RACE for 2030
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B4: Fast track

Flexing industrial refrigeration:
A feasibility study for Australian abattoirs

Final report

Australian Government
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AusIndustry
Cooperative Research Centres Program

RACE for Business Program

Flexing industrial refrigeration

A feasibility study for Australian abattoirs

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What is RACE for 2030?

The Reliable Affordable Clean Energy for 2030 Cooperative Research Centre (RACE for 2030) is a 10-year, $350 million Australian research collaboration involving industry, research, government and other stakeholders. Its mission is to drive innovation for a secure, affordable, clean energy future.

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Executive summary

Abattoirs are energy-intensive businesses that use vast amounts of energy for both heating (steam and hot water) and cooling (refrigeration). Approximately 70% of the electrical load for an abattoir is used in the refrigeration plant to chill or freeze meat, with a relatively minor amount for cold storage. Currently, there are more than 134 operational abattoirs broadly distributed across Australia, with an average refrigeration load of 1.5 MW_e.

There has been great success in load shedding systems installed on cold stores. These systems can significantly reduce operating costs for participants while also alleviating issues within the wider electricity network, such as local constraints, generation imbalances etc.

This project aimed to identify and quantify possible load flexing options within the significant refrigeration loads of abattoirs. Detailed investigation was performed across the sector, including discussions with abattoirs, refrigeration providers, technology suppliers and energy retailers to facilitate this study.

Key findings include:

- There is limited opportunity to flex loads directly (i.e. without storage). The two most likely solutions for this are optimisation of the low side suction pressure and of blast freezer fan speeds in response to varying energy rates. These would both be possible with a minor upgrade of controls resulting in an attractive payback. However, the quantity of flexible load available is relatively small and would not be available for additional demand response payments.
- Many boning rooms are fed with a chilled glycol loop (with more sites are being converted to this system). This is a suitable load in which to include thermal storage, although it can be a relatively small load in relation to the site. The thermal storage can charge/discharge in relation to pricing and demand response levels. However, after factoring in the COP of the refrigeration systems and the available charge/discharge rates, the overall economics are not attractive.
- Electrical batteries can be used to offset loads during times of high electricity prices and provide some effective flexible demand. Of the opportunities identified, this offers the most significant amount of flexible demand and its economics are worthy of further investigation.
- High temperature heat pumps (HTHP) operating in conjunction with existing hot water generation systems are an effective method to flex load and optimise energy use and carbon emissions.

Three pricing regimes were reviewed:

- A simple retail tariff with peak/off peak pricing where use during off peak times is maximised.
- The retail tariff, but also including participation in a demand response programme.
- A wholesale tariff, which sees use minimised during times of very high pricing.

The table below outlines the savings per kWh of flexible demand, along with the simple payback in years. As highlighted, operating load shed systems on a wholesale plan provides the lowest overall cost and highest possibility for savings. An electric battery provides a more attractive solution than a thermal battery (in this circumstance), but there are pros and cons of each. Further, while the paybacks of a HTHP are relatively poor on average, there will be circumstances where the economics are very favourable due to the gas versus electricity price ratio and applicable demand charges. We believe these will be a good solution at a number of sites and should therefore be assessed on a case-by-case basis.

Savings per kWh of flexible demand, along with simple payback in years, for three pricing regimes.

	Retail tariff		Retail with DR		Wholesale[1]	
	Savings	**Payback**	**Savings**	**Payback**	**Savings**	**Payback**
	$/kW(h)	years	$/kW(h)	years	$/kW(h)	years
Suction pressure modification[2]	0.88	Immediate	N/A	N/A	7.26	Immediate
Blast fan optimisation (1 h @ 75%)[2]	6.05	Immediate	N/A	N/A	27.79	Immediate
Thermal battery (980 kWh)[3]	2.19	123	5.13	53	16.52	16
Electric battery (1 h)[3]	14.95	53	24.66	32	135.78	6
Hot water heat pump[4]	44.41	17	N/A	N/A	56.22	13

1 Annual savings presented in the table are based on Queensland, the most favourable NEM region during the 2020/21 year.
2 Annual savings are per kW of compressor capacity.
3 Annual savings are per kWh of storage capacity.
4 Annual savings are per kW_{th} of heat pump capacity.

Unfortunately, despite the significant refrigeration loads onsite, given the time critical process cooling requirements of abattoirs, these sites are unable to adequately adjust their cooling demand profiles, resulting in limited load shed opportunities. The use of thermal batteries can offset some loads. Batteries may also be useful for reducing the size of refrigeration equipment and/or avoiding upgrades. Initial modelling has indicated that the relatively slow recharge rates reduce available savings, but this has not been reviewed in detail as part of this report. Electrical batteries provide good flexibility and a significant potential for varying net demand.

Should an electrical battery (or any of the items above) be implemented, it is essential that proper consideration be given to its operation in order to maximise savings and prolong life. In particular a plan should be prepared that covers:

- pricing contract with demand response aggregator to maximise load shed revenue
- clear control strategy to optimise daily operation for energy and demand cost reductions, including interactions with other systems onsite
- detailed modelling that predicts the overall operation and economics of the project—the model developed as part of this project is ideally suited for this.

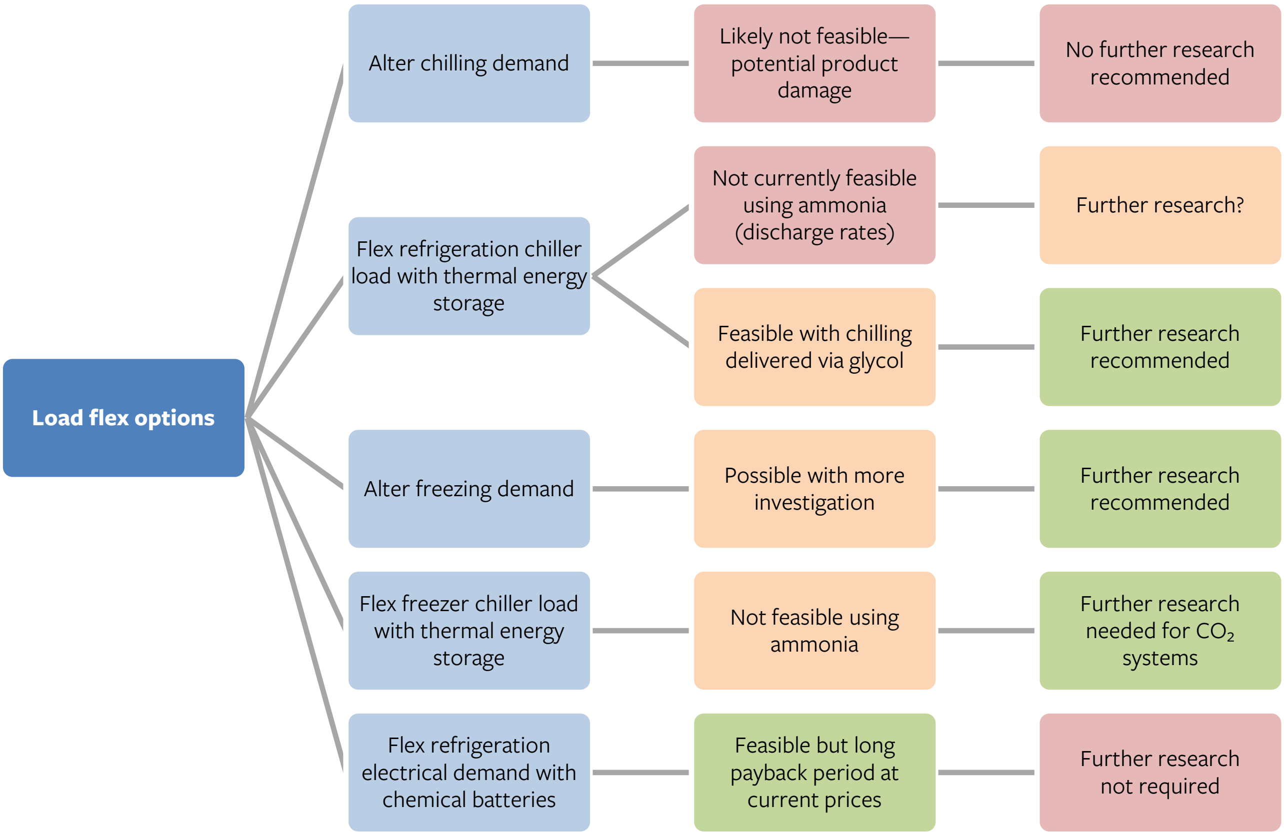
Sites with cold storage are much better suited to load shed programmes, and the abattoirs reviewed that had large cold storage facilities were using them to good advantage.

In summary, the following characteristics of abattoir refrigeration loads make them difficult to flex.

- **Time sensitive cooling profiles**—chilling of meat is subject to critical and time sensitive cooling profiles that cannot be interrupted.
- **Very limited production flexibility**—production throughput is not flexible without making significant changes to work shifts and days.
- **Relatively small demand charges**—abattoirs are large energy users with relatively low energy tariffs and demand charges, which erode the customer-side value from load shifting.
- **Thermal storage limited to high-side loads**—the availability of phase change materials is limited to the high-side (chiller) loads.
- **Loads that can be flexed are small**—suction pressure variation and blast fan speed variations were found to be loads that can be flexed but offer very minor load reductions relative to site demand.
- **Battery storage may facilitate load flexing**—however the business case for this investment was shown to be a case-by-case proposition that would require detailed investigation and careful consideration.

While these characteristics limit the feasibility of flexing loads, particularly those that require capital investment for enabling equipment (e.g. thermal storage or batteries), greater benefits may be achieved by incorporating load flex into the design of greenfield facilities. In this way, FD can displace the need for capital investment in compressors and hence will achieve significantly greater ROI than a retrofit application. Where thermal energy storage (TES) is installed to help offset compressor installation, the incremental capital cost will be reduced but a different control methodology will be required to limit site refrigeration demand on an ongoing basis.

The following chart highlights various load flex options, their feasibility and avenues for further research, as identified in this report.



Other industrial refrigeration loads that do not have these limitations may benefit more from load flexing. Particularly, businesses or operations that include inherent storage or process flexibility, or ‘peaky’ loads are more suited to load flexing.

Finally, the typical demand profile of abattoirs was found to lend itself well to solar PV generation. The addition of HTHPs with intelligent controls will further enhance this alignment.

Contents

1 Introduction

Abattoirs are energy-intensive businesses that use vast amounts of energy for both heating (steam and hot water) and cooling (refrigeration). Approximately 70% of the electrical load for an abattoir is used in the refrigeration plant to chill or freeze meat, which represents 3–5% of their total operating costs. Currently, there are more than 134 operational abattoirs broadly distributed across Australia, with an average refrigeration load of 1.5 MW_e.

This project investigated the feasibility of flexing the electrical demand from refrigeration plant at Australian abattoirs. Load flexing can involve several price-responsive modifications of electrical load including *shedding*, *shifting*, *shaping* or *shimmying* (discussed further in Section 2). However, the focus of this project was load shedding (rapid curtailment of demand through switching off equipment) and load shifting (moving loads to a different time of the day) to minimise the energy costs for the abattoir, increase utilisation of behind-the-meter generation (e.g. on-site solar), and provide stabilisation services to network service providers.

Specifically, the project sought to:

1. identify low-capex opportunities for abattoirs to flex their demand using existing assets
2. investigate opportunities for technology implementation (e.g. thermal storage) to enhance this capability, and
3. review opportunities for High-Temperature Heat Pump (HTHP) implementation to produce hot water and provide additional load flex.

1.1 Project background—the need for increasing demand flexibility

The National Electricity Market (NEM) is a wholesale spot market and electricity transmission network that supplies electricity to the eastern and southern regions of Australia. Within this market supply and demand determine prices over five-minute dispatch periods. Generators make offers to sell power into the market and the Australian Energy Market Operator (AEMO) uses merit order to schedule the lowest priced generation available to meet demand. Like electrical distribution networks around the globe, the NEM is undergoing a transition from centralised fossil fuel generation to variable distributed generation, such as wind and solar. AEMO's 2020 Integrated System Plan forecasts that 63% of coal-fired generation is set to retire by 2040 (AEMO 2020). While this transition will be managed by installations of wind and solar farms and firming generation such as pumped hydro, battery storage and gas, it places greater strain on network operators to balance supply and demand.

Over the past 10 years the rate of adoption of rooftop photovoltaic (PV) solar has grown steadily, placing Australia as the country with the highest uptake of residential solar systems in the World (Cranney 2021). As of 30 September 2021 there are more than 2.96 million PV installations in Australia with a combined capacity of 23.5 GW (APVI 2021). The energy generated from these systems is not traded on the NEM. Excess power is fed back into the network lowering the demand that market generators need to meet.

In regions of the grid with high penetration levels of distributed PV, such as South Australia, network operators are now facing challenges with minimum operational demand. Rooftop solar is injecting so much energy into the network that the frequency of negative real-time prices is increasing rapidly, up from 1.6% of the time in 2018–19 to 6.8% in 2019–20—a 423% increase (AEMO 2020). These periods are most common during the middle of the day on weekends, when baseline grid demand is lowest. Figure 1 below shows the rapid increase in the number of negative-price trading intervals over the past few years. While the number of negative-price intervals has increased markedly, they are most commonly in the 0 to –100 $/MWh bracket, suggesting the market responds quickly to this price signal to reduce supply and/or increase demand. It also highlights that demand response strategies that aim to exploit these occurrences need to be mindful of the relative magnitude of the 'free energy' compared to the potential cost imposition of the less frequent extreme price events that approach the market price cap ($15,100/MWh).

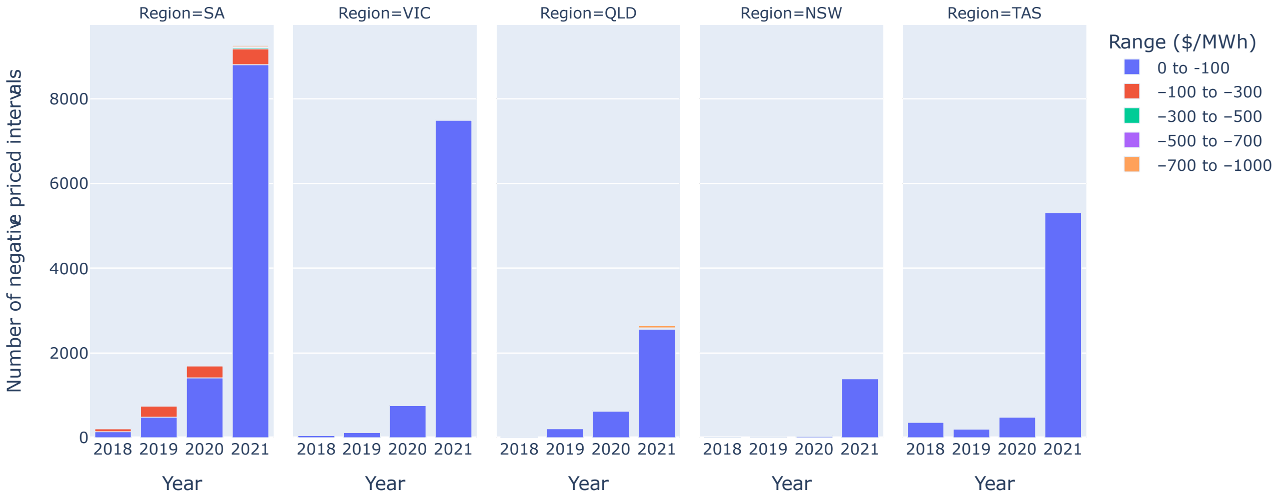


Figure 1. Number of negative trading intervals in the National Electricity Market (NEM) by region. Data for 2021 is to end September. (Data Source: AEMO)

The increased levels of variable renewable generation in the NEM combined with the retirement of several large dispatchable coal (and gas) generators have made the task of managing network reliability more difficult, particularly during hot summer weather (AER 2021).

As renewable technology costs continue to decrease and businesses actively seek to lower energy costs and associated emissions, consumers will meet an increasingly proportion of their energy needs from behind-the-meter generations (i.e. PV) and localised energy storage (e.g. batteries). Demand response is a form of distributed energy resource that provides 'firming capacity' to help fill supply gaps and is growing in importance as the network undergoes the inevitable transformation away from centralised generation.

1.2 Energy consumption in Australian abattoirs

Figure 2 shows the total annual production of red meat by Australian state since 1980. Production has been trending up since the 1980s and reached 3.56 Mt of carcass standard weight in 2020 (ABS 2021). These data underline the importance of Australia's red meat and livestock industry as both a source of sovereign protein supply and a major contributor to gross domestic product (GDP)—contributing $17.6 billion to GDP in 2018–19 (MLA 2020).

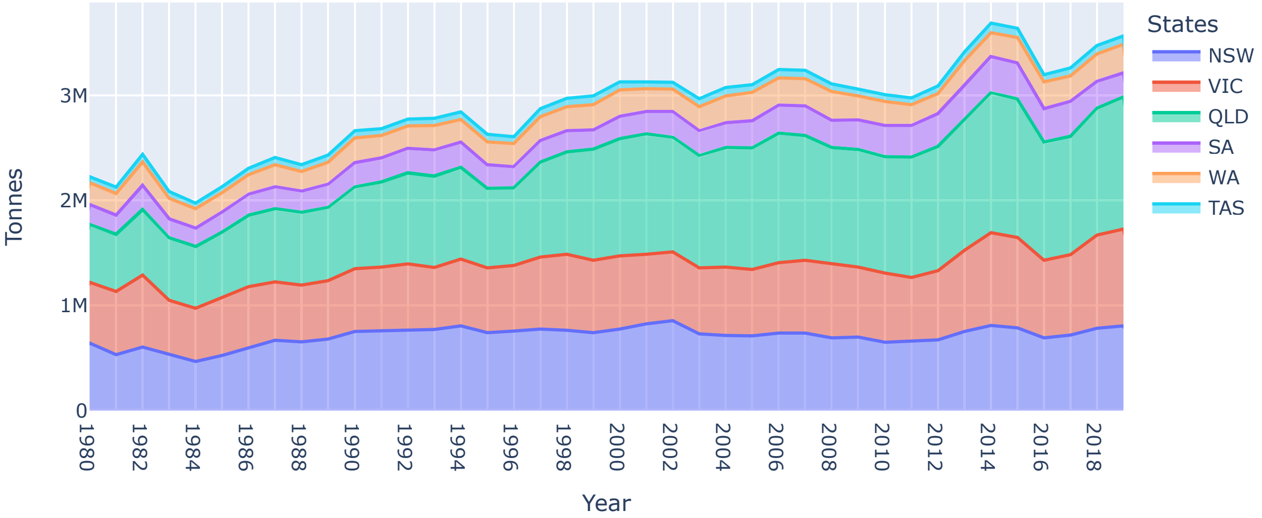


Figure 2. Australian red meat production by year. (Data source: ABS)

The meat industry consumes very large quantities of energy, principally as thermal energy for steam production for rendering, sterilisation and cleaning, and as electrical energy for refrigeration. Energy costs are significant for abattoirs and range from $100,000 to more than $10 million per year for large facilities (DELWP 2018). In 2020 an environmental performance review commissioned by AMPC calculated the average energy intensity of the Australian red meat industry to be 3316.2 MJ/t hot standard carcass weight (HSCW) based on 26 sites (17.3% of total businesses, 41.3% of total production volume) (Energy 2021). Excluding rendering, the energy intensity figure was 2092.9 MJ/t HSCW. This figure was a 43% increase from 2015 despite total site greenhouse gas emissions being 8.1% lower. The energy figure is challenging to interpret as energy consumption was partly attributed to improved on-site wastewater treatment. Figure 3 shows the energy breakdown by fuel source and associated emissions for the Australian meat processing industry. Electricity is the largest source of energy and contributes the majority of emissions. Currently there are only eight facilities in Australia with cogeneration, of which two use natural gas.

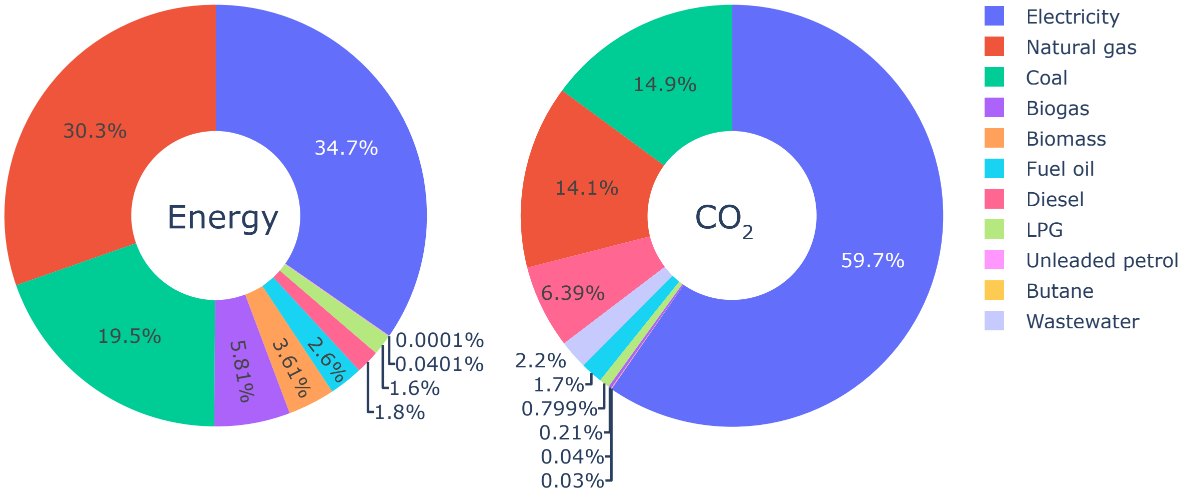


Figure 3. Meat processing industry energy source breakdown and associated emissions. (Data sourced from (Energy 2021)).

The average electricity consumption in 2020 was found to be 336 kWh/t HSCW (Energy 2021), a 6.7% increase from 2015. Based on this energy performance indicator and the total annual red meat production, the total meat industry electricity consumption is ~1.2 TWh/year, of which ~69% or 0.83 TWh is associated with refrigeration.

Despite some indications of downward trends in emissions, the 2020 environmental performance review comments that the industry will need to accelerate their decarbonisation if they are to meet their ambitious target of carbon neutrality by 2030. Considering this, opportunities for load flexing from refrigeration plant should be viewed as providing both cost savings, and the ability to reduce the carbon intensity of site operations through alignment of demand with cleaner sources of power (e.g. on-site generation or renewable energy power purchase agreements).

This study has not modelled abattoirs with onsite generation. One site considered had solar installed, but the output was not sufficient to fully offset site load and would therefore not have had an overall impact on findings. In general, solar load generation profiles work well with abattoir electricity use profiles given the large amount of generation and use in the middle of the afternoon. Sites with significant cogeneration would need to be treated separately as, depending on the amount and timing, it could affect the opportunities identified in this report. However, only eight abattoirs in Australia currently have cogeneration systems.

1.3 Research methods

This study involved the following major elements:

- consultation and interviews with numerous refrigeration contractors
- engagement with and review of load flexing with four abattoirs
- site visits (conducted virtually owing to COVID-19 restrictions) of two abattoirs
- data collection and analysis
- modelling of load flex scenarios, and
- consultation with the broader industrial refrigeration community.

Notably, the sites that participated in this study were representative of medium and large-scale abattoirs.

2 Flexible demand

2.1 What is flexible demand?

Flexible demand (FD) is the modification of an energy end-user's electrical demand in response to an incentive. FD involves moving electricity consumption to a different time of the day or shutting off equipment entirely. Generally, there are four distinct classifications of FD that are recognised: **shape**, **shift**, **shimmy** and **shed** (Brinsmead *et al.* 2021). A description of each of these is provided in Table 1.

Table 1. The four classifications of flexible demand.

FD classification	Description
Shape	Modifying regular demand to better align with a desired profile. Shape FD may be used to align energy demand with historical times of cheap energy—either through retail TOU tariffs, or wholesale market prices.
Shift	Moving demand irregularly in response to an external signal. Shift FD can be used to help reduce network demand during peak times, or to soak up excess renewable generation
Shimmy	Moving demand over very short timescales in response to an external signal. Shimmy FD can be used to provide rapid demand alterations that in aggregation offer frequency control ancillary support services to the network.
Shed	Curtailing demand by switching off/turning down equipment. Shed FD is used to provide rapid demand reductions which offer contingency support services to the network in peak times.

2.2 How is flexible demand engaged?

There are several mechanisms by which flexible demand can be deployed, each offering distinct benefits to the electrical supply system.

Direct engagement with DNSPs

Often large energy users may engage directly with their distribution network service provider (DNSP) to provide contracted demand response services specific to the needs and limitations of the local network (poles and wires). Typically, this kind of FD involves an agreement between parties for the energy user to provide a nominated amount of load shed (normally 100s to 1000s of kilowatts) at short notice. The end-user would receive a capacity payment based on the contracted flexible load and a discharge payment, received each time the FD is called upon.

Wholesale market pricing

Large energy users can also purchase energy from the wholesale spot market, either directly or through a retailer. The real-time variations of cost on the NEM reflecting the supply and demand balance offers energy-conscious businesses the chance to use FD, particularly load shed, shift and shape, to make considerable savings. However, exposure to pricing volatility comes with risk. At times of extreme demand, spot prices can reach a market price cap, currently $15,100/MWh (which is more than 150 times the annual average cost). It is common for businesses to protect themselves against these extreme prices using measures such as partial wholesale exposure, price hedges (such as swap or cap contracts), long-term renewable power purchase agreements, or via direct use of on-site backup generation during extreme events. Anecdotal evidence suggests that businesses that implement FD practices become progressively more confident in their ability to curtail load during peak times and, as such, are happy to expose themselves more fully to the wholesale market.

Reliability and Emergency Reserve Trader (RERT)

The RERT is a reliability mechanism used by AEMO to manage forecast shortfalls in supply by providing contingency demand response support for the NEM. Under the scheme, AEMO secures contracted generation capacity and load shed from large customers, which is called upon in times of extreme network stress. The RERT program had only been used to procure backup capacity (but never activated) three times prior to the 2017–18 summer. Since then, extreme weather events, coal-fired generator retirements and breakdowns have led to more than 10 RERT activations across the mainland NEM states (Queensland, NSW, SA and Victoria). The cumulative cost of FD contracted within the RERT scheme between 2017 and 2020 was $110 million (AER 2021).

Frequency control ancillary services (FCAS)

Secondary to the energy-only NEM wholesale market, AEMO procures different types of frequency-controlled ancillary services (FCAS) to provide frequency stabilisation for the network. There are eight different markets: two *regulation services* markets used to maintain variations within the normal operating limits (50 ± 0.15 Hz), and six *contingency services* markets to correct major deviations caused by events such as the loss of a generator or failure of a major transmission line. The contingency services markets are separated as *raise* and *lower* and then over three different response speeds: *fast* (6 seconds), *slow* (60 seconds) and *delayed* (5 minutes). Traditionally FCAS costs were low compared to energy costs, but have climbed dramatically in recent years, driven largely by local costs in South Australia. Costs are recuperated using a ‘causer pays’ mechanism.

Wholesale demand response mechanism (WDRM)

The WDRM commenced operation in October 2021 and was established to provide large energy consumers or third-party aggregators a mechanism for selling load reductions into the NEM without the need for being a retailer. There is little available data on the deployment of the WDRM or capacity of registered participants.

2.3 Flexible demand in Australian industry

A recent opportunity assessment (OA) for FD in the Australian energy market (Brinsmead *et al.* 2021) investigated the current levels of FD and what kind of loads have potential for greater engagement. The study found that, aside from controlled residential hot water loads, the main existing application of FD was the RERT scheme, serving as a predominantly load shed contingency FD. Over the past two years there have been 1422 MW of contracted FD delivering 5223 MWh of FD.

A sectoral assessment of Australian industry (based on 32% coverage by total energy consumption) estimated there could be 1511 MW of load shift FD that is currently untapped. This figure describes peak load reduction, while estimates for the possible minimum load increase were too difficult to determine.

The OA also ranked the potential for FD in industrial sectors using a qualitative HUFF framework that prioritised FD sources that were **H**omogeneous, **U**biquitous, **F**easible (techno-economic) and **F**easible (fit well with industry practices and priorities). This analysis determined the most prospective technologies and sectors were those that involve energy storage in some form, including:

- **commercial buildings**—particularly HVAC loads

- **water treatment/agriculture**—especially the pumping and movement of water
- **food and beverage manufacturing**—focusing on refrigeration and cold storage.

Based on international literature, the study indicated refrigeration offered the second largest source of FD services in Europe, offering on average a load reduction potential of 8%. However, the exact applications that constitute this figure are not provided. Generally, unlocking refrigeration load flexing requires utilisation of the thermal inertia of the cooled product or use of thermal energy storage (TES) to buffer the supply and demand. Estimates suggest that with these measures, refrigeration could offer 15–20% peak load reduction based on load shifting, and up to 30% based on load shed (Brinsmead *et al.* 2021).

Additional sources of FD were also identified but were not investigated in detail as they were outside the scope of the study. These included standby generators, electric batteries, electric vehicle battery management, distribution substation voltage tapping, and solar PV curtailment (to address minimum demand and voltage regulation).

2.4 Benefits of flexible demand in abattoirs

The benefits of FD to the provider are generally expressed in terms of energy cost savings. These may be via avoided energy and demand charges or through an incentive payment from a retailer, DNSP, or third-part aggregator. For abattoirs looking to provide FD using their refrigeration plant, there are several additional benefits to the business including:

- **Increased cooling capacity in peak times**—shortages of chilling capacity are sometimes experienced during peak production times coincident with extreme weather. Utilising TES to supply part of the cooling loads frees up existing refrigeration plant capacity for meeting these peak cooling demands.
- **Greater utilisation of existing assets**—load shifting flattens the demand profile and allows plant to be operated more consistently over the 24-hour cycle. Compressor scheduling can be used to reduce the part load operation of compressors or potentially reduce/eliminate the need for some plant.
- **Reduced carbon intensity**—increasing the ability to flex refrigeration loads enhances the ability for abattoirs to align their demand profiles with renewable generators. This may be via a direct renewable power purchase agreement (PPA) or to 'soak up' excess solar or wind power in the NEM.

2.5 Barriers to flexible demand in abattoirs

Despite refrigeration being identified as a potential industrial load that offers flexible demand potential, there are several barriers associated with its implementation, particularly in abattoirs. These include:

- **High utilisation rate**—generally, there is a perception that there is little slack in the operation of refrigeration plant. This is truer of large sites with higher diversity factors (i.e. less diversity in demand).
- **Product specific cooling demands**—abattoirs use refrigeration for the chilling and freezing of meat, a biologically active, porous product with cooling process dependent value (for example, poor cooling rates can lead to significant moisture loss and considerable decline in quality). Chilling of meat, in particular, has very tight temperature profiles that are governed by Australian Standards for food safety as well as product quality.
- **Refrigeration equipment COPs**—while refrigeration plant demand can be very large (100s to 1000s of kilowatts), the electrical inputs to achieve these thermal loads can be three-to-four times less, owing

to the coefficient of performance (COP)[1] of refrigeration equipment. This means that very large loads need to be flexed to achieve strong financial incentives.

- **Competition from alternative investments**—many other business interests, including energy efficiency upgrades, renewables, alternative freezer technology (plate versus blast), and implementation of spray chilling, are seen to offer better returns on investment (ROIs) than load flexing.
- **Lack of reward for participation**—particularly in light of the above point, there has been insufficient flow through of the financial benefits obtained from network operators, distribution service providers and retailers to the businesses offering FD services.
- **Lack of awareness**—many abattoirs remain unaware of the potential revenue streams from FD and the potential for it to facilitate site decarbonisation via aiding the implementation and utilisation of renewables. Despite being very energy-intensive businesses with large energy costs, many abattoirs do not employ energy managers.

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[1] COP describes the ratio of cooling rates to the electrical input power required.

3 Energy and demand pricing

3.1 Retail tariff structures

There are myriad different retail price structures that vary based on retailer, state and size of the business being served. However, in general terms electricity bills are made up of the following components:

- **Energy charges**—are consumption charges related to the quantity of electricity consumed. Typically, commercial and industrial (C&I) customers will have time-of-use (TOU) tariffs that charge different prices for electricity consumed during peak, off-peak and shoulder periods.
- **Network charges**—are charges related to services performed by the distribution network service provider and generally also vary based on TOU (i.e. peak, off-peak and shoulder), which may be different to the times defined by the retailer for energy charges. Network charges also include demand and supply charges.
- **Environmental charges**—are charges associated with state and federal government environmental schemes designed to incentivise the uptake of renewable energy and energy efficiency. Examples include the Large-scale Renewable Energy Target (LRET), Small-scale Renewable Energy Scheme (SRES), NSW Energy Saving Scheme (ESS), and the Victorian Energy Upgrades (VEU) program.
- **Other charges**—are additional charges not included in the above, such as certain market or services charges. Examples include AEMO pool fees, AEMO ancillary charges, metering charges, retail service fees or interest charges.

It is common for large energy consumers to negotiate their energy charges directly with the retailer, with larger consumers securing lower priced electricity to reflect their larger market volume. As a result, the prices paid for electricity differ considerably between different abattoirs both by scale and region.

All retail pricing modelled in this work was based on nominal tariffs and charges that reflect a typical use case.

3.2 Wholesale spot market

Figure 4 shows the annual average spot price per trading interval for electricity in the NEM from 2018 until 2021. The data for 2021 includes January through September (as five-minute settlement periods were introduced on 1 October). The cost profile reflects the supply and demand challenge faced in each NEM region; i.e. higher prices correspond with times of high demand, and vice versa. All regions show a morning and an evening peak period with cost and demand dropping away in between.

Year-to-year variation in the profiles is immediately apparent, particularly in regions such as Victoria, Tasmania, and South Australia. Although the annual average price for electricity decreased for all states during this time, in Victoria and Tasmania the price has more than halved. The other feature that stands out is the dramatic increase in evening peak prices, particularly in Queensland, New South Wales and Victoria. This considerable variation is due to changes in the generation mix in these states and is very difficult to forecast.

The differences between the peaks and troughs in price represent opportunities for businesses that purchase energy from the wholesale market to capitalise using load shifting.

The modelling of wholesale electricity prices in this work considered historical data only and did not attempt to project future price effects on the viability of the FD opportunities identified.

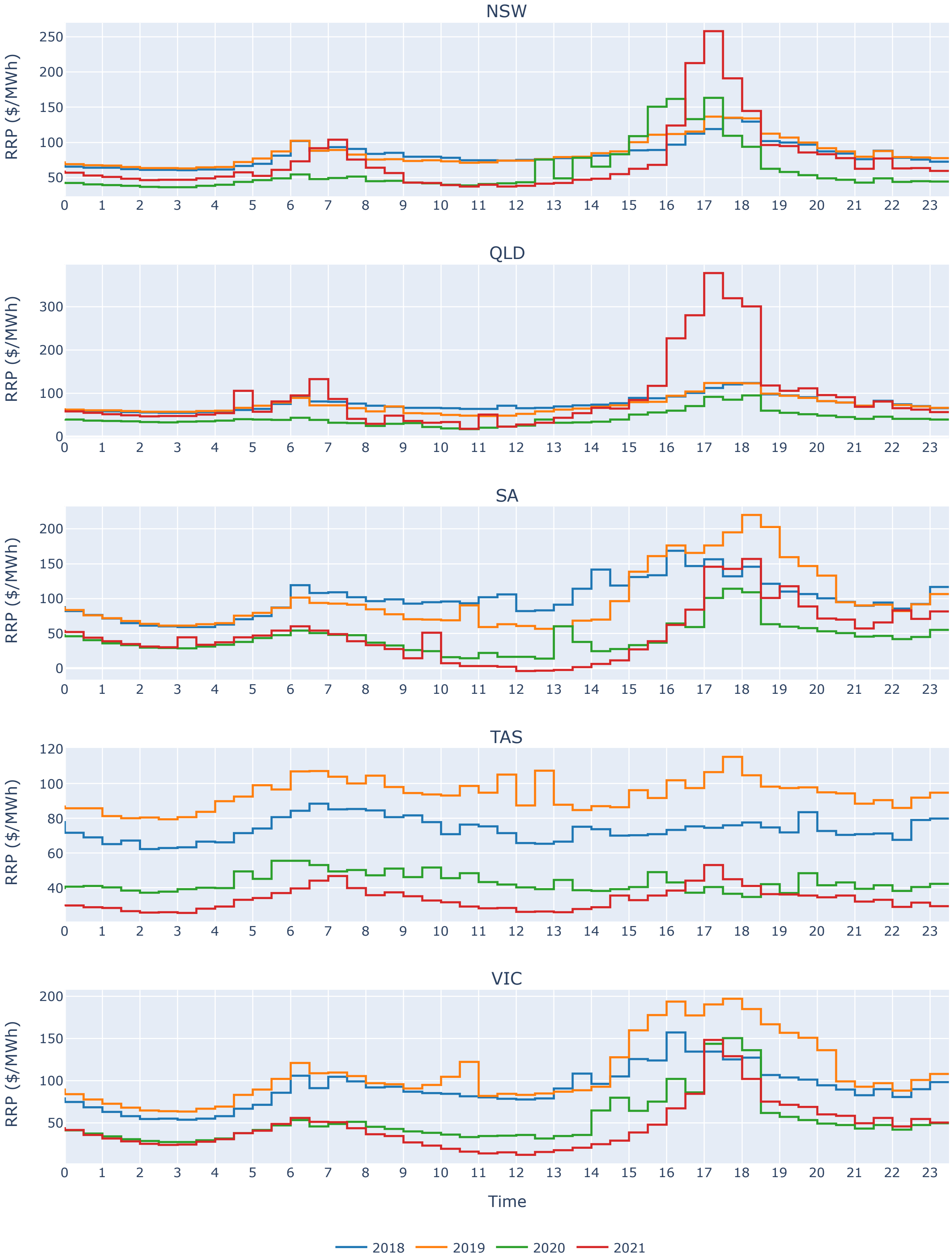

Figure 4. Annual average spot price in the NEM by Australian state and calendar year. 2021 data includes the year until end of September.

3.3 Demand response pricing

Generally, contracted flexible demand arrangements are negotiated and must reflect value to both parties. For a retailer this may be in the form of reduced risk in estimates for energy contracts with generators via higher confidence in avoiding costs during extreme peak events. For DNSPs it reflects the reduced costs of network augmentation to handle peak loads that are experienced for short durations. For the FD service provider (energy user) the contract needs to reflect sufficient value to incentivise participation and potential investment in capital to facilitate this.

For the current study, AGL provided estimates for the typical financial incentives an FD provider could expect. These values are listed in Table 2 for load flex durations from 1 to 4 hours.

Table 2. Flexible demand value to the provider by duration in $/MW.

	NEM region			
Load flex duration	**NSW**	**VIC**	**QLD**	**SA**
(hours)	($/MWh)	($/MWh)	($/MWh)	($/MWh)
4	43,239	31,273	35,128	45,710
3	32,430	23,455	26,346	34,282
2	21,620	15,637	17,564	22,855
1	10,810	7,818	8,782	11,427

For example, an abattoir located in NSW that managed to load shed 1 MW for 1 hour would receive a payment of $10,810. If the abattoir was to shed 1 MW for 4 hours, it would receive $43,239. Alternatively, if the same abattoir was to reduce its demand by 2 MW for 1.5 hours, it would receive $32,430.

These payments are per season and businesses could typically anticipate up to 40 hours per year, although there are more numerous shorter duration events and fewer that would extend to 4 hours.

4 Abattoir refrigeration

Refrigeration is vital to the successful operation and value creation of all abattoirs, and is used for chilling, freezing and space conditioning. While the main reason for the post-mortem refrigeration of carcass meat is preservation, its effect on meat goes well beyond prevention of spoilage, with refrigeration influencing: meat toughness and tenderness, product yield in relation to weight loss, the intensity and stability of meat colour, and the hardness of fat (Husband 1993). The process of chilling meat products is highly regulated to ensure hygiene is maintained. Regulation of the chilling and freezing of meat and meat products (including carcases and offal) is detailed in Australian Standard AS 4696:2007 and the Export Control (Meat and Meat Products) Orders 2005. Since 2005 the performance of refrigeration systems to meet these criteria has been measured using the Refrigeration Index (RI)—a measure of the potential growth of generic *E. coli* at the monitored site (EMIAC 2020).

Unlike other industrial refrigeration loads, abattoirs involve the handling of organic products undergoing a vast number of biological changes in the period immediately after slaughter. Owing to continuing metabolic activity and no blood flow to remove heat, temperatures in the deep tissue of the carcass can reach as high as 40°C. AS 4696 requires the outer surface of carcases, sides, quarters or bone-in major cuts to be reduced to under 7°C (5°C for carcass parts) within 24 hours of the animal being stunned (Browne 2007)—the threshold temperature below which *E. coli* and *Salmonella* stop growing.

Owing to these stringent food safety controls, which are designed to prevent spoilage, the opportunity to interrupt or vary the cooling process is very limited. Unlike cold storage of other agricultural produce, such as vegetables, it is much harder to use the chilled or frozen product as a thermal battery.

4.1 Refrigeration system types

The predominant refrigeration system in Australian abattoirs is two-stage ammonia (NH_3—R717), with a small number of smaller facilities using alternative refrigerants (e.g. CO_2—R744). Screw compressors are more common than reciprocating compressors and are operated in parallel to achieve the desired cooling capacity of the process, with sequencing used to control when a particular compressor is operational. The loading and unloading of a screw compressor unit is either by slide valve, or in the more advanced sites using VFD/VSD drives to ensure maximum energy efficiency at part load operation.

Generally, chillers and freezers are operated as direct expansion (DX) with ammonia refrigerant circulated through the evaporator coils/freezer plates supplying the cooling. Areas with high human occupancy and higher temperature cooling demand, such as the boning rooms, are often supplied with a secondary fluid like glycol to avoid potential exposure to ammonia in the unlikely event of a leakage or system failure. Many facilities are currently converting older DX systems in boning rooms to glycol.

Many abattoirs use spray chillers, which intermittently apply water sprays to the carcass to reduce product weight loss due to evaporation and surface dry out. During a spray cycle, cooling is ceased, carcasses are sprayed with water for a short period (~20–30 seconds), before cooling re-commences. This process is repeated at 45–60-minute intervals over the residence time within the chillers.

The use and type of on-site meat freezers depend on several parameters such as the product type (e.g. prime cut or offal), destination market (e.g. local or export) and facility size. Blast freezers, which use high speed streams of air blown across the product to cool it, are common, particularly at smaller sites. Plate freezers are four-to-five times more efficient than blast freezers and are much more common in larger abattoirs. These systems place the meat or offal in cardboard cartons (or directly in the case of 'naked' plate freezers) between freezer plates, which are then compressed against the product and supplied with low temperature refrigerant.

Table 3 summarises the major refrigeration loads, the typical evaporator setpoints and the desired process temperatures.

Table 3. Typical refrigeration plant and settings.

System type	Refrigerant	Typical evaporator temperature	Process/air temperature
		(°C)	(°C)
Carcass chiller	Ammonia	−8 to −12	−1 to −7
Boning room	Glycol	−8 to −12	8 to 10
Plate freezer	Ammonia	−36 to −40	−20
Blast freezer	Ammonia	−30 to −40	−20

The typical discharge pressure is around 1000–1100 kPa in winter and 1100–1250 kPa in summer. Variation of discharge pressure can enable the plant to save energy, as lower pressure increases the COP of the compressors. However, it is not a practical means of increasing FD, as it depends on maintaining sufficient temperature to reject heat to the ambient.

4.2 Electrical demand profile

The electrical demand profiles of abattoirs reflect the process flows on site. Understanding these is critical for identifying potential opportunities to load flex. Influencing factors include the product stream (kind of animal), throughput, plant type, layout of the plant, climate and other operational specifics (e.g. number of personnel and ancillary thermal loads). Electrical demand is also linked to the number of shifts a site runs—e.g. two shifts back-to-back followed by washdown (typical for large abattoirs), or a single shift with washdown (small/medium sites).

Figure 5 shows the typical electrical demand profile for a large abattoir with a single kill-shift, indicating the daily variation and inter-week process-related fluctuations. Refrigeration is the largest end use of electricity and consumes around 70% of site electricity during days of production (QFF 2017) and almost all electricity on weekends and non-production days (Cain 1985).

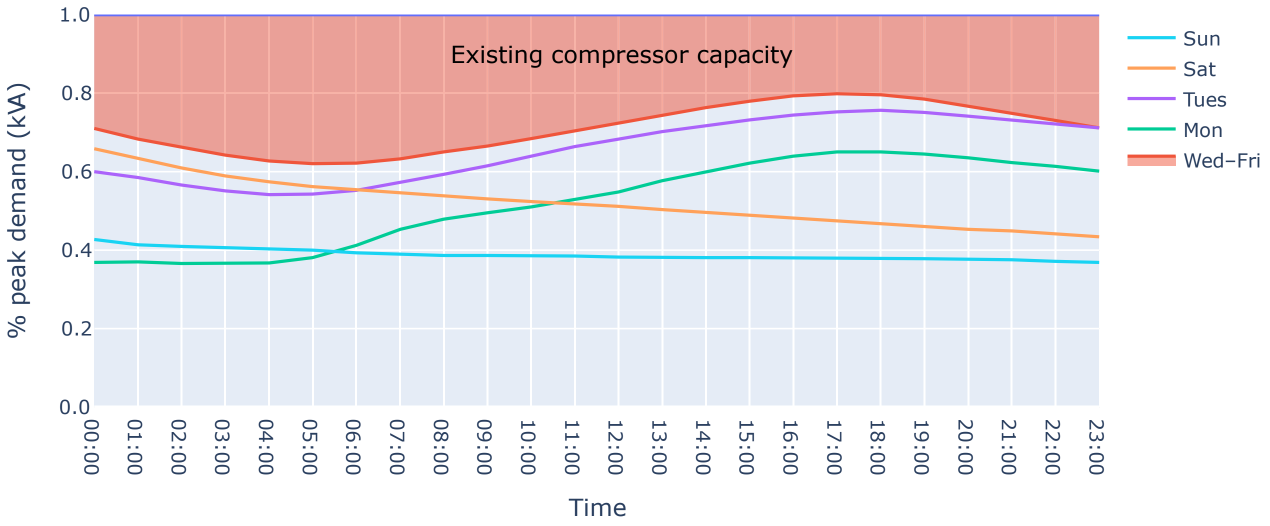

Figure 5. Typical electrical demand profile for large abattoir (single kill shift).

Typically, refrigeration loads will ramp up quickly from baseload levels when slaughtering begins early in the morning. Animals are slaughtered, then eviscerated and rinsed before being taken directly to the chillers. Each chiller will be progressively filled and the carcasses chilled as quickly as possible. Loads rise as chillers are sequentially filled and peak in the early afternoon (2–4 pm). From here the load decreases progressively towards baseload level overnight.

The breakdown of total refrigeration demand by end load is highly site-specific and depends on the amount of on-site freezing and the degree of processing (i.e. boning) etc. Based on figures provided by the refrigeration contactors interviewed for this report, a representative breakdown is shown in Figure 6.

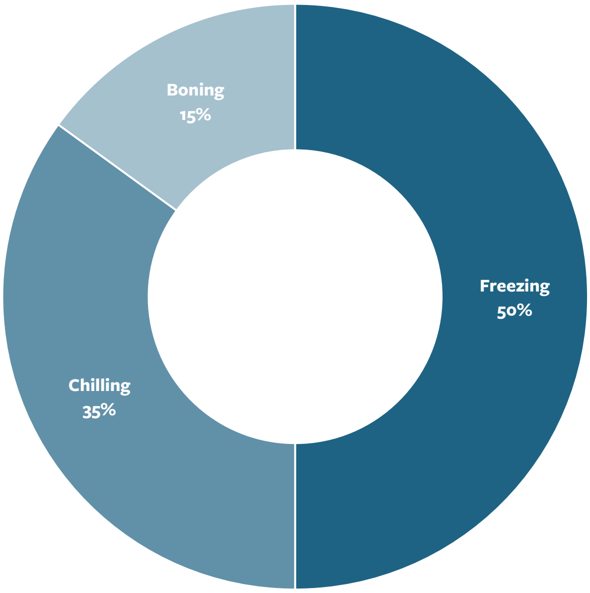

Figure 6. Typical breakdown of refrigeration electrical demand by load.

4.3 Demand for chilling

Generally, immediately following the loading and closure of the chiller, the air temperature will be controlled at −1°C with the evaporator fans running at 100% capacity. This initial process is critical in reducing the moisture levels at the surface of the meat, which suppresses growth of enteric bacteria. Once the monitored surface temperature of the product falls just below the target temperature of 7°C (say 6.9°C), the fan speed is reduced (~70%) and the air temperature is increased to 6.9°C. This is to minimise the moisture loss from the carcass. These conditions will then be maintained until the deep butt temperatures fall below 20°C (cold boning).

Further to meeting these standards to comply with food safety regulations, the cooling profile of the meat is known to have a marked impact on product quality. Properties such as marbling, pH levels, colour and muscle shortening, among others, are all impacted by the cooling process and impact the Meat Standard Australia (MSA) grading given to the product (MLA 2021) and ultimately, the meat value. Adherence to the MSA standards attracts a price premium at point of sale, which for an average carcass is of the order of $0.24/kg (Bonny *et al.* 2018), equating to potentially ~$15,000–20,000 per chiller per cooling cycle.

Key factors in achieving good quality chilling of carcasses include (Macfarlane 1993):

- Commencing cooling as quickly as possible after killing. This is one of the reasons typical chillers hold 1.5–2 hours of production.
- Applying sufficient chilling during loading to prevent condensation on the chiller surface.
- Ensuring sufficient evaporator and engine room capacity to achieve rapid initial chilling, with the aim of achieving return air temperatures of 0–2°C within 1 hour of commencing active chilling.
- Reducing fan speed once surface temperature targets are met. This prevents drying through evaporation until deep butt temperature targets are met.

Owing to these requirements, cooling units and their associated refrigeration plant are designed for peak loads and are often running at low efficiency when the chillers are full of chilled carcasses. Chilling loads are typically four times lower at the end of the chilling cycle compared to the start (Graham 1979). However, the diversity factor[2] used in designing refrigeration plant is considerably higher for large sites (~70%) compared to small and medium sites (~35–40%); i.e. large sites have much more consistent thermal demand profiles. This is due to large sites having many chillers (and freezers) each at different stages of the cooling cycle. The cumulative effect of this is to flatten the demand on the engine room plant.

4.4 Demand for freezing

Carton product is either chilled or frozen. Generally, the eight primal cuts (e.g. chuck, rib, loin, round etc.) are chilled (either vacuum packed or individually wrapped), while offal, lower grade cuts and manufacturing meat are usually frozen (EMIAC 2020).

The freezing process does not have the same stringent control of cooling rates compared to meat chilling. Product that is to be frozen is generally packaged into carboard cartons and frozen in either blast or plate freezers, both of which aim to get the product to the desired frozen temperature as quickly as possible. As such, the demand profile for freezing is a muted version of the chilling profile, with a time-shift to account for the process delay for the boning room to produce the packaged cartons. The influence of this slightly flatter profile on the overall electrical demand profile will depend on the ratio of chilled to frozen product at each site.

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[2] Diversity factor measures the variability in the demand profile from full-load capacity.

5 Potential load flexing opportunities

5.1 Thermal storage

Implementation of thermal storage represents the greatest opportunity to enhance refrigeration load flexibility. However, thermal energy storage does not reduce total energy consumption but only shifts consumption to another time of the day. This is due to thermal losses, ancillary loads from pumps etc., and the reduction in compressor COP that are required when charging the load.

Both *sensible* (storing energy by increasing or decreasing the temperature of the storage media) and *latent* (storing energy in the phase change of the storage media) storage solutions are possible for industrial refrigeration systems. Generally, there are more opportunities for implementing thermal storage on the high-side loads (chilling) and fewer for low-side loads (freezing). The merits of these and most likely solutions for abattoirs are discussed below.

5.1.1 Sensible energy storage (glycol)

Boning rooms—processing areas in which edible cuts are separated from the carcass of the animal by workers—represent large refrigeration loads that are at relatively high temperatures (8–10°C). In modern facilities, these areas are cooled by circulating glycol as a secondary refrigerant at around −5 to −3°C through evaporator coils within the space. Older facilities sometimes use direct expansion of ammonia at −10 to −12°C to provide this load; however, these are being progressively upgraded to glycol owing to food safety and OH&S concerns.

It is possible to implement thermal storage for these high-side loads using chilled glycol storage. In this case the storage would be charged (chilled) using ammonia refrigerant during times of low-cost energy or low network demand and then discharged (provide cooling to the load) during times of high-cost energy or peak demand periods.

However, there are several major drawbacks from sensible energy storage, particularly using aqueous glycol solutions. These include, but are not limited to, the following:

1. **Minimum practical storage temperature**—as the storage needs to be charged using the intermediate ammonia suction, which is ~−10°C, the lowest temperature possible in the storage is ~−5°C. Despite having a freezing point of −15°C (@33% concentration by volume propylene glycol) it is not possible to precool the storage closer to this value, which would maximise the energy per unit volume of storage, without reducing the suction pressure of the compressor and decreasing the COP.
2. **Diminishing cooling rate with time**—when operated in a closed-loop, the cooling rate possible from storage decreases as the storage is discharged. This is because the evaporator temperature increases with time as the heat from the load is transferred to the storage vessel. This effect can be minimised by careful storage vessel design using stratification and baffling.
3. **Stringent temperature controls**—boning room conditions are closely monitored as prolonged exposure of the meat to temperatures above 8°C begins to affect product quality. Passing glycol above the design supply temperature of −5°C through evaporators will impede the ability for the system to meet the desired air temperature in the space.
4. **Large volumes required**—to reduce the effect of the above factors on the refrigeration capacity, very large volumes of storage are required. However, glycol is relatively expensive, which means this solution becomes unviable for large quantities of energy storage.

5. **High cost**—UPS (food) grade propylene glycol with corrosion inhibitor is around $5.80/L. Approximately 180,000 L of storage is required (33% by volume, 5°C ΔT) per MWh of thermal energy storage, costing $450,000 (assuming 33% by volume PG, 5°C ΔT, insulated storage cost = $400/kL).

Consensus amongst refrigeration contractors interviewed for this work was that using glycol or any sensible thermal storage was a less than ideal solution if the sole driver was FD for cost reduction. For the reasons outlined, sensible thermal energy storage was not modelled as a solution in this work.

5.1.2 Latent thermal storage (phase change energy storage)

Eutectic fluids, ice or other media that offer a constant temperature of phase change provide a constant temperature to drive the cooling process. The much higher energy density associated with the enthalpy of phase-change also reduces the requirement for large storage volumes.

The application of each fluid would be limited by the alignment of the phase change temperature with the need for cooling. For example, typically ammonia is supplied to freezers at –40°C, precluding the use of most phase change materials to meet 100% of this demand (though phase change energy storage may still meet a portion of this load). Evaporators in chillers are typically supplied liquid ammonia at –10°C. There may be some opportunity to use thermal storage to reduce chiller loads.

This work modelled the commercially available Thermcold system (Glaciem 2021), by Glaciem Cooling Technologies. The product houses phase change material (PCM) in rectangular tanks, through which polypropylene piping circulates the working fluid to charge or discharge the unit. Features of the system are included in Table 4.

Table 4. Thermcold PCM storage characteristics (@ –11°C delivery temperature).

Parameter	Value	Unit
Thermal storage capacity	658–2124	kWh
Total storage volume	17.8–41.3	m^3
Maximum operating pressure	1000	kPa

Ice storage is an alternative lower cost PCM. However, it requires the application of a secondary refrigerant for temperatures greater than 0°C. Ice storage has the obvious benefits of an effectively free PCM. However, considering there needs to be a temperature difference to drive the heat transfer from the storage to the secondary working fluid, the practical temperature that can be used for cooling is 2–3°C. As a result, ice storage is more suitable for applications at higher temperatures, such as space conditioning.

Ice storage has been deployed widely for space cooling of buildings. Reports of applications in building HVAC systems from the USA suggest installed costs are around 200 US$/kWh (275 A$/kWh) (Deru *et al.* 2018). Estimates of the volume of a system suitable of delivering large quantities of energy storage that would be needed for FD applications in abattoir refrigeration are difficult. Based on the enthalpy of phase-change for water, 1 MWh requires ~10,800 L of water. However, extrapolation of the system characteristics from the reference above suggests just over 66,000 L of volume, including the heat exchanger and storage vessels. It is highly likely that customised systems for large energy quantities would require less than this.

5.2 Refrigeration controls

5.2.1 Suction pressure variation

The operating temperatures of evaporators are linked to suction pressures and varying this pressure is a simple means of improving the COP of the compressor, thereby reducing electrical demand. In a two-stage ammonia system, suction conditions are maintained at −36 to −40°C for the low-side compressors and −12 to −8°C for the high side. Typically, these suction conditions are set to deliver optimal freezing and chilling conditions while achieving the highest COP for the systems as possible. Unnecessary 'safety margins' in suction pressure come at the expense of increased energy consumption. As such, suction pressure should be maintained as high as possible while still meeting the cooling requirements. Efficiency gains from increasing suction pressure are very application specific, but improvements in the range of 2% for each 1°C increase in suction temperature are possible (SV 2009).

Several refrigeration contractors interviewed for this study noted that low-side refrigeration plant is designed with the capacity to reduce suction conditions to as low as −50°C. This allows the freezer plant to run harder in certain circumstance, such as following a power outage.

Our modelling investigated increasing the suction pressure on the low-side compressors during times of peak demand/high price to provide some flexible demand.

5.2.2 Blast freezer fan speed reduction

Blast freezers pass high velocity air at −30 to −40°C past the naked or packaged product to maximise the rates of cooling (since heat transfer rates are proportional to air velocity). To achieve uniform freezing of the product, it is crucial to allow the air to circulate around the product and access all surfaces (Stoecker 1998). Owing to the requirement for high flow rates of air, the electric motors on blast freezers can be up to 20 kW in capacity per freezer and contribute as much as 25% of the thermal load in the space.

We explored reducing fan speed using VSDs during times of peak demand as a simple measure to increase FD. Like varying low-side suction pressure, this measure should have no impact on product quality but may result in lengthening of the time required to freeze the product. Any implications from this would need to be assessed against the economic returns from the FD provision.

5.3 High temperature heat pumps

While less likely to provide flexible demand from an existing system, high temperature heat pumps (HTHPs) were broadly regarded as a good opportunity to make use of waste heat streams, reducing thermal fuel use and increasing electricity use. Currently, commercially available heat pumps are limited to hot water (~85°C) and are ideally placed to provide sterilisation and wash down water. Most sites with rendering need significant quantities of steam (desired temperature of 160°C in the cooker). However, some sites are currently installing confidential R&D-stage HTHPs producing 120°C pressurised water. The goal would be for a HTHPs to replace boilers entirely. However, HTHPs capable of economically producing the large volumes of steam required are not yet commercially viable.

It was noted that the best way to integrate an HTHP was to preferentially produce hot water as needed by upgrading waste heat from refrigeration plant (when refrigeration reject heat was available). Further, abattoirs typically have large volumes of water storage and thus can have a relatively constant flow of potable water through the generation system. This presents significant opportunities for energy management (and potentially demand response) but will require a re-evaluation of controls and standard practices.

Two key options for heat pumps were assessed:

- **Ammonia**—A high pressure ammonia compressor coupled with the existing refrigeration system provides a good option for provision of heat. This upgrades heat from the existing high-stage refrigeration system (at ~30°C) to a more usable temperature for hot water, typically 80°C+, depending on flow rates and requirements. This would operate with a COP of around 4. The COP is highest with a low incoming water temperature, but the system can operate well even with a 75–80°C incoming temperature. This means it is ideal for a recirculating hot water loop for potable water makeup.
- **CO_2**—A stand-alone transcritical CO_2 system can provide hot water at up to 90°C. The COP is maximised when chilled water/glycol is also provided, but the system can also be air-cooled. The incoming water temperature is more limited with this system (typically <60°C) so is better suited to a potable water makeup supply, most likely at a site without rendering (where significant heat recovery already exists).

Large scale units using either ammonia or CO_2 are similarly priced (~\$750/kW$_{th}$) and the COPs are also similar in general, although CO_2 units have higher COPs when coupled with a refrigeration demand while ammonia units have higher COPs with higher incoming water temperature (whereas for CO_2 units, COP drops off).

In order to provide load flexibility, a heat pump would need to be coupled with the existing hot water generation system and the existing boiler would be retained. We anticipate that when the hot water generation cost from the heat pump (effectively the cost of electricity divided by the COP) is less than that from the existing system (effectively the cost of gas or coal divided by the boiler COP), the heat pump would operate. When the cost is higher, the existing generation system would be used. Likewise, at times when load shedding is required, the heat pump could be turned off and the existing system used.

5.4 Non-refrigeration related opportunities

While the focus of this study is abattoir refrigeration systems, there are several other non-refrigeration options for FD. Modelling of these alternatives was conducted to provide a point of comparison with refrigeration-only based FD solutions.

Engine generators

Engine generators are often used in industry to supply power for remote applications (e.g. mining) or as standby generators providing power supply redundancy or a means to minimise maximum demand for grid-tied businesses. Several types of engine generator are common, including diesel (reciprocating) and natural or propane gas (reciprocating or turbine), each with different performance characteristics and price points that lend themselves to certain applications.

There is also potential for abattoirs to use biogas produced on-site to provide FD via an engine generator or co-generation unit. Abattoirs produce large streams of biowaste that has the potential to produce biogas. Some sites are already producing biogas and using it to produce heat to supplement natural gas demand for either hot water or steam production. However, bellows over biogas ponds allow for biogas to be stored at 1 atm pressure. There is potential to investigate using buffered gas storage to power a generator during peak electrical demand times to provide load shed FD. This solution is likely to work best when paired with a high-temperature heat pump for hot water production, hence lowering the demand for biogas and allowing buffer gas for used in this way.

A detailed investigation of the techno-economics of generators was beyond the scope of this study, but should be considered by sites reviewing load shedding.

5.4.1 Electric batteries

Grid-scale batteries were not commercially viable in Australia until recently. Reductions in the costs of battery technologies and expanding market opportunities (e.g. FCAS) have seen their deployment increase significantly (AER 2021). Electric batteries are being deployed at very large scale within the NEM to provide firming generation and ancillary services. Currently 261 MW of grid-scale batteries have been installed, with more than 85 big batteries with a total capacity of 23,418 MW in the planning pipeline (2021).

In addition to these large grid-scale batteries, more businesses and homes will be installing batteries to manage their own demand as the price of batteries continues to fall and renewable feed-in tariffs decline. Various battery chemistries are available, but the predominant technology for large batteries is lithium-ion (Li-ion), offering the highest energy density and efficiency compared to alternatives (such as flow or zinc-hybrid).

The modelling in this work is based on Li-ion technology, with prices depending on storage duration based on data published by the Australian Energy Council (Kitchen 2021). Currently the business case for batteries as private installations used solely for renewable energy storage or market price arbitrage remains a case-by-case proposition. However, value stacking by use of the battery for secondary services such as standby power, power quality management, avoidance of remote restart, or provision of FCAS services provides additional revenue.

An example of such as arrangement is the 2 MWh battery recently installed by the Victorian abattoir, Hardwicks. The project was supported by the Victorian Government and involved a commercial arrangement with the network service provider, Powercor, whereby the battery concurrently contributes to both the site's energy needs and grid stabilisation services.

6 Abattoir load flex modelling

Numerical modelling has been used in this study to enable a detailed investigation of load flex scenarios identified in Section 5. The results from the model complemented the analysis that was undertaken for several abattoirs using real energy interval data, production schedules and historical throughputs, and refrigeration plant data.

Modelling allowed the research team to explore the influence of several parameters on the feasibility of load flexing, including:

- energy tariffs (e.g. retail TOU versus wholesale)
- regional differences within the wholesale electricity market (e.g. price and frequency of extreme price events)
- energy storage capacity (discharge rates and energy capacity)
- site-specific refrigerant equipment, and
- demand management strategies.

This section provides a review of these elements and presents results of the load-flex optimisation. A more complete description of the model, including the mathematical algorithms and optimisation methodology, can be found in Appendix A.

6.1 Modelling approach

This study used an object-oriented time-series model called *PowerFlex* that has been developed by the Institute for Sustainable Futures for modelling on-site demand flexibility. This powerful and flexible model is composed of modules to simulate site equipment, smart controllers, demand schedulers, forecasters and optimisation engines.

What is PowerFlex and how does it work?

A generalised PowerFlex site model is shown in Figure 7. In essence, PowerFlex is an energy-based model that adds or deducts energy consumption from a given time-period by evaluating the interaction of the system components such as loads (e.g. fans, compressors etc.), generators (e.g. diesel engine) or energy storage devices (e.g. thermal or electrical batteries). The modules for these components or 'equipment' enable a simple way to model the impact of complex demand behaviour, such as COP variation from compressor plant, or thermal discharge variation as a function of energy storage state-of-charge, on the total electrical demand. Each item of 'equipment' is given a range of characteristics that describe its status, electrical demand characteristics, and its ability to respond to a call for more or less demand.

Within PowerFlex, the ability for an individual piece of equipment to increase or decrease demand are referred to as flexibility dispatch, and the addition and deduction of demand from the overall demand curve are referred to as charge or discharge, respectively.

In this study, modelling was completed at a 30-minute time resolution, matching the electricity demand data and wholesale market dispatch period;[3] however PowerFlex is capable of modelling at much smaller time

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[3] Historical NEM data was used from before October 2021, prior to the introduction of five-minute settlement.

periods. Higher frequency short duration effects, such as thermal and power system effects, are only handled by considering how these factors impact electrical demand on aggregate during the time-period.

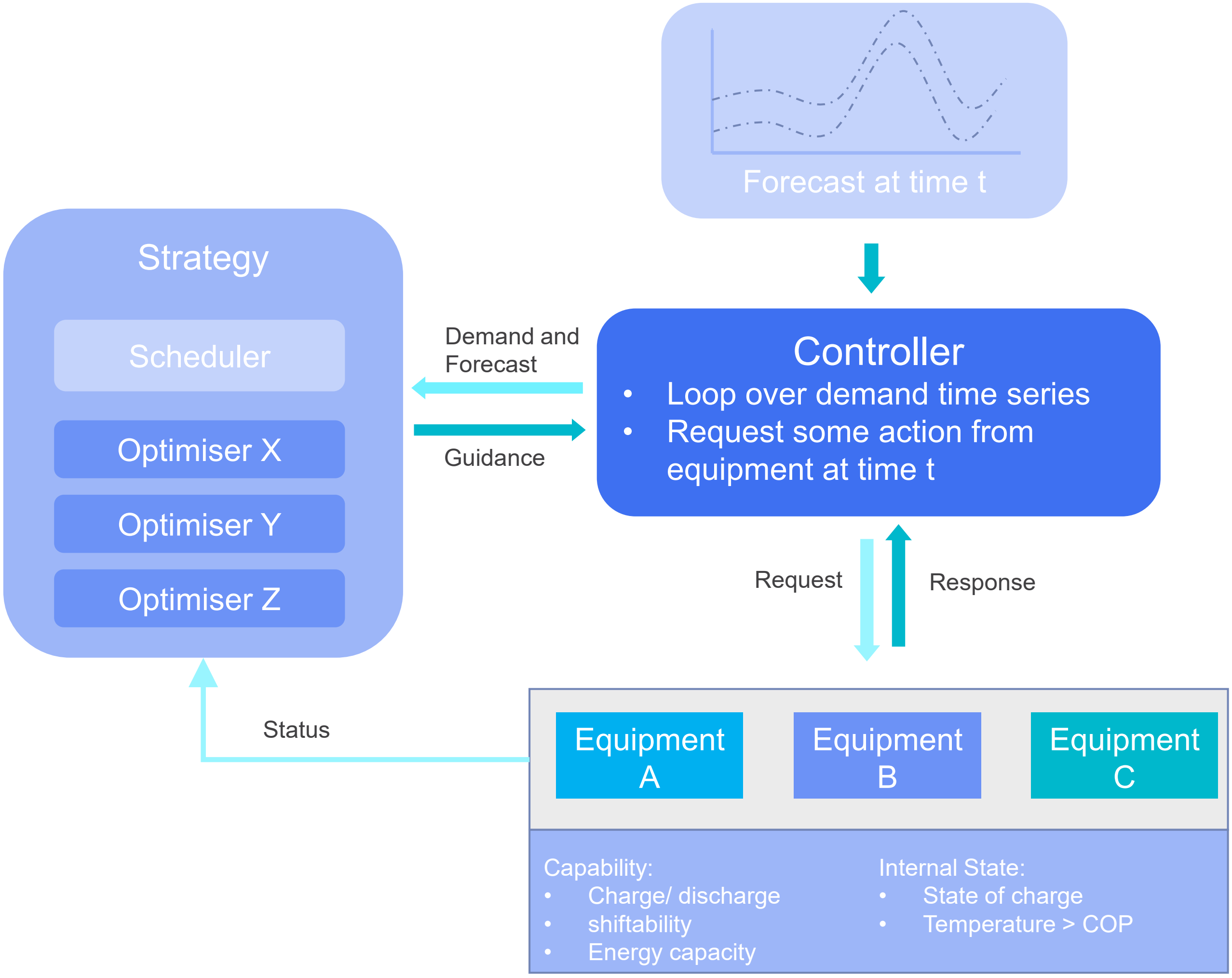

Figure 7. PowerFlex model overview.

A centralised control unit within the model iterates through the time-series and uses forecasts of demand and electricity price to optimise the scheduling and dispatch of equipment, subject to constraints such as meeting the necessary demand for refrigeration, plant and storage limitations and pricing thresholds. The output from the model is a load-flexed net demand curve that is that has been optimised to reduce the energy costs for the site, as shown in Figure 8.

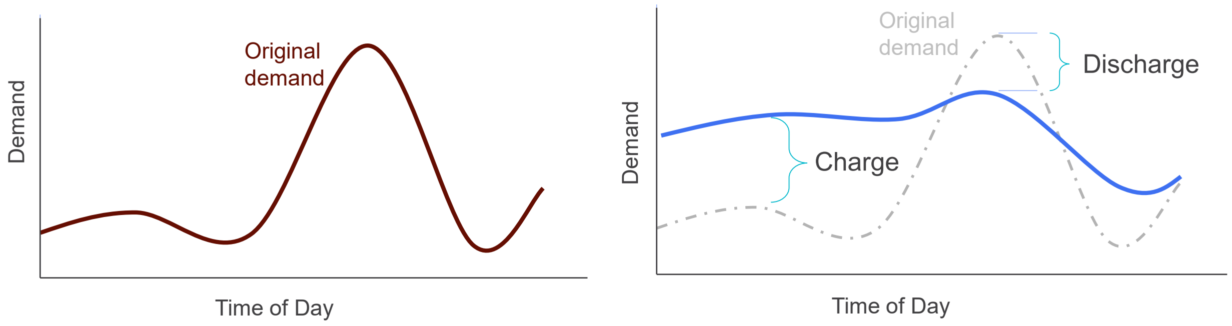

Figure 8. Summing dispatch and demand to form a new net demand curve.

6.2 Optimising load flexing

The principal of reducing energy costs from load flexing involves shifting loads from periods of high electricity prices and distributing these loads to times of low prices. While simple in principle, maximising the financial return from such load-flexing is very challenging and requires estimates for future demand, forecast of energy and demand pricing, and detailed control of equipment and processes.

The following two optimisation strategies were developed in this study. A detailed description of each can be found in Appendix A.6.

- **Time-of-use shifting (with or without contracted demand response)**—used for retail contract optimisation. This approach seeks to maximise the amount of energy consumed during off-peak pricing periods and minimise energy consumption during peak periods, without changing the total energy consumption. Figure 9 shows an example of this strategy deployed for an abattoir with an electrical battery used to load shift and the resultant demand curve with level shaved peaks.

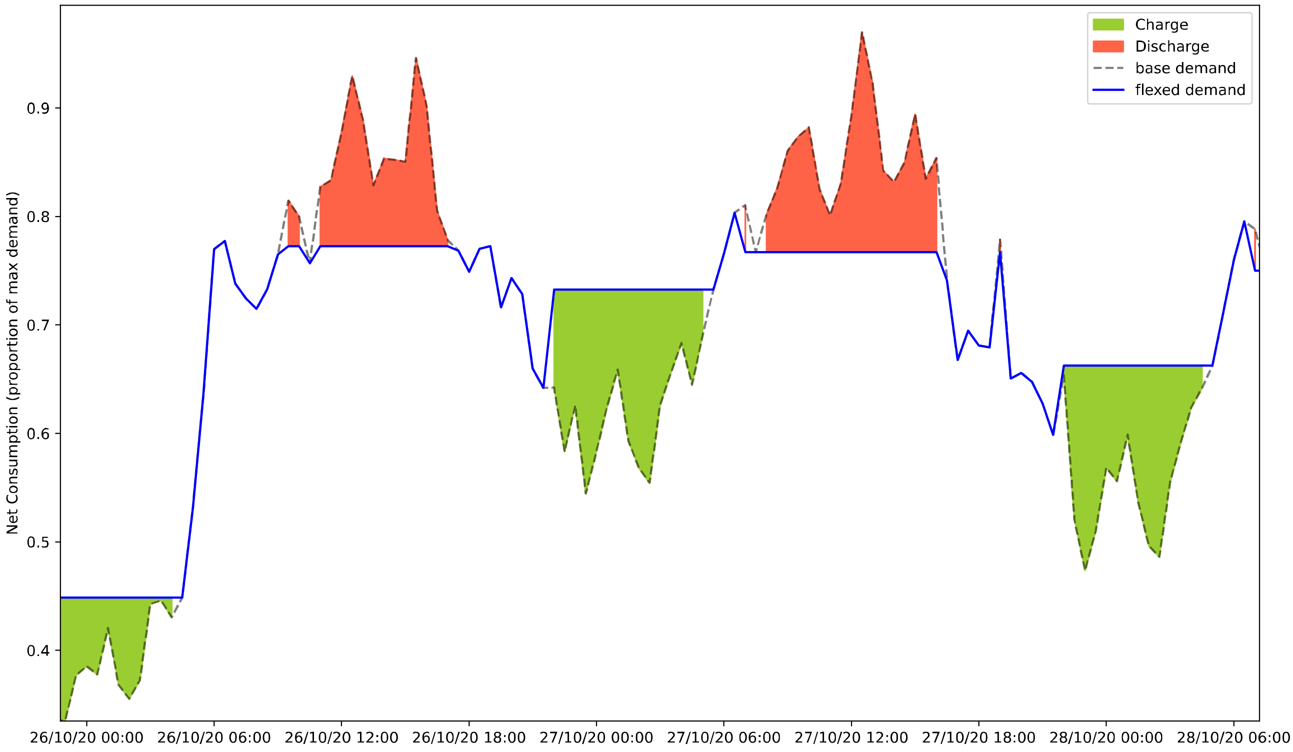

Figure 9. Time-of-use shifting example of charging during off peak (10 pm–7 am) and discharging during peak times (7 am–10 am).

- **Tranched capacity with future price pairing**—used for wholesale pricing optimisation. This method seeks to maximise the amount of energy consumed during periods of low spot prices and minimise energy consumption during periods of high spot prices, without changing total energy consumption. The procedure to determine periods of charge and discharge is much harder than for retail pricing as it requires some degree of foresight on energy prices in the wholesale market. The process involves ranking the forecast energy prices per time interval over a future period (typically 1 day) and then allocating available charge and discharge *tranches* sequentially to these price periods in pairs to prioritise the greatest profitability. Figure 10 demonstrates the designation of charge and discharge tranches and Figure 11 shows an example of a battery enacting the strategy.

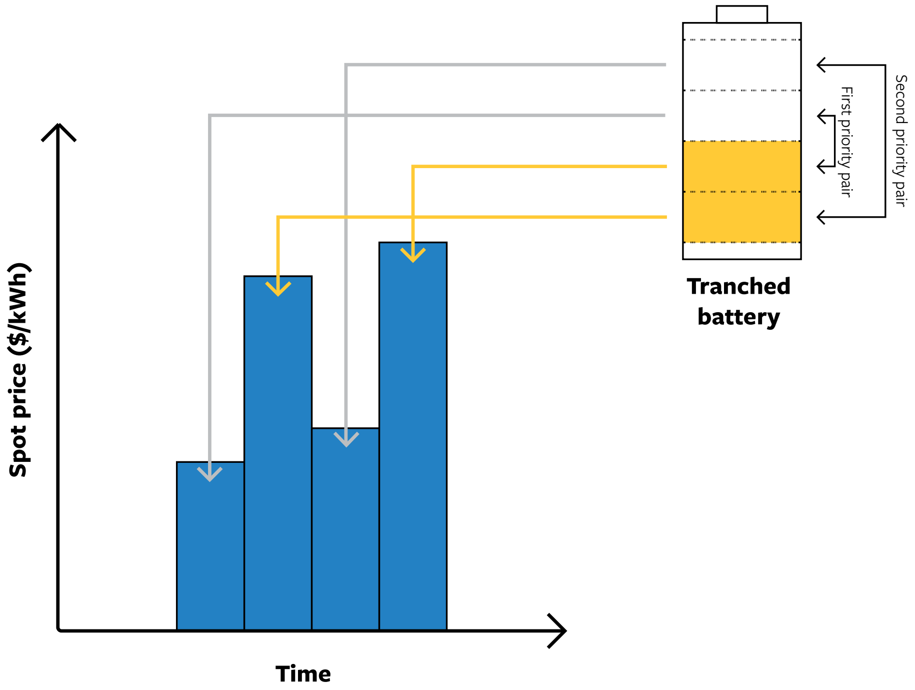

Figure 10. Tranched battery charge discharge allocation.

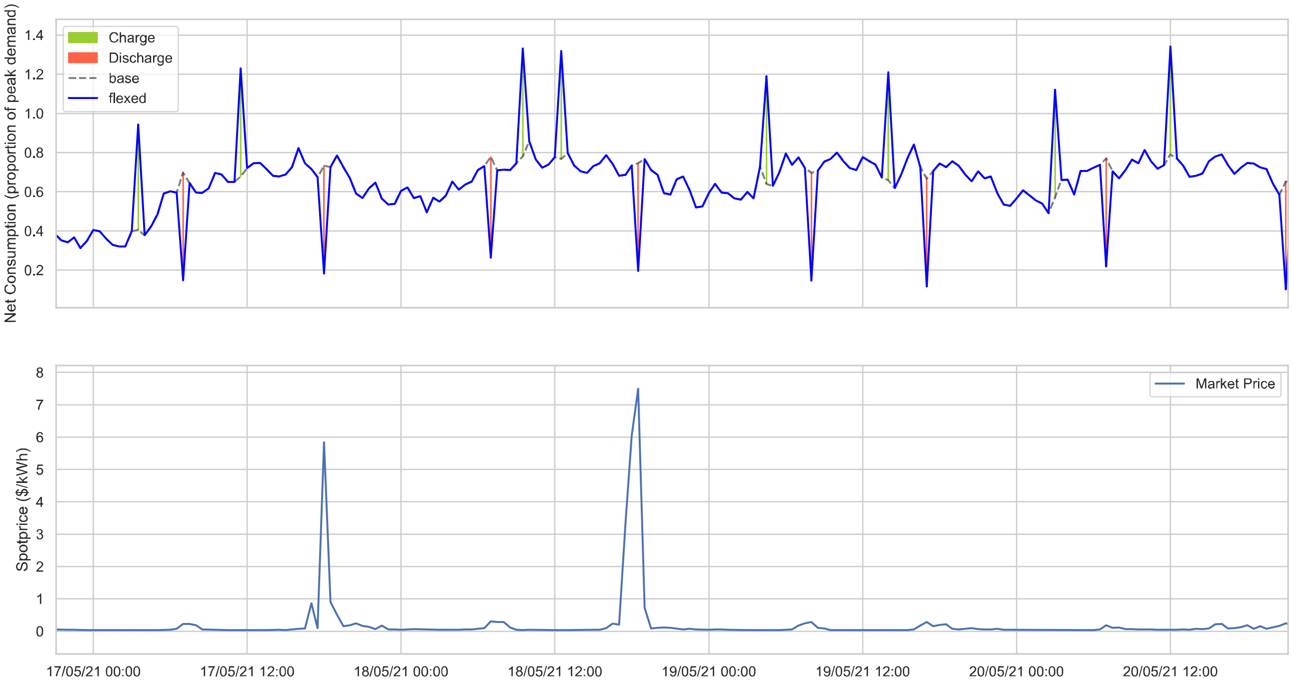

Figure 11. Example of tranched capacity with price pairing strategy enacted with a battery. (Top: energy consumption as a proportion of peak demand, and bottom: spot price $/kWh).

6.3 Modelling scenarios and inputs

Inputs to the PowerFlex model include:

- energy tariffs (retail and wholesale)
- site electricity demand data (12 months duration @ 30-minute intervals)
- equipment specifications, and
- weather (e.g. solar irradiance for solar generation modelling).

Modelling was conducted for different sized abattoir loads in each of the five NEM states.

6.3.1 Load-flex technologies, strategies and costs

The technologies and scenarios modelled in this project are shown in Table 5 along with basic input parameters, optimisation strategies and levelised costs.

Table 5. Technology and inputs scenarios.

Flex technology/ control option	Model details/parameters	Cost estimate
Chemical battery	Generic chemical battery capability: Cost and savings are normalised per kWh of energy capacity Sizing is site appropriate, i.e. discharge rate is assumed to be unconstrained by minimum site demand 1–4 hours storage	\$800/kWh (1 h storage) \$600/kWh (2 h storage) \$550/kWh (3 h storage) \$500/kWh (4 h storage)
PCM thermal storage	Specific products considered: Model: Glaciem DYN 420 /DYN 900 Design flow rate: • 7 L/s (DYN 420) • 14 L/s (DYN 900) Design capacity (95% depletion): • 980 kWh (DYN 420) • 2060 kWh (DYN 900)	\$260–280/kWh$_{th}$
Low-side suction pressure variation to increase and decrease COP according to price times	Low side suction setpoints: • Baseline= –38°C, COP = 2.57 • Reduced = –34°C, COP = 2.72 • Increased = –40°C, COP = 2.49	Practically \$0/kW of compressor capacity
Blast fan speed reduction	Speed reductions considered: • 50% • 75%	Practically \$0/kW of compressor capacity
High temperature heat pump	Replacement of gas boiler for hot water heating where boiler is kept for backup	\$750/kWh$_{th}$

6.3.2 Retail and network tariffs

Retail electricity tariffs vary significantly by region and from customer-to-customer reflecting the generation profile within the regional network and the purchasing power and demand profile of the business. To simplify the modelling, the indicative retail and network tariffs shown in Table 6 were applied in the modelling, as provided by AGL. The time-of-use tariff is a retail charge and was used for time-of-use shifting, but not for the tranched capacity with future price pairing model. All other charges applied by the distribution network and so are applied in all models.

Table 6. Typical time-of-use electricity prices by region. Data provided by AGL.

Tariff type	NSW	VIC	QLD	SA	Avg
			($/MWh)		
Time-of-use—peak	85.9	74.48	72.8	74.1	77
Time-of-use—off-peak	43.1	31.9	39.2	38.3	38

Electricity network tariffs are composed of several different charges, which include a variety demand charges, block charges, capacity charges and connection fees. Gas retail and distribution tariffs include single rate consumption charges, block charges and connection fees. These tariff structures are included in the modelling and are explained in detail in Table 18 (Appendix A).

6.3.3 Market prices

Wholesale market data for the 2020/21 year was downloaded from the AEMO website and used to simulate real-time demand and prices. In October 2021 the market moved from 30-minute to five-minute settlement periods. All modelling in this study considered prices averaged at 30-minute intervals or greater as this is more reflective of achievable forecast horizons and little data is available for the impact of five-minute settlement on price and demand volatility. As an example of pricing volatility, Figure 12 shows the distribution of averaged hourly wholesale prices for NSW. The horizontal line within each green bar represents the median price for that hourly period over the year. Reviewing the evening time periods, such as 5–6 pm, we can see that despite the median price being only about twice the price during the middle of the day, the large interquartile range (green bar—where 50% of price values are contained) and long whiskers (vertical lines—show the maximum and minimum price) indicate that high prices are common.

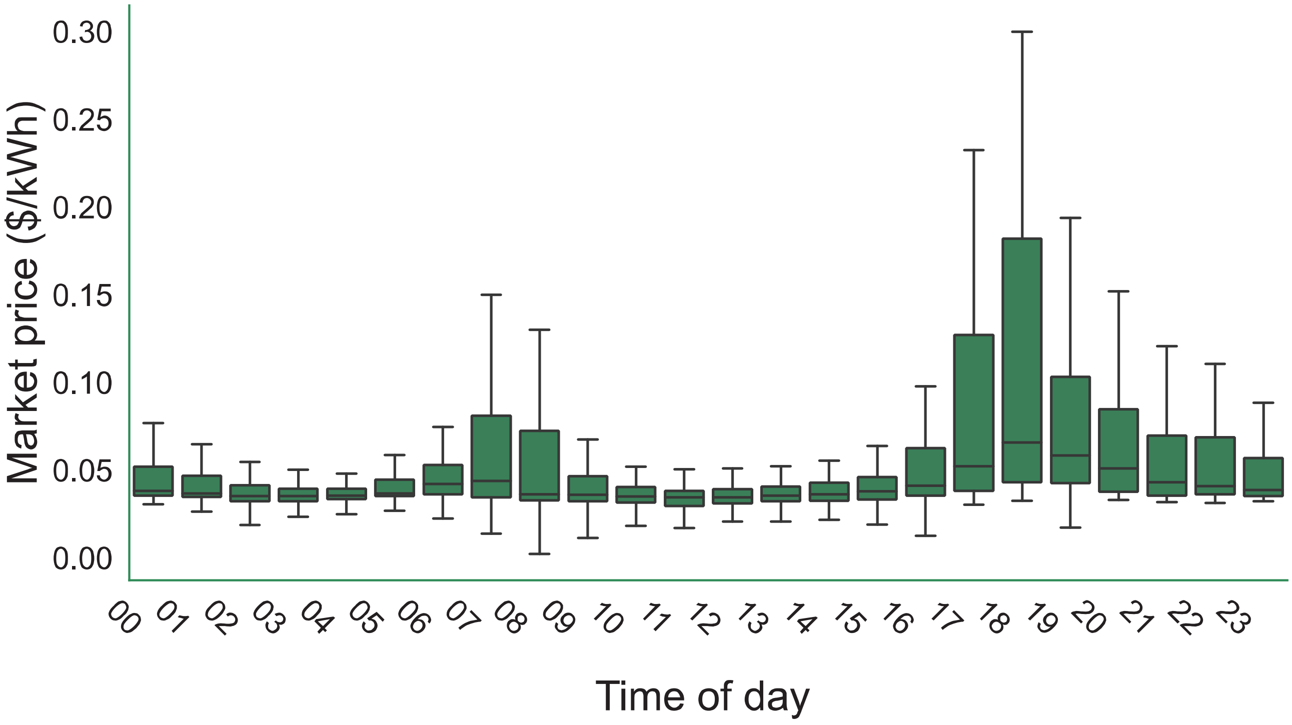

Figure 12. Averaged hourly electricity market price distribution for the year 2020/21.

6.4 Results

6.4.1 Suction pressure settings

Reduction in compressor demand due to variation in suction pressure was modelled by varying the compressor COP. Empirical data was used to determine three discrete settings where COP is known for given suction pressures: baseline pressure, low pressure and high pressure (see Table 5). The model also assumes there is variation in the cooling rate during the time periods with adjusted suction pressure, and 'repays' this lost cooling at a later period (typically within 7–8 hours) when energy costs are low by lowering the suction pressure.

Table 6 presents the energy cost savings for abattoirs exposed to wholesale market pricing, normalised by kilowatt of compressor capacity per hour of deployment. Given the variation of suction pressure is a simple control modification requiring little or no capital expenditure, the payback is effectively immediate. Similar savings were also found for abattoirs on TOU retail contracts, as presented in Table 8 where bill savings are expressed per kW of compressor capacity and per hour of suction pressure reduction.

Table 7. Annual bill savings from suction pressure variation when exposed to the wholesale market. Price optimization is based on tranched capacity and future price pairing load-shifting. Savings and payback periods are normalised by kW of compressor capacity.

	Bill savings				
Parameter/price component	**NSW**	**QLD**	**VIC**	**SA**	**TAS**
	(\$/kW$_e$ compressor load)				
Spot price	5.19	7.97	2.16	3.65	1.50
Network charges	−0.70	−0.72	−0.71	−0.73	−0.71
Total	**4.49**	**7.26**	**1.45**	**2.93**	**0.79**
Payback period (years)	Immediate				

Table 8. Annual bill savings from suction pressure variation when on a typical retail TOU electricity contract. Time-of-use shifting—annual savings and payback periods.

Parameter/price component	**Bill savings**
	(\$/kW$_e$ compressor load/hour of pressure adjustment)
Retail time-of-use	1.23
Network charges	−0.35
Total	**0.88**
Payback period (years)	Immediate

Although suction pressure variation was shown to return cost savings for both wholesale and retail supply contracts, the size of the load reduction and savings are small. For example, where high suction pressure improves COP values from 2.57 to 2.72, the change in compressor load is 5.5%. It also comes with added disruption to the cooling performance, which needs to be carefully monitored. As such, it is not a particularly strong opportunity for load flexing and is unlikely to be deployed, unless included as part of a more comprehensive load shedding strategy or aggregated demand response arrangement that enables revenue creation from load shedding.

6.4.2 Blast fan optimisation

Blast fan speed was modelled for two levels of speed reduction: 75 and 50% of full speed. Power consumption savings were estimated using fan affinity laws, which state that power reduces proportionally to the cube of the ratio of speed reduction. For 75 and 50% of full speed, this resulted in a reduction in fan power to 42.2 and 12.5%, respectively. Where the fan makes up 20% of the compressor electrical load, this yielded compressor load savings of 8.4 and 2.5%, respectively. Modelling considered savings with daily speed reduction durations of between 30 minutes and 6 hours. At 6 hours, savings per hour begin to plateau.

Table 8 and Table 9 show annualised savings from the shortest and longest durations for wholesale market-exposed abattoirs at 75 and 50% of full speed. Figure 14 and Figure 15 show savings as a function of duration in 30-minute increments. Results are normalised per unit of compressor load reduction. Somewhat expectedly, the savings are greatest for the NEM states that experience the greatest variation between peak and average price (e.g. Queensland and NSW) and less for states with more consistent pricing (e.g. Tasmania).

Table 9. Annual bill savings from 75% blast fan speed when exposed to the wholesale market. Price optimisation is based on future price pairing load-shifting. Savings are normalised by kW of compressor capacity.

Parameter/price component	Bill savings (75% fan speed)									
	NSW		QLD		VIC		SA		TAS	
	($/kWe compressor load/hour of pressure adjustment)									
Deployment duration (h)	0.5	6	0.5	6	0.5	6	0.5	6	0.5	6
Spot price	11.08	31.47	15.34	43.53	4.73	18.03	6.22	21.08	3.59	10.64
Network charges	−0.11	−0.62	0.00	−0.50	0.00	−0.57	0.00	−0.60	0.00	−0.43
Total	**10.97**	**30.85**	**15.34**	**43.03**	**4.73**	**17.46**	**6.22**	**20.48**	**3.59**	**10.22**
Payback period (years)	Immediate									

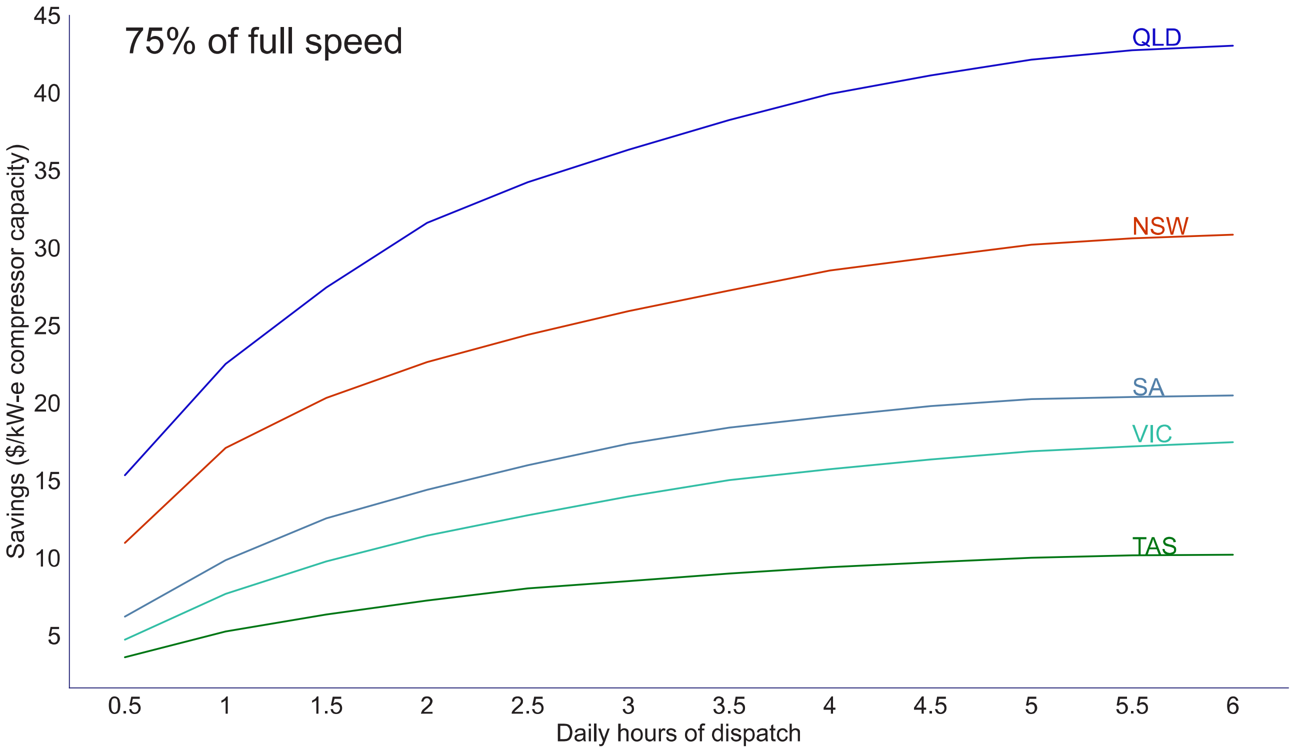

Figure 13. Savings as a function of number of hours of blast fan speed according to wholesale prices—75% of full speed.

Table 10. Annual bill savings from 50% blast fan speed when exposed to the wholesale market. Price optimisation is based on future price pairing load-shifting. Savings are normalised by kW of compressor capacity.

Parameter/price component	Bill savings (50% fan speed)									
	NSW		QLD		VIC		SA		TAS	
	($/kW compressor peak load)									
Deployment duration (h)	0.5	6	0.5	6	0.5	6	0.5	6	0.5	6
Spot price	16.77	47.64	23.22	65.88	7.16	27.29	9.42	31.91	5.43	16.11
Network charges	−0.33	−1.74	−0.28	−1.56	−0.12	−1.62	−0.14	−1.69	0.00	−1.49
Total	**16.43**	**45.90**	**22.94**	**64.32**	**7.05**	**25.67**	**9.27**	**30.22**	**5.43**	**14.62**
Payback period (years)	Immediate									

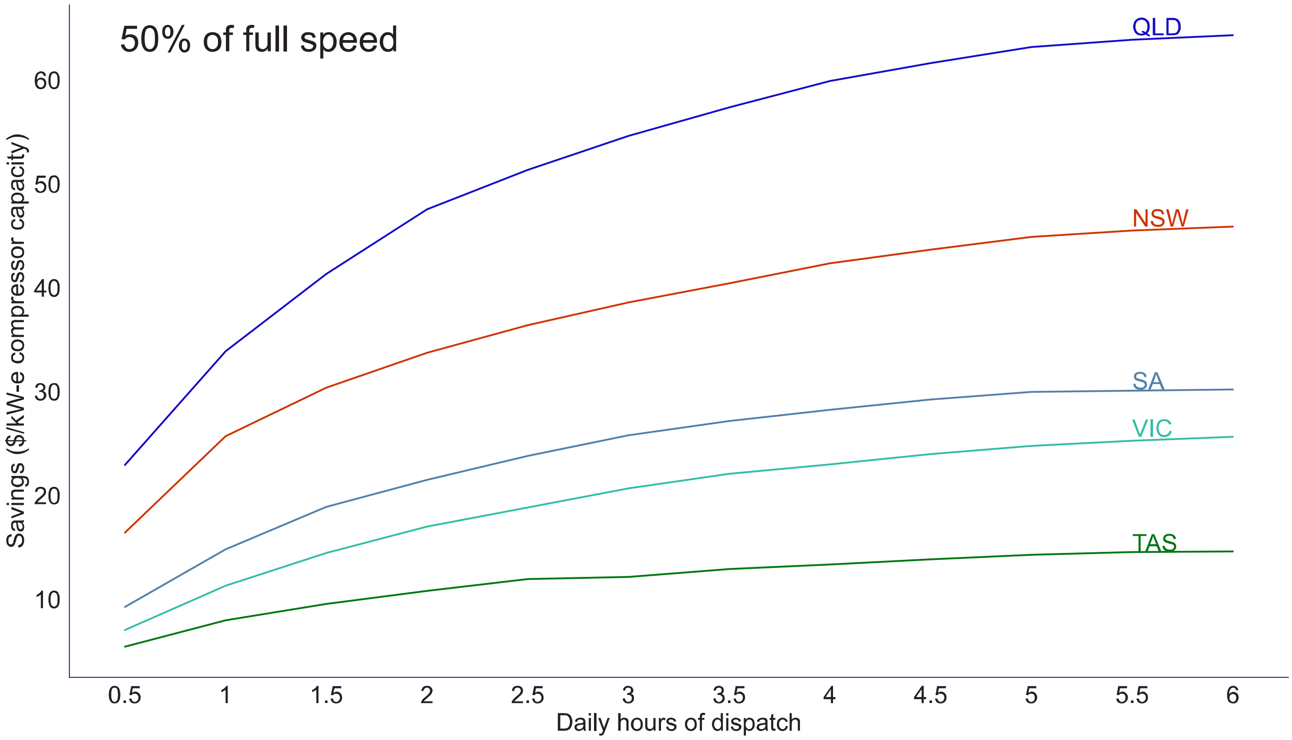

Figure 14. Savings as a function of number of hours of blast fan speed according to wholesale prices—50% of full speed.

Table 10 presents the savings for retail TOU electricity contracts. Savings are expressed per kilowatt of fan motor reduction, per hour of deployment. Unlike the wholesale market scenario, savings per hour of deployment for retail time-of-use contracts increase linearly. While the savings here are less than are possible for wholesale markets, they can be increased simply by enacting the fan speed reduction for more time periods (i.e. they are less dependent on forecast prices to determine opportunity).

Table 11. Annual bill savings from blast fan speed reduction when on a typical retail electricity contract. Price optimisation is based on time-of-use shifting. Savings and payback periods are normalised by kW of compressor capacity per hour of deployment.

Parameter/price component	Bill savings	
	75% fan speed	50% fan speed
	($/kW compressor peak load/hour of throttling)	
Retail time-of-use	2.90	4.39
Network charges	3.15	3.14
Total	**6.05**	**7.53**
Payback period (years)	Immediate	

With savings of between 2 and 9% of the compressor load alone, it is unlikely blast fan optimisation would be used for load-flexing in isolation, but rather as part of a suite of measures.

6.4.3 Energy storage

The two tables below present the annual bill savings for thermal energy storage and battery storage systems respectively, based on retail TOU electricity tariffs. Thermal energy storage results are presented for two different rated capacities and are based on the Glaciem Thermcold system (see Table 5). Thermal storage systems are unsuitable for time-of-use shifting, with payback periods beyond 50 years (most likely exceeding the lifespan of the system). Batteries demonstrated payback periods ranging from 20 years for 1 hour storage to 10 years for 4 hours storage. However, these values include revenue from contracted demand response, assuming up to 10 events per year. Removing DR payments, the battery becomes unsuitable for time-of-use shifting with payback periods exceeding 30 years.

Table 12. Thermal storage time-of-use shifting. Annual savings and payback periods, normalised by kWh of battery storage capacity.

Parameter/price component	Annual bill savings	
	980 kWh capacity	2,060 kWh capacity
	($/kWh$_{th}$ thermal storage)	
Retail time-of-use	0.28	0.35
Network charges	1.91	0.93
Total	**2.19**	**1.28**
Payback period (years)	**123**	**211**
Contracted DR payment[1]	2.94	2.02
Total with DR	**5.13**	**3.30**
Payback period (years)	**53**	**82**

1 assumes 10 demand response event per year using nominal $10k/MW/hr pricing.

Investment in such a technology would need to be approached with caution given energy market needs and DR payments beyond the near term are very difficult to predict.

Table 13. Battery time-of-use shifting. Annual savings and payback periods, normalised by kWh of battery storage capacity.

Parameter/price component	Annual bill savings 1 h storage	 2 h storage	 3 h storage	 4 h storage
	($/kWh$_e$ storage)			
Cost	800	600	550	500
Retail time-of-use	10.5	11.08	11.45	12.37
Network charges	4.45	2.08	0.98	-0.08
Total	**14.95**	**13.16**	**12.43**	**12.29**
Annual battery cycles	265	280	291	315
Payback period without DR (years)	53	38	40	41
Contracted DR payment[1]	9.71	19.42	29.13	38.84
Total with DR	**24.66**	**32.57**	**41.56**	**51.13**
Payback period with DR (years)	**32**	**18**	**13**	**10**

1. Assumes 10 demand response events per year using average DR prices over the four states presented in Table 2.

Table 14 and Table 15 present the results for the thermal storage and battery systems respectively when exposed to wholesale market pricing. Thermal storage is again unable to deliver sufficient savings to justify deployment for load flexing alone, with minimum paybacks of 16 years for the 980 kWh unit and 17 years for the 2,060 kWh unit in the most favourable region (Queensland). The major limitation of the thermal storage system is the dependency of discharge rates on the state of charge of the storage. The average discharge rate (equivalent to electrical displacement) was 28.8 and 41.6 kW$_e$ for the 960 and 2060 kWh battery, respectively. This limitation is explored further in Section 6.5.

Battery storage systems can be seen to offer much greater value and return payback periods of 5–6 years in the most favourable region (Queensland). This performance depends greatly on the region and becomes considerably longer for states such as Victoria and Tasmania.

Table 14. Thermal storage tranched capacity and future price pairing shifting. Annual savings and payback periods, normalised by kWh of storage capacity.

Parameter/price component	Annual bill savings NSW	 QLD	 VIC	 SA	 TAS
			($/kWh$_{th}$ storage)		
			980 kWh$_{th}$ capacity		
Spot price	11.17	14.16	7.10	9.51	3.64
Network charges	2.20	2.36	1.98	1.72	1.57
Total	**13.36**	**16.52**	**9.09**	**11.23**	**5.20**
Payback period (years)	20	16	30	24	52
			2,060 kWh$_{th}$ capacity		
Spot price	10.68	13.30	6.90	9.25	3.43
Network charges	2.12	2.29	1.92	1.67	1.47
Total	**12.80**	**15.60**	**8.82**	**10.93**	**4.91**
Payback period (years)	21	17	31	25	55

Table 15. Battery: Tranched capacity and future price pairing shifting—annual savings and payback periods, normalised by kWh of battery storage capacity

	Annual bill savings				
Parameter/price component	**NSW**	**QLD**	**VIC**	**SA**	**TAS**
	($/kWh$_e$ storage)				
	1 h storage				
Spot price	105.71	158.62	52.29	87.71	34.05
Network charges	-22.56	-22.84	-22.43	-22.33	-22.45
Total	**83.15**	**135.78**	**29.86**	**65.37**	**11.60**
Annual battery cycles	280	276	291	286	294
Payback period (years)	**10**	**6**	**27**	**12**	**69**
	2 h storage				
Spot price	86.23	120.93	45.05	72.51	26.28
Network charges	-11.91	-11.77	-11.99	-12.18	-11.43
Total	**74.32**	**109.16**	**33.06**	**60.33**	**14.85**
Annual battery cycles	299	291	302	302	303
Payback period (years)	8	5	18	10	40
	3 h storage				
Spot price	69.29	99.63	38.86	60.33	21.57
Network charges	-8.19	-8.18	-8.10	-8.30	-7.78
Total	**61.10**	**91.45**	**30.76**	**52.03**	**13.79**
Annual battery cycles	302	300	307	307	305
Payback period (years)	9	6	18	11	40
	4 h storage				
Spot price	58.13	85.79	33.96	50.97	18.55
Network charges	-6.28	-6.27	-6.37	-6.36	-5.93
Total	51.85	79.52	27.59	44.61	12.62
Annual battery cycles	308	304	309	310	306
Payback period (years)	10	6	18	11	40

6.4.4 High temperature heat pump

As discussed in Section 5.3, the modelling considered high temperature heat pump (HTHP) as a replacement for gas boilers. Where the model was optimised against wholesale electricity prices, the heat pump was dispatched at times of day when it was more cost effective than using gas. Where the model considered retail prices, the heat pump was always more cost effective and therefore deployed to replace gas use entirely. There is an implicit assumption that the boiler is kept as a backup regardless of the optimisation strategy used.

Gas consumption was calculated as the thermal load divided by the efficiency of the gas boiler. Gas costs included retail cost per megajoule as well as distribution charges. Electricity consumption was calculated as thermal load divided by heat pump COP and electricity costing included network charges in addition to either retail or wholesale prices.

Table 15 and Table 16 summarise the results for the wholesale and retail scenarios, both demonstrating that heat pumps are generally cheaper to run than gas boilers. Wholesale electricity prices during afternoon market peaks do occasionally make gas boilers more economical, but the overall benefits in wholesale and retail-exposed scenarios were roughly equal. The tables below assume a heat pump cost of 750 $/kW$_{th}$. While the payback periods below are between 13 and 17 years, they depend greatly on the ratio of gas price to electricity price, and the type of network charges (both electricity and gas). Further, capital costs vary significantly (typically 500–1000+ $/kW$_{th}$) depending on site requirements. As such, we would strongly recommend a review on a case-by-case basis as we expect many sites would have paybacks significantly better than those below.

Table 16. Annual savings and payback periods from use of high temperature heat pump to offset gas—wholesale electricity.

Parameter/price component	Annual bill savings				
	NSW	QLD	VIC	SA	TAS
	($/kWh$_{th}$ heat pump thermal capacity)				
Gas retail	45.61	45.97	45.67	45.38	46.02
Gas distribution	44.11	50.34	45.74	43.76	50.59
Electricity market	−21.43	−15.28	−20.62	−15.30	−19.24
Electricity network	−24.69	−24.81	−24.71	−24.62	−24.82
Total	**43.60**	**56.22**	**46.08**	**49.23**	**52.55**
Payback period (years)	17	13	16	15	14

Table 17. Annual savings and payback periods from use of high temperature heat pump to offset gas—retail electricity.

Parameter/price component	Annual bill savings
	($/kW$_{th}$ heat pump thermal capacity)
Gas retail	46.35
Gas distribution	60.71
Retail time-of-use	−37.72
Electricity network	−24.93
Total	**44.41**
Payback period (years)	17

6.4.5 Summary

Table 18 below summarises the above results, outlining the savings per kWh of flexible demand, along with the simple payback in years.

Table 18. Savings per kWh of flexible demand, along with simple payback in years, for three pricing regimes.

	Retail tariff		Retail with DR		Wholesale[1]	
	Savings	Payback	Savings	Payback	Savings	Payback
	$/kW(h)	years	$/kW(h)	years	$/kW(h)	years
Suction pressure modification[2]	0.88	Immediate	N/A	N/A	7.26	Immediate

Blast fan optimisation (1 h @ 75%)[2]	6.05	Immediate	N/A	N/A	27.79	Immediate
Thermal battery (980 kWh)[3]	2.19	123	5.13	53	16.52	16
Electric battery (1 h)[3]	14.95	53	24.66	32	135.78	6
Hot water heat pump[4]	44.41	17	N/A	N/A	56.22	13

[1] Annual savings presented in the table are based on Queensland, the most favourable NEM region during the 2020/21 year.
[2] Annual savings are per kW of compressor capacity.
[3] Annual savings are per kWh of storage capacity.
[4] Annual savings are per kW_{th} of heat pump capacity.

6.5 Discussion

The future price pairing optimisation modelling described in Section 6.2 identified that market prices offer many opportunities for deriving value from load flexing. In this strategy, future price pairs are chosen from a forecast and ranked based on their spread. That is, the highest forecast price is paired with the lowest forecast price, the second highest price is paired with the second lowest price, and so on. In this way dispatch can be allocated and scheduled to maximise charging at the lowest prices and discharging at the highest prices. Importantly, pair ranking removes the time dimension of prices and there can be any degree of overlap between price pair occurrences. Higher ranked pairs must be prioritised by the dispatch scheduler such that capacity is reserved for the greatest spread value. The more pairs on which the scheduler attempts to capitalise, the harder scheduling becomes without causing opportunity costs for higher ranked pairs. Figure 16 is a box plot showing the distribution of spread across the daily pair rank for one year, given a 24-hour forecast window with a half-hour resolution.

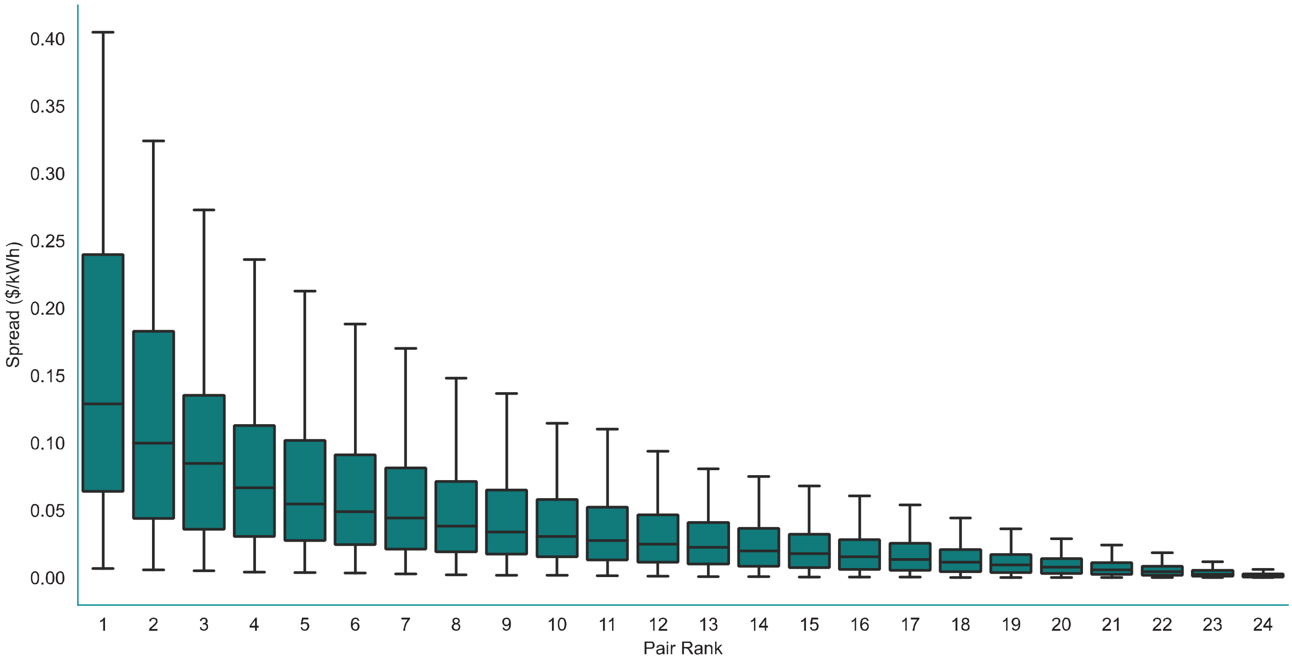

Figure 15. Distribution of wholesale price spread in ascending order (24 × half hour pairs). Data here is based on NSW.

While Figure 17 shows the quartiles of distribution of price spread, it is interesting to note that extreme outliers are increasingly common. This means that the spread is highly skewed and mean values are far higher than median values. Figure 17 shows the same data as Figure 16 with the outliers included.

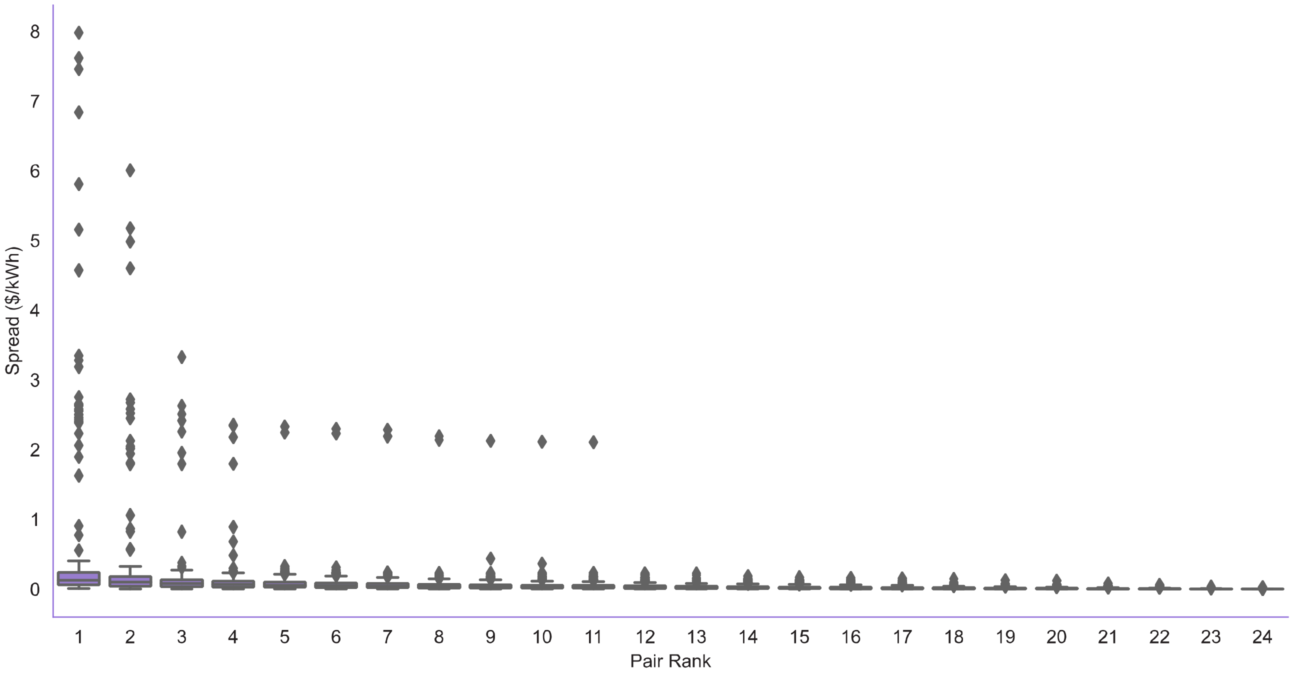

Figure 16. Distribution of wholesale price spread in ascending order (from Figure 16) including outliers.

The most important finding from the future pairing strategy modelling is that the average spread of market prices is far greater than the spread of time-of-use retail tariffs, for any set of price pairs. Figure 18 shows this comparison.

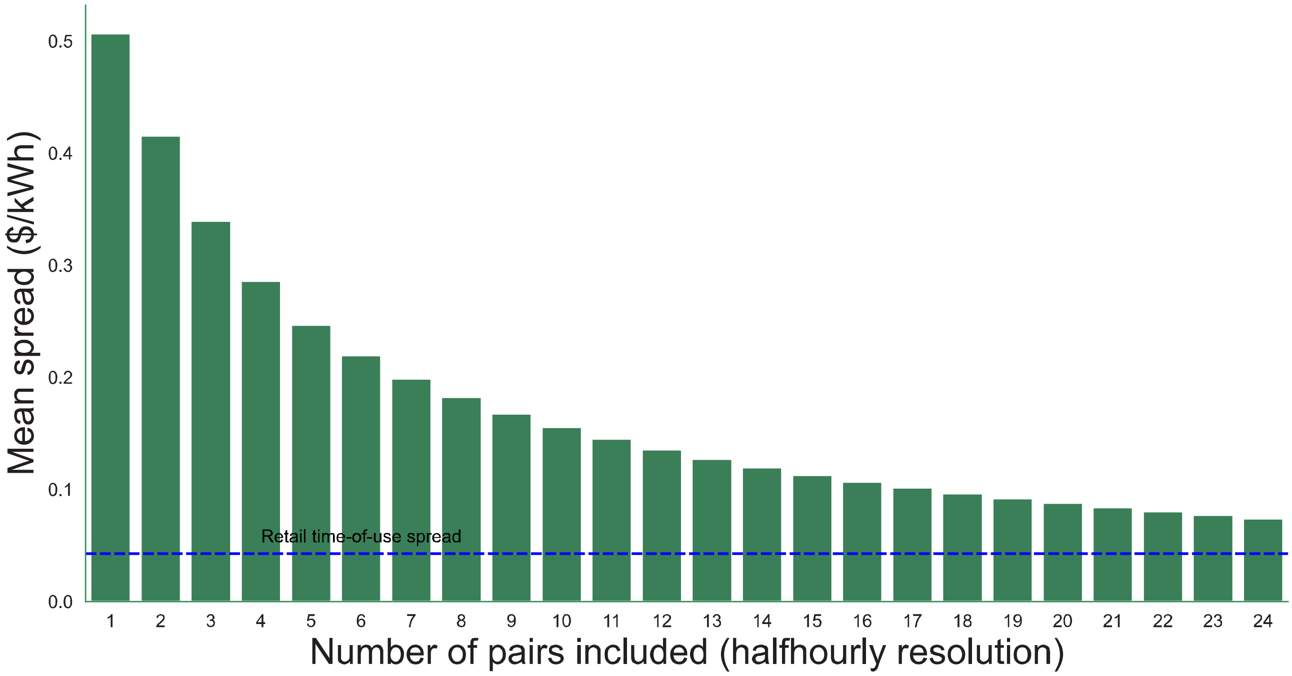

Figure 17. A comparison of the mean spread in market prices versus retail time-of-use spread.

While this comparison does imply that there is more value to be gained by exposing load flexing sites to market prices, there are operational caveats around how to access that value. This can be summarised at a high level by noting that rate of charge and discharge are the greatest determiners of how much market value may be accessed by load flexing technology. Time-of-use retail prices do not require that technology, as high charge and discharge rates derive value, and total daily shiftable energy capacity is the biggest determinant of the total available value. The ratio of dispatch rates to total energy capacity of a technology is a key determiner of its viability where cost is driven by capacity.

6.5.1 Suction pressure modelling

Modelling indicated that aligning suction pressure settings with market prices can deliver savings. With baseline, high and low COPs of 2.57, 2.72, and 2.49, respectively, the modelling derived a normalised annual savings of $4.49/kW of compressor load. In different site settings the daily value that is derivable from this strategy would depend on the consistency of compressor loads. Given this option is practically free, the payback period is immediate.

6.5.2 Storage modelling

Time-of-use tariffs do not incentivise load flexibility via storage

Neither battery nor thermal storage were capable of deriving value from time-of-use retail tariffs. This is due to:

- the high system price per kilowatt-hour of storage
- the low spread of time-of-use prices, and
- the limitation of a single time-of-use cycle per day (i.e. one daily peak and one daily off-peak period).

The rate of discharge and the ratio between dispatch rates and storage capacity are inconsequential in this case owing to there being ample time to charge and discharge storage devices completely during off-peak and peak times.

We can develop a simple heuristic for understanding the price per kilowatt-hour threshold at which a storage device becomes viable based only on the time-of-use price spread, and by assuming specific payback periods. Consider a unit storage device (i.e. capacity = 1 kWh) and the following deductions:

1. a single time-of-use cycle per day limits energy shifting to one storage cycle per day (i.e. 1 kWh / day)
2. assuming 1 kWh of shifted energy per day limits the total annual potential of shifted energy to 365 kWh/year
3. For a viable installation, the ratio of viable unit cost ($/kWh) to price spread ($/kWh) is:

$$\frac{\text{viable unit cost (\$/kWh)}}{\text{price spread (\$/kWh)}} = 365 \text{ (kWh/year)} \times \text{desired payback (years)}$$

Therefore, for a three-year payback and with a spread of $0.04/kWh, the cost of storage needs to be $44/kWh or lower. In our scenarios, batteries were costed at $500/kWh. Figure 19 shows viable unit cost as a function of desired payback period where price spread is $0.04.

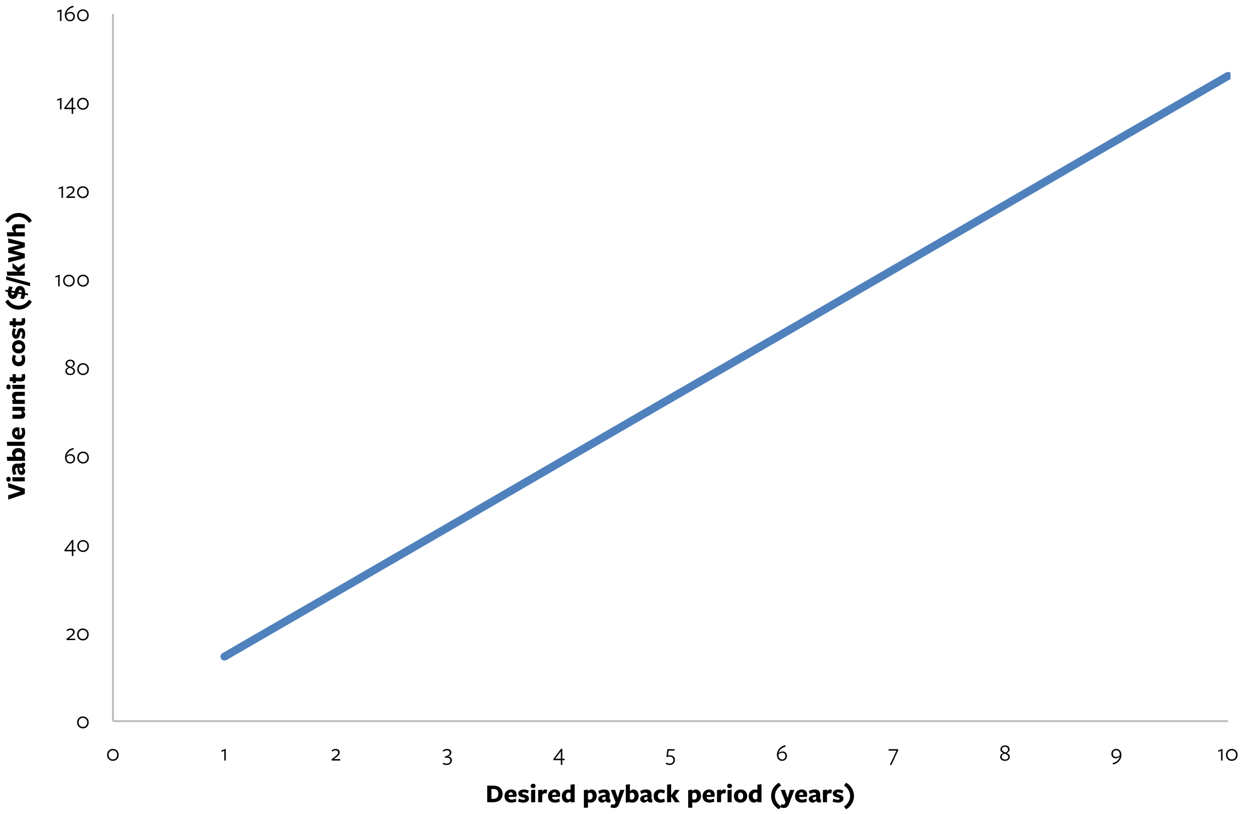

Figure 18. Viable unit storage cost (in $/kWh of storage) when tariff spread is $0.04.

Modelling of both battery and thermal storage demonstrated that the relationship above holds and that the ratio between storage cost and price spread is presently too high. Payback periods were several decades for battery storage and an order of magnitude higher for thermal storage—both greater than the expected life of each system.

To understand the particularly poor economics of thermal storage in time-of-use flex modelling, we must acknowledge that the system cost is expressed in thermal capacity units. This means that the equivalent electrical value of stored energy is undermined by the coefficient of performance. Specifically, the electrical energy displaced by dispatching thermal energy is equal to the thermal energy divided by the coefficient of performance of charging, which may range somewhere around 3–5. The system cost of $270/kWh (thermal) is therefore equivalent to around $1080/kWh (electrical), over twice the lowest battery cost.

Where network tariffs were considered in addition to time-of-use tariffs, modelling showed that savings on demand charges increased the viability of both batteries and thermal storage, but not enough to bring payback periods below, or even near, 10 years.

Market prices may incentivise load flexibility via batteries but not via thermal storage

As described in Section 6.2, the market price optimiser divides predicted future prices into ranked pairs of greatest spread so that storage capacity can be allocated and dispatched at times of highest and lowest prices. Storage capacity tranches are quantised by the amount of energy that can be dispatched within a specific market price period where periods are defined by the forecast resolution. The greater the dispatch rates, the greater the tranche size, and the greater the energy that can be prioritised for the best price pairs. This means that a storage device's ability to derive value from market prices is strongly related to dispatch rate. Since storage devices are costed per kilowatt-hour, the balance of savings versus costs depends strongly on the ratio of discharge rate to storage capacity. This ratio also affects the total number of price pairs that can have storage capacity allocated to them.

Modelling showed that batteries may be financially viable if flexible operation is exposed to market prices, but thermal storage is too expensive and may not be suited to the time-sensitive dynamics of market prices. Under the tranched capacity optimisation strategy, the principal advantages of batteries compared to thermal storage are:

- they can be scaled with greater flexibility—specifically the dispatch to storage capacity ratio can be modified to better suit the task
- battery dispatch rates are more consistent and reliable because they are largely unaffected by state of charge.

The best payback period achieved for batteries in the modelling was roughly six years. While this is longer than typically accepted payback periods in the abattoir industry, it indicates that with near future price decreases and refined optimisation strategies, an acceptable financial case may soon exist for batteries, purely due to market prices.

Aside from their high cost per equivalent electrical kilowatt-hour, thermal storage systems struggle to derive value from market prices due to their dispatch limitations. Their best payback in the modelling was around 20 years.

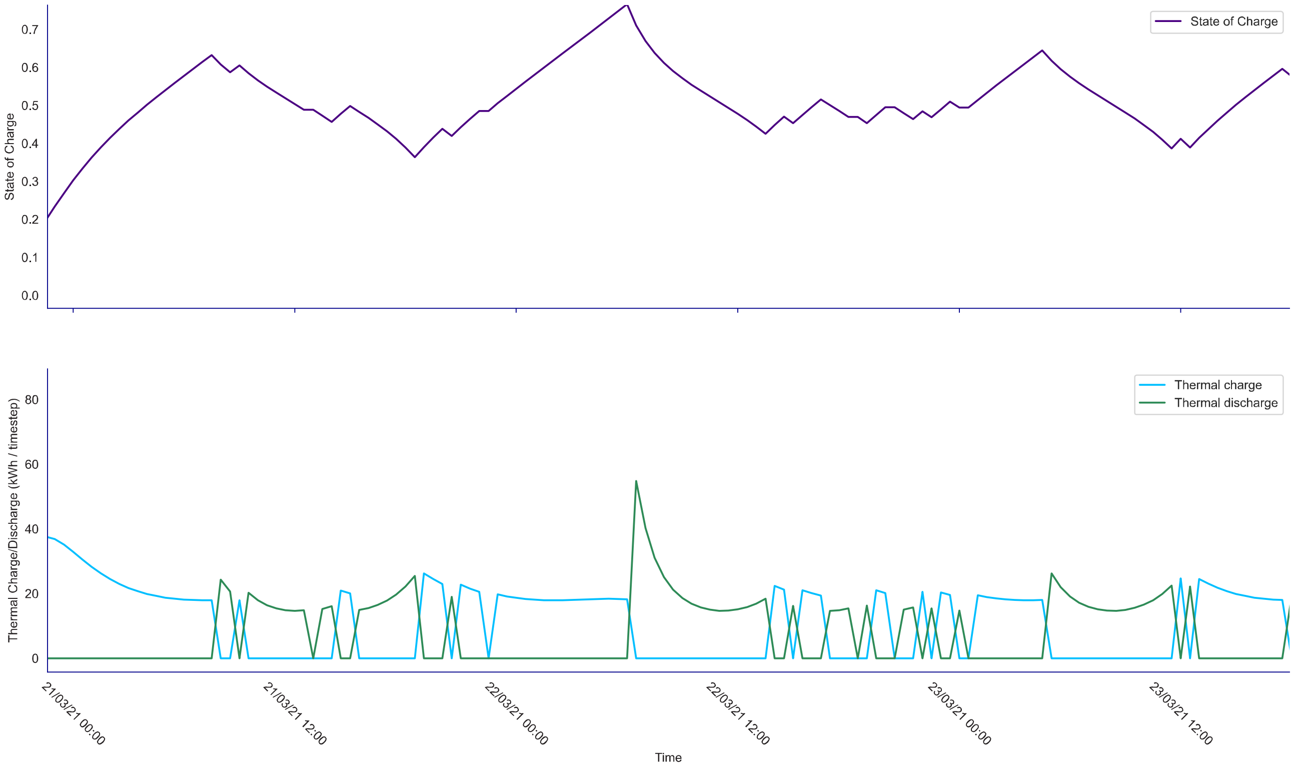

Figure 19. The impact of state of charge on thermal dispatch rate.

As explained in Section 6.1, both charge and discharge of PCM thermal storage systems are affected by state of charge. The relationships for charge and discharge compared to the thermal state of charge are roughly inverse. The higher the state of charge, the higher the discharge rate and the lower the charge rate. The lower the state of charge, the lower the discharge rate and the higher the charge rate. Under the tranched capacity strategy, these relationships are detrimental because they cause the state of charge to tend towards 50%, which is suboptimal for both the charge and discharge rates. Figure 20 shows the limitation of dispatch rates at different state-of-charge values.

TES in greenfield site

Additional modelling has been performed to assess thermal energy storage solutions in a greenfield site, and thermal energy storage (TES) can be used to offset cooling demand on an ongoing basis, thus reducing the required compressor capacity. However, the relatively slow recharge rate of the systems means that peak-to-off-peak pricing differences cannot be fully utilised as the recharge time is greater than the off-peak pricing times. As recharge rates improve and capital pricing reduces, this type of operation would become more economically attractive.

6.5.3 High temperature heat pumps

The modelling conducted in this study demonstrated some potential for heat pumps to displace boilers for hot water product while offering FD. However, it is important to exercise caution when extrapolating these figures more broadly, as the economics are based on site specifics. Most notably, these include the ratio of electricity to gas costs, but will also include factors such as hot water demand, access to waste heat streams (i.e. rendering or not), and the demand charges for the site. The specific energy tariffs applied in this modelling represent typical values for a large site, for which demand charges were not significant. Other sites with larger demand charges may experience much greater cost savings from HTHPs, along with an associated reduction in emissions. Potential emissions savings depend on the emissions factors for grid-sourced electricity, which are state based.

Capital costs per kilowatt-thermal (kW_{th}) vary significantly from site to site, with the bulk of charges being made up of electrical and piping work. For a simple-to-install site, we would expect a cost of 500 $\$/kW_{th}$, but more complex sites could be in excess of 1000 $\$/kW_{th}$.

7 Options for implementing load flexing

7.1 Low-capex load flexing strategies

Of the load flexing opportunities presented in Section 5, modification of refrigeration system controls represents the only low-capex load flex opportunity. Specifically, this included variation of low-side compressor suction pressure and reduction of blast freezer fan speed. Modelling of the suction pressure variation based on COP variations and recuperation of total cooling demand showed this strategy could result in immediate payback for an abattoir. Variation of the blast fan speed also resulted in immediate payback. However, these measures offer minimal load reduction potential relative to total site demand.

7.2 High-capex load flexing strategies

Unfortunately, the modelling in this study revealed that there are few, if any, viable options for refrigeration-related load flexing in abattoirs. Thermal storage was seen to have payback periods in excess of 20 years, which would preclude these from consideration in almost all cases. The charge and discharge capacities of the thermal storage system were shown to be critical features impacting viability. The inability to rapidly use the stored energy prevented complete capitalisation of the stored energy, which eroded the value of the asset. Additionally, the COP of the refrigeration plant reduces the quantity of electrical demand by a factor of 3–4 (plant and condition dependent), which dampens the price arbitrage for the business and the utility of this load as a source of FD for network stability.

Electric batteries do not face these issues and provide much greater charge and discharge rates. Results indicate payback periods of around six years are possible. Given the ongoing reduction in prices for batteries and the additional utility batteries can provide (i.e. electrical energy can be used for any load, any time), they would seem a much more attractive FD solution.

7.3 High temperature heat pumps

As outlined in Section 5.3, the operation of a heat pump can be optimised based on the cost of hot water generation. The savings of this are maximised when the system is subjected to the wholesale market, either through base electricity rates or through load shed systems, and this also drives operational behaviour that helps the overall market. However, depending on the retail electricity and natural gas prices, we anticipate that savings will also be realised in this scenario.

7.4 Productivity and non-energy benefits

This study has shown that there are several features of abattoir refrigeration that make it a difficult load to flex. Despite this, there was some potential for electric batteries to provide reasonable levels of FD. Beyond the direct energy cost savings, FD offers abattoirs other benefits, including:

- FD can increase refrigeration resiliency.
- FD from thermal storage can reduce or eliminate the need to invest in refrigeration compressor upgrades as it can be used to meet demand during peak times.
- FD from thermal storage can also provide additional redundancy or prolong plant service life.

7.5 Process to implementation

Unfortunately, while there are several refrigeration-related measures to increase FD in abattoirs, the analysis in this report suggests they are unlikely to be adopted. The controls-based FD options were both seen to offer immediate payback, assuming the implementation of these measures required only minor software programming updates. However, while these measures provide energy cost savings, they are minor relative to the total energy spend.

Thermal storage can provide FD but is currently severely hampered by constraints on charge and discharge rates. Future improvements to the technology that address this may warrant reinvestigation of the feasibility of coupling thermal storage with refrigeration loads, particularly for new plants.

Batteries, while non-refrigeration specific, were shown to offer a viable FD option in certain circumstances. However, a detailed investigated would be needed on a site-by-site basis to justify the large capital expenditure.

7.6 Implementation risks

As discussed above, at the present time batteries represent the only marginally feasible large-scale FD option for abattoirs. There are considerable risks associated with investment in a battery for FD purposes. Modelling of revenue streams from batteries not only depends on load and energy price forecasts, but estimations of the demand response payments, which are very difficult to predict. Financial returns that are contingent on these predictions should be viewed judiciously; the major risk being that revenues from FD markets do not eventuate and the ROI for the battery would be much lower than anticipated.

Furthermore, there is anecdotal evidence that some early adopters of battery storage in the commercial and industrial sectors are achieving underwhelming performance. These examples highlight the importance of thoroughly understanding the dynamics of batteries and for intelligent controls that enable value stacking from energy arbitrage and ancillary services markets, for example. At the current cost of technology, profitability is not guaranteed.

7.7 Replication possibilities

There is considerable duplicability within the meat processing industry, as the general equipment, processing steps and constraints are comparable across the sector. As such, there will be considerable replicability around the country, and we anticipate that almost every abattoir would be able to utilise the options presented in this report.

It is likely that the opportunities and economics for small facilities will be different to large ones, mostly due to differences in refrigeration capacity and energy and demand charges. To a lesser extent, the location of the abattoir will also impact this.

7.8 Impact tracking

Based on the findings of this study, there are few opportunities to increase FD in Australian abattoirs. As such, there will be minimal impact on the energy system more broadly.

8 Electricity network impacts

8.1 Grid stabilisation from flexible demand

The modelling presented in this study indicates abattoir refrigeration is unlikely to provide significant FD for the NEM. Challenges with interrupting the meat chilling cycle limit the potential size of the electrical demand that can be curtailed, without significant, and currently unviable, investment in energy storage. Based on the current technologies, electrical batteries appear to provide the greatest ROI for businesses seeking to unlock FD.

While there is some precedent for large batteries installed at Australian abattoirs to be used to provide both energy storage for the business and grid stabilisation services for the DNSP, this remains a case-by-case prospect. Furthermore, the pipeline of proposed large-scale batteries in the NEM points to significant competition for secondary revenue streams such as FCAS markets that these batteries may offer.

As the cost of battery storage declines, the batteries will offer abattoirs a cost-effective means of maximising the utilization of on-site renewable energy generation, particularly solar PV. However, the economics of this proposition are site-dependent and warrant further investigation prior to investment.

8.2 Decarbonisation drivers for flexible demand

Although enhancing the flexibility of refrigeration may not present large cost savings for abattoirs, it does present a means of decreasing the carbon intensity of the business. The shape of the typical electrical demand profile from abattoirs aligns well with the generation profile of solar PV; i.e. demand grows in the early hours of the morning, peaks from mid-day to early afternoon, and then tapers off. Many Australian abattoirs have identified this and already invested in large on-site PV systems, reducing their typical demand substantially and offering considerable energy cost savings.

However, solar PV is variable and cannot guarantee peak demand reduction without the implementation of some degree of FD. Electrical energy storage is a likely candidate here, particularly, as discussed above, as prices continue to fall. Irrespective of the cost of energy storage, the magnitude of the total electrical demand of abattoirs (up to 10s of megawatts peak) limits the ability for batteries and solar to completely meet their energy needs. As such, as businesses progress along their carbon abatement journeys, alternative solutions will be needed.

One such option is renewable power purchase agreements (PPAs), whereby an abattoir may enter a long-term contract to purchase energy at fixed prices from renewable generators, such as wind or solar farms. There are several advantages of renewable PPAs, including:

- facilitating the purchase of more clean energy than can be generated on-site because of, for example, roof space or land limitations
- allowing renewable assets to be installed in locations that are best suited for the resource (e.g. high wind) and transmission infrastructure (e.g. renewable generation zones in the NEM)
- encouraging users to align their consumption profiles to match generation.

Figure 20 shows the annual average daily generation profile of a sample of renewable generators currently engaged in PPAs with industrial customers in Victoria. The output from the solar farms follows the typical daytime generation profile. Output from the wind farms is more location specific but is generally much flatter throughout the 24-hour period. Purchasing a portion of energy from each of these sources may allow abattoirs to hedge against the variability of these sources and use load flexing to align their demand with these generators.

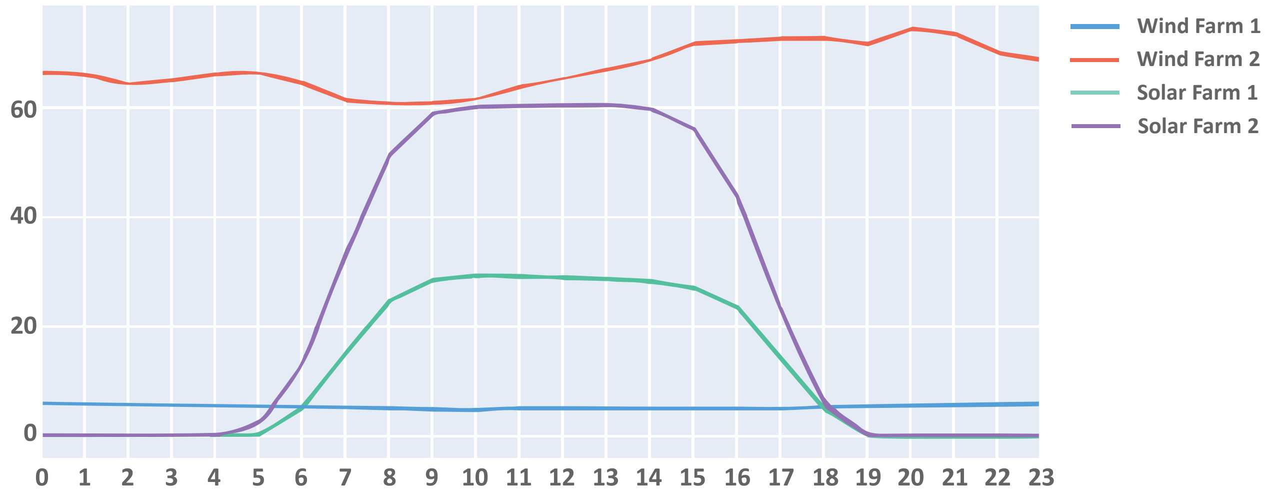

Figure 20. Annual average hourly generation from Victorian solar and wind farms.

9 Conclusions

This project investigated the feasibility of flexing the electrical demand from refrigeration plant at Australian abattoirs. This included a detailed review of the refrigeration needs, production processes and energy systems at two case study sites, discussions with refrigeration contractors, and highly detailed load flex modelling.

Four specific load flex opportunities were modelled using a time-series energy optimisation model, PowerFlex, including suction pressure variation, blast fan speed variation, thermal storage and battery storage.

Suction pressure variation and blast fan speed variation both demonstrated immediate payback, but minimal load reduction capacity. In effect this means these measures would be unlikely to be pursued for cost savings, particularly given the concerted focus of the meat sector on improving energy efficiency and reducing carbon emissions (i.e. there are many competing alternatives).

Thermal storage is severely impeded by low rates of charging and discharging, which limit the 'flexibility' of these assets. Under no retail or wholesale market price scenario did the thermal battery demonstrate feasible performance. Future technical modifications that address this constraint may change this.

Batteries were found to provide the greatest level of FD for abattoirs. The value of the battery depends on the storage capacity (kWh) and spread of energy costs in the market. The greatest financial returns from batteries were found to be for 1-hour storage when exposed to wholesale market electricity pricing.

Heat pumps were also investigated and shown to provide good returns for abattoirs. However, the suitability of these is also site-dependent, with financial viability being strongly linked to each site's network charges and the ability for heat pump operation to avoid these. While HTHPs add electrical load, they do not necessarily increase peak demand, particularly for sites that retain boilers for backup.

9.1 Abattoirs do not make good candidates for load flexing

In general, this study has concluded that abattoirs do not make good candidates for load flexing for the following reasons:

- **Time sensitive cooling profiles**—chilling of meat is subject to critical and time-sensitive cooling profiles that cannot be interrupted.
- **Very limited production flexibility**—production throughput is not flexible without making significant changes to work shifts and days.
- **Relatively small demand charges**—abattoirs are large energy users with relatively low energy tariffs and demand charges, which erodes the value from load shifting.
- **Thermal storage limited to high-side loads**—the availability of phase change materials is limited to the high-side (chiller) loads.
- **Loads that can be flexed are small**—suction pressure variation and blast fan speed variations were found to be loads that can be flexed but offer very minor load reductions relative to site demand.
- **Battery storage may facilitate load flexing**—however the business case for this investment was shown to be a case-by-case proposition that would require detailed investigation and careful consideration.

The meat processing industry has adopted aggressive carbon reduction targets and is making considerable in-roads towards achieving these. The current focus on energy efficiency and adoption of renewables appears to be the best strategy.

Long-term initiatives to reduce carbon intensity from refrigeration plant include: low charge ammonia systems, dynamic discharge pressure, variable speed controls on compressors, elimination of air infiltration, improve/maintain insulation, increase measurement and monitoring.

The chart below highlights various load flex options, their feasibility and other commentary, as identified in this report. Additionally, items for further research are highlighted.

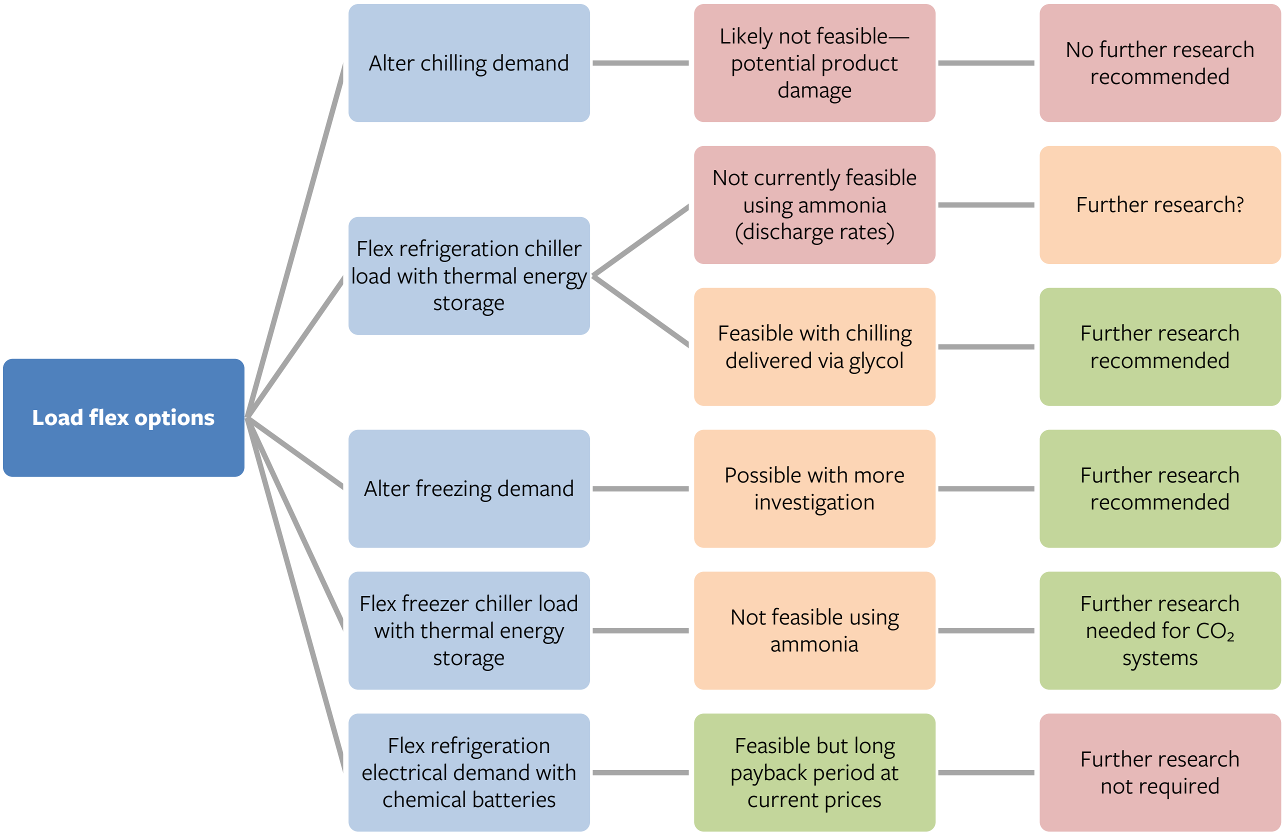

Figure 21. Various load flex options, their feasibility and opportunities for further research.

9.2 Favourable load characteristics for flexible demand

Refrigeration systems in other sectors are not necessarily subject to the limiting constraints mentioned above, and therefore may offer strong opportunities for load flexing. Cold storage, for example, offers great potential for FD as cooling of the product can be switched off or turned down without immediate risk of spoilage.

In general, the following characteristics make a particular application or site more suitable to load flexing:

- **Processes or products that are not temperature sensitive.** Tolerance for plateaus or even slight increases in temperature unlock the potential for compressors to be shut off, offering much greater load shed without the need for thermal storage.
- **Processes or industries with inherent storage.** System involving pumping or movement of liquids, for example, often contain buffer or storage tanks, which can provide inherent energy storage. Likewise, batch processes or material stockpiles can act as storage provided there is production flexibility.
- **Peaky demand curves.** Spikes in demand generally correspond to discrete equipment or processes, which offer the potential for direct load shedding or targeted load shifting to reduce demand charges or provide revenue from contracted demand response programs.

While, in general, meat plants are not suitable for load shedding, inclusion in new developments would help in its application:

- Utilising an intermediate fluid for chilling and HVAC loads, such as glycol. This will result in a much greater portion of site load being able to be shed via thermal batteries.
- Installation of excess refrigeration capacity that would allow flexibility in operation.
- Utilising a high temperature heat pump with boiler backup (or storage) to generate hot water. This is a very efficient and cost-effective method of hot water generation, which can be shed as required.
- Inclusion of a comprehensive control and monitoring system to provide insight into how the site is operating.

Items such as the above would greatly improve the ability and scale of load shedding onsite.

9.3 Suitability for solar power

There is considerable opportunity for abattoirs to use solar PV to minimise energy costs and carbon emissions. Electrical demand for abattoirs increases from early in the morning and peaks in the afternoon, which aligns well with solar generation peaks. Abattoirs are also generally large sites with plenty of available roof space or surrounding land on which to install a PV system. In aggregate, solar PV will reduce demand for electricity, but will not necessarily ensure peak demand reduction owing to variable generation. Renewable PPAs may also be a means of decarbonising the electrical demand, with wind power supplying night loads and solar PV during the day.

9.4 Future research

The need for flexible demand as the Australian energy market transitions towards a cleaner generation mix is indisputable. Agile energy consumers will be able to capitalise on opportunities from load flexing to reduce costs and better align their operations with on-site renewables or grid-sourced PPAs. However, there are several opportunities for future research in this area to investigate additional benefits from FD. Future research may address the following questions:

What is the average carbon intensity for different trading intervals throughout the day?

Currently, AEMO publishes a carbon intensity for the energy generated in the NEM at daily resolution. Generating this data per trading period would provide clarity on the average carbon intensity of grid-sourced electricity at different times throughout the day. This data may provide a tool that enables energy retailers to establish new tariffs that incentivise climate-conscious customers to flex their demand profiles towards ‘cleaner’ generation, or also allow wholesale-exposed customers to optimise their loads for lowest carbon intensity.

How can flexible demand be used as an additional driver for decarbonization?

Currently, consumption of renewable energy is typically considered on a net benefit basis, whereby businesses aim to reduce their Scope 2 emissions using renewable generation but typically retain some dependency on grid power. As the energy network moves towards net zero, there will be greater value and importance in minimising the consumption of carbon-intensive power. Additional research may explore the ways that FD can enable alignment between renewable generation and consumption—leading to less problematic renewable energy penetration in the NEM.

What is the ideal heat transfer medium for an abattoir?

Research should be conducted around what is the best medium for refrigeration systems, considering both process capability, energy efficiency and demand response. In particular, CO_2 is becoming increasingly common as a heat transfer fluid, and this may help enable TES.

What are the optimal chilling and freezing rates and can these be safely varied to enable load flexing?

Abattoirs are currently very hesitant to modify cooling or freezing parameters given the significant risk of product degradation and spoilage. These are valid concerns and additional research should be performed to confirm the possible changes to processing times and temperatures.

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Appendix A—PowerFlex model

A.1 Modelling approach

PowerFlex was developed by the Institute for Sustainable Futures for modelling onsite demand flexibility. It is composed of modules which simulate site equipment, smart controllers, optimisation engines, schedulers and forecasters. PowerFlex's modules follow object-oriented design principles and therefore provides off-the-shelf modelling capability which is extensible and adaptable for the purpose of developing bespoke site models. PowerFlex takes a stepwise time series approach to modelling where strategic decisions are calculated for each time step of demand data. The principal input is typically electricity consumption interval data provided at sample rates between 1 minute and 1 hour.

Load flexing opportunities range from very simple to the complex. Accordingly, in PowerFlex, equipment objects range from simple models, for example finite blocks of flexible demand which may be rescheduled within given constraints, to complex models, for example energy storage devices or dispatchable generators with dynamic dispatch capabilities and modelled internal states. What is common to all equipment is the ability to add or deduct demand from the demand curve at different times for the purpose of load flexibility modelling. This is generically referred to in the model as flexibility dispatch, and the addition and deduction of demand are referred to as charge or discharge respectively.

Equipment models in PowerFlex operate using both static and dynamic parameters. Static parameters are defined at the instantiation of the model. Dynamic parameters take an initial value at model instantiation but change according to component interactions during runtime. Concretely, this means that dynamic parameters change according to some internal model. This is one of the principal reasons PowerFlex prioritises object oriented design principles—they facilitate the deployment of models within models.

It is important to note that PowerFlex is an *energy* modelling tool and so it only deals with very limited power systems and thermal system calculations. For example, energy to power conversions with given power factor parameters, and thermal energy to electrical energy conversions with given coefficients of performance. This facilitates certain tariff calculations, like demand charges which are based consumption of kilowatts, and to facilitate the analysis of the effect thermal storage dispatch on electrical energy load curves. But the primary focus of flexibility in PowerFlex is the manipulation of electrical energy consumption at different times of day—power and thermal calculations reflect these energy consumption changes only.

A.2 Modelling procedure

A generalised PowerFlex site model is shown in Figure 22. . Once configured, a site model iterates over demand data to simulate live demand conditions. Load flexing in the model is determined in the following way:

1. The controller iterates over demand intervals, noting present demand conditions
2. At scheduled time intervals, forecasters with specified accuracy and foresight models provide predictions of future demand and in some cases energy spot market prices
3. The controller passes predictions to an optimisation engine. The optimisation engine also receives status updates directly from equipment objects (e.g., state of charge)
4. Each optimisation engine is configured to calculate the optimal dispatch for a specific strategy, for example, peak shaving, to minimise demand at peak hours, or arbitrage on market prices

5. The optimisation engine either calculates setpoints, designed to constrain equipment dispatch during time periods, or alternatively it schedules exact dispatch rates at exact times in the future

6. As the controller continues to iterate over the demand time intervals, it refers to the setpoints or dispatch schedule to determine a dispatch proposal for each interval which specifies charge or discharge

7. The controller passes the dispatch proposal to the site equipment as a request. The equipment responds to the request according to its capability at that moment in time, which may be affected by its internal status. For example, an energy storage device with a low state of charge may not be able to supply the total discharge requested by the controller, or a flexible block of demand may be constrained and cannot be shifted to operate at certain times of the day

8. When the controller has finished iterating over the demand interval data, the dispatch and demand are summed to generate a new net demand curve, as shown in Figure 8.

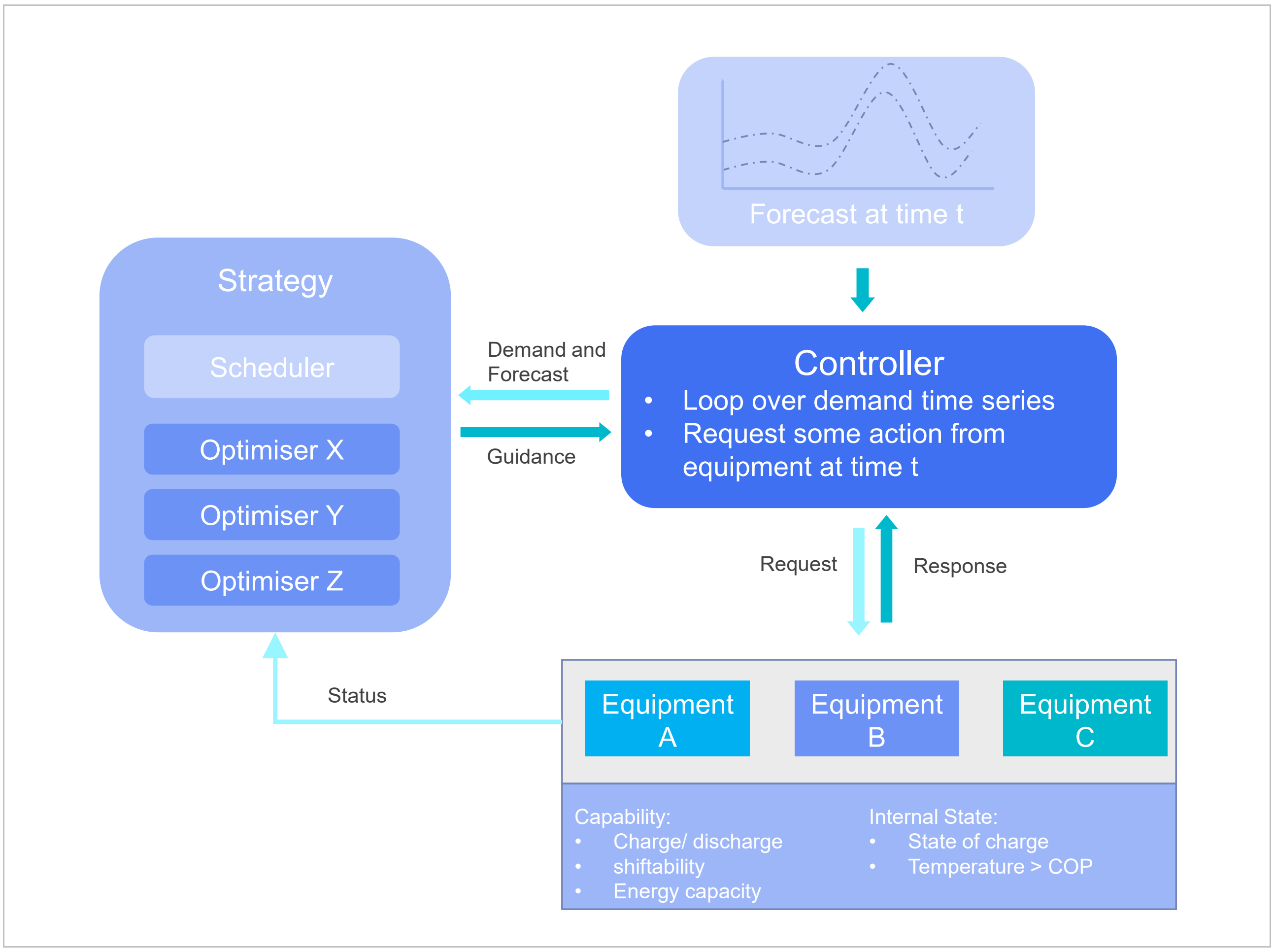

Figure 22. PowerFlex model overview.

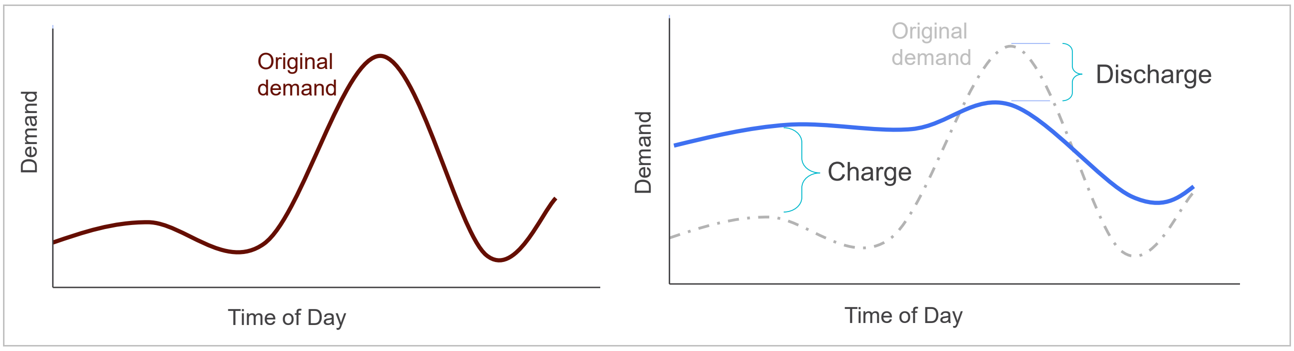

Figure 23. Summing dispatch and demand to form a new net demand curve.

A.2.1 Site metering and tariff modelling

PowerFlex handles site meter data and tariff calculation with *TS-Tariffs*, an open source Python library also developed by the Institute for Sustainable Futures. TS-Tariffs has built-in tools for handling interval meter data and tariff calculation capability for all common electricity tariff structures applied by retailers and electricity networks in Australia, including those listed in Table 17. TS-Tariffs allows the PowerFlex model to specify a site with any number of consumption meters and any regime of tariffs which are applied individually to each meter. TS-Tariffs generates site bills for each meter with a line item for each tariff that applies to a site.

Table 19. Modelling tariff calculation capability.

Tariff type	Applied by	Description	Typical charge units
Time-of-use	Retailer	Energy consumption charge which varies by time of day	\$/kWh at time *t*
Single rate	Retailer	Flat rate energy consumption charge	\$/kWh
Connection charge	Network	Flat rate applied to regular time intervals. Rate is independent of consumption	\$/day
Demand charge	Network	Rate applied for highest power demand recorded in a meter interval for a specific period	\$/kVA or \$/kW for maximum half hourly demand in billing month
TOU demand charge	Network	Demand charge (as above) split into time-of-use components	\$/kVA for maximum half hourly demand in time-of-use period within billing month
Block charge	Network	Progressive rate of charge, increasing as consumption breaches given thresholds in a period (analogous to a progressive tax model)	\$/kWh within block thresholds
Capacity charge	Network	Rate of charge applied for estimated kVA capacity required by the site	\$/kVA
Solar feed in tariff	Retailer	Payment to consumer for energy exported from site to grid	\$/kWh

The PowerFlex library augments *energy* consumption profiles. Since network tariffs not only apply to *energy* profiles, but their equivalent *power* profiles too, PowerFlex must augment power profiles according to the dispatch of equipment in the model. To do this, PowerFlex extends TS-Tariffs metering capability by adding basic power-energy conversions based on power factors observed in baseline interval meter data. This calculation introduces the assumption that power factor is unchanged by load flexing in the model. This assumption must be acknowledged when considering the comparison of site bills before and after the PowerFlex model has been applied.

A.3 Control settings models

A.3.1 Suction pressure variation

As described in Section 5.2.1, compressor suction can be adjusted within limits to manipulate COP. Change in COP from suction pressure adjustment is very application specific, so PowerFlex's suction pressure variation model is a simple COP conversion model that relies on operational knowledge of real-world equipment. That is, it considers empirical data, rather than deploying a theoretical model of pressure and COP. PowerFlex considers three settings where COP is known for given suction pressures: baseline pressure, low pressure, and high pressure. When the model switches between two settings it simply modifies the electrical load based on the ratio of relevant COPs. PowerFlex also assumes that the system's rate of heat exchange is affected when suction pressure is changed. Therefore, for every cooling cycle where a COP setting is changed, PowerFlex 'repays' the change at some time in the near future (typically within 7-8hrs) with the opposite and equivalent setting dispatch. For example, where the high pressure setting is dispatched in a cooling cycle, the low pressure setting is scheduled some time later in the cooling cycle to 'repay' the energy disparity in the product being cooled.

A.3.2 Blast fan speed variation

Powerflex's blast fan model uses fan affinity laws to estimate power consumption savings when fan speeds are reduced. According to fan affinity laws, when fan speed is reduced, air speed reduces in proportion to the relative fan speed change, and power reduces in proportion to the cube of the fan speed change. This implies. Similar to the suction pressure variation, cooling rates are reduced when fan speed is reduced because less air is passed over the product. Accordingly, when PowerFlex deploys fan speed variation to reduce power consumption, it 'repays' the difference in cooling rate at some time later in the cooling cycle.

A.4 Energy storage models

PowerFlex's built in battery and thermal storage models consider four categories of parameter, two are static and two are dynamic:

- financials (static)
- nominal technical capabilities (static)
- internal battery state (dynamic)
- dynamic technical capabilities (dynamic)

The nominal technical capabilities, internal state and dynamic technical capabilities directly affect how the battery and thermal storage models perform load flexing. Financial parameters are principally used for calculating equipment's' financial viability but may be accessed by optimisers to make strategic decisions about dispatch, depending on the configuration of the optimisers in use.

A.4.1 Battery storage

The battery's dynamic internal status is relatively simple, containing only one dynamic parameter—the state of charge. State of charge represents the amount of energy contained in the battery as a proportion of the total energy capacity where a value of 1.0 and 0.0 represent a full and empty battery, respectively. State of charge is changed by dispatch, and dispatch is sometimes affected by state of charge according to the following calculation procedures:

State of charge at time step T:

$$\text{state of charge}_T = \text{state of charge}_{t=0} + \sum_{t=0}^{T} \text{charge}_t + \text{discharge}_t - \text{efficiency losses}$$

where:

$\text{charge} = \{x \in R : x \geq 0\}$
$\text{discharge} = \{x \in R : x \leq 0\}$
if $\text{charge}_t > 0$, $\text{discharge}_t = 0$
if $\text{discharge}_t < 0$, $\text{charge}_t = 0$

Charge and discharge (as energy) during time step T:

$\text{discharge}_t <= \min \{\text{available energy}_t, \text{discharge capacity}_t\}$

$\text{charge}_t <= \min \{\text{available storage}_t, \text{charge capacity}_t\}$

where:

$\text{available energy}_t = \text{nominal energy capacity} \times \text{state of charge}_t$
$\text{available storage}_t = \text{nominal energy capacity} \times (\text{state of charge}_t - 1.0)$
$\text{discharge capacity}_t = \text{nominal discharge rate} \times \text{time step duration}$
$\text{charge capacity}_t = \text{nominal charge rate} \times \text{time step duration}$

A.4.2 Thermal energy storage

PowerFlex's built in thermal storage model operates in much the same way as the battery model except that it implicitly assumes dispatch and storage values represent thermal energy rather than electrical energy. The controller explicitly dispatches on thermal sub loads as opposed to a site's gross electrical demand curve, allowing this assumption to hold. To determine the conversion between electrical and thermal energy during charging the thermal storage model specifies a coefficient of performance (which may or may not be dynamic) that is passed to the controller which manages conversions.

The most significant operational difference between the battery and thermal models is that the thermal model dispatch is dynamically calculated. Dispatch rates not only depend on there being either enough energy or storage capacity to accommodate a proposed charge or discharge, the actual rate of discharge is affected by the exact state of charge. The exact thermal dispatch capacity models deployed in this project were provided by project partners and are commercial in confidence and will not be included in this report. For comprehension of the thermal storage model it can be assumed that the charge capacity is roughly inversely proportional to the state of charge and the discharge capacity is roughly proportional to the state of charge.

A.5 Forecasting

Realistic load flexibility optimisation generally requires demand forecasting, and in some cases, weather condition and market price forecasting. PowerFlex's forecasting module provides a flexible range of options for forecast emulation. PowerFlex typically uses historical load data, so the simplest option is a perfect forecast, which is useful for modelling raw load flexing opportunity that is unhindered by uncertainty. To emulate more realistic real-world forecast, uncertainty can be introduced by either:

- the addition of random deviation onto perfect forecast base values using a statistical distribution model

- forecasting at a reduced sample rate, which aggregates forecast values by either summation or averaging
- Extending the module with real forecasting models, including machine learning (e.g. LSTM neural networks), statistical regression or purely theoretical models

The forecasting module allows the specification of different forecast window lengths and resolutions. For example, a forecaster in PowerFlex may deliver a 24-hour foresight window at a 30-minute resolution, or alternatively a six-hour window with a five-minute resolution. Adjusting these parameters facilitates different optimisation scenarios and emulates different levels of model realism.

A.6 Optimisation strategies

The financial value of load flexibility is dependent on the spread of prices energy at different times of day, as well as the impact of flexibility on network tariffs, like demand charges. As such, optimisation strategies generally prioritise the ability to shift load from expensive to cheap time periods and may balance this against the ability to reduce peak loads by peak shaving, depending on the significance of the demand charge a site is exposed to.

In this project we considered retail time-of-use and network tariffs, wholesale electricity market price exposure and a typical suite of network tariffs, including demand charges. Consequently, we developed two core strategies for load flexing optimisation, time-of-use-shifting, and tranched capacity with future price pairing. Each strategy may be extended with a peak minimisation directive where demand charges are more significant than the value of price spread. It should be noted that peak minimisation was not optimal as a priority based on the small network demand charges considered in this modelling but may be more significant on smaller sites.

A.6.1 Time-of-use shifting (retail optimisation)

The time of use shifting strategy seeks to maximise the amount of energy consumed during off-peak pricing periods and minimise energy consumption during peak periods, without changing the total energy consumption. As a matter of good practice, this strategy also avoids sudden spikes or dips in net demand by reserving its dispatch to ensure there is enough capacity at peak times, which are anticipated via a load forecast. This results in a load curve with level, shaved peaks. Figure 24 shows an example of battery dispatch where the off-peak period is between 10 pm and 7 am and the peak period is between 7 am and 10 pm.

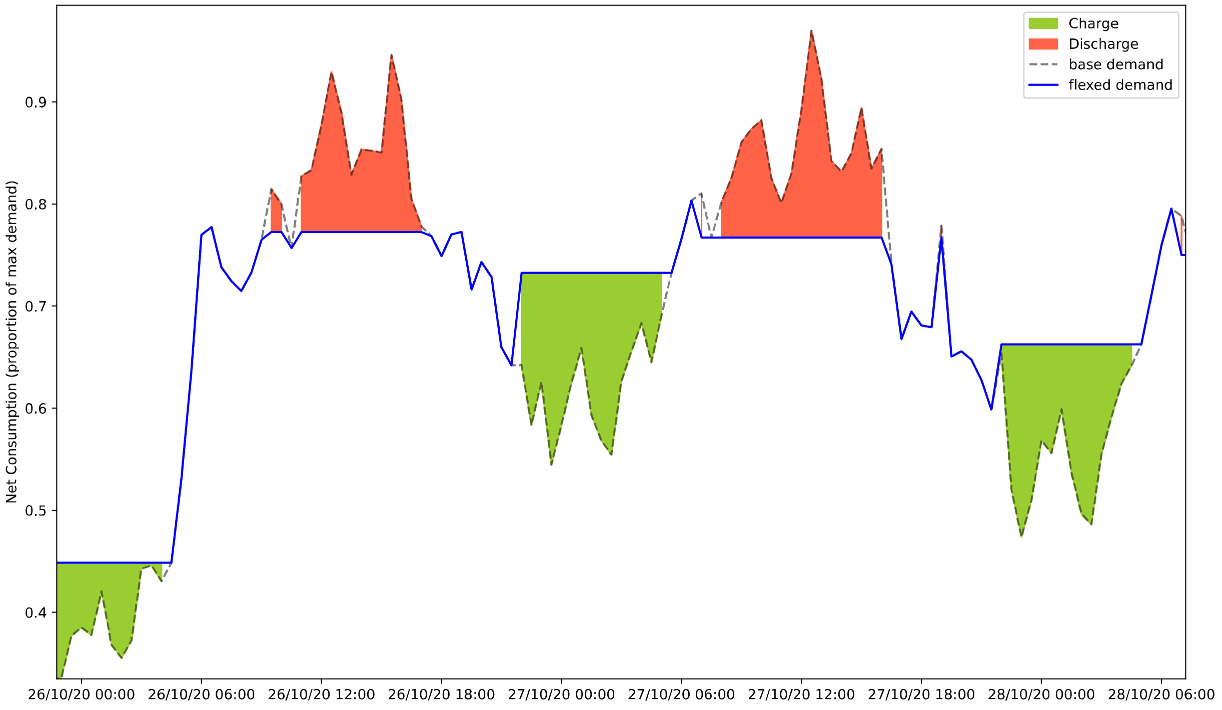

Figure 24. Time-of-use shifting example where charging during off peak (10 pm–7 am) and discharging during peak times (7 am–10 am).

A.6.2 Time-of-use shifting plus contract demand response (retail optimisation + DR)

In addition to optimisation of the standard retail tariff, various demand response programmes are available to contract into. For the purposes of this report, we have assumed the pricing as outlined in Section 3.3.

A.6.3 Tranched capacity with future price pairing (wholesale optimisation)

The tranched capacity with future price pairing strategy assumes that the site is exposed to wholesale electricity prices. It seeks to maximise the amount of energy consumed during periods with low spot prices and minimise energy consumption during high spot prices, without changing the total energy consumption. The optimisation procedure is calculated as follows:

- The forecaster predicts spot price for specified time increments in a forecast window (increments typically between 0.5 hours and 2 hours, forecast windows typically between 2 hours to one day ahead). Each time increment in the forecast window is ranked from highest to lowest price
- The dispatch capacity is split into charge and discharge tranches, each of which is equal to the amount of energy that can be dispatched in a forecast time increment
- Each charge and discharge tranche is then sequentially allocated to be dispatched during the lowest and highest price periods respectively. This establishes a list of price pairs where each pair represents a spread of a maximum and minimum available price. The list is ranked by greatest to lowest spread
- capacity tranches are allocated sequentially to the best price pairs. Each tranche is designated to dispatch during its allocated price period in the forecast window
- This strategy can be designated at any forecast resolution and window length, depending on the accuracy desired.

Figure 25 demonstrates the designation of charge and discharge tranches and Figure 26 shows an example of a battery enacting the strategy.

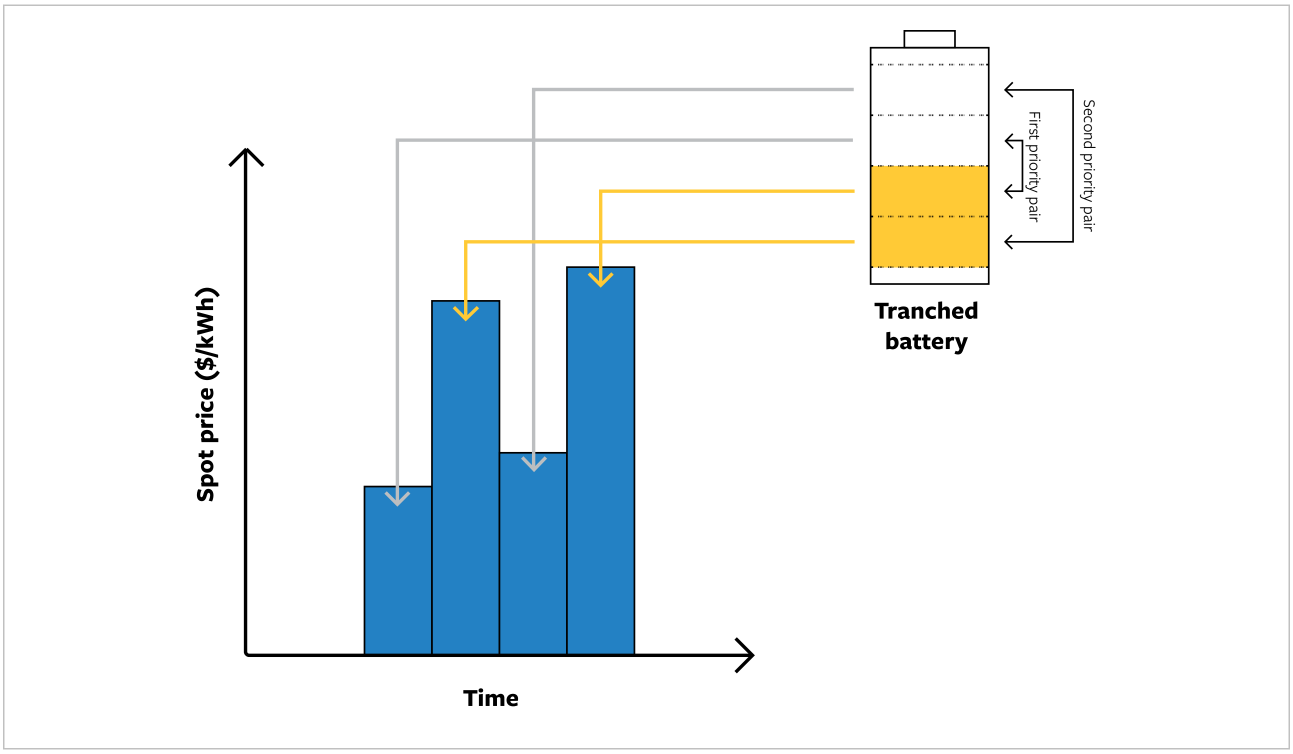

Figure 25. Tranched battery charge discharge allocation.

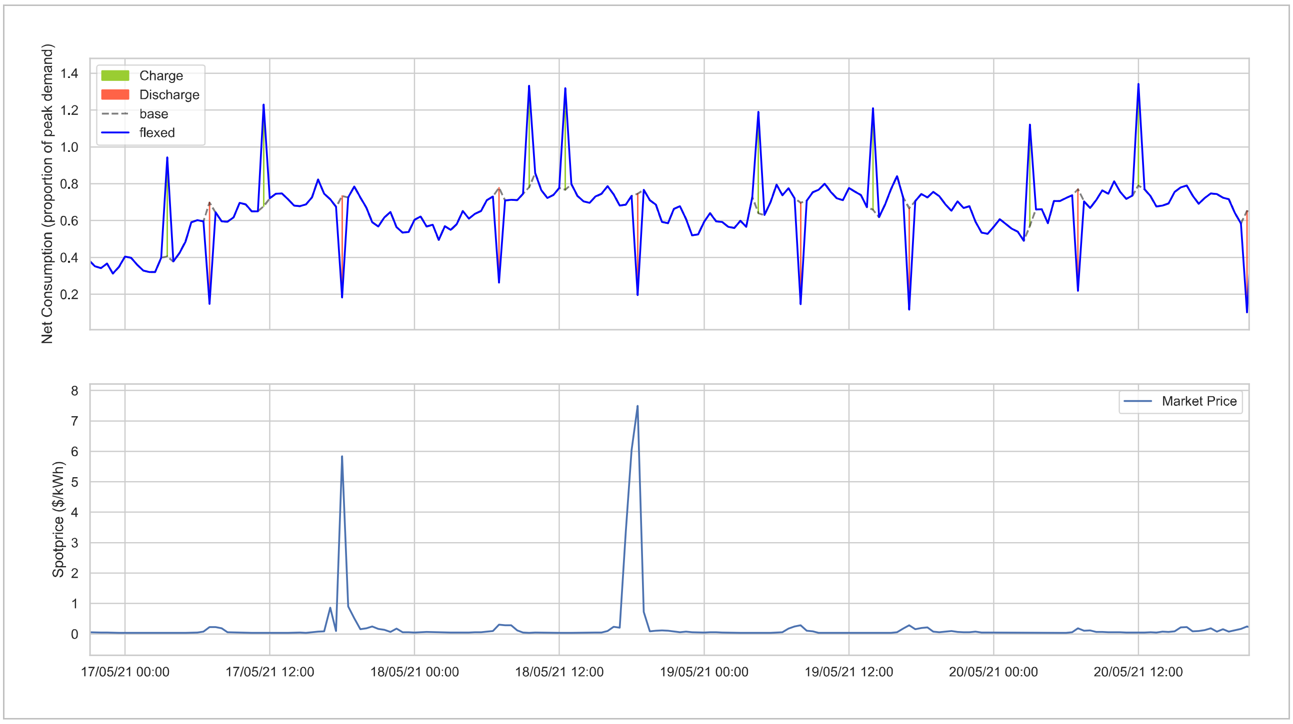

Figure 26. Example of tranched capacity with price pairing strategy enacted with a battery.

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