Department of Mechanical Engineering

Industrial Waste heat energy recovery systems – technology overview and approaches for selection of system

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A thesis submitted in partial fulfilment for the requirement of degree in
Master of Science in Renewable Energy Systems and the Environment
2010

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Signed: Peter Gent Date: 10th September 2010

ABSTRACT

Waste heat emission occurs in almost all processes. In an industrial context these emissions typically occur in the form of hot water, steam or flue gases. The scale of energy in these waste heat emissions can be large and the losses, both monetary and in terms of energy, can amount to significant values. The most significant influences on selection of waste heat energy recovery technology can be briefly summarised as local planning considerations and financial or budgetary considerations.

The objective of this thesis is to survey the technical options for waste heat capture and consider in greater depth the rationale behind the choice of waste heat capture method through the use of real life examples as case studies.

The thesis is structured as follows:

The techniques and technology involved in certain waste heat recovery processes that are in use today are surveyed and reviewed with emphasis on solutions that may play a part in future energy recovery.

Secondly consideration was made as to the environmental, economic and geographic context and what influences, factors and situations play a part in the decision making process.

A number of case studies have been researched and presented to showcase waste heat energy capture projects in the real world. Original research involved performing interviews with responsible engineers at case study sites as well as desk and library based research. These highlight the most important criteria.

A decision making process taking these selection factors into account is proposed and an alternative offered for comparison.

ACKNOWLEDGEMENTS

I would like to thank just a few people for their encouragement, friendship and wisdom. It has been an interesting topic and period to write this thesis in, to say the least and without you lovely people, this would have not been possible. Thank you to Susan & Jonathan, Dr Tri, Andrea, my Parents, Karen & Ian Binnie, the “Hydro Boys” and all the WTMC people who have been so generous over the winter, here in Wellington.

I'd also like to thank all those who have helped out with the case studies, especially EECA's business energy unit, Paul Trafford for information regarding the Sewage treatment project, Phil Searle-Barnes for details of the east London communications centre and Leonid Itskovich at Christchurch city council & Bob Weston at Entec for information regarding the Christchurch city council's tri generation project.

The final mentions go to John Ogle at Aecom for the project direction, and Paul Strachan & Craig Mclean from the department at Strathclyde.
I'm sorry if I've missed anyone crucial to the story but you know who you are!

Thank you
Pete

To Kerstin and Claudia
with love

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1. INTRODUCTION

Interest in waste heat recovery can be traced back to the 1970's energy crisis when there was the external pressure, especially in certain sectors of industry to reduce energy costs as the price of oil rose significantly due to the energy crisis of 1973 (Reay, 1979). Many schemes were proposed for example the then Central Electricity Generating Board (CEGB) in the United Kingdom which looked at retailing its waste products from electricity generation to both domestic and industrial customers (Murgatroyd, 1977). However this vision did not come to fruition. Some schemes went ahead including, a European wide effort into research & development on industrial energy efficiency (Pilavachi, 1987) for instance.

35 years on, there is renewed interest in the capture of waste heat for reuse. In this era of man made climate change, the spectre of peak oil and concerns surrounding security of energy supply, the need for maximising the amount of energy utilised per pound spent is considered more pressing than ever.

The manufacture of cement for example, accounts for around 2% of the world's total energy consumption in this one process alone (International Energy Agency, 2007). With the potential of reducing energy consumption from high density energy consumers such as cement manufacture by reusing the energy dissipated in waste heat, there are enormous overall energy efficiency gains to be made. The cement industry for example is global in its nature. In these days of high speed communications, the ability to transfer technology on a large scale, to similar industrial sites, means mature technological solutions can be rolled out with relative ease.

Energy intensive industries, OECD countries and to an increasing extent developing countries, are facing increasing pressure to reduce expensive direct energy consumption per se, as well as accompanying carbon (dioxide) emissions.
These various methods to increase efficiency include the following:

Emission trading schemes are coming into effect across OECD nations. New Zealand has expanded its scheme to electricity and petrol this year (Ministry of Agriculture and Forestry, 2010) and Europe as a whole is verging on implementation of trying to reduce the amount of CO_2 emitted by various producers (EU directive 2003/87, 2003).

There is also pressure to reduce energy waste through national regulation and planning rules. With net zero carbon building regulations in the residential sector being introduced in the United Kingdom in the near future for example (Department of communities, 2007).

The bottom line is that in most cases where waste heat recovery is not being carried out, energy and money are in effect being sent up the chimney as hot air, or dumped into seas and rivers. Ultimately in almost all business, financial incentives are paramount.

Despite regulatory, planning and energy cost considerations, waste heat recovery is not yet uniformly implemented globally nor across all industrial sectors.

The two main business models for recovering energy from waste heat are as follows:

Firstly to reduce the energy consumption that a business incurs directly. By using the available energy inside the business to reduce expenditure on energy from external sources and thereby increase the overall energy efficiency of the business.

Secondly to supply energy to an external consumer, that (if regulated correctly) brings mutual benefit to both the initial producer of the heat and the external consumer of the energy recovered from the waste heat.

This mutual benefit could be either financial or in the form of carbon credits for the supplier of the energy. It may also provide a competitively priced & relatively “green” source of energy for the external energy consumer.

2. SCOPE OF PROJECT AND OBJECTIVES

This thesis will outline the technical stages in realising the capture and use of waste heat as a viable and valuable source of energy.

It begins with an introduction to various engineering cycles that are used as the basis of waste heat recovery technology.

It then offers an overview of various technologies that convert this waste heat into energy that is useful and usable.

A range of criteria are suggested that might be useful in the selection of technology for energy recovery.

A number of case studies are presented, with discussion around the implementation decisions inherent in their development.

A look at the criteria for choice of technology is made. Possible methods of selection for the solution are explored.

Finally, possible areas of further work are highlighted and conclusions are drawn with regards to selection criteria and technology.

3. ENGINEERING CYCLES

There is a wide range of sources of waste heat in an industrial context. The main forms of waste heat that are usually available for energy recovery are exhaust gas, steam or warm liquid.

There are a range of different cycles which can enable waste heat energy recovery. Those that are detailed in the following pages, are some of the most common cycles in use in the technologies described in the following Chapter.

3.1 Rankine Cycle

The basic Rankine cycle is a relativity simple and widely used thermal cycle, forming the basis for thermal power generation, amongst other processes.
In Figure 1, the outline of a simplified set up of a Rankine cycle is shown. There are four major parts to it. These parts are the water pump, boiler, turbine to carry out external mechanical work and a condenser, which correspond to the four distinct steps described below and the temperature verses entropy diagram following on.

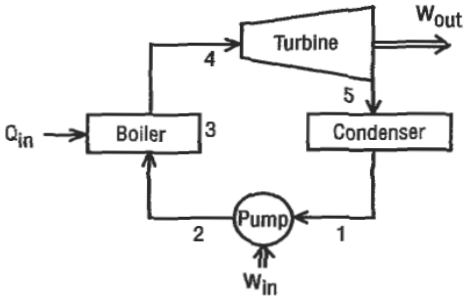

Figure 1 – Basic implementation of the Rankine cycle (Mohanty, 1996, P61)

The fundamental stages of a Rankine cycle are four distinct steps (Singh, 2006) which are as follows, where water is used as the working fluid in the cycle:

1. Isobaric heat addition occurs – Water is heated in a boiler by an external supply of energy (eg burning coal or flue gas) to raise steam under pressure

2. Adiabatic expansion - The raised steam is used to drive a turbine to produce mechanical work (which can go onto be coupled to a generator and therefore generate electricity).
3. Isobaric heat release – The rejected steam is cooled back to water in a condenser
4. Adiabatic pumping - The water is pumped under pressure back to boiler to be reheated as per stage 1. This pressurisation does also increase the temperature of the steam a relativity small amount.

The T-s (Temperature verses Entropy) plot of this process is shown below in Figure 2 and each plotted point on the graph corresponds to one of the steps listed in the Rankine cycle.

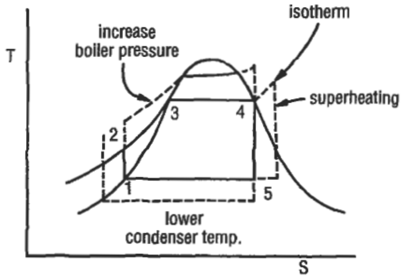

Figure 2- T-s graph of a simple ideal Rankine Cycle (Mohanty, 1996, P61)

Now in reality, there are inefficiencies in processes in the real world, so this T-s graph would not hold true, but gives an indication of how ideal operation of the cycle occurs.

The Rankine cycle is a well established route for power generation, along with other uses. The use of tried and tested components over a long period of development and refinement have contributed to the proven effectiveness of the Rankine cycle.

The Rankine cycle is not just implemented in a high temperature high pressure steam scenario. The following sections discuss variations on the principles of the Rankine cycle and how they differ from a water based, steam raising cycle.

3.11 Organic Rankine Cycle

Where high grade steam or flue gases are available, these can easily be utilised. However, if only low grade heat is available, this will not raise water to high pressure steam so other options should be considered.

By changing the working fluid in a Rankine cycle for a waste heat energy recovery system from water to another substance, the properties of the new working fluid can be used to take advantage of lower grades of waste heat.

The non water working fluid, must have characteristics that enable it to be vaporised at a lower temperature than water, so a turbine can be ultimately driven (Liu, et al., 2004) to produce mechanical work (and thus drive a generator).

Some of the working fluids that are being used at the present time for organic Rankine cycle include the “R” series of refrigerants. In Yamamoto's (2001) paper for example, R123 is used for the working fluid for design purposes. Physical properties of the working fluid should be used to evaluate and select a fluid that will allow efficient operation. Dossat & Horan (2001) offers a number of examples of some common “R” fluids in a typical refrigeration situation. Here ten specific characteristics are noted. These are the boiling point at standard atmosphere pressure. The evaporator pressure at 258°K and 303°K. The specific volume of the suction vapour, refrigeration effect, the mass flow of refrigerant per ton, compression ratio, compressor ratio, compressor discharge temperature, power consumption and the coefficient of performance. Data tables of major “R” fluids are generally available from manufacturers, to allow for property comparison and aid selection.

Ideally the working fluid should be chosen just on its properties. However in reality it will be a balancing act between weighting up the financial cost, physical properties, handing regimes surrounding the fluid, its environmental impact and potential damage to off the shelf components that might be used in the implementation of an organic Rankine cycle system (Hung, 2001).

It is in low temperature waste heat situations where the organic Rankine cycle finds its main use. Due to the small temperature differences, any engineering cycle that is employed will only be able to capture a small amount of the energy available as governed by the second law of thermodynamics. Never the less some energy is being recovered.

3.12 Kalina Cycle

Some researchers (Hettiarachchi, et al., 2007) believe that a significant development in the choice of working fluids for an organic Rankine cycle is the Kalina cycle.
The first suggestions of this idea was seen in 1982 (Kalina, United States patent 4346561).

Instead of using a single working fluid such as one from the "R" series of refrigerant fluids (Hung, 2001), which are typical of the working fluids of choice for an organic Rankine cycle, the working fluid is changed in the Kalina cycle to a multi component working fluid. This multi component fluid is a combination of water and ammonia.

There are some subtle differences between the organic Rankine cycle and relatively new Kalina cycle. The four main points of difference between the Kalina and organic Rankine cycles are (Mlcak, 1996):

1. "The Ammonia Water mix has a variable boiling point unlike a single working fluid in an organic Rankine cycle.
2. The thermal properties of the working fluid can be altered by varying the ratio of Ammonia to water. For example, one can take advantage of seasonal

variations in waste heat supply temperature or external heat sink temperature with a change in ratios of one to the other.

3. The combined Ammonia Water fluid allows for a change in temperature without a change in the heat content of the fluid. Thus the finite heat sources and sinks of the real world can be integrated.
4. Finally due to the lower freezing point of ammonia at 195°K, temperatures below the freezing point of water at 273°K can be used as a heat sink in terms of improving the Carnot efficiency."

Despite this change in working fluid characteristics, the plant that is used for making a Kalina cycle in reality is the same. No higher specification is required to build a plant and there is also an increase in efficiency, with the potential to reduce capital costs and recover similar amounts of energy when compared to traditional single working fluid organic Rankine cycle installations (Mlcak, 1996).

Figure 3 shows an diagram of a KCS11 Kalina cycle, optimised and set up for low temperature operation. Each temperature range requires a different set up. However this particular system will be explained as it is focused on low temperature waste heat recovery. Hettiarachchi goes onto explain the steady state operation of each of the stages (as per Figure 3) in a Kalina cycle and they are as follows:

Condenser (1-2); The working fluid is condensed by an external heat sink, for example river water.

Pump (2-3); The working fluid passes through the pump to increase its pressure to move the working throughout the process.

Regenerator part 1 (3-4); Pre heating of the working fluid occurs by the regenerator (see regenerator part 2)

Evaporator (4-5); The working fluid is heated at the evaporator by the external heat source. For example waste heat from an industrial process

Separator (5, 6 & 7); Saturated rich vapour of the working fluid is sent to the turbine, whist weak saturated liquid is sent to the regenerator.

Turbine (6 – 10); Saturated rich vapour undergoes isentropic expansion to drive the turbine to produce mechanical work.

Regenerator part 2 (7-8); Saturated weak liquid preheats the working fluid as seen at 3-4.

Valve (8-9); Pressure of the saturated weak liquid is throttled down for use in the absorber.

Absorber (9, 10 & 1); The vapour and liquid components of the working fluid are mixed back together, ready to be fed to the input of the condenser.

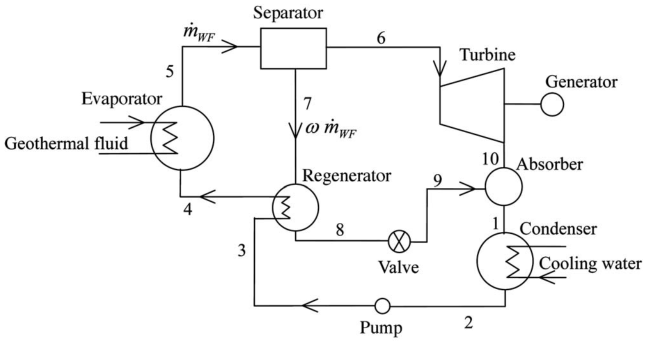

Figure 3 – Kalina cycle schematic (Hettiarachchi, et al., 2007, P244)

The ratio of ammonia to water in the cycle can be varied as previously noted by Mlcak (1997). This variation of ratio of the mixture offers the chance of capturing energy over a range of temperatures. Figure 4 shows the enthalpy of various ratios of water & ammonia at a pressure of 30 bar.

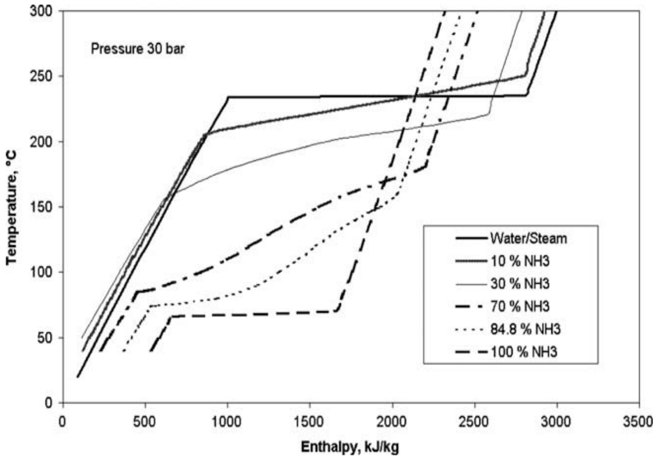

Figure 4 – Enthalpy of various ammonia water mixtures (Ogriseck, 2009, P2844)

Mlcak's initial difference discusses the variable boiling point in the multi component fluid, as there are a range of temperatures as which the mixture will vaporise to a gas. This variability is the key to the Kalina cycle and Figure 5 shows this phase variation with a number of points plotted to demonstrate it using a 70% mixture ratio.

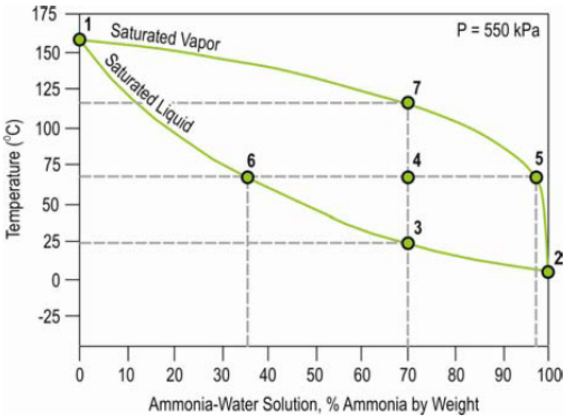

Figure 5 – Water ammonia phase diagram (Mlcak, 1997, P4)

Point 1 is at 429°K which is the saturation point of pure water, with point 2 at 279°K the saturation point of pure ammonia. At point 3, the ammonia in the mixture is starting to boil off - 298°K. Point 4 shows the 70% average mix at 339°K, with point 5, indicating the vapour part of the solution (mostly ammonia), where as point 6 is mostly water as it is below water's saturation point. Point 7 is the saturated liquid point mixture at 389K.

Factors of plant design that should be considered for mixture optimisation include the turbine inlet pressure, the superheater temperature and condenser temperature (Pouraghaie, et al., 2010). These variables can cause conflicts when selecting the optimised ratio, so decisions must be made about the optimisation of the mixture.

One final point to make on the ratio of ammonia to water is that a 70% ratio is one of the most commonly used for analysis of the Kalina cycle (Mlcak, 1997).

There are however a couple of potential draw backs to a Kalina cycle operation. First of all, part of the working fluid mix is now ammonia. Despite many years of the development of safe handling regimes and operational requirements for ammonia (Ogriseck, 2009), it is still a dangerous chemical to deal with.

Secondly Moghtaderi and Doroodchi in their 2007 patent application (Moghtaderi, 2007), raise these points regarding to the complexity of a Kalina cycle loop as follows:

> "A disadvantage of the Kalina cycle is that the absorption and distillation equipment added to the cycle creates further complexity to the system, and significantly increases the cost of plant installation compared with other types of power plants."
>
> and
>
> "Furthermore, the Kalina cycle has a high sensitivity towards the pressure and composition of the ammonia- water mixture, which limits the operation of the cycle over the whole range of possible geothermal reservoir temperatures"

It could be argued however that these potential problems are far outweighed by the efficiencies gained from using the Kalina cycle in the first place.

Commercial installation of the Kalina cycle has occurred at a number of sites around the world, including Japan, the United States, Germany and a geothermal district heating scheme in Husavik Iceland (Arslan, 2010). However wide spread implementation of the process has not been seen so far (Hall & Taylor, 2006) as current operations have not established favourable returns. So at the present time, the Kalina cycle has a small market share of low temperature Rankine cycle projects (Ogriseck, 2009).

3.2 Stirling cycle

The Stirling cycle has been around for almost 200 years, first development by the Stirling brothers in 1815 (Joel, 1996). The physical realisation of a Stirling cycle is a Stirling Engine which is a heat engine that is classified as an external combustion engine. This is because thermal energy is being applied to the external body of the engine for work to be carried out. As a result no internal combustion takes place in a Stirling cycle.

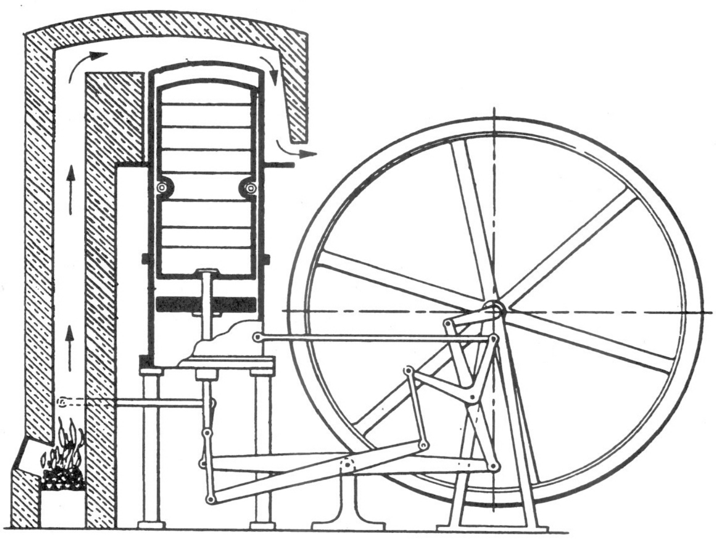

Figure 6 – A Stirling Engine (Stine, 1998, P8-67)

Çengel (2008) describes the four stages of a Stirling cycle in the following terms.

1. Constant expansion occurs in the internal space on the working fluid due to the addition of heat from the external source.
2. Constant regeneration happens by the process of internal heat transfer from the working fluid to the regenerator.
3. Constant compression of working fluid occurs by heat rejection to the external sink.
4. Constant regeneration by the process of internal heat transfer from the regenerator to the working fluid and then the cycle moves back to stage 1.

Constant volume heating takes place in between stages 2 and 3 and in a perfect cycle, this would be carried out by the heat sent to the regenerator during the constant volume cooling that takes place between stages 4 and 1 of the cycle and is subsequently stored for heating to occur between stages 2 and 3. Figure 7 shows a typical T-s graph of the Stirling cycle.

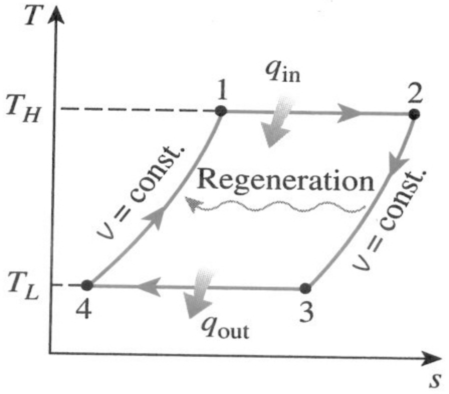

Figure 7 – Stirling Cycle T-s Diagram (Çengel & Boles, 2008, P504)

A regenerator is used within the Stirling cycle, which is a thermal energy storage device (Çengel & Boles, 2008) and in an ideal Stirling cycle, this storage is 100% efficient (Moran & Shapiro, 1998). In reality, no regenerator is 100% efficient however. Further details on the regenerator can be found in the gas – gas heat exchange section – 4.23.

Though the cycle in principle is simple, the requirements for a highly efficient regenerator have added complexity in the realisation of a commercially viable model (Çengel & Boles, 2008). However with the renewed interest in increasing the efficiency of the use of a primary fuel, the reality of the Stirling cycle in everyday use is upon us. For instance, in the United Kingdom, Baxi has a residential unit available that uses a Stirling engine as an integral part of a wall mounted combined heat and power unit (British Gas, 2010).

3.3 Brayton cycle

The Brayton cycle is one which is primarily a closed engineering cycle with two constant pressure parts to the cycle. Though discussed by Joule (and known as the Joule cycle by some engineers), George Brayton was the first to demonstrate this cycle for internal combustion use in 1876 (Joel, 1996).

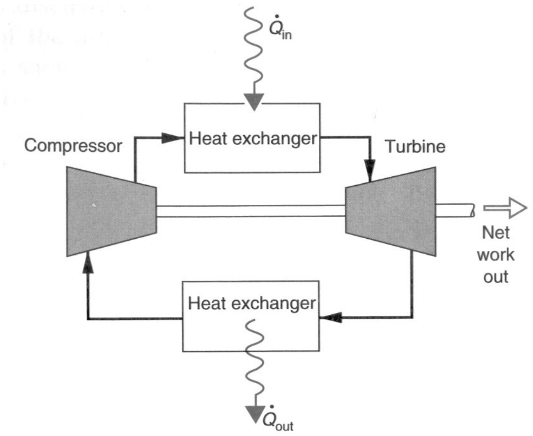

Figure 8 – Gas turbine using the Brayton cycle (Moran & Shapiro, 1998, P383)

Air is the predominant working fluid used in a Gas turbine. This provides a source of oxygen for use in the combustion stage of the cycle where the fuel is ignited.

Figure 8 shows a diagram of the physical realisation of the 4 stages of the Brayton cycle and Moran (1998) describes thus:

1. The working fluid in the closed system is compressed by a compressor, which is mechanically linked to the turbine (see stage 3)
2. Energy in the form of heat is added to the closed loop. This is typically carried out using combustion of an external source of fuel, which adds energy to the working fluid.
3. Work is carried out at the turbine by the working fluid to produce both net mechanical work out and to drive the compressor back in stage 1.
4. Heat is dissipated from the working fluid via a second heat exchanger and working fluid continues back to stage 1.

Linking in with the four stages of the cycle, the temperature verses entropy graph is shown in Figure 9.

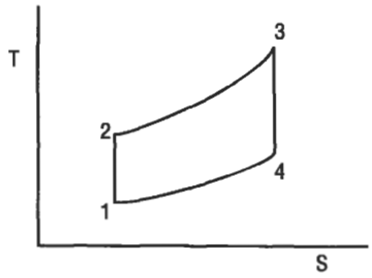

Figure 9 - Brayton cycle T-s graph (Mohanty, 1996, P62)

One disadvantage of using air as the working fluid is that substantial energy is required in the compressor to increase air pressure, compared to using a liquid (Moran & Shapiro, 1998).

The Brayton cycle is the most basic application of a closed loop gas turbine, though there are further refinements using recouperators and intercoolers. The Brayton cycle displays the elegance of the idea for a cycle for gas turbine operation.

3.4 Refrigeration cycles

Refrigeration is typically carried out by using one of two different methods. Though other methods exist for cooling applications, the vapour compression cycle and the absorption cycle are the most dominant refrigeration cycles in use in everyday applications.

3.41 Vapour compression cycle

The vapour compression cycle can be considered a reverse Rankine cycle implementation, and Moran & Shapiro (1998) describes the four major steps in the cycle to remove heat (and thus energy & reduce the temperature surrounding the evaporator) from one heat exchanger (the evaporator) and transport it to a secondary heat exchanger to add energy to the surroundings at this heat exchanger (the condenser).

These four steps are as follows:

1. Heat is transferred to the working fluid (ie refrigerant) at constant pressure through the evaporator.
2. Isentropic compression of the working fluid occurs, usually by mechanical pumping with an external supply of energy to carry out the work.
3. Heat is transferred from the working fluid as it flows at constant pressure through the condenser to the air surrounding the condenser. The working fluid leaves the condenser as a liquid
4. Expansion of the working fluid occurs by use of an expansion valve. The working fluid is "throttled" to a two phase liquid vapour mixture, by the time the working fluid enters the evaporator. The working fluid then returns to the first stage of the vapour compression cycle.

A simplified P-h (Pressure - Enthalpy) diagram of a vapour compression cycle is shown in Figure 10.

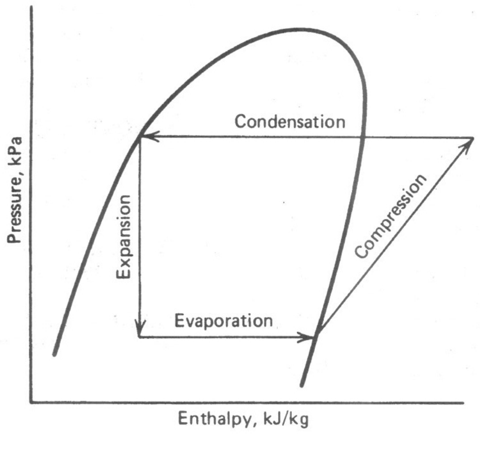

Figure 10 - P-h graph of Vapour compression cycle (O'Neil, 1998, P1880)

This cycle has to be implemented using a working fluid which allows boiling and evaporation at lower temperatures that water. Ammonia could be used or alternatively one of the refrigerants in the "R" series of fluids could be used. (see section 3.11 for further information on R fluids) Each fluid has a different set of properties and would usually be chosen for the specific application and budget available to build it.

3.42 Absorption cycle

A second method of cooling is the Absorption refrigeration cycle. Moran & Shapiro (1998) goes onto describe the set up for this process. The second stage of the vapour compression cycle (ie the compressor) is replaced by equipment consisting of an absorber, pump, generator and valve and a secondary absorbent to be added into the cycle. Figure 11 below shows a simplified absorption cycle system layout, with a complementary T-s graph to show the relationship between temperature and entropy in the absorption refrigeration cycle shown in Figure 12.

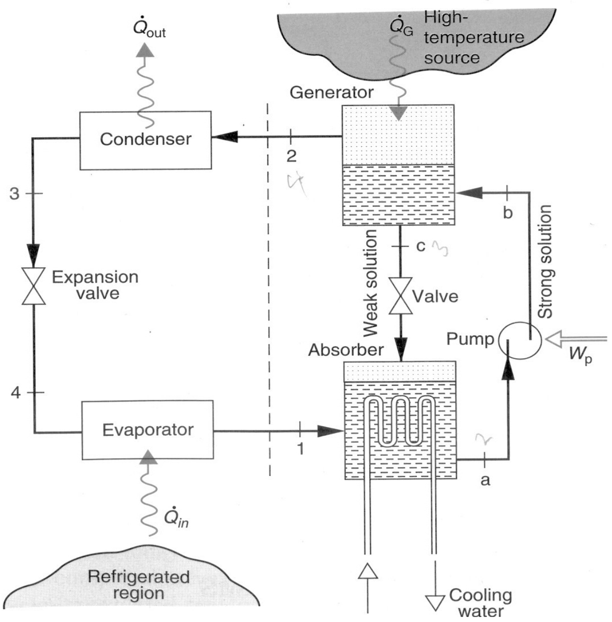

Figure 11 – Absorption refrigeration cycle layout (Moran & Shapiro, 1998, P463)

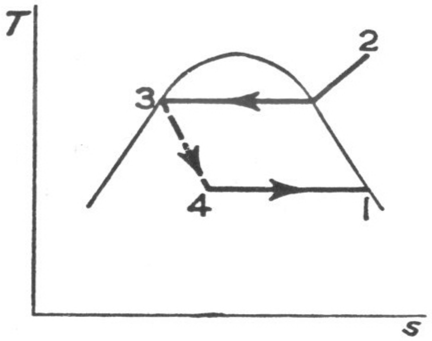

Figure 12 Absorption refrigeration T-s diagram (Rogers & Mayhew, 1980, P263)

Once the working fluid leaves the evaporator, it goes into the absorber where it is absorbed by the secondary absorbent to form a liquid solution. This solution is then raised to a higher pressure (usually by mechanical means) and at this point, the solution is classed as a strong solution. In the generator, the initial working fluid is reclaimed by means of additional heat being added to the system and a weak solution is fed back to the absorber by a one way flow valve.

An advantage of the absorption cycle is that less energy is required to pump the two part component solution, than if a single working fluid is used in the vapour compression cycle such as ammonia (Roger & Mayhew, 1980). However consideration needs to be made as to the thermal energy requirements for absorbent recovery. Where there are waste heat sources available however, the absorption cycle can use this thermal energy for absorbent recovery (Moran & Shapiro, 1998), which offers the advantage of helping to provide a cooling solution with waste heat.

Sometimes water is used as the the cooling medium in the condenser and Lithium Bromide as the absorbent fluid in a vapour absorption cycle. This use of water as the refrigerant does however offer a cooling limitation of 273°K (Dossat & Horan, 2001). An alternative, and one which can overcome this 273°K limit is to use Ammonia as the refrigerant and water as the absorbent fluid, however this is less frequently used nowadays. Despite its temperature limitations, the lithium bromide based cycle is the more commonly used in the implementation of the vapour absorption cycle in commercial applications.

4. TECHNOLOGY OVERVIEW

In this Chapter, the types of energy that can be delivered by waste heat energy recovery systems will be discussed.

In addition, almost all waste heat recovery processes involve the use of heat exchangers to recover energy and transfer it to a second working fluid for another process. Some different types of heat exchanger and their applications are considered.

In the final part of this Chapter, an overview of heat pumps and electricity generation technologies are given. These technologies incorporate some of the engineering cycles discussed in Chapter 3.

4.1 Energy Delivered

From the outset, how the captured energy will be handled and used must be considered. Though various technologies can offer different forms of recovered energy for reuse, the 2 most typical forms of energy that can be ultimately made available for further use, are thermal and electrical energy. These are discussed in the following section.

4.11 Thermal Energy

Thermal energy is one of the two typical delivered types of recovered energy, usually in the form of heat.

One of the problems with thermal energy primarily when it is in the form of waste water or warm air, is that it can be difficult to convert the energy into other forms of useful energy. At low levels, it is therefore really only usable for heating and cooling applications (Bonilla, et al., 1997)

Two examples of the direct reuse of thermal energy are as follows.
First of all, waste warm water from an industrial process is seen at Browns Ferry nuclear power station in North Alabama, in the United States (Nelson, et al., 1983). At the site, the warm water from the power station is fed into a number of tanks to

allow fish to be farmed. Despite the waste water being supplied at only around 300°K from the cooling loop, this is more than adequate to raise fish that could not otherwise be raised in open fresh water.

Across the Atlantic ocean at Billingham, on Teeside, England a similar scenario has been played out with the direct use of waste heat products from industry. At the TerraNitrogen plant where food grade ammonia is produced, a number of waste heat products are being exported off site for reuse. These products are piped down a dedicated 2 km long supply network into a group of purpose built greenhouses. These greenhouses enable tomatoes are grown year round (ETAP, 2008), offering a reduction in the distance that the fruit has to travel to market (Packaging Gateway, 2010).

4.12 Electrical Energy

The second form of energy that is typically derived from waste heat processes is electrical energy. Electricity has significant flexibility in its uses and distribution, over thermal energy.
It can power a wide range of applications either at the site of the initial industrial process or it could be injected into the existing local electricity grid and be distributed efficiently over large distances to distant consumers.

Electricity can only be realistically generated at high efficiencies by means of mechanical work carried out on a turbine to produce mechanical work and then drive an electrical generator.

The thermoelectric effect can also be used to generate electricity, with Peltier devices being one such example. They have the advantage over thermal cycles as they require few moving parts for operation. However they unfortunately have a rather low efficiency in their operation when compared with thermal cycles (Heap, 1979).

4.2 Heat Exchangers

There are many different designs of heat exchangers and each has its advantages and disadvantages. It is useful to have a range available for consideration when looking for a specific process. Two of the main types of heat exchangers are highlighted (Shah & Bell, 1997) and following on, discussion surrounding the four scenarios found in waste heat recapture:

4.21 Shell and tube heat exchangers

The shell and tube heat exchanger is a highly regarded and widely used device. Typically it is used for liquid to liquid heat exchange, but phase change can occur in the heat exchanger if required.

The outer part of the heat exchanger is known as the shell. This section of the heat exchanger is designed to allow the working fluid to flow across the outside of the tubes. With the addition of baffles inside the shell, the fluid can be forced over the run of pipes a number of times before exiting the exchanger. This increases the forced exposure to the tubes surface and thus increase the amount of energy transferred from one fluid to another. Figure 13 below shows a typical cut away view of a Shell and two pass tube heat exchanger.

The second part of the shell and tube construction is the tube section. Usually multiple thin walled pipes are combined to form the "tube", which allows for an increase in the surface area available for heat exchange with the liquid flowing though the shell side of the heat exchanger.

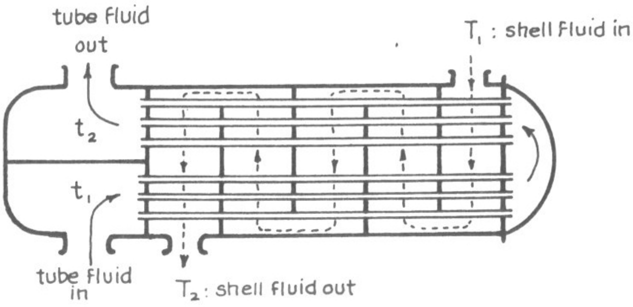

Figure 13 - Shell and tube heat exchanger, two tube pass design (Levenspiel, 1998, P258)

Where fouling may occur by either working fluid, this must be taken into account. If possible the fluid that may subject the heat exchanger to fouling should be placed into the tube side of the heat exchanger, as it is easier to remove scale from the tubes of the heat exchanger, rather than the shell section. If fouling is expected to become a major problem, then an alternative design should be considered.

4.22 Compact heat exchangers

A second area of heat exchanger technology is the compact heat exchanger. These essentially are high density heat exchangers which have the properties of large surface areas in a relatively small overall volume.

A car's radiator for example has large surface area that allows the heat from the primary fluid, ie the engine coolant – to be exposed to the secondary fluid in the heat exchanger – outside air. This secondary fluid is forced over the radiator by a number of methods. Passively by the intake of air through the front of the car when the vehicle is moving and actively by mechanical fans to make sure that air is consistently flowing to remove heat, ultimately from the engine block.

Another common implementation of a compact heat exchanger is the cross flow heat exchanger. Here two fluids flow at right angles through the exchanger, with the fluids being physically isolated from each other.

Analysis and design in the cross flow exchanger can be complex, with designers having to initially deal with two temperature gradients at right angles to each other.

An additional complication in cross flow heat exchangers is the path that either fluid can take. Cross flow heat exchangers can have the working fluid flowing either mixed or unmixed across the heat exchanger. The mixed situation is where the liquid is "open" across the surface. Whereas unmixed fluids flow in discrete paths across the heat exchanger. Figure 14 shows a cross section of a cross flow heat exchanger which has the "hot" side having a mixed flow and the "cold" side an unmixed flow.

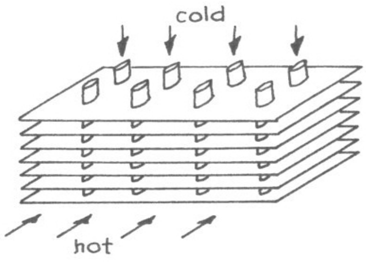

Figure 14 – Cross flow heat exchanger (Levenspiel, 1998. P266)

Potential problems with the cross flow heat exchanger include the size and capacity that is available. Shell and tube heat exchangers can be scaled to a large size where as compact heat exchangers have been employed in applications where space is at a premium.

4.23 Gas – Gas heat exchange

For gas to gas heat exchange situations, 1. recouperators, 2. waste heat boilers and 3. regenerators are typical heat exchange methods (Levenspiel, 1998) with practical applications.

A recuperator is a heat exchanger in which there is physical separation between 2 gases. Thus the 2 gases do not come into direct contact with each other. Heat energy is transferred by conduction from the primary fluid through the walls to the secondary fluid in the exchanger.

A second example of a gas to gas heat exchanger is a waste heat boiler, which is by definition a recuperator. This boiler is used for raising water to steam, which can then either drive a turbine for electrical generation or be used in the absorption cycle for cooling purposes. It gets a specific mention because it changes the phase of one of the fluids involved in the heat exchanger.

Alternately a regenerator acts as a thermal storage device. Thermal energy is stored, usually in a solid and the energy is then available for transfer to either a secondary gas or the same gas once work has been carried out by the gas in another part of its cycle.

An example of regenerator use, is seen in the Stirling cycle. This cycle requires short term thermal storage for it to operate and the regenerator provides this necessary process. Section 3.2 has further details on the Stirling cycle and its operation.

4.24 Gas – liquid heat exchange

An example of a gas to liquid heat exchanger in an industrial setting is an economiser in a thermal power station. The economiser is used for instance, in the pre-heating of feed water going into a boiler. This in effect increases the thermal efficiency of the steam raising process as less energy is required to heat the now pre-warmed feed water.

4.25 Liquid – liquid heat exchange

A typical liquid to liquid heat exchanger would provide isolation between two working fluids. For example, to provide a demarcation point between a supplier of waste heat in liquid form and a consumer of the waste heat (Searle-Barnes, 2010).
Heat exchanger solutions also fall into this category when two liquids cannot be directly mixed for heat exchange, as it might be dangerous or impossible to separate them again (Levenspiel, 1998).

4.26 Liquid – Gas heat exchange

A final heat exchange situation would be to transfer energy from a liquid to a gas. This might be useful for an organic Rankine cycle process where a warm liquid would ideally heat a gas (typically a refrigerant gas), to go onto drive a turbogenerator for example. Section 3.12 offers further details on the organic Rankine cycle.

4.3 Heat Pumps

Heat pumps operate using the same cycles as described in the refrigeration cycles section - section 3.4. The vapour compression cycle is the most common application and additional information is available in section 3.41.

The basic premise of operation is that heat pumps take advantage of the properties of their working fluid in a closed loop system. The closed loop set up has the potential for 2 distinct modes of operation. The first mode of operation is moving energy from a cooler place to a warmer place and this is typical heat pump operation. The second (and reverse of the heat pump) mode of operation is where heat energy is moved from a warmer place to a cooler place. For heat pump equipment, this is known as air conditioning.

Figure 15 below shows a basic heap pump schematic which is remarkably similar to the vapour compression cycle. The 4 essential components are a condenser, evaporator, expansion valve and compressor. If the heat pump is to provide a cooling mode, as well as space heating, a fifth core component – a reversal valve needs to be included in the system, to allow for a change in direction of the working fluid through the condenser and evaporator.

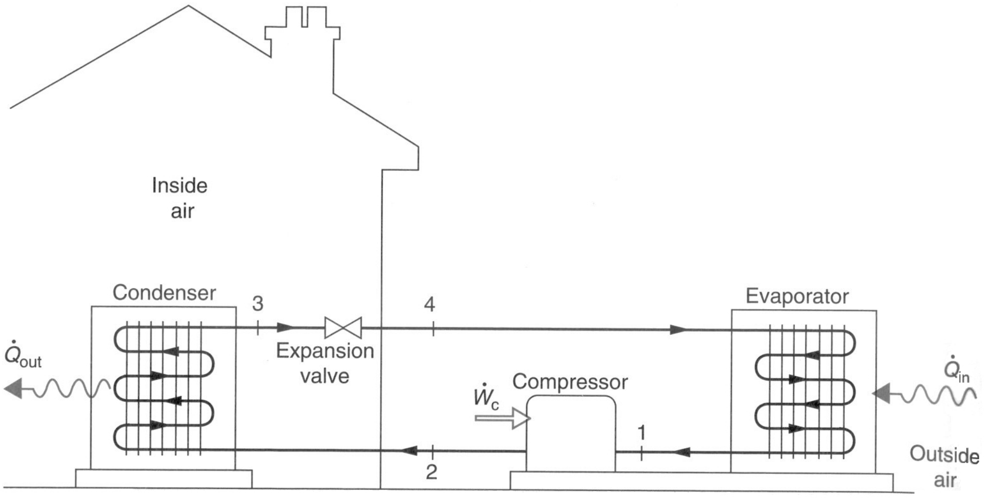

Figure 15 – Heap pump schematic (Moran & Shapiro, 1998, P466)

Heat pump performance is measured by the coefficient of performance or COP. This is a measure of the ratio between the energy supplied for work to be carried out on the working fluid (usually in the form of electrical energy) and the useful thermal energy that is delivered at the output of the heat pump to the area being heated or cooled.

Equation 1 demonstrates this.

$$COP_{(Heatpump)} = \frac{Desired\ output}{Required\ input} = \frac{Q_{Heat}}{W_{net.in}}$$

Equation 1 (Çengel & Boles, 2008, P287)

The source of the heat energy for a heat pump can either be a fluid, for example water or air, or the heat pump can use a geothermal source, as in the ground.

Waste heat does not usually originate underground so a fluid based heat pump solution would be the right candidate for energy recovery from waste heat. Typically for energy recovery, a stream of warm air or water could be the source of heat for the heat pump.

However to highlight an issue surrounding sources of energy for the heat pump, ground source heat pumps will be used as an example.
Initially it may seem a good idea to implement a ground source heat pump as the earth's temperature is fairly stable (Çengel & Boles, 2008). However long term use of a ground source heat pump causes a decrease in temperature and a resulting loss of energy capture over time (Hettiarachchi, et al., 1997).
If a supply of energy which is continually being replenished (eg the stream of warm water from from an on going industrial process is available), this offers the scope for heat pump integration (Rebello, 1988) and energy recovery.

A second issue surrounding heat pump operation is that air source heat pumps have some significant problems at very low temperatures, where they struggle to efficiently remove energy from air below 273°K as the moisture in the air will begin to freeze and accumulate on the outdoor heat exchanger which can impair operating efficiency (Langley, 1983).

It does have to be noted, that with the right conditions and product sizing, heat pumps can be very useful but they are not suited to every application in every location (Miles, 1994).

4.4 Electrical Generation

Electrical energy as mentioned in section 4.12, is the most flexible type of energy that can be produced from a waste heat source.

One example of this conversion is possibly the most high profile and in the authors opinion, the foremost system for waste heat recovery for a number of reasons.
This example is the combined cycle gas turbine power station and three reasons stand out for this opinion.

1. Its wide scale implementation in combined cycle gas turbine (CCGT) electrical power stations.
2. Secondly the increase in efficiency of these CCGT plants over stand alone gas turbines.
3. Thirdly the potential to use any high temperature source of waste heat and increased efficiencies across a number of industries.

The CCGT by virtue of its name, has 2 engineering cycles encompassed in an single overall system. The first of these cycles is typically a Brayton cycle working inside a gas turbine. The second cycle is usually a water based Rankine cycle using the flue gas from the gas turbine in the initial cycle to raise steam. Figure 16 offers a schematic of a CCGT.

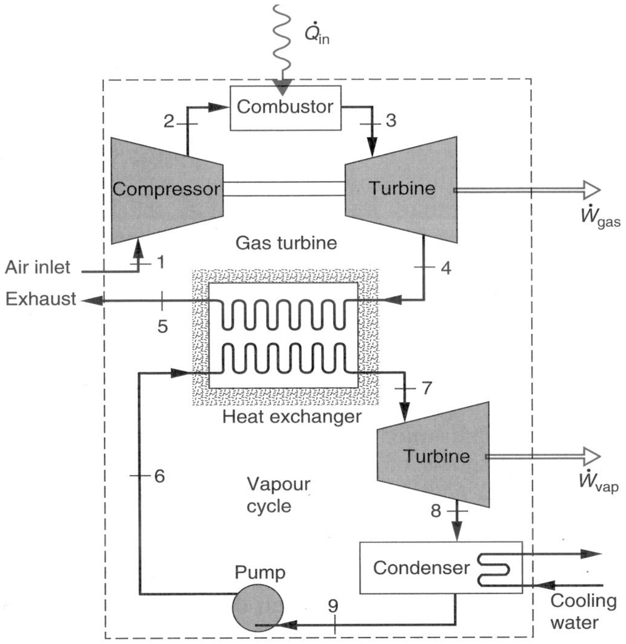

Figure 16 – combined cycle plant overview (Moran & Shapiro, 1998, P417)

Typically a CCGT plant consists of the following set up. A gas turbine is feed by air and incoming fuel (Saravanmuttoo, et al., 2001). This follows the Brayton cycle of the air (or working fluid) being compressed and then mixed with the fuel in the combustion chamber, to be ignited. The result of the combustion process goes into the turbine, to produce mechanical work, to drive both the air compressor and to generate electricity. The flue gases, which in a stand alone set up would be dumped to the atmosphere, are then taken into a heat exchanger to raise a working fluid of water to high pressure, high temperature steam. As the turbine emits relatively high temperature exhaust gases - at around 900°K, sufficient steam can be raised so as to mimic the Rankine cycle of a tradition thermal (typically coal or nuclear fired) power station.

This second cycle, sees an overall efficiency of up to 60% being achieved by the reuse of waste heat (Saravanamutto, et al., 2001) from the exhaust of gas turbine equipment. Without this steam raising, the stand alone efficiency of a gas turbine with standard operation parameters comes in at up to 36%.

A second example of electricity generation from a waste heat resource comes along in the form of the organic Rankine cycle. When the situation arises where there is not enough energy to raise water to drive a conventional high pressure steam turbine but can raise another working fluid for driving a turbine, electricity generation can occur. This is the case at four of the Saskatchewan gas compression stations operated by NR Green Power in Canada (NR Green Power, 2008). At these four sites, the waste heat from the gas compressors is used to generate power using the organic Rankine cycle. This power is fed back into the grid connection at the compression station, and resold to the local electricity retailer for use by other consumers in the locality. There are a large number of these compression stations so there is wide scope for implementation providing the grid connections allow for such a set up.

5. SELECTION PROCESS CRITERIA

If waste heat recovery is to be considered for implementation at a site, there are a number of criteria that might need to be considered from a business point of view. The factors are cover a range of criteria. Potential selection factors are described and explained below.

5.01 Type of energy delivered in secondary process

With a number of types of technologies for energy recovery available, both electrical and thermal energy can be ultimately recovered and utilised as noted in the previous Chapter.

Certain sites or situations may lend themselves to one or other of the two options, depending on the usefulness of the type of energy produced, for either on site consumption or export off site.

5.02 Value of energy recovered and reduction in consumption

Energy demands from countries like India and China are soaring as the middle classes demand more goods and services. Also, China's position as a growing manufacturing economy means that the demand for the finite resources of hydrocarbons can only increase. Therefore being able to reduce the amount of energy required to operate a business, or supply energy to external consumers is advantageous.

A basic sensitivity analysis is the ideal tool for comparison of a range of scenarios involving potential fluctuation in the value of recovered energy verses the cost of energy from an external source.

5.03 Quantity of heat

This is defined as the amount of waste energy expended from the primary process, at the exit of the initial system and is measured in kW.

5.04 Quality of heat

This is defined as the temperature of the waste heat (Pacific Gas & Electric, 1997) that could be delivered to the input of the waste heat recovery plant, after being expended from the initial process.

5.05 Availability of heat

Does the initial industrial process that produces waste heat always run, or does it operate on a part time basis?

What are the maintenance black out periods required through out the year on the initial system that produces the waste heat?

Is there a guarantee of this waste heat being offered? Or is the waste heat on offer, just a by product of the initial process, with the primary industry not wanting to become an energy supplier (Searle-Barnes, 2010)?

5.06 Corrosion and fouling factors

The waste heat may present itself in a number of forms, low grade hot air would be a typical example being expelled from HVAC equipment which is fairly benign in its composition. However if the flue gases of a gas turbine were to be used for waste heat recovery, then there may be particles and contaminates present which might either foul or corrode the heat exchanger equipment used (Brooks & Reay, 1982). If correctly identified and the contaminates reduced appropriately, then impairment of the process of waste heat recovery can be avoided by contaminated waste heat.

5.07 Pressure of the waste heat

Along with the temperature and amount of waste heat that is available, the pressure of the exiting waste heat needs to be taken into account when considering the use of the waste heat (Bonilla, et al., 1997).

<u>5.08 Distance from source of heat to demand centre</u>

The distance from the source of waste heat to the centre of demand is a further factor to consider (Baker & Goldsmith, 1975).

If the potential destination for the waste heat is not directly next to the source of the waste heat, then what transport mechanisms would be required to overcome the distances involved? What would be the implication for efficiency of the energy capture and would a specific solution need to be employed to over come these longer transmission distances (Baker & Goldsmith, 1975)?

The implications for the efficiency of energy capture need to be considered. These longer transmission distances will require a specific answer.

Another point to note at this stage is the availability of land that may be suitable for building the waste heat energy recovery equipment on. In built up areas, this might not be available. Built up areas are ideal in providing suitable density of centres of demand however, when looking at district heating scheme operations (Wang, et al., 2006).

However there is a paradox to this land dilemma, as sighting a plant in a less built up area may provide the location for building the waste heat energy recovery plant, but at the same time, the reduction in density of building use, might cause a situation to occur where there is not the density of centres of demand for waste heat reuse.

If considering the capture of waste heat from a moving vehicle, other scenarios may need investigating. Could the recovered energy be put to efficient use, or would it be under-utilised as there might not be a suitable load for the captured energy? In addition, would the mass of the additional machinery increase the fuel consumption of the vehicle beyond an acceptable level? Eg would the amount of energy that is recovered by the additional equipment be less than the increase in the consumption of fuel in the primary system due to the additional weight?

5.09 Efficiency of solution

What is the efficiency of the proposed waste heat energy recovery solution? For instance, the Carnot efficiency governs the maximum thermal efficiency of every thermodynamic process (Moran & Shapiro, 1998). Unfortunately some waste heat streams that are available, will allow low overall efficiency of energy recovery, due to the relatively small temperature differences that are available. Though this might sound disappointing, energy is at least being recovered. In addition, with even just a small increase in the efficiency of a process, there are major gains to be made when assessing potential energy capture of over a period of time.

5.10 Reliability of technology

Though waste heat recovery is not a new area, there are new ideas and solutions emerging all the time. There are however potential problems when attempting to introduce new or unproven technologies.

There are risks in unknown long term operating characteristics, maintenance issues surrounding new technology and the support of a product when engaging a company which may have limited history (Grogan, et al., 1983).

5.11 Planning considerations

In many developed counties, the onset of emission trading schemes has started to implement the system of polluter pays (Ministry of Agriculture and Forestry, 2010). New and existing large public buildings for example in the United Kingdom now have to display an energy rating for the building (Department of Communities, 2008) in a prominent place. In the London region for instance, the planning department of the Mayor of London is encouraging the matching of sources and centres of demand for waste heat reuse (Searle-Barnes, 2010).

5.12 Impact on primary process

Any energy recovery solution should ideally not impair the initial industrial process that provides the waste heat. If there is an impact on the reduction of heat lost in a cooling loop, then these inefficiencies must be taken into account when considering the amount of energy available to be recovered, or a reduction in the efficiency of the initial process will occur.

5.13 Embodied energy and CO_2 in the energy capture technology

Capturing energy from the waste heat available at the exhaust of an industrial process is desirable and the reduction in consumption of initial energy consumed is advantageous.

However if the embodied energy or the CO_2 used in the construction of the waste heat energy recovery plant is greater than the possible amount of energy that may be captured, there is little environmental benefit to the waste heat being captured (Khurana, et al., 2002). Thus an assessment of the embodied energy and carbon intensity of the plant should also be considered in the decision making process.

5.14 Capital cost

What would be the capital cost of the proposed energy recovery solution in a project? Investment banks and company boards must consider financial factors such as net present value, depreciation, cost of borrowing / use of capital, interest rates, taxation and the proposed payback period before any capital investment takes place.

5.15 Operating costs

What would be the monetary cost of operating the waste heat energy recovery equipment? Also would the equipment require an expensive supply of consumables during normal operation?

A secondary point for consideration when looking at the cost of operation, is how much routine maintenance is required on the system, and how much down time would be needed for such maintenance?

Thought needs to be given on the proposed system and its potential impact on both the productivity and uptime of the initial industrial process.

6. CASE STUDIES

In this Chapter, three case studies are presented. Each case study is discussed and considered with regard the to fifteen selection criteria noted in Chapter 5.

These selection criteria have been grouped into 5 stages that correspond to the salient points of those criteria in Chapter 5.

Further explanation of these 5 stages are offered in section 7.1.

6. 1 Sewage works, Auckland, New Zealand

This first case study looks at a proposed organic Rankine cycle installation, at the Mangere sewage treatment works. The site is directly north of Auckland's International airport, 10 km south of the central business district.

Currently the biogas consisting of methane, carbon dioxide, nitrogen, and oxygen, which is recovered from the waste treatment plant, is combusted to drive an electrical generator. There is at present no further capture of energy in this process.

However there is a proposal for capture of this currently unused energy. Watercare, the treatment plant owners have commissioned a number of studies that have investigated this proposed capture of energy.

This scheme has the potential to recover waste heat in two separate routes from the current electrical generation plant.

First of all from cooling of the engine in the initial generation process, and secondly from the flue gases from the primary combustion process (both these strands are similar to two of the four strands used for heat recovery in the Christchurch city council's tri generation plant in case study 3).

These two sources of waste heat will go on to heat a working fluid and drive a turbine in an organic Rankine cycle process (see section 3.11 for further details).

By capturing some of this waste energy using an organic Rankine cycle process, the amount of electricity generated for use on site is increased, with the expenditure and reliance on external electricity supplies reduced.

Ideally, the solution would have a high degree of automation as operation of an organic Rankine cycle plant is not part of the core business for Watercare and its staff. Additionally, since this site is near the airport, the technology supplier is investigating the potential to use this plant to demonstrate the technology of an organic Rankine cycle.

Each of the stages of the selection criteria are used in the following five sections (as described in Chapter 7) to consider the sewage treatment plant project in Mangere.

6.11 Final energy outcomes

The outcome of the energy recovery system is electrical energy for use by Watercare on site at the Mangere facility.

Currently the Mangere site produces around 60% of its own requirement for electricity from the Jenbacher engines. Additional generating capacity is sought, to reduce external consumption. Currently electricity is purchased at an average price of (NZ)$85/MWh (~£40), by contract, in advance from the New Zealand electricity market place.

6.12 Grade of energy

There are currently four Jenbacher gas engines installed on site. Three are normally in operation at any one time. Each of the engines are 38% efficient, with each engine rejecting ~2.7MW of heat through their water cooling loops and the flue gases. At present ~1.3MW of this heat is reclaimed already. However the remaining heat is either emitted as flue gases ~1MW, or dumped to the waste water process ~0.4MW.

The 1MW of flue gases leave each of the Jenbacher engines at 723°K and there are suitable gas to liquid heat exchangers already installed, in line for energy capture. The

0.4MW of heat that is currently displaced from the cooling loops at 308°K ends up in the waste water process.

The primary process of the 3 Jenbacher engines has an operating availability of 99%. This is set by a maintenance contract with an external party. Apart from these periods of routine maintenance, the supplies of biogas for combustion comes from a process on site. No shortage of treatable waste is foreseen.

As there are two sources available for energy capture – cooling water and flue gases, both must be considered.

The waste heat water used for cooling is sourced from the final effluent of the treatment process. This is further screened through a 0.5mm fine mesh screen and disinfected with hypochlorite. Minor fouling and corrosion occur in the components used.

The main constituents of the biogas are methane and carbon dioxide. The methods employed to reduce the potential for contamination in the heat exchangers with the flue gases are 2 separate scrubbers removing contaminates and a dryer to aid this process. Due to the primary source of the biogas, there is little chance of particulates being present in the flue gas.

The pressure of the cooling water system is at approximately 3 Bar. No steam is required for on site use however. The pressure of the flue gas is between 60 – 100 kPa and this is due to the compressors at the input of the biogas engines.

6.13 Technology Selection

The proposed location is next to the currently installed biogas combustion gen set, so major energy losses are not anticipated with the small distances involved between the primary process and the secondary energy recovery equipment. The proposed installation locations are within the same building as the biogas engines.

Additionally suitable electrical distribution networks at 400V and 11kV are already in place because of the Jenbacher generators. This allows efficient power distribution to the electrical loads across the site.

The efficiency of the proposed process is estimated to be 8%. This is dependant on a number of factors, including the choice of working fluid and available cooling sources eg fresh air or cold water. Suitable cold sinks allow for satisfactory operation of the cycle, by allowing optimal operation of the working fluid in the cycle.

The organic Rankine process is a proven cycle, as there is a good track record of installation and operation of organic Rankine cycle plants world wide.

There was no planning push from the local authorities, however Central Government through the Energy Efficiency and Conservation Authority offered a grant of (NZ) $100,000 (~£48,000) towards the project.

6.14 Impact of energy recovery system

The efficiency and operation of the Jenbacher engines are not impaired by the capture of the waste heat, as currently the heat is dumped either into the atmosphere or into cooling water on site.

6.15 Costs of the project

The embodied energy and carbon footprint of the organic Rankine cycle plant were not considered during the course of the project investigation.

The capital costs of the plant were examined using a number of financial factors. Life cycle and payback of the proposed installation is considered to be ten years.

Finally the operational costs of the plant were considered. These are perceived to be minimal, as the source of energy for the plant is a by product which is currently not being utilized.

The maintenance costs of the plant have been estimated, in the region of 2- 5% of the initial capital expenditure. The typical routine maintenance period for potential use on the site is every five years. The suppliers of some plant however mandate a first year servicing requirement on their products costing (US)$12,500.

6.2 Communications Centre, East London

The second case study takes a look at a recently built site, in London. A newly built communications centre in London's second financial district in the east end in Docklands, is situated on a high density site. It is next to a number of existing communication centres owned and operated by the same company. It is also at a location that is mutually advantageous to both the business itself and its customers alike. This is due to the density of data and communications facilities in the surrounding area, including a number of locations that host the London Internet Exchange, which when combined, form one of the main points of internet connectivity for the United Kingdom (LINX, 2010).

The main consideration for including a waste heat recovery system was the planning push from the office of the Mayor of London. As this driving force came about at the planning stage, the waste heat recovery equipment was designed into the scheme at the planning stage, to allow building consent.

Conventional HVAC systems are provided for the building to keep the equipment (and thus the primary business) at optimal operation conditions.

Typically the building requires a greater cooling load to be provided than a heating load, at the site due to its location and nature of the electronic equipment operated inside.

Energy is recovered from waste heat by the following method.

Two heat exchangers are situated in the plant room in the chiller loop. Here water used as the cooling fluid, passes through one of the 2 heat exchangers on the top floor and on the secondary side of the heat exchanger is a second working fluid – also water which is heated, and piped out of the room. The warm water is delivered by pipes down the outside of the building, to manholes on the site boundary for interconnection to third parties for use off site. Figure 17 illustrates the scale of the pipes running down the building from the on site plant room.

Figure 17 – Communications centre with external water pipes (Searle-Barnes, 2010)

The primary use of this warmed water is to provide a constantly replenished energy stream for water sourced heat pumps for use in near by residential dwellings, making the heat exchanger effective for the primary process – the communications centre. The feed water to the input at the secondary side of the heat exchanger must be cooler than the exit temperature of the secondary side of the heat exchanger.

The communications centre project selection process is discussed in separate stages, in the same way that the sewage treatment works was broken down and analysed in section 6.1.

6.21 Final Energy outcomes

For the communications centre, the waste heat is a by product of keeping the core business function running. No monetary value has been placed on its recovery. The communications centre will however have the potential to increase its overall efficiency with the additional heat removal from the chillers (see section 6.23 for further details).

The advantage of the scheme for the developers and owners of the complex comes from the reduction in conventional energy (electricity or nature gas) required for the site.

There is also the additional factor of having a “green” source of thermal energy, boosting the communication centre's owner, the residential apartment developers and the development's green credentials.

In this scheme, very low grade thermal energy expelled from the communications centre can be readily utilised by incorporating a heat exchanger in the HVAC plant. A heat pump installation then allows this energy to be used by a large scale residential complex in the vicinity.

6.22 Grade of energy

In the plant room, two heat exchangers have been installed. Both are rated with a heat capacity of 4 MW, with water being used as both the primary and secondary working fluids in this system.

Low temperature waste heat is produced at the centre, primarily from computer equipment which has to be kept cool. The operating temperature of the equipment in the centre must not exceed 300°K, otherwise equipment failure would occur, resulting in problems with business continuity and the business's reputation would be severely affected.

The temperature of the available waste heat from the cooling circuit ranges from 285°K in winter to up to 318°K in summer. It is dependent on the cooling requirements inside the building, which are influenced by the outside air temperature.

The communications centre must have a high up time and availability, to maintain its core business operation. Though the communication centre does not guarantee heat being produced continuously, the operational nature of the primary business function lends itself to the continuous expulsion of waste heat (excluding periods of planned maintenance).

The waste heat is available as warm water at the heat exchangers in the plant room. There are strainers in the system, to provide filtering on the primary side of the heat exchanger. These help to minimise the potential for fouling and hence reduction in the performance of the heat exchanger. The third party clients are responsible for the secondary side of the heat exchanger and all components connected beyond the heat exchanger.

The warm water is under pressure. This is because the water being pumped around the cooling system, to provide primary cooling on site. Since the heat exchangers are placed into the cooling loop, a slight increase in pressure may be required to move the water through the additional friction of the heat exchanger. However this is deemed insignificant by the engineers.

6.23 Technology selection

The centre of demand at the residential complex is a short distance away (under 1km) from the communications centre. Moreover to aid construction and connection, the pipes from the heat exchanger have been extended out to 2 manholes at the edge of the property. This is similar to a “point of presence” for a telecommunications provider, allowing interested parties to connect to the streams of waste heat, without interrupting the day to day operations of the communication centre.

The potential efficiency of the energy capture is low, since only a low grade of energy is available. The exit temperature of the heat exchangers range from 385 to 418°K. However as heat pumps are proposed for utilising this low grade of waste heat, they can take advantage of the waste heat expelled by the communications centre.

The efficiency of the cooling loop is increased by incorporating a heat exchanger in it. However this has the knock on effect of decreasing the communication centre's power usage effectiveness (the PUE is the ratio of IT electrical load to the overall building electrical load (Rawson, et al., 2008)). Thus the overall energy demands of the centre is reduced and the benefits of the project further increase.

The water based heat pumps for energy recovery are known to be reliable and there is a broad industry knowledge of operation, performance and maintenance. The installation is seen to be on an equal footing to a water source heat pump installation using a bore hole. This is due to the continuous reliable low grade source of energy from the waste heat but using this above ground solution removes the added complications of drilling a bore hole in an urban environment.
There are of course, specific aspects to the system which will be unique to this installation.

The Office of the Mayor of London was involved in a number of roles during the planning process of the communications centre.
Due to the crowded site, there was little potential for the large scale implementation of renewable energy sources. Some photo voltaic panels were incorporated into the project. However the waste heat recovery system was implemented to allow the building to pass through the planning process. This was a concession in response to the small amount of renewable energy generation installed on site.

Secondly the Mayor's office facilitated the relationship between the communications centre and the developer of the residential apartments near by, to allow the waste heat from the centre to be used appropriately for energy recovery.

6.24 Impact of energy recovery system

There is some impact on the primary building HVAC system with the addition of the heat exchanger for heat recovery. Thus the performance of the primary cooling system for the building can be increased, at least in warmer periods. With a reduction in water temperature in the cooling system after the heat exchanger, this allows for more energy efficient cooling to be carried out, resulting in a reduction in overall energy consumption for the building.

6.25 Costs of the project - in terms of energy, carbon and money

The embodied energy and carbon footprint of the installed equipment for energy recovery was not considered for this project.

The capital expenditure of the additional heat exchangers and pipe work to hand over the waste heat on the boundary was considered, but there was no major increase in expenditure. With the planning rules being crucial to the new centre, unless the installation of the heat exchanger and pipe work had been prohibitively expensive, capital cost was not the main consideration.

The operating costs associated with the installation and maintenance of the heat exchanger and associated pipe work are minimal so these costs are not considered to be significant in the operational budget.

6.3 Civic offices, Christchurch, New Zealand

Christchurch city council's new offices were recently commissioned and have been opened to users. To date (August 2010), not all staff have relocated, but the transfer is well under way.

A tri generation plant has been installed on the roof of the building by Entec, who have a long standing relationship with the city council. The recovery of waste heat has been built in from the start, to meet the demands of the building with a system that offers a high overall efficiency.

The plant is fed by biogas, which is piped in from across the city, from the Burwood landfill. However before the pipeline reaches the civic offices, a feed is taken off at a local swimming pool in the city (Christchurch city council, 2010) to provide energy requirements for that site as well.

The biogas is initially combusted to drive an electrical generating set to generate electricity for use in the building.

Waste heat is recovered in a number of different ways from the initial combustion process.
First of all, the engine casing is water cooled.
Secondly the oil used for lubrication is passed through a heat exchanger to remove heat for further use and to cool the oil at the same time
Thirdly heat is recovered from an intercooler that is situated in the combustion chamber of the primary process, located to help achieve the overall thermal energy requirements of the overall process.
These three heat recovery processes are closed loop systems, enabling close control of pressure, fluid flow and contaminates in these systems.
Finally the flue gases from the initial combustion process are also captured via a heat exchanger, enabling the energy contained in the flue gases to be recovered.

The recovered hot water is delivered at either 353°K or 363°K depending on the requirements needed for uses inside the building. These can include heating, domestic hot water or for the heat requirements of an absorption chiller system, which has been included in the building for cooling purposes.

The biogas from the Christchurch landfill at Burwood consists of two major components, methane and carbon dioxide.

The building was completed in early 2010 and the tri generation plant finally commissioned and handed over at the start of August 2010. The system is now up and running. However there is no long term operating experience of the plant.
The building is only the second building project to achieve a 6 star energy rating in New Zealand. However it is the first to actually be commissioned (New Zealand Green Building Council, 2010).

The following points for the civic offices are noted against the 5 stages, in the same way as in the two previous case studies.

6.31 Final energy outcomes

The desired outcome of the overall system was both electrical energy and thermal energy, with the thermal component of the energy coming from the waste heat side of the system.
The thermal energy is required for both heating and cooling purposes, via an absorption chiller – section 3.42 has more information on the absorption refrigeration cycle.

The calculated energy savings from the energy recovered system are (NZ)$500,000 (~£230,000) per annum, thus offering a three years pay back for the additional costs when compared to a “standard” installation.

6.32 Grade of energy

The waste heat is ultimately recovered from two sources. The oil and engine cooling loops using water as the working fluid, exit the engine jacket at a 375°K and the working fluid containing 373kW of energy.

Meanwhile the flue gas leaves the engine's combustion chamber containing 368kW of energy at a temperature of 678°K.

The overall amount of thermal energy supplied to the main hot water feed from the sum of all the waste heat recovery processes is 712kW and is presented at a temperature of 363°K.

At present, the plant has no storage capability of the biogas from landfill, and the process must shut down when the gas supply is interrupted. There is currently an investigation by the city council into the potential for storing biogas, which if implemented, will buffer any short term supply problems. The operation must be stopped when routine maintenance is required on any part of the overall process. The up time is estimated by the user to be well over 95%.

The potential for significant contaminate occurrence exists in the flue gas. To mitigate this contaminate potential the exhaust gas from initial combustion process is deliberately kept high at 423°K at the exit of the heat exchanger, to minimise the potential for condensation and particle release from the flue gas.

However the three closed loop systems are under pressure and not considered to have contaminate potential since they are physically isolated via heat exchangers.

The heat exchangers and system components have been designed to remove the heat from the engine and to allow the waste heat from the primary process to be recovered to hot water.

The flue gas is raised to above atmospheric pressure by the compressors that drive incoming biogas from the landfill. However the exhaust gas is vented to the atmosphere after heat recovery.

6.33 Technology Selection

The centre of demand is already on site, as the biogas is pumped onto site from the landfill for combustion in the initial process, so no concerns have been raised.

The tri generation process is reasonably resource efficient. The overall efficiency of the installation is 87%. There is however a small reduction in the overall efficiency of the plant in the summer months, this is due mainly to increased demands of the chiller unit.

So far the technology has proved itself during the commissioning stages. The firm behind the plant are Entec who have carried out a wide range of projects and installations in the past 28 years. Though this is the first tri generation set up installed by the company, the company has experience in similar co generation gas schemes.

Christchurch city council intended to build a high profile, highly efficient building with a 6 star energy efficiency rating. It is the first to be built in new Zealand. No significant planning requirements were specified by the planning authorities in the design of the building.

6.34 Impact of energy recovery system

The energy capture of the waste heat from the initial process was built into the plant from the design stage. Therefore no degradation in the primary process is expected.

6.35 Costs of the project

For the tri generation scheme, neither the embodied energy, nor the embodied carbon of the heat recovery plant were considered.

The additional expenditure for the Tri generation systems was (NZ)$1.5M (~£720,000), when considered against traditional separate electrical and thermal plants. At the present time, electricity costs are inexpensive when compared to other fuels in New Zealand.

The operating costs of the system are estimated by the user to be ~1c (NZ) per kWhr of energy generated for the building. The compressors for gas will require routine maintenance. No major supply problems in the near future are foreseen, as the landfill will vent biogas for the foreseeable future and biogas from sewage is literally in the pipeline. The price of the raw fuel is not considered to be a major threat to the viability of the scheme. Both the capital expenditure and the operating costs were seen by the system designers and the client as the major decision making issue, although the plant is new to New Zealand, it has a track record in operation overseas.

7. DECISION MAKING PROCESS

Looking at the case studies presented in Chapter 6, there are a range of criteria which influence the selection of waste heat energy recovery solutions.

7.1 Discussion of the decision making process

Clearly waste heat recovery is at the forefront in some projects from the outset. For example, the Christchurch tri generation plant was set up to meet the energy demands of the building from the outset, with four separate heat recovery systems helping to meet the thermal demands of the building.

However if retrofitting of a primary process is intended, there must be a route to obtaining the best fit solution for energy recovery. The sewage treatment works in the first case study is a prime example of retrofitting an installation for energy capture.

Some factors will have a greater influence on maximising the energy recovered from the available energy than others however.

At the outset of any project the amount of energy available, the availability of space to construct an energy recovery solution and the financing available for the project will provide an initial snapshot into the project's potential as shown in Figure 18.

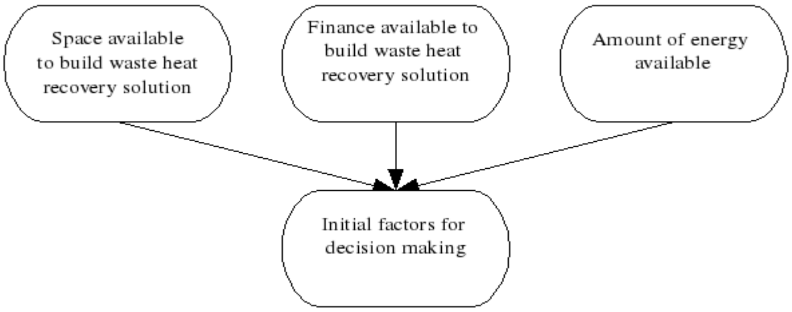

Figure 18 – Basic selection criteria

However to provide what Bonilla et al (1997) describes as the “pre screening process” for selecting technologies, there needs to be a comprehensive range of factors taken into account. Using the numerous criteria highlighted in Chapter 5, the criteria were grouped into a number of stages for the selection of energy recovery technology.

These stages, as applied to the case studies in Chapter 6, are:
The final energy outcome. Deciding on what type of energy would ideally be delivered to the consumer of the recovered energy. This would take into account the potential value of the recovered energy versus the cost of additional energy being used on site. A further consideration is whether the initial process owner seeks financial gain as well as or instead of energy gain.

The amount of energy available. Investigating the quantity, quality, availability, pressure and corrosive potential of the waste heat eg the “grade” - though they are separate factors, consideration of these factors are complementary. The combination of these five factors dictates the physical properties of the waste heat stream for energy recovery.

Technology selection. In this third stage, factors influencing the direct operation of the energy recovery process are considered. The distance from the source of the waste heat to the demand centre of recovered energy needs to be calculated. Also, the efficiency of the energy recovery process of the technological solution needs to be taken into account. The reliability of the equipment and manufacturer support will determine the availability of the energy recovery process. Finally planning issues from both a local and national perspective will need to be investigated and satisfied.

Energy, carbon and financial costs. From a businesses point of view, the financial pay back period of any proposed solution is critical to making the primary business case.
However the cost of the project in terms of embodied carbon and energy needs to be evaluated. Basic energy and carbon balances of the proposed solution would be ideal.

Baker & Goldsmith (1975) offers a similar opinion that non financial indicators are valid criteria when taking into consideration the viability of a process.

When considering each stage, there is a need for potential refinement of the selection process using feedback mechanisms at each stage.
For example, the communication centre project has the potential to increase of its cooling system (the primary process), using the heat pump in the residential complex to reduce the temperature of the water in the communication centre chiller. This change in efficiency should be investigated to allow refinement of the selection process.

7.2 The selection process

Taking into account these stages and the need to allow for refinement of the scheme, a work flow diagram was drawn up to offer a pathway to decision making for the technology selection.

A work flow diagram presented in Figure 19 incorporates opportunities for refinement. Two separate opportunities in the selection process are offered to achieve the best possible balance towards the site specific situation and criteria that have been specified by the client for a site.

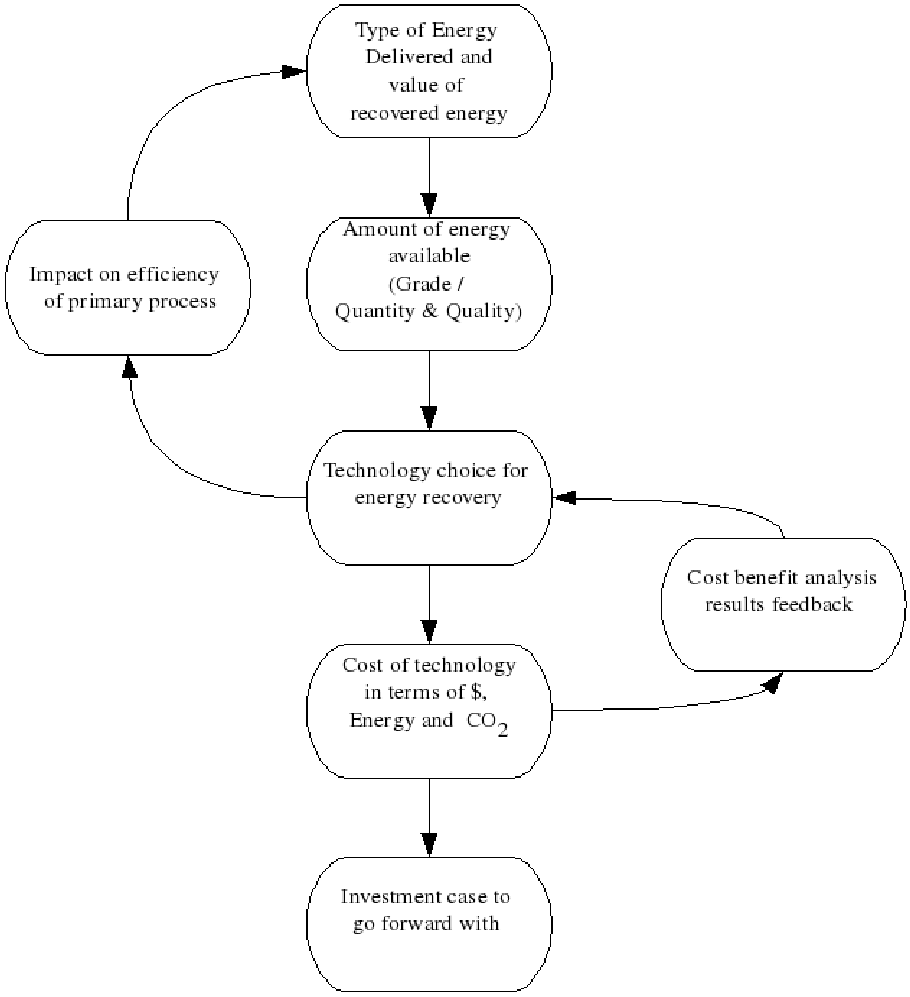

Figure 19 – Selection flow diagram

In addition to the flow diagram in Figure 19, the central technology choice stage is expanded to provide at a glance, a table of heat recovery techniques. This being an overview of Chapters 3 & 4 is shown in Table 1.

Technology	Temperature and grade of waste heat	Advantages	Disadvantages	Additional details
Rankine cycle	> 650°K to allow for raising high pressure steam.	Well proven technology. Used on a wide scale.	High temperature and grade of energy required.	Water based cycle, typical of thermal power stations.
Organic Rankine cycle	~>350°K depending on the choice of working fluid.	Proven cycle. Can use lower temperatures than Rankine cycle.	Working fluids need to be chosen and used with care.	Usually "R" series of fluids used in an ORC.
Kalina cycle	~>350°K depending on the choice of working fluid.	Can increase the efficiency of energy capture process over an ORC.	Requires specialist optimisation to work. No wide spread uptake to date (August 2010).	Proprietary cycle, needs support from licensed engineers
Stirling cycle	Dependent on gas used inside the Stirling engine. Direct solar use is becoming a common solution.	Highly efficient. Entails no direct combustion process as heat directly expands gas inside the cycle.	Needs highly efficient regenerator to achieve anywhere near its optimum efficiency.	Coming back into fashion for use in low temperature applications. The regenerator is crucial to the cycle.
Brayton cycle	High temperate hot air required, ideally up to 900°K.	Ideal if high grade of hot air available. Electricity is usual form of delivered output.	High temperature source of air usually required.	Used primarily for gas turbine implementation.
Absorption refrigeration cycle	Depends on working fluid used, one example seen requires heat at 353°K.	Can use thermal energy (heat) to provide cooling.	Multi component working fluid and cold sinks also required for optimal operation.	Compression cycle can also be used for cooling but has no thermal requirements.
Heat pumps	Continuous supply of energy at constant temperature required for operation	When considering against direct electrical heating, highly efficient.	Continuous replenishment of energy source required. Performance deteriorates as air temperature → 273°K.	Either liquid or gas can be used for heat pumps.
Thermoelectric effect	No specific grade of energy, must be able to maintain as greater temperature difference as possible between hot and cold sinks for best performance.	No moving parts or noise.	Very poor efficiency and low output voltage generated. High capital cost for energy recovered.	Used mainly in specialist applications where cost is not the greatest factor.
Direct thermal use	Depends of the source of waste heat and proposed application. Example seen at temperatures as low as 293°K.	Relatively low tech. Heat exchangers are usually the most complicated part of the process.	Supply and centre of demand of waste heat must be near by to each other – depending on transport mechanism.	Care must be taken to adequately size & to be aware of potential contamination in the heat exchanger.

Table 1 - Summary of energy recovery technologies

To provide a comparison to the Author's suggested selection flow diagram in Figure 19, Bonilla et al (1997) offers a method for an initial screening when looking at different waste heat recovery options. This scheme was used as the basis for comparative analysis of waste heat sources across the Basque region of northern Spain, using software tools to carry out rapid and repeatable analysis of a number of solutions. This is shown in Figure 20.

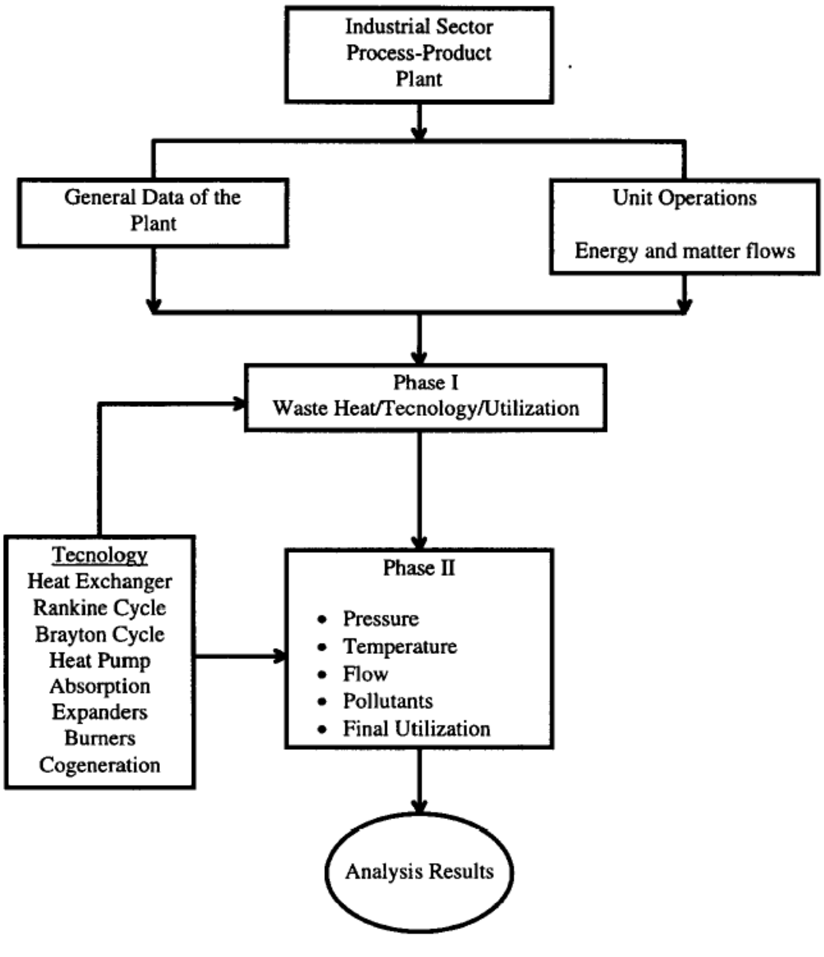

Figure 20 – Pre screening flow diagram (Bonilla, et al, 1997, P286)

The two selection processes, though constructed separately and by different authors, offer a number of similarities in their routes to selection of an optimal waste heat recovery technology.

Therefore this work flow is available for use, in projects like the sewage treatment plant, to suggest a route for selecting an optimal waste heat recovery program.

8. FURTHER DISCUSSION OF CASE STUDIES

Further discussions around the three case studies are presented in this section to comment on the projects outlined in Chapter 6.

8.1 Sewage treatment works

The energy capture project that is proposed at the Mangere sewage works in Auckland, highlighted a number of influential selection criteria. These are:

1. The long payback of the project, estimated at ten years is possibly a major hurdle. Compared to a payback period of only three additional years for the tri generation plant at Christchurch civil offices, the sewage treatment project maybe seen as financially unacceptable. However the outcome is positive for the primary investment case carried out by the consulting engineers.
2. The desire for autonomous operation is interesting. Watercare sees the benefit of increasing the proportion of electricity generated locally on site, but recognise that daily operation of an organic Rankine process is not a core business operation.
3. Also having a demonstrator unit will be valuable, offering a chance to showcase the organic Rankine cycle to the South Pacific market where few installations of the type exist.

8.2 Communications centre

With the communications centre in case study 2, a number of selection factors were seen that were different to the other case studies. Factors which the author believes are crucial to selection and implementation of the waste heat recovery project are:

1. The Planning and regulatory framework led the direction that the project took in terms of waste heat recovery.
2. Having a suitable local centre of demand, tied in with the planning incentives and allowed a negotiated solution that benefited all the parties involved.
3. The current trend is to encourage businesses to employ renewable energy technologies on site. In this instance, space on site is constrained for a large

deployment of renewable energy source. Though there has been a small deployment on site, the waste heat recovery system is a concession to the authorities for the new building.

4. The increase in performance of the chillers, makes the heat recovery system of mutual benefit to the primary process (in this case the communications centre) and the secondary user. As more energy is removed from the cooling loop, the efficiency increases for the communications centre and there is more heat available to the secondary user. This is a positive situation for both parties.

8.3 Civic Offices

In the final case study, Christchurch city council gave the impetus for an energy efficient building that has so far paid off. The factors provide the impetus for the scheme are:

1. The availability of a local independent source for the primary fuel offers long term supply of energy. The addition of a second source of fuel from the waste treatment works offers diversity in fuel supply options.
2. The centre of demand was located directed next to the supply of waste heat which makes the project highly efficient with the short distances involved, between waste heat source and its utilization.
3. With the availability of biogas plus extra fuel from a local waste treatment works, and using technological proven heat recovery systems, then an economically viable case can be made for the civic office project.

9. CONCLUSIONS

Chapter 5 outlines fifteen selection criteria for waste recovery processes. In Chapter 6, these criteria have been applied to the analysis of three case studies involving waste heat recovery.

It was somewhat surprising that in none of the case studies researched, the embodied energy and carbon were considered.

Studies such as Khurana (2002), that investigated a cement works, have previously had energy balances calculated, so this area is not entirely ground breaking.

In light of such facts, the embodied energy and carbon of waste heat recovery solutions will play a more significant role, as energy conservation and a focus on energy use becomes more prevalent. This should be put into the context that some large scale and expensive projects may require a long term analysis of the situation.

Despite the initial case study covering an organic Rankine cycle, very few projects were available for review as a case study. This is a relevant observation since the organic Rankine cycle is a proven and useful technology for energy capture.

No further significant factors came to light during the research and discussion of the case studies with the engineers involved (Reid, 2010) (Searle-Barnes, 2010) (Trafford, 2010) (Weston, 2010).

However the requirements for autonomous operation at the Sewage plant and the desire for non intervention by the operators of the communication centre may indicate a trend for concentrating on core business operation, although the capture of waste heat may be beneficial to the primary process.

In addition, financial reporting may have to be increased for funding approval however, since one engineer highlighted a number of calculations that might be required before funding is granted by a financial institution.

Finally the major factors for selection in the case studies were:

- Financial considerations as seen as the major factor in the Auckland sewage treatment plant and Christchurch tri generation case studies.
- Planning consideration was mandatory for the development of the Communications centre project.

10. FURTHER WORK

There are a number of potential area for further work that have been identified during the course of the project. These are:

Planning implications. Planning authorities around the world, including London (Searle-Barnes, 2010) and Sydney (Weston, 2010) now have influence over non residential projects for increasing the uptake of waste heat recovery solutions. The communications centre in London's Docklands indicates that planning controls are becoming more influential and prescriptive and this can only increase in the future.

Energy security and value of recovered energy. In any project security of supply of energy and the value of recovered energy will be considered. With the landfill gas in Christchurch for example, what happens if the gas runs out or demand increases? At the present time this seems unlikely, as the council controls the landfill, and additional fuel capacity from the waste treatment works is being bought on stream, but this should be explored further.

Financial control and reporting of projects. In the real world, businesses and banks want to see very minute details of how a project will perform over its lifetime. Further research into requirements for reporting and payback need to be evaluated.

Additional case studies. Much useful information could be obtained from additional case studies, using the selection criteria and work flows outlined in this paper.
If an engineering team involved in the real design process used the flow charts and critiqued the selection criteria, some very useful feedback could be obtained about the selection process.

11. REFERENCES

Arslan, O. 2010. Exergoeconomic evaluation of electricity generation by the medium temperature geothermal resources, using a Kalina cycle: *Simav case study. International Journal of Thermal Sciences.* Vol 49, Issue 9, September 2010. Pp 1866-1873.

Baker, J & Goldsmith, D. 1975. *The economic merit of low-grade heat. Energy recovery in process plants - Conference proceedings.* Institute of Mechanical Engineers.

British Gas. 2010. *Ecogen Boiler overview* [online].
Available at: http://www.britishgas.co.uk/our-universe/your-home/ecogen-boiler.html [accessed on 20th July 2010].

Bonnilla, J., Blanco, J., Lopez, L & Sala, J. 1997. Technological potential of Waste heat in the Industry of the Basque country. *Applied Thermal Engineering.* Vol 17 No 3. Pp 283 -288.

Brookes, G & Reay, D. 1982. Comparative merits of heat recovery equipment. *Heat recovery systems.* Vol 2. No1. Pp 31 – 36.

Christchurch city council. 2010. *How the renewable energy fuels the council buildings* [online].
Available at: http://www.ccc.govt.nz/thecouncil/howthecouncilworks/energyefficiencyatthecouncil/projects/wastetorenewableenergyburwoodlandfill.aspx [accessed on 21st August 2010].

Çengel, Y & Boles, M. 2008. *Thermodynamics: An engineering approach, seventh edition.* McGraw Hill.

Department of Communities. 2007. *Building a greener future policy statement.* [PDF] London: Department of communities.
Available at: www.communities.gov.uk/documents/planningandbuilding/pdf/building-greener.pdf [accessed on 31st July 2010].

Department of Communities. 2008. *Improving the energy efficiency of our buildings - A guide to Display Energy Certificates and advisory reports for public buildings.* [PDF] London: Department of communities.
Available at: http://www.communities.gov.uk/documents/planningandbuilding/pdf/20.pdf [accessed on 31st July 2010].

Dossat, R & Horan, T. 2001. *Principles of Refrigeration (fifth edition).* Prentice Hall.

ETAP. 2008. *Powering Tomato Growth.* ETAP Newsletter Issues 12 September 2008. [PDF] Brussels: European Union.
Available at: http://ec.europa.eu/environment/etap/published_files/07112008_newsletter_etap_12.pdf [accessed on 28th June 2010].

EU directive 2003/87. 2003. *DIRECTIVE 2003/87/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC* [online].
Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:275:0032:0032:EN:PDF [accessed on 31st July 2010].

Grogan, P., Brown, H & Hamel, B. 1983. Economic evaluation of competing industrial waste-heat recovery technologies. *WASTE HEAT – Utilisation and Management (Conference proceedings).* Editors: Lee, S. & Sengupta, S. Pp 911– 926. Hemisphere Publishing.

Hall, N & Taylor, C. 2006. *Emerging supply side technologies. Report for the New Zealand Ministry of Economic Development.* [PDF] Wellington: PB Power.
Available at: http://www.med.govt.nz/upload/37184/emerging-energy-technologies-report.pdf [accessed on 21st August 2010].

Heap, R. 1979. *Heap pumps.* E & F N Spon Ltd.

Hettiarachchi, H., Golubovic, M., Worek, W & Ikegami, Y. 2007. The performance of the Kalina cycle system 11 (KCS11) with low-temperature heat sources. *Journal of Energy Resource Technology.* Vol 129. Pp 243 – 247. American Society of Mechanical Engineers.

Hung, T. 2001. Waste heat recovery of organic Rankine cycle using dry fluids. *Energy Conversion and Management.* No 42. Pp 539 - 553.

International Energy Agency. 2007. *Tracking industrial energy efficiency and* CO_2 *emissions.* [PDF] Paris: International Energy Authority.
Available at: http://www.iea.org/Textbase/npsum/tracking2007SUM.pdf [accessed on 20th July 2010].

Joel, R. 1996. *Basic Engineering Thermodynamics.* Fifth Edition. Pearson Education Limited.

Kalina, A. 1982. *United States Patent 4346561.* [PDF] Washington: United States patent office.
Available at: http://www.freepatentsonline.com/4346561.pdf [accessed on 9th August 2010].

Khurana, S., Banerjee, R & Gaitonde, U. 2002. *Energy balance and cogeneration for a cement plant.* Applied Thermal Engineering. Vol 22. Pp 485 – 494.

Langley, B. 1983. *Heat pump technology.* Reston Publishing Company Inc.

Levenspiel, O. 1998. *Engineering flow and heat exchange – revised edition.* Plenum Press.

LINX. 2010. *LINX network topology* [online].
Available at: https://www.linx.net/pubtools/topology.html [Accessed on 9th August 2010].

Liu, B., Chien, K & Wang, C. 2004. Effect of working fluids on organic Rankine cycle for waste heat recovery. *Energy.* Vol 29. Pp 1207–1217.

Ministry of Agriculture and Forestry. 2010. *Agriculture in the New Zealand Emissions Trading Scheme* [online].
Available at: http://www.maf.govt.nz/climatechange/agriculture/ [Accessed on 31st July 2010].

Miles, L. 1994. *Heat pumps: Theory and Service.* Delmar Publishing Inc.

Mlcak, H. 1996. *An Introduction to the Kalina Cycle.* PWR - Vol 30. Proceedings of the International Joint Power Generation Conference. Editors: Kielasa & Weed. American Society of Mechanical Engineers.

Moghtaderi, P & Doroodchi, E. 2007. *World patent 2007131281* [online].
Available at: http://www.wipo.int/pctdb/en/wo.jsp?WO=2007131281
[Accessed on 3rd August 2010].

Mohanty, B. 1996. Thermodynamic – Chapter 3. *Rules of thumb for mechanical engineers.* [e-book]. Edited by Pope, J : Elsevier Gulf
Available at Engineering Village E books.
http://www.engineeringvillage.com/controller/servlet/Controller?CID=expertSearchAbstractFormat&SEARCHID=6c535612ab226194619bcprod3data2&DOCINDEX=1&database=131072&format=expertSearchDetailedFormat [accessed on 15th July 2010].

Moran, M & Shapiro, H. 1998. *Fundamentals of engineering thermodynamics: SI version. Third edition.* John Wiley & Sons.

Murgatroyd, W. 1977. Local Energy Centres – A policy on improved resource utilisation. *Proceedings of the local energy centres conference.* Editor: Lucas. Pp 1 – 17. Applied Science Publishers.

Nelson, R., Behrends, L., Waddell Jr, E & Bruch, D. 1983. Tilapia culture in heated effluents: Economic aspects. *WASTE HEAT – Utilisation and Management (Conference proceedings).* Editors: Lee, S & Sengupta, S. Pp 397 – 404. Hemisphere Publishing.

NR Green power. 2008. *NR Green Power projects overview* [online]. Available at: http://www.nrgreenpower.com/projects.html [accessed 20th July 2010].

New Zealand Green Building Council. 2010. *Christchurch Civic Building achieves 6 Green Star - Office design certification* [online].
Available at: http://www.nzgbc.org.nz/main/resources/articles/ChristchurchCivicBuilding [accessed on 21st August 2010].

Ogriseck, S. 2009. Integration of Kalina cycle in a combined heat and power plant, a case study. *Applied Thermal Engineering.* No 29. Pp 2843 – 2848.

O'Neil, D., Cooper, K & Hickman, K. 1998. *Mechanical Engineers Handbook.* Editor Kutz, M. John Wiley and Sons.

Pacific Gas and Electric. 1997. *Industrial Heat – Recovery Strategies. Application note.* [PDF] San Francisco: Pacific Gas and Electric.
Available at: http://www.pge.com/includes/docs/pdfs/about/edusafety/training/pec/inforesource/heatreco.pdf [accessed on 21st August 2010].

Packaging Gateway. 2010. *John Baarda Tomato packaging* [online]. Available at: http://www.packaginggateway.com/projects/john_baarda/ [accessed 28th June 2010].

Pilavachi, P. 1987. Energy conservation research and development in industry. Heat recovery systems and CHP, Vol 7 No 4. Pp 329 – 335.

Pouraghaie, M., Atashkari, K., Besarati, S & Nariman-zadeh, N. 2010. Thermodynamic performance optimization of a combined power/cooling cycle. *Energy Conversion and Management.* Vol 51. Pp 204–211.

Reay, D. 1979. *Heat recovery systems – A directory of equipment and techniques.* E & F N Spon Ltd.

Rawson, A., Pfleuger, J & Cader, T. 2008. *Green Grid data center power efficiency metrics: PUE and DCIE. Green Grid white paper 6.* [PDF] Oregon: The Green Grid.
Available at: http://www.thegreengrid.org/~/media/WhitePapers/White_Paper_6_-_PUE_and_DCiE_Eff_Metrics_30_December_2008.ashx?lang=en [accessed on 21st August 2010].

Rebello, W. 1998. Heat Pumps for Low Temperature Industrial Waste Heat Recovery. *Heat transfer equipment design (Conference proceedings).* Editors: Shah, Subbarao & Mashelkar. Pp 655 – 678. Hemisphere publishing.

Reid, D. 2010. Solutions development general manager – waste heat in industry. [Emails & phone calls] (Personal communication, August 2010).

Rogers, G & Mayhew, Y. 1980. *Engineering thermodynamics: work and heat transfer: SI units - Third edition.* Longman Group

Saravanamuttoo, H. Rogers, C & Cohen, H. 2001. *Gas turbine theory (fifth edition).* Pearson Education.

Searle-Barnes, P. 2010. WSP Communication centre design [Emails & phone calls] (Personal communication, June – August 2010).

Shah, R & Bell, K. 1997. Heat Exchangers. *The CRC handbook of mechanical engineering.* Editor in chief - Kreith, F. CRC Press.

Singh, O. 2006. *Engineering Thermodynamics.* Pp 241 – 243. New Age Publishers.

Stine, W. 1998. Stirling engines - Chapter 8.5. *CRC Handbook of mechanical engineering.* Editor in chief - Kreith, F. CRC Press.

Trafford, P. 2010. Watercare Treatment planner (Wastewater), Sewage works ORC design [Emails & phone calls] (Personal communication, August 2010).

Wang, L., Ni, W & Li, Z. 2006. Emergy evaluation of combined heat and power plant eco-industrial park (CHP plant EIP). *Resources, Conservation and Recycling.* Vol 48. Pp 56–70.

Weston, B. 2010. Managing director, Entec Services, Tri generation design and operation [Emails & Phone calls] (Personal communication, August 2010).

Yamamoto, T., Furuhata, T., Arai, N & Mori, K. 2001. Design and testing of the Organic Rankine Cycle. *Energy.* Vol 26 Pp 239 – 251.

12. BIBLIOGRAPHY

Çengel, Y. 1998. *Heat transfer: A practical approach.* WCB McGraw-Hill.

Hewitt, G., Shires, G & Pelezhaev, Y (Editors). 1996. *International Encyclopaedia of Heat and Mass Transfer.* CRC press.

Wallace, F & Linning, W. 1970. *Basic Engineering Thermodynamics.* Pitman Press.