Investigation into Modular Micro-Turbine Cogenerators & Organic Rankine Cycle Cogeneration Systems for Abattoirs.

- Final Report -

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Project description

Energy costs for heat and power represent major operating costs for abattoirs. These costs have increased more than the consumer price index (CPI) in recent years and are expected to increase further in coming years. Cogeneration (or CHP, combined production of heat and power) is increasingly seen by the meat processing industry as a way of improving energy efficiency, and thus reducing costs and also greenhouse gas emissions. MLA and AMPC have investigated cogeneration on several occasions over recent years, with a number of reports prepared on its various aspects. Most recently, work on AMPC project 5011 identified micro-turbines and organic Rankine cycle (ORC) units as equipment worthy of further consideration relative to reciprocating engines for the provision of cogeneration in abattoirs.

Cogeneration is already used widely around the world. The targeted technologies show commercial viability at a range of scales and across a variety of applications. The applications for micro-turbines are often different to those for ORC units. This project has reviewed several different sizes and configurations for cogeneration using these units, combining data from experienced vendors with operating conditions for a typical meatworks. Cost benefit analysis has been used to assess commercial viability.

For each of the technologies considered (organic Rankine cycle (ORC) units, micro-turbines and reciprocating engines) budget pricing for supply, installation and operation was gathered from experienced Australian vendors, along with data from industry reports and technical literature. These provided the basis for cost benefit analyses to examine the commercial viability of the cogeneration systems at a range of scales and operating situations.

Project content

The base case analysis was completed for a “typical” red meat process facility, which processes 625 head of cattle per day[1], running a 2 shift per day roster for 250 days per annum. The principal assumptions made for the base case cost-benefit analysis were:

	Assumption	**Information / Reference**
1	Natural gas lower heating value (LHV) 47.13 MJ/kg	http://hydrogen.pnl.gov/tools/lower-and-higher-heating-values-fuels
2	Natural gas price $12 / GJ.	Approximate median commercial rates
3	Electricity - Peak: $ 0.1269 / kWh Electricity - Off Peak: $ 0.0876 / kWh Network Charge: $ 262.308/kVA/y	Approximate commercial rates for businesses on 11 kV grid power feed
4	Operation during peak power cost periods: 3,500 h/y	Peak 7am - 9pm M-F
5	Operation during off peak power cost periods: 4,924 h/y	Off-peak: 9pm – 7am M-F, plus weekends
7	Power factor for facility of 0.9	Integrated industrial facility without power factor correction

[1] www.mla.com.au/download/finalreports?itemId=3112, accessed 3 August 2016.

	Assumption	Information / Reference
8	688 kWt of hot water, or 5,830 kWt of 6 bara steam can be utilized on-site during operating hours	Mass and energy balance result for a "typical" facility based on industry data.
9	Up to 2,661 kWe of power can be consumed during operating hours	
10	No indexing (CPI), discounting, tax considerations or depreciation applied to future revenue / costs.	

For some meatworks, biogas produced on site may be an alternative to natural gas. The typical facility described above is anticipated to produce sufficient biogas for operating the 250 kWe ORC unit, 633 kWe reciprocating engine and 200 kWe turbine at full capacity, and the biogas option was considered for these smaller systems. Operation of larger systems on a mix of biogas and natural gas was not investigated. Biogas was assumed to be "free issued" from a co-located anaerobic digester. This biogas can be used to create large scale renewable energy credits under the Australian Government's Renewable Energy Target (RET) scheme, which were valued at the spot price of $86 / MWh[2].

Project outcomes

For cogeneration units operating consistently at capacity and with natural gas as feed, reciprocating engines were found to provide better payback periods than either micro-turbines or ORC units. We attribute this primarily to the ability of the engines to achieve more efficient electricity generation than micro-turbines or ORC units, resulting in significantly improved revenues from an equivalent quantity of gas for these operating conditions.

While the modelling done for this project assumed constant operation at capacity, in real-world applications it is likely that units will be required to operate at partial loads. For such operation micro-turbines and ORC units both offer greater flexibility than reciprocating engines. The ambient temperature for operation has an effect on system efficiency, and reciprocating engines appear to be less sensitive to temperature than micro-turbines.

All cogeneration systems considered were capable of generating hot water at 90^{O}C, which can contribute to the meatwork's process heating needs, but is potentially limited by the actual process needs for hot water and its existing availability from other sources within the plant. ORC units also offer an alternative approach. When coupled with new heat plant, the combined system can provide process steam instead of hot water, potentially offering greater flexibility when the meatworks requires a new heat plant. Micro-turbines can also be used to generate steam, via a purpose-built heat recovery unit capturing waste heat from the turbine. We were advised that 5 bar steam could be produced in this way.

Larger cogeneration systems were found to offer economies of scale, with lower capital cost per unit of energy output. However this did not always mean that such systems achieved shorter payback periods. While small cogeneration systems are able to target peak electricity replacement, the larger systems rely more on the replacement of cheaper, off-peak electricity and this was found to have an adverse effect on their profitability that was greater than any capital cost benefits achieved through economy of scale.

[2] http://greenmarkets.com.au/, accessed 20 Oct 2016.

Most of the cogeneration systems modelled using the base case assumptions did not show a feasible payback period. Sensitivity analyses were also undertaken. The payback periods improved for all systems when electricity prices were increased relative to the price of fuel used for cogeneration. Similarly, lower fuel prices had a positive impact on payback periods. It would appear unlikely that natural gas prices will reduce in the future. However, alternative fuels may offer lower fuel costs in specific situations:

- If waste management at a meatworks necessitates anaerobic digestion, all forms of cogeneration that are partly or completely fuelled with the digester gas (biogas) could show a better payback than the same system operating only on natural gas. This is based on the premise that the cost of the digester gas is lower than the cost of equivalent natural gas.

- If a new heat plant is required, a plant that uses biomass (e.g. local wood wastes) as a fuel could show improved economic viability over a natural gas-fired unit. Such plants will have greater capital costs, however the lower cost of fuel may mean that the whole of life costs are better for a biomass system than a natural gas system. Selection of a sustainable biomass fuel that is eligible under the Renewable Energy Target will also mean that marketable renewable energy certificates may be created from the electricity generation.

Conclusions and recommendations

Cogeneration systems can be developed at a wide range of scales and using an equally wide variety of equipment. Australia has multiple vendors for the equipment considered (engines, micro-turbines, ORC units) and these vendors have commercial experience in Australia and overseas for cogeneration applications in a range of industries.

For the fuel costs and electricity costs that may be experienced across the meat processing industry, it was determined that cogeneration systems ranged from being uneconomic to offering attractive payback periods.

When a cogeneration system is operated smoothly at capacity reciprocating engines showed the best economics, however micro-turbines and ORC units provide greater flexibility in operation at partial load. All the systems can provide heat as useful hot water; alternatively ORC units and micro-turbines may be set up to provide heat as process steam.

All systems can use biogas (directly or indirectly) if it is available. ORC units use heat rather than fuel as their energy source, and they may also be coupled to a new biomass boiler when cheap local biomass is available.

The examples provided in this report can be of assistance in preliminary assessments of cogeneration at individual meatworks. For those meatworks that consider this report and believe that there is a case for more detailed investigation, the next stage could be via engagement with vendors. It is considered important to look at more than one technology for cogeneration so that the best possible match for each site's needs can be achieved.

It is recommended that AMPC follows up with its members after this report has been distributed to gauge the interest in further information. If there is sufficient interest AMPC could arrange for interaction with vendors, for example via a session at the national conference, or via webinars.

2.0 PROJECT DESCRIPTION

This project has investigated how two innovative new energy technologies – micro-turbines and Organic Rankine Cycle (ORC) units – can be used to reduce energy costs and greenhouse gas emissions in meat processing facilities. The outcomes are technical and cost benefit analyses that demonstrate how these units might be utilized by Australian meat processors.

A three stage project has been carried out:

- Stage one consolidated earlier work by AMPC and MLA and combined it with practical data on these particular technologies. A literature review and technical summary were prepared. The operation of the units and their use across various industries were discussed.
- Stage two applied this knowledge to a typical abattoir. It built on the preliminary work carried out in AMPC Project 5011, and a techno-economic model for meat processing facilities previously developed by All Energy Pty Ltd. It defined commercial outcomes that take advantage of the range of ORC and micro-turbine equipment available, tailored to the specific needs of the site. For comaprison, reciprocating engines have also been considered. Fuels modelled included natural gas and biogas.
- Stage three involved final reporting, discussion with AMPC, then dissemination of the project's information.

The report provides practical information for meat processors to use when considering such equipment. This will allow them to move ahead with more detailed appraisals and decisions.

3.0 PROJECT BACKGROUND

Energy costs for heat and power represent major operating costs for abattoirs. These costs have increased more than the consumer price index (CPI) in recent years and are expected to increase further in coming years.

Cogeneration (or CHP, combined production of heat and power) is increasingly seen by the meat processing industry as a way of improving energy efficiency, and thus reducing costs and also greenhouse gas emissions. MLA and AMPC have investigated cogeneration on several occasions over recent years, with a number of reports prepared on its various aspects. Most recently, work on AMPC project 5011 has identified micro-turbines and organic Rankine cycle (ORC) units as equipment worthy of further consideration for the provision of cogeneration in abattoirs.

Cogeneration is already used widely around the world. Examples of integrated energy use with the targeted technologies include:

a) Micro-turbines, providing:
   - Electricity, heating and cooling in buildings in Australia and globally, generally using natural gas as fuel.
   - Electricity from combustion of landfill gas and digester gas. Heat recovery is also possible.

b) Organic Rankine cycle units:
   - Generating electricity from underutilized boiler capacity, such as units already installed at saw mills and a food processing plant in Australia. (Waste heat from the ORC can also be recovered as hot water, with some loss in electrical efficiency.)

- Utilizing waste heat from large engines or industrial processes, such as the ORC unit installed in north Western Australia.
- Generating electricity from geothermal heat, such as the 23 MW ORC plant operated in New Zealand.
- Providing electricity and district or industrial heating at multiple sites in Europe.

In summary, these units show commercial viability at a range of scales and across a variety of applications. The applications for micro-turbines are often different to those for ORC units. This project has reviewed several different sizes and configurations for cogeneration using these units, combining data from experienced vendors with operating conditions for a typical meatworks. Cost benefit analysis is then used to assess commercial viability.

4.0 ABBREVIATIONS

AEPL	All Energy Pty Ltd (sub-consultant to Enecon for this assignment)
AMPC	Australian Meat Processor Corporation
ARENA	Australian Renewable Energy Agency
CBA	cost benefit analysis
CHP	combined heat and power
Cogen	cogeneration – a facility for the combined generation of power and heat
GHG	greenhouse gas
GT	gas turbine
hr	hour
HSCW	hot standard carcase weight
ISO	International Standards Organisation
kg	kilogram
kPa	kilopascals as unit of pressure (gauge)
KPI	key performance indicator
kVA	kilo volt amperes
kVAr	kilo volt amperes reactive
kW	kilowatts
kWc	kilowatts of cooling
kWe	kilowatts of electrical load / generation
kWh	kilowatt hour
kWt	kilowatts of thermal load / generation
LRET	large-scale RET (often referred to as the REC generated by the LRET part of the Federal Government's RET scheme)
MJ	megajoule
MLA	Meat and Livestock Australia Ltd
MT	micro-turbine
MW	megawatt
MWh	megawatt hour

ORC	organic rankine cycle
s	seconds (time)
S	entropy
ST	steam turbine
t	tonne (1,000 kg)
TCI	total capital investment
tpa	tonne per annum (year)
tpd	tonne per day
tph	tonne per day
tpw	tonne per week
W	watt (joule per second)
y	year

5.0 SUMMARY OF BACKGROUND LITERATURE

MLA report A.ENV.0095 advises that the combined factors of continually increasing energy costs and environmental policy, both current and future, justify close inspection of energy usage and energy sources for the Australian meat industry (MLA, 2010)[3]. MLA, AMPC and industry partners acknowledge that reducing energy consumption is an important challenge for the industry, and aim to achieve a 10% reduction in consumption (among other environmental objectives)[4] within the next few years, by a combination of projects and initiatives[5].

Cogeneration is one energy strategy that can be implemented. It is also known (particularly overseas) as combined heat and power (CHP). Simply defined, cogeneration is the coproduction of two forms of useful energy, most commonly electrical and thermal, from a single fuel source; offering increased energy efficiency and operational benefits in economic and environmental terms.

The NSW Government Office of Environment and Heritage outlines the following general indicators that a cogeneration project will be successful at a particular site (NSW Government, 2014)[6]:

- When there is significant, simultaneous need for thermal and electrical energy.
- Thermal requirements greater than electrical loads.
- Constant loads and long operating hours.
- Access to a “free” energy source.

[3] Meat & Livestock Australia Limited, 2010, *Renewable Energy and Energy Efficiency Options for the Australian Meat Processing Industry*
[4] Australian Meat Processor Corporation, *Energy*, available http://www.ampc.com.au/site/assets/media/Factsheets/Food-Safety-Meat-Science-Market-Access-Marketing-Consumer/Energy-environmental-best-practice-manual.pdf
[5] Meat & Livestock Australia Limited, 2014, *Energy Consumption,* available http://off-farm.mla.com.au/Environment/Energy-consumption
[6] NSW State Government Office of Environment and Heritage, 2014, *Cogeneration Feasibility Guide*, available from http://www.environment.nsw.gov.au/resources/business/140685-cogeneration-feasibility-guide.pdf

When considering the feasibility of implementation of cogeneration with greater specificity, AMPC 2013.5011 reports that for each meat processing facility there will be a minimum value for cogeneration to become technically viable, and that larger scale shows more scope for the feasibility of implementing cogeneration. Ongoing increases in energy costs and greater competition by equipment manufacturers would both increase the attractiveness of cogeneration.

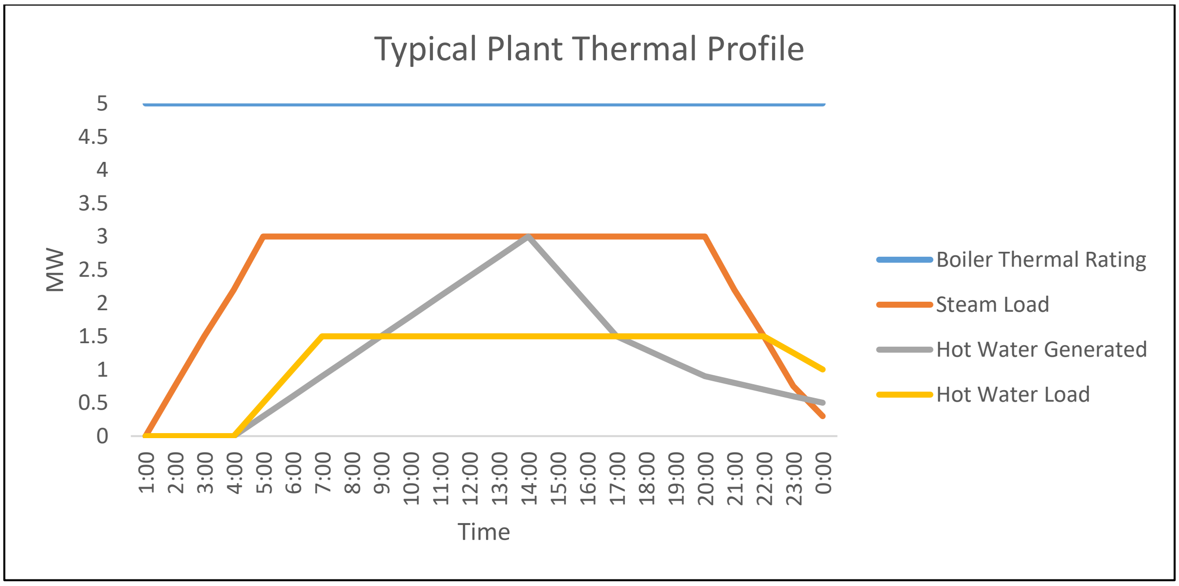
Although the energy demand of a meat processing plant is obviously dependent on throughput and on-site operation (e.g. with or without rendering), the most recent KPIs developed by MLA give a mean of 3,389 MJ per tHSCW (ranging from 2,000-6,000)[3], of which electricity accounts for approximately one third, steam approximately one half, and hot water the remainder[7].

MLA report A.ENV.0102 describes the following potential benefits of implementing cogeneration technology in a meat processing facility (MLA, 2010)[8]:

- Reduced on site energy costs through increased energy efficiency.
- Increased reliability, security, and quality of electricity supply.
- Reduced GHG emissions.
- Less sensitivity to future electricity price increases.
- Opportunities to move towards more decentralised electricity generation, meeting site needs while also providing high efficiency, flexibility, and avoiding transmission losses.

The sketch in Figure 1 below is based on site visits by All Energy Pty Ltd (AEPL), and shows the typical thermal profile of a representative meat processing facility.

Figure 1: Indicative thermal profile of a typical meat processing facility



[7] Colley, T, 2007, *Meeting Heat and Power Loads Down Under – Australian Meat Processing Plants are a Fine Match for Cogeneration.* Available from http://www.cospp.com/articles/print/volume-8/issue-6/features/meeting-heat-and-power-loads-down-under-australian-meat-processing-plants-are-a-fine-match-for-cogeneration.html

[8] Meat & Livestock Australia Limited, 2010, *Economic and Technical Potential for Cogeneration in Industry*

Some of the justifications for this study are illustrated in the example above:

- A typical plant may have a significant amount of spare boiler capacity, shown as the vertical difference between the boiler thermal rating and the actual steam load.
- A considerable amount of spare low-grade heat may be available once rendering heat recovery comes online, shown as the large triangular area between the hot water generated and hot water load.

This observation is also supported by AMPC's *Energy Consumption Guide for Small to Medium Red Meat Processing Facilities,* which suggests that in the area of cogeneration, significant improvement can be made in the area of system sizing, matching output with demand to avoid oversupply of energy. When considering existing oversized boiler plant, it is evident that significant heat reclaim opportunities during steam generation, distribution, and usage exist at such plants[9].

To address the steam distribution and usage aspects of thermal efficiency, AMPC report 2013.5011 (AMPC, 2015)[10] provides initial guidance on known and emerging cogeneration technologies that are deployable and available in Australia, yet not necessarily mainstream in the red meat processing industry. Of particular interest in that report was the exploration of cogeneration via combustion micro-turbines and organic Rankine cycle (ORC) units integrated with existing or new boiler plant.

6.0 TECHNOLOGY REVIEW

6.1 Organic Rankine cycle units

Steam turbines convert thermal energy into mechanical energy via the Rankine cycle, with water as the working fluid. The thermodynamic principles for organic Rankine cycle (ORC) units are identical to those of steam turbines, however the operational temperatures and pressures differ. This is made possible by using an organic (carbon-based), high molecular mass working fluid instead of water. There are many such fluids and they can provide a liquid-vapour phase change at a lower temperature than the water-steam phase change. Thus, ORC technology has many possible applications with respect to cogeneration; particularly for the ability to recover low grade waste heat from processing, as low as 85°C in current operation in European food processing plants. Refer to Figure 2 below for a general schematic and explanation of steps of commercially available ORC plant[11]. Figure 3 below shows a typical ORC unit as a skid-mounted assembly in an industrial setting.

Experienced ORC unit vendors may recommend one of a variety of readily available organic liquids as the working fluid for a particular ORC unit. The choice is heavily dependent on operational temperatures, pressures, and other auxiliary thermodynamic considerations. For an in-depth technical exploration of ORC

[9] Australian Meat Processor Corporation, *Thermal Energy Use in Meat Processing Plants,* available http://www.ampc.com.au/site/assets/media/Climate-Change/Energy-Efficiency-Research/8.-Thermal-energy-use-in-meat-processing-plants.pdf

[10] Australian Meat Processor Corporation, 2015, *Options to Maximise Process Heat Recovery at Red Meat Processing Facilities*

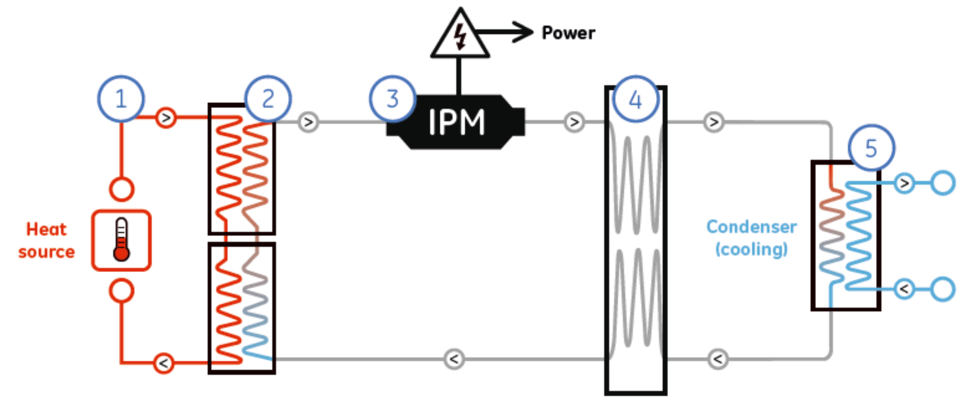
[11] GE Power & Water, Distributed Power, 2014, *Clean Cycle II R-Series Technical Specification,* retrieved from https://powergen.gepower.com/content/dam/gepower-pgdp/global/en_US/distributed-power-downloads/documents/factsheet_ge_cleancycleii_r_en_2014.pdf

technology (which will not be reproduced here for the sake of brevity), refer to *Potential for ORC Application in the Portugese Manufacturing Industry,* Universidade Nova de Lisboa, 2014.

ORC systems for heat recovery have found good application around the world in a range of sizes and industries. Turboden are a major supplier of ORC equipment; their website lists more than three hundred units built and installed around the world in various applications over the past thirty-five years[12]. There are twenty-five references to plants successfully utilising ORC units for electricity generation via heat recovery. A few examples of these are:

- 4000 kW system, Holcim S.A., Romania, cement industry.
- 2200 kW system, ORI Martin S.p.A, Italy, steel industry.
- 600 kW system, Stadtwerke Kempen GmbH, Germany, internal combustion engine.
- 1300 kW system, Gea Bischoff/AGC, Italy, glass industry.

Figure 2: Schematic of commercially available ORC plant[11]



1. Thermal energy is brought to the Clean Cycle II system's heat exchangers through a pressurized hot water, steam, or thermal oil loop.
2. The working fluid in the Clean Cycle II system is pumped through its heat exchangers and changes state from a liquid to high pressure vapor.
3. The high pressure vapor enters the Integrated Power Module (IPM) and expands across a turbine generator, causing it to spin and generate power.
4. Low pressure vapor is pumped from the heat source through the recuperator to optimize energy efficiency.
5. A condenser cools the vapor to a liquid and then is pumped back across the recuperator and to the heat source.

Examples of ORC units in Australia and New Zealand, include:

- A prototype unit of 25 kWe at a saw mill in Victoria, where it uses excess steam from a biomass boiler to generate electricity for use on site.
- A 600 kWe unit at a food processing facility in Victoria. This site burns its own waste biomass as fuel and uses spare boiler capacity to drive the ORC unit and generate electricity for use on site.
- A 240 kWe unit at a saw mill in Queensland. This unit is connected into the thermal oil system at the mill and excess energy from combustion of saw mill residues is used to generate electricity, for on-site use or export.

[12] http://www.turboden.eu/en/references/references.php

- An oat milling company in Western Australia is using its residues as fuel in an onsite boiler and excess energy can be employed to drive an ORC unit for local power.
- In New Zealand, large organic Rankine cycle units are used with geothermal heat to generate electricity. Plants use one or more ORC units and overall plant outputs range from 2.5 MWe to more than 100 MWe[13].

Figure 3: Skid-mounted ORC unit (Turboden)

6.2 Micro-turbines

Micro-turbines, or combustion micro-turbines, are small gas turbines, most of which feature an internal heat exchanger called a recuperator[14]. In a micro-turbine a radial flow compressor is used to compress the inlet air, which is then preheated in the recuperator using heat from the turbine exhaust. The heated air mixes with fuel (such as natural gas) and is combusted, and the hot combustion gas is expanded through the turbine. In single shaft models this drives both the compressor and the generator. Single shaft models typically operate at speeds of 60,000 rpm or more.

The hot exhaust gases are passed through the recuperator to preheat the feed air. They may then be used for additional heat recovery, typically as hot water for space heating or to drive absorption chillers for cooling applications when micro-turbines are used in commercial buildings.

[13] http://www.ormat.com/global-project
[14] http://www.slideshare.net/AbrarAmin/microturbine

Micro-turbines with recuperators can achieve electrical efficiencies of 30% or better when operating at ISO conditions. This efficiency is reduced with increased ambient temperature, increased altitude and operation at partial load[15].

Micro-turbines in commercial use have shown a number of useful attributes:

- They are very reliable – with availability as high as 98%.
- Operation can be unattended and monitored remotely.
- They are quiet.
- They have lower emissions than reciprocating engines.

Individual micro-turbines from commercial suppliers range in size from 30 kWe to 250 kWe. Some vendors package multiple units together to offer container-sized plants capable of up to 1 MWe of power generation.

International vendors in this space include Ansaldo Energia S.p.A, Bowman Power Group Ltd., Capstone Turbine Corp., Elliott Co. Inc., and FlexEnergy Inc. Capstone has sold several thousand units world-wide since 1998[16]. The most common applications for such micro-turbines are for CHP or CCHP in office buildings, educational facilities, hotels and motels.

The main alternatives to micro-turbines are reciprocating engines also operating on natural gas or bio-gas.

The Brayton cycle

The thermodynamic cycle for gas turbines is the Brayton cycle. Although technically not a cycle as it occurs in open configuration, it can be idealised and closed by the application of the air standard assumptions:

- The working fluid is air and it behaves as an ideal gas.
- The cycle is modelled as closed with the air cooled before recirculation to the compressor.
- The combustion chamber is idealised as a heat exchanger.
- All processes are internally reversible.

The cycle can be represented schematically and on the temperature – entropy (T – S) diagram as shown in

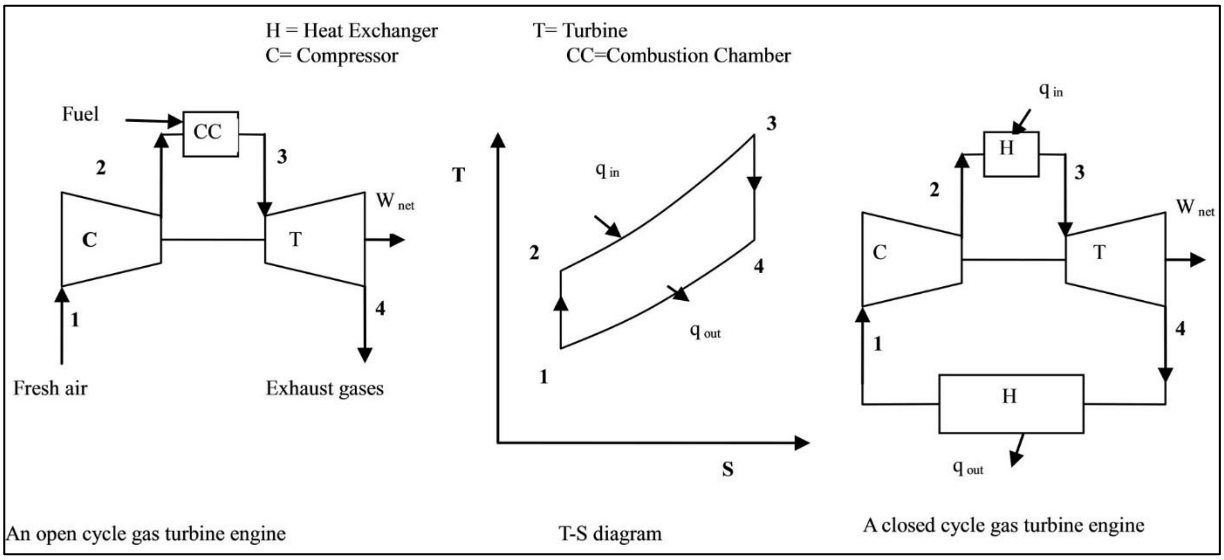
[15] Technology Characterisation: Micro-turbines – Prepared for the US EPA by Energy and Environmental Analysis, December 2008

[16] http://foresternetwork.com/daily/energy/cogeneration/microturbines-power-to-the-people/

Figure 4. The steps of the Brayton cycle are:

- 1 – 2 Isentropic compression.
- 2 – 3 Constant pressure heat addition.
- 3 – 4 Isentropic expansion.
- 4 – 1 Constant pressure heat rejection.

Figure 4: Schematic representation of the Brayton cycle, and associated T - S diagram[17]



6.3 Steam micro-turbines

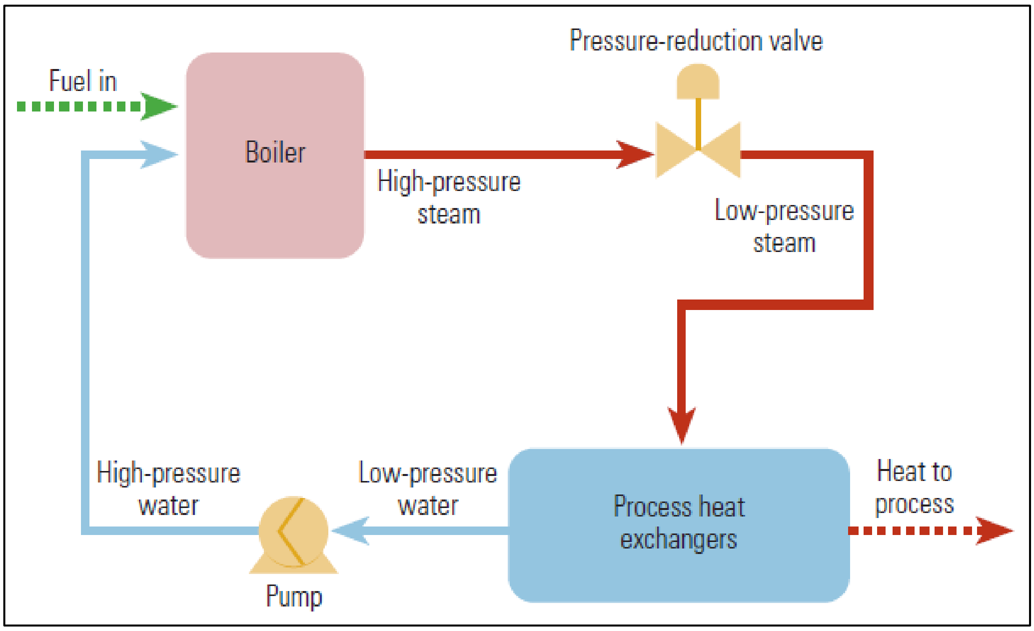
The terms 'micro-turbine' and 'pressure reduction micro-turbine' are also used to refer to small steam turbines that capture energy during pressure reduction in steam lines. Such turbines are outside the scope this project, however we have summarised them here to avoid any confusion with combustion micro-turbines.

In the typical meat plant (refer Figure 5 below), steam is produced at pressures in excess of process requirements, and a series of pressure reduction valves (PRV) reduce this pressure at various points in the steam network. The case for cogeneration here is that the fuel energy it took to raise the steam pressure is effectively wasted at the PRV, and that by employing steam micro-turbines (instead of a PRV) to harness this currently wasted energy, significant savings in energy costs can be made[18,19,20].

The examination of steam micro-turbines was not a part of the brief for this project.

[17] http://file.scirp.org/Html/4-6401034%5Cd944a9ab-4e84-4a8f-b67c-a7953af3e28e.jpg
[18] Casten, S, 2005, *Recycling Waste Pressure into Electricity*. Turbosteam Corp.
[19] Turbo Steam, 2011, *Backpressure Steam Turbines for CHP Applications,* available from http://files.harc.edu/sites/GulfCoastCHP/CHP2011/Bullock_backpressure_CHP2011.pdf
[20] Micro-turbine technology - Reduce steam pressure and generate electricity - www.spiraxsarco.com/uk

Figure 5: Typical thermal plant schematic[21]



7.0 COGENERATION

7.1 Forms of cogeneration

Cogeneration involves the Combined generation of Heat and Power and for that reason it is also abbreviated to CHP. The main benefit of cogeneration over generation of just heat or power alone is that the recovery of useful (and valuable) energy is greater. Electricity generation via combustion plant typically achieves conversion efficiencies (energy in the fuel recovered as electrical energy) in the range of 20 to 30%. However, depending on customer needs and plant configuration, cogeneration can achieve double or triple these conversion efficiencies overall. In many situations this can create a compelling commercial argument for construction and operation of a cogeneration plant.

There is a wide variety of equipment that can use steam to generate electricity. Condensing and back-pressure steam turbines are routinely used to achieve this in some industries. The focus of this project is to examine the use of ORC units and combustion micro-turbines. A number of configurations are possible to achieve cogeneration with these units, as described below.

Power generation via ORC unit and underutilised boiler capacity

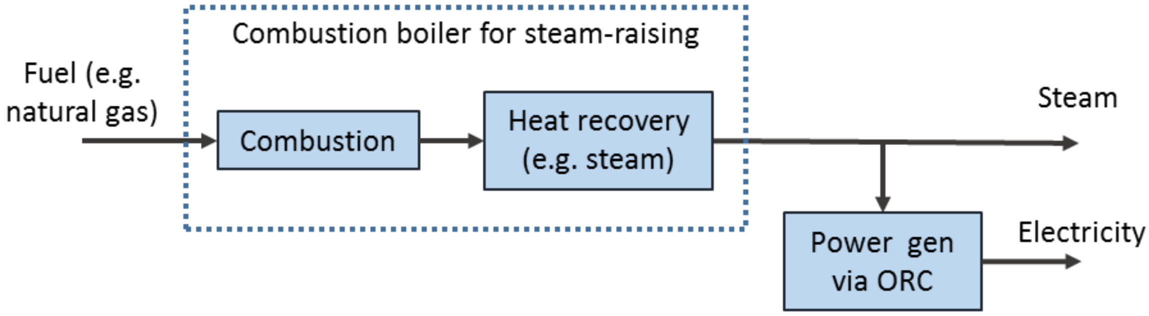
The operation of boilers in meatworks follows the needs for process heat in the facility. These requirements vary with activities during the shift and non-shift periods and, as a result, the boiler is not run at capacity all the time to make process steam. This unused boiler capacity could be used to drive an ORC unit and generate

[21] Australian Meat Processor Corporation, *Thermal Energy Use in Meat Processing Plants,* available http://www.ampc.com.au/site/assets/media/Climate-Change/Energy-Efficiency-Research/8.-Thermal-energy-use-in-meat-processing-plants.pdf

electricity. Instead of sending all the steam to the plant, some or all of it could be diverted to the ORC unit, as shown in Figure 6 below.

ORC units are flexible; they can respond rapidly to variations in steam supply and also operate quite efficiently at low steam rates relative to their design maximum. However, the generation of additional steam (over and above the process needs) for the ORC unit does require the use of additional fuel.

Figure 6: Electricity generation using an ORC unit and spare boiler capacity



An ORC unit can be incorporated into an existing boiler system. Alternatively it can be installed as part of a boiler upgrade, expansion or replacement.

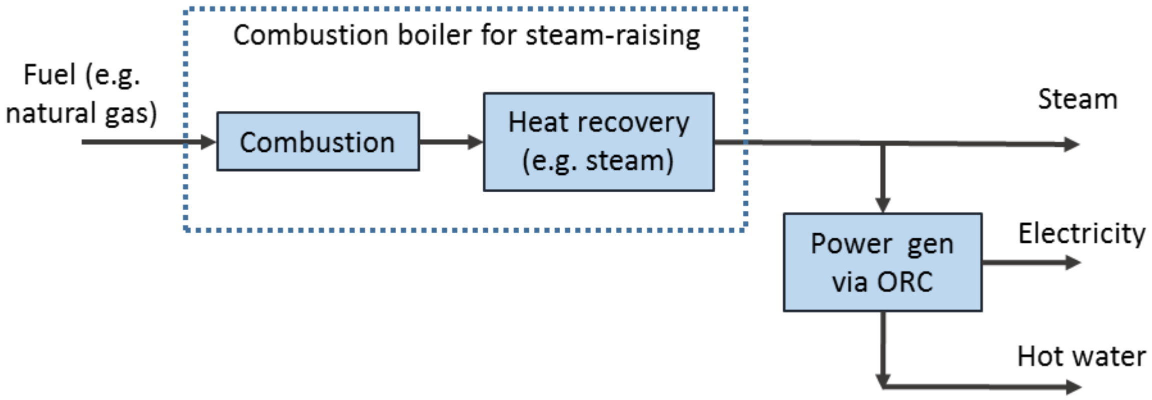
Power and hot water via ORC unit and underutilised boiler capacity

ORC units can be configured to maximise electricity generation. With suitable steam temperature as much as 26% of the incoming energy in the steam can be converted into electricity. When the ORC is operated to maximise electricity generation the exhaust energy from the ORC is removed at low temperature, via a cooling tower or air coolers. No useful heat recovery takes place.

Alternatively the ORC unit can be configured to produce electricity plus useful hot water (see

Figure 7 below). The energy converted to electricity is diminished but overall energy recovery is increased. The hot water can be produced at temperatures up to 120 ^{0}C (using increased pressure to maintain the liquid state). The preferred operating configuration and the relative outputs of electricity and hot water are quite flexible and can be chosen to best suit the needs of each site. In this configuration the hot water created via the ORC unit will reduce the amount of hot water that may have been produced previously via process steam.

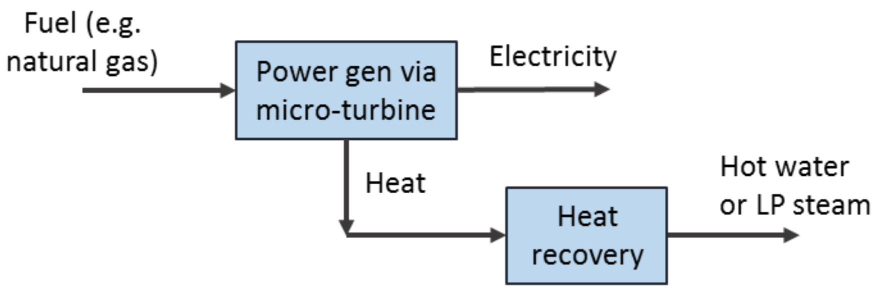
Figure 7: Electricity and hot water generation using an ORC unit and spare boiler capacity



Power and heat via micro-turbine

Whereas ORC units are driven by a heat source such as steam (or thermal oil), micro-turbines require a fuel source such as natural gas. They are used in the main to generate electricity, but much of the energy in the hot combustion exhaust gases can be recovered and used to heat water or even generate low pressure steam[22].

Figure 8: Electricity and heat generation using a combustion micro-turbine



7.2 Trigeneration

Trigeneration involves the Combined generation of Heat, Power and Cooling and is also referred to as CCHP or CHPC. It increases the opportunities available to cogeneration by providing an additional use for excess heat.

Absorption chillers can be used in trigeneration systems, as they provide cooling or refrigeration. They do this via an absorption cycle: heating two different substances that are in thermal equilibrium to separation, then reuniting them and simultaneously achieving heat removal.

[22] do Nascimento *et al* - Micro gas turbine engine: A review. Available at http://cdn.intechopen.com/pdfs-wm/45114.pdf

Heat can drive the absorption process, so absorption chillers can be combined with cogeneration units to provide trigeneration. The heat input and removal, which is achieved using a vacuum under varying pressure conditions (~8-70 mbar), brings the materials in the absorption unit into imbalance, thereby forcing them to undergo desorption or absorption:

- Water acting as the refrigerant and lithium bromide salt acting as the absorbant are generally used for the generation of chilled water in the temperature range 6-12°C.
- Alternatively, when using ammonia as the refrigerant and water as the absorbant, lower temperature chilling down to -60°C can be achieved[23].

Trigeneration systems are already operating at commercial sites in Australia. A typical example is the office development at 990 Latrobe St in Melbourne, where a natural gas-fired stationary engine provides:

- Peak electricity 386 kWe
- Peak cooling 290 kWt
- Peak heating 230 kWt

This system achieves 77% energy efficiency overall and, even with energy provided by a fossil fuel, it contributes to the building achieving a 6 star rating by the Green Building Council of Australia[24].

7.3 Major variables for cogeneration

The theory behind cogeneration is quite straightforward, however the optimal utilisation and commercial viability of equipment will vary with the source of energy and client requirements. The development of commercially viable projects for the red meat industry can utilise experience and equipment already in use in other industries. But success will also depend on a range of factors that are specific to this industry, including:

1. Variability of use for both electricity and heat within the abattoir over each day – a cogeneration plant represents a significant capital cost and its commercial viability is improved if its hours of operation at, or close to, capacity are maximized. Its integration into an abattoir should seek to achieve this. A related issue is whether the cogeneration unit is sized to address base energy load or peak energy load for the abattoir.
2. Scale – larger cogeneration systems generally offer lower unit costs because they achieve economies of scale (although this is less so for micro-turbine plants, which normally achieve scale via duplication and not by larger individual units). However, building a larger cogeneration plant may also mean that for extended periods it only achieves partial utilization on energy needs within the abattoir. It is possible to sell excess electricity via the grid, but the associated complexities, grid connection costs, and lower returns for such wholesale electricity sales versus on-site use, can mean that such export may not be worth pursuing.
3. Abattoir configuration – in particular whether it operates a rendering plant and has on-site refrigeration and exporting facilities.
4. The ability of the abattoir's existing boiler(s) to meet current, and future, energy needs. As previous reports have noted, cogeneration has a better chance of commercial viability if it is introduced to coincide with planned system change and capital expense. Micro-turbines and ORC units can all provide heat and power, however the ORC units are driven by heat while micro-turbines would be fuelled directly by

[23] https://www.clarke-energy.com/gas-engines/absorption-chillers/
[24] http://cogentenergy.com.au/990-la-trobe-street-melbourne/

natural gas (or biogas). So micro-turbines typically offer new capacity whereas ORC units can offer new capacity or a reworking of existing boiler capacity.

5. Electricity to heat ratios differ for micro-turbines and ORC units. They are different again to other forms of cogeneration, such as reciprocating engines. So the relative costs for heat and power within the abattoir and the ability to satisfy base load for one or the other will influence the choice (and size) of equipment.
6. Available space, within or adjacent to existing energy plant. Micro-turbines and ORC units can all be presented in modular fashion. Gas, electricity and steam lines can all be extended if a new plot is needed for the cogeneration plant, however the cost of such works must be included in the planning and financial evaluation for the project.
7. Planning and permits – only equipment and systems that are capable of meeting necessary requirements will be considered in this report.
8. Units available – ORC units are readily available in a wide range of sizes, from several hundred kWe to several MWe. Micro-turbines typically come in sizes up to 250 kWe and can be installed in multiples to create larger cogeneration plants. Each of these technologies has a different peak efficiency, and the electrical efficiencies will generally reduce during operation at partial load and, in the case of ORC units, optimization for electricity and heat recovery as opposed to only electricity generation.

8.0 MATCHING COGENERATION TO ENERGY USE

As described above, cogeneration (and trigeneration) via ORC units and micro-turbines can be developed at a wide variety of scales and configurations. Technical and commercial success will be achieved when the each configuration is matched closely to the energy needs of the meat processing facility. A "typical facility" and initial cogeneration choices are described below.

8.1 Meat processing facility basis of design – typical facility

A "typical facility" for an Australian meat processing facility is outlined in Table 1. A mass and energy balance was developed by AEPL for this facility as the basis for the characterization and comparison of cogeneration systems.

Table 1: Basis of design: A "typical" red meat processing facility

Basis of Design			
General			
Site Location		Qld, Australia	8
Head Processed per day	Head pd	625	9
HSCW tonnes / head		0.24	8
Plant Operating Schedule			
Available operating hours per day	h	16	8
Available operating days per year	d	250	8
Operating hours per year	h	4000	6

8.2 Power load profile

A typical energy consumption profile for a 2-shift-per day facility (corresponding to the plant present in Table 1 above) was developed based on averaged weekday and averaged weekend data. The maximum load occurs when boning periods, initial stages of carcass cooling and ambient conditions are hottest, in particular from 11am to 5pm, Monday-Friday. The weekend electricity consumption was approximately half that of a weekday profile.

Table 2: Electrical consumption data - typical facility

Basis of Design				
Plant Operating Schedule				
Available operating hours per day		h	16	8
Available operating days per year		d	250	8
Operating hours per year		h	4000	6
Electrical Supply System				
Source			Grid	8
Unit cost		$/kWh,	23	8
Unit consumption	kWh/t HSCW	kWh/t	317.2	10
Total consumption		kWh/day	47580	
Total Consumption Continuous equivalent		eMW	1.98	
Total Consumption- during shift		eMW	2.97	

Table 3: Power requirements in a typical meat processing facility[25].

Power load	% of annualized electricity use
Refrigeration	42.6
WWTP: DAF and aerators	11.6
Lighting	8.3
Boning room	8.9
Rendering plant	6.8
Compressors	5
Boilers	3.7
Value add	2.4
Water dist.	2.3
Kill floor	1.3
Admin	0.9
Other	6.2

[25] AMPC / MLA Report A.ENV.0090 Env Data Analysis July 2011.

Daily electrical demand profiles are shown in Figure 9 and Figure 10 for a typical meat processing plant operating on a weekday and weekend respectively.

Figure 9: Weekday demand profile for a typical facility.

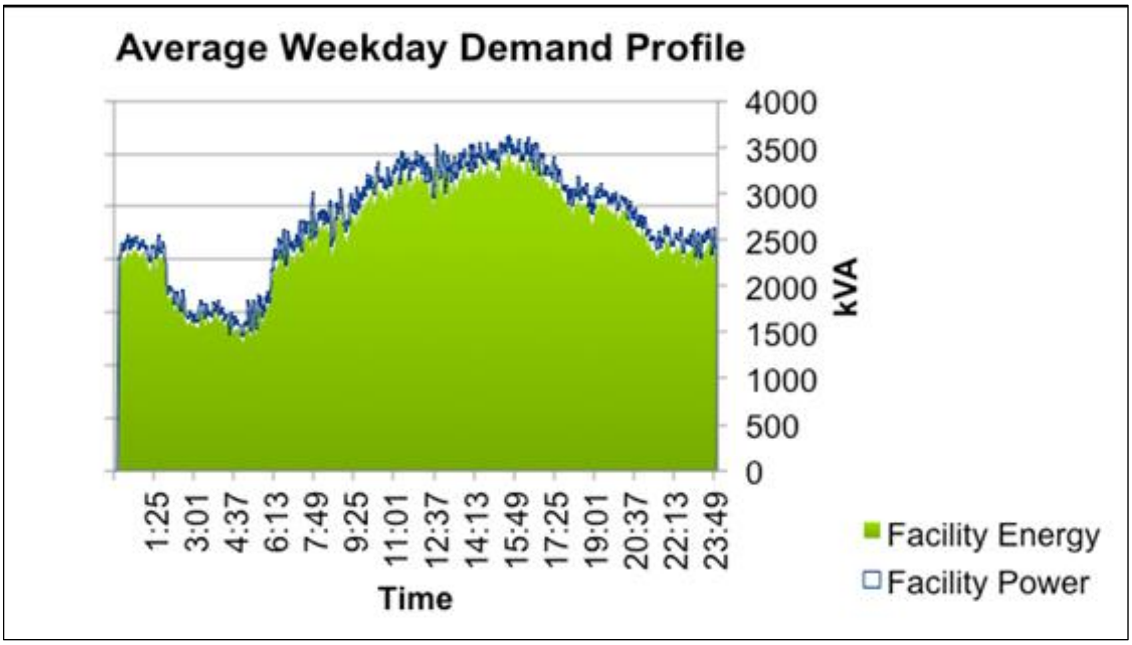
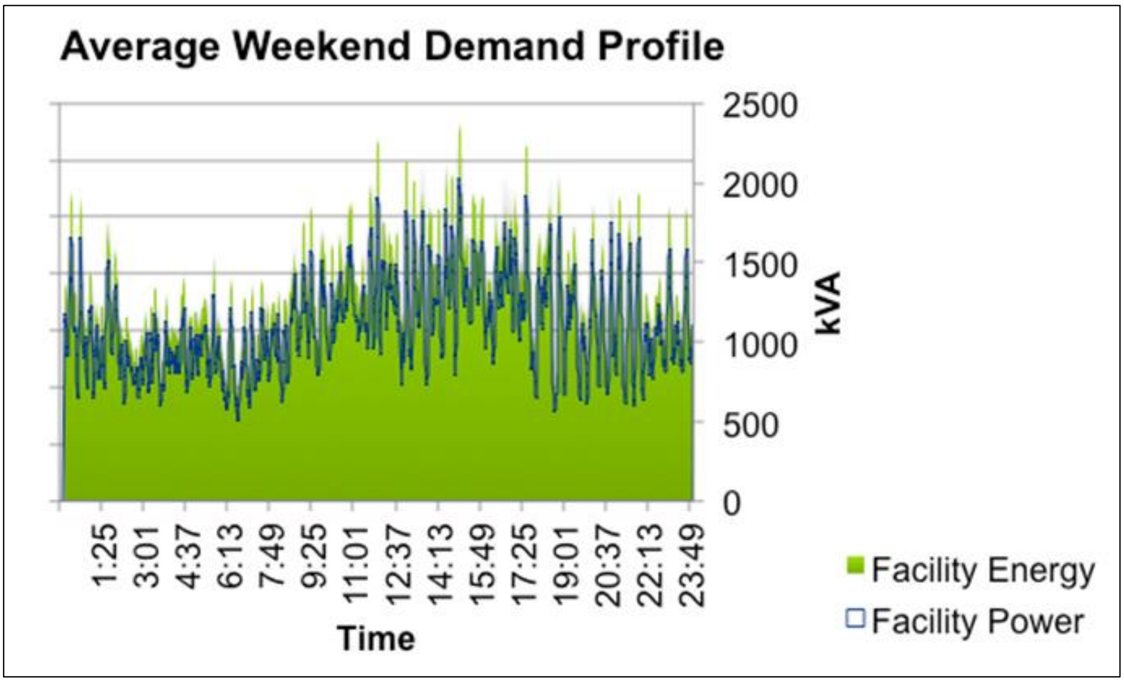


Figure 10: Weekend demand profile for a typical facility



If on-site electrical generation is being considered, it can be seen from the figures above that the scale of the generating equipment will have a large impact on its utilisation. Consider three different plant sizes for electricity generation:

a) A unit capable of providing 3,500 kVA (net) will supply all electricity for the peak load on this site. In theory, there would no longer be a need for electricity to be purchased from the grid. However for much of the shift this large generator would be only partially utilised for on-site power, and at weekends the on-site power needs could be met by the unit operating at less than half its capacity. Such operation would adversely affect the efficiency of the unit.
b) A unit sized to provide 1,500 kVA will operate at capacity to supply the base load during shift. Peak electrical needs during plant operation will have to come from other sources. In contrast, at the weekend this on-site unit it will be considerably oversized.
c) A smaller unit, sized to provide approximately 700 kVA, will be able to operate continuously at capacity for the provision of power solely to the meat works.

The larger plants are of interest because they typically offer significant economies of scale, meaning that if operating continuously at capacity they will provide lower cost power. Partial utilisation diminishes this benefit. It may be possible to compensate for reduced on-site demand by using excess capacity to generate electricity for sale into the grid, but such “export” sales are likely to be at a much lower value than for the electricity that is generated for on-site use. Also, such sales require a separate power purchase agreement and additional equipment for grid connection.

The smallest plant has the benefits of steady operation for more hours each year, and all of its electricity going to the more valuable use (on-site, rather than export to the grid). Against this, such a generator will be more capital intensive per unit of output.

Another factor that could influence the sizing of a cogeneration unit is the potential for using heat to drive an absorption chiller that could help the site to meet its needs for refrigeration. Use of heat in this way would reduce the site electrical load, with the scale of the reduction dependent on a number of factors. The absorption chiller could represent a relatively consistent use for heat from a cogeneration plant, however the other energy uses on site are more variable and this may limit the extent to which a cogeneration plant can be “matched” to all the on-site energy needs.

8.3 Thermal heat load profile

Presented in the tables below and associated figures are the various thermal heat sinks for a typical meat processing facility.

The overall use of steam will vary through each shift in a way that reflects the particular operating needs of the facility.

Figure 11 below provides an indication of this, showing steam load from 2 am through to 1 am the following day for a meat processing plant with single shift operation[8]. Peak steam use, around 9 am, is 5 MWt.

Table 4: Summary of fuel usage in a typical meat processing facility

Natural gas assumed as fuel	Number	Units
Unit consumption	2241	MJ / t HSCW
Total consumption	336,150	MJ / day
Approximate annual cost @ $9 / GJ	756,338	$ pa
Approximate annual cost @ $12 / GJ	1,008,450	$ pa
Total consumption - continuous equivalent	3.89	MWt
Total consumption - during shift	5.84	MWt

Table 5: Summary of steam and hot water usage in a typical meat processing facility[26]

Steam heat sink	% natural gas consumption
Rendering	63.40%
Hot water make up	11.80%
Boiler house losses	10.00%
Blood processing	8.50%
Piping losses	4.20%
Tallow processing	2.10%

Hot water heat sink	% hot water consumption
Sterilizers	34.10%
Hand wash stations	5.70%
Kill / evisceration	17.00%
Cleaning	28.40%
Amenities	5.70%
Tripe washing	2.30%
Hook wash tanks	1.10%
Piping losses	5.70%

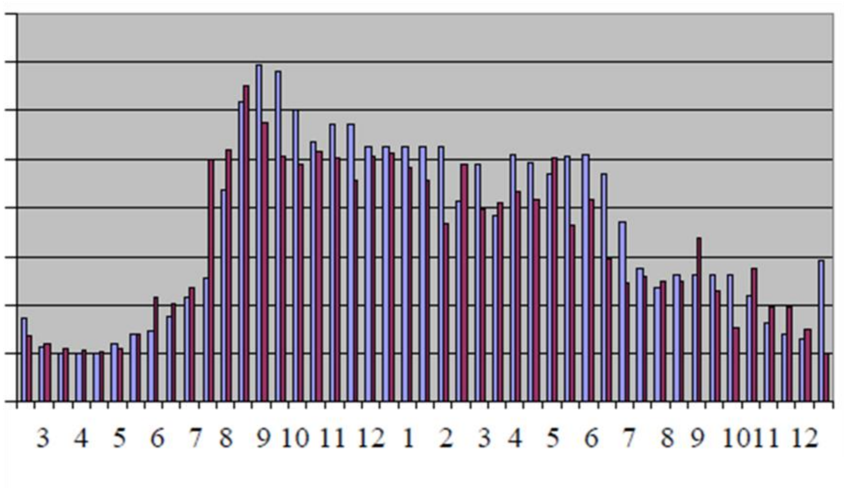
Table 6: Potential use of low grade heat – incoming process water pre-heating: process (potable mains) water usage in a typical meat processing facility

Basis	Number	Units
Volume	ML / day	2.4
Supply Temperature	°C	20
Use per head	kL / head	3.8

[26] AMPC / MLA Report A.ENV.0090 Env Data Analysis July 2011.

An ORC unit could be installed at this site to use the boiler capacity that is not serving the plant steam requirements at any particular time. And if some of the initial steam needed for the shift is associated with production of hot water, additional hot water production via the waste heat from the ORC unit may improve the overall energy efficiency on the site. As with the above example for electricity generation, the optimisation of a system and associated payback will vary from site to site and will generally require a thorough understanding of the site energy needs and the impacts of cogeneration units at several scales and using a variety of equipment.

Figure 11: Steam flowrates, red meat processing plant, single shift, Thursday (blue) and Friday (red)



9.0 EQUIPMENT VENDORS

To facilitate project modelling and cost benefit analysis, a number of vendors were approached to provide budget pricing for suitable CHP systems. Restrictions were set as to the vendors approached. Most importantly they needed to have an active presence in Australia and operating plant in Australia. Pre-commercial equipment and equipment without representation in Australia have not been included in this report as it is felt that there is little likelihood that such equipment would be considered by AMPC members in the near term.

Several vendors were considered in each category. This list is not necessarily exhaustive and there is no intention to suggest that the vendors selected are in any way more appropriate than other vendors.

9.1 Organic Rankine cycle (ORC) units

Data collection

Three companies were approached for budget pricing on ORC units. All companies are represented in Australia and have units operating here. While all companies provide ORC units, it must be remembered that such units may be designed for a wide variety of conditions and sizes, and each company favours a particular set of outputs and operating conditions for their units:

- **Verdicorp**[27] offer individual ORC units that range from 60 – 1,260 kWe in gross electrical output, and use a variety of heat sources (including steam) with temperatures up to 160 ^{O}C. Heat recovery from the ORC units for this analysis is as hot water at 90 ^{O}C.

- **g-TET**[28] offer ORC units sized across the target range of 250 – 1,000 kWe of gross electrical output and capable of using process steam in a meatworks (in this case, saturated steam at 8 bar). Heat recovery from the ORC units for this analysis is as hot water at 90 ^{O}C.

- **Turboden**[29] offered systems somewhat different to those of Verdicorp and g-TET. Turboden can provide standalone ORC units with electrical output as small as 250 kWe, but most of their units are 1,000 kWe or larger. They have also teamed with European combustion plant company Bono Sistemi to offer integrated systems. Using natural gas or biomass as fuel, these systems heat thermal oil that is then used to simultaneously generate electricity via the ORC unit and steam via a boiler. The boiler can be designed to provide 5 bar steam such as that used in many meatworks.

The approach taken in this case by Turboden offers useful process steam but is based on a need for new boiler capacity at the site under consideration.

The equipment offered by these vendors is summarised in Table 7 below:

Table 7: ORC units considered for project

Offering for this report	***Turboden***	***g-TET***	***Verdicorp***
Size of individual ORC units for CHP (kWe gross)	600 – 3,000	25 – 1,000	60 - 500
Input temperature for heat to ORC unit	Thermal oil	Wide range, including 8-10 bar steam	135 -150 ^{O}C
Thermal plant for heat source	Included	Separate	Separate
Heat output	Process steam	Hot water	Hot water
Pricing provided for this report?	Yes	Yes	No

Summary of costs

The following pricing for g-TET units provides an indication of the installed costs for an ORC unit[30].
g-TET offers ORC units plus heat recovery. With additional costs added in by the authors, the overall budget pricing for ORC units by g-TET as installed systems is as follows:

[27] http://www.verdicorp.com/
[28] http://www.g-tet.com/
[29] http://www.turboden.eu/en/home/index.php
[30] Turboden provided comprehensive pricing for a combined thermal plant and ORC system. Verdicorp did not provide pricing.

Table 8: Budget pricing for installed cost of ORC units

Gross capacity (kWe)	***250***	***500***	***1,000***
Budget price	900,000	1,200,000	2,000,000
Additional items *	540,000	715,000	1,200,000
Total installed price	1,440,000	1,915,000	3,200,000
Installed cost per kWe	5,760	3,830	3,200

* Civil and structural works, connections, project management etc.

Efficiencies

The gross electrical efficiency of an ORC unit will vary significantly according to the conditions of operation, with units proposed in this project showing efficiencies from 26% to as low as 15%. Higher temperatures for the source of thermal energy tend to facilitate higher efficiencies.

The efficiency is also influenced by whether or not the unit is operating for power only or in cogeneration mode. The recovery of thermal energy (such as 90^{O}C water in this project) reduces the electricity generated.

Finally the parasitic loads vary between units and it is important to look at the net efficiencies as well as the gross efficiencies when considering the useful electricity that may be recovered.

9.2 Micro-turbines

Data collection

Data was requested from organisations with Australian presence and local micro-turbine (MT) project experience. Contacts and responses are summarised in the table below. Also referenced is a major report by the CHP Partnership of the US EPA, published in March 2015[31]. It provides standalone data for the USA gathered from many operating micro turbine CHP systems, and has also been used as a cross reference for local costs.

Table 9: Micro-turbines considered for project

Micro turbines (MTs)	**Data provided**
Optimal – supply Capstone MTs	Cost data provided for equipment supply and operation & maintenance.
Aquatec Maxcon – supply Flex Energy MTs (formerly Australian supplier of Capstone)	Cross reference provided between the US EPA report and Aquatec Maxcon's Australian experience with hundreds of MTs and engines.
US EPA - CHP partnership report	Cost data for USA - equipment costs , installed costs and O&M costs averaged for multiple CHP projects involving MTs.

[31] Catalog of CHP technologies. US EPA Combined Heat and Power Partnership, March 2015

Summary of costs

Each of the micro-turbine suppliers provided partial costing for their units. Full costing, for installed systems, was achieved by combining these costs with data provided in the US EPA report, adapted to Australia. This may be summarised as per the following table:

Table 10: Budget pricing for installed cost of micro-turbines

Item	***Unit***	***200 kWe***	***1,000 kWe***
Nominal capacity	kWe	200	1,000
Equipment			
Generator package	$US	359,300	1,188,600
Heat recovery	$US	0	275,000
Gas compression	$US	42,600	164,000
Interconnection	$US	0	0
Installation	$US		
Labour/materials	$US	80,400	293,000
Proj.& const. m'ment	$US	48,200	195,000
Engineering & fees	$US	44,200	162,000
Contingency	$US	20,100	81,400
Financing costs	$US	3,700	14,800
Total installed cost USA	$US	598,500	2,374,900
Exchange rate	1.32		
Location factor	1.15		
Unit cost per kWe *	$A	4,860	3,608

* Based on local pricing proved by vendors and adaptation of US cost factors to compile a fully installed cost.

Operation and maintenance (O&M) costs

Vendors commented that O&M costs can be difficult to estimate as they depend on total run hours for the micro-turbine per year. As an example of costs, Optimal provided data for a Capstone-backed Factory Protection Plan which comprises scheduled maintenance, breakdowns, parts and labour. It is a 9 year fixed cost maintenance plan, paid annually. Costs are based on hours of operation each year and are summarized in the table below:

Table 11: Typical operating and maintenance costs for micro-turbines

Unit size	***Cost ($/y) of O&M based on running hours (fuel costs additional)***		
(kWe)	< 4,000 h/y	4 - 6,000 h/y	> 6,000 h/y
200	30,169	37,882	50,281
1,000	150,843	189,415	251,406

Efficiencies
(based on LHV natural gas)

Electrical:

- Aquatec Maxcon advise that conversion efficiency to electricity is 30% at 15^{O}C, dropping to 27% at 40^{O}C.
- Optimal advise that electrical efficiencies for the 200 kW unit are 33% at 15^{O}C and approximately 28% at 40^{O}C. For the 1,000 kWe system the efficiency at 15^{O}C is 31%.

Heat recovery
For heat recovery to hot water at 90^{O}C the two companies report a range from approximately 65% to 105% of the electrical output, i.e. 130 – 210 kWt for a 200 kWe unit.

9.3 Reciprocating engines

Data was requested from organisations with Australian presence and local CHP project experience. Data was received in particular from Aquatec Maxcon and Clarke Energy. Also referenced is a major report by the CHP Partnership of the US EPA[31]. It provides standalone data for the USA and has been recommended as a useful reference for local costs by Aquatec Maxcon.

Table 12: Budget pricing for installed cost of reciprocating engines

Supplier, or other source of data	***Engine output kWe@415V***	***Heat output kWth @90^{O}C***	***Engine plus heat recovery, delivered and commissioned (A$)***	***Equip't plus delivery and commission (A$/kWe) ****	***Cost inc. instal'n & project costs (A$/kWe) *****
Clarke	300	368	759,917	2,533	
	847	977	1,093,876	1,291	
	1,067	1,234	1,192,345	1,117	
US EPA	633			1,188	**3,168**
	1,121			1,155	**2,833**

* It can be seen that the cost of all equipment (engine and heat recovery) delivered and commissioned is significantly greater than the cost of the engine ex-works.

** The cost for a complete project is significantly greater again, and includes allowances for:

- Interconnections
- Related material and labour (duct work, piping, wiring etc)
- Project management
- Engineering
- Contingency (approx. 5% of equipment cost)
- Project financing

These data are averages of pricing across a number of projects. The actual overall cost for each project will be site-specific, and interested parties for engines or the other systems discussed here should work with vendors to determine more accurate pricing for their particular circumstances.

Operation and maintenance

Australian engine suppliers did not provide the study team with operation and maintenance (O&M) costs. However, the US EPA report[31] provides information on such costs, which are reproduced below. The costs in US dollars have been converted to Australian dollars (at an exchange rate of 1.32:1) and then multiplied by 1.15 to account for the relative wages in Australia and the US and the extra distance to reach meatworks in regional locations.

Table 13: Typical operating and maintenance costs for reciprocating engines

Nominal capacity (kWe)	633	1,121
Service contract ($/kWh)	0.030	0.027
Consumables ($/kWh)	0.015	0.015
Total O&M costs ($/kWh)	0.035	0.032

Efficiencies

Vendor-supplied efficiency data is summarised in the following table:

Table 14: Typical efficiencies for reciprocating engines

Supplier	***Engine output kWe***	***% Elec eff LHV***	***%Thermal eff LHV***	***% Total eff @25^{O}C LHV***	***% Elec eff HHV***	***%Thermal eff HHV***	***% Total eff @25^{O}C HHV****	***Convert to LHV***
Clarke	300	38.2	46.8	**80**				
	847	40.5	46.7	**87.2**				
	1,067	40.9	47.4	**88.3**				
US EPA	633				34.5	44.4	78.9	**87.4**
	1,121				36.8	41.6	78.4	**86.9**

It can be seen that reciprocating engines typically provide greater electrical efficiency than micro-turbines. Note that reciprocating engines are normally rated at an ambient temperature of 25^{O}C whereas gas turbines are quoted at ambient temperature of 15^{O}C. Typical data for gas fired micro-turbines (Table 5.4 US EPA report) shows that turbine efficiency at 25^{O}C is similar to the efficiency at 15^{O}C, but that it is reduced when temperature is higher than 25^{O}C.

The effect of increasing ambient temperature is different for engines and turbines. Reciprocating engine efficiency reduces by approximately 1% for every 6^{O}C increase in temperature (US EPA report, section 2.4.2) whereas gas fired micro turbine efficiency drops more rapidly, at approximately 1% for every 1^{O}C (US EPA report Figure 5.4).

Some data are quoted for Lower Heating Value (LHV) while some are quoted for Higher Heating Value (HHV), which is the value typically used in natural gas procurement pricing. The ratio for HHV to LHV for natural gas is 1.108:1[32]. When this ratio is applied there is good correlation between the above data from Clarke and the US report.

10.0 COST BENEFIT ANALYSIS

10.1 Cost estimation

The budgetary costs provided by vendors ranged from equipment only through to pricing for fully installed pant. For example, Turboden's budget cost is for all equipment ex-works (Italy) plus transport, installation and commissioning assistance. g-TET has provided pricing for an installed unit, but excluding costs such as civil and structural works and connections.

Costs have been estimated for the items not covered by vendors. Typical costs or cost factors are listed in major estimating texts[33] and the US EPA cogeneration report. These may include:

- Equipment supply, typically ex-works overseas
- Equipment transport to seaboard port in Australia
- Equipment delivery to site and unloading
- Civil works and structural works (e.g. concrete pads, buildings
- Equipment installation (mechanical, electrical, control, structural)
- Connections to existing services and utilities
- Project management
- Engineering design (for items not covered in vendor quote)
- Construction management
- Contractor and legal fees
- Contingency
- Project financing

10.2 Modelling assumptions

To provide an initial assessment of commercial viability, the costs for the systems described above were used in a Cost Benefit Analysis (CBA) by All Energy Pty Ltd. This analysis was based on the typical meat processing facility also described above, which was used to provide data on the variable loads for heat and power during peak and off peak periods.

Assumptions were made for energy costs and other variables; these are summarised in Table 15 below. Base case values for fuel (natural gas) and electricity are shown in bold; these values in particular have a major

[32] https://www.clarke-energy.com/2013/heating-value/

[33] Peters M.S. et al, Plant Design and Economics for Chemical Engineers 5th Edition, McGraw Hill – Table 6-9

effect on the viability of cogeneration systems and payback periods were found to vary considerably when different fuels are used or higher electricity charges apply.
All of the units described above can produce hot water at 90^{O}C, which can be utilised within the meat processing facility. Generation of process steam is also possible. For example:

- A heat recovery steam generator may be fitted to a micro-turbine. Optimal advised that such a unit on the exhaust stream form their micro-turbine can generate steam at up to 5 bar.
- The cogeneration systems offered by Turboden are an exception. Because they include new thermal plant they can be designed to provide process steam from that plant in parallel with the electrical output of the ORC unit.

A particular advantage of having process steam as an output is that it can offset a larger proportion of the meat processing facility's overall heat requirements (up to 100%), whilst hot water via cogeneration can only provide a partial offset (up to 11.8% of total plant thermal energy requirements for the typical plant modelled here).

Table 15: Principal assumptions for cost benefit base case

Assumption	***Reference***
Natural gas LHV 47.13 MJ/kg	http://hydrogen.pnl.gov/tools/lower-and-higher-heating-values-fuels
Natural gas price $12/GJ.	**Basis of design**
Peak hour electricity cost $0.1269/kWh	**Basis of design**
Operation during peak power cost periods: 3,500 hr/y	Peak 7am - 9pm (M-F)
Operation during off peak power cost periods: 4,924 hr/y	Off-peak: 9pm – 7am & weekends
Power factor for facility of 0.9	
Any biogas used is assumed to be at no cost from a co-located anaerobic digester. This gas creates large scale generation credits (LGCs) under the Australian Federal Government's Renewable Energy Target (RET) scheme	LGCs valued at spot price of $86/MWh http://greenmarkets.com.au/, accessed 20 Oct 2016.
No indexing applied to future power or fuel costs	
Up to 688 kWt of hot water or 5,830 kWt of 6 bara steam can be utilized on-site during operating hours	
Up to 2,661 kWe of power can be consumed during operating hours	Power generated by all systems completed utilized during operational hours.
Typical plant processing 625 head per day, 250 operating days per annum in a two shift roster.	

Most of the modelling for cost benefit analyses carried out for this report has used natural gas as the energy source purchased to drive the cogeneration systems. Other fuels are also considered in some circumstances:

- It is estimated that the typical abattoir could generate up to 1,398 kWt of biogas equivalent (60% methane biogas) via an anaerobic digester that processes all available organic wastes (including paunch, red stream organics, green stream organics). This equates to up to 3,062 kWt when utilized during operational hours only. Hence a typical biogas plant is anticipated to produce sufficient biogas for all of the fuel required to operate several of the examples considered in this report: the 250kWe ORC unit, 633 kWe reciprocating engine or the 200 kWe micro-turbine. The 100% biogas option has therefore been considered for these smaller systems, but not for the larger systems. Note that no variations in capital and operating costs have been considered for use of biogas in the energy plant, which was all costed on the basis of natural gas as fuel. Biogas (as opposed to natural gas) potentially requires cleaning prior to use and may have lower energy content than natural gas. These conditions may impose additional costs, which should be considered in a more detailed appraisal.

- Some abattoirs have reasonable proximity to sources of woody material that could fuel a new thermal plant. Biomass is often available at lower cost than natural gas per unit of energy and, like biogas, it can be used to generate renewable energy credits (LGCs). However the capital cost of thermal plant to utilise biomass is generally much greater than the equivalent thermal plant for natural gas. Note also that gas-fired energy plant has better load following capability than plant fuelled by biomass plant. The use of an ORC unit to even out the energy delivered from a biomass plant could help to mitigate any load following problems. So any decision to use bioenergy rather than natural gas for new thermal plant must examine the capital and operating costs for a whole of life comparison. An example of the possible cost impact is provided later in the report.

10.3 Methodology

For each of the technologies under consideration, capital pricing was determined as described above, along with quoted maintenance costs under a contract agreement, or using approximations from scientific and technical literature. Estimates for additional fuel costs were also factored into the model.

Revenue from volume and demand power charges, renewable generation certificates, and abated fuel from boilers was estimated to calculate simple payback as capital expenditure divided by net revenue per annum. Two scenarios were considered:

- Where the cogeneration plant is run only during peak hours.
- Where the cogeneration plant is run for peak and off-peak hours.

The table below lists the thermodynamic calculations used during economic analysis.

Table 16: Thermodynamic formulae used in economic analysis

Calculation of	Formula	Pronumerals
Fuel Burned F [tonnes per annum (tpa)]	$\frac{\boldsymbol{P \times h \times 3600}}{\boldsymbol{\eta e \times 1000 \times c}}$	*P* = Power [kWe] *h* = Hours per annum *ηe* = Electrical efficiency c = Fuel calorific value [kJ/kg]
kWt Available (Unless Specified)	$\frac{\boldsymbol{F \times \eta t \times 1000 \times c}}{\boldsymbol{3600 \times h}}$	*ηt* = Thermal efficiency
Hot Water Available (Unless Specified) [tph]	$\frac{\boldsymbol{kWt \times 3.6}}{\boldsymbol{cp * \Delta t}}$	*cp* = Water specific heat 4.18 *cp* kJ/kg.K *Δt* = Temperature change

Fuel Abated from Boiler [tph]	$\frac{100 \times ms \times (hs - hf)}{\eta \times c}$	*ms* = Steam mass flow rate [t/h] *hs* = Steam enthalpy [kJ/kg] *hf* = Feedwater enthalpy [kJ/kg] *η* = Boiler efficiency

10.4 Results

The following table summarises the cost benefit analyses performed for each technology and scale.

Table 17: Cost benefit analysis summary

Unit	Scale (kWe gross)	TCI ($AUD)	Simple Payback Period in years	
			Nat Gas as only fuel	Biogas as only fuel
ORC	250	1,440,000	N/A*	6.3
	500	1,915,000	N/A	4**
	816	4,824,600	N/A	6.4**
	1,000	3,200,000	N/A	3.3**
	1,382	6,299,700	N/A	4.8**
	2,093	8,131,200	N/A	4**
Reciprocating engine	633	3,168,000	24	5.7
	1,121	2,833,000	12	2.8**
Micro-turbine	200	972,000	N/A	4.3
	1,000	3,608,000	N/A	3**

* N/A denotes that a payback period could not be determined as costs exceeded revenues.
** It is estimated that sufficient biogas would not be generated from the organic wastes of a typical facility for 100% fuelling the larger engine options.

Prior to discussion of results, it should be noted that the large range of parameters and inherent differences in technologies, scales and capabilities mean that comparison is not clear cut.

Organic Rankine cycle units

It can be observed in Table 17 that, for the prices of natural gas and electricity in the base case, none of the ORC units returns a positive net annual revenue. Thus the simple payback period cannot be calculated. The cost of natural gas as fuel has a significant impact on the commercial viability of the cogeneration plants.

Economics improve when considering biogas as a free issue fuel, with the additional benefit of the revenue from generating and selling LGCs. Simple payback periods ranging from 6.3 – 3.3 years in the plant scale of 250 – 2,093 kWe are achieved.

A further scenario was run for the Turboden 816 system simulating operation in a regional area (e.g. a feedlot). The key assumptions were:

- $0.24516 / kWh charged for power (which is significantly higher than the base case used above).
- No power utility capacity (i.e. kVA) based charges.
- Thermal energy to drive the ORC unit provided by a biomass-fired boiler at a cost of $5 /GJ.
- LGCs created for all power generated, based on using one of the many biomass feeds that are eligible for certificate creation under the Australian Government's RET legislation.

The simple payback period for this scenario was estimated at 6.3 years. Also, because of the approach by Turboden to combine electricity generation with process steam supply, this approach provides process steam rather that hot water.

Micro-turbines

As with the ORC units considered, gas micro-turbines were found to be uneconomic for the base case model, because the net revenue is negative.

Micro-turbines running on nil cost, renewable biogas with LGC sales revenues show good economic feasibility. Simple payback periods of 4.33 and 3 years were calculated for the 200 and 1,000 kWe systems respectively.

Reciprocating engines

Reciprocating engines were the only technology to return a positive net revenue when using natural gas as the fuel. A conventional economy of scale is observed, with the 633 kWe unit offering a simple payback of 24 years whilst the 1,121 kWe has a 12-year payback period.

The engines described above operate during peak periods only. When running a reciprocating engine during peak and off-peak periods, the net revenue for the base case becomes negative and any economic viability is lost. This is due to the additional costs for fuel and maintenance not being offset by sufficient additional value for the off-peak power that is generated.

As with the other technologies, the use of biogas (assumed to be at nil cost) generated onsite improves the economics due to its assumed lower cost and the ability to earn LGCs. With biogas, the 633 and 1,121 kWe systems show simple payback periods of 5.7 and 2.8 years respectively.

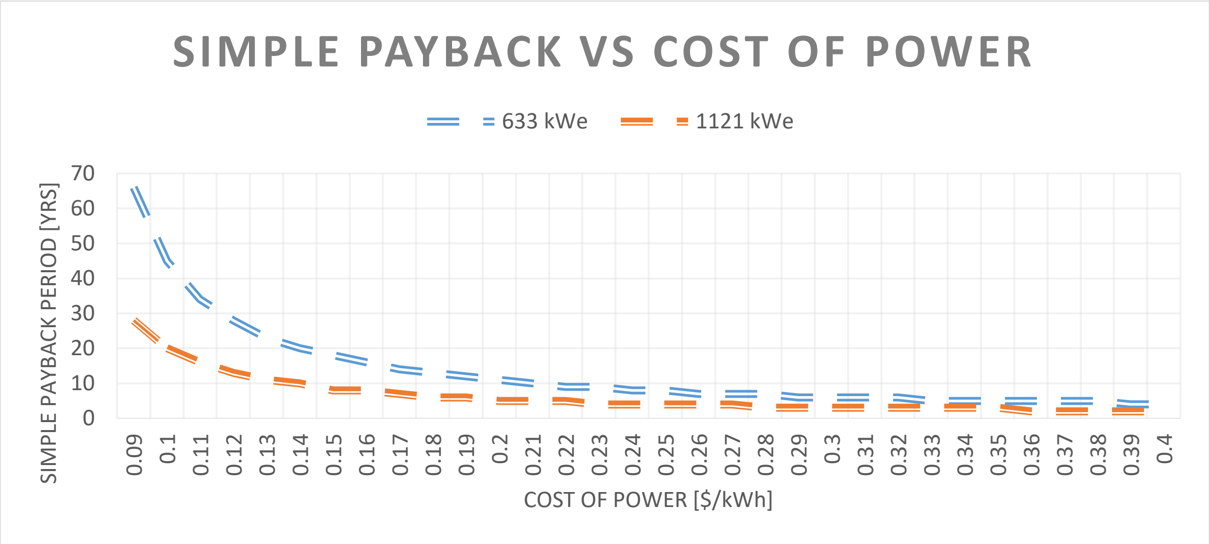
Sensitivity analysis

Reciprocating engines were the only technologies to return a positive net revenue for the base case with natural gas as fuel. A sensitivity analysis on project payback was performed for two engines, to examine the variation in payback period as the value for the electricity is varied between $0.09 and $0.40 / kWh. Figure 12 shows the results of this analysis; with increasing value of power the simple payback periods for the 633 and 1,121 kWe systems progressively reduce to approximately 4 and 2 years respectively.

The improved economic viability with increased cost of power means that meat processing facilities located in more regional areas where grid power is more expensive or unavailable are perhaps more suited to implementation of cogeneration systems.

A rudimentary sensitivity analysis was also done for ORC units and micro-turbines, increasing the value of power to 25%, 50%, and 100% above the base price. With natural gas a fuel it was determined that for a +200% power price ($0.2538 / kWh), a 250 kWe ORC unit achieves a simple payback of 7.85 years; and that a 200 kWe micro-turbine achieves a simple payback of 12 years.

Figure 12: Cost of power- sensitivity analysis



11.0 DISCUSSION

The results described above demonstrate several important points with regard to new cogeneration systems:

Although cogeneration improves the efficiency of energy use it still requires energy, from direct use of fuel or via thermal energy (itself derived from combustion of fuel).

When natural gas is used as fuel in the base case, for most of the systems that were modelled the value of the electricity and heat produced by the cogeneration plant did not offset the cost of the energy needed to drive the system. The exception was provided by reciprocating engines, which have a higher conversion efficiency of fuel to electricity than either ORC units or micro-turbines.

In some situations biogas can be produced on site via the anaerobic digestion of plant wastes. If the digester is set up for environmental management it can potentially provide biogas as fuel at nil cost, and electricity from biogas creates Large Generation Certificates that are marketable via the Renewable Energy Target. This improves the economics of cogeneration and in these circumstances all technologies showed positive cash flows and potentially attractive payback periods.

The simple payback periods described above made allowance for the different values of electricity in peak and off peak periods. Results highlight the importance of matching the scale of the cogeneration plant to the demand for the more expensive peak electricity. It appears that this factor can be more important than the economy of scale that is achieved via larger cogeneration plant.

In the above examples it was assumed that the cogeneration plants always operated at capacity, with the reasoning that this would maximise any profitability and allow faster payback of the capital cost of the system. It is important to note that in practice the system may well operate at partial load for a significant amount of time, according to the specific needs of the meat works. The different technologies have different turndown capabilities, with some offering better partial load operation than others. Also, the efficiency of each system will vary with partial load. These factors should be considered as part of the assessment of actual projects.

12.0 CONCLUSIONS AND RECOMMENDATIONS

Cogeneration systems can be developed at a wide range of scales and using an equally wide variety of equipment. Australia has multiple vendors for the equipment considered (engines, micro-turbines, ORC units) and these vendors have commercial experience in Australia and overseas for cogeneration applications in a range of industries.

The overall conclusion from this project is that cogeneration with ORC units, micro-turbines and reciprocating engines may provide a cost-effective approach to on-site energy, but on a case by case basis and subject to the specific conditions of each site.

- Fuel and electricity values determine the general viability of cogeneration, and low cost fuels such as biogas or biomass improve viability relative to natural gas. For the fuel costs and electricity costs that may be experienced across the meat processing industry, it was determined that cogeneration systems ranged from being uneconomic to offering attractive payback periods.
- Once it is determined that there is a case for cogeneration, the scale of the system and selection of technology are functions of the site's energy needs and existing/planned energy infrastructure. Each of the three technologies considered (ORC units, micro-turbines, reciprocating engines) comes with a particular set of benefits and limitations that must be taken into account when an evaluation of cogeneration is being carried out for a site.

When a cogeneration system is operated smoothly at capacity, reciprocating engines showed the best economics. However micro-turbines and ORC units provide greater flexibility in operation at partial loads. All the systems can provide heat as useful hot water; alternatively ORC units and micro-turbines may be set up to provide heat as process steam.

All systems can use biogas (directly or indirectly) if it is available. ORC units use heat rather than fuel as their energy source, and they may also be coupled to a new biomass boiler when cheap local biomass is available.

The examples provided in this report can be of assistance in preliminary assessments of cogeneration at individual meatworks. For those meatworks that consider this report and believe that there is a case for more detailed investigation, the next stage could be via engagement with vendors. It is considered important to look at more than one technology for cogeneration so that the best possible match for each site's needs can be achieved.

It is recommended that AMPC follows up with its members after this report has been distributed to gauge the interest in further information. If there is sufficient interest AMPC could arrange for interaction with vendors, for example via a session at the national conference, or via webinars.