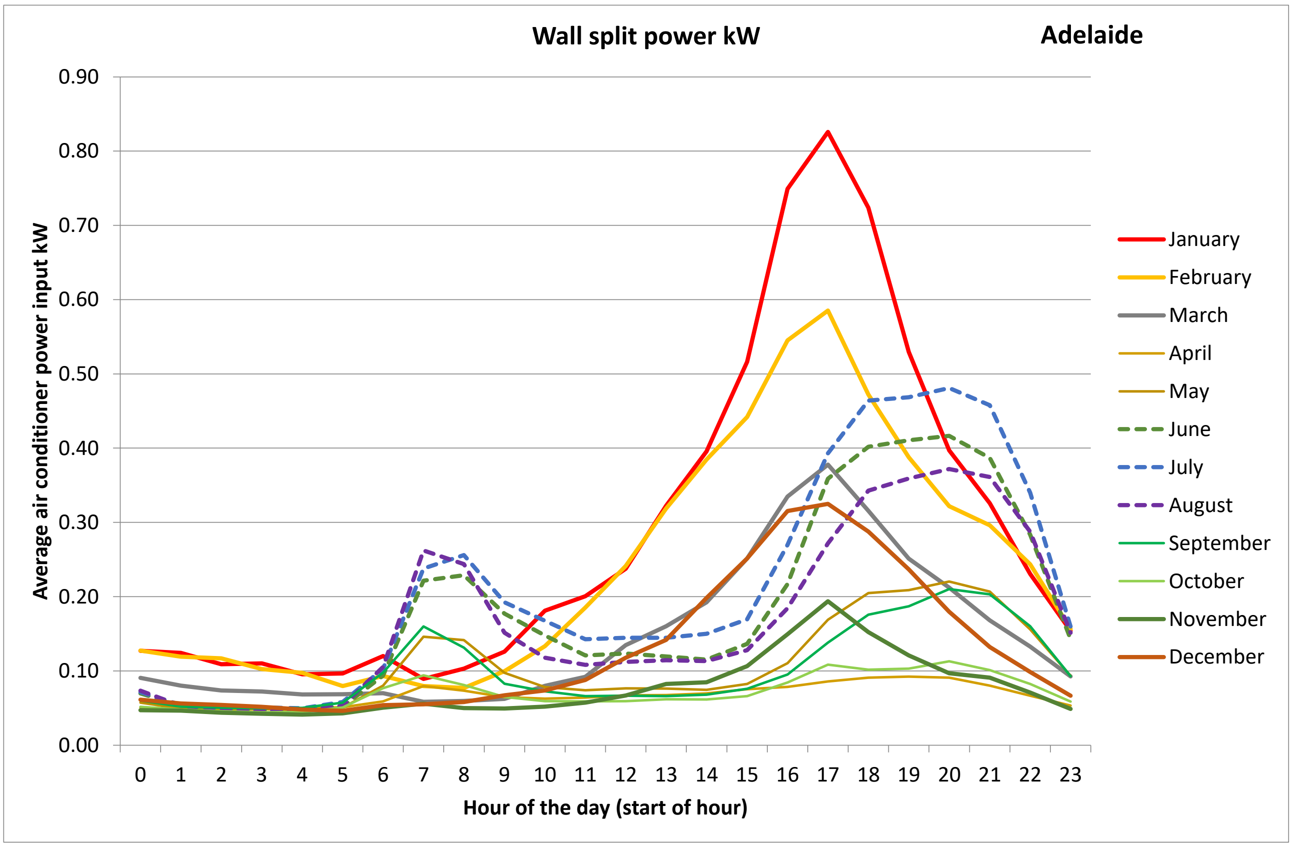

Figure 40: Time-of-day usage for split system air conditioners by month, Adelaide

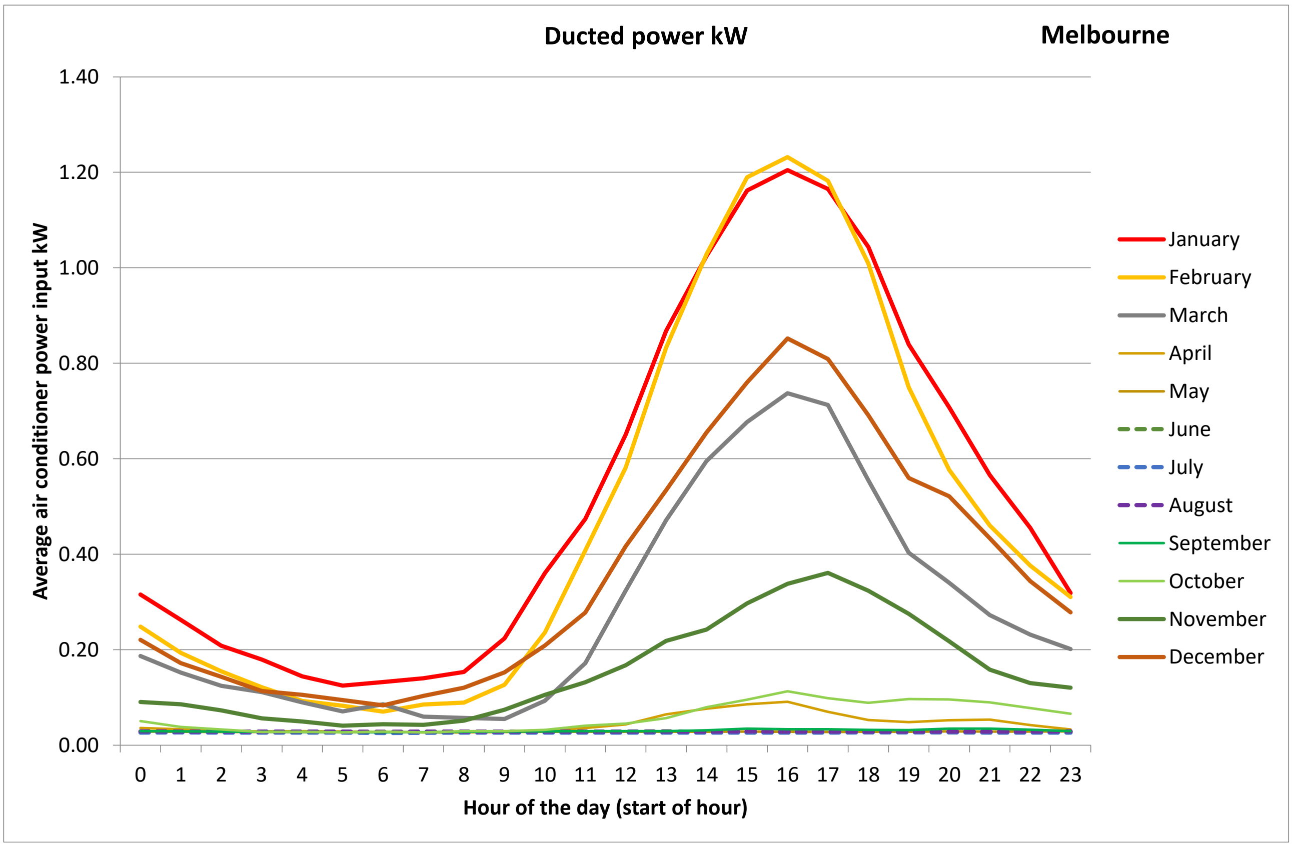

Figure 41: Time-of-day usage for ducted air conditioners by month, Melbourne

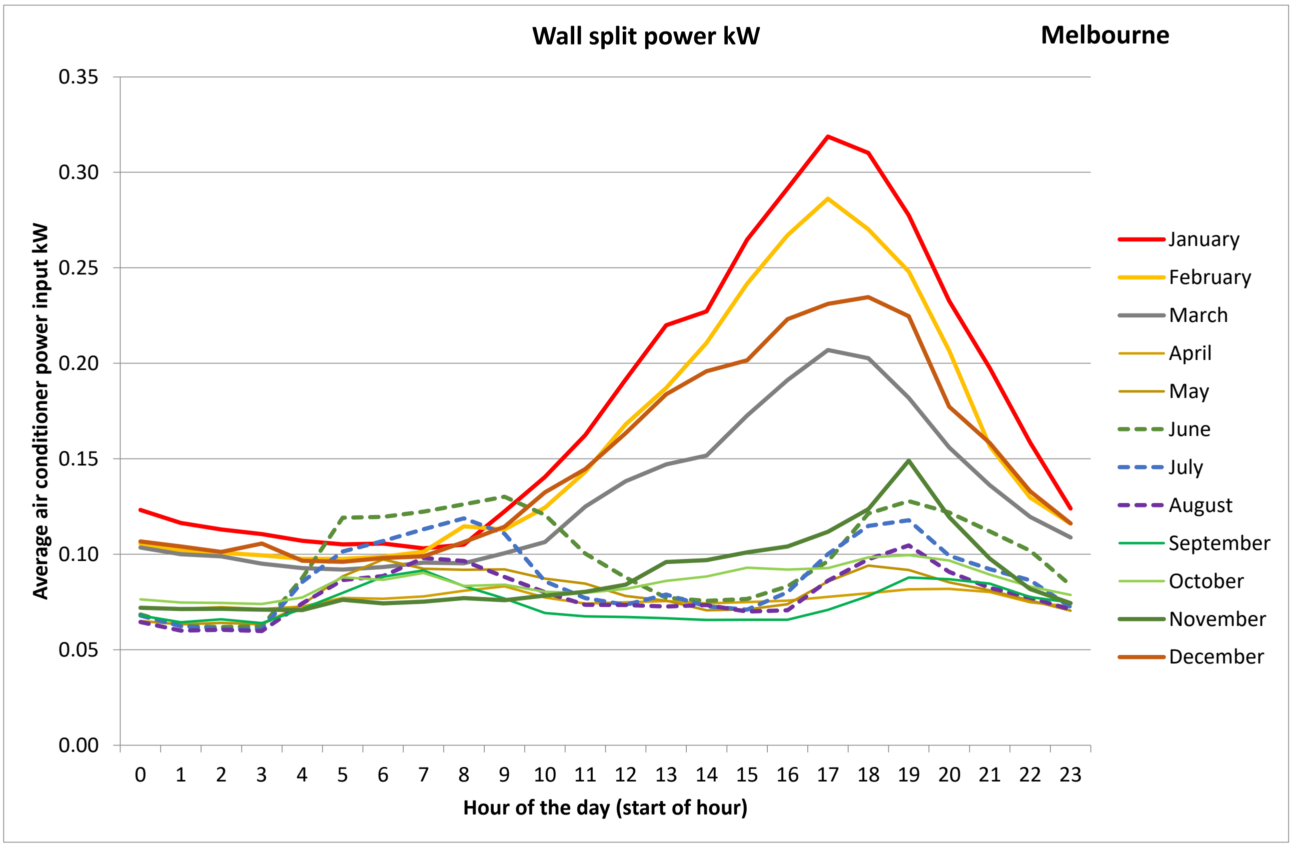

Figure 42: Time-of-day usage for split system air conditioners by month, Melbourne

Key observations from this data are as follows:
Brisbane

- Cooling peaks are typically at around 14:00 to 15:00 (i.e. the hours from 14:00 to 16:00)
- Split system cooling peaks are about half that of ducted systems
- The load shape for heating and cooling is similar for ducted and split systems
- There is significant cooling in November and March
- There is some residual cooling overnight in summer months
- There is a morning winter heating peak at around 07:00 with little heating during the day and an evening winter heating peak at around 19:00
- There is an underlying base load of consumption of 80W for ducted systems and 60W for split systems that is likely to be standby and crank case heaters.

Adelaide

- Cooling peaks are typically at around 17:00 (i.e. the hours from 17:00 to 18:00 daylight saving time, which is 16:00 to 17:00 Central Standard Time or 16:30 to 17:30 Eastern Standard Time)
- In general terms, split system peaks for heating and cooling are about half that of ducted systems, except for January and February where splits appear to be used more heavily
- The load shape for heating and cooling is similar for ducted and split systems, although the energy balance for each is slightly different (ducted systems used more for heating)
- There is significant cooling in March
- There is relatively little residual cooling overnight in summer months
- There is a morning winter heating peak at around 07:00 to 09:00 (06:00 to 08:00 Central Standard Time) with some heating during the day and a broad evening winter heating peak from 18:00 to 21:00 (17:00 to 20:00 Central Standard Time)
- There is an underlying base load of consumption of 70W for ducted systems and 60W for split systems that is likely to be standby and crank case heaters.

Melbourne

- Cooling peaks are typically at around 17:00 (i.e. the hours from 17:00 to 18:00 daylight saving time, which is 16:00 to 17:00 Eastern Standard Time)
- In general terms, split system peaks for cooling are about one third of that of ducted systems
- There is only a low level of heating used for split systems and no heating for ducted systems
- There is significant cooling in March and some cooling in November
- There is some residual cooling overnight in summer months
- For split systems, there is a broad morning winter heating peak from around 05:00 to 09:00 with some heating during the day and an evening winter heating peak from 18:00 to 20:00
- There is an underlying base load of consumption of 30W for ducted systems (which indicates some may be switched off at the power board in winter) and 40W for split systems that is likely to be standby and crank case heaters.

While this average load profile data is useful, it masks the volatility of air conditioner loads on a day to day basis. To illustrate this, the daily energy consumption of ducted air conditioners in Brisbane during 2013 is depicted in Figure 43. The highest energy day is a factor of 10 times larger than the lowest energy day.

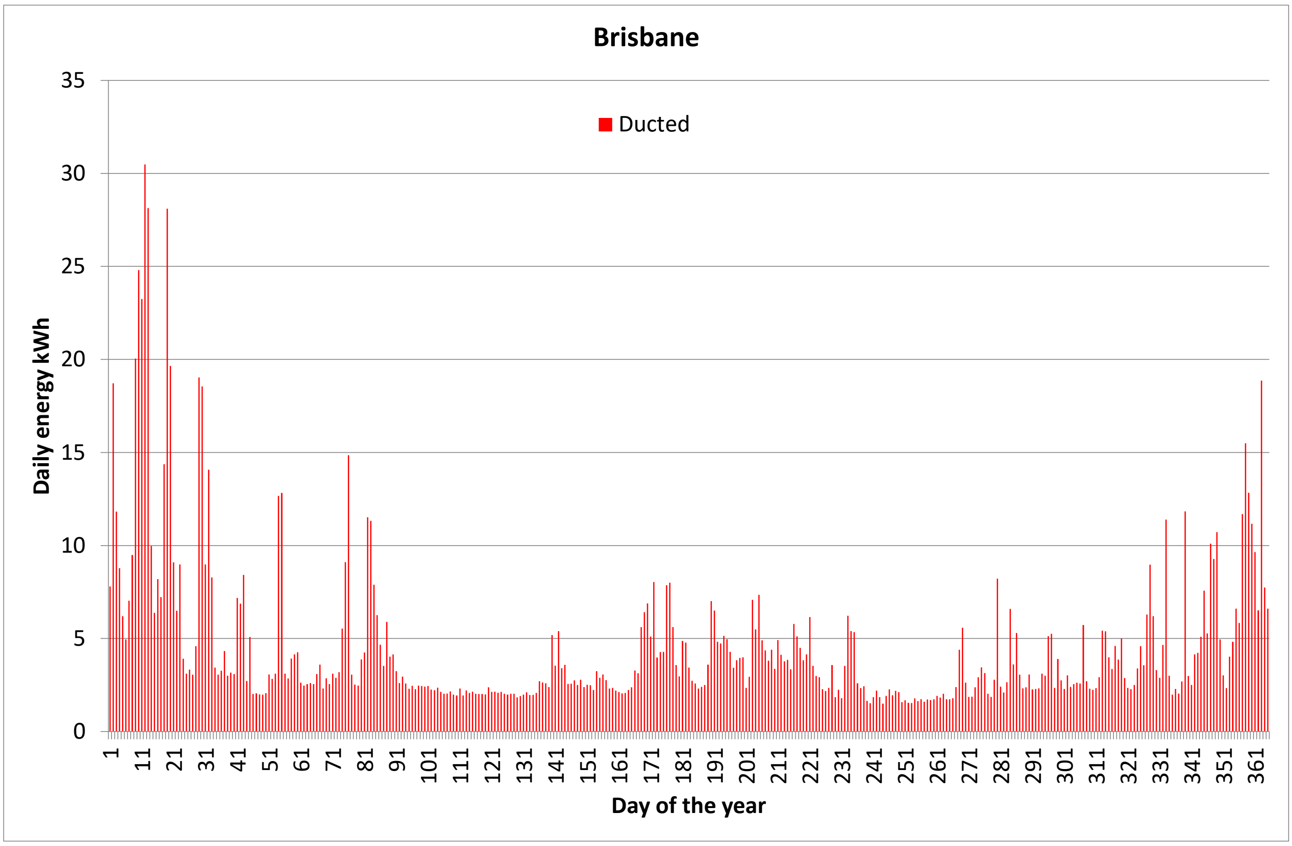

Figure 43: Daily energy consumption for ducted air conditioners, Brisbane, 2013

To also illustrate the volatility, the hourly data for January, February and December 2012 is represented for each city in the following figures.

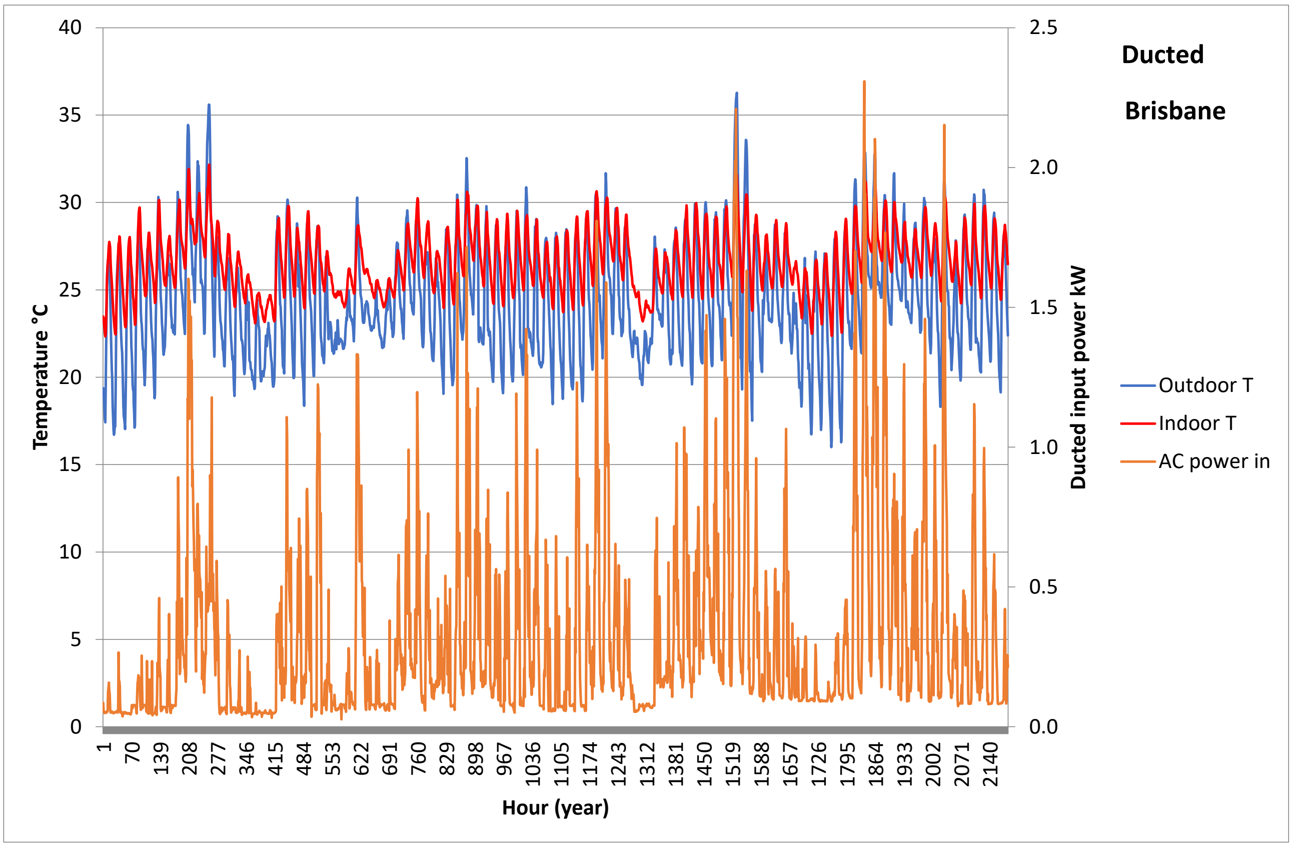

Figure 44: Hourly temperature and ducted power data for Brisbane: Jan, Feb and Dec 2012

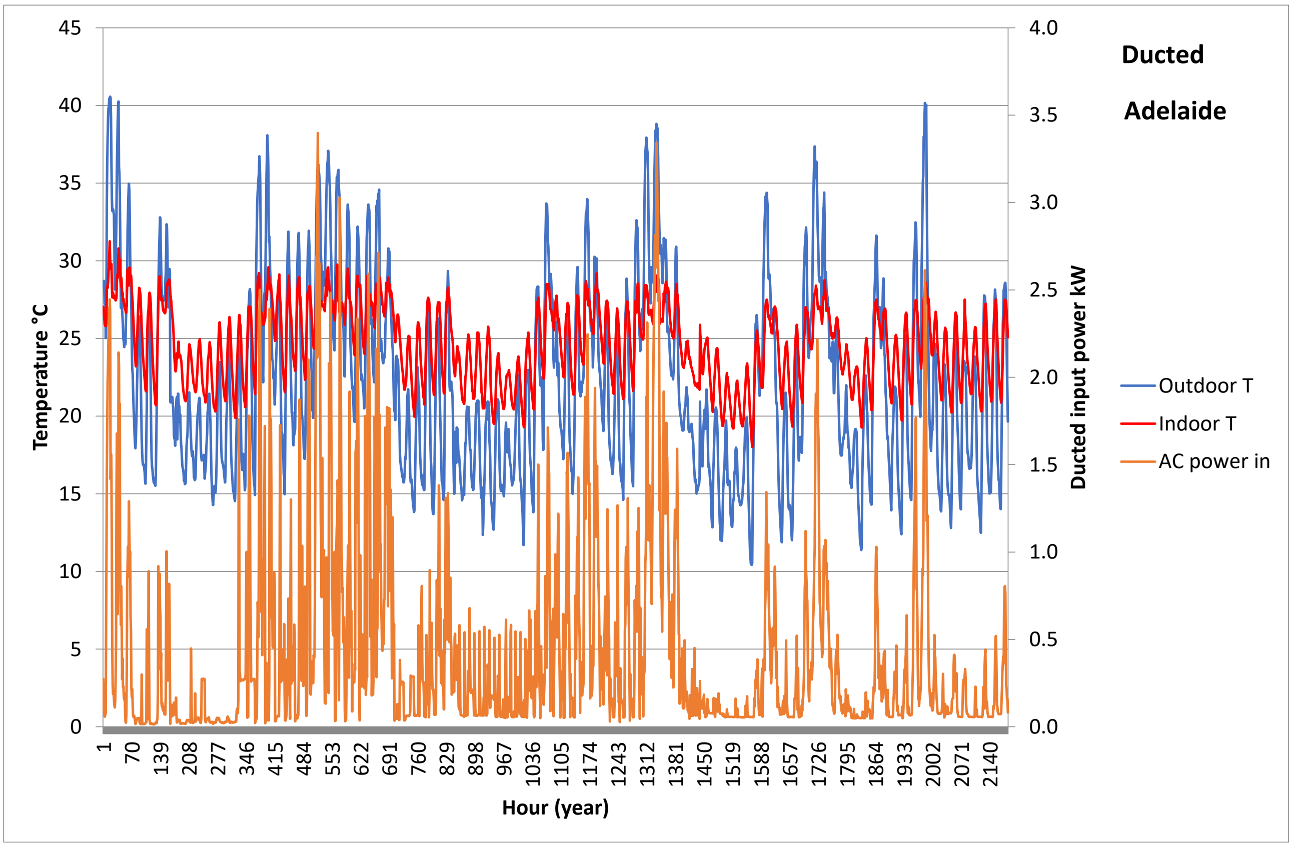

Figure 45: Hourly temperature and ducted power data for Adelaide: Jan, Feb and Dec 2012

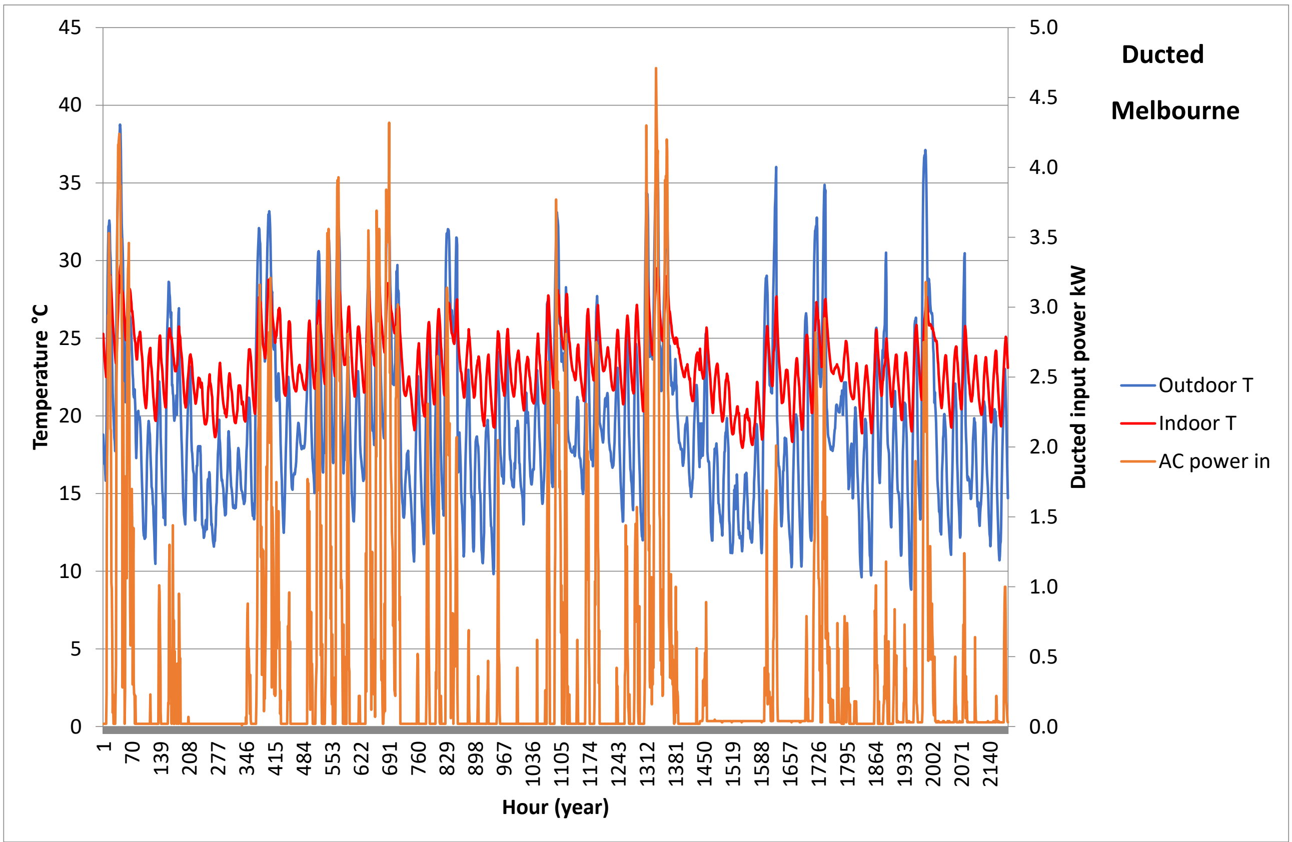

Figure 46: Hourly temperature and ducted power data for Melbourne: Jan, Feb and Dec 2012

This data reveals that air conditioner use is, to a large extent, driven by indoor ambient temperature conditions, rather than the external temperature conditions alone. Once indoor temperatures approach 30°C in Brisbane (and about 28°C in Adelaide and 27°C in Melbourne), the air conditioner use increases very rapidly in a non-linear manner relative to temperatures up to that point. Indoor temperatures are influenced to some extent by outdoor temperature but also a range of other factors such as solar radiation, wind speed and temperature history in the building and thermal mass. Humidity is also likely to be an important factor in human comfort. Warm temperatures overnight can drive air conditioner use a lot on the following day if the weather is hot.

CSIRO have analysed this data in great detail and estimate that the thermostat ON settings for cooling in the houses monitored are 28°C in Brisbane, 27°C in Adelaide and 26°C in Melbourne (50% acceptability range) (Ren & Chen 2018). They also estimate the thermostat ON settings for heating in the houses monitored are 19°C in Brisbane, 17°C in Adelaide and 16.5°C in Melbourne (50% acceptability range). However, it is difficult to apply this in a general way for this study as there is no straightforward way to predict indoor temperatures in homes. To illustrate this effect, hourly data for ducted systems in Brisbane has been plotted for January, February and December 2012 as shown in Figure 47. This shows that indoor temperature is the main driver for air conditioner usage.

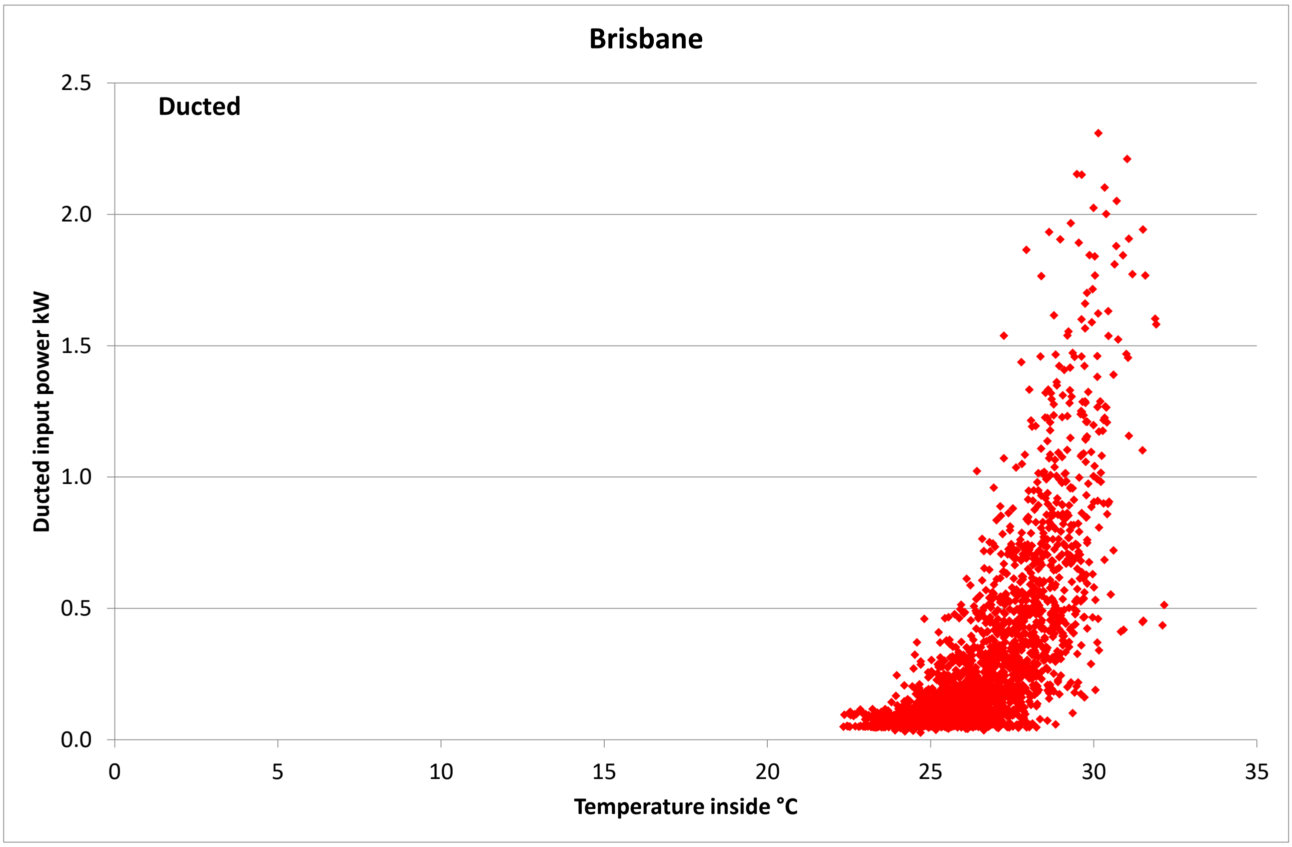

Figure 47: Hourly indoor temperature vs ducted power data for Brisbane: Jan, Feb and Dec 2012

The same data can be plotted against outdoor temperature for the same period as shown in Figure 48. While this illustrates that there is a general correlation between outdoor temperature and air conditioner power, this relationship is quite variable. So outdoor temperature is a less reliable predictor of air conditioner power.

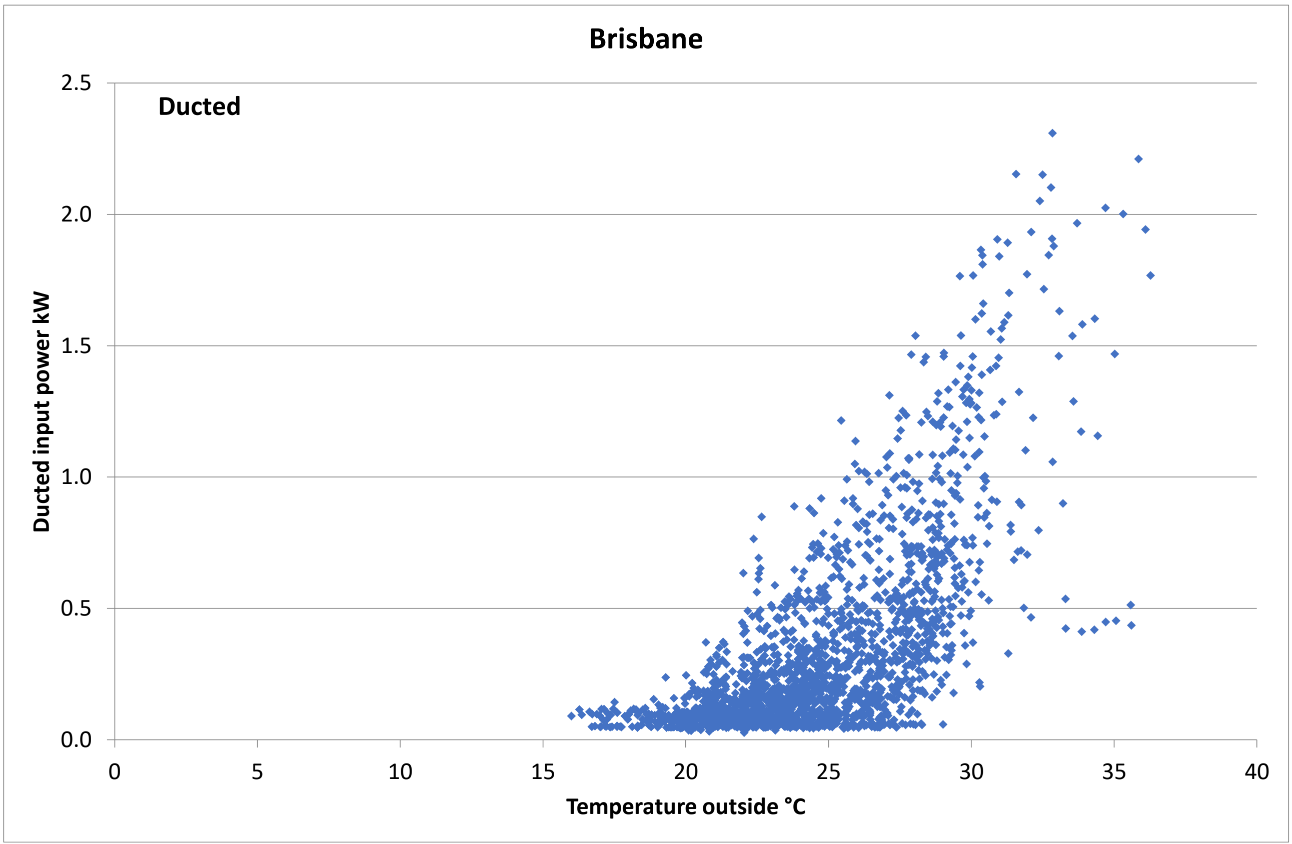

Figure 48: Hourly outdoor temperature vs ducted power data for Brisbane: Jan, Feb and Dec 2012

Another way to examine this data is to look at daily average energy consumption versus daily average temperatures. This approach tends to smooth out some of the volatility of hourly data, some of which is generated by the time lag between outdoor temperatures and a change in indoor temperature.

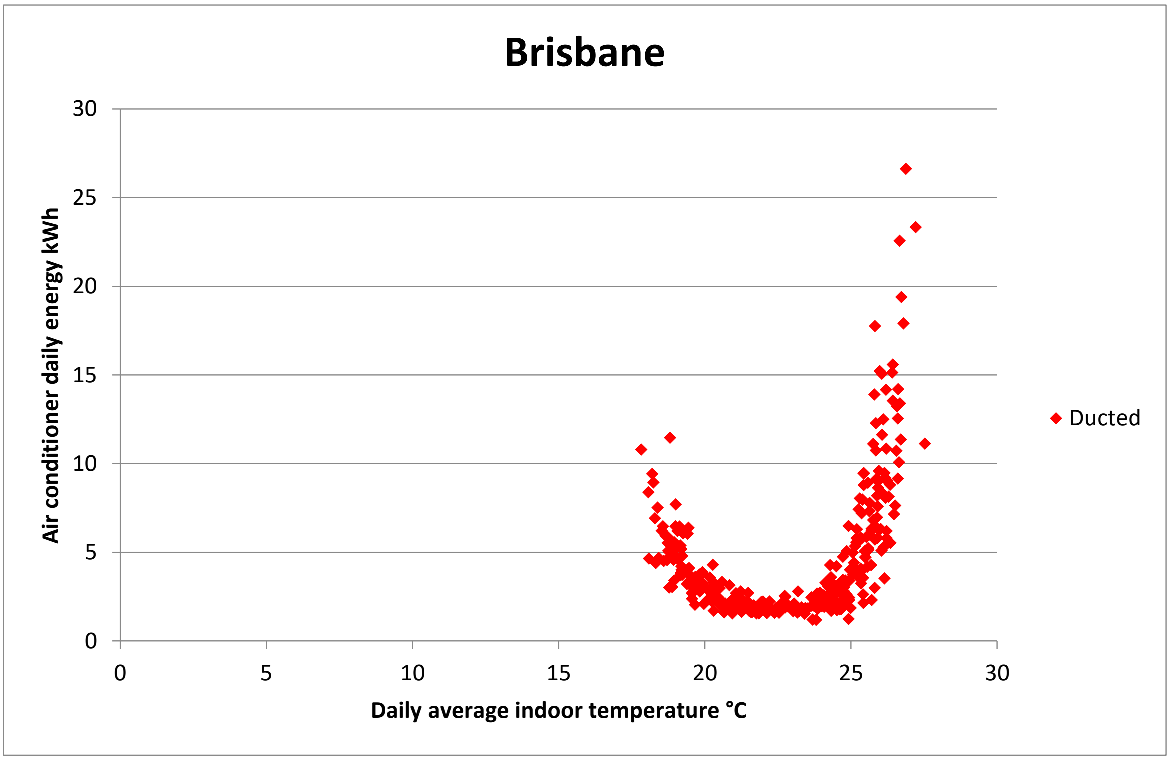

Figure 49: Daily average indoor temperature versus ducted air conditioner energy: Brisbane, 2012

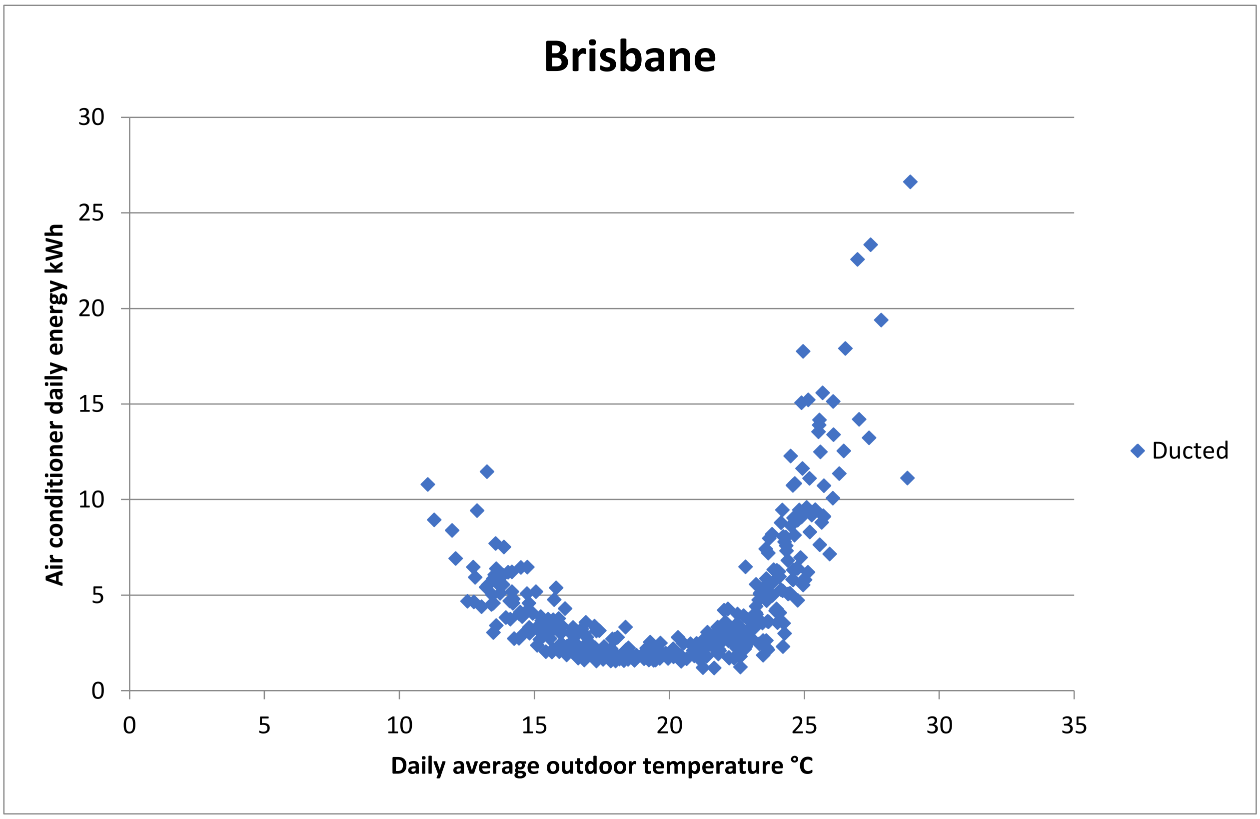

Figure 50: Daily average outdoor temperature versus ducted air conditioner energy: Brisbane, 2012

Figure 49 illustrates the broad thermostat settings used for ducted air conditioners, which is consistent with the data analysis by CSIRO (Ren & Chen 2018). Note that these are daily average temperatures so they smooth out the peaks seen in daily maximum temperatures typically reported by the Bureau of Meteorology. For example, the hottest day on this figure (4 Dec 2012) had a daily average temperature of 28.9°C and this day had a maximum temperature of 36.3°C. The next hottest day (11 Jan 2012) had an average temperature of 28.8°C, which was mainly caused by very warm overnight temperatures with a daily maximum of 34.5°C, but there was a cool change at 17:00, reducing the daily air conditioner energy consumption. This type of data could be further analysed to generate a predictive model of air conditioner use, but that is beyond the scope of this study. However, it could be a fruitful area of further research, both for fault modelling and for short term peak load energy forecasts generated by air conditioners.

Figure 37 to Figure 42 give solid average load data by month and by type of air conditioner for three major cities in Australia. However, air conditioner use is highly volatile on a day to day basis. To illustrate this, hourly data for each day of January 2013 in Adelaide is illustrated in Figure 51. Air conditioner use on (presumably) hot days is very high but on other days is almost nothing. To examine the issue of volatility in a more general way, the daily energy values across several years were examined and the highest energy day in each month was identified and compared to the average energy day in each month. This provides a reasonable indication of the expected maximum energy day compared to an average energy day in each month. These values were tracked separately by month and equipment type for each city and 4 years of data were examined (2012 to 2015 inclusive). Reviewing all of the data showed that there was some volatility driven by weather, but in general terms, the overall ratios were, on average, fairly similar by city, year and equipment type. The overall data is illustrated in Figure 52. In round figures, a peak energy day is around 4 times an average day for cooling months (November to April inclusive) and less than 2 times in winter. The 4 year average figures have been used to develop further analytical approaches for this study for residential air conditioners for all NEM sub-regions. The minimum value for all months is nearly always close to zero.

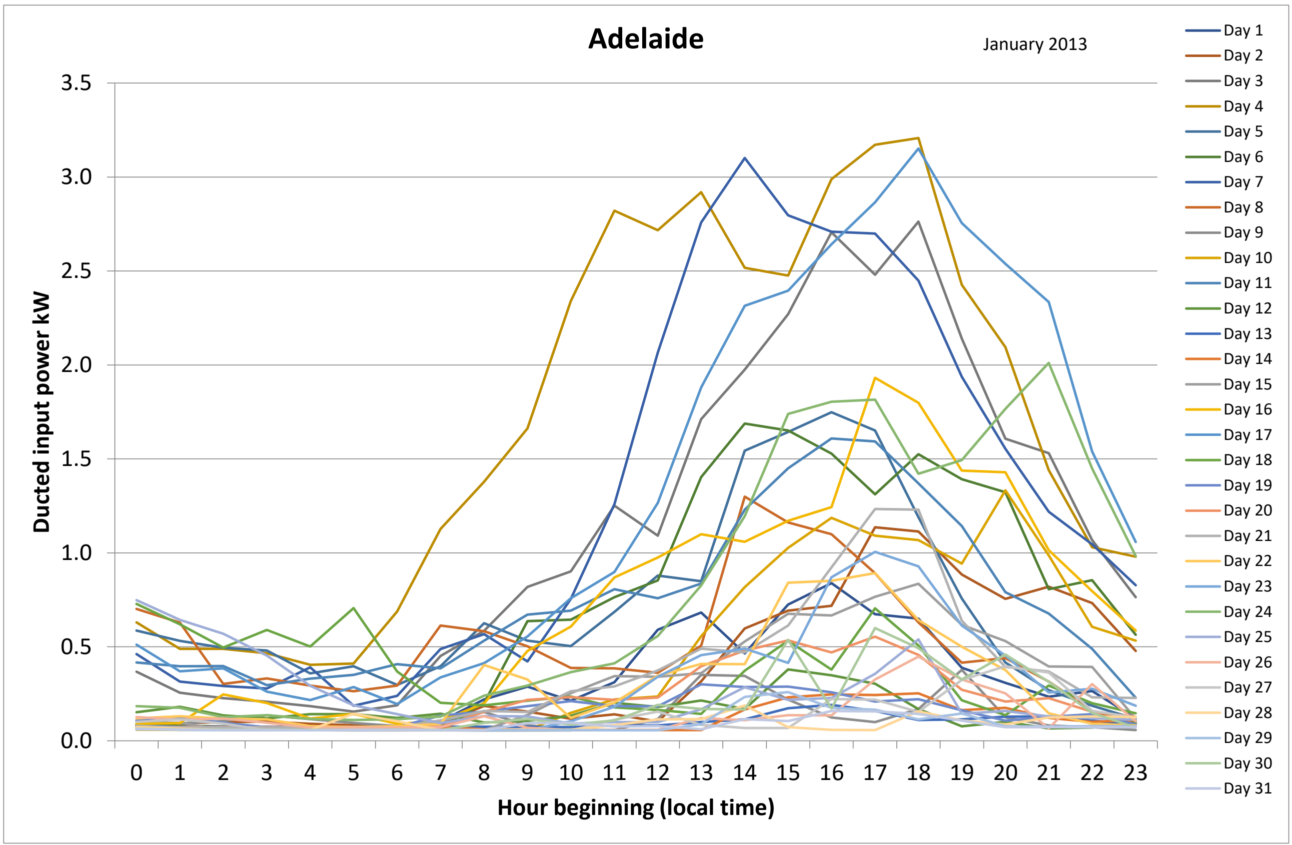

Figure 51: Daily power input traces for ducted air conditioners in Adelaide, January 2013

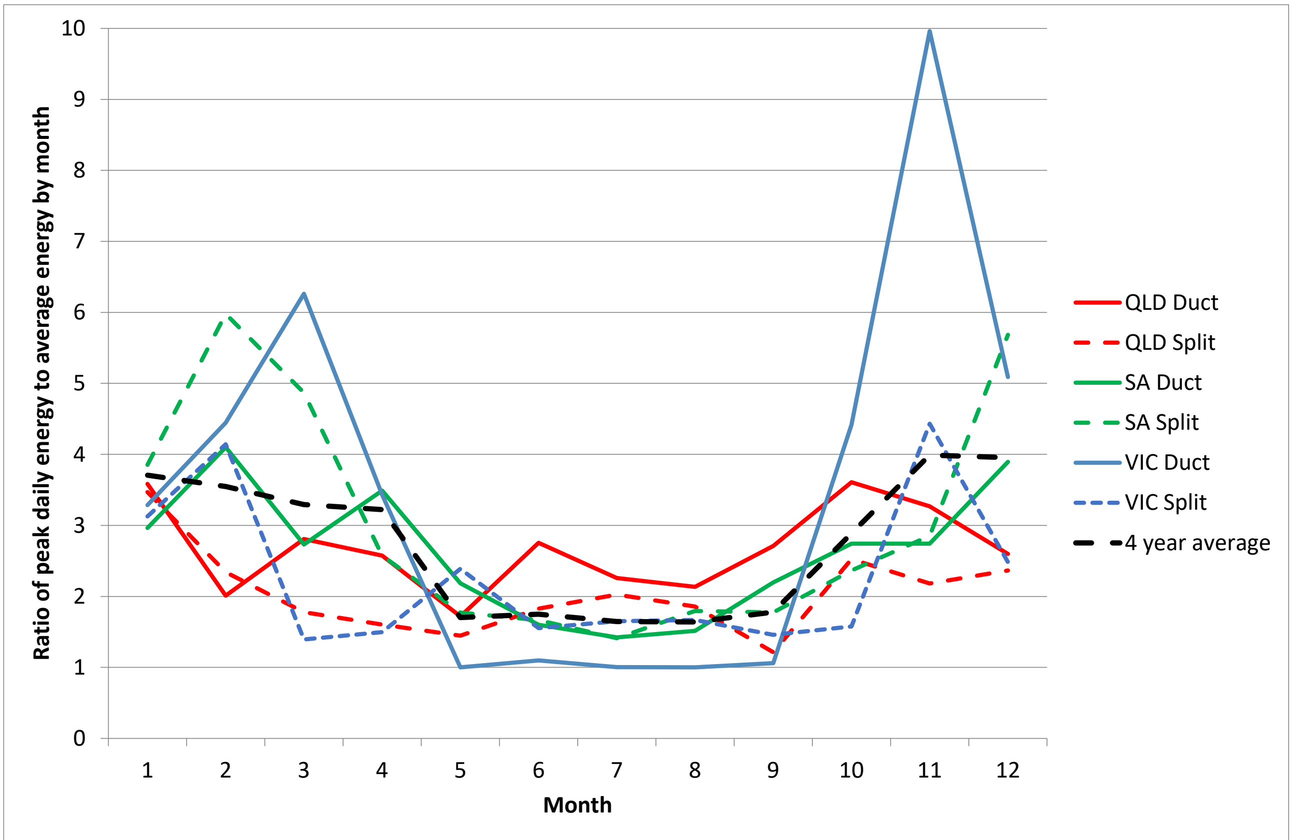

Figure 52: Ratio peak daily energy to average energy by equipment type and city: 2012

Notes: 4 year average shown is across all equipment types and years 2012 to 2015 inclusive.

For this study, AEMO want to predict the share of Motor D load on the NEM from the specified loads throughout the year (typical value, as well as a maximum and minimum value). The main focus is the percentage of total NEM load by sub-region that can be attributed to Motor D loads under different conditions. For residential air conditioners, this requires a longitudinal assessment of NEM loads and air conditioner loads in parallel, because air conditioner loads themselves will drive the total NEM load to a large degree under more extreme weather. This makes average air conditioner loads of lower value. As there is only end use data for 3 cities within the NEM regions of interest, it was necessary to undertake some more generic analysis to allow this data to extrapolate like air conditioner loads in the other NEM sub-regions.

The first step was to develop a model to predict the average air conditioner energy based on typical climatic values for these cities where data was available. This initial analysis is illustrated in Figure 53 and Figure 54.

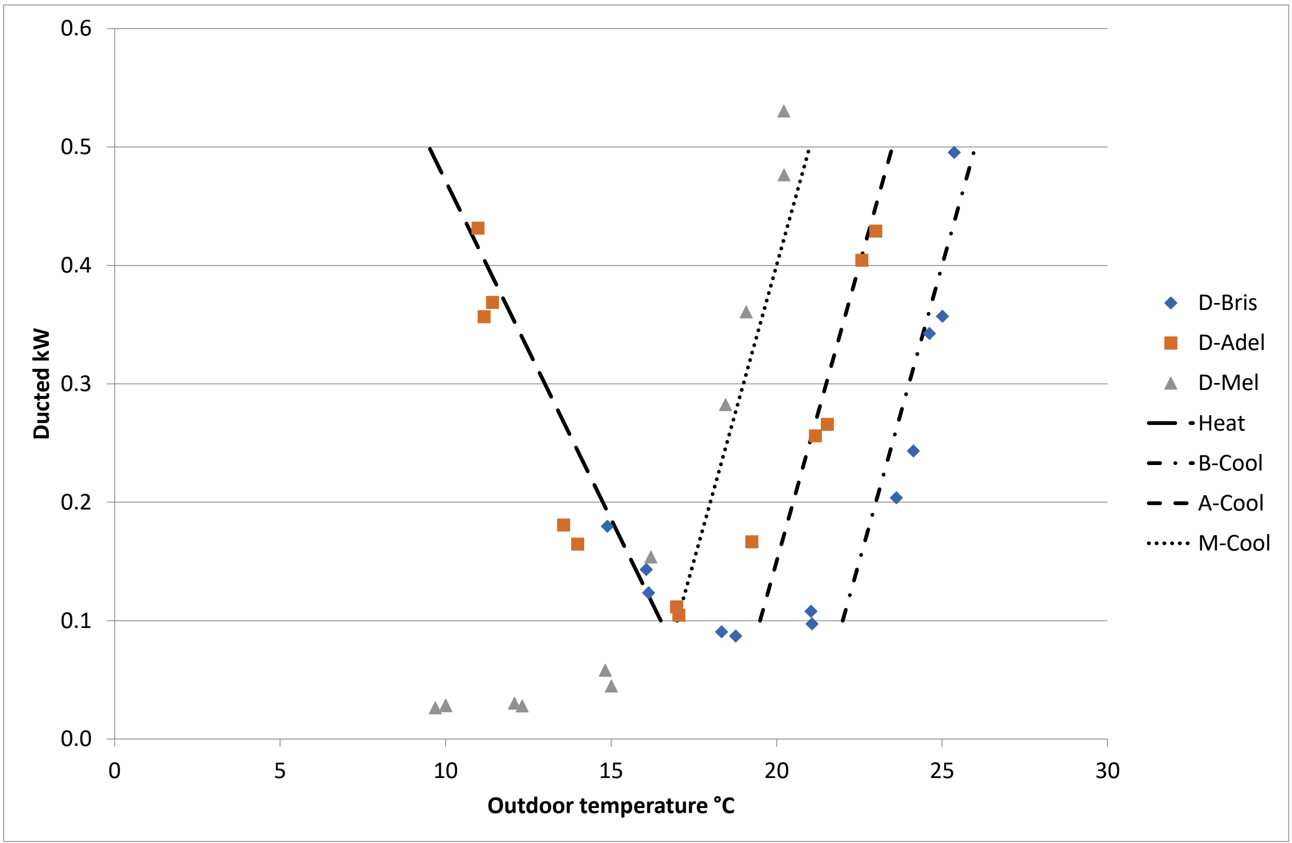

Figure 53: Average monthly ducted air conditioner by outdoor temperature

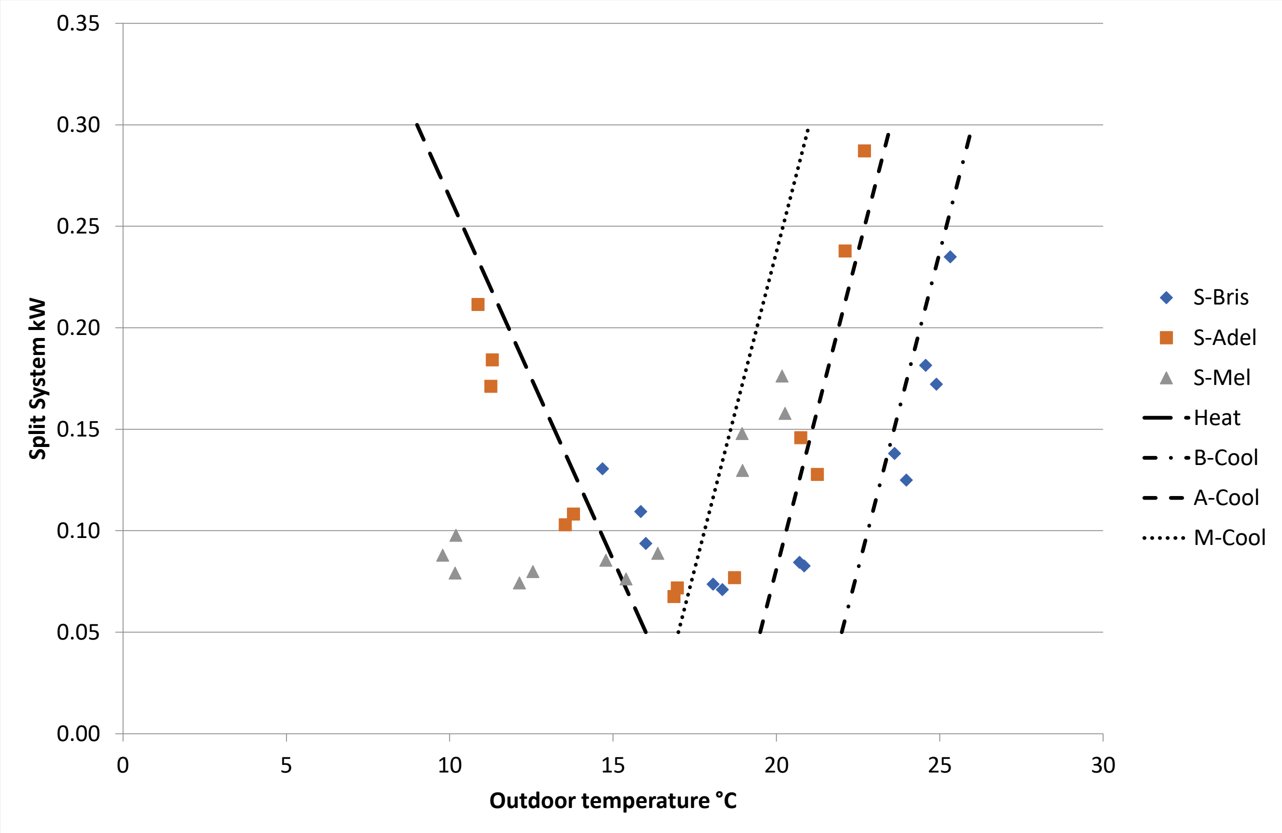

Figure 54: Average monthly ducted air conditioner by outdoor temperature

The lines of best fit in Figure 53 and Figure 54 broadly match with CSIRO analysis of the same data (Ren & Chen 2018). This data suggests that heating requirements are similar across all climates (in terms of how much outdoor temperature drives heating needs). However, it appears that people living in hotter climates are more tolerant of heat and therefore only use their air conditioners in warmer conditions. This manifests as a higher temperature threshold when air conditioners start to be used, but the average power requirement for each incremental temperature increase is similar across all climates. It is well known that for tropical climates (Queensland Central and North), there is a greater tolerance for warmer weather, so it is expected that the Brisbane curve would be ameliorated by a further 1.5K in the tropical north. While there is very limited data to confirm this affect, it does align with the anecdotal data available. This effectively reduces the air conditioner loads in Queensland Central and North and matches well with the higher level AEMO sub-region analysis in Chapter 2, which shows relatively low temperature sensitivity in summer months. The lines of best fit are set out below in Table 15 and Table 16.

Table 15: Line of climate energy best fit for ducted air conditioners

Climate/Mode	Valid monthly temperatures	a	b
All - Heating	<16.0°C	-0.05714	1.042857
Tropical - Cooling	>24.5°C	0.1	-2.35
Brisbane – Cooling	>22.0°C	0.1	-2.1
Adelaide – Cooling	>19.5°C	0.1	-1.85
Melbourne – Cooling	>17.0°C	0.1	-1.6

Table 16: Line of climate energy best fit for split air conditioners

Climate/Mode	Valid monthly temperatures	a	b
All - Heating	<16.0°C	-0.03571	0.621429
Tropical - Cooling	>24.5°C	0.0625	-1.48125
Brisbane – Cooling	>22.0°C	0.0625	-1.325
Adelaide – Cooling	>19.5°C	0.0625	-1.16875
Melbourne – Cooling	>17.0°C	0.0625	-1.0125

The form of the equation to calculate annual monthly air conditioner power is:

$$Power_{month} = a \times T_{outdoor} + b$$

Where T_{outdoor} is the outdoor average temperature, in degrees Celsius.

This provides a sound basis for calculating average energy by climate zone and therefore for all NEM sub-regions. Based on the 2016 Typical Mean Year (TMY) AccuRate weather files (CSIRO 2017; Energy Inspection 2018), the monthly average temperature by climate zone is shown in Table 17. This allows an average monthly air conditioner energy value to be calculated for each climate zone for each NEM sub-region as shown in Table 18 and Table 19. This approach effectively estimates an average energy consumption value by month and NEM sub-region. However, typical time-of-day profiles need to be generated. Figure 37 to Figure 42 gives load profiles by month. However, these are of less value as the energy input varies substantially by month. However, it is obvious from these figures that the general load shapes are similar during summer (cooling) months and winter (heating) months, even if the absolute energy values vary. It is possible to re-examine the daily load shapes (by time of date) by normalising the hourly values relative to the average energy for that month. This provides a more useful representation of cooling and heating demands in each city. These are depicted in Figure 55 to Figure 60. For this data the time has been corrected back to Eastern Standard Time to match the NEM data.

Table 17: Outdoor monthly temperature (°C) by climate zone

State/NEM sub-region	Climate	January	February	March	April	May	June	July	August	September	October	November	December
New South Wales	Sydney	22.5	22.5	21.8	19.0	15.8	13.6	12.7	13.7	16.5	18.7	19.8	21.4
Victoria	Melbourne	20.6	21.0	18.6	16.5	13.0	11.4	11.1	11.8	13.5	15.3	18.1	18.8
Queensland North	Townsville	28.0	27.8	26.7	24.8	22.9	20.4	19.6	20.4	22.5	25.2	26.6	27.7
Queensland Central	Rockhampton	26.7	26.8	25.2	23.4	20.2	16.8	16.3	18.2	20.3	23.4	25.3	26.2
Queensland South	Brisbane	24.8	25.1	23.8	20.8	17.8	14.9	14.7	15.4	18.4	20.0	22.4	24.1
South Australia	Adelaide	23.1	23.1	20.5	17.9	15.0	12.1	11.0	12.3	13.2	16.2	18.7	21.4
Tasmania	Hobart	17.4	16.6	15.3	13.5	10.9	8.9	8.5	9.5	10.8	12.0	14.0	15.6
ACT	Canberra	20.9	21.1	17.4	12.8	9.0	7.0	6.3	7.1	10.3	13.0	15.9	19.0

Table 18: Average monthly ducted air conditioner power (kW) by climate zone

State/NEM sub-region	Climate	January	February	March	April	May	June	July	August	September	October	November	December
New South Wales	Sydney	0.404	0.402	0.329	0.100	0.138	0.266	0.318	0.260	0.100	0.100	0.129	0.289
Victoria	Melbourne	0.462	0.503	0.263	0.100	0.299	0.391	0.410	0.369	0.271	0.167	0.215	0.281
Queensland North	Townsville	0.449	0.428	0.324	0.131	0.100	0.100	0.100	0.100	0.100	0.168	0.311	0.420
Queensland Central	Rockhampton	0.321	0.329	0.167	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.177	0.268
Queensland South	Brisbane	0.380	0.412	0.279	0.100	0.100	0.193	0.204	0.163	0.100	0.100	0.143	0.310
South Australia	Adelaide	0.465	0.457	0.199	0.100	0.188	0.349	0.414	0.341	0.289	0.100	0.100	0.288
Tasmania	Hobart	0.135	0.100	0.168	0.271	0.423	0.537	0.559	0.501	0.425	0.355	0.241	0.149
ACT	Canberra	0.489	0.509	0.140	0.313	0.528	0.643	0.684	0.635	0.455	0.303	0.136	0.305

Table 19: Average monthly split air conditioner power (kW) by climate zone

State/NEM sub-region	Climate	January	February	March	April	May	June	July	August	September	October	November	December
New South Wales	Sydney	0.240	0.239	0.193	0.050	0.056	0.136	0.169	0.132	0.050	0.050	0.068	0.168
Victoria	Melbourne	0.276	0.302	0.152	0.050	0.157	0.214	0.226	0.200	0.139	0.074	0.122	0.163
Queensland North	Townsville	0.268	0.255	0.190	0.069	0.050	0.050	0.050	0.050	0.050	0.093	0.182	0.250
Queensland Central	Rockhampton	0.188	0.193	0.092	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.098	0.155
Queensland South	Brisbane	0.225	0.245	0.162	0.050	0.050	0.090	0.097	0.072	0.050	0.050	0.077	0.181
South Australia	Adelaide	0.278	0.273	0.112	0.050	0.087	0.188	0.228	0.183	0.150	0.050	0.050	0.168
Tasmania	Hobart	0.072	0.050	0.075	0.139	0.234	0.305	0.319	0.283	0.235	0.192	0.120	0.063
ACT	Canberra	0.293	0.306	0.075	0.165	0.299	0.372	0.397	0.366	0.254	0.159	0.054	0.178

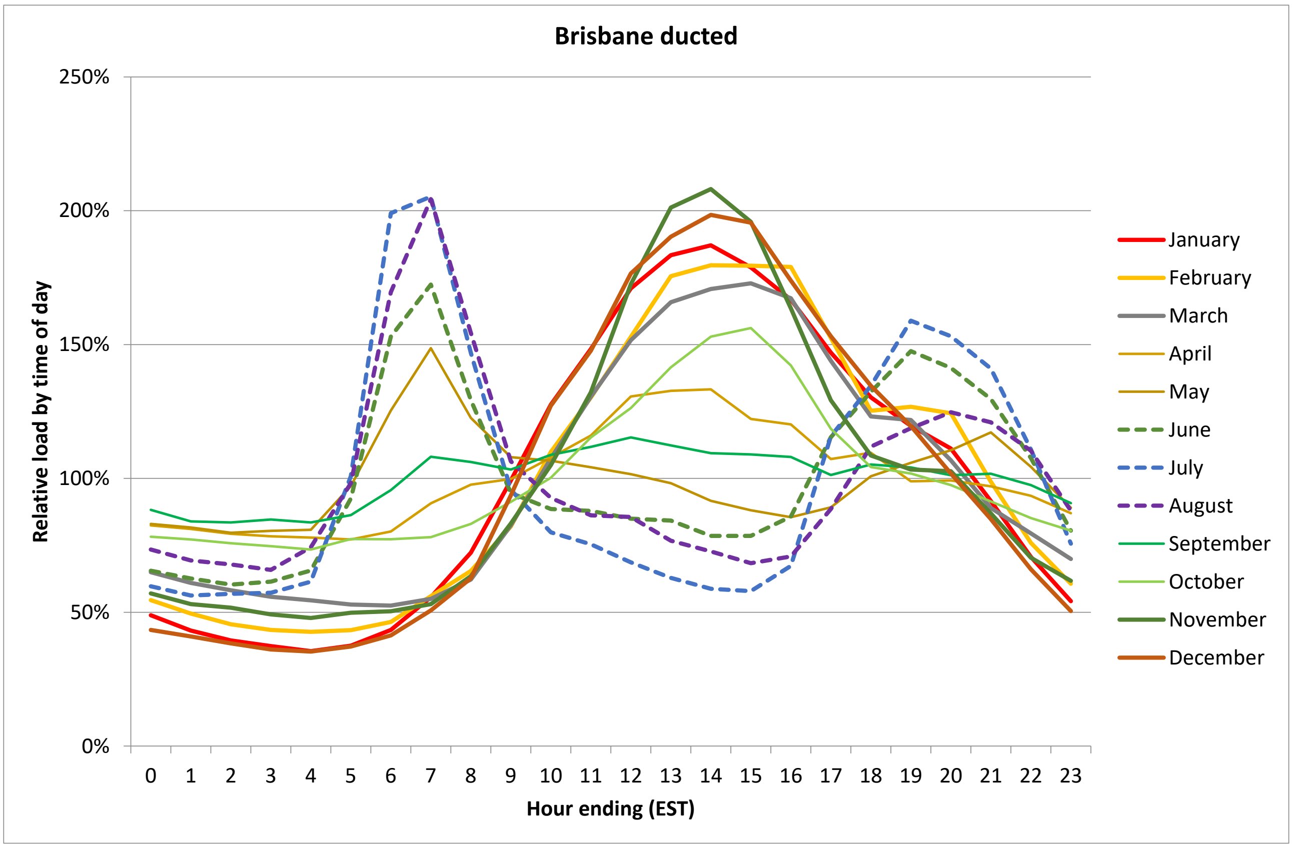

Figure 55: Relative time-of-day profile for ducted air conditioners, Brisbane

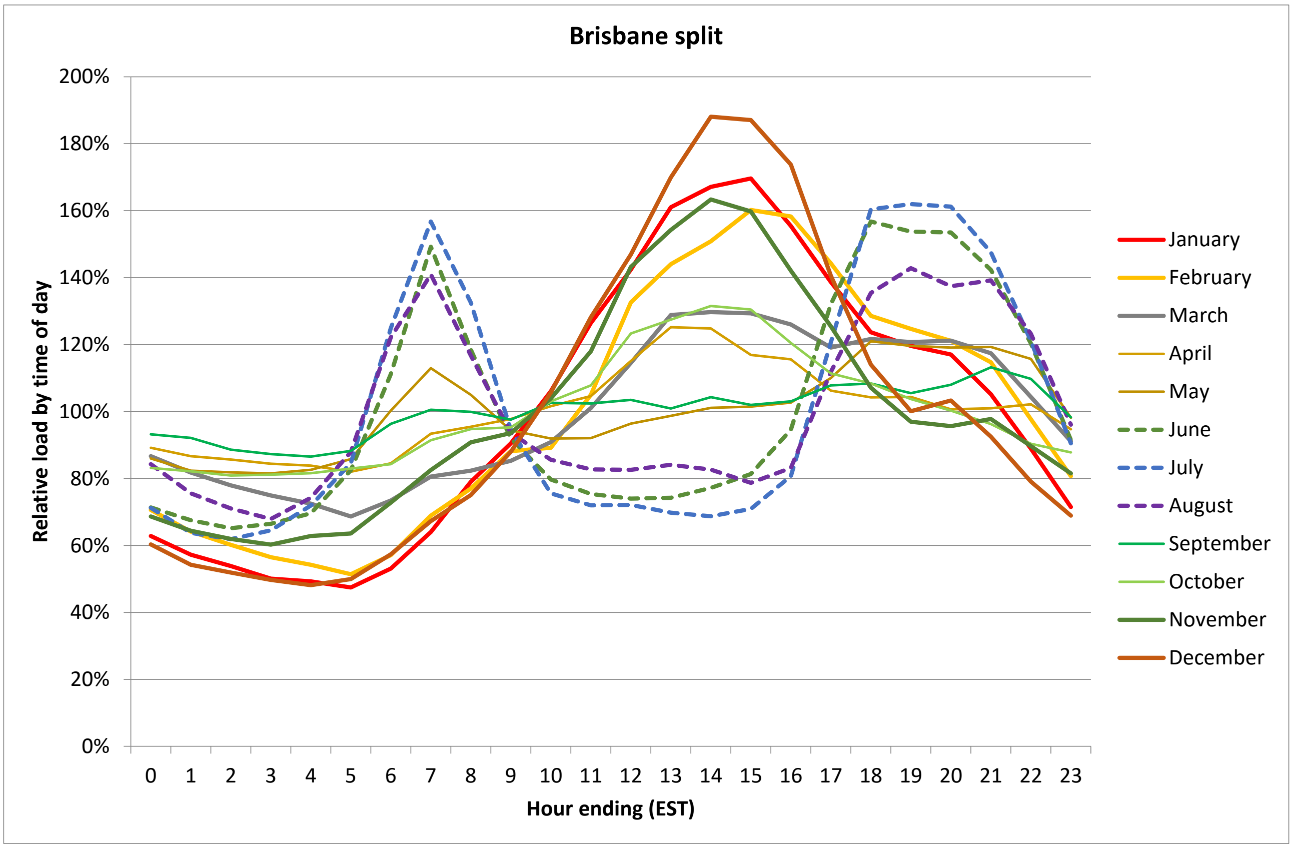

Figure 56: Relative time-of-day profile for split air conditioners, Brisbane

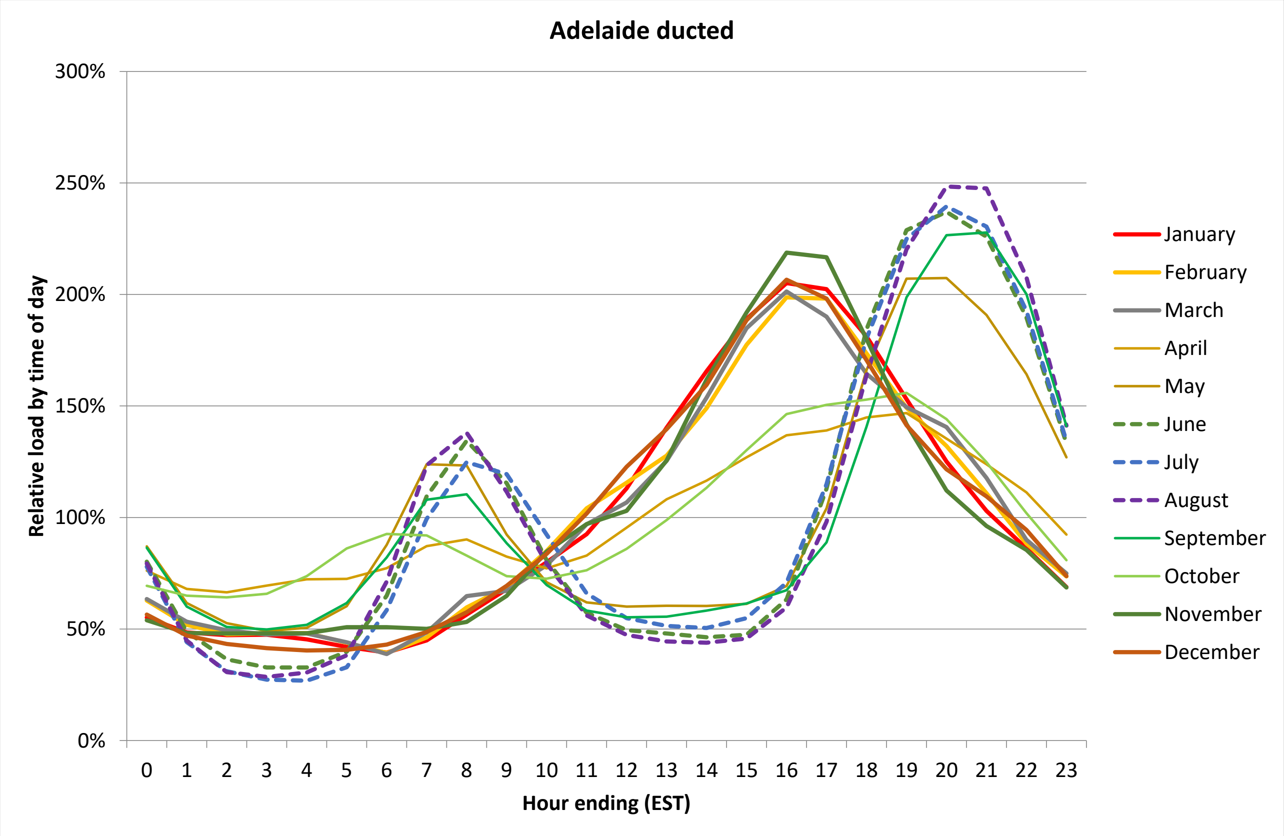

Figure 57: Relative time-of-day profile for ducted air conditioners, Adelaide

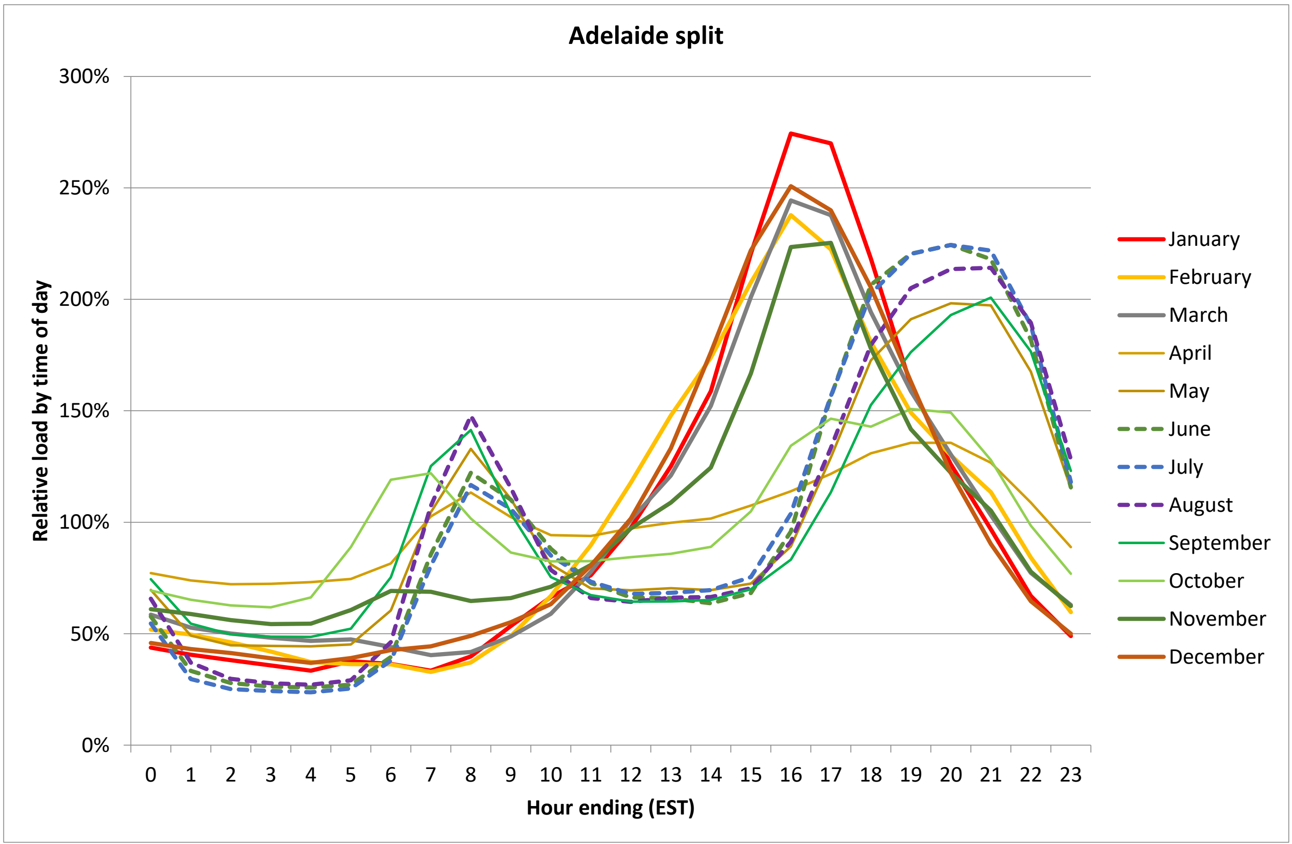

Figure 58: Relative time-of-day profile for split air conditioners, Adelaide

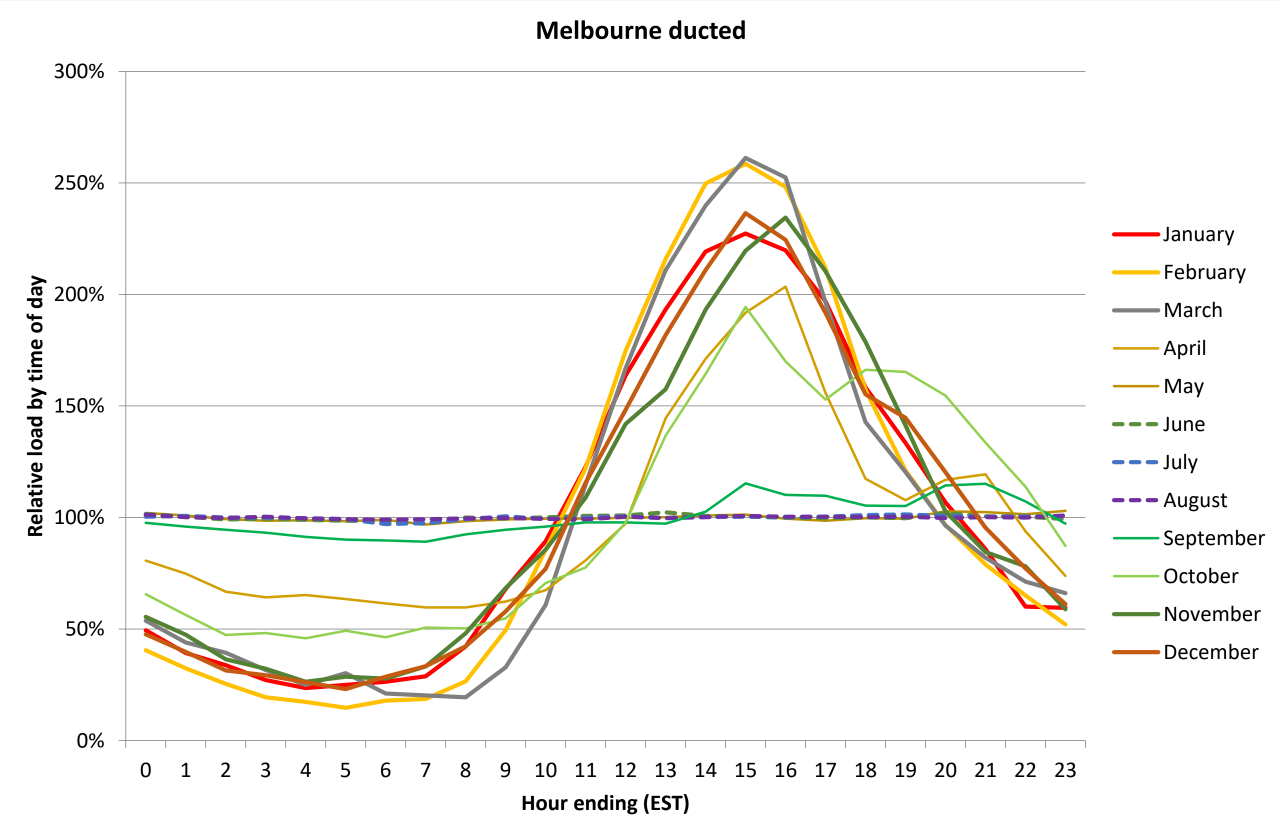

Figure 59: Relative time-of-day profile for ducted air conditioners, Melbourne

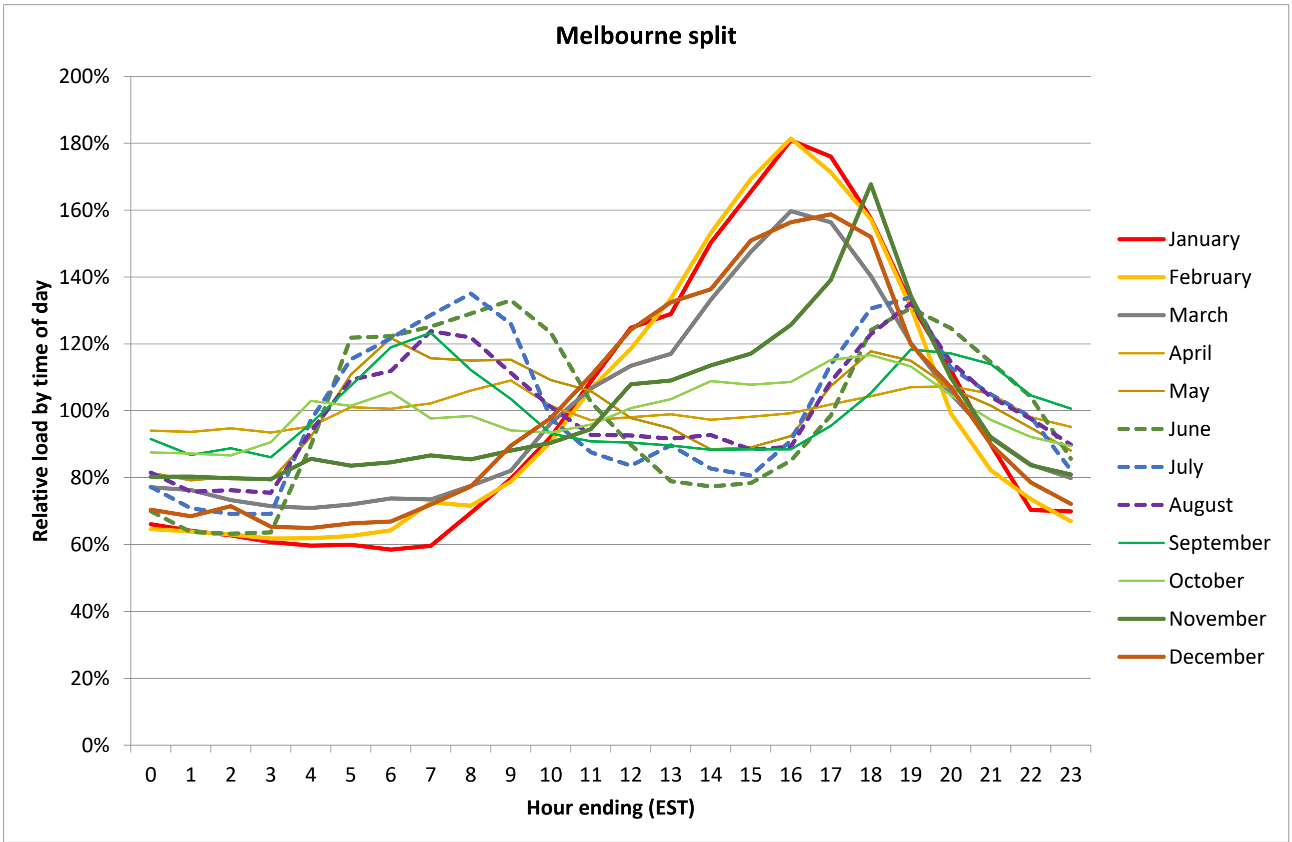

Figure 60: Relative time-of-day profile for split air conditioners, Melbourne

It is clear from the data in Figure 55 to Figure 60 that the load shapes for heating and cooling are very similar across all heating and cooling months. While there are some small differences between ducted and split systems, for practical purposes, the time-of-day patterns are very similar. From this data, a series of generic load shapes have been developed for each of the three cities where data was available. These are depicted in Figure 61. It is important to note that these time-of-day curves merely allocated the expected daily energy for the specific climate into a 24 hour time-of-day profile. The total energy by month is set by the data in Table 18 and Table 19. For example, the shoulder profile (nominally April and October) is quite flat over 24 hours, but the energy is also very low in most climates.

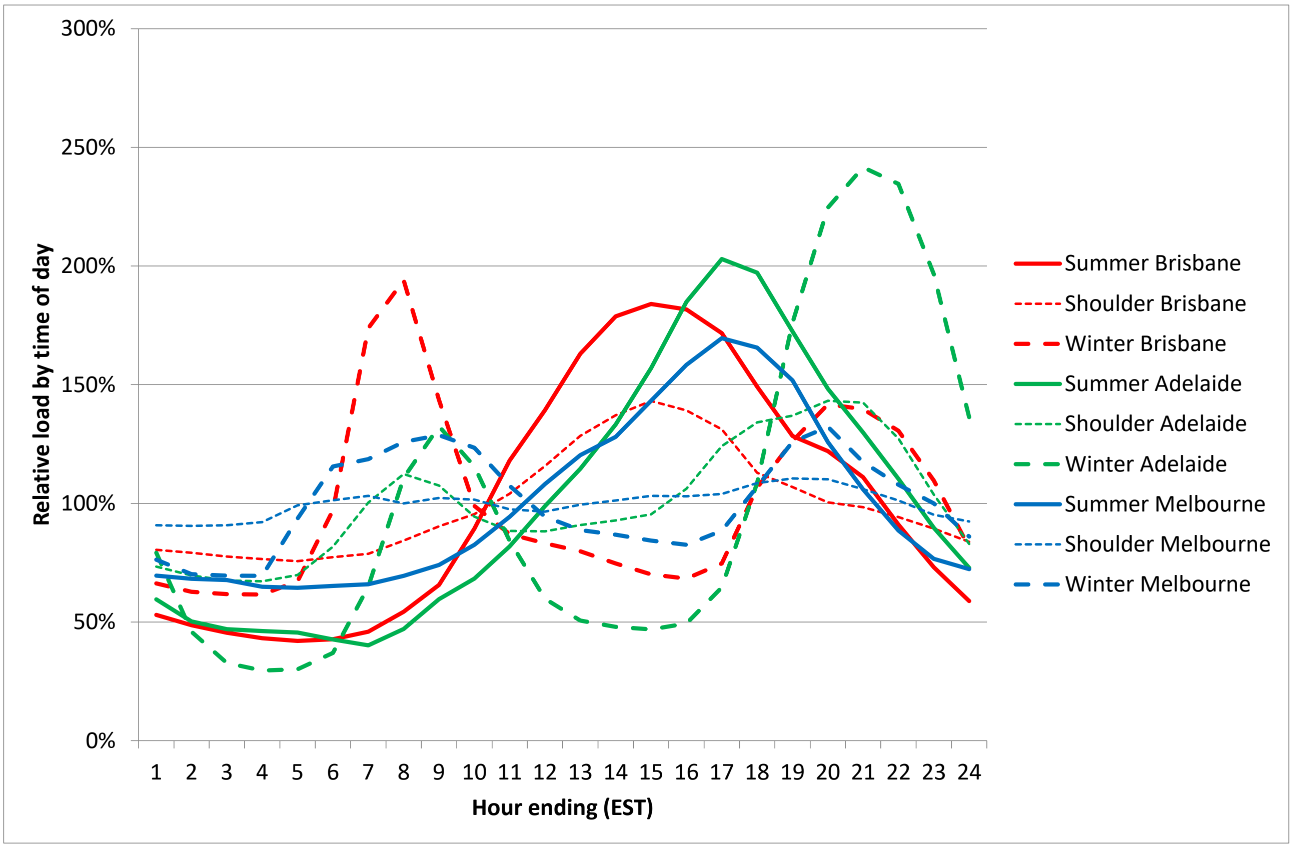

Figure 61: Generic air conditioner time-of-day load shapes – residential main air conditioners

Each city has a slightly different profile, which to some extent is affected by the local time and climate. When developing load profiles for each of the NEM sub-regions in this study, the time-of-day profiles have been allocated as follows:

- Brisbane: allocated to Queensland South, Queensland Central and Queensland North
- Melbourne: allocated to NSW (and ACT), Victoria and Tasmania
- Adelaide: allocated to South Australia.

The summer profile has been allocated to the months from November to March inclusive, the winter profile from May to September inclusive and shoulder to April and October.

For secondary air conditioners, a uniform profile was assumed for heating and cooling as shown in Figure 62. The assumed energy ratio of a secondary air conditioner is 0.4 of that of a main air conditioner.

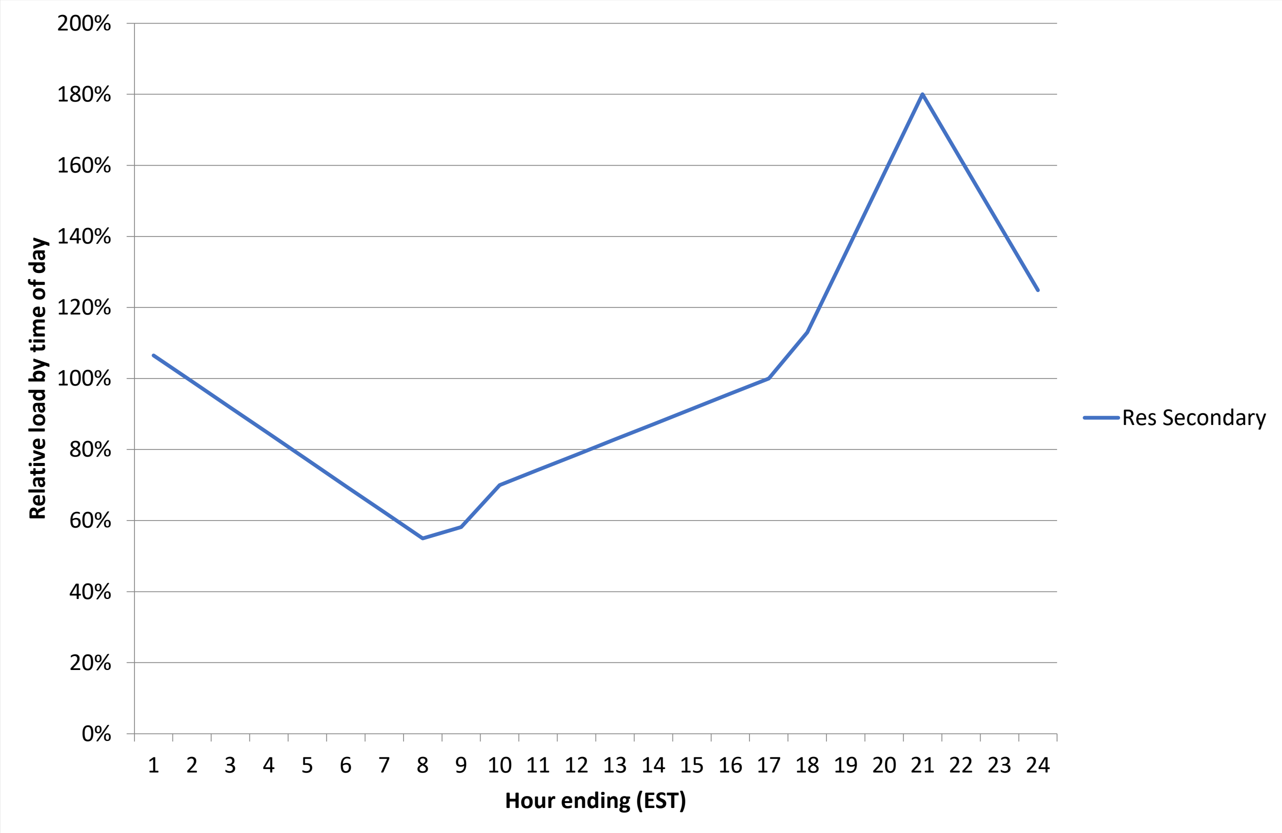

Figure 62: Generic air conditioner time-of-day load shapes – residential secondary air conditioners

These energy estimates and load profiles allow a generic average time-of-day energy profile for air conditioners to be developed for every NEM sub-region and month, day and hour. While this approach does give a good estimate of the "average power" by time-of-day and month, it does not reflect the high level of variability that is reflected in household air conditioning (for example, see Figure 51, which shows a huge variation from day to day).

To investigate this variability, the estimated stock of each air conditioner type (refer to the analysis in Section 4.1) was multiplied by the CSIRO end use measurement air conditioner data for Brisbane, Adelaide and Melbourne and compared to the NEM sub-region data (Queensland South, South Australia and Victoria) over the period 2012 to 2018 to give total air conditioner load in MW. For the NEM data, the minimum day for each month by type of day (weekday or weekend) was used as a base reference and the power difference of every hour in the month relative to the minimum base was calculated (see detailed analysis in Section 2.3.2 and Figure 11). The bottom-up estimate of air conditioner load generally matched the additional load on the NEM from the reference base, but there were some days where there appeared to be load on the NEM that was not driven by household air conditioners and there were days where the air conditioner load should have been significant but the NEM data did not show as much movement from the reference base. In part this can be explained by the fact that there are many loads in addition to household air conditioners that drive NEM load peaks, but in general terms, air conditioners do contribute a significant share. The other issue is that the small sample of monitored air conditioners used to estimate bottom-up state wide air conditioner use may not be fully representative of all air conditioners in each NEM sub-region or the specific weather patterns on those days for the whole sub-region. To some extent this analysis exercise is somewhat blind in that it assumes (indirectly) that load increases on the NEM are primarily driven by weather, but no weather data has been used for this analysis.

In order to generate a better representation of the variability of household air conditioner use, the additional MW for each NEM sub-region for each hour (relative to the minimum day base by type of day) was calculated for the sample year 1 July 2018 to 30 June 2019, which was used to generate sample profiles. The ratio of this additional NEM load for each hour relative to the reference base minimum load for that month and day type was calculated and these values were averaged for the month. The calculated values are shown in Table 20. For example, for NSW in February 2019 (month=2), the average incremental MW load (above the minimum reference base) for all hours in February 2019 was 9.0% above the minimum base MW by hour and day type for that month. As an example, the hourly ratio of incremental load to reference minimum monthly value for the sample year for NSW is shown in Figure 63.

Table 20: Monthly average values of NEM power to minimum

Month	NSW	SA	TAS	VIC	QLDNORTH	QLDCENTRAL	QLDSOUTH
1	19.6%	24.6%	6.9%	21.1%	6.9%	4.1%	13.8%
2	9.0%	15.6%	5.0%	10.0%	18.9%	3.7%	10.9%
3	6.0%	17.2%	4.7%	13.9%	7.1%	4.1%	11.9%
4	8.9%	13.3%	7.6%	11.0%	6.8%	2.6%	8.4%
5	4.3%	4.4%	8.4%	8.4%	7.0%	3.2%	12.6%
6	13.6%	15.2%	7.6%	15.1%	6.9%	5.4%	4.4%
7	9.1%	8.5%	7.0%	6.0%	6.9%	2.6%	4.3%
8	5.3%	11.3%	5.8%	5.1%	9.7%	2.6%	5.0%
9	5.0%	5.5%	7.5%	9.7%	9.0%	2.7%	2.1%
10	8.7%	3.8%	9.3%	2.1%	9.0%	3.4%	9.9%
11	5.2%	4.5%	5.6%	10.1%	15.1%	2.3%	8.9%
12	13.0%	13.9%	4.4%	12.6%	19.4%	9.0%	18.7%

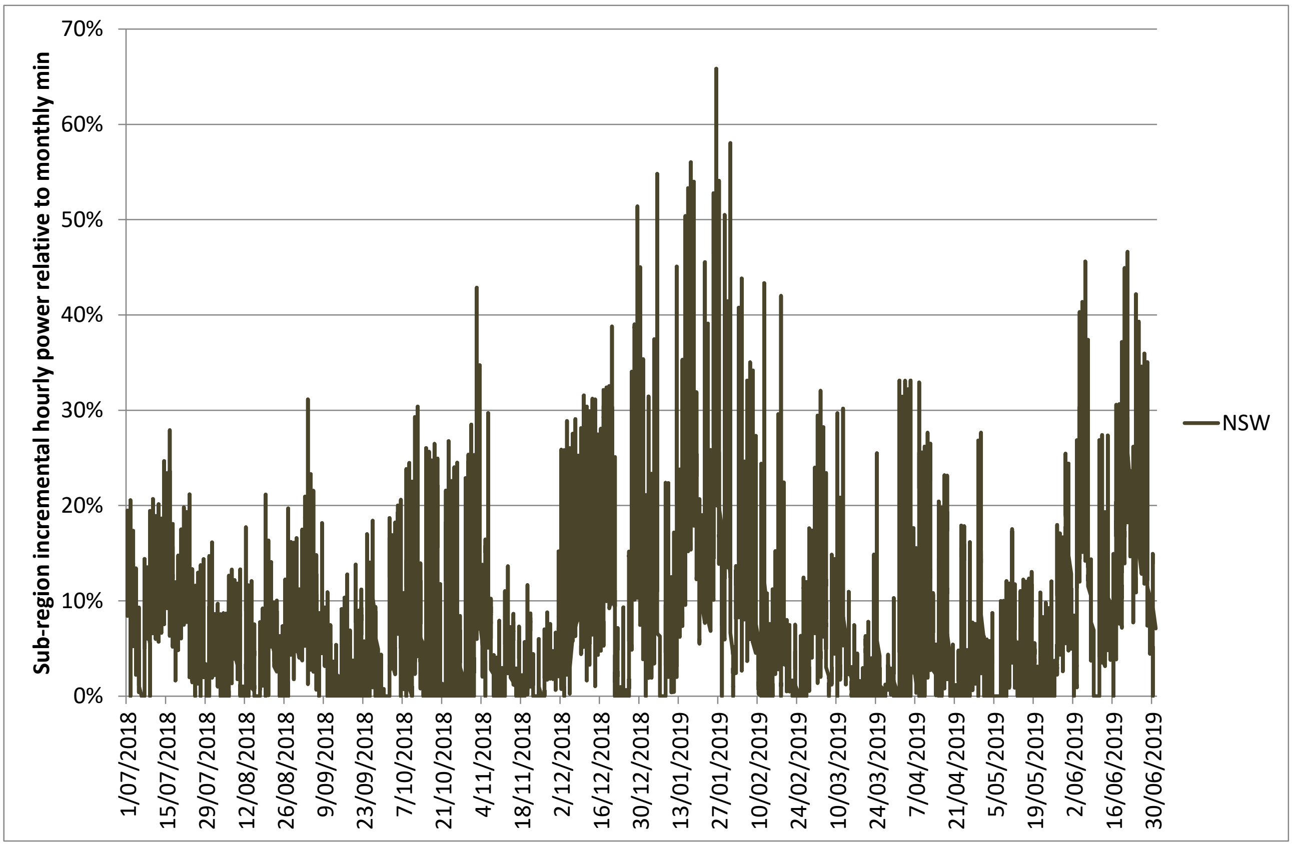

Figure 63: Incremental hourly load above the minimum reference base, NSW, 2018-19

In order to generate a realistic residential air conditioner profile, the average air conditioner load generated from the average profiles above for the year were adjusted as follows. For each hour of a standard average year, the estimated power was multiplied by the NEM hourly incremental load percentage (relative to the reference) (see Figure 63) and divided by the average incremental load percentage for that month (see values in Table 20). This adjusts the hourly energy up and down in proportion to the relative load in the NEM sub-region (some days will be 3 to 4 times the average air conditioner load, some days will effectively have zero air conditioner load). But the average energy for the month will be normalised back to the expected base values set out in Table 18 and Table 19. This appears to provide a highly realistic profile for residential air conditioners both in terms of energy consumption by month and variability from day to day.

4.4.2 Daily load profiles for business air conditioners

Air conditioning load profiles for the business sector are poorly documented and there is very limited end use data around. Based on the limited data available, a similar approach to generating underlying average demand for the residential sector was used. As business air conditioners are used more intensively and consistently than residential air conditioners, the assumed overall energy consumption ratio of business air conditioners is 1.8 times that of residential (on average). Generic load profiles were generated for business air conditioners as shown in Figure 64.

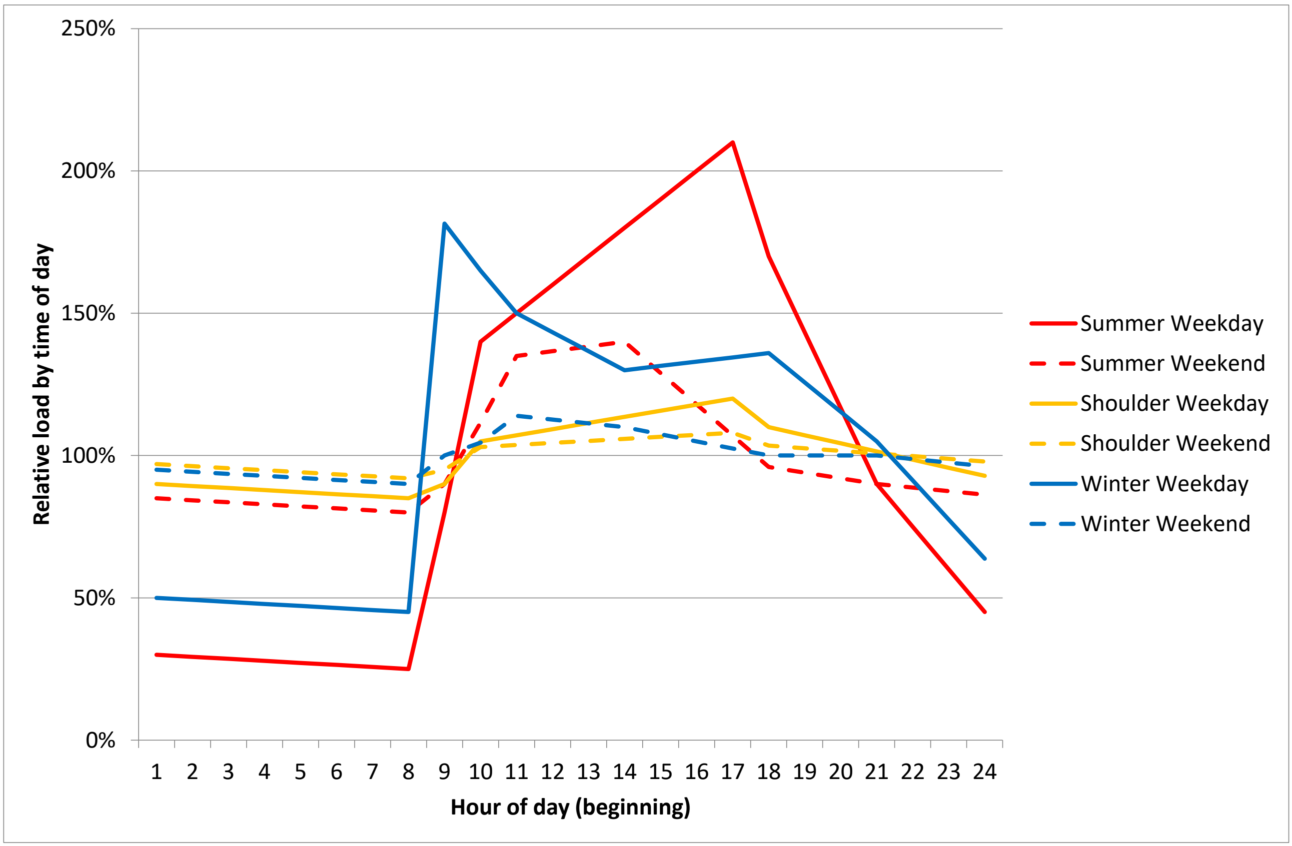

Figure 64: Generic air conditioner time-of-day load shapes – business air conditioners

The time of use is strongly influenced by business hours as shown in Figure 64. In addition to the generic load profiles, an energy ratio of 1.3 has been applied to week days and a ratio of 0.25 to weekends[8] (same load profiles are applied). For all years from 2012-13 to 2018-19 the energy values are adjusted to reflect these values by day of the week.

For business air conditioners, a different approach to the residential sector was used to scale the data for variations in weather as air conditioner use is much more consistent in the business sector. While there is some weather driven variation in demand for business sector air

[8] A factor of 1.3 × 5 days plus 0.25 × 2 days gives a total of 7, which is an average ratio of 1.0 for all 7 days.

conditioners, this is modest and of the order of ±20% of the mean value. As a basis for adjusting the business air conditioner load from day to day, the volatility of daily demand (actual NEM average over the month averaged for the day type) is used (see Figure 12 to Figure 18 as examples but adjustments have been made to all years from 2012-13 to 2018-19). A scaling factor of 5 has been used to accentuate this effect, as the day to day volatility is generally small within each NEM sub-region. For example, if the NEM daily average energy was 1.02 relative to the reference energy for the day type for that month, the business air conditioner load would be scaled by a factor of 1.10. Similarly, if the NEM daily average energy was 0.98 relative to the reference energy for the day type for that month, the business air conditioner load would be scaled by a factor of 0.90. If the NEM daily average energy was 1.00 (and average day), the business air conditioner load would be scaled by a factor of 1.00 (no scaling). It is important to note that these business loads are relatively small and represent only a few percent of the total NEM load.

4.4.3 Compilation of annual load profiles

The residential and business (commercial sector) air conditioner load profiles were compiled for a typical year based on the expected energy consumption and load profiles by air conditioner type. Profiles were generated for the following air conditioner types:

- Residential ducted cooling only
- Residential ducted reverse cycle
- Residential split system cooling only (main)
- Residential split system reverse cycle (main)
- Residential window wall cooling only (main)
- Residential window wall reverse cycle (main)
- Residential evaporative systems
- Residential split system cooling only (secondary)
- Residential split system reverse cycle (secondary)
- Residential window wall cooling only (secondary)
- Residential window wall reverse cycle (secondary)
- Commercial split system cooling only
- Commercial split system reverse cycle
- Commercial window wall cooling only
- Commercial window wall reverse cycle
- Split and ducted systems were split into inverter driven units and single speed compressors (Motor D) and were separately tracked
- Window wall units were all assumed to be single speed compressors (Motor D).

For each year from 2012-13 to 2018-19, weather adjustments were applied to the hourly data as set out above (different adjustments for residential and commercial). A day of the week adjustment was applied to the commercial air conditioner use as set out above. Analysis of the CSIRO data showed that residential air conditioner energy was shown to be unaffected by day of the week, so no day of the week adjustments were applied. This generated a load profile of 8760 hours of data for each type of product listed above (8784 hours in the one leap year analysed 2015-2016). These were then aggregated for more detailed analysis.

Detailed results for all products are set out in Chapter 7.

4.5 Sources of uncertainty in energy estimates for air conditioners

The energy estimates for residential air conditioners have been generated from a bottom-up model of energy consumption based on a large scale end use metering program. The model uses measured field data for many air conditioners in three cities. This is by far the best available data source and there has been extensive analysis to get this data into the format required by AEMO and to extrapolate use to other climates. Air conditioner use in the residential sector is highly variable from day to day and predicting this use has defied many attempts at analysis in the past.

The baseline average energy estimates by air conditioner type are considered reasonable. A novel approach to account for short term variations in weather and associated air conditioner use has been developed to generate a realistic variation in residential air conditioner loads. Note this is not a predictive tool, but it does generate realistic load profiles for detailed internal analysis by AEMO. Simulations of estimate indoor temperatures in homes would provide a better model to predict residential air conditioner use (Energy Efficient Strategies 2004; Ren & Chen 2018; Strategy.Policy.Research 2019), but this would require a range of sophisticated new approaches, including forecasting of a wide range of weather parameters for modelling and prospective building simulations.

Energy consumption estimates for commercial air conditioners are less certain as only limited end use metering data is available. However, the estimates appear to be reasonable and they constitute a minority of the total air conditioner load. Estimates for evaporative cooling is based on little field data, so engineering estimates have been made. Only two states (Victoria and South Australia) has a significant stock share for evaporative cooling.

The stock of residential air conditioners are considered very robust as they are based on regular national surveys conducted by the ABS (Australian Bureau of Statistics 2014). The last survey was in 2014, but ownership changes are very slow for such a large stock of appliances. Estimates of the number of air conditioners in the commercial sector are less certain and have been estimated indirectly from a long term sales stream. The uncertainty could be as high as 20% for this sub-segment, generated because of the uncertainty of stock numbers and to some extent uncertainty in the energy consumption estimates.

This report estimates for the first time the share of inverter driven air conditioners. This was based on a mixture of quite solid historical industry data (George Wilkenfeld and Associates 1993, 2001; E3 2009, 2018; BIS Shrapnel 1988, 2006, 2010; Informark 2008) and government registration data (since 2008). The share of inverter driven compressors is now quite stable, with the share of Motor D products at less than 5% for new split and ducted units. All window wall units still appear to be driven by Motor D, but these are only a few percent of the market and declining.

5 Household refrigeration

5.1 Stock of household refrigeration

Household refrigerators and freezers have been an essential household appliance since they became readily available and affordable from the 1950s. There has been very good data collected on the stock of household refrigerators and freezers by the ABS from a range of surveys since 1980 (Australian Bureau of Statistics 1987, 2014), providing an accurate assessment of the total stock now and into the near future. Most households had a refrigerator by the 1960s (Vohralik & Sloot 1963; Dingle 1998; Harrington 2018) and currently over 99% of households have at least one refrigerator. The average ownership increased gradually to a peak of about 1.35 refrigerators per house in 2010 and is now falling very slowly. This is due to larger refrigerators and declining household sizes.

In contrast, freezer penetration was quite low in the 1960s (less than 10%) but increased rapidly to a peak of about 50% of households in the mid-1980s. Since 1990, freezer penetration and ownership has been slowly declining. This is also likely to be driven by smaller household sizes and larger freezer compartments in normal household refrigerator-freezers. Of all the states and territories, Tasmania stands out as having significantly higher separate freezer ownership, primarily driven by a larger rural population. The other more rural states and territories (Queensland, Western Australia, South Australia and Northern Territory) have slightly higher ownership of separate freezers while the more urban states and territories (NSW, Victoria, ACT) have a slightly lower ownership of separate freezers. Trends in refrigerator and separate freezer ownership at a state level is shown in Figure 65 and Figure 66.

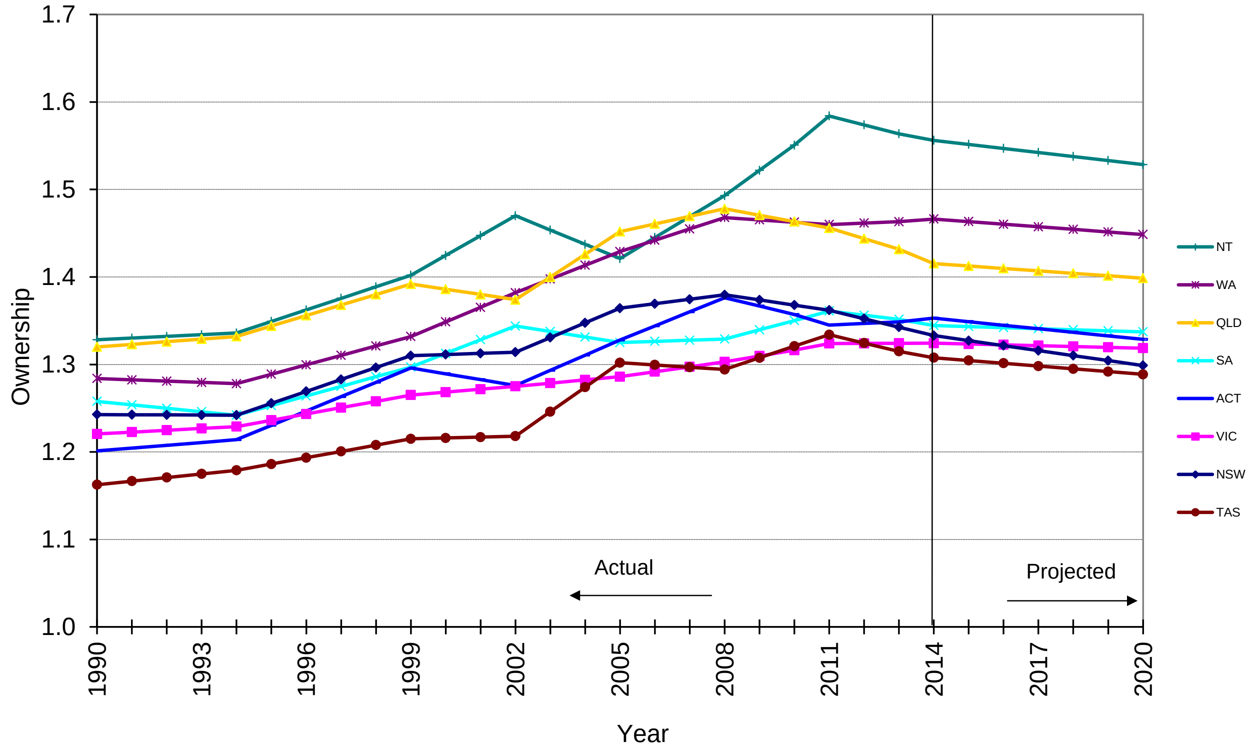

Figure 65: Trends in household refrigerator ownership by state

Notes: Ownership is stock divided by total number of households

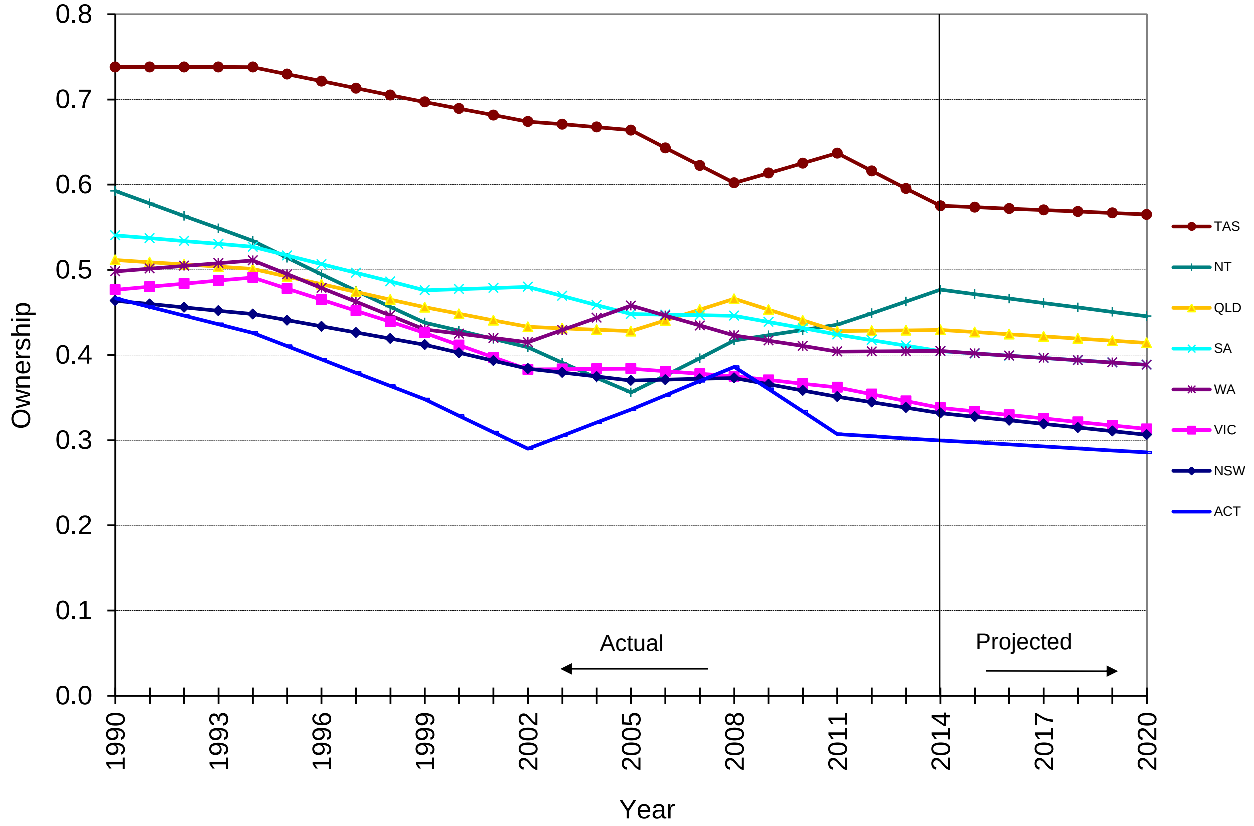

Figure 66: Trends in household freezer ownership by state

Most data analysis shows that the characteristics of household refrigerators and freezers are uniform across states, with little or no differences in average size or share by group (Energy Efficient Strategies 2016). For household refrigerators, ownership is very uniform across capital cities and the balance of the state. However, for separate freezers, the ownership outside of capital cities tends to be significantly higher than the rest of the state (reflecting the broader trend in rural/urban at a state level as noted above). All of the NEM sub-regions are at a state level for this study, expect for Queensland. The 2014 ABS survey showed that capital city penetration for freezers in Queensland (nominally Brisbane) was around 31.8% while the balance of state data was 44.3%. Given that the capital city value for Queensland is likely to be broadly representative of the NEM Queensland South sub-region, this allows the penetration for the NEM Queensland Central and NEM Queensland North sub-regions to be estimated by deduction. Assuming a NEM Queensland South freezer penetration of 33% (slightly above Brisbane) gives an average penetration of 57.6% for NEM Queensland Central and NEM Queensland North sub-regions, or a scaling ratio of 0.844 for NEM Queensland South and 1.473 for NEM Queensland Central and NEM Queensland North sub-regions.

Using ownership data, together with the number of households by NEM sub-region allows an accurate assessment of the stock of refrigerators and freezers by sub-region as set out in Table 21 and Table 22.

Table 21: Installed household refrigerators by NEM sub-region in 2020

State/sub-region	Refrigerator Ownership	Refrigerator Ownership NEM region	Total Refrigerators	NEM Refrigerators
New South Wales	1.2987	1.2987	4043827	4043621
Victoria	1.3187	1.3187	3392091	3392022
Queensland	1.3986		2752541	
Queensland North		1.3986		431942
Queensland Central		1.3986		226775
Queensland South		1.3986		2069431
South Australia	1.3373	1.3373	968444	966726
Western Australia	1.4486		1476958	0
Tasmania	1.2887	1.2887	296308	294903
Northern Territory	1.5285		124651	0
ACT	1.3287	1.3287	227766	227766
Other Territories	1.3500		2125	0
Australia			**13,284,711**	**11,653,186**

Table 22: Installed household freezers by NEM sub-region in 2020

State/sub-region	Freezer Ownership	Freezer Ownership NEM region	Total Freezers	NEM Freezers
New South Wales	0.3064	0.3064	953975	953926
Victoria	0.3132	0.3132	805656	805640
Queensland	0.4142		815174	
Queensland North		0.6102		188456
Queensland Central		0.6102		98941
Queensland South		0.3496		517255
South Australia	0.3885	0.3885	281339	280840
Western Australia	0.3885		396119	0
Tasmania	0.5650	0.5650	129908	129292
Northern Territory	0.4455		36332	0
ACT	0.2856	0.2856	48959	48959
Other Territories	0.3000		472	0
Australia			**3,467,934**	**3,023,309**

For the purposes of modelling for this report, a detailed stock model was used to generate an estimate of each type of refrigerators and freezers as set out in the tables above for each year from FY 2012-13 to 2018-19 inclusive.

5.2 Stock of household refrigerators and freezers used in business

A significant number of household style refrigerators are used in offices and workplaces around Australia. These are primarily used for domestic purposes (storing lunch and other personal food items, storing milk and drinks). The main difference is that usage is concentrated more during office hours and the spaces in which they operate are (by and large) conditioned spaces (heated and cooled for human comfort). Most of these appliances are standard refrigerator-freezers (Group 5T) or larger all-refrigerators (Group 1) in larger offices while small bar refrigerators are used in small work places (Group 2) with a small numbers of employees. Estimates of the number of household refrigerators used for domestic purposes in the commercial sector are very poor, with no official data sources available. However, there are some 12.5 million employees in Australia (Vandenbroek 2018), although data on the number of workplaces is not readily available. Based on an informal survey of workplaces, it is estimated that 1 refrigerator would be available per 10 workers on average, giving a total stock of household style refrigerators at about 1.25 million units across Australia. This fits reasonably well with industry estimates that 10% of Group 2 products and 10% of Group 5T/5B products are destined for use in the commercial sector. Note that this does not include any household style products that are used as commercial refrigerators or for professional storage (which are likely to be minimal). It is assumed that very few separate household freezers are used in workplaces as refrigerator-freezers typically have enough freezer storage capacity if required. For the purposes of this study it is assumed that an additional 3% of household freezers are used for personal purposes in business workplaces around Australia. Note that the estimated stock of products is distributed across NEM sub-region on a population pro-rata basis (not households). The values used for modelling are set out in Table 23.

Table 23: Estimated stock of household refrigerators and freezers in the business sector in 2020

State/sub-region	All household refrigerators used in business	NEM region household refrigerators used in business	All household freezers used in business	NEM region household freezers used in business
New South Wales	399815	399794	33277	33275
Victoria	326626	326619	27185	27185
Queensland	250646		20861	
Queensland North		39333		3274
Queensland Central		20650		1719
Queensland South		188442		15684
South Australia	85039	84888	7078	7065
Western Australia	128300	0	10678	0
Tasmania	25888	25765	2155	2144
Northern Territory	12287	0	1023	0
ACT	21174	21174	1762	1762
Other Territories	225	0	19	0
Australia	**1,250,000**	**1,106,665**	**104,038**	**92,108**

5.3 Share of household refrigerators and freezers with inverter driven compressors

There are no formal data sets that reveal the share of household refrigerators that use inverter driven compressors. Unlike air conditioners, the registration system for energy efficiency does not record whether each model uses an inverter. Recent changes to the regulatory system for refrigerators mean that data on inverter driven compressors is now being collected (from 2020), but it will be some time before useful data will be available.

Anecdotally, it is known that inverter driven compressors have been used on high end European and Asian products for more than a decade, but initially these tended to be niche products rather than mainstream. By 2012, around 85% of the household refrigerator market in Japan used inverter driven compressors. However, there were specific drivers in the Japanese market, most notably the testing of energy at two ambient temperatures, which gave a significant advantage to inverter driven products and aspects of the Top Runner program that encouraged efficient technologies (Ministry of Economy, Trade and Industry, Japan 2015). Increases in market share for inverters in several major markets has meant that developments in smaller inverters suitable for refrigeration have been rapid in recent years, with several of the largest compressor suppliers focusing much of their research and development efforts on inverter driven products.

Given that inverter driven household refrigerators and freezers are increasing their share rapidly in Australia, quantifying this was an important element for this study. However, data sources are scarce and this presented a significant data challenge. The method used is set out briefly below.

Identify major suppliers: From detailed model level sales data, the top suppliers of refrigerators and freezers were identified. The data set used was based on GfK retail sales data over the period 2010 to 2017 (Energy Efficient Strategies 2016; E3 2017a). Note that this data set is not generally available for analysis by third parties. Sales data was broken up by brand into each of the 10 Groups defined in AS/NZS4474 (AS/NZS4474 2018).

Contact major suppliers for data: Major suppliers were contacted by EES with a list of all their current refrigerator models and were asked to identify which models used inverter driven compressors. They were also asked to provide some history on the use of inverters and any future plans over the next 5 years. In some cases where there were few models, data on the supplier website was used to ascertain whether or not an inverter was used. The brands investigated were:

- Electrolux, Kelvinator and Westinghouse
- Fisher & Paykel and Haier
- Hisense
- LG
- Liebherr
- Miele
- Mitsubishi Electric
- Panasonic
- Samsung
- Sharp.

These brands represented over 85% of all refrigerator and freezer sales in Australia over the past 15 years and can be assumed to be representative of the general market trends over this period.

Track the share of inverter driven products over time: Based on the data provided by all the suppliers, the share of inverter driven products was estimated from 2010 to date (2020) and projected to 2025 and beyond based on trends and stated plans. This was done for each brand and Group (type of refrigerator) for each year.

Aggregate whole market data: The overall share of inverters for refrigerators and for separate freezers over time was then aggregated from the available data. The overall trend in market share of inverters based on a best fit curve of the data is depicted in Figure 67. Based on these trends it would appear that the share of inverter driven refrigerators is likely to saturate at 85% to 90% (similar to Japan) by 2040. Freezers appear to be much slower to adopt inverter technology and are about 10 years behind refrigerators. In part, this is likely due to a large part of the freezer market being low end and very price competitive. Despite their high efficiency, inverter driven products are still more expensive to manufacture.

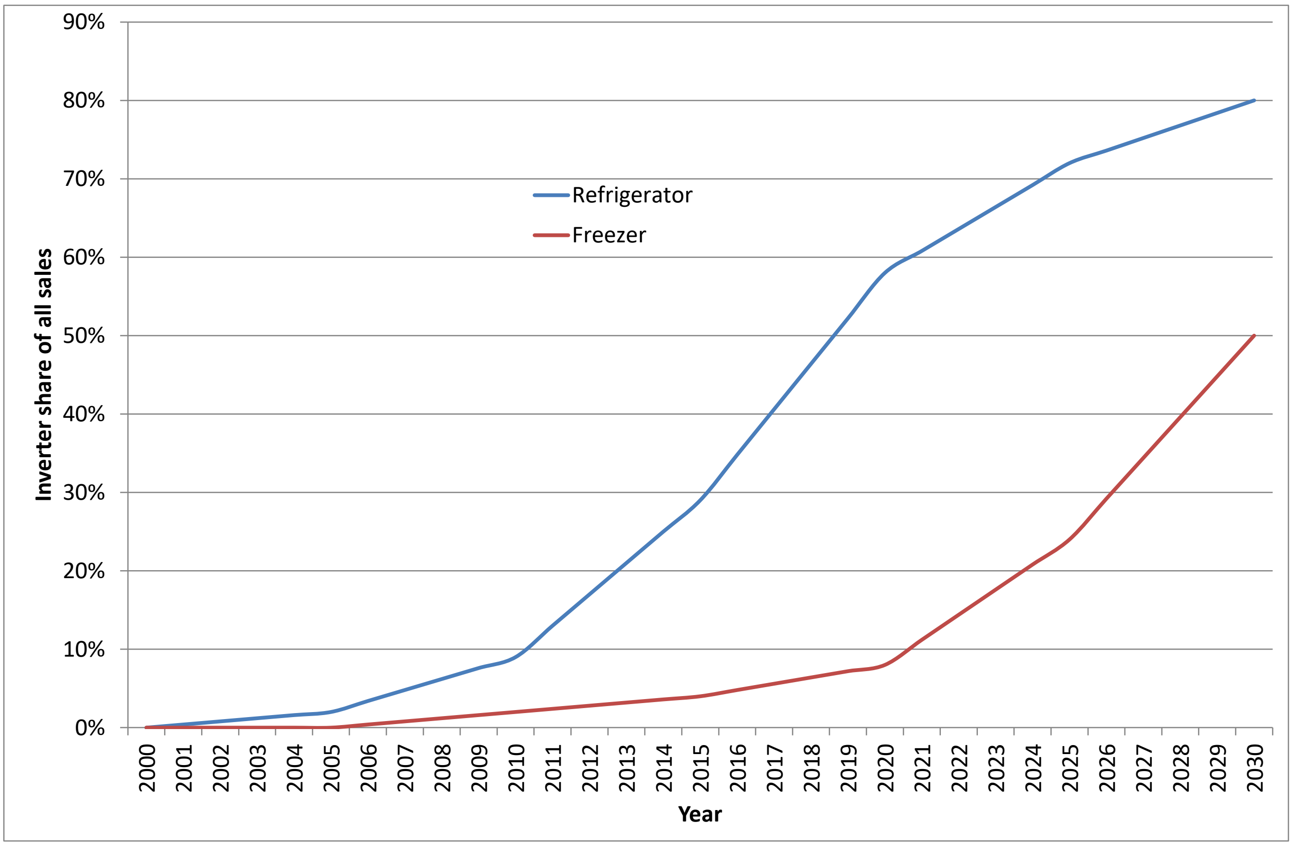

Figure 67: Estimated sales share of inverter driven refrigerators and freezers in Australia

Notes: Based on author survey of major suppliers with author projections

The data set out above is based on sales of new products into the market each year. For this study, the stock of products split into Motor D (single phase induction motors) and inverter driven motors is required. In order to convert this sales stream into a stock equivalent value, a standard stock model was used. The basic parameters of the stock model are:

- Separate sales stream for refrigerators and freezers
- Assumed lifetime of 15 years for refrigerators and 21 years for freezers (E3 2017a; Beyond Zero Emissions 2013; Energy Efficient Strategies 2008)
- A normal distribution retirement function (see Figure 68 and Figure 69).

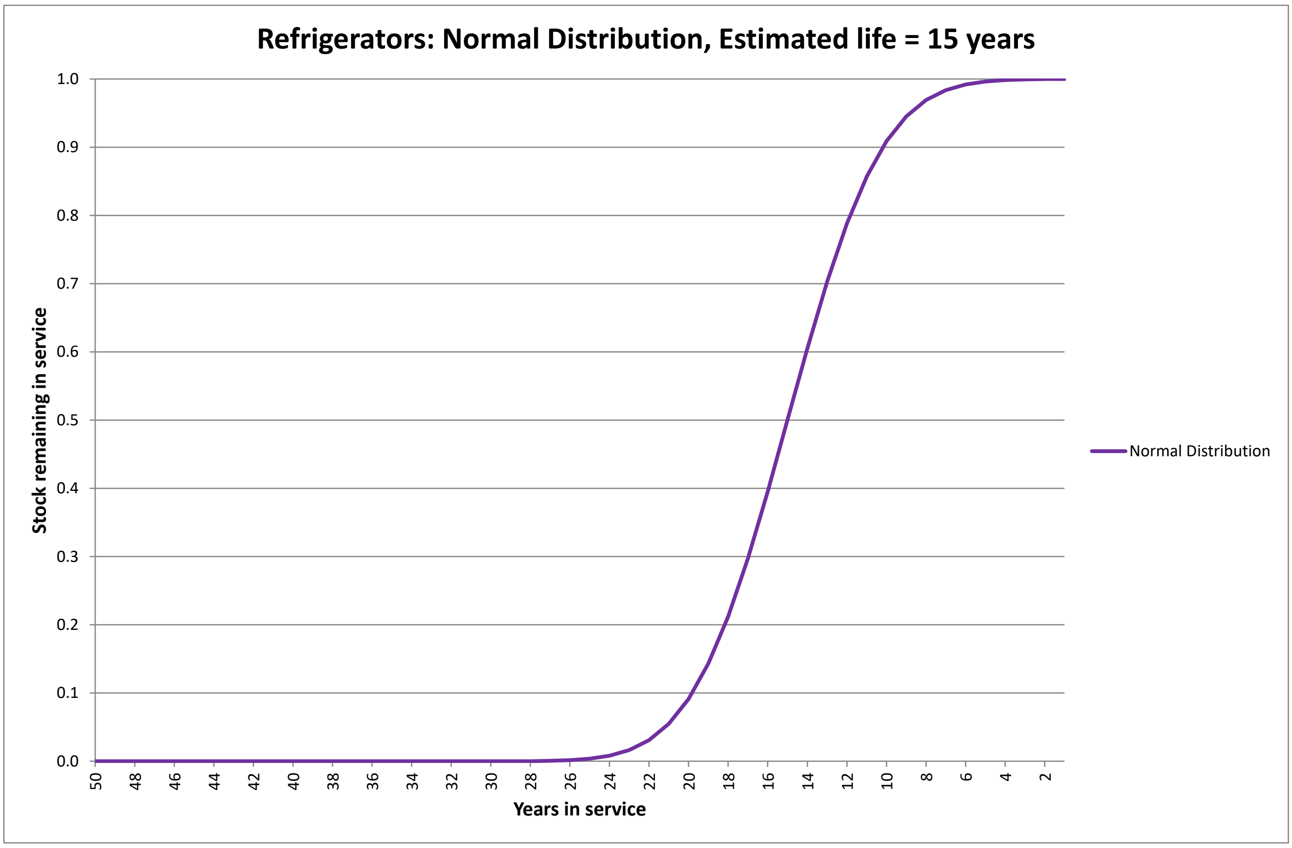

Figure 68: Retirement function (stock remaining) for refrigerator stock model

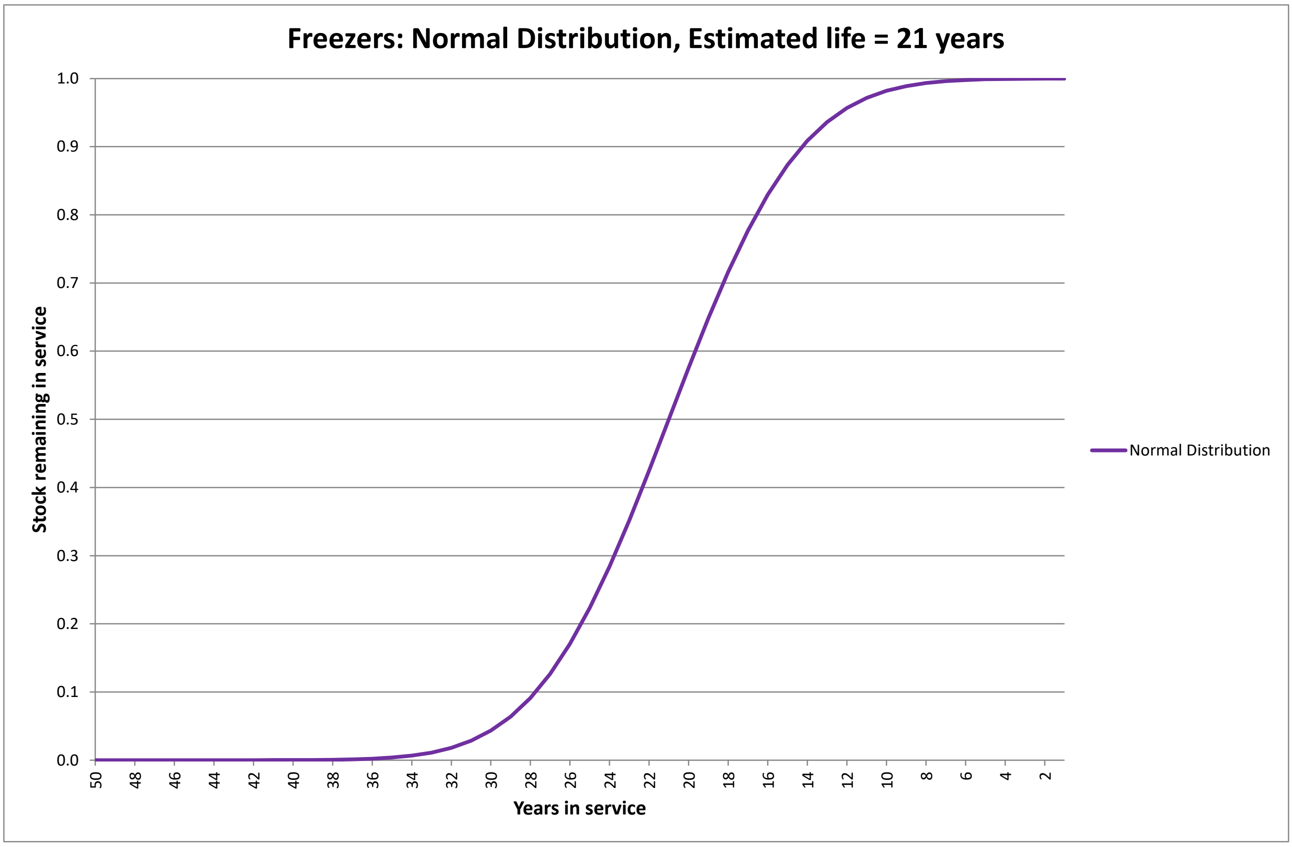

Figure 69: Retirement function (stock remaining) for freezer stock model

Once the sales stream has been processed through the stock model, an estimate of the stock share of inverter driven refrigerators and freezers can be made. This is depicted in Figure 70 up to 2030.

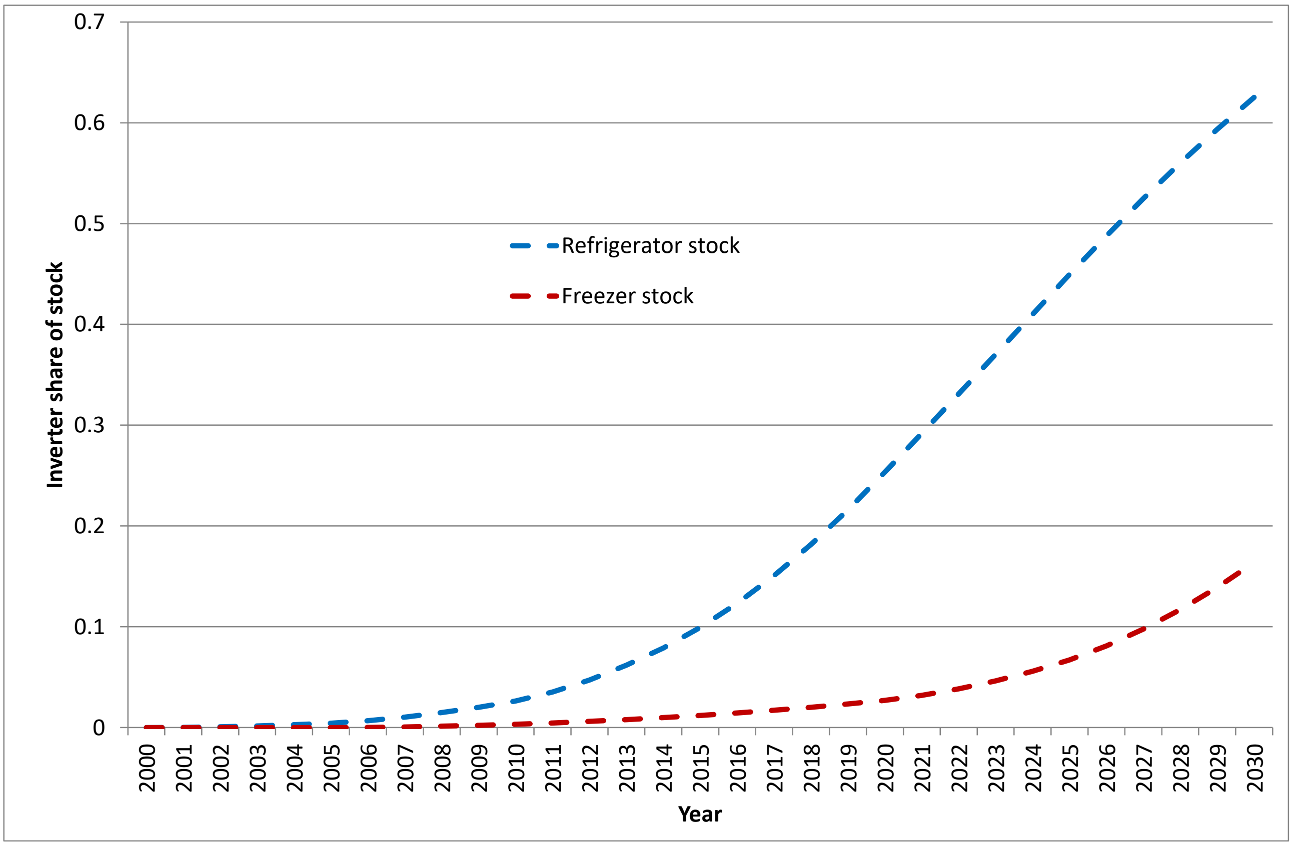

Figure 70: Stock share of inverter driven refrigerators and freezers in Australia

5.4 Energy consumption and load profiles for household refrigeration

It is well documented that the energy consumption of refrigerators and freezers is driven by a range of factors, but primarily by the room temperature in which the appliance operates (Harrington 2018; Harrington, Aye & Fuller 2018a, 2018b). Given that the NEM sub-regions vary from tropical in the north to cool temperate in the south, it is important that an energy model for household refrigeration takes into account the indoor ambient temperature.

5.4.1 Indoor temperatures in residential houses and businesses

The first important step is to develop estimates of average indoor ambient temperatures in homes for each of the NEM sub-regions. Analysis undertaken by the author has developed a model of indoor temperature in Australian homes based on analysis of 300 sites from Melbourne to Cairns and corroborated with data from 736 sites measured by CSIRO in Brisbane, Adelaide and Melbourne (Harrington 2018; Harrington, Aye & Fuller 2015; Ambrose et al. 2013; Ambrose 2015).

Three separate models of indoor temperatures in homes were developed on the basis of building age as follows (Harrington, Aye & Fuller 2015), where T_o is the monthly average outdoor temperature and T_{indoor} is the monthly average indoor temperature in degrees Celsius:

- Old houses (pre 1990): $T_{indoor} = 0.0275 \times T_o^2 - 0.37 \times T_o + 18.152$
- Intermediate houses (1990-2005): $T_{indoor} = 0.0179 \times T_o^2 - 0.0072 \times T_o + 15.367$
- Newer houses (after 2005): $T_{indoor} = 0.0115 \times T_o^2 + 0.1809 \times T_o + 14.805$

For each of the NEM sub-regions, a suitable climate was selected from the Australian Climate Database, which are used for various simulations, including National House Energy Rating Scheme (NatHERS) for home star ratings (Department of Industry, Science, Energy and Resources 2020) using thermal modelling software for building shells called AccuRate (CSIRO 2017; Energy Inspection 2018). For this project, the latest 2016 climate files (depicting a typical mean year) were selected. Climates selected are set out in Table 24. Note that these files provide hourly data for most climate parameters (temperature, humidity, wind speed and direction, cloud cover and solar radiation) and while selected from real historical data, the hourly patterns do not represent a data sequence for any particular year.

Table 24: Australian Climate Database climates selected for modelling of household temperatures

State/NEM sub-region	Climate	ACDB Ref
New South Wales	Sydney	17
Victoria	Melbourne	21
Queensland North	Townsville	5
Queensland Central	Rockhampton	7
Queensland South	Brisbane	10
South Australia	Adelaide	16
Western Australia	Perth	13
Tasmania	Hobart	26
Northern Territory	Darwin	1
ACT	Canberra	24

Using the selected Australian Climate Database (ACDB) files, it is possible to then calculate monthly average outdoor temperatures (dry bulb) for each of the selected climate zones as shown in Table 25. Using the household temperature model for newer homes (after 2005) given above, the monthly average indoor temperature for each NEM sub-region has been calculated in Table 26. Most refrigerators are located in conditioned spaces in the home. However, most freezers are located in unconditioned spaces in the home, such as laundries. Detailed research developed a model of indoor air temperatures in unconditioned spaces for a typical 3 star home as follows (Harrington 2018):

$$T_{unconditioned} = 0.000502446 \times T_o^3 - 0.031052 \times T_o^2 + 1.4408 \times T_o + 1.8416$$

Using this equation, estimates of indoor temperatures in unconditioned parts of homes were made as shown in Table 27.

The final piece of the analysis was to develop an estimate of temperatures in commercial spaces. While some offices have tightly controlled ambient conditions all year, many offices and spaces in retail and manufacturing, operate space conditioning during office hours and let the temperature drift when the spaces are not occupied. This is difficult to model and there is little data, but as a proxy to estimate this effect, it is assumed that indoor temperatures in offices and other conditioned spaces is the same as households in the same climate zone, except with a temperature floor of 19°C and a temperature ceiling of 25°C applied. This narrows the expected operating temperature range in these types of premises, as shown in Table 28.

Table 25: Average monthly outdoor temperatures (°C) for each NEM sub-region based on ACDB TMY files (2016)

State/NEM sub-region	January	February	March	April	May	June	July	August	September	October	November	December
New South Wales	22.5	22.5	21.8	19.0	15.8	13.6	12.7	13.7	16.5	18.7	19.8	21.4
Victoria	20.6	21.0	18.6	16.5	13.0	11.4	11.1	11.8	13.5	15.3	18.1	18.8
Queensland North	28.0	27.8	26.7	24.8	22.9	20.4	19.6	20.4	22.5	25.2	26.6	27.7
Queensland Central	26.7	26.8	25.2	23.4	20.2	16.8	16.3	18.2	20.3	23.4	25.3	26.2
Queensland South	24.8	25.1	23.8	20.8	17.8	14.9	14.7	15.4	18.4	20.0	22.4	24.1
South Australia	23.1	23.1	20.5	17.9	15.0	12.1	11.0	12.3	13.2	16.2	18.7	21.4
Western Australia	24.6	25.1	23.6	19.6	15.2	13.3	12.9	12.5	14.2	16.7	20.0	23.7
Tasmania	17.4	16.6	15.3	13.5	10.9	8.9	8.5	9.5	10.8	12.0	14.0	15.6
Northern Territory	28.0	27.9	27.8	27.7	26.8	25.0	24.3	25.2	27.5	28.9	29.4	28.8
ACT	20.9	21.1	17.4	12.8	9.0	7.0	6.3	7.1	10.3	13.0	15.9	19.0

Table 26: Average monthly indoor conditioned temperatures (°C) for each NEM sub-region for newer homes based on Harrington, Aye & Fuller (2015)

State/NEM sub-region	January	February	March	April	May	June	July	August	September	October	November	December
New South Wales	24.7	24.7	24.2	22.4	20.6	19.4	18.9	19.4	20.9	22.2	22.9	23.9
Victoria	23.4	23.7	22.2	20.9	19.1	18.4	18.2	18.5	19.3	20.3	21.9	22.3
Queensland North	28.9	28.7	27.9	26.4	25.0	23.3	22.8	23.3	24.7	26.7	27.8	28.6
Queensland Central	27.8	27.9	26.6	25.3	23.2	21.1	20.8	21.9	23.2	25.3	26.7	27.4
Queensland South	26.4	26.6	25.6	23.5	21.7	20.0	19.9	20.3	22.0	23.0	24.6	25.8
South Australia	25.2	25.1	23.3	21.7	20.1	18.7	18.2	18.8	19.2	20.8	22.2	23.9
Western Australia	26.2	26.6	25.5	22.8	20.2	19.3	19.1	18.8	19.7	21.0	23.0	25.6
Tasmania	21.4	21.0	20.3	19.3	18.1	17.3	17.2	17.6	18.1	18.6	19.6	20.4
Northern Territory	28.9	28.8	28.7	28.7	27.9	26.5	26.0	26.7	28.5	29.6	30.1	29.6
ACT	23.6	23.7	21.4	19.0	17.4	16.6	16.4	16.7	17.9	19.1	20.6	22.4

Table 27: Average monthly indoor unconditioned temperatures (°C) for each NEM sub-region for newer homes based on Harrington (2018)

State/NEM sub-region	January	February	March	April	May	June	July	August	September	October	November	December
New South Wales	24.3	24.3	23.7	21.4	18.9	16.9	16.1	17.0	19.4	21.2	22.1	23.4
Victoria	22.7	23.1	21.2	19.4	16.4	15.0	14.7	15.3	16.9	18.4	20.8	21.3
Queensland North	28.9	28.7	27.8	26.1	24.6	22.6	21.9	22.6	24.2	26.5	27.7	28.6
Queensland Central	27.7	27.8	26.4	25.0	22.4	19.7	19.2	20.8	22.5	25.0	26.5	27.3
Queensland South	26.1	26.4	25.3	22.9	20.5	18.1	17.9	18.5	21.0	22.2	24.2	25.6
South Australia	24.8	24.7	22.6	20.6	18.1	15.7	14.6	15.8	16.6	19.2	21.2	23.4
Western Australia	26.0	26.4	25.2	21.9	18.4	16.7	16.3	15.9	17.5	19.6	22.3	25.2
Tasmania	20.1	19.5	18.4	16.9	14.5	12.5	12.1	13.1	14.4	15.6	17.3	18.7
Northern Territory	28.9	28.8	28.7	28.6	27.8	26.3	25.7	26.5	28.5	29.7	30.1	29.6
ACT	23.0	23.1	20.2	16.2	12.7	10.6	9.8	10.7	13.9	16.4	18.9	21.5

Table 28: Average monthly indoor conditioned temperatures (°C) for each NEM sub-region for business spaces

State/NEM sub-region	January	February	March	April	May	June	July	August	September	October	November	December
New South Wales	24.7	24.7	24.2	22.4	20.6	19.4	19.0	19.4	20.9	22.2	22.9	23.9
Victoria	23.4	23.7	22.2	20.9	19.1	19.0	19.0	19.0	19.3	20.3	21.9	22.3
Queensland North	25.0	25.0	25.0	25.0	25.0	23.3	22.8	23.3	24.7	25.0	25.0	25.0
Queensland Central	25.0	25.0	25.0	25.0	23.2	21.1	20.8	21.9	23.2	25.0	25.0	25.0
Queensland South	25.0	25.0	25.0	23.5	21.7	20.0	19.9	20.3	22.0	23.0	24.6	25.0
South Australia	25.0	25.0	23.3	21.7	20.1	19.0	19.0	19.0	19.2	20.8	22.2	23.9
Western Australia	25.0	25.0	25.0	22.8	20.2	19.3	19.1	19.0	19.7	21.0	23.0	25.0
Tasmania	21.4	21.0	20.3	19.3	19.0	19.0	19.0	19.0	19.0	19.0	19.6	20.4
Northern Territory	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
ACT	23.6	23.7	21.4	19.0	19.0	19.0	19.0	19.0	19.0	19.1	20.6	22.4

5.4.2 Energy characteristics of refrigerators and freezers

Attempting to characterise the energy consumption of household refrigerators and freezers across such a wide range of climates is a significant challenge given that climate is such a significant driver. There are several ways that this could have been done. A bottom-up end use model based on the characteristics of new refrigerators was considered. However, the current energy labelling system does not provide enough information to reliably allow energy to be estimated under a wide range of operating conditions, including different defrost regimes and user interactions.

The approach selected is to use long term end use measurements on some 250 refrigerators and freezers located from Melbourne to Cairns as a basis for developing a robust tool to develop energy estimates for both refrigerators and freezers. Individual daily records of energy and indoor temperature at each site were analysed for all available sites (representing 62,000 days of data) and these were then tagged with the climate zone and its average measured temperature for each month. This allowed a single function of indoor temperature versus average refrigerator power to be developed for all sites to provide a sound basis for developing an energy model for refrigerators. Note that this energy data includes the aggregated impact of ambient temperature, user interactions and defrosting. The overall results of the analysis are shown in Figure 71.

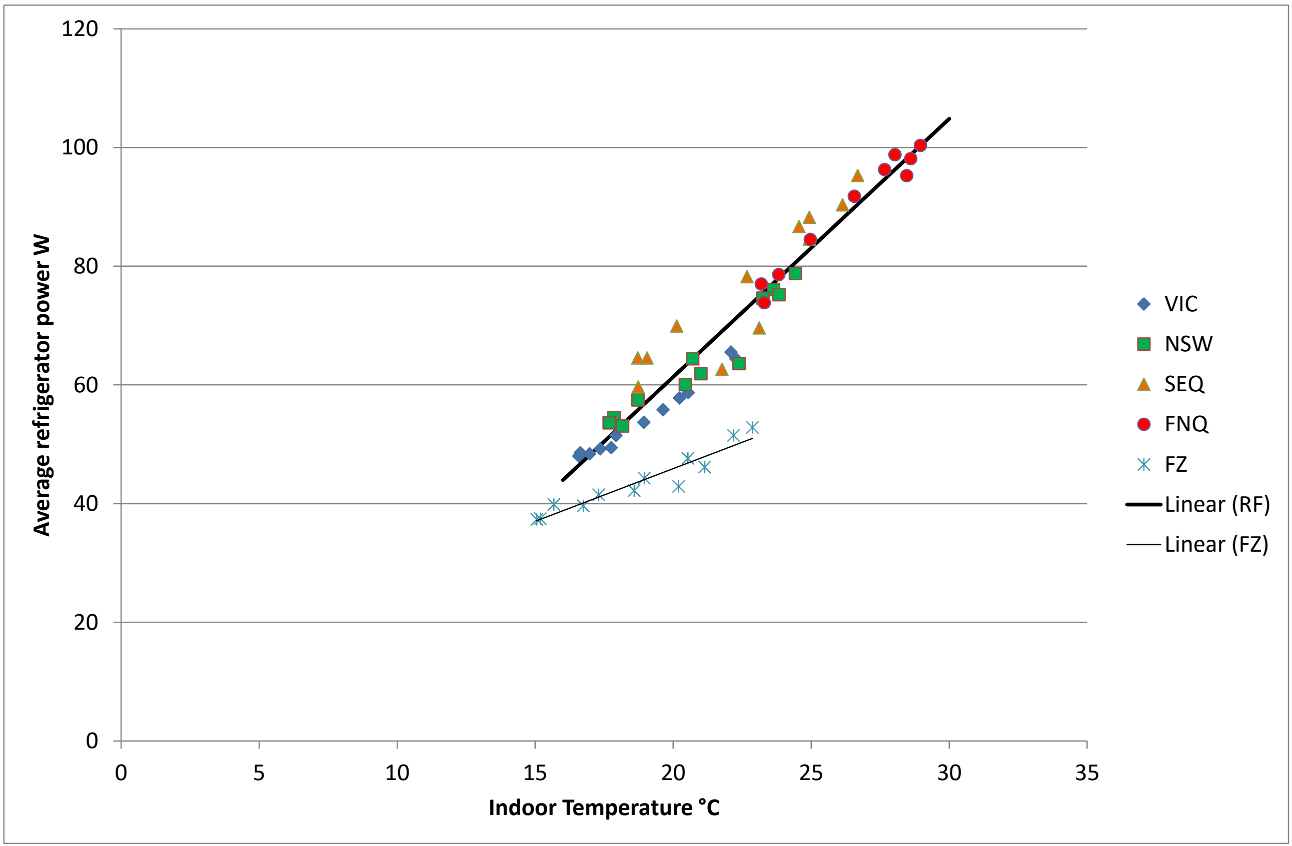

Figure 71: Model of power versus indoor temperature for household refrigerators and freezers

Notes: Field data collected for PhD thesis for more than 250 sites as documented in Harrington (2018). VIC is sites in Melbourne and Gippsland, NSW is primarily Sydney with some in Byron Bay, SEQ is Brisbane and the Gold Coast, FNQ is Cairns and Innisfail.

The resulting linear regressions are given as follows:

$P_{rf} = 4.35 \times T_i - 25.647$ $\qquad$ $R^2 = 0.94$

$P_{fz} = 1.776 \times T_i + 10.366$ $\qquad$ $R^2 = 0.909$

Where the refrigerator and freezer power P_{rf} and P_{fz} is in watts and T_i is the indoor temperature in degrees Celsius.

These equations allow average refrigerator power, and therefore energy, to be calculated for each month for the indoor conditions set out in the previous tables. The field measurements used to calculate these regressions were conducted over the period 2010 to 2014 so can be considered to be representative of the overall stock as installed and operating at 2012. Detailed analysis undertaken for the Regulatory Impact Statement for household refrigerators showed that the overall stock energy consumption for household refrigerators is expected to decline over the period to 2030. This is due to small changes in ownership (the number of appliances per household is expected to fall marginally for refrigerators and significantly for separate freezers) as well as improvements in the stock average energy consumption of household refrigeration (E3 2017a). When corrected for changes in ownership over time, the per unit energy consumption for refrigerators and freezers is expected to change as shown in Figure 72.

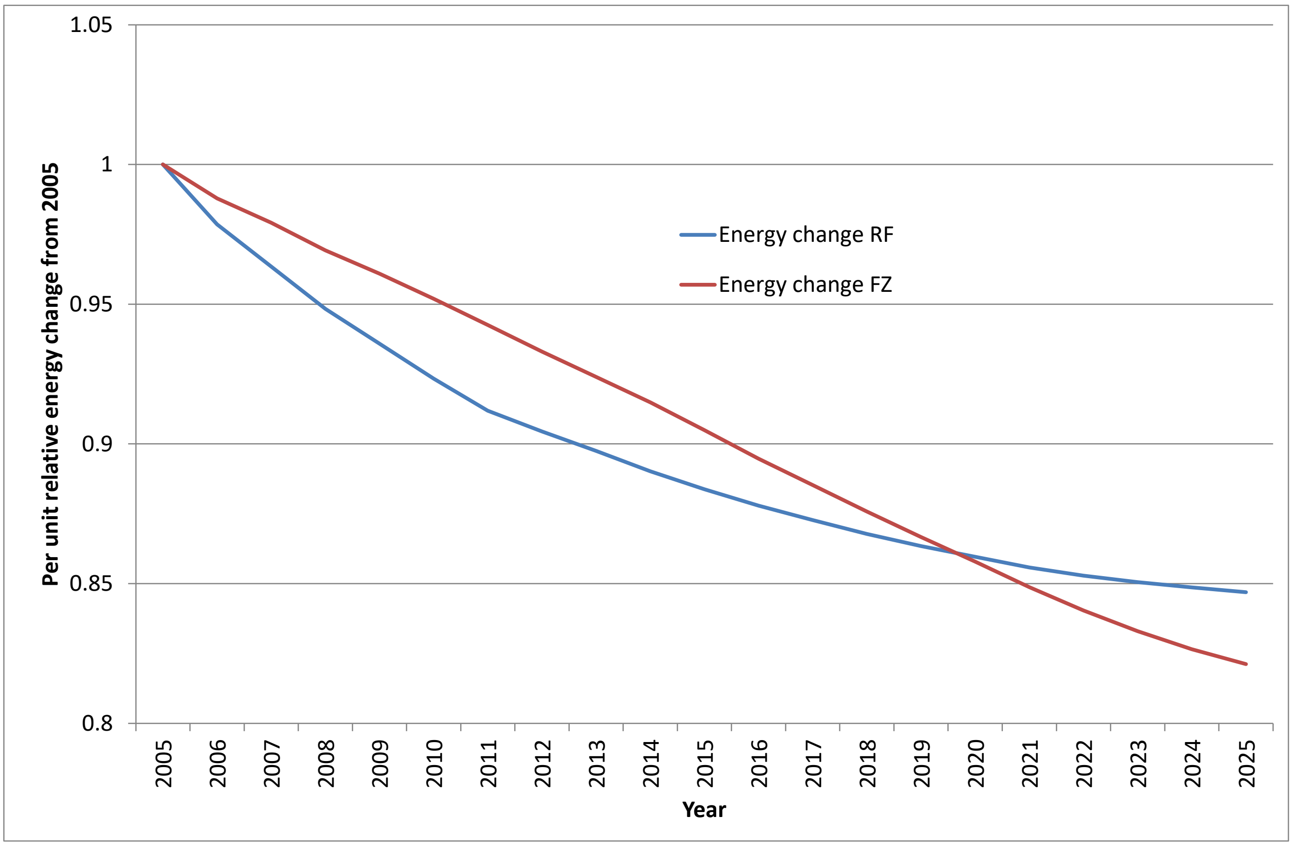

Figure 72: Changes in stock average energy from 2005

Notes: Data derived from the Regulatory Impact Statement (E3 2017a)

From this data, an adjustment for the overall stock energy from 2012 (field data measurements) to future years can be derived for refrigerators and freezers as follows:

- Stock energy adjustment for refrigerators in 2020 is 0.9504
- Stock energy adjustment for refrigerators in 2025 is 0.9364
- Stock energy adjustment for freezers in 2020 is 0.9195
- Stock energy adjustment for freezers in 2025 is 0.8802
- Intermediate values for refrigerators and freezers were calculated for each intermediate year from 2012-13 to 2018-19.

To calculate the energy associated with household refrigeration, the following factors are applied to the calculated power:

- Hours per day and days per month (adjusting for leap years where applicable)
- The estimate of the stock of appliances in each NEM sub-region

* Stock energy adjustment factors as set out above.

This gives an estimate of total energy by NEM sub-region. This can be further split into single speed induction motors (Motor Type D) and inverter driven motors by applying the stock inverter factors derived in Section 5.3 for refrigerators and freezers. In 2020, it is estimated that about 25% of the stock of refrigerators were inverter driven, while less than 3% of freezers were inverter driven. For refrigerators, this is changing very rapidly and is expected to be 45% of the stock in 2025 and to exceed 60% by 2030. The stock share of inverter driven freezers is also increasing, but at a slower rate and is expected to be 7% in 2025 and to exceed 16% by 2030.

The results of the energy analysis for household refrigeration systems are summarised in Table 29 for 2020. The estimated total annual energy consumption of all types of household refrigeration systems is about 8,500 GWh/year within the specified NEM sub-regions. This is broadly consistent with the energy estimates in the regulatory impact statement for household refrigeration (E3 2017a). For comparison, an estimate for 2025 has also be made to illustrate the rapid change in inverter loads over the coming decade as shown in Table 30. The energy has increased slightly (mainly due to population growth and an increase in households), but the share of inverter driven energy increased from 22% in 2020 to 40% in 2025. This share will continue to increase to beyond 2030.

5.4.3 *Daily load profiles for household refrigeration*

Refrigerators and freezers that use a single speed compressor are cycling on and off continuously over time. Over short periods the average power profile appears to be very noisy and ragged. However, over long periods, the average power by time-of-day smooths out. Typically many months of data are required in order to obtain a relatively smooth average power profile. In order to estimate a daily load profile from daily or monthly energy data, a range of data sources were examined. Firstly, data from a large end use metering campaign conducted by Pacific Power in the mid-1990s is the most comprehensive, measuring data for 300 households over a year (Pacific Power 1994). While this data is quite old, it is useful as it shows that the average power profile for refrigerators and freezers is relatively flat over a typical 24 hour period.

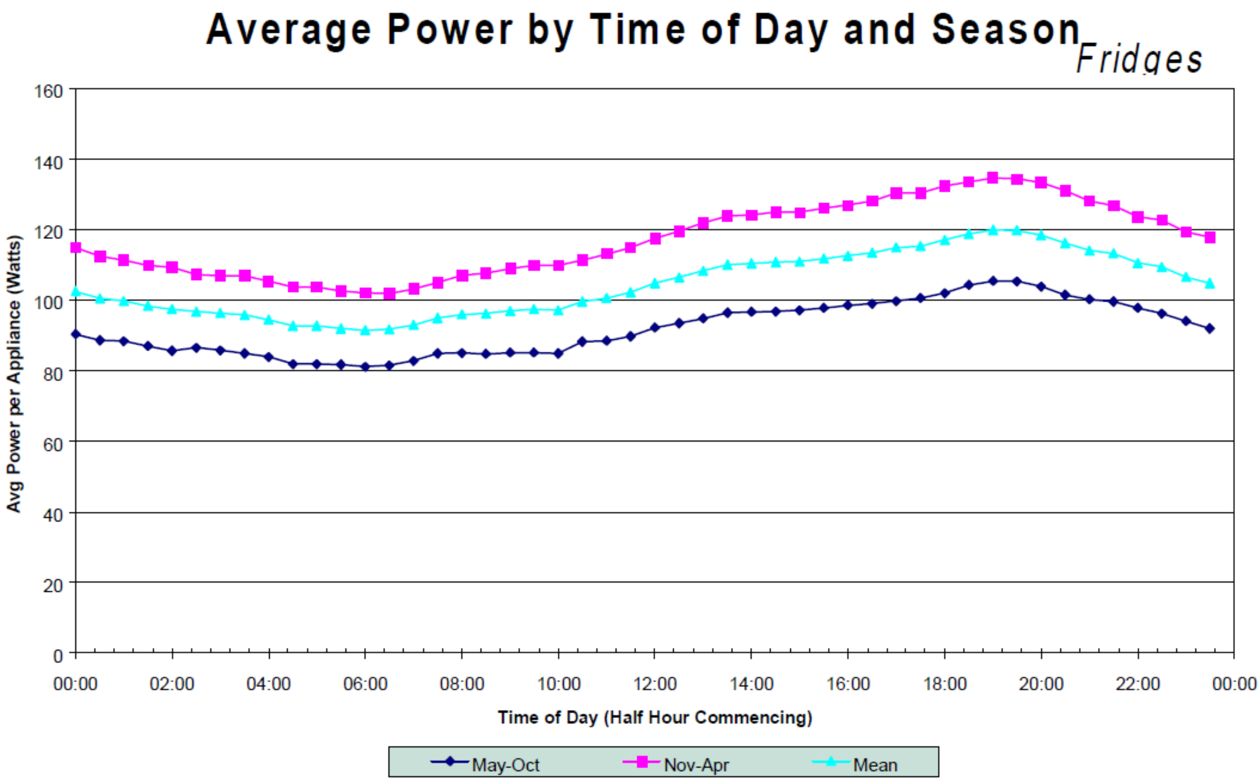

Figure 73: Average time-of-day by season for refrigerators in NSW in 1994 (Pacific Power 1994)

Table 29: Estimated annual energy consumption of household refrigeration by type and NEM sub-region in 2020 (GWh/year)

State/NEM sub-region	Household Refrigerator Type D	Household Freezer Type D	Business Refrigerator Type D	Business Freezer Type D	Total Type D	Household Refrigerator Inverter	Household Freezer Inverter	Business Refrigerator Inverter	Business Freezer Inverter	Total Inverter	Inverter share
New South Wales	1761.5	352.4	174.2	12.9	2301.0	598.0	9.8	59.1	0.4	667.3	22.5%
Victoria	1354.5	275.6	131.8	10.1	1772.0	459.9	7.6	44.8	0.3	512.5	22.4%
Queensland North	236.4	83.0	19.8	1.4	340.6	80.3	2.3	6.7	0.0	89.3	20.8%
Queensland Central	115.7	41.3	10.0	0.7	167.7	39.3	1.1	3.4	0.0	43.8	20.7%
Queensland South	972.6	203.0	86.7	6.3	1268.5	330.2	5.6	29.4	0.2	365.4	22.4%
South Australia	405.5	100.0	35.8	2.7	544.0	137.7	2.8	12.2	0.1	152.7	21.9%
Tasmania	105.0	39.4	9.6	0.8	154.8	35.7	1.1	3.3	0.0	40.0	20.5%
ACT	84.0	15.1	8.3	0.6	108.1	28.5	0.4	2.8	0.0	31.8	22.7%
Total NEM	5035.1	1109.9	476.2	35.4	6656.6	1709.5	30.7	161.7	1.0	1902.9	22.2%

Table 30: Estimated annual energy consumption of household refrigeration by type and NEM sub-region in 2025 (GWh/year)

State/NEM sub-region	Household Refrigerator Type D	Household Freezer Type D	Business Refrigerator Type D	Business Freezer Type D	Total Type D	Household Refrigerator Inverter	Household Freezer Inverter	Business Refrigerator Inverter	Business Freezer Inverter	Total Inverter	Inverter share
New South Wales	1359.7	332.6	136.4	12.3	1841.0	1110.1	23.9	111.4	0.9	1246.3	40.4%
Victoria	1080.0	270.2	105.5	9.8	1465.6	881.8	19.4	86.1	0.7	988.1	40.3%
Queensland North	186.0	80.2	15.6	1.3	283.1	151.9	5.8	12.7	0.1	170.4	37.6%
Queensland Central	91.0	39.9	7.8	0.7	139.5	74.3	2.9	6.4	0.0	83.6	37.5%
Queensland South	765.3	196.0	68.3	6.0	1035.6	624.8	14.1	55.7	0.4	695.1	40.2%
South Australia	306.5	92.6	27.0	2.5	428.6	250.2	6.7	22.0	0.2	279.1	39.4%
Tasmania	78.9	36.6	7.2	0.7	123.5	64.5	2.6	5.9	0.1	73.0	37.2%
ACT	66.5	14.9	6.6	0.6	88.6	54.3	1.1	5.4	0.0	60.8	40.7%
Total NEM	3933.9	1063.1	374.4	34.0	5405.4	3211.7	76.5	305.7	2.4	3596.4	40.0%

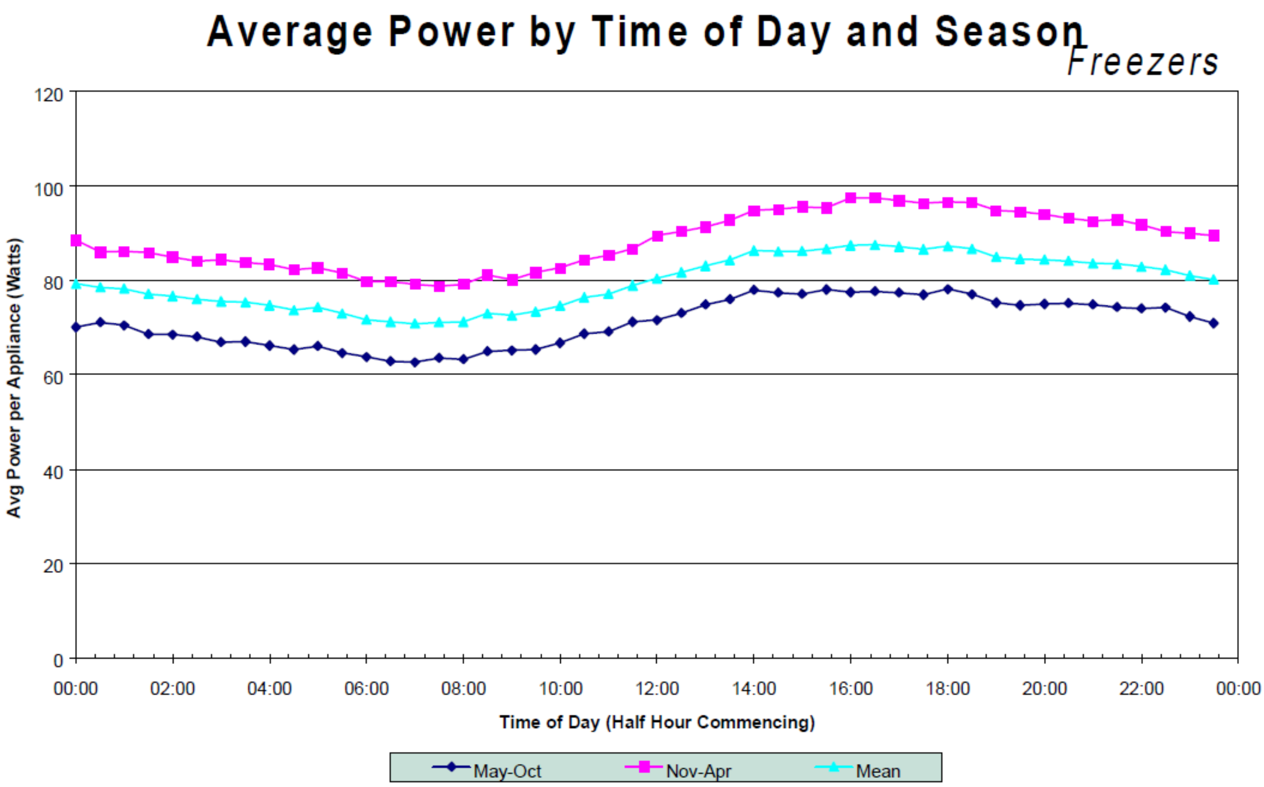

Figure 74: Average time-of-day by season for freezers in NSW in 1994 (Pacific Power 1994)

The first observation from this data is that the average power is considerably higher than would be expected for a stock average model operating today, but given the improvements in product efficiency over the past 25 years, this is expected ((Energy Efficient Strategies 2016; Weiss et al. 2010). The next point to note is that the average energy moves by season – this is as expected as indoor room temperatures in Australian homes vary by season. The final observation is that the diurnal variation is slightly larger for refrigerators than freezers. This is expected as freezers tend to be in unconditioned spaces and therefore diurnal temperature variations are smaller. Refrigerators are also subjected to more active user interactions (compared to freezers) and this manifests itself as higher energy during the day and evening. Unfortunately the Pacific Power study collected no data on the appliances measured or the indoor temperatures in homes.

Room temperature data collected by Harrington in major cities allowed an analysis of temperature profiles in homes in order to better understand the variation in indoor conditions (Harrington 2018). This showed that almost all Australian houses experience a small but regular diurnal variation in indoor room temperatures. This is in part driven by outdoor temperatures, but also the operation of space conditioning equipment (heating and cooling). The following figures show average indoor temperature profiles by season for Cairns, Brisbane, Sydney and Melbourne. These are based on data collected in parallel for 25 to 40 homes in each city.

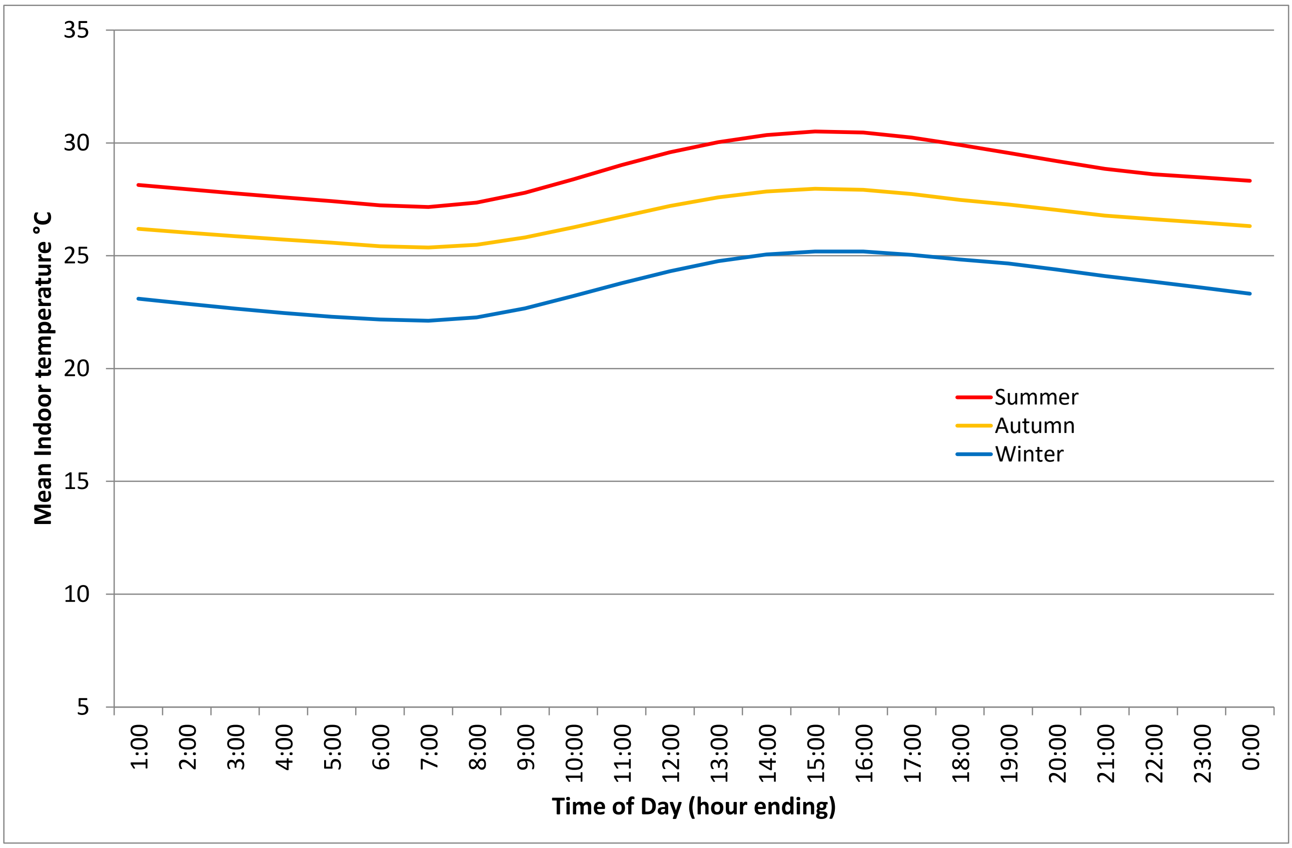

Figure 75: Seasonal indoor temperature profiles for houses in Cairns (Harrington 2018)

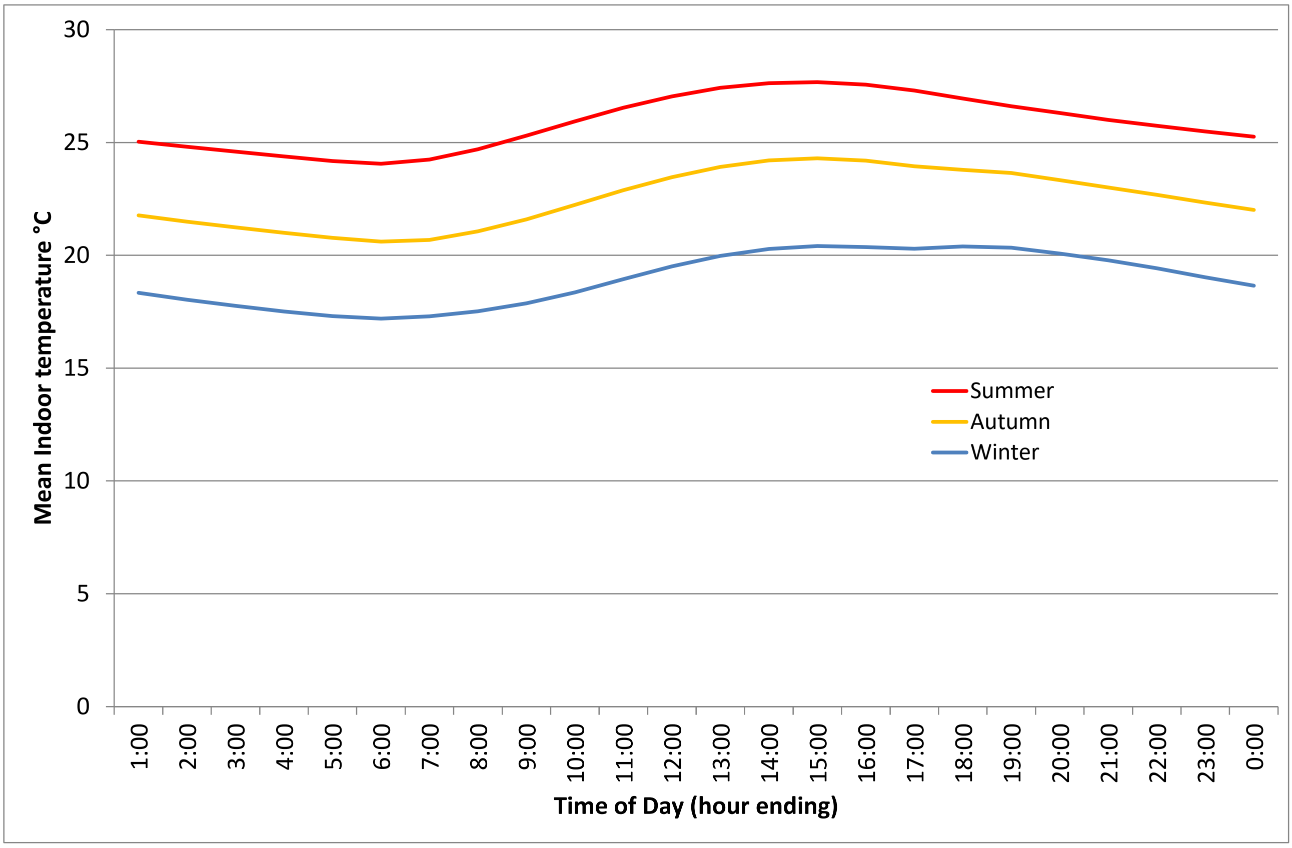

Figure 76: Seasonal indoor temperature profiles for houses in Brisbane (Harrington 2018)

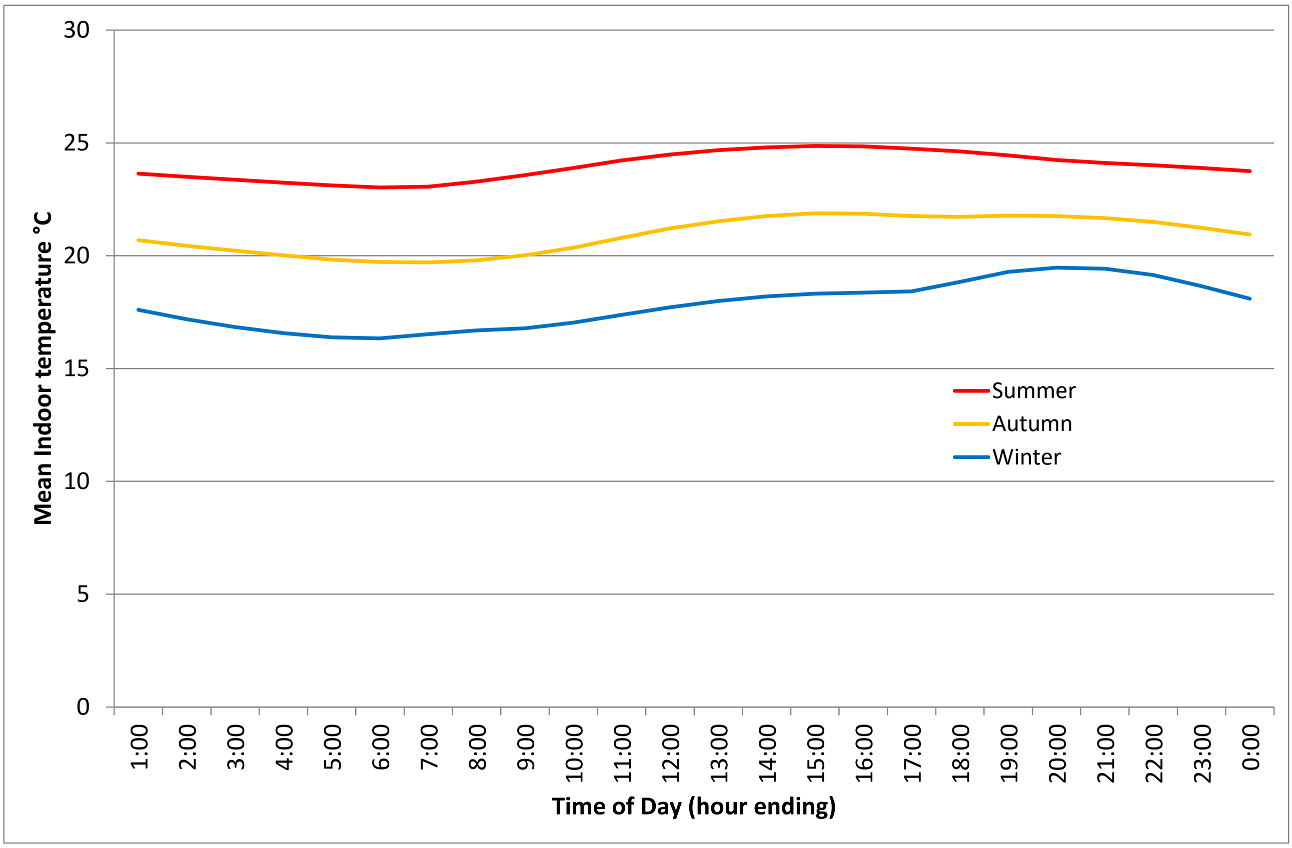

Figure 77: Seasonal indoor temperature profiles for houses in Sydney (Harrington 2018)

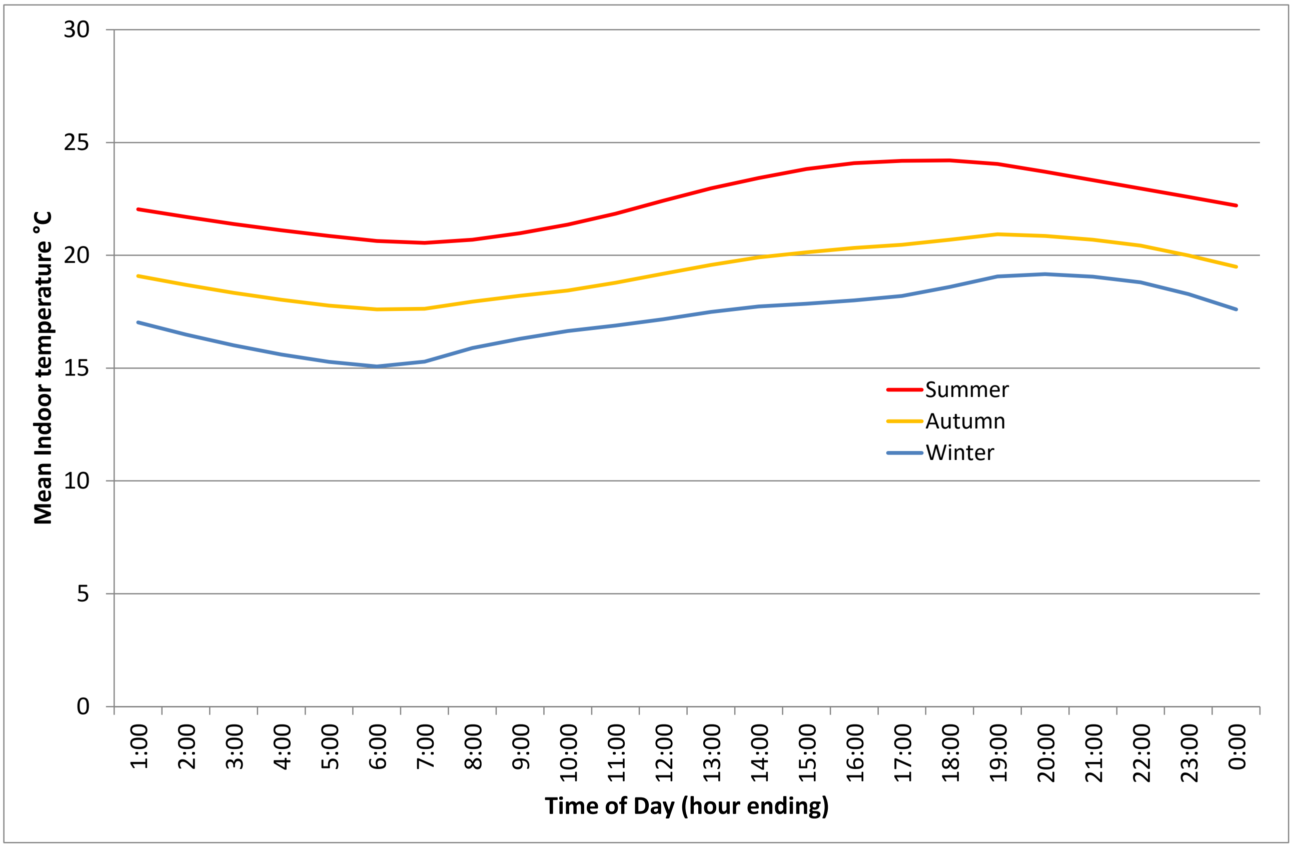

Figure 78: Seasonal indoor temperature profiles for houses in Melbourne (Harrington 2018)

Notes: The slightly irregular shape of the winter profile for Sydney and Melbourne indicates active evening heating.

The analysis across sites shows that the standard deviation of daily temperature is remarkably consistent across climates, typically at 3°C to 3.5°C. This diurnal change in temperature will have some impact on household refrigeration energy and explains the “smooth” diurnal pattern in the refrigerator and freezer energy from the Pacific Power data.

To examine this more closely, a sample of seven refrigerators and three freezers were analysed. These units were selected as they had data collected over a minimum three year period. The raw refrigerator data is shown in Figure 79.

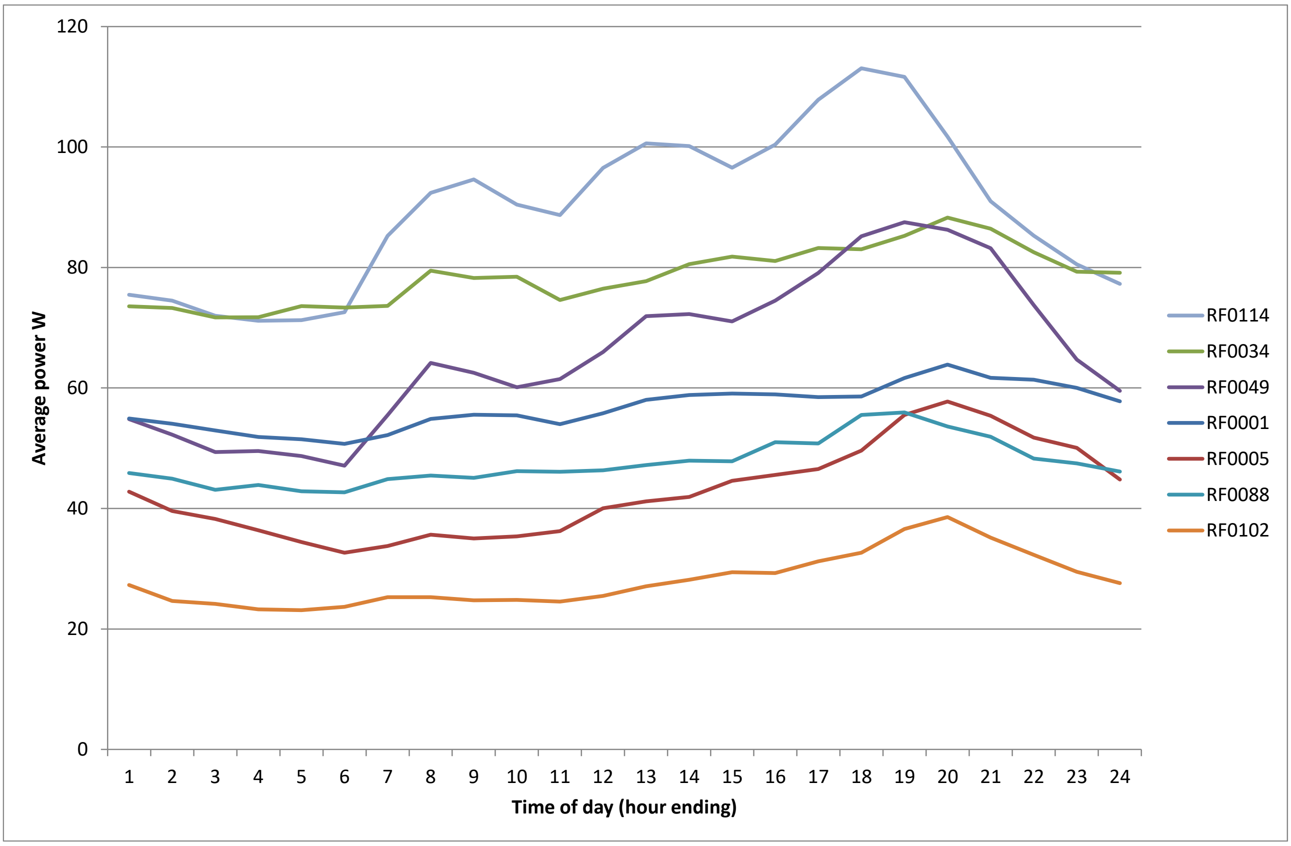

Figure 79: Time-of-day average power for seven refrigerators (Harrington 2018)

In general terms, the load shape for these very different products in different households is quite similar, with a minimum occurring at around 06:00 and an evening peak at around 20:00 each day. As this data is all collected on Eastern Standard Time, there will be some noise around the evening peak as half that data will be on standard time and half the data will be on daylight saving time (where applicable). In general terms, user behaviour tends to be dictated by clock time rather than sun time. To allow a more detailed comparison, the above data has been normalised against the average power for the appliance, so the time-of-day values are shown as values close to 1 (less than one indicates lower than daily average power, more than one indicates higher than daily average power). The same seven appliances together with the normalised Pacific Power data is shown in Figure 80.

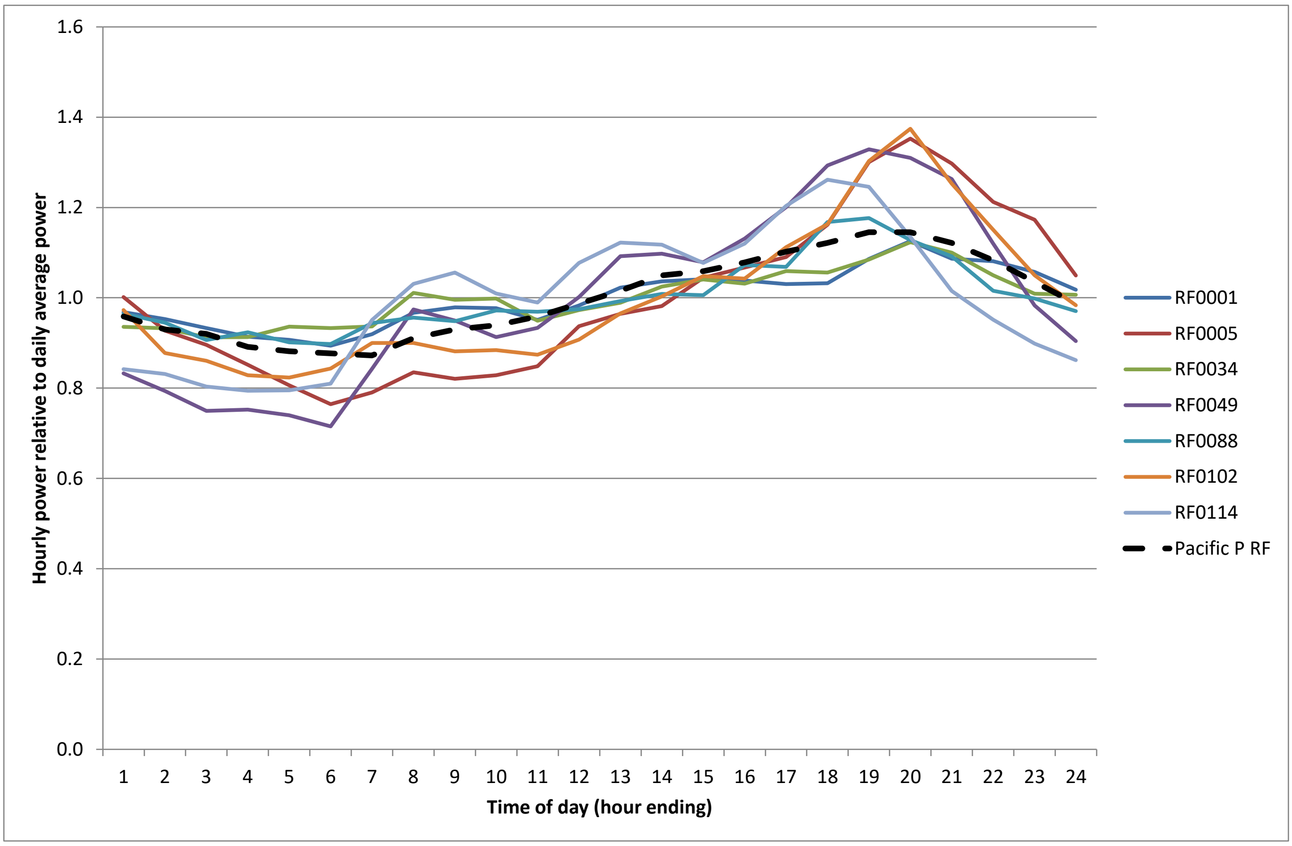

Figure 80: Normalised time-of-day for a selection of refrigerators

The Pacific Power data load shape is broadly representative of the other appliances selected for analysis. In general terms the overnight minimum power is generally about 0.85 of the average, while the evening peak is typically 1.2 times the average. Most appliances exhibit a small peak in the morning (08:00) while some show a small peak at around 13:00 (lunch). However, this varies by site as occupancy levels vary (stay at home occupants versus at work/school during the day). A similar set of values was compiled for freezers as shown in Figure 81. The diurnal variation for freezers is generally smaller as they are mostly located in unconditioned spaces (with smaller temperature variations) and the level of user interaction is generally low. The Pacific Power data showed a slightly larger diurnal variation when compared to the more recent appliances, but the data is broadly consistent.

A generic load profile for household refrigerators operating in a business environment was also developed. These appliances are generally subject to smaller daily temperature variations, with higher levels of usage through the day during office hours and into the early evening. Generic load profiles for household refrigerators, household freezers in the home and household refrigerators operating in a business environment are shown in Figure 82. It is assumed that the load profile of a household freezer in a business environment the same as a household freezer at home.

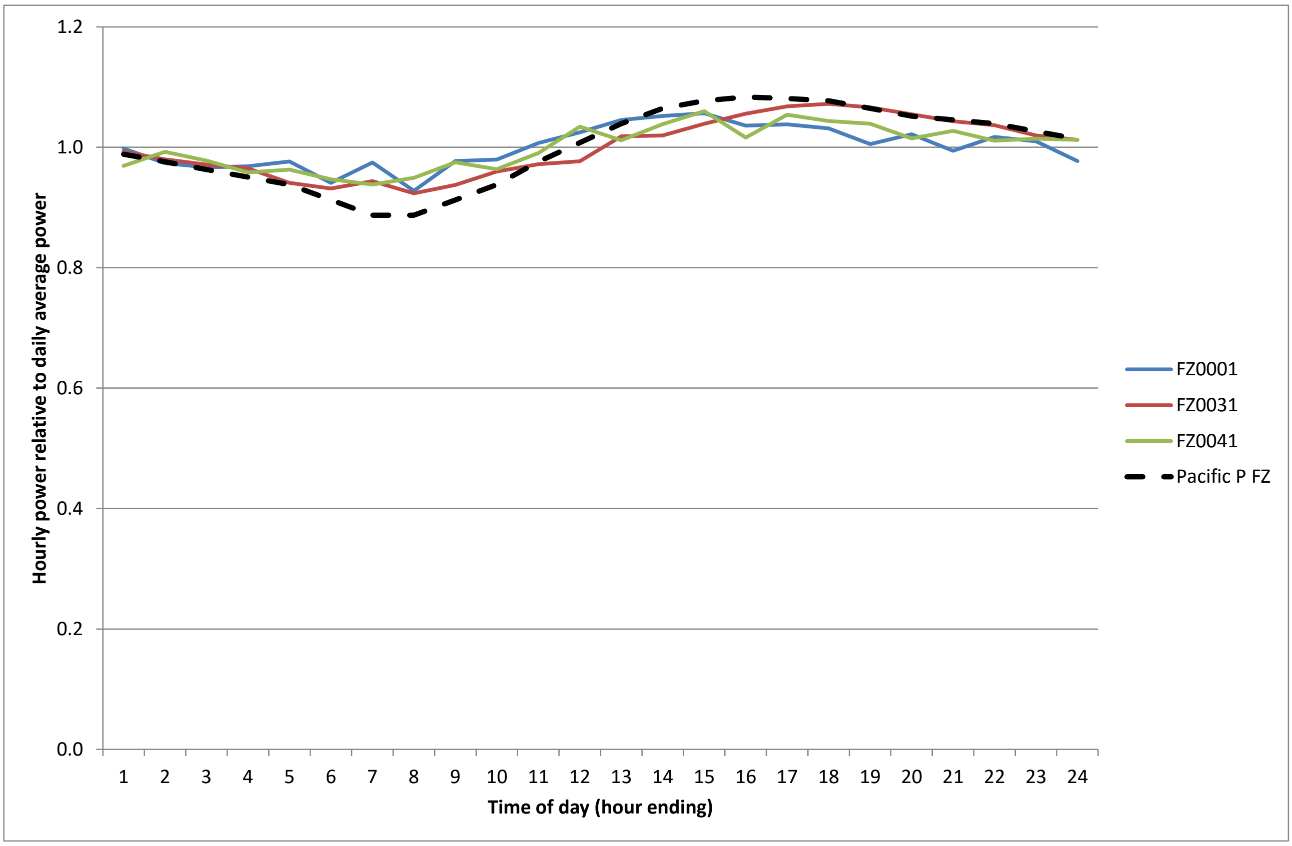

Figure 81: Normalised time-of-day data for a selection of freezers

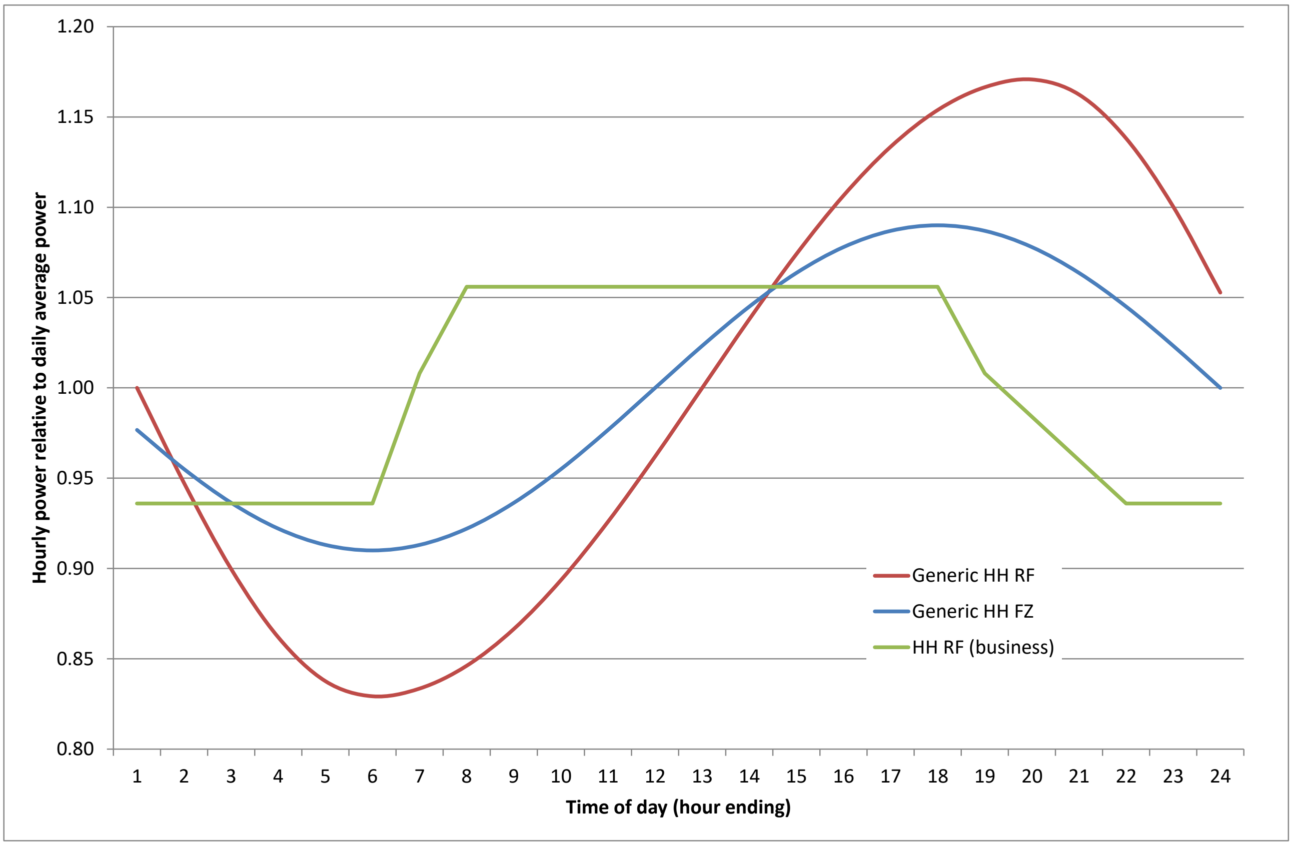

Figure 82: Generic load profiles for refrigerators and freezers

Notes: Average of all profiles over 24 hours is equal to 1.000. Note the Y axis scale.

5.4.4 *Peak day increases in energy for household refrigeration*

The previous data shows average energy by month for a typical average indoor temperature. However, it is well known that extreme weather events can increase indoor temperatures (in the absence of active space cooling, which can rarely eliminate all of the effects of extreme weather), which is likely to increase household refrigerator and freezer energy consumption. In order to assess this, long term data for some 250 sites was analysed. The daily average power and room temperature was examined for each month of the year and the maximum daily power and maximum daily temperature was also calculated. The analysis showed that the warmest indoor temperature in each month was typically around 2K to 3K warmer that the average indoor temperature by month for the four different climate zones examined, with the exception of Melbourne, where the hottest day in summer in any one month was around 4K to 5K warmer than average, as shown in Figure 83. Note that this data is averaged across 250 sites spread across all climates and includes the maximum across several years (for a specific month) for those sites where long term data was available. Interestingly, in Victoria, the warmest day is still around 3K warmer than average even in winter, indicating more variability in heating.

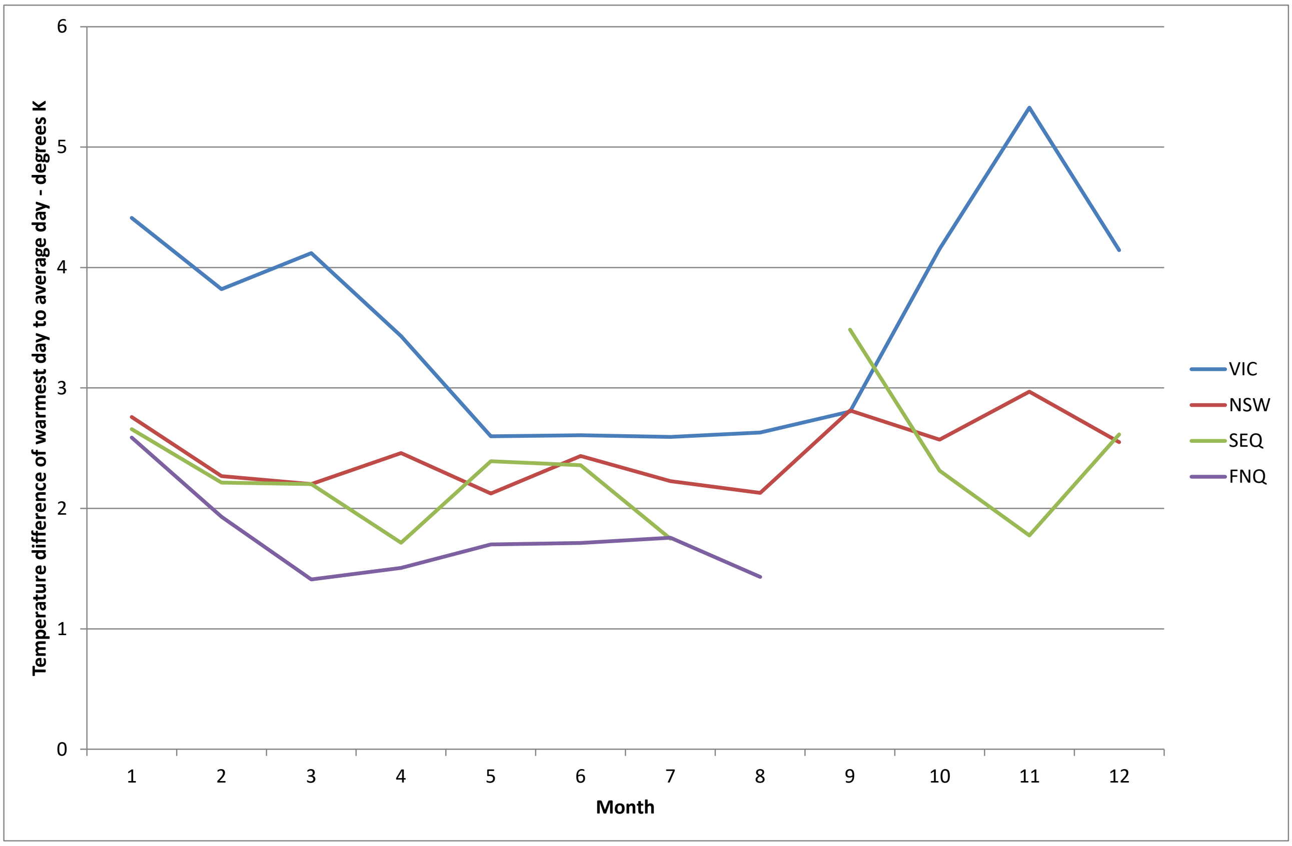

Figure 83: Indoor temperature difference between warmest day and an average day by month

Based on these "warmest" days by month, it is expected that the maximum energy day driven by weather for refrigerators is typically about 15% above an average day for all states except Victoria, where it is more typically 25% to 30% above the average. This suggests that some "loading" of the refrigerator profile could be undertaken to take account of more extreme weather events.

In parallel to the maximum temperature days, the highest energy days were compared with the average energy by climate and month. This is illustrated in Figure 84. On closer investigation it was found that "peak energy" days rarely correlated with the warmest day for the month. This suggests that the highest energy days are primarily driven by user interactions (parties, celebrations) rather than weather. Effectively, these events are somewhat random in nature and there is no need to provide any correction for these larger peaks in the AEMO models. So a model based on measured daily temperature maximums (Figure 83) and the temperature response curve in Figure 71 was used to develop energy variations in higher and lower energy days on the NEM.

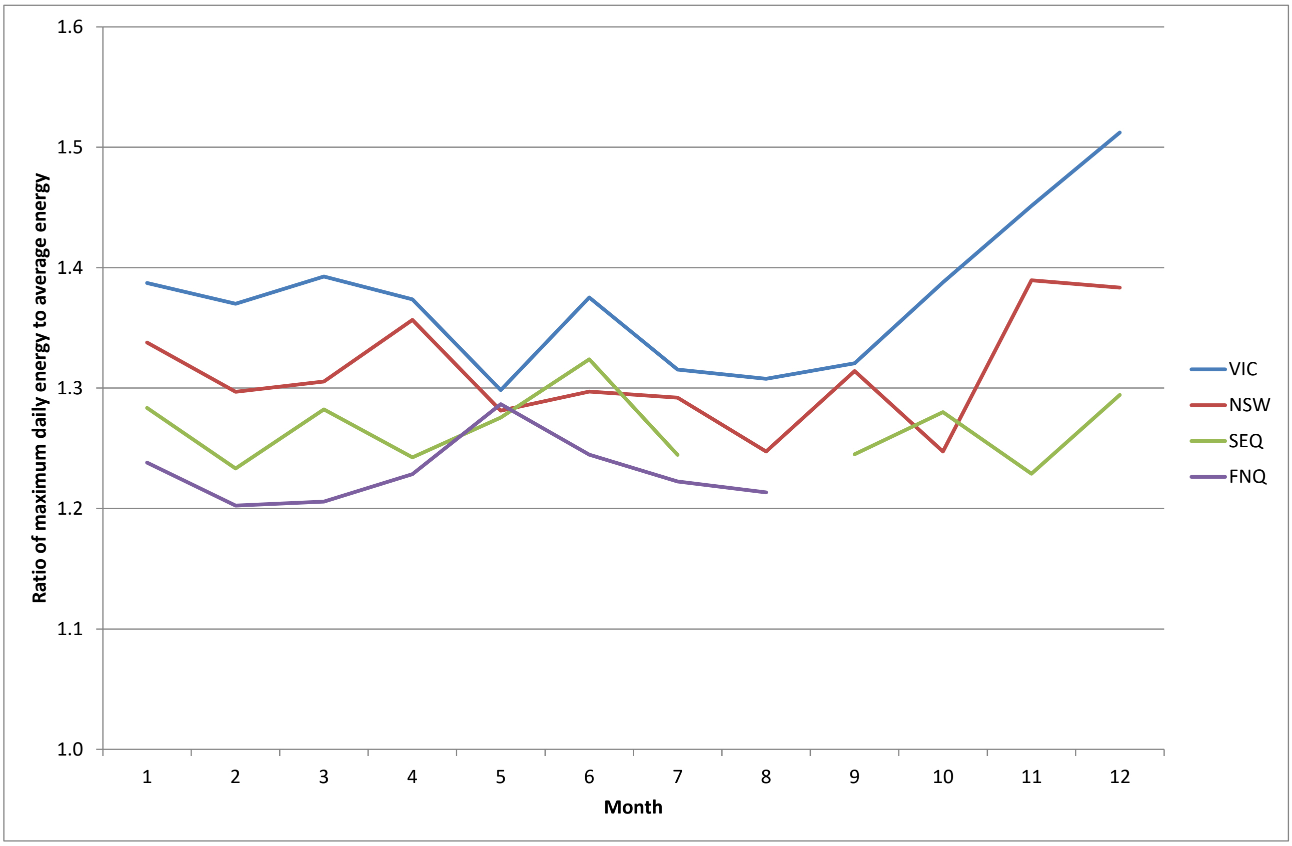

Figure 84: Ratio of maximum daily energy to average energy by month and climate

5.4.5 Compilation of annual load profiles

The residential and business (commercial sector) refrigerator load profiles were compiled for a typical year based on the expected energy consumption and load profiles by refrigerator and freezer type. Profiles were generated for the following appliance types:

- Residential refrigerators
- Residential freezers
- Residential refrigerators used in a commercial context
- Residential freezers used in a commercial context
- These four categories were divided into inverter driven units and single speed compressors (Motor D) and were separately tracked.

For the sample year, weather adjustments were applied to hourly data as set out above. It is assumed the residential refrigerators are unaffected by day of the week, so no day of the week adjustments were applied. This generated a load profile of 8760 hours of data for each type of product listed above. These were then aggregated for more detailed analysis.

Detailed results for all products are set out in Chapter 7.

5.5 Sources of uncertainty in energy estimates for household refrigeration

The energy estimates for household refrigeration have been generated from a bottom-up model of energy consumption. The model uses measured field data for a large number of households across a wide range of climates. Indoor temperature estimates have been developed from a very large sample of long term measurements in over 700 homes so is considered to be very robust

(Harrington, Aye & Fuller 2015; Ambrose et al. 2013). The energy estimates in this report are slightly higher than those documented in the Commonwealth Regulatory Impact Statement (E3 2017a), primarily because additional household appliances operating in the business sector have been included in order to provide a more comprehensive model.

The stock of appliances for household refrigeration in the residential sector are considered very robust as they are based on regular national surveys conducted by the ABS (Australian Bureau of Statistics 2014). The last survey was in 2014, but ownership changes are very slow for such a large stock of appliances. The energy estimates for household refrigeration in the residential sector should have an overall uncertainty of less than 5% as they are well documented and based on a validated model (Harrington 2018). Estimates of the number of household appliances in the business sector are not well documented, so several indirect approaches to estimate the stock have been used. The uncertainty could be as high as 20% for this sub-segment, generated mostly because of the uncertainty of stock numbers, but this makes up less than 8% of the overall energy estimates, so the overall impacts are small.

This report estimated for the first time the share of inverter driven household refrigerators and freezers. This was based on a comprehensive survey of 18 major suppliers in the Australian market covering all models and more than 85% of national sales, so is considered to be an accurate representation of market trends. The share of inverter driven compressor is changing very quickly over the next 10 years, so this will make the share of Motor D and inverter driven energy quite dynamic in the short term. There is, of course, some uncertainty in how quickly inverter driven compressors will be adopted in the remaining models for household appliances. The rate of change projected is considered reasonably robust, but probably conservative (change may be faster than predicted). So there is some uncertainty in the future energy estimates for the Motor D and inverter energy split. AEMO needs to keep their data sets updated over the coming years to monitor this dynamic parameter.

The model has assumed that all refrigerators operate in conditioned household spaces and all freezers operate in unconditioned spaces. While this is a partial simplification of the end use model, it should not have an adverse effect on the overall energy estimates.

6 Commercial Refrigeration

6.1 Stock of commercial refrigeration

Commercial refrigeration includes a wide range of equipment used in the commercial sector, primarily for the storage of food at suitable temperatures prior to use or sale. The recent regulatory impact statement provides a succinct description of these products (E3 2017b):

- Refrigerated display cabinets - commercial fridges designed to display food or drink for sale. These cabinets are used by retailers such as supermarkets, corner stores and bakeries to keep food and beverages cool or frozen. Many are open-fronted (to allow customer or staff access), or include transparent doors or lids.
- Refrigerated storage cabinets - (also known as professional storage cabinets or service cabinets) typically have solid doors, are often used behind the scenes in kitchens or by catering companies and are not intended to display food for sale. They are commonly found in restaurants, hospitals, nursing homes and a wide range of other institutions that store, prepare and serve food.

Both refrigerated display and storage cabinets are important in the food sector. They are widely used by a range of companies, from small owner-operated businesses to large companies such as supermarket chains. Refrigerated display cabinets have been regulated for energy efficiency since 2004. Storage cabinets are being regulated for energy efficiency for the first time from 2020.

In addition to the above products, it is known that small cool rooms used in the retail sector (as storage for perishable items) also often use single phase induction motors. Cool rooms are not currently regulated for energy efficiency so there is only limited data available. For this study, it is assumed that large cool rooms used for industrial and very large commercial sites will be powered by three phase motors, so will be out of scope.

With respect to refrigerated display cabinets (which are designed for access by customers) there are effectively two main types:

- Remote cabinets: these are where the compressor and condensing unit are located away from the refrigerated cabinet and where refrigerant is piped to the display cabinet, which contains the evaporator, fans, lights etc. These are effectively built-in units (customised and designed for each site) and tend to have much larger refrigeration systems. Examples are very large display cabinets in supermarkets and coffin display units that are permanently mounted on the shop floor. Most of these have large refrigeration capacity and most are driven by three phase motors, so are out of scope.
- Self-contained cabinets: These are self-contained, factory assembled units where all the refrigeration components (compressor, evaporator, condenser, fans) are located in a single cabinet, which has a single power cable that is ready to plug in and use on delivery. Most self-contained units are single phase, but there are three phase units on the market.

By and large, professional storage cabinets are also self-contained units, but custom systems with remote refrigeration systems are available for larger applications. Storage cabinets are generally broken into two main groups:

- **Institutional**: including hospitals, nursing homes, tertiary institutions, schools, work or private canteens, charitable organisations and Government canteens (i.e. prisons, military).
- **Commercial**: including restaurants, cafes, hotels/motels, fast food or take-away outlets, clubs, caterers, function centres, fresh meat (including fish and poultry retailing); fruit and vegetable retailing and liquor retailing.

According to the regulatory impact statement, there are nearly 7,000 smaller convenience stores and small supermarkets in Australia (<400m^2) while there are a further 3,500 sites with larger stores and supermarkets. It is estimated that supermarkets account for 25% of all commercial refrigeration cabinets in Australia. In addition, there are another 10,500 sites for specialised retail such as liquor, meat/fish/poultry, fruit and veg and other specialised food retail.

The RIS estimates that there are some 15,500 institutional establishments that use storage cabinets. The commercial food sector is somewhat larger with over 55,000 sites that include cafes, restaurants, catering services, clubs, hotels, motels and take away (E3 2017b). A summary of estimated stock of commercial refrigeration systems by sub-sector is shown in Table 31.

Table 31: Summary of the commercial refrigeration stock in 2016

Sub-sector	Remote	Integral	Storage	Coolrooms
Supermarkets	116000	70000		All 3 phase
Convenience	6000	65000		7500
Liquor	4000	24000		1500
Meat/fish/poultry retail		17000		7000
Fruit and veg retail		4000		1800
Other specialised food retail		7000		1000
Other food storage retail	4500		3000	5000
Food service channel	26500	268100	147400	All 3 phase
Total	**157000**	**455100**	**150400**	**23800**
Share units single phase	5%	90%	90%	50%
Single phase	**7850**	**409590**	**135360**	**11900**
Share energy single phase	2.5%	80%	80%	35%
Share energy unconditioned	5%	10%	20%	75%

Notes: Data extracted from the regulatory impact statement (E3 2017b) with author estimates.

Unfortunately, there is little published data on the share of single phase and three phase commercial refrigeration systems. This data is not included in the registration system for these products. The estimates above were developed by the author based on discussions with a range of vendors and industry experts. The RIS estimates that the sector growth rate is just under 3% per annum (E3 2017b), so the above stock numbers need to be increased by approximately 12.5% to estimate the stock in 2020.

6.2 Share of commercial refrigeration with inverter driven compressors

Based on discussions with a range of suppliers to the commercial refrigeration market, at this stage there are virtually no models on the Australian market with single phase inverter driven compressors. Hydrocarbon refrigerants such as Isobutane (R600a) are now fairly common in commercial refrigeration systems. However, it appears that the market drivers that are present in the air conditioner and household refrigerator market are not yet present in commercial refrigeration. There are inverter driven compressors on larger commercial refrigeration systems (e.g. industrial cool rooms), but at this stage, these are exclusively three phase and outside the scope of this project. Given the developments in household refrigeration, single phase inverter driven compressors are likely to appear in smaller commercial refrigeration systems over the coming years, but the timing is unclear.

The project brief suggested that some digital controllers on commercial refrigeration systems may be able to provide protection and shut the system down during low voltage events. Discussions with design engineers and refrigeration mechanics has revealed that many digital controllers used in commercial refrigeration monitor operation and are able to sense some adverse conditions on the compressor and disconnect them before the motor stalls. This was confirmed with the test results conducted on 27 commercial refrigeration units; 60% had digital controllers that shut the compressor down before it stalled under low voltage conditions and a further 10% of models did not stall under low voltage conditions (see Section 3.3). However, 30% of new units tested had a digital controller that did allow the compressor to stall on low voltage, so this characteristic is by no means universal for digital controllers. Digital controllers may need to be adjusted for the specific motor in order to offer suitable protection. This is an area of some uncertainty. Based on the field measurements of commercial refrigerators in 2020 (which were a mixture of new and older products) a sales share estimate of commercial refrigerators that use digital controllers that protect the compressor from stalling under low voltage conditions has been developed as shown in Figure 85. The sales share has been run through a stock model to estimate the stock share of commercial refrigeration with digital controllers that protect the compressor. The remaining products are all assumed to be using Motor D compressors that would stall under low voltage conditions and then go into thermal overload.

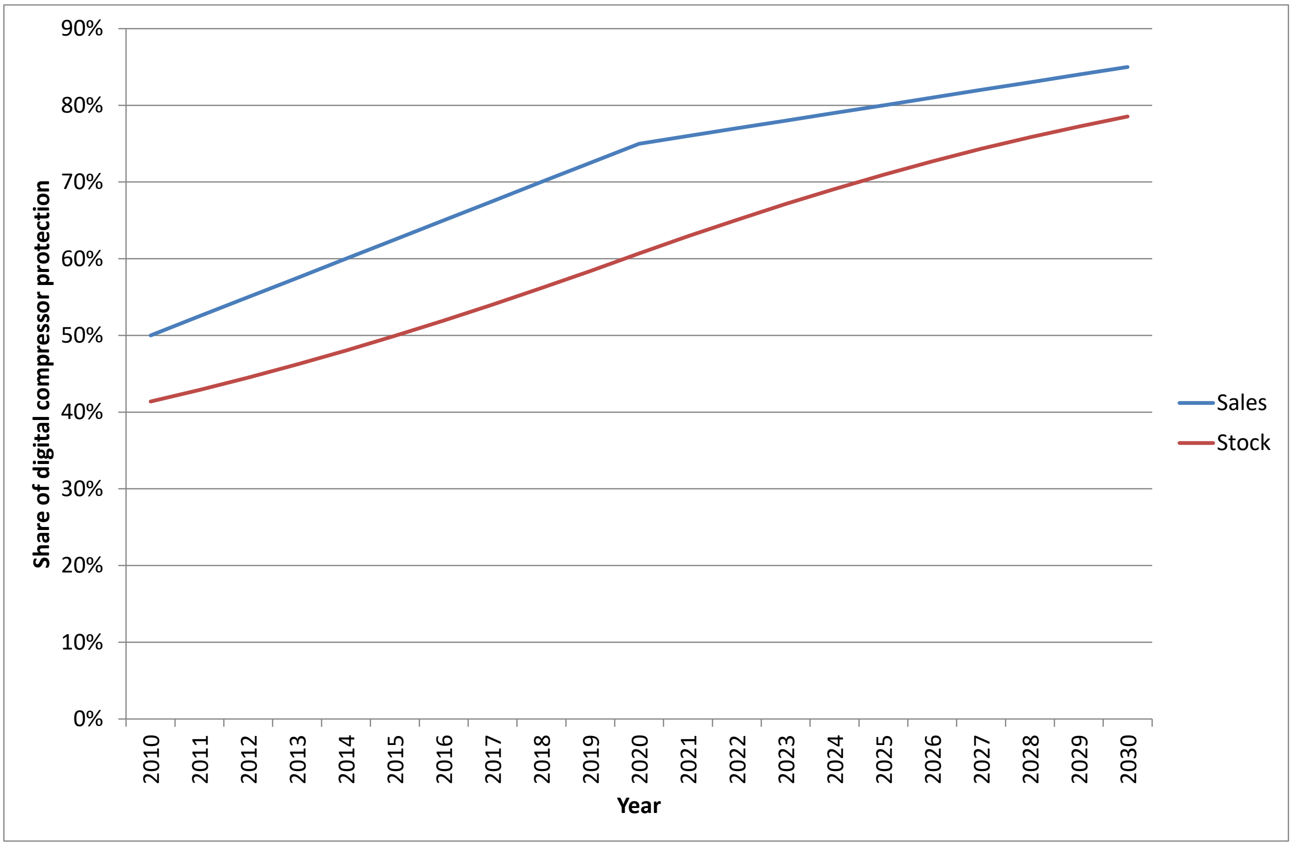

Figure 85: Estimated sales and stock share of commercial refrigerators with digital compressor protection

Given the developments in compressor manufacturing, the share of inverter driven compressors for commercial refrigeration may increase in the future, but currently there are no signs of this occurring for single phase products. AEMO should keep a watching check on possible market changes into the future.

6.3 Energy consumption and load profiles for commercial refrigeration

6.3.1 National energy consumption of commercial refrigeration

The regulatory impact statement provides projections of energy consumption for the sector to 2020, where it is estimated that total energy consumption is 7,490 GWh/year for the whole of Australia. A split in energy by type of cabinet is shown in Figure 86. In addition to this, there is additional energy from smaller single phase cool rooms, estimated to be 85.7 GWh in 2020.

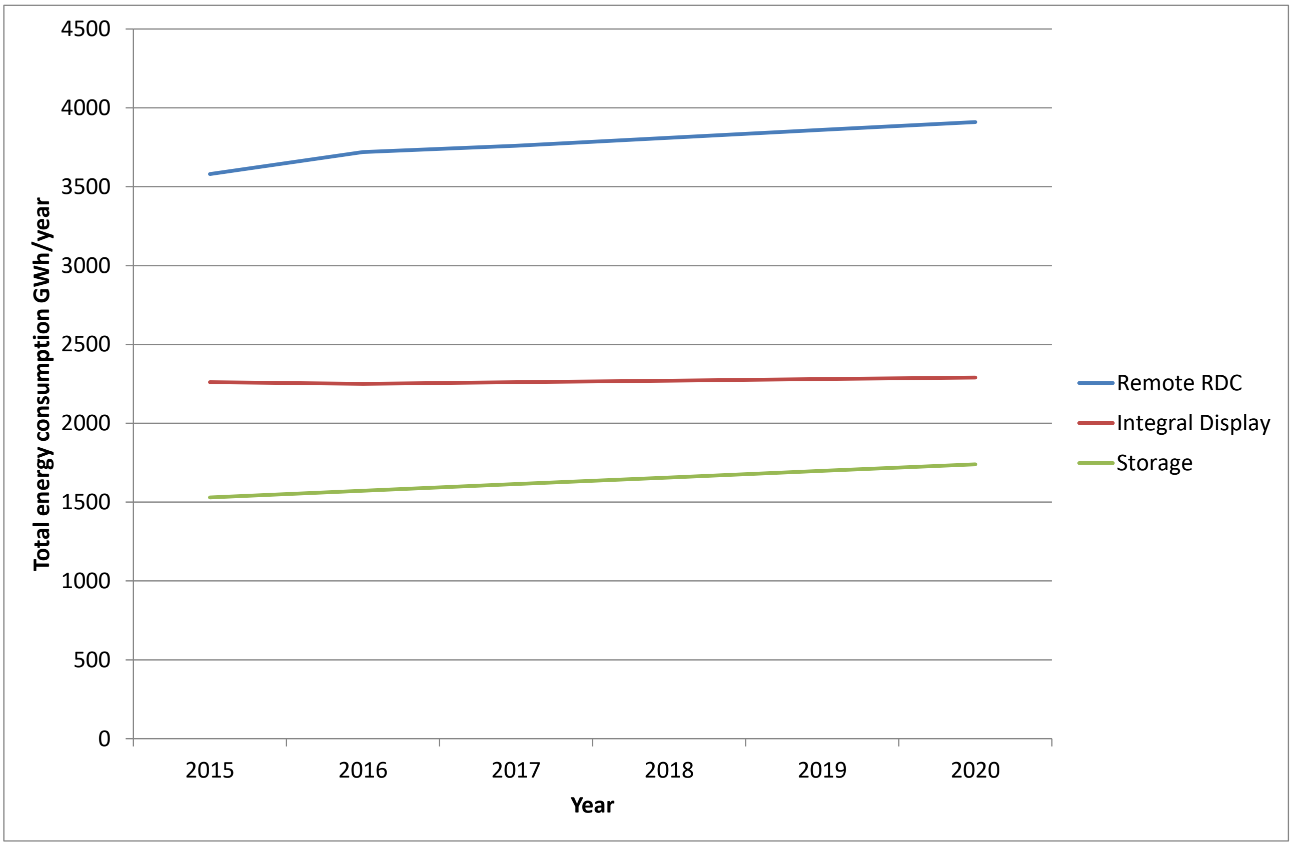

Figure 86: Energy consumption of commercial refrigeration by type (E3 2017b)

Notes: Total energy consumption for Australia including three phase and single phase equipment.

In general terms, it is expected that the share of all commercial refrigeration will be proportional to population across all NEM sub-regions. However, the energy consumption for commercial refrigeration is somewhat impacted by local climate and operating conditions, which varies considerably across the NEM sub-regions. In order to obtain more accurate energy estimates at the NEM sub-region level, analysis was undertaken on the temperature response of a range of commercial refrigeration systems. This allowed a climate weighted energy to be estimated within each NEM sub-region that was consistent with the overall energy estimates for the equipment type.

In order to develop a suitable climate/ambient temperature function for commercial refrigeration systems, long term end use measurement data was examined from a number of sites. It was possible to plot ambient temperature versus average power for each of these units. In order to develop a more generic and useful temperature function, each of these regressions were normalised against an average annual energy value for the site. This effectively allowed a function of ambient temperature change versus percentage energy change for each unit. While the temperature/energy slope of each unit was somewhat different, averaging the slope for all of the available models gave a representative typical slope that could be applied to all commercial refrigeration units. This is depicted in Figure 87.

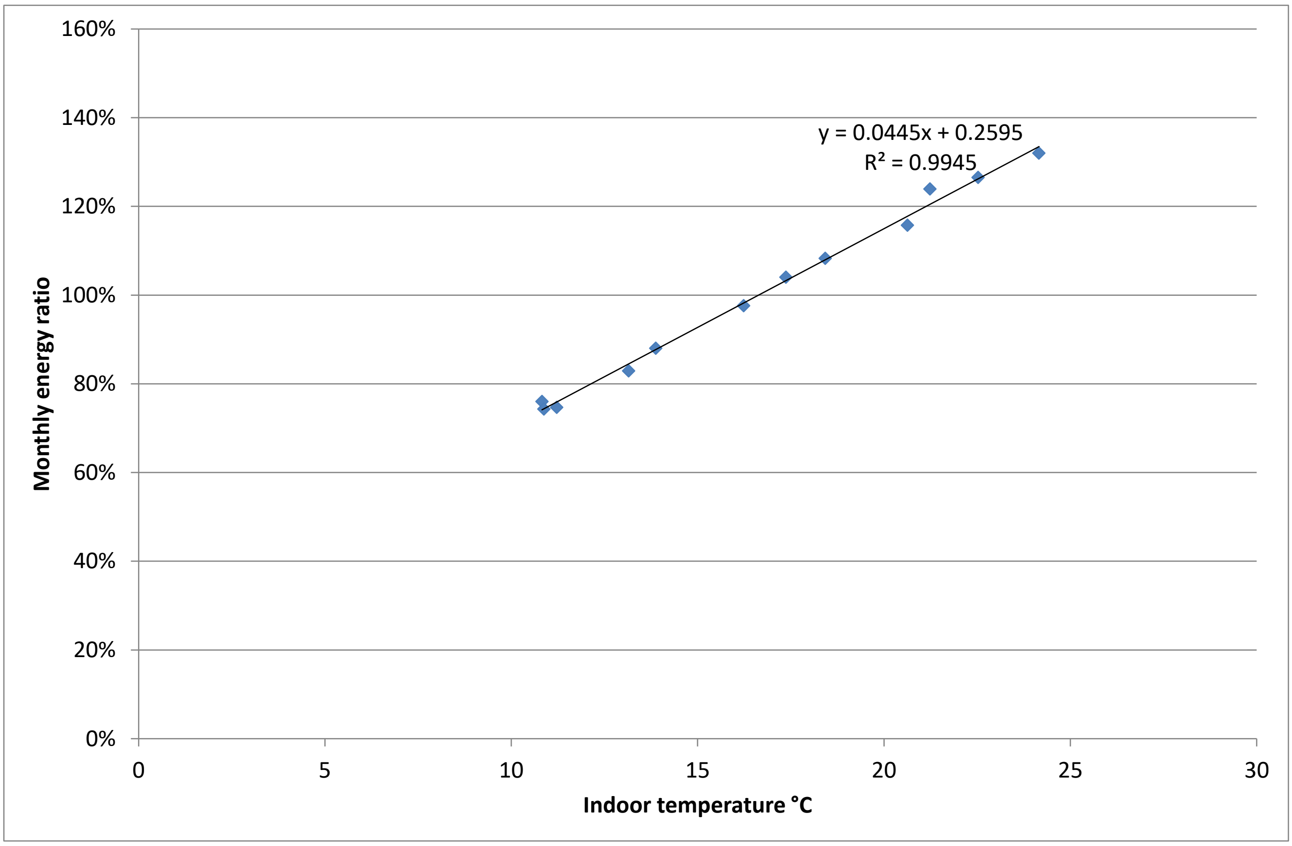

Figure 87: Typical energy response to temperature changes for commercial refrigeration

Notes: Based on author analysis of end use measurement data for 10 RDCs across a range of sites.

This temperature/energy slope is only used to more accurately apportion the energy consumption estimated in the RIS for different types of commercial refrigeration to each NEM sub-region. For example, the resulting scaling factor for conditioned spaces in NSW is about 1, for Victoria it is about 0.96, for Tasmania it is about 0.92, for Queensland North it is 1.095 and for Queensland Central it is about 1.068. For unconditioned spaces, the scaling factors are slightly more pronounced (e.g. Tasmania is about 0.8 and Queensland North is 1.244).

6.3.2 Indoor temperatures in commercial sites

For commercial sector sites, the majority will have some form of space conditioning to control the indoor air temperatures. This is true for both retail display cabinets and for professional storage cabinets. However, there will be some sites in retail and professional storage where there may be minimal or no space conditioning. The exception here is for cool rooms, where many will be effectively operating in unconditioned or partly conditioned spaces. For cool rooms, the refrigeration unit may be outside, but part or all of the cool room walls may be indoors.

In order to apportion the total energy from commercial refrigeration systems, it is necessary to undertake estimates of indoor ambient operating conditions. As for household refrigeration, a climate was allocated to each NEM sub-region and the relevant 2016 representative mean year files from the Australian Climate Database were selected (CSIRO 2017; Energy Inspection 2018). These files have hourly data that was used to develop monthly average values for each NEM sub-region.

For conditioned spaces, an approach for household appliances operating in a business setting has already been documented in Section 5.4.1 (refer to Table 28 and Table 32). Effectively this assumes that the indoor temperature profile will follow the weather and climate to some extent, with a floor on minimum temperature and a ceiling on maximum temperature. This same temperature profile is assumed to apply to all commercial refrigeration systems operating in conditioned spaces, which accounts for the majority of systems.

For unconditioned spaces (e.g. warehouses without any space heating or cooling) long term data from several sites indicated that monthly indoor temperatures are, on average, 2.5K warmer that outdoor temperatures throughout the year. This is in fact quite similar to the unconditioned residential model used for household refrigeration, but with some small deviations in the cooler climates in winter. The assumed ambient operating temperatures for commercial refrigeration systems for conditioned and unconditioned spaces are set out in Table 32 and Table 33.

6.3.3 Allocating energy consumption to NEM sub-zones for commercial refrigeration

The first step in allocating national energy consumption for commercial refrigeration into NEM sub-zones is to separate the total energy into components. There are several aspects to this:

- Splitting national energy into the broad equipment types as outlined in Figure 86
- Splitting national energy into three phase and single phase (only single phase is of relevance to this project)
- Splitting national energy by type into equipment operating in conditioned and unconditioned spaces
- Splitting energy on a climate weighted population basis into each of the relevant NEM sub-regions for this project.

The regulatory impact statement provides national data for each of the major equipment types. In addition, the author has estimated the number of smaller cool rooms in operation in the food sector and included this data nationally (cool rooms are not within the scope of the current regulations or the RIS). Table 31 provides the best available data on the stock of commercial refrigeration equipment in Australia. Unfortunately, there is little high level data on the share of equipment that requires single phase power versus three phase power. After discussions with several suppliers, the share of single phase equipment has been included for each of the main equipment types. There is of course some uncertainty associated with this estimate and this could be an area for further research. Note that the share of energy for single phase equipment is usually somewhat lower than the share of the raw count of equipment as three phase systems are usually substantially larger (especially remote systems) and therefore they consume a much larger share of the total energy for that type of equipment.

In terms of operating conditions (conditioned versus unconditioned), there is little hard data around. The best estimates by the author have been made based on discussions with selected major equipment suppliers and observations at a range of sites. While this does appear to be a source of uncertainty, the energy impact of conditioned versus unconditioned is less important because the unconditioned share is being used to allocate the total energy into different sub-segments and NEM sub-regions while keeping the total energy constant. A higher assumed share of unconditioned equipment ends up pushing a small amount of the estimated energy from cooler NEM sub-regions to warmer sub-regions. This was examined to assess the sensitivity, but the effects were very small.

Table 32: Average monthly indoor conditioned temperatures (°C) for each NEM sub-region for commercial refrigeration

State/NEM sub-region	January	February	March	April	May	June	July	August	September	October	November	December
New South Wales	24.7	24.7	24.2	22.4	20.6	19.4	19.0	19.4	20.9	22.2	22.9	23.9
Victoria	23.4	23.7	22.2	20.9	19.1	19.0	19.0	19.0	19.3	20.3	21.9	22.3
Queensland North	25.0	25.0	25.0	25.0	25.0	23.3	22.8	23.3	24.7	25.0	25.0	25.0
Queensland Central	25.0	25.0	25.0	25.0	23.2	21.1	20.8	21.9	23.2	25.0	25.0	25.0
Queensland South	25.0	25.0	25.0	23.5	21.7	20.0	19.9	20.3	22.0	23.0	24.6	25.0
South Australia	25.0	25.0	23.3	21.7	20.1	19.0	19.0	19.0	19.2	20.8	22.2	23.9
Western Australia	25.0	25.0	25.0	22.8	20.2	19.3	19.1	19.0	19.7	21.0	23.0	25.0
Tasmania	21.4	21.0	20.3	19.3	19.0	19.0	19.0	19.0	19.0	19.0	19.6	20.4
Northern Territory	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
ACT	23.6	23.7	21.4	19.0	19.0	19.0	19.0	19.0	19.0	19.1	20.6	22.4

Notes: This data is the same as Table 28.

Table 33: Average monthly indoor unconditioned temperatures (°C) for each NEM sub-region for commercial refrigeration

State/NEM sub-region	January	February	March	April	May	June	July	August	September	October	November	December
New South Wales	25.0	25.0	24.3	21.5	18.3	16.1	15.2	16.2	19.0	21.2	22.3	23.9
Victoria	23.1	23.5	21.1	19.0	15.5	13.9	13.6	14.3	16.0	17.8	20.6	21.3
Queensland North	30.5	30.3	29.2	27.3	25.4	22.9	22.1	22.9	25.0	27.7	29.1	30.2
Queensland Central	29.2	29.3	27.7	25.9	22.7	19.3	18.8	20.7	22.8	25.9	27.8	28.7
Queensland South	27.3	27.6	26.3	23.3	20.3	17.4	17.2	17.9	20.9	22.5	24.9	26.6
South Australia	25.6	25.6	23.0	20.4	17.5	14.6	13.5	14.8	15.7	18.7	21.2	23.9
Western Australia	27.1	27.6	26.1	22.1	17.7	15.8	15.4	15.0	16.7	19.2	22.5	26.2
Tasmania	19.9	19.1	17.8	16.0	13.4	11.4	11.0	12.0	13.3	14.5	16.5	18.1
Northern Territory	30.5	30.4	30.3	30.2	29.3	27.5	26.8	27.7	30.0	31.4	31.9	31.3
ACT	23.4	23.6	19.9	15.3	11.5	9.5	8.8	9.6	12.8	15.5	18.4	21.5

The first step is to split national energy into single phase/three phase and conditioned and unconditioned as set out in Table 34.

Table 34: Estimated energy consumption of commercial refrigeration in 2020 by type and phase

Equipment type	Three and Single phase GWh/year	Single phase GWh/year	Single phase conditioned GWh/year	Single phase unconditioned GWh/year
Remote Display	3910	97.8	92.9	4.9
Integral Display	2290	1832.0	1648.8	183.2
Professional Storage	1740	1392.0	1113.6	278.4
Cool rooms	N/A	85.7	17.1	68.5
Total	7940[a]	3407.4	2872.4	535.0

Notes: Based on RIS data (E3 2017b) with energy splits documented in Table 31.
Note a: Excludes all cool rooms.

As set out in Section 6.3.1, the energy in each NEM sub-region was weighted in accordance to its expected temperature of operation, based on the expected monthly average temperatures. The resulting split of energy by equipment type and NEM sub-region is documented in Table 35 and Table 36. This data shows that 88.3% of the total national energy for commercial refrigeration is connected to the NEM sub-regions (slightly higher than the population share).

Table 35: Energy consumption for conditioned commercial refrigeration by NEM sub-region in 2020

State/NEM sub-region	Conditioned climate weight	Population share	Climate weighted energy pop share	Included in NEM sub-region	Remote Display GWh/y	Integral Display GWh/y	Prof. Storage GWh/y	Cool rooms GWh/y	Total GWh/y
New South Wales	1.005	31.99%	32.16%	99.995%	29.86	530.15	358.06	5.51	923.57
Victoria	0.962	26.13%	25.15%	99.998%	23.35	414.61	280.03	4.31	722.29
Queensland North	1.095	3.32%	3.63%	94.789%	3.20	56.80	38.36	0.59	98.95
Queensland Central	1.068	1.65%	1.76%	100.000%	1.64	29.10	19.65	0.30	50.69
Queensland South	1.038	15.08%	15.65%	99.969%	14.53	257.98	174.24	2.68	449.44
South Australia	0.987	6.80%	6.71%	99.823%	6.22	110.50	74.63	1.15	192.51
Western Australia	1.005	10.26%	10.31%	0.000%					
Tasmania	0.921	2.07%	1.91%	99.526%	1.76	31.29	21.13	0.33	54.51
Northern Territory	1.113	0.98%	1.09%	0.000%					
ACT	0.947	1.69%	1.60%	100.000%	1.49	26.44	17.86	0.27	46.06
Other	1.005	0.02%	0.02%	0.000%					
Total		**100.00%**	**100.00%**	**88.53%**	**82.05**	**1456.86**	**983.96**	**15.14**	**2538.02**

Table 36: Energy consumption for unconditioned commercial refrigeration by NEM sub-region in 2020

State/NEM sub-region	Unconditioned climate weight	Population share	Climate weighted energy pop share	Included in NEM sub-region	Remote Display GWh/y	Integral Display GWh/y	Prof. Storage GWh/y	Cool rooms GWh/y	Total GWh/y
New South Wales	1.007	31.99%	32.21%	99.995%	1.57	59.01	89.68	22.08	172.34
Victoria	0.918	26.13%	23.98%	99.998%	1.17	43.93	66.76	16.44	128.30
Queensland North	1.244	3.32%	4.13%	94.789%	0.19	7.17	10.90	2.68	20.94
Queensland Central	1.168	1.65%	1.93%	100.000%	0.09	3.53	5.37	1.32	10.32
Queensland South	1.083	15.08%	16.34%	99.969%	0.80	29.92	45.47	11.20	87.39
South Australia	0.964	6.80%	6.56%	99.823%	0.32	11.99	18.23	4.49	35.03
Western Australia	1.018	10.26%	10.45%	0.000%					
Tasmania	0.801	2.07%	1.66%	99.526%	0.08	3.03	4.60	1.13	8.84
Northern Territory	1.355	0.98%	1.33%	0.000%					
ACT	0.822	1.69%	1.39%	100.000%	0.07	2.55	3.88	0.95	7.45
Other	1.021	0.02%	0.02%	0.000%					
Total		**100.00%**	**100.00%**	**88.53%**	**4.30**	**161.14**	**244.88**	**60.29**	**470.61**

For the purposes of modelling for this report, a detailed stock model was used to generate an estimate of each type of commercial refrigeration equipment type as set out in the tables above for each year from FY 2012-13 to 2018-19 inclusive.

6.3.4 Daily load profiles for commercial refrigeration

Daily load profiles for commercial refrigeration have been derived from end use metering data for about 20 appliances spread over 6 sites. Changes in the energy consumption throughout the day are driven by changes in ambient temperatures and user interactions.

For remote and integral display units, much of the change in energy throughout the day is driven by increased user interactions. This varies by site, but most appliances tend to have the heaviest usage during office hours (nominally 8am to 6pm). There are many sites (such as convenience stores and smaller shops) that operate for much long hours and these tend to exhibit flatter time-of-day profiles. The profiles used are a composite of different operating hours. Larger energy changes throughout the day occur for sites that are not conditioned as the operating temperature for the refrigeration system also varies as outdoor temperatures vary. As can be seen from the data in Table 35 and Table 36, the vast major of energy for commercial refrigeration is in conditioned spaces. In terms of days of the week, display cabinets are most commonly in retail outlets, and these tend to have usage concentrated on weekdays, with lower user interactions on weekends. Based on the available data, on average it is assumed that weekday energy for display cabinets is 2% higher than the monthly average and weekend energy is 5% lower than the month average.

Another consideration is that almost all display cabinets have internal lighting systems. These used to be fluorescent lamps, but all new products tend to have LED lighting, which is lower power. Lighting has some influence on energy consumption as the lamps consume some power and typically the lamps are located inside the refrigerated space, so the heat generated also needs to be removed. The other consideration is that most display cabinets will have their lights turned off by the users/owners when the retail outlet is closed, so this is somewhat dependent on the site and the operating hours and to some extent, the equipment. An analysis of end use data has estimated that the lighting energy could be as high as 20% of the energy during the day for older fluorescent systems, although this share is substantially lower for LED systems. As the share of LED lighting increases in the stock of commercial refrigeration, the load share attributable to lighting will decrease in time. It is likely that the lighting share of the load for display cabinets is around 8%

from 7am to 7pm each day and around 2% from 7pm to 7am. No specific energy correction for lighting has been made for this report.

Professional storage refrigeration systems tend to be located in conditioned spaces and the additional energy generated from usage tends to occur around the preparation of meals (e.g. restaurants, hospitals, nursing homes etc.). So the usage induced energy curves are a lot flatter than would be expected for display cabinets in retail outlets, with small peaks occurring before meal times. The number of usage peaks will depend on the specific site and their times and days of operation. The profile generated is a composite of all the main types of sites. Lighting consumption in professional storage refrigeration systems is negligible (most illuminate only during use). In terms of days of the week, many of the sites that use professional storage refrigeration systems operate 7 days per week. Many cafes tend to operate during weekdays and less on weekends, while many restaurants tend to operate more in the evenings and are busier later in the week (Thursday/Friday/Saturday). So average professional storage energy consumption, in aggregate, does not vary substantially by week day or weekend split (even though there are variations at a site level). There may be slightly lower energy on Sunday/Monday/Tuesday, but this is expected to be a small overall variation and has been ignored for this study as there is insufficient data to accurately quantify such changes.

For cool rooms, most of these are associated with retail outlets, so the assumed load profile is similar to display cabinets. The lighting in cool rooms is assumed to be negligible. The assumed daily load profiles for different types of commercial refrigeration are shown in Figure 88.

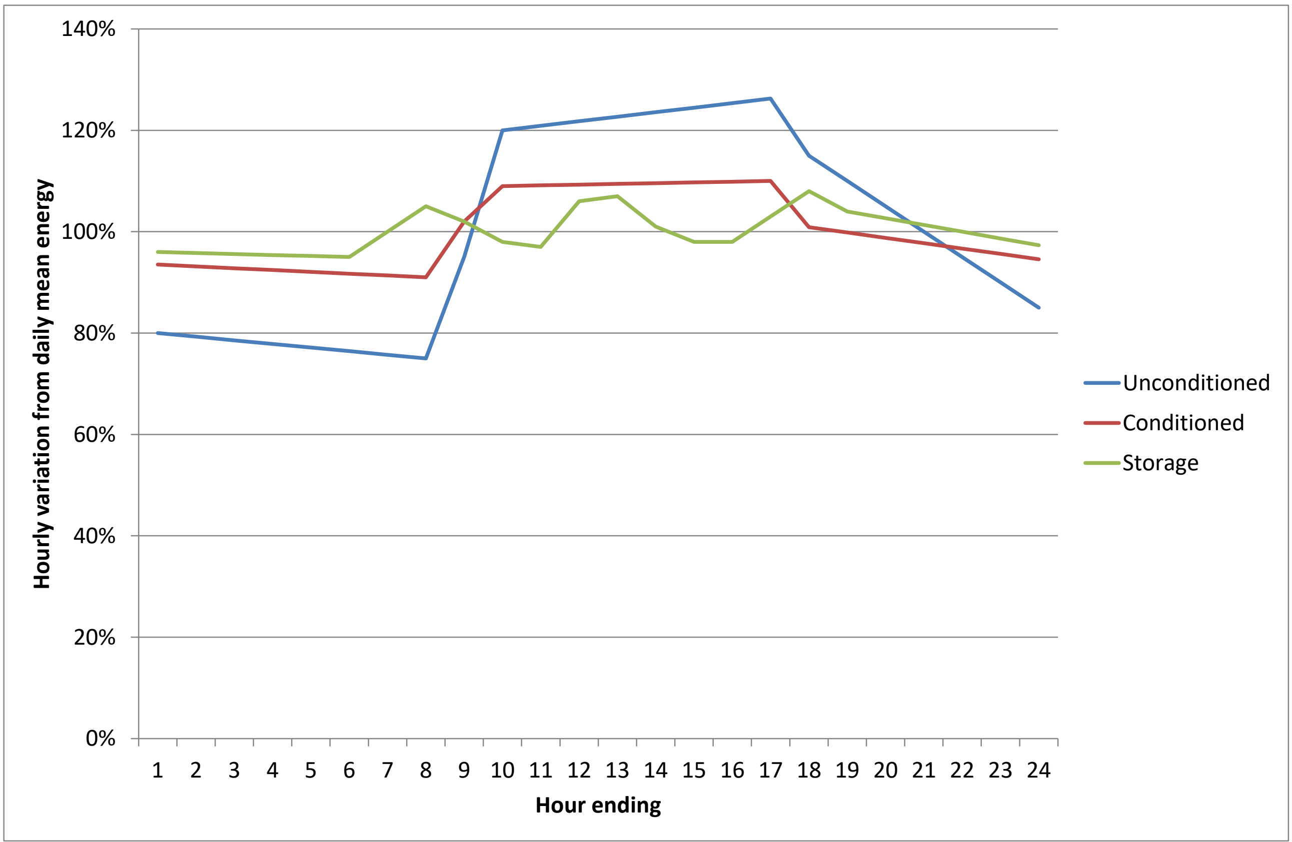

Figure 88: Assumed time-of-day variation for commercial refrigeration by type

Notes: All profiles average to 100%

6.3.5 Peak day increases in energy for commercial refrigeration

Based on a review of the available end use metering data, a peak energy day for commercial refrigeration could be as much as 35% to 40% higher than an average day within any particular month. However, this increased usage is primarily associated with user interactions (higher levels of customer activity, loading of non-chilled stock into the refrigerators) rather than hotter weather or indoor conditions. As with household refrigeration, these peak days do not correlate with hot weather or peak energy events on the NEM. Examining temperature fluctuations as a driver for increased energy in commercial refrigeration shows that for an unconditioned site, the energy increase associated with the hottest day in a month leads to an increase in daily energy of about 20%. This ratio appears to apply all year round, although the absolute energy increase is smaller in winter due to the lower base energy. For conditioned sites, the daily temperature fluctuations are much smaller, leading to a peak energy day associated with warm indoor conditions of less than 10% more than the average energy.

6.3.6 Compilation of annual load profiles

The commercial refrigerator load profiles were compiled for a typical year based on the expected energy consumption and load profiles by product type and operating conditions. Profiles were generated for the following appliance types:

- Remote Display Cabinets – conditioned spaces
- Integral Display Cabinets – conditioned spaces
- Professional Storage Cabinets – conditioned spaces
- Cool Rooms – conditioned spaces
- Remote Display Cabinets – unconditioned spaces
- Integral Display Cabinets – unconditioned spaces
- Professional Storage Cabinets – unconditioned spaces
- Cool Rooms – unconditioned spaces
- An overall factor divided the stock into those with digital controllers that protect the compressor from stalling and those with single speed compressors (Motor D) where the motor can stall on low voltage – the overall stock factor illustrated in Figure 85 was applied to each category.

For each of the years analysed, weather adjustments were applied to hourly data as set out above. As set out above, it was assumed that remote display cabinets and integral display cabinets, in aggregate, had 2% higher energy on weekdays and 5% lower energy on weekends. It was assumed that professional storage and cool rooms had no day of the week adjustment to energy consumption. This generated a load profile of 8760 hours of data for each type of product listed above (8784 hours for the leap year). These were then aggregated for more detailed analysis.

Detailed results for all products are set out in Chapter 7.

6.4 Sources of uncertainty in energy estimates for commercial refrigeration

The core energy estimates for commercial refrigeration are from the Commonwealth Regulatory Impact Statement (E3 2017b). The uncertainty associated with these estimates is not known, but could be as much as 10%. This is the best available source of data for this type of equipment.

The largest source of uncertainty in the energy estimates for commercial refrigeration lies in the split between single phase and three phase systems. The majority of systems will be three phase, but there are no primary sources of data available, so estimates from selected industry experts have been used. The uncertainty in these estimates is unknown, but could be as high as 20%.

A significant uncertainty lies in the estimates for the share of digital controllers that protect Motor D systems from stalling in low voltage conditions. At this stage, slightly more than half of the stock is estimated to have such controllers, and this is forecast to increase over time. However, this estimate is based on a limited sample of product measurements plus discussions with a few suppliers. At this stage, single phase inverter driven commercial refrigeration systems are rare, but this may change into the future.

The share of equipment operating in conditioned and unconditioned spaces is based on author and expert estimates. But different assumptions on the share of conditioned operation has little impact on the overall energy estimates and share by NEM sub-region as the overall energy is constrained by the model.

The estimates of indoor operating temperature are based on field data from a range of sites and this has been used to develop a generic approach that is independent of climate, so should be reasonably solid. Additional field data may improve the temperature response estimates and time of use profiles, but these are considered to be reasonably robust in general terms. They may not reflect the operation at specific sites, but should give a good overall representation of operating conditions across different NEM sub-regions. Because the energy impact of changes in operating temperature is modest (because there is effectively a larger fixed energy component and a smaller temperature sensitive energy component), errors in the assumed operating temperature have a relatively small impact overall. Operating temperature errors should generate uncertainties in energy estimates of less than 5%.

7 Results

7.1 Introduction

This study examines the energy consumption of air conditioners, household refrigeration and commercial refrigeration in each of the seven NEM sub-regions as specified by AEMO. Of particular interest to AEMO is the share of load on the NEM that is made up of Motor D (i.e. single speed single phase induction motors). Total energy consumption for single phase products of these specific end uses, as well as the Motor D energy consumption, has been estimated.

As set out in previous sections, the general approach used for all of these products was to ascertain energy consumption by month, then to examine typical load shapes in order to estimate a typical hourly (average) profile by time-of-day for the month. Data were then compiled into a nominal year for each of the sub-categories examined to provide a nominal 8760 hours of data (8784 hours in 2015-16). This was matched against actual data from AEMO from 1 July 2012 to 30 June 2019. Stock levels for each product were adjusted for each year of analysis. As noted in previous sections, all times values were corrected back to Eastern Standard Time (without daylight saving), which is used throughout the NEM. Some weather corrections were then applied to the data.

A spreadsheet for each of the seven financial years 2012-13 to 2018-19 has been provided to AEMO with a breakdown of data by end use by hour as part of the report outputs.

7.2 Overview

The average share of load for the end uses examined for the project, split into Motor D and inverter/digital controllers is shown in Table 37 for the year 2018-19.

Table 37: Average share of Motor D by end use and NEM sub-region in 2018-19

NEM sub-region → End use category ↓	NSW +ACT	SA	TAS	VIC	QLD NORTH	QLD CENTRAL	QLD SOUTH
Air conditioners Motor D	0.9%	1.8%	0.5%	1.5%	0.9%	0.2%	0.8%
Air conditioners inverter	5.5%	6.0%	2.5%	7.0%	4.7%	1.0%	4.8%
Total air conditioners	6.4%	7.8%	3.0%	8.5%	5.6%	1.2%	5.5%
Household refrigeration Motor D	3.7%	4.5%	1.7%	4.3%	4.9%	1.2%	4.0%
Household refrigeration inverter	0.9%	1.0%	0.4%	1.0%	1.1%	0.3%	0.9%
Total household refrigeration	4.5%	5.5%	2.0%	5.3%	6.0%	1.5%	5.0%
Commercial refrigeration Motor D	0.7%	0.7%	0.3%	0.8%	0.7%	0.2%	0.7%
Commercial refrigeration digital cont	1.0%	1.0%	0.4%	1.1%	1.0%	0.2%	0.9%
Total commercial refrigeration	1.6%	1.8%	0.6%	1.9%	1.7%	0.4%	1.6%
Total all end uses Motor D	5.2%	7.1%	2.5%	6.6%	6.5%	1.6%	5.5%
Total all end uses inverter/digital	7.3%	8.0%	3.2%	9.2%	6.7%	1.5%	6.7%
Total all end uses	12.6%	15.1%	5.7%	15.7%	13.2%	3.1%	12.1%

Table 37 shows that there is substantial variation in Motor D as a share of the average NEM load, ranging from 1.6% in Queensland Central to 7.1% in South Australia. However, there is a significant variation in the share of Motor D across seasons and by hour of the day. The following figures illustrate these effects by NEM sub-region. A detailed year chart of Motor D share for each hour of the year by end use is initially shown for NSW (including ACT) to illustrate the data in broad terms. There is an obvious weekly pattern apparent in the data, especially for household and commercial refrigeration (Figure 90 and Figure 91). This pattern is primarily caused by lower system loads on the weekend rather than changes in these end uses by day of the week.

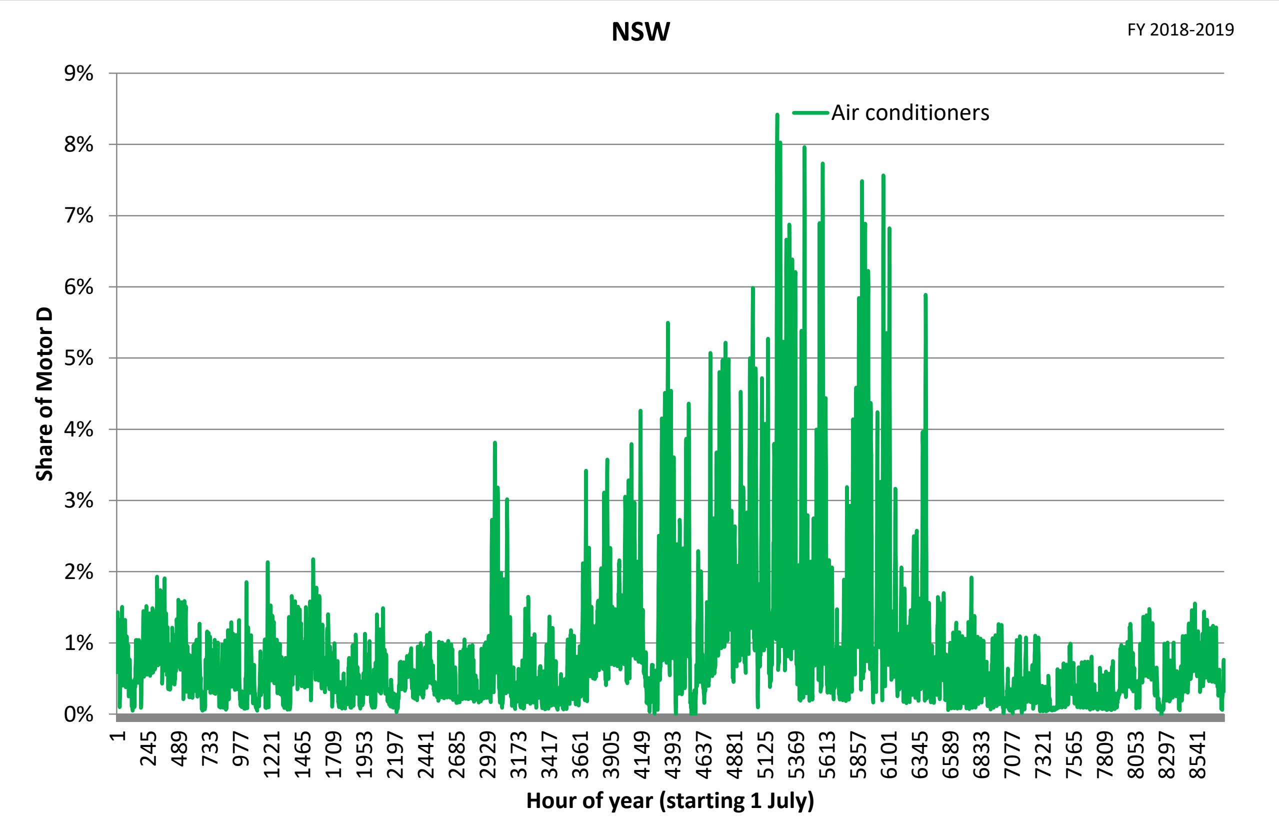

Figure 89: Hourly Motor D load for air conditioners in NSW and ACT, 2018-19

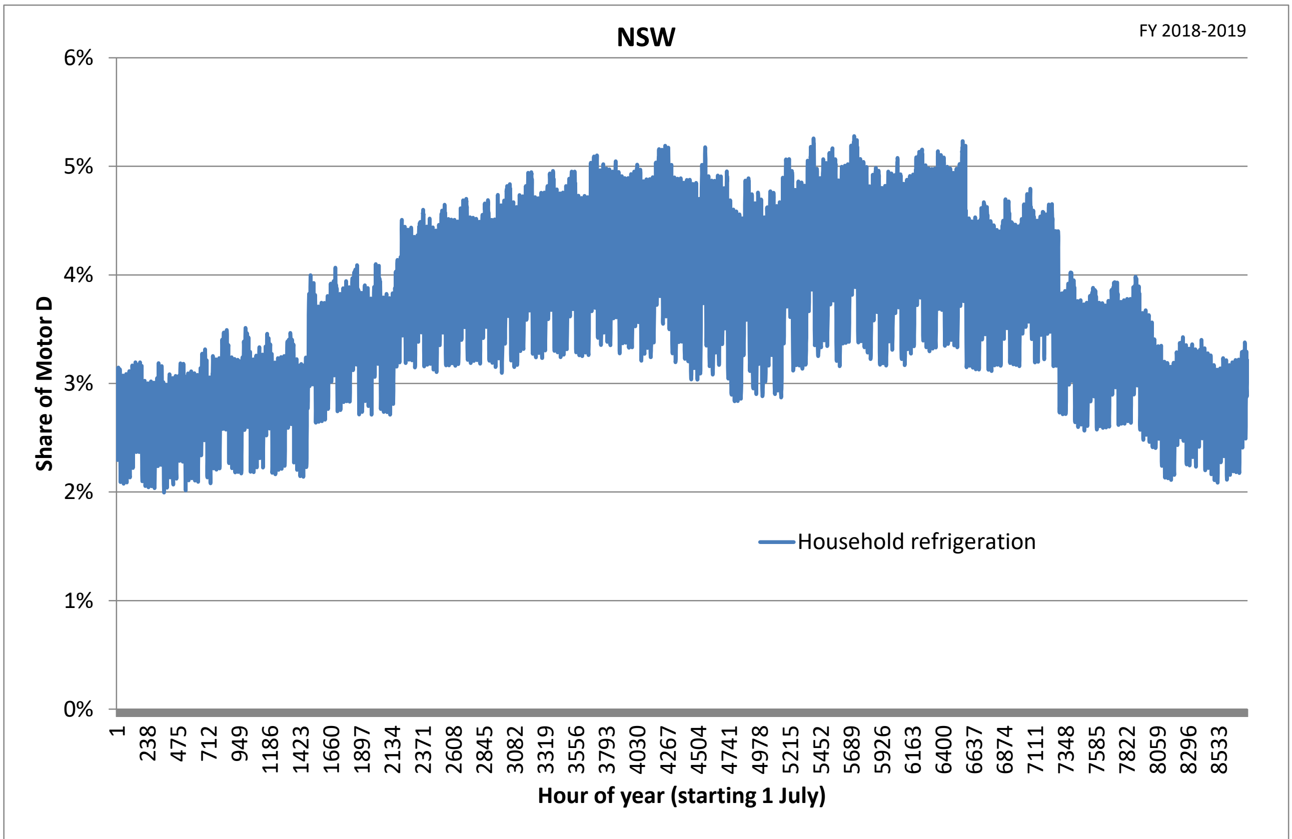

Figure 90: Hourly Motor D load for household refrigeration in NSW and ACT, 2018-19

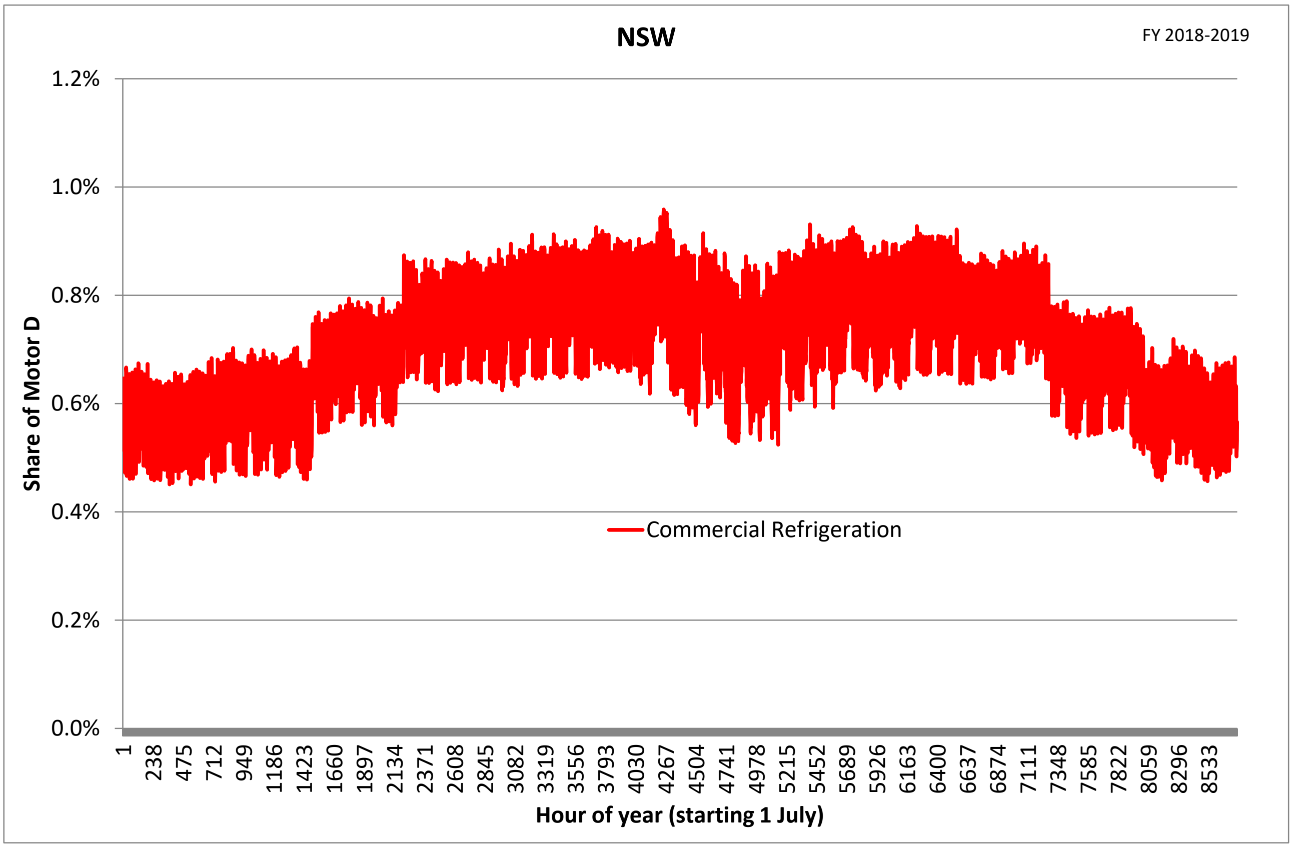

Figure 91: Hourly Motor D load for commercial refrigeration in NSW and ACT, 2018-19

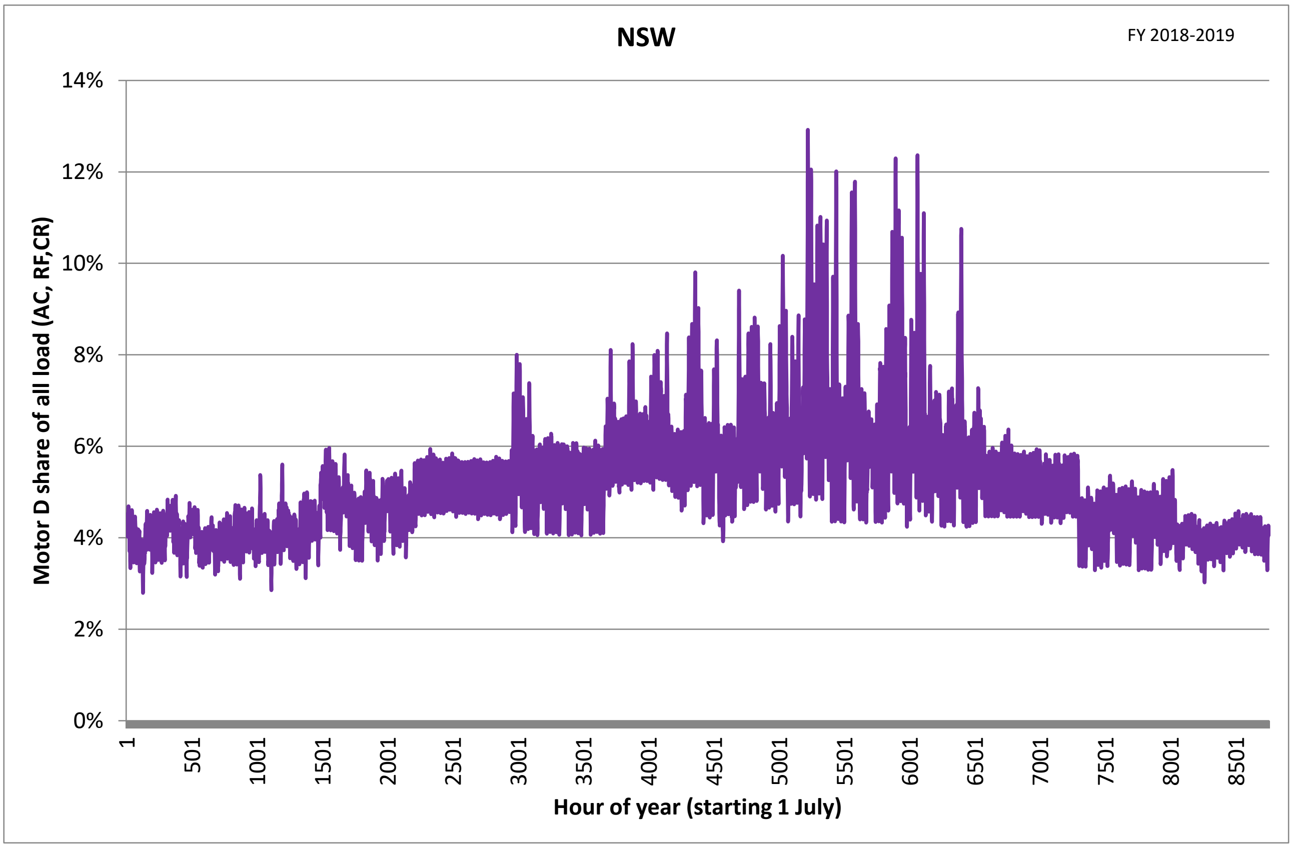

Figure 92: Hourly Motor D load for all covered loads in NSW and ACT, 2018-19 (1)

Below are area charts that show the sum of Motor D loads split by end use for the sample year for each NEM sub-region in 2018-19. Note the different Y axis scales for each NEM sub-region. All NEM sub-regions show a higher share of Motor D in summer, except for Queensland North.

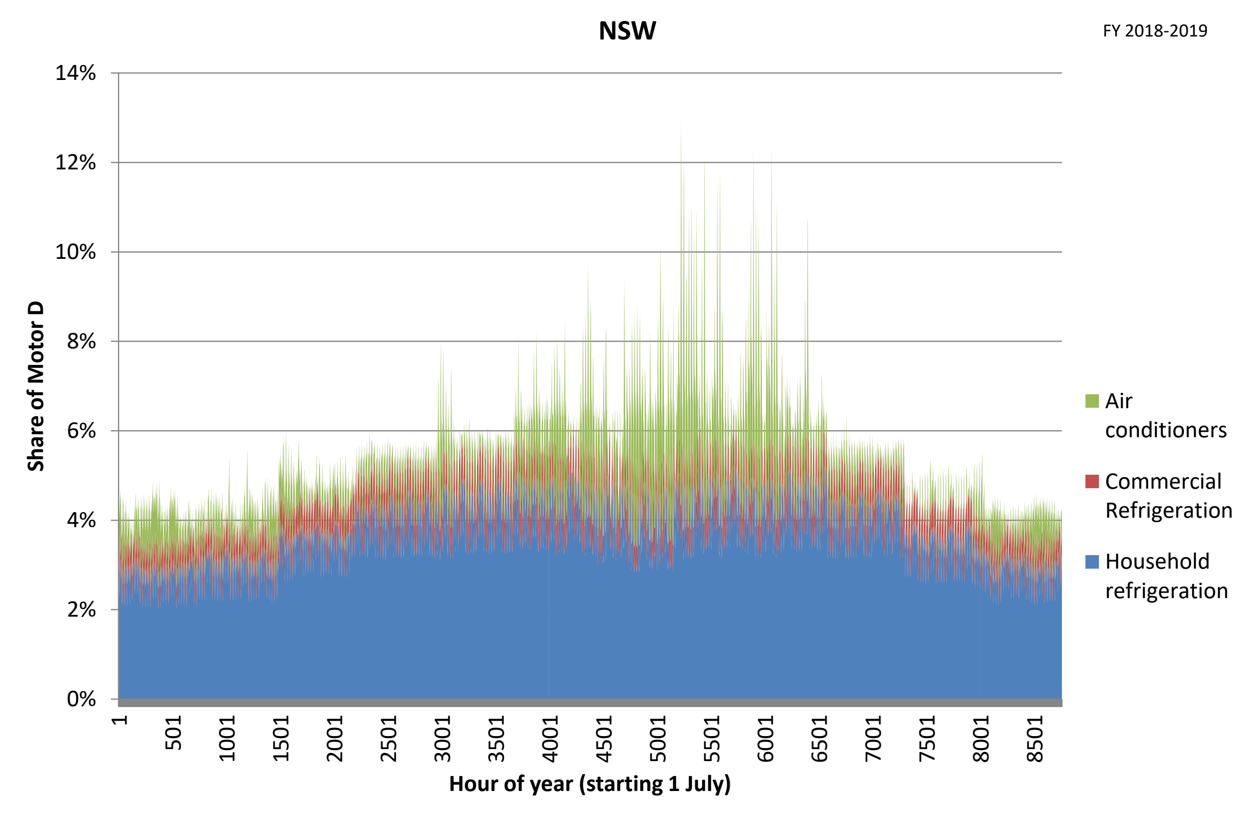

Figure 93: Hourly Motor D load for all covered loads in NSW and ACT, 2018-19 (2)

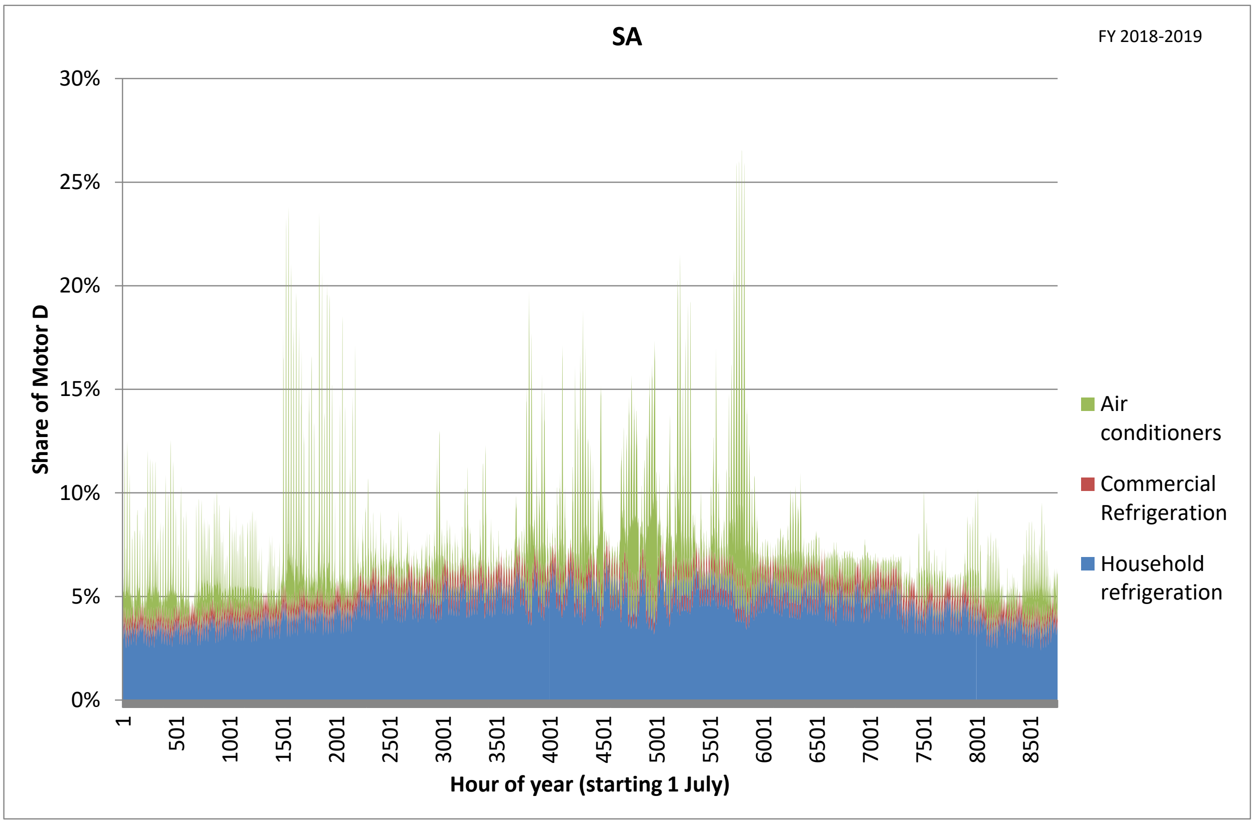

Figure 94: Hourly Motor D load for all covered loads in South Australia, 2018-19

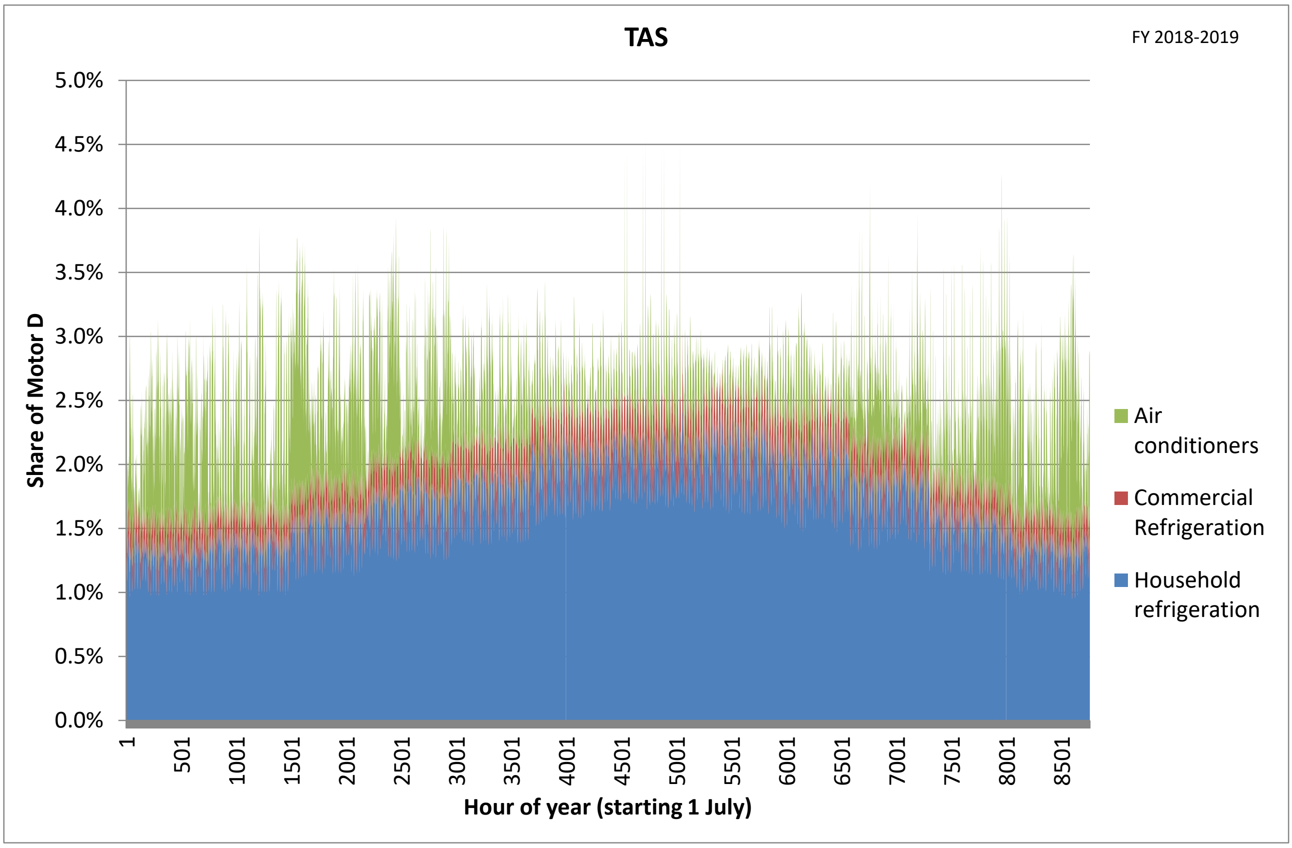

Figure 95: Hourly Motor D load for all covered loads in Tasmania, 2018-19

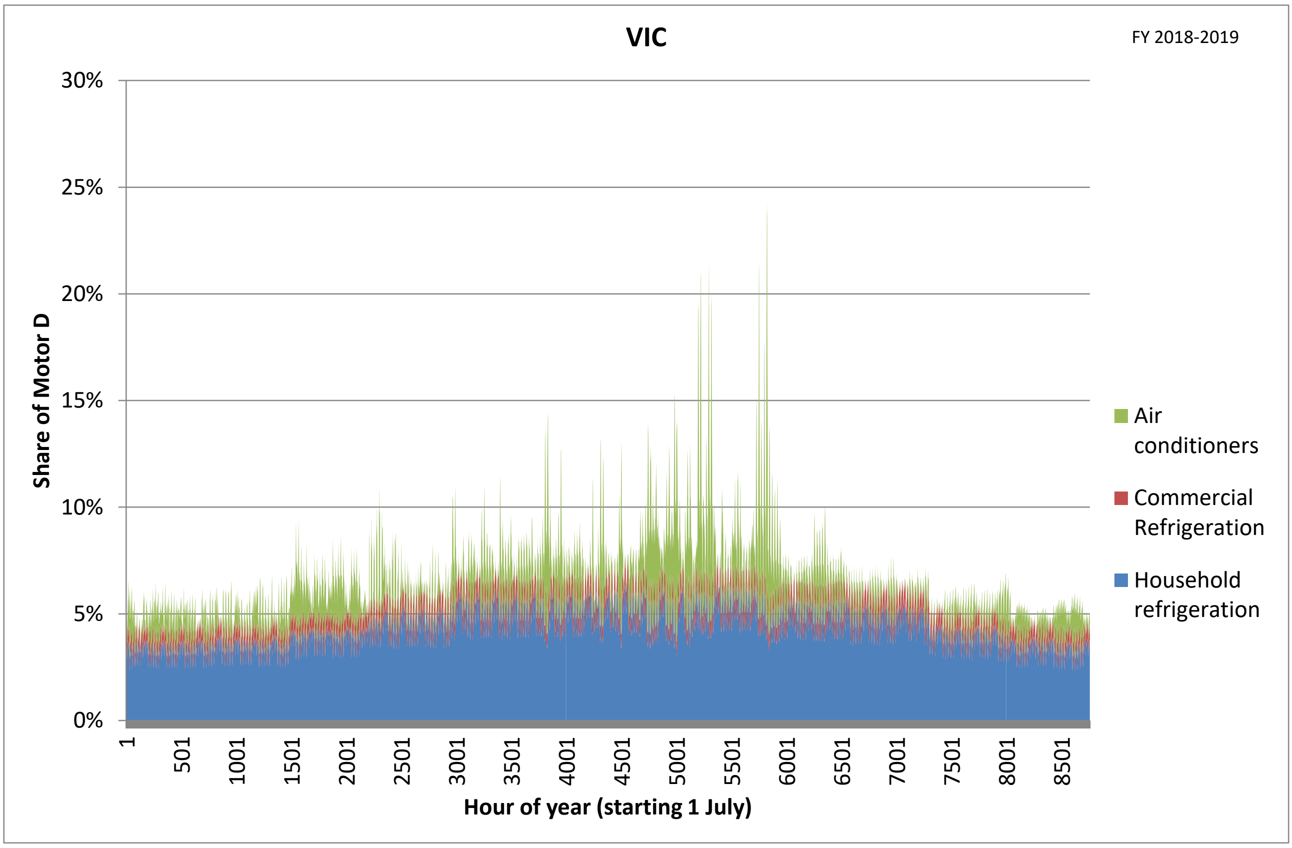

Figure 96: Hourly Motor D load for all covered loads in Victoria, 2018-19

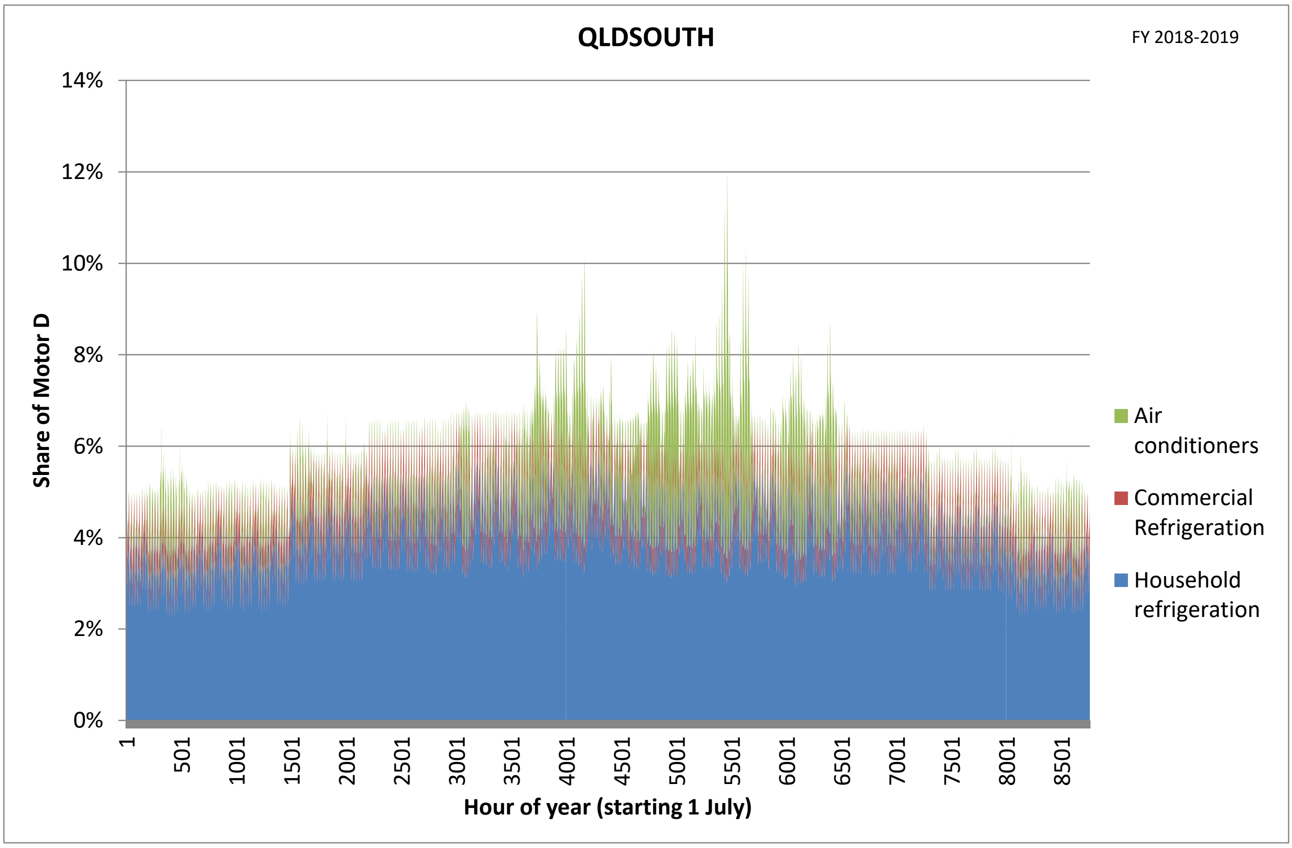

Figure 97: Hourly Motor D load for all covered loads in Queensland South, 2018-19

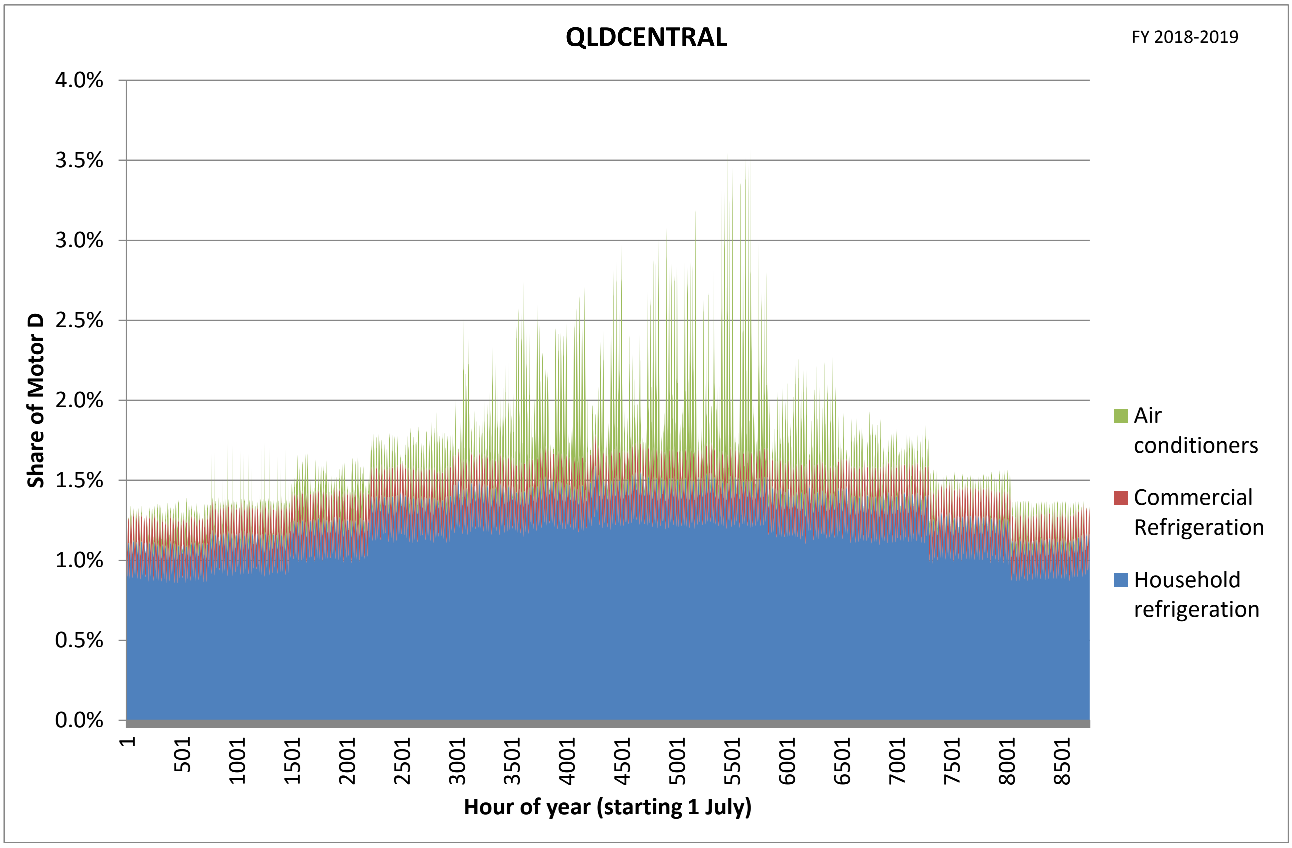

Figure 98: Hourly Motor D load for all covered loads in Queensland Central, 2018-19

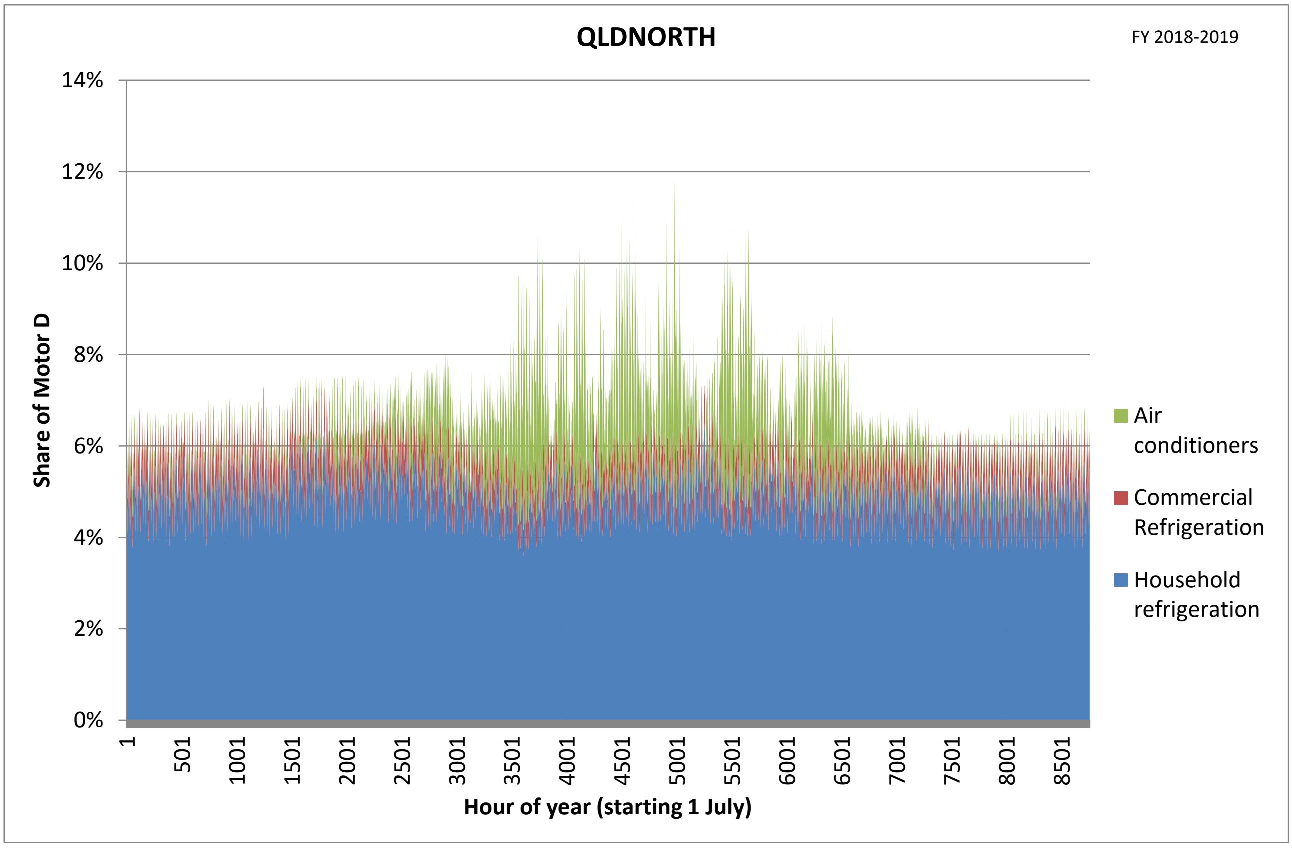

Figure 99: Hourly Motor D load for all covered loads in Queensland North, 2018-19

Detailed spreadsheets with hourly data estimates for each of the years 2012-13 to 2018-19 have been provided and these have dynamic charts that allow specific items to be graphed. There are too many options across all possible charts, NEM sub-regions and years to be included in this report.

AEMO requested a number of specific data sets to be included in the final spreadsheets. Some of these are illustrated and described in this section. Firstly, AEMO provided a template data output sheet to calculate the average, minimum and maximum[9] Motor D load by time-of-day, day of week type (weekend or week day) and season (winter (June, July, August), summer (December, January, February) and shoulder (all other months)). There are therefore six possible figures for each NEM sub-region and each year, giving a total of 294 possible figures for this parameter alone across all years. To illustrate this data, values for 2018-19 for NSW+ACT summer, winter and shoulder weekdays are shown in Figure 100 to Figure 102.

AEMO also requested that the annual system maximum and minimum for each year be identified in each NEM sub-region, together with the Motor D load at that time. An example table for year 2018-19 is shown in Table 38. Data for all years is included in the relevant spreadsheets.

[9] Average Motor D share for the hour of the day was calculated for that hour for all days in the season for the day type (typically an average of around 26 values for weekends and 64 values for week days for summer and winter, double the number of days for shoulder). The maximum value was the single maximum Motor D share for any one of the hours in that season. The minimum value was the single minimum Motor D share for any one of the hours in that season. AEMO refer to the average as the central estimate, the maximum as the upper estimate and the minimum as the lower estimate.

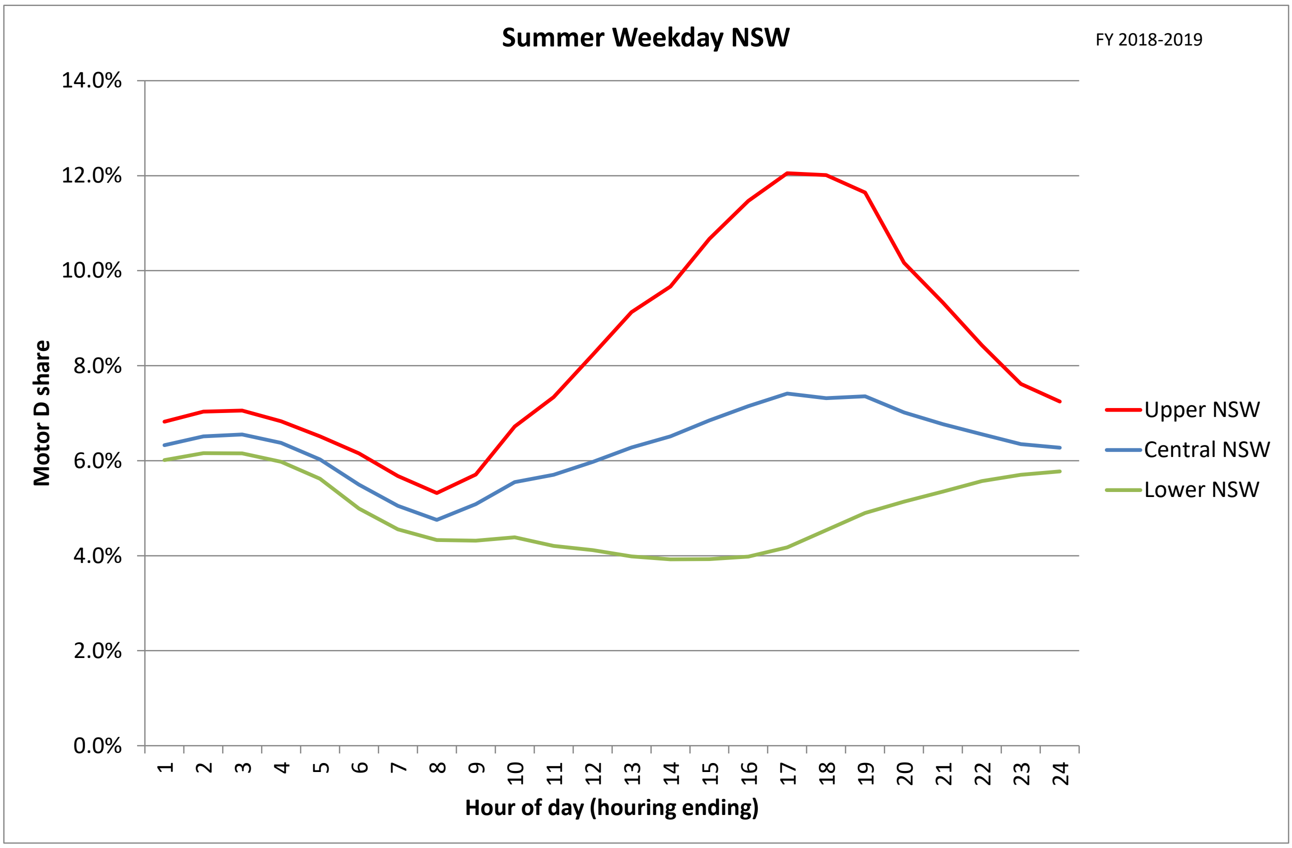

Figure 100: NSW and ACT share of Motor D by time-of-day for summer weekdays, 2018-19

Figure notes: AEMO refer to the average as the central estimate, the maximum as the upper estimate and the minimum as the lower estimate in these figures.

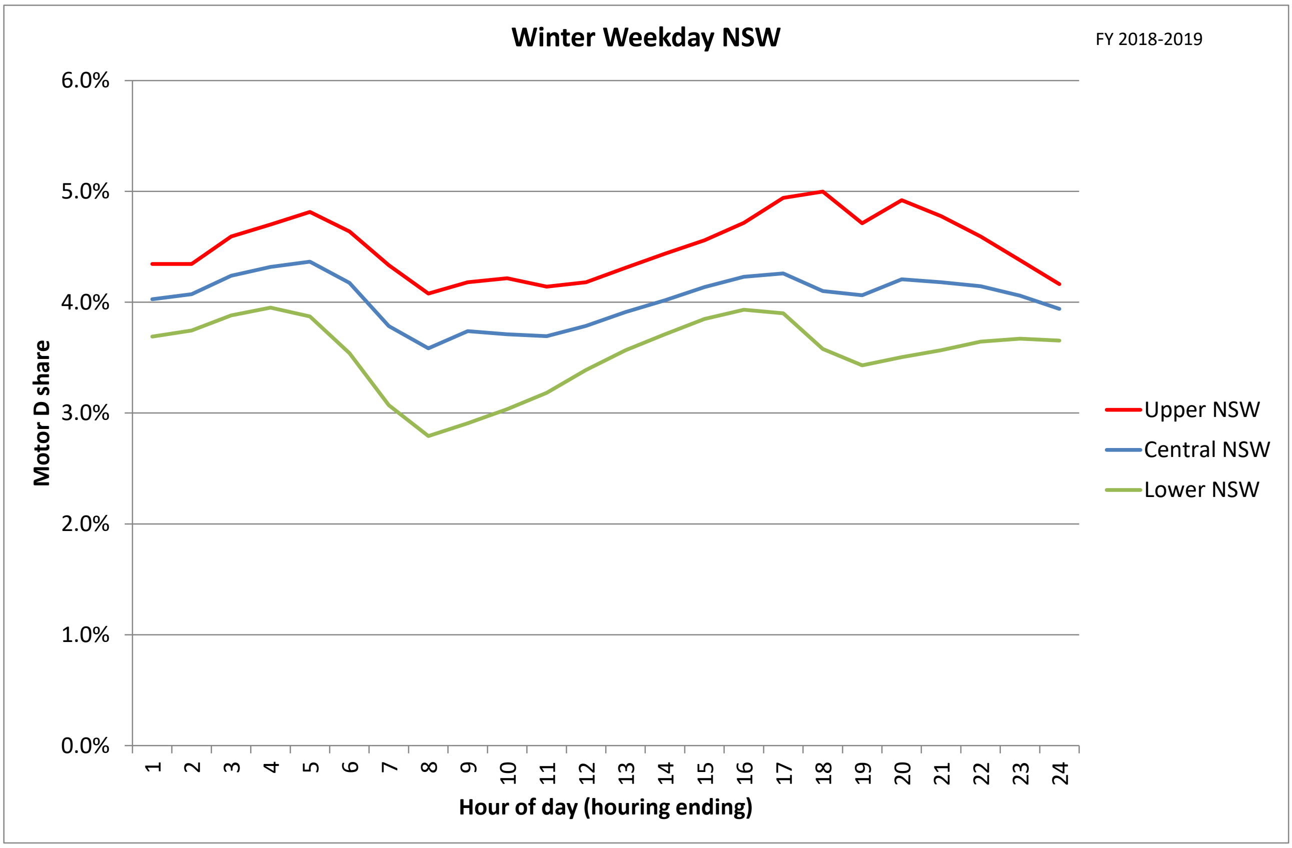

Figure 101: NSW and ACT share of Motor D by time-of-day for winter weekdays, 2018-19

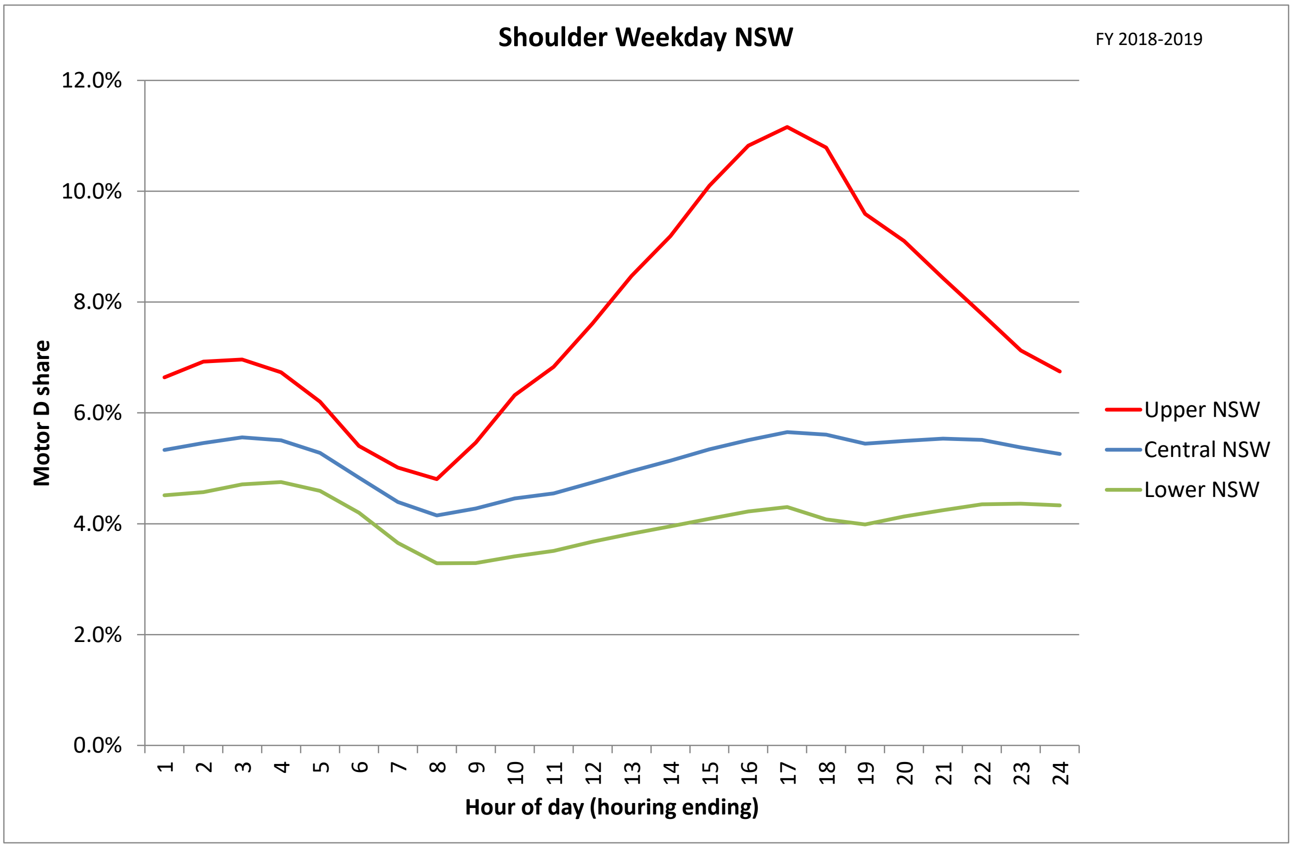

Figure 102: NSW and ACT share of Motor D by time-of-day for shoulder weekdays, 2018-19

Table 38: System maximum and minimum load in year 2018-19 by NEM sub-region

NEM sub-region	NSW	SA	TAS	VIC	QLDNORTH	QLDCENTRAL	QLDSOUTH
Annual Max MW	13602.0	3188.3	1600.1	9839.3	1383.3	1888.3	6958.0
Time/date	31/01/2019 16:00	24/01/2019 16:00	24/06/2019 9:00	25/01/2019 13:00	28/11/2018 14:00	15/03/2019 12:00	13/02/2019 16:00
Motor D	8.5%	16.8%	3.4%	14.0%	9.5%	2.1%	11.9%
Annual Min MW	5242.6	948.9	770.9	3237.6	467.0	1262.7	2379.3
Time/date	25/12/2018 4:00	22/04/2019 6:00	27/01/2019 17:00	22/04/2019 5:00	21/08/2018 5:00	24/03/2019 4:00	22/10/2018 3:00
Motor D	6.2%	6.4%	3.0%	6.4%	6.8%	1.6%	6.6%

AEMO also requested an X-Y chart of Motor D share versus underlying system load for each year and NEM sub-region. An example for NSW in 2018-19 is shown in Figure 103 and for Queensland South in 2018-19 is shown in Figure 104. Similar charts are available for each NEM sub-region and each year from 2012-13 to 2018-19 (total of 49 possible charts). The absolute values vary somewhat by NEM sub-region, but the general pattern is similar in that there is not a strong correlation between underlying system load and the share of Motor D load.

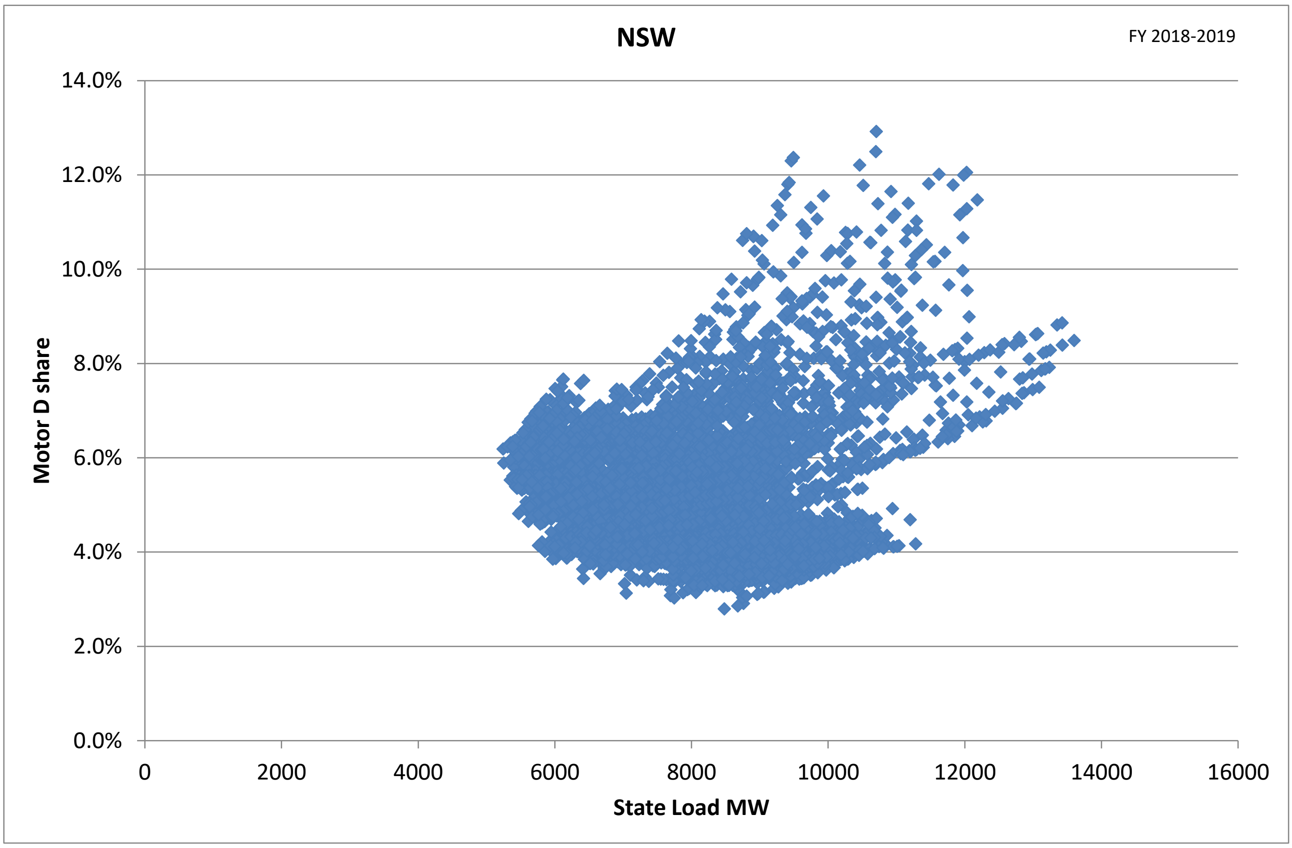

Figure 103: Motor D share versus underlying system load for NSW and ACT in 2018-2019

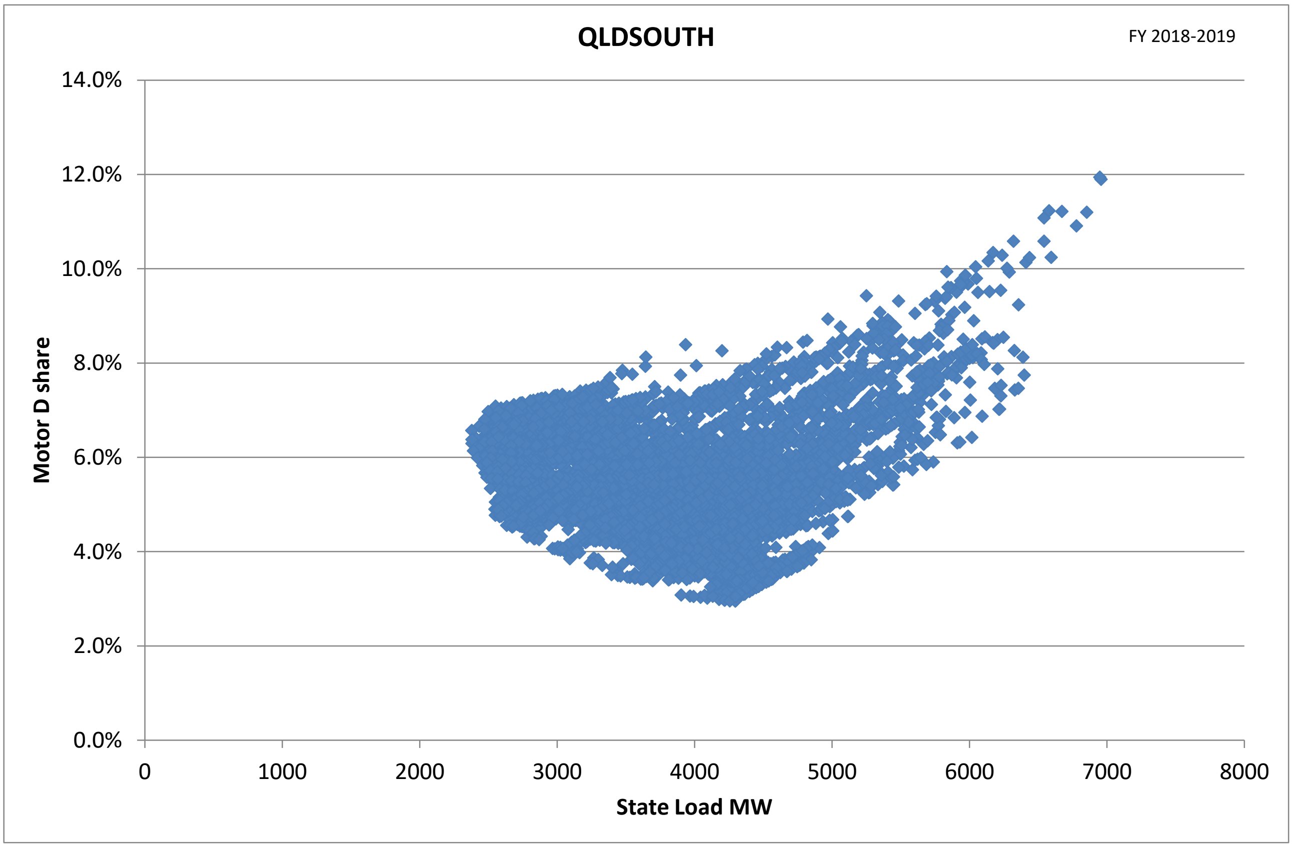

Figure 104: Motor D share versus underlying system load for Queensland South in 2018-2019

7.3 *Longer term trends in Motor D share*

While the brief did not require future estimates of Motor D share, discussions with AEMO during the project made it clear that changes in the share of Motor D in the historical record and likely trends of Motor D share into the future were important and of great interest. Historical estimates of Motor D share of underlying system load by NEM sub-region (for each hour) have been included in the analysis files provided to AEMO. These take into account key changes in the market over time, such as the stock share of inverter driven air conditioners, the growth of inverter driven household refrigeration systems and the prevalence of digital controllers that protect compressors from stalling under low voltage conditions in commercial refrigeration systems as well as the likely stock of products by type over time and changes in household growth rates. This allowed an estimate of Motor D to be developed for each of the seven years analysed in detail from 2012-13 to 2018-19. While the changes in Motor D over the past 7 years are informative, this does not necessarily reflect the likely changes over the coming decade. In particular, the market for inverter driven air conditioners is already quite saturated, so further large changes not expected, while for household refrigeration, significant changes in the share of inverter driven products to 2030 are expected.

To assist AEMO in understanding the likely future trends in Motor D share, some simple projections have been developed. These are not formal forecasts and we make no particular claim regarding their accuracy or robustness. But they do build on the existing data sets and also take into account the likely market changes expected in the share of so called electronic loads over the coming decade for each of the major end uses.

The first step was to look at the total load of air conditioners, household refrigeration and commercial refrigeration as a percentage of the underlying system load from 2012-13 to 2018-19 to see how this is changing over time. Using the same rate of change from 2012 to 2019, the total load share was then projected to 2030. The results are illustrated in Figure 105.

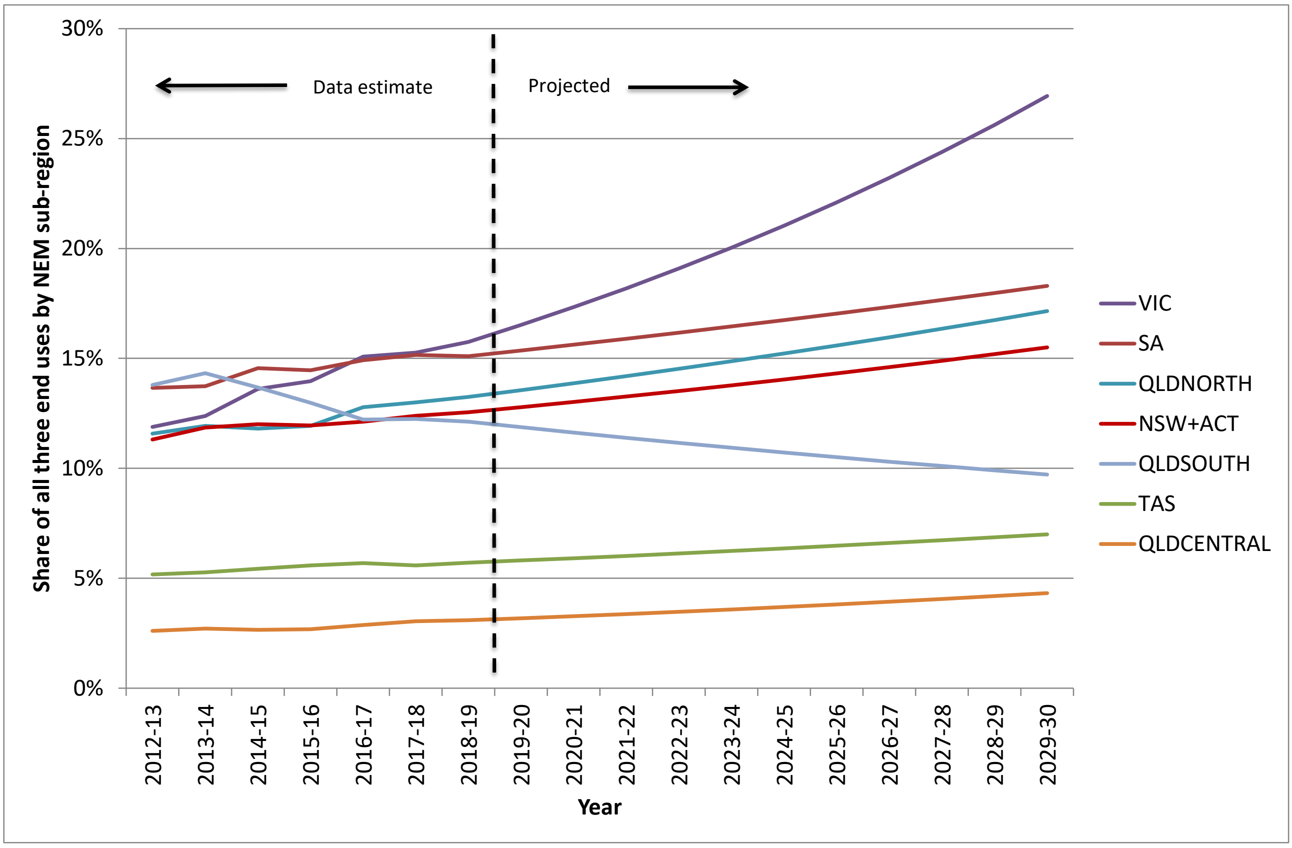

Figure 105: Projected share of energy for all air conditioners, household and commercial refrigeration based on trend data

All of the NEM sub-regions show a small annual increase in share of total load from air conditioners, household and commercial refrigeration to 2030, except for Victoria and Queensland South. Victoria shows a large projected increase, which is most likely incorrect: this is driven by the fairly fast decrease in total NEM load from 2012-19, whereas the energy consumption from these three end uses is projected to be stable or increasing slightly over time. The other obvious problem is for Queensland South which shows a significant decrease: this is also likely to be incorrect as this is driven by the significant increase in underlying NEM load from 2012-19. We don't have access to the energy forecasts by NEM sub-region and reconciling the modelled energy share with NEM energy forecasts is not within the scope of works for this project. Also, we have not prepared a detailed end use stock model to 2030 for these end uses, which would require substantial work. However, these data trends need to be viewed as a qualitative assessment of possible trends. The absolute values in this step are not of great interest – this is a stepping stone to the estimation of the Motor D trend below.

The next step was to apply the projected share of key controls that will affect the share of Motor D into the future. These are:

- Stock share of inverter driven air conditioners to 2030 (split systems and ducted systems) – refer to Figure 33;
- Share of window wall systems that will continue to use Motor D driven compressors;
- Stock share of inverter driven household refrigerators and freezers – refer to Figure 70;
- Stock share of digital controllers in commercial refrigeration systems that protect single phase compressors from stalling in low voltage conditions – refer to Figure 85.

This process can be used to derive a projected share of average Motor D share by year out to 2030. The example of NSW and ACT is illustrated in Figure 106. Similar figures can be generated for each NEM sub-region. The key trend evident is that the share of Motor D for air conditioners and commercial refrigeration is expected to change little up to 2030, while for household refrigeration, the share of Motor D is expected to fall significantly (to around half of the current levels). All NEM sub-regions show a broadly similar trend, although the absolute values vary.

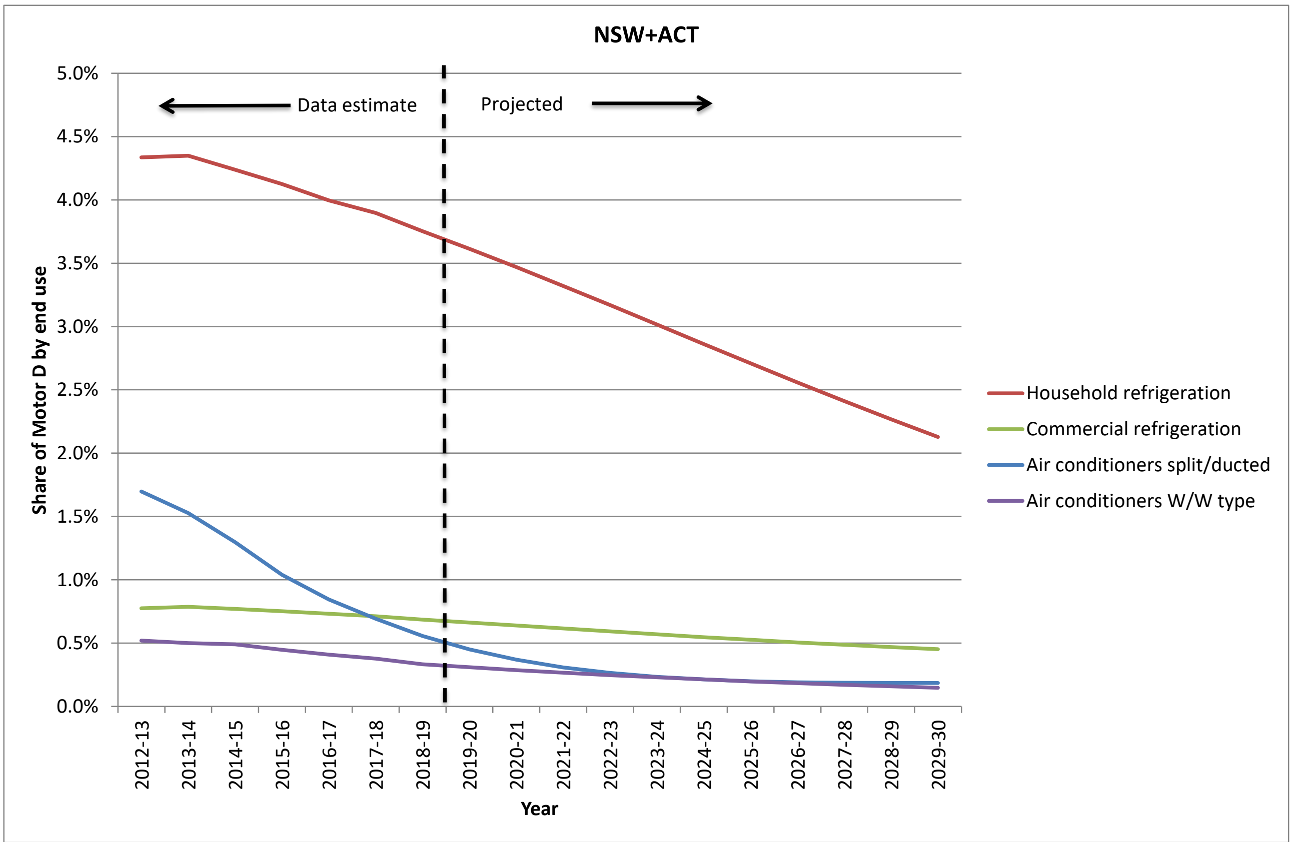

Figure 106: Projected share of Motor D of underlying system load by end use for NSW and ACT

The historical and projected share of these critical controls provides an explanation for these trends. For air conditioners, most systems installed are now of the split and ducted type and these already have a very high share of inverter driven products (over 95%) and little change to this is expected over the coming decade. The share of window wall systems, which continue to use Motor D driven compressors, is now only a few percent of the market and this share is in long term decline. For household refrigerators, the advent of inverter driven compressors is relatively new and these are making substantial inroads into the current market. Large increases in the stock share of inverter driven refrigerators, and to a lesser extent, freezers, are expected over the coming decade, which leads to a corresponding significant reduction in Motor D driven household refrigeration. For commercial refrigeration systems, there are some uncertainties about the change in stock share of digital controllers with motor protection over time. However, it is apparent that most new products have these features, so a gradual long term decline in Motor D share for this product type is expected (digital controller growth more than offsets overall load growth for this product). The total Motor D share can be projected in a similar way for all NEM sub-regions as illustrated in Figure 107. Notwithstanding the obvious issues using this approach for Victoria and Queensland South in particular (as noted previously), this data does provide a good ***qualitative*** assessment of the likely trends in Motor D share out to 2030 for these three major end uses. It is clear that the long term decline in Motor D share for all NEM sub-regions is primarily driven by changes in household refrigeration, with only small contributions from air conditioning and commercial refrigeration, although the absolute contribution does vary somewhat by NEM sub-region. The Victorian future decrease in Motor D is likely to be underestimated using this approach while the future decrease in Queensland South is likely to be overestimated. It is important to note that these are based on average annual values only and there is always still significant variation in Motor D share across seasons, by day of the week and hour by hour, especially during more extreme weather events.

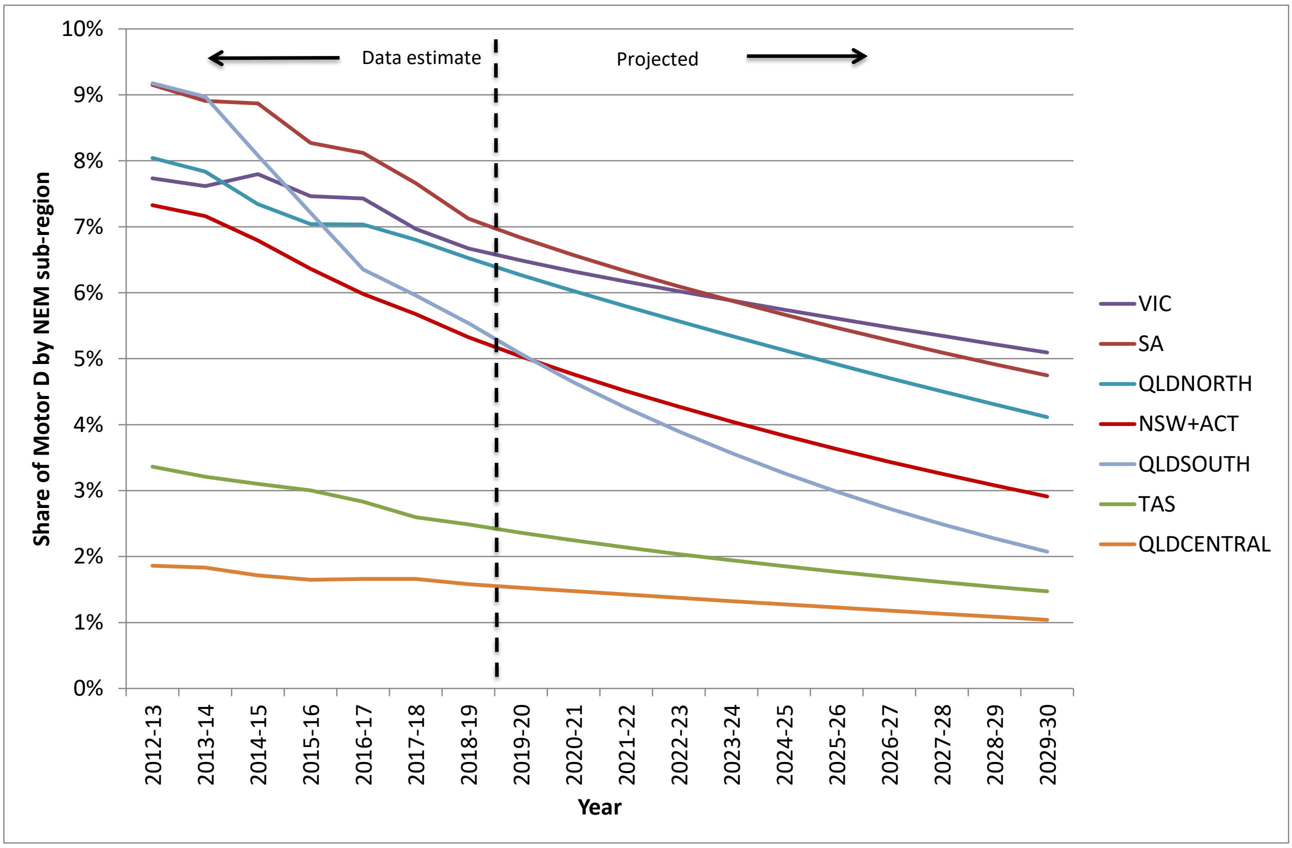

Figure 107: Projected share of Motor D of underlying system load by NEM sub-region

7.4 *Discussion*

The data compiled for this report pulls together a wide range of detailed end use data in order to estimate that share of single phase induction motors (Motor D) on the NEM and different times throughout the year. Detailed yearly data profiles for each year from 2012-13 to 2018-19 year have been compiled and provided separately to AEMO for more detailed analysis. On average, Motor D loads make up between 2% and 7% of the total NEM load, depending on the NEM sub-region examined. This varies by month and time-of-day and is affected by weather. Most NEM sub-regions showed a higher share of Motor D loads in summer, except for Queensland North, which appeared to be fairly constant through the year, and Tasmania, which showed higher air conditioner heating loads in winter. An important factor is likely to be the share of residential loads in each NEM sub-region as a share of the total system load.

Air conditioners, on average, make up around 20% of total Motor D loads across all NEM sub-regions. However, this masks the volatility of this end use. The maximum Motor D share of total NEM load from air conditioners alone that occurred during extreme events in South Australia and Victoria in 2018-19 was 20%, while in NSW, Queensland South and Queensland North the maximum air conditioner contribution was lower at 10%. However, all are driven by air conditioner peak loads for cooling in summer. Even though Motor D now only makes up a small share of all air conditioner loads (and this is declining), the highly volatile nature of air conditioner loads, especially in the residential sector, will mean that the Motor D share during peak demand events can be significant for short periods.

Household refrigeration makes up a large chunk of total Motor D loads in all NEM sub-regions – typically around 65% to 75% on average of all Motor D loads (typically between 1% and 5% of total NEM load). This does vary somewhat by season (higher in summer), but is less volatile as the impact of weather events is much lower than air conditioners. As the share of inverter driven refrigerators is increasing fairly quickly, this share is expected to fall significantly over time.

Commercial refrigeration is estimated to make up a very modest share of Motor D, of the order of 10% across all NEM sub-regions. There is some uncertainty in this estimate because the precise prevalence of digital controllers that can stop and disconnect Motor D compressors without stalling has only been estimated from a limited testing sample. A summary of average share of Motor D by NEM sub-region is shown in Table 39.

Table 39: Share of Motor D loads by end use and NEM sub-region in 2018-19

Share	NSW +ACT	SA	TAS	VIC	QLD NORTH	QLD CENTRAL	QLD SOUTH
Air conditioners Motor D	16.9%	25.7%	21.9%	22.4%	13.7%	11.7%	13.8%
Household refrigeration Motor D	70.0%	63.9%	67.3%	65.3%	75.7%	77.2%	73.9%
Commercial refrigeration Motor D	13.1%	10.4%	10.7%	12.3%	10.6%	11.1%	12.3%

Preliminary analysis shows that the projected share of Motor D of underlying system load is likely to decrease significantly over the next decade, primarily through changes in the household refrigeration market. Small decreases in Motor D share are also coming from air conditioners and commercial refrigeration.

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