EG4013 – MEng Engineering Report (Winter Progress Report) January, 2015

Review of the *Winter Report* 'Optimisation of Energy Systems in Smart Cities' by David Andrew

The manuscript reports initial literature review and analysis of power, heating and cooling systems. A relatively in-depth overview of the existing power cyle technologies relevant to (C)CHP was undertaken by Mr Andrew including: (a) water/steam-based (standard Rankine), (b) organic Rankine, (c) gas-turbine (Brayton), (d) combined and (e) refrigeration cycles.

The report is relatively well-written with a number of typos and unrevised sentences. Several sentences are confusing and disconnected with no clear objectives and inter-connectivities. Most of all, the paper is well-structured with clear division and linkages between sections, leading to a relatively easy and smooth reading. My main concern is that there is no clear indication of actual objectives (project's and report's) neither in the *Abstract* nor in the *General Introduction* Sections. A few general comments,

1. The main aim of *Abstracts* is to briefly describe the work undertaken by the author. In general *Abstracts* are divided in 4 parts: (i) motivation, (ii) main objectives, (iii) summary of the main procedures / techniques / technologies (optional) and (iv) main findings. The current *Abstract* encompass only (ii), but very superficially.

2. The main *Introduction* section usually has the same (but more in-depth and descriptive) four parts of the *Abstract* and a brief summary of the remaining of the work. In addition, it is <u>always</u> expected a few clear statements -re main background (thus recent innovations related to the main topic), initial literature review and, most of all, technological / scientific gaps in the current understanding. Also, it is expected a summary of the remaining sections at the end of the *Introduction*. Current *Introduction* covered only (i) above but lacked explain/summarise the main state-of-the-art aspects of the subject area. In fact, the *Introduction* section introduces and describes the main motivation for the work – the dual sustainability and smart cities, however no explanation is given to the terms and the plots/figures.

3. Quality of figures are very poor. Also, several figures are 'floating' with no explanation/description in the main text.

4. The *References* have a few missing fields and no clear distinction between articles, conference proceedings, reports (internal or external), book chapters, books, communications (internal or external) etc. A few *references* used in the manuscript are incomplete and/or wrong. Regardless of the chosen citation style (e.g., ACS, AIP, AMS, IEEE, AIAA, etc) any reference **must** contain the following fields:

   (a) For journal papers: Authors, Paper Tittle, Journal Name, Volume, Pages, Year of publication;

   (b) For books: Authors, Book Tittle, Publisher, Year or Edition;

(c) For book chapters: Authors, Chapter Tittle, Book Tittle, Editors, Publisher, Year or Edition;

(d) For conference papers: Authors, Paper Tittle, Conference Tittle, Place (Country and/or City) where the conference was held, Year of the conference;

(e) For reports, private communications and Lecture Notes: Authors, Tittle, Place issued (Country and/or City and Institution where the document was originated), Year;

(f) For PhD Thesis and MSc Dissertations: Author, Tittle, Institution (University and Department/School), Year.

Thus, for example:

[1] P.L. Houtekamer and L. Mitchell, 'Data Assimilation Using an Ensemble Kalman Filter Technique', *Monthly Weather Review*, 126:796-811, 1998.

[2] K. Pruess, 'Numerical Modelling of Gas Migration at a Proposed Repository for Low and Intermediate Level Nuclear Wastes', Technical Report LBL-25413, Lawrence Berkeley Laboratory, Berkeley (USA), 1990.

[3] K. Aziz, A. Settari, *Fundamentals of Reservoir Simulation*, Elsevier Applied Science Publishers, New York (USA), 1986.

[4] R.B. Lowrie, 'Compact higher-Order Numerical Methods for Hyperbolic Conservation Laws', PhD Thesis, Department of Aerospace Engineering and Scientific Computing, University of Michigan (USA), 1996.

5. Nomenclature tables must contain the relevant units associated the main symbols.

6. You <u>must</u> avoid use *colloquial (informal)* writing.

7. Equations <u>must</u> be placed in a separated line (centered aligned with uniform font) followed by numbers (rhs aligned). All terms used must be defined afterwards as part of the main text.

The paper is a good review of power, heating and cooling systems. Although there is no clear objectives associated with either the report or the project, Mr Andrew managed to make an in-depth review of the current technologies that he will use in the second part of his project.

In the attached scanned document:

- **PE:** Poor English;
- **SC:** Sentence(s) is/are very confusing and do(es) not make much/any sense.

Optimisation of Energy Systems in Smart Cities

Submitted by
David Andrew

Supervisor: Dr Jefferson Gomes

This Project Progress Report was submitted as part of the requirements for
the MEng degree in Engineering (Mechanical) at the
School of Engineering, University of Aberdeen

Motivation: ×

Objectives: ✓

Methods/Procedures/etc: ×

Main Findings: ✓×

Abstract

This paper presents an overview on sustainability and gives a summary of the concept of a smart city and presents predictions of what this is expected to achieve. It then goes on to explore the advancements in steam, gas and refrigeration cycles, and shows how these systems can work in conjunction with each other for more efficient power production in a cogeneration or tri-generation configuration.

Contents

units?

Nomenclature

T	Temperature
P	Pressure
ρ	Density
x	Quality
h	Enthalpy
s	Entropy
η	Efficiency
$\dot{W}$	Rate of work done
$\dot{Q}$	Heat transfer rate
$\dot{E}x$	Exergy
$\dot{m}$	Mass flow rate
C_p	Specific heat capacity
ω	Acentric Factor

Abbreviations

HP	High pressure
MSR	Moisture Separator Re-heater
LP	Low Pressure
IP	Intermediate Pressure

Subscripts

CC	Combined cycle
B	Brayton cycle
R	Rankine cycle
GT	Gas turbine
ST	Steam turbine
EX,CC	Exergy of combined cycle
F	Fuel
g, in	Gas inlet / input
s, in	Steam in
s, out	Steam outlet / output
g, out	Gas out
w, in	Water in
HRSG	Heat Recovery Steam Generator
g	Gas
o	out
w, s	Feed water

1. Introduction

In 2010, the world consumed $5.53 * 10^{20}$J of primary energy and is projected to consume $8.65 * 10^{20}$J by 2040. This is an annual increase of 1.5%. Electricity accounts for a large portion of this. In 2010 the world generated $0.73 * 10^{20}$J of electricity and is expected to generate $1.4 * 10^{20}$J by 2040, an average annual increase of 2.2%. Assuming a constant average thermal conversion efficiency of 38%, electricity generation accounted for 34.6% of the world's total primary energy consumption in 2010 and is projected to grow to account for 42.6% in 2040. Hydrocarbon fuels account for the majority of the primary energy consumed to produce electricity. In 2010 they accounted for 66.6% of worldwide electricity generation [1].

To ensure that electricity generation of this scale is sustainable, it is necessary to reduce the waste energy from the power cycles. At this point in time, the best way of doing so would appear to be the use of cogeneration and tri-generation technology which involves joining more than one power cycle together in order to maximize the usage of each unit of primary fuel.

The world is experiencing a period of extreme urbanization. In China alone, 300 million rural inhabitants will move to urban areas over the next 15 years. SC This will require building an infrastructure equivalent to the one housing the entire population of the United States in a matter of decades. In the future, cities will account for 90% of global population growth, 80% of wealth creation and 60% of total energy consumption [2].

A 'Smart city' is a place where the traditional networks and services are made more efficient through the use of digital and telecommunication technologies, for the benefit of its inhabitants and businesses. The concept goes beyond the use of improved ICT to better use of resources and reduced emissions. It means smarter urban transport networks, upgraded water supply and waste disposal facilities, and more efficient ways to light and heat buildings [3]. In Europe, the EU has decided to focus the implementation of the smart cities concept on medium sized cities rather than large metropolises. This means cities with a population ~~of~~ between 100,000 and 500,000. They selected 77 cities based on a number of criteria and ranked then by the criteria shown in [Fig.1], which shows the city profile for Aberdeen. Each city in the 77 is evaluated in the same way and its average score as depicted by the lowest bar determines its overall ranking. This type of chart shows where each city is performing well and also

Intro:

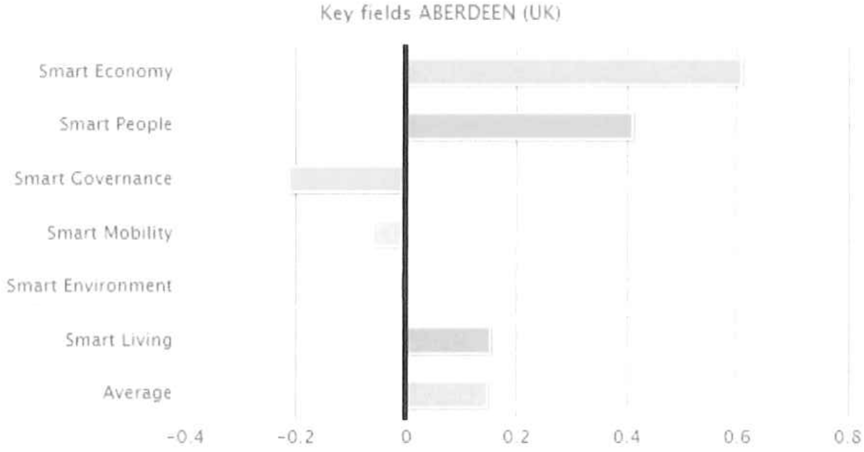
Motivation: ✓

Objectives: ✗

Methods & Procedures: ✗

Summary of the Report: ✗

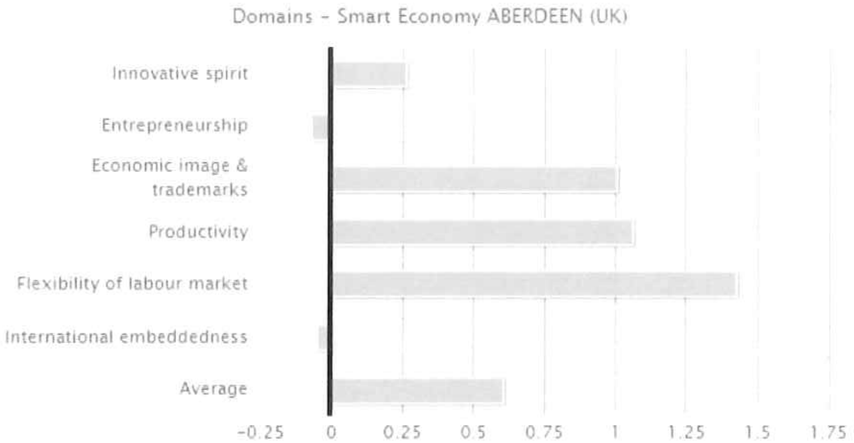
where there is room for improvement. Each field of the graph has a related graph showing further relevant information of how its score was achieved. [Fig.2] shows the data relating to the 'Smart Economy' of Aberdeen.



Poor Quality

?

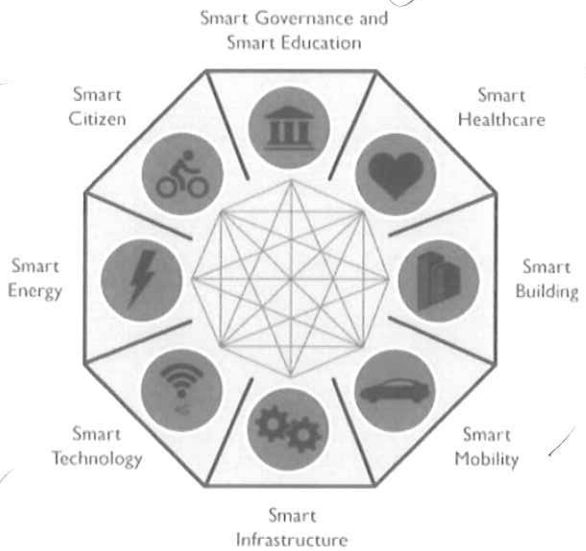
[Fig.1] City Profile for Aberdeen [4]



[Fig.2] Smart Economy Data for Aberdeen [4].

[5] defines a smart city as one which displays at least 5 out of the 8 parameters listed in [Fig.3]. Those cities which are only displaying a couple of these parameters are described as eco-friendly cities. It is expected that by 2025, there will be 26 global smart cities, 50% of which will be situated in Europe or North America. PE

But what do these parameters/attributes mean?

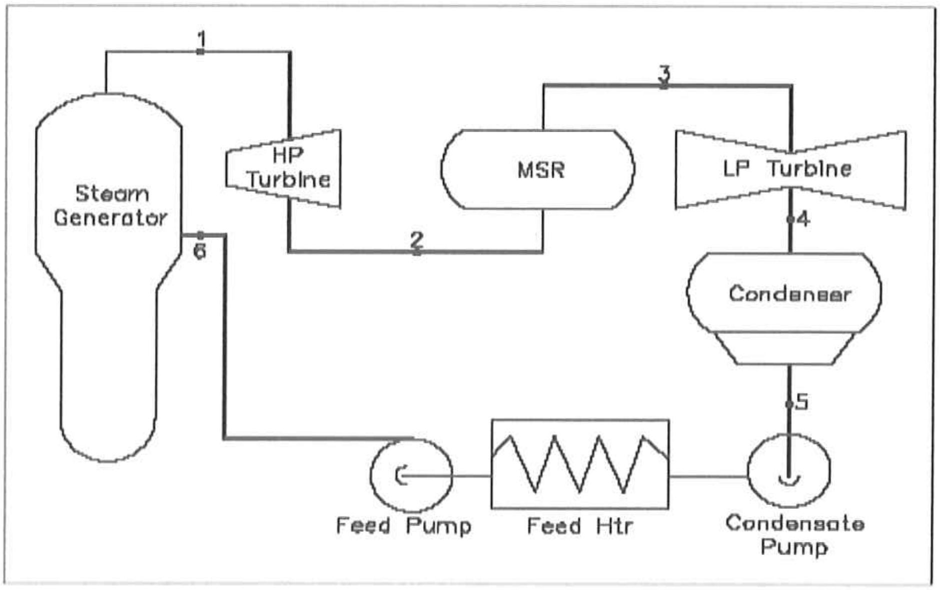


[Fig.3] Smart City Concepts [5]

2. Steam Cycles

2.1. Rankine Cycle

The Rankine cycle is the most common form of steam cycle used for energy production and takes the form shown in [Fig. 4].



[Fig.4] Schematic of typical Rankine cycle [6]

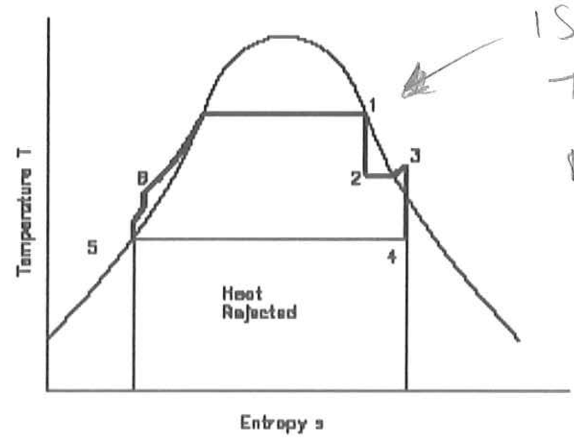
The steps of such a cycle are as follows:

1→2: Saturated steam from the boiler is expanded in the high pressure turbine to provide shaft work output at constant entropy [6].
2→3: The moist steam from the exit of the HP turbine is dried and superheated in the MSR [6].
3→4: Superheated steam from the MSR is expanded in the LP turbine to provide shaft work output at constant entropy [6].
4→5: Steam exhaust from the turbine is condensed in the condenser in which heat is transferred to the cooling water under ~~a~~ constant vacuum conditions [6].
5→6: The feed water is compressed as a liquid by the condensate and feed water pump and it is pre-heated by the feed water heaters [6].
6→1: Heat is added to the working fluid in the boiler under constant pressure conditions [6].

CYCLE

The model described above is a simplified and idealised version of a Rankine cycle that would be used in power plants. The difference between this cycle and an actual cycle is that ~~the~~ turbines and pumps in an actual cycle would display an increase in entropy whereas in the idealised case they do not.

[Fig. 5] shows the T-s model of an ideal Rankine cycle. [Fig. 6] shows the same model but for an actual cycle where an increase in entropy is present.

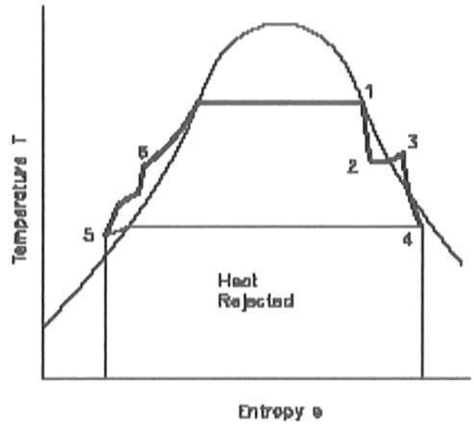


ISN'T THIS SUPPOSED TO BE SUPERHEATED FLUID?

[Fig. 5] T-s model of an ideal Rankine cycle [6].

LOW QUALITY

Low QUALITY!

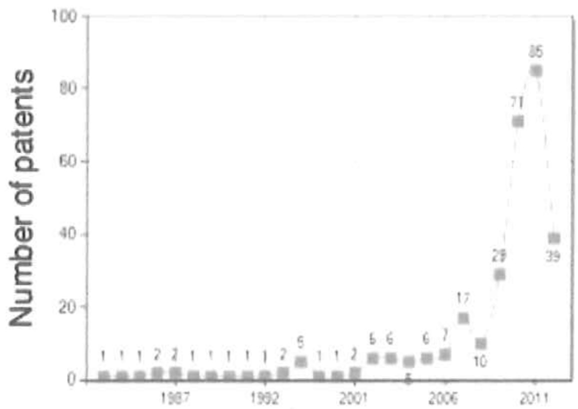


[Fig. 6] T-s model of an actual Rankine cycle [6]

2.2. Organic Rankine Cycle

Modern advancements in the simple Rankine cycle have produced the Organic Rankine Cycle (ORC). The key difference between the ORC and a simple Rankine cycle is the working fluid used. The ORC uses a chosen organic fluid with a low boiling point rather than water. This allows for the utilisation of low grade thermal energy sources such as solar energy and geothermal energy which were not viable sources when using water as a working fluid. The ability of the ORC to operate across a wider range of temperatures also makes it ideal to be used as the bottoming cycle of a cogeneration system in conjunction with a gas turbine.

Since the early 80s, there has been steady interest in ORC technology, with approximately 1 new patent each year. 2006 saw a rapid growth in interest in this technology which saw the number of patents in 2011 reaching a massive total of 85. The evolution of patents in ORC technology is displayed in [Fig. 7].



[Fig. 7] Evolution of number of patents [7]

Low QUALITY!

In conventional Rankine cycles, inlet temperature is increased to improve the turbine output. This is not the case when low grade heat sources are used [8]. Often this is because there is little or no control over the inlet temperature. This would be the case if using geothermal or solar heat, or if using the waste heat from a gas turbine when using the ORC as a bottoming cycle. In addition, Rankine cycles operating at low temperatures have low thermal efficiency [8].

It is preferable to use a working fluid with a low latent heat and a high density. This is necessary to increase the turbine inlet mass flow rate. The cycle efficiency is also highly dependent on the pressure ratio across the turbine. It is therefore preferable to operate at a higher pressure ratio such as 5 to increase the cycle performance [8].

SC PG

There have been many papers investigating ORC working fluids and their selection. This is because, as of yet, there has been no fluid found which covers all the desired objectives to optimise the performance of the ORC. Among these ? are a multitude of different methods. Typically, thermodynamic properties for a series of working fluids will be entered into a program where they are assessed based on the parameters of a given ORC. After this process it is possible to select an optimum fluid to maximise either power output, cycle efficiency or both. The most common program used to evaluate these properties is REFPROP. Cases where this is used include [1] and [9].

In [1], a 'Peng- Robinson' equation of state (EOS) was used to perform the cycle calculations. In order to do this, the thermodynamic properties T, P, ρ, x, h and s must be known at several state points around the cycle. To, Po, ω and Cpo are also needed to implement the EOS. For some of the potential working fluids, such information is not available. In such a case, they use group contribution methods to estimate the unknown properties. These methods produced the values with a RMSE% (root mean square error) of 9.2%. In [9], they opted to use a 'Backbone' EOS. This is a family of EOS that is physically based and is able to describe the thermodynamic properties of non-polar, di-polar and quad-polar fluids. ?

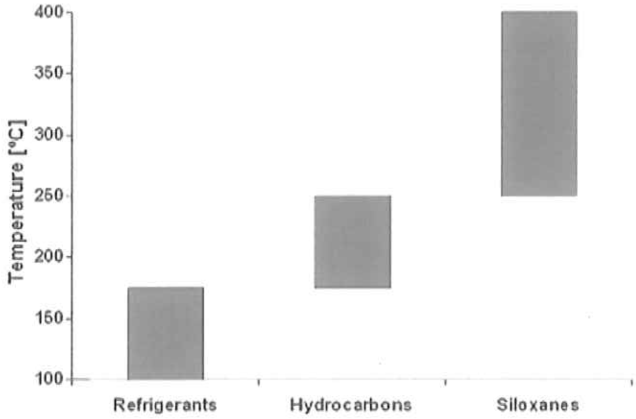
An important aspect for the selection of the working fluid is the temperature of the heat source. This can range from low temperatures of about 100°C to medium temperatures of about 350°C. For medium temperature heat sources it can sometimes be better to use water as the working fluid due to its obvious cost advantages. At this sort of temperature, the efficiency lost by using water causes less financial loss than using an organic substance. For low temperature heat sources, it is definitely better to use an organic substance because of the volume ratio of the working fluid at the turbine outlet and inlet. This can be smaller by an order of magnitude for organic fluids than water and hence allows the use of simpler and cheaper turbines [9].

[10] outlines the problems of using water as being, the need for superheating to prevent condensation during expansion, risk of erosion of turbine blades, excess pressure in the evaporator and the need for complex and expensive turbines. They also go on to give advantages of using an organic fluid. These are, less heat needed during the evaporation process, evaporation process takes place at a lower pressure and temperature and the expansion process ends in the vapour region, hence the superheating is not required which avoids the risk of blade erosion. On top of this, the smaller temperature difference between evaporation and condensation also means that the pressure drop will be much smaller and thus simple single stage turbines can be used.

[10] also gives the following list of potential substances which have been identified for use in ORC's:

-Hydrocarbons (HC)
-Hydrofluorocarbons (HFC)
-Hydrochlorofluorocarbons (HCFC)
-Chlorofluorocarbons (CFC)
-Perfluorocarbons (PFC)
-Siloxanes
-Alcohols
-Aldehydes
-Ethers
-Hydrofluoroethers (HFE)
-Amines
-Fluids mixtures (zeotropic and azeotropic)
-Inorganic fluids

low quality

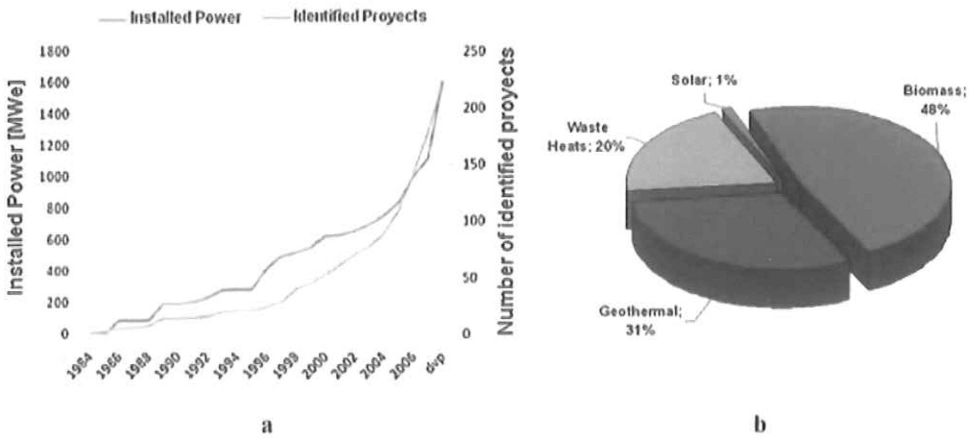


[Fig. 8] Typical classifications of working fluids in ORC systems, according to the level of temperature of the heat source [11]

[Fig. 8], as taken from [11] shows over which temperature ranges a selection of the substances outlined by [10] would be used in an ORC. PE

As mentioned previously, the ORC can be used in conjunction with other cycles such as the gas turbine cycle. [11] also brings to light the fact that the ORC has been experimented with as a combined cycle with an internal combustion engine. This led to a 7% improvement in the efficiency of the fuel conversion and a decrease of 18% in specific NOx and CO2 emissions. [11] discusses potential configurations of ORC, one of which is to set it up as a cascade. In this mode, one ORC would be coupled to either a conventional Rankine cycle or another ORC where the condenser of one would act as the evaporator of the next. In theory you could have multiple ORC's in the cascade placed one after the other, however, at some point the cost of installing the additional plants would outweigh the benefits gained from them.

Excellent!



[Fig. 9] Evolution and distribution of application of the ORC technology [11]

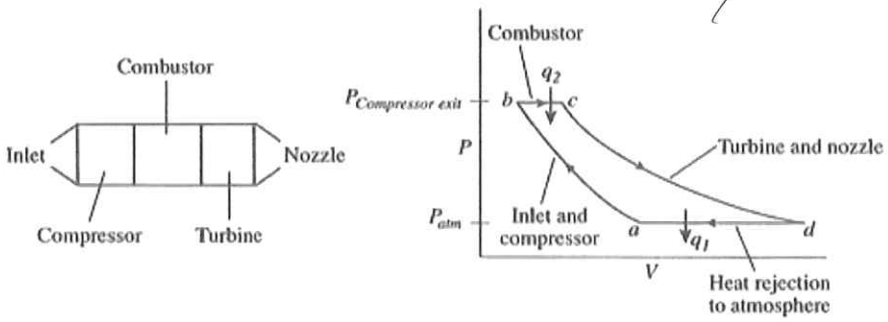
low quality

Since the early 80s when this technology first started to break through, there has been a steady increase in the number of plants worldwide based on the ORC. [Fig. 9] illustrates this increase and also shows which heat sources account for the energy and in what respective percentages.

3. Gas cycles

3.1. Brayton Cycle

low quality!



[Fig. 10] Sketch of the jet engine components and corresponding thermodynamic states [12]

[Fig. 10] illustrates the Brayton cycle in its most basic form. As well as being the cycle commonly used for aircraft propulsion systems, this is also the base for how gas turbine power plants operate. Referring to the graph in [Fig.10], the steps of the cycle are as follows:

a→b: Adiabatic, quasi static (or reversible) compression in the inlet and compressor [12].
b→c: Constant pressure fuel combustion (idealised as constant pressure heat addition) [12].
?
c→d: Adiabatic, quasi state expansion in the turbine and exhaust nozzle, with which we: 1. Take some work out of the air and use it to drive the compressor.
2. Take the remaining work out and use it to accelerate the fluid to turn a generator for electric power generation [12].
d→a: Cool the air at constant pressure back to its initial condition [12].

too colloquial

PE

Improvements in blade technology and the introduction of sophisticated cooling systems have allowed for greater turbine entry temperature which gives greater potential for power generation. Fundamental studies of fluid dynamics of

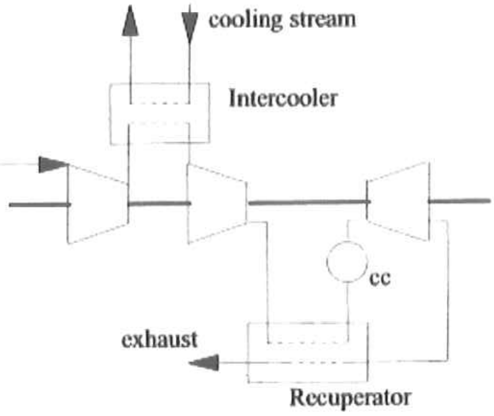
PE turbomachinery, of combustion, of high temperature materials and the introduction of nozzles and turbine blade cooling have made the current technology reach compressor and turbine efficiencies well above 92%, a pressure ratio of axial compressor up to 30 and a turbine inlet temperature of 1700K [13]. SC

According to [13], the following are areas in which modifications can be made to further improve the performance of the gas turbine cycle:

1. Recuperation
2. Intercooling
3. Reheating
4. Regeneration
5. Wet compression

3.2. Recuperation

Recuperation cycles use recovered heat from the exhaust of the cycle in the same cycle. Exhaust recuperation has been used in conjunction with industrial gas turbines for more than 50 years but there have always been underlying metallurgical problems due to the heat exchanger temperature. Increasing the pressure ratio increases the compressor exit temperature but reduces the exhaust temperature and, in modern gas turbine designs, the limiting conditions for the transfer of heat from the exhaust stream are easily achieved. Inter-cooling reduces the heat transfer problem and allows recuperation with high efficiency turbines [14]. SC/PE



[Fig.11] A Recuperator and intercooler working in conjunction with a Brayton cycle [14]

3.3. Intercooling

Carrying out the compression process in stages and cooling the gas in between the lower and higher pressure stages will decrease the work required to compress a gas between two specified pressures. This is called 'multistage intercooled compression'. As the number of stages is increased, the compression process becomes nearly isothermal at the compressor inlet temperature, and the compression work decreases. Also, as the number of stages is increased, the thermal efficiency will approach the theoretical limit (the Carnot efficiency). However, the use of more than two or three stages cannot be justified economically [15].

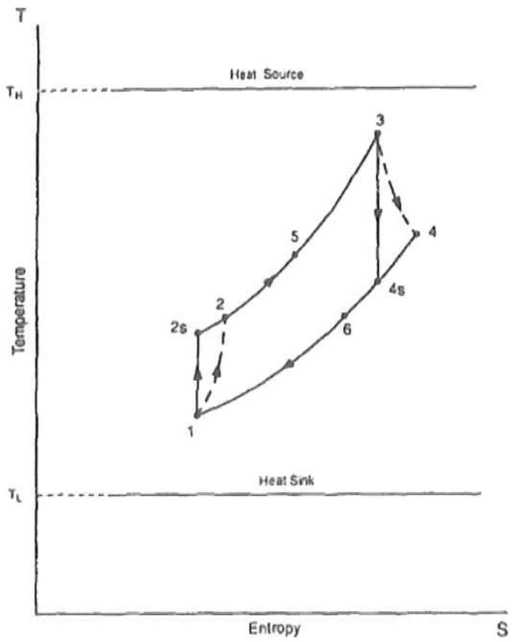
3.4. Reheating

The work output of a turbine operating between two pressure levels can be increased by expanding the gas in stages and reheating in between. This is called 'multistage expansion with reheating'. This process involves dividing the turbine into two parts, a HP and LP turbine. After the gas passes through the HP turbine it is extracted from the turbine and admitted into a second combustor. Reheated gas flows into the LP turbine, which may be on a separate shaft, or both turbines and the compressor may be connected to a common shaft. Combustion in gas turbines typically occurs at four times the amount of air needed for combustion to avoid excessive temperatures. Therefore, the exhaust gasses are rich in oxygen, meaning that reheating can be accomplished by simply spraying additional fuel into the exhaust gases between two expansion states [15].

The back work ratio of a gas turbine improves as a result of intercooling and reheating. However, in the absence of regeneration, they will decrease the thermal efficiency [16].

3.5. Regeneration

A regenerator takes heat from the hot gases exiting the turbine and uses it to heat the cold gas leaving the compressor. In an ideal regenerator the gas will leave the regenerator at the same temperature as the hot exhaust gases from the turbine.



poor quality

[Fig.12] Temperature-entropy diagram of a regenerative Brayton cycle [17]

Referring to [Fig.12], the gas enters the compressor at state 1. At state 2, the cold gas leaving the non-isentropic compressor enters the regenerator where it is heated to temperature 5. The primary heat addition process takes place between states 5 and 3. The gas enters the gas turbine at state 3 and expands non-isentropically to state 4 or isentropically to state 4s. The hot gas exits the non-isentropic gas turbine at state 4 and enters the regenerator, where it is cooled to state 6 at constant pressure. The cycle is completed by cooling the gas to the initial state. The process 1 to 2s is an isentropic compression and 1 to 2 takes into account the non-isentropic nature of a real compressor. The non-ideal Brayton cycle would follow the steps as follows: 1,2,5,3,4,6,1 [17].

3.6. Wet Compression

Wet compression consists of injecting atomized water into the compressor inlet air stream; this water, flowing through compressor stages, because of the heating due to the pressure increase, evaporates and cools the air stream. Following the drop in the compressor discharge temperature, compressor work decreases and mass flow increases because of the water injected into the compressor; consequently, there is a significant enhancement of the gas turbine power output and efficiency. A reduction of polluting emissions, particularly nitrogen oxides, is also possible [18].

If the relative humidity of the air is lower than 100%, as in actual ambient conditions, wet compression also determines a first air cooling, called 'Fogging', in the proximity of the compressor intake. The fogging effect increases the compressor mass flow rate and reduces the compressor outlet temperature; consequently, there is a remarkable enhancement of both the turbine power output and the cycle efficiency. Wet compression and fogging can both lead to compressor blade erosion and turbine load-bearing structure distortion [18]. The extent of the damage caused by these effects can be reduced simply by reducing the size of the water particles that are injected.

4. Combined Cycles

4.1. Brayton-Rankine Combined Cycle

This combined cycle can be thought of as an upper and lower heat engine in series, with the upper engine consisting of some variation of the Brayton cycle and the lower engine a Rankine cycle. The Rankine cycle used will usually be an ORC, as the waste heat from the gas turbine can be thought of as a low grade heat source.

The two cycles are connected through the use of a Heat Recovery Steam Generator (HRSG), which recovers the waste heat from the gas turbine and uses it to heat the working fluid for the ORC. The HRSG is arguably the most important component in the combined cycle, as the effectiveness with which it recovers heat will have a dramatic effect on the overall cycle power output and efficiency.

The overall efficiency of the combined cycle can be expressed as follows:

$$\eta_{cc} = \eta_B + \eta_R - \eta_B \eta_R \quad [19]$$

As an example, if the Brayton cycle efficiency was 40% and the ORC efficiency was 30% then, based on the above equation, the combined cycle efficiency would be 58% [19].

In the conventional scheme, the exhaust heat from the open circuit gas turbine is recovered in the HRSG to raise steam for the bottoming ORC. In another configuration, exhaust gas is utilised as pre-heated combustion air for the boiler or exhaust heat is recovered by pre-heating boiler feed water. An externally fired gas turbine may also be combined with a direct fired boiler. In integrated configurations, steam may be used as a working fluid or cooling medium in the gas turbine [20].

4.2. Heat Recovery Steam Generator (HRSG)

An HRSG may contain up to 3 pressure levels, LP, IP and HP. Each pressure level contains 3 main groups of heat exchangers named economizer, evaporator and super-heater. When the turbine gases pass over the HRSG heating elements, fluid inside the tubes recovers energy from the hot gases and changes phase from liquid to steam. The steam produced is used for driving turbines and generating shaft power in the Rankine cycle. Water pre-heating and evaporation occur in economizers and evaporators respectively. After separating the liquid and steam, the liquid goes through the evaporator down-comers and the steam enters the super-heater [21].

Finding the optimal configuration of such a thermal system is of primary interest due to extensive use of combined cycles as a preferred method for generating electricity. These systems are designed mainly based on the gas turbine exhaust mass flow rate and temperature. It is expected that finding the optimum configuration of HRSG can improve the total efficiency of the combined cycle [21].

Gas turbine temperature, compressor pressure ratio and pinch point temperatures are significant design parameters. [22] bases its study on a cycle with two gas turbines, two compressors, two HRSGs, two de-aerators, one steam turbine and a cooling system. Exhaust gases from the turbine enter the HRSG at 550°C. After passing the 3rd super-heater, the supplementary firing increases the flue gas temperature. Each dual pressure HRSG generates HP and LP steam at 523°C and 233.8°C respectively.

Through the use of the first and second laws of thermodynamics, [22] finds:

Plant efficiency $$\eta_{cc} = \frac{\dot{W}_{GT}+\dot{W}_{ST}}{\dot{Q}_{in}} - \dot{W}_{Pump}$$

Plant exergy efficiency $$\eta_{\mathrm{EX,CC}} = \frac{\dot{W}_{GT}+\dot{W}_{ST}}{\dot{E}_F} - \dot{W}_{Pump}$$

Exergy destruction $$\dot{E}x_{\mathrm{HRSG}} = \dot{E}x_{g,in} + \dot{E}x_{s,in} - \dot{E}x_{s,out} - \dot{E}x_{g,out} + \dot{E}x_{w,in}$$

Exhaust gas exergy flow $\dot{E}x_{HRSG} = \dot{m}_g C_p, \text{g}[(T_g - T_o) - T_o \text{Ln}\frac{T_g}{T_o}]$

Feed water exergy $\dot{E}x_{w,s} = \dot{m}_{w,s}[(h - h_o) - (s - s_o)]$

HRSG exergy destruction rate over the whole HRSG $\eta_{EX,ST} = \frac{\dot{E}x_{HRSG}}{\dot{E}x_{g,in}}$

Exergy efficiency of the steam turbine $\eta_{EX,ST} = \frac{\dot{W}_{ST}}{\dot{E}x_{s,out} - \dot{E}x_{s,in}}$

Using this information, optimization and analysis of the HRSG was done using the genetic algorithm.

The operation of the genetic algorithm can be described by the following 5 steps:

1. A random population of individuals is generated. The identity of each individual is determined by decision variables [23].
2. The fitness function for each individual is evaluated and individuals are sorted based on this criterion [23].
3. The individuals with greater values of fitness function are selected as parents to the next generation. For this purpose, fundamental genetic rules are applied to this selected group and a new generation with the same number of individuals as the previous generation is generated [23].
4. The new generation is again evaluated based on the fitness function. It is expected that the new generation that had healthy parents is better than the previous generation [23].
5. This process continues until health and fitness of all individuals reaches a specific value [23].

Decision variables in HRSG optimization are pinch point temperature difference, approach point temperature difference, super-heater temperature, pressure of evaporators and heat exchangers break points temperature [23].

Through this optimization, [22] found that the most exergy destructive parts of the HRSG are the HP evaporator and the second HP super-heater. This is due to the high temperature difference between the inlet and outlet flue gas temperatures for these components. In general they found that LP components are more influenced by changes in inlet temperature. They add, that by increasing the inlet gas temperature stack and reducing the HRSG losses, the bottoming cycle output power increases. Such changes will lead to an optimum point.

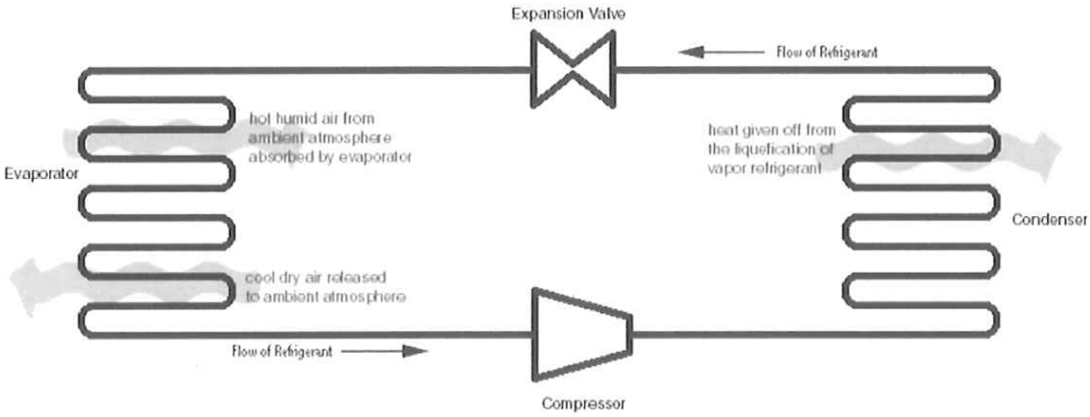
[23] concludes that exergy losses have the greatest effect on steam cycle power production. Optimization results show that some decision variables converge to their upper or lower limits. This shows that the higher superheat temperature and lesser pinch point and approach temperature difference cause both the exergy recovery from the gas stream and net power output from the steam cycle to increase. Another conclusion they draw is that reheating results in a severe decrease in the steam mass flow rate. Therefore in a two pressure cycle with reheating, due to lack of appropriate energy recovery in the economizer, the stack temperature does not reach the minimum limit. This problem is not seen in a 3 pressure level cycle with reheating due to good exergy recovery in the IP level by reheating and good energy recovery in the LP level.

The most important parameter affecting the net power output are HRSG type and the method of its heat exchanger layout. Results indicate that these parameters can increase power by up to 22.5% compared to a single pressure cycle and severely affect the exergy recovery in the HRSG [23].

[24] also states the importance of reducing exergy losses to improve cycle performance. To reduce exergy losses, they suggest that the use of multi-pressure levels with the possibility of fractioning the total mass flow rate in the liquid side would be advantageous. The results displayed by [24] show that the application of reheat does not contribute to further efficiency increases in supercritical steam conditions. They agree with [22] and [23], in that double or triple HRSG configurations are more efficient, but add that this is not the case when operating above 1000K. They also add that using commercially available gas turbines, it is possible to reach efficiency levels between 55 and 60%. However, if using optimized supercritical HRSG configurations operating with rational efficiency of the group steam turbine and HRSG, it is possible to reach an efficiency of 70 to 80%.

5. Refrigeration Cycles

5.1. Compression Refrigeration System



[Fig.13] Schematic of Compression Refrigeration System [25]

Shown in [Fig.13], is the simplest form of refrigeration system, which follows the following steps:

1. Pressure of the refrigerant is raised as it flows through the compressor [26].
2. Refrigerant flows through the condenser and changes state from vapour to liquid, giving off heat in the process [26].
3. The refrigerant goes through the expansion valve, where it experiences a pressure drop [26].
4. The refrigerant finally goes through the evaporator. The refrigerant draws heat from the evaporator, causing the refrigerant to vaporize. The evaporator draws its heat from the region that is to be cooled [26].

The most common compressor type for domestic and small commercial refrigeration is the reciprocating compressor. This can be thought of like an internal combustion ie: as the piston moves down it draws in the vapourized refrigerant, then as it moves up it compresses the refrigerant and expels it to the condenser.

The role of the condenser is to remove heat given off during the liquification of the vapourized refrigerant. Heat is given off as the temperature drops to condensation temperature. Then, more heat (specifically the latent heat of condensation) is released as the refrigerant liquefies [26]. It is most common to use an air cooled condenser. In this case, a fan is often used to force air over the tubes of the condenser, which will be arranged in such a way as to maximize surface area.

Hot air from the area that is to be cooled is blown onto the finned tubes of the evaporator by a fan. These finned tubes are made from metals with high thermal conductivity so as to maximize heat transfer. The refrigerant then vaporizes from the heat it absorbs [26]. Since the heat absorbed is likely to be at quite a low temperature, it is necessary to use a working fluid with a low evaporation temperature.

The flow control device controls the flow of the liquid refrigerant into the evaporator. Most expansion valves are thermostatic, meaning that they are responsive to the temperature of the refrigerant [26].

5.2. Alternative Refrigeration Systems

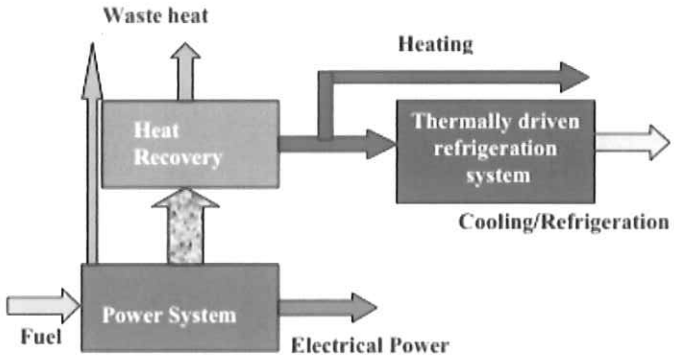
[27] presents 7 different alternative and emerging technologies for food refrigeration applications which are as follows:

1. Tri-generation
2. Air cycle Refrigeration
3. Sorption Refrigeration-Adsorption Systems
4. Thermoelectric Refrigeration
5. Stirling Cycle Refrigeration
6. Thermoacoustic Refrigeration
7. Magnetic Refrigeration

The first four systems on this list have been commercially available for some time, whereas numbers 5 to 7 are still in the research and development stage. COLLOQUIAL

Tri-generation technology is of key interest as it is very applicable to the smart cities concept. This type of system involves recovering waste heat from some form of electric power generation system, potentially a combined Brayton-ORC plant. This recovered heat can then be used for heating applications and thermally driven refrigeration systems.

Low quality!



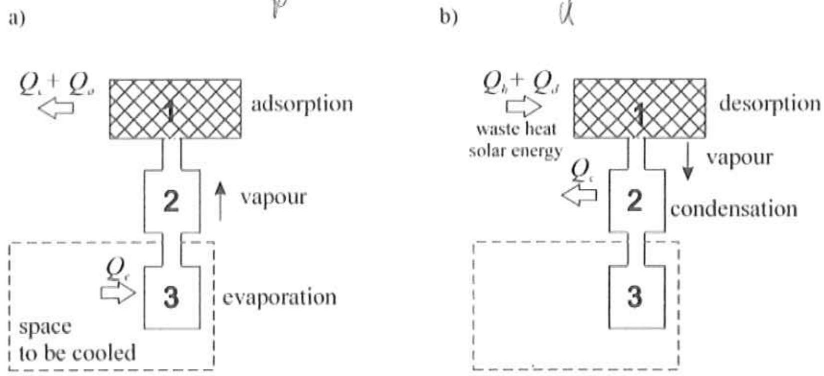
[Fig.14] Schematic of a tri-generation system [27]

Quality fig

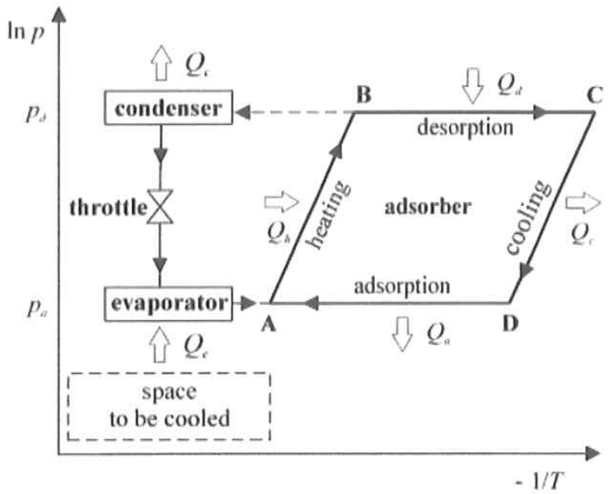
Tri-generation systems can have overall efficiencies as high as 90%. Developments in recent years which have led to this efficiency mainly focus on the individual subsystems such as the power system, heat recovery system, thermally driven refrigeration machines and system integration and control [27]. Advancements in the power systems include the aforementioned Brayton-Rankine combined cycle which would be ideally suited to this type of application. Advances in heat exchanger technology and in heat transfer have allowed for the use of more compact heat recovery systems, which could prove useful in the domestication of such systems. Recent steps in thermally driven refrigeration technology have been largely focused on the development of adsorption cooling systems and multi-effect absorption systems. ?

5.3. Adsorption Cooling Systems

The main elements of an adsorption cooling system are an adsorbent bed, a condenser and an evaporator. The adsorbent plays a similar role to the compressor in traditional cooling systems.



[Fig.15] Schematic of a Typical Adsorption Cooling System [28]



[Fig.16] Adsorption Cooling Cycle [28]

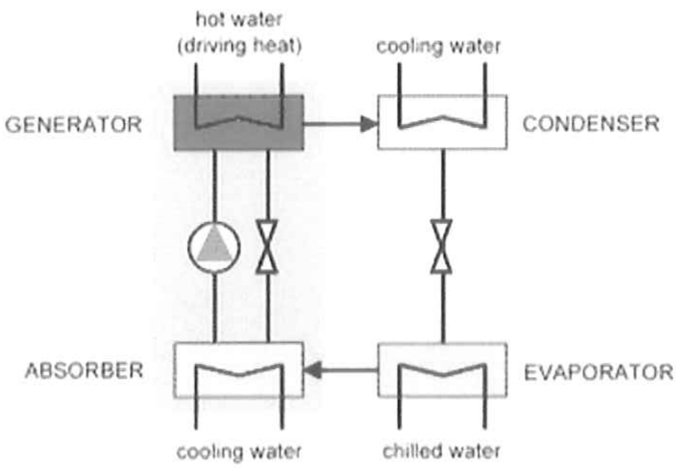
A complete cycle consists of 4 steps as shown in [Fig.16]. At point A, the adsorbent bed is saturated with adsorbate. Heating leads to an increase in temperature and pressure in the system. At point B, condensation pressure is reached and endothermic process of desorption starts, during which the adsorbate is removed from the adsorbent surface and flows into a reservoir or directly into the condenser. The pressure remains approximately constant, while the temperature rises. At point C, the temperature reaches the highest value and the bed is theoretically completely regenerated. From this moment cooling of the bed begins and the pressure decreases. When the pressure drops to the evaporation pressure (point D), the adsorbate begins to boil. The heat necessary for this process is taken from the space to be cooled and thus a cooling effect is created. Adsorbate molecules are adsorbed on the surface of the adsorbent (section D-A), and the cycle is closed [28].

As well as its use in the tri-generation cycle, significant research has been done in the use of adsorption cooling in automobiles, as presented by [29], [30] and [31]. This system helps to reduce the environmental impact of the vehicles cooling system and increases the overall cycle efficiency.

The adsorption cooling cycle can be operated in a number of layouts. The first is the basic one as described above, the problem with which is that it cannot produce a continuous cooling effect. To achieve this, it is necessary to operate with 2 adsorption beds, in which case the adsorber to be cooled will transfer its heat to the adsorber to be heated. This layout will greatly increase the cycle output power. This setup is called 'continuous heat cycle recovery' and can be run with additional adsorption beds to increase the cycle output power further still. A 'thermal wave cycle' assumes a large temperature gradient along the adsorption bed. For a two bed system, high temperature thermal fluid flows into the adsorber, exchanges heat with the bed, and the temperature goes down along the bed rapidly, thus the outlet temperature will be close to ambient. After being cooled by ambient surroundings, the fluid flows into another adsorption bed, absorbs heat from the bed, and the temperature of the fluid goes up. At the exit of this bed, the thermal fluid temperature will be very close to the temperature of the heat source. In this case, less heat is added to the system, and less released to the environment, thus heat recovery ratio is very high and the cycle output power is increased. The cycle can also be operated in a cascading mode in which zeolite-water/ activated carbon-methanol, or zeolite-water/ silica gel-water and zeolite-water/ zeolite-water are usually used for cascading. The high temperature heat source (eg: 200°C) is usually used to drive the high temperature stage adsorption refrigeration cycle (typically 100-200°C for zeolite-water). The low temperature stage adsorption refrigeration is driven by the sensible heat and heat of adsorption for high temperature stage, for example, activated carbon-methanol or silica gel-water adsorption refrigeration cycles are suitable for generation temperature of 100°C, which are operated from 30-100°C [32]. For real applications, the two bed mode is the most common due to it being the most cost effective.

5.4. Multi-Effect Absorption Cooling Systems

low quality!



[Fig.17] Schematic of a single effect absorption cooling system [33]

In an absorption cooling system, compression of the refrigerant is achieved by using a liquid refrigerant/ sorbent solution and a heat source, which replaces the electric power consumption of a mechanical compressor. The cooling effect is based on the evaporation of the refrigerant in the evaporator at very low pressures. The vaporized refrigerant is absorbed in the absorber and dilutes the solution contained within (typically H20/ LiBr). The solution is continuously pumped into the generator, where the regeneration of the solution is achieved by applying heat. The refrigerant leaving the generator condenses through the application of cooling water in the condenser then passes through an expansion valve back to the evaporator [34].

In the double effect cycle, the solution is regenerated twice, with only the first regeneration being performed with external heat input. The second is performed by utilizing internal heat exchange. In LiBr coolers, the heat of condensation of the vapour boiled off from the first generator is used for this purpose [35]. If this principle is applied twice, then you reach a triple effect cycle and so on. A greater driving temperature will always be necessary for every additional effect that is added.

6. Project Progress

6.1. Work Carried Out In Winter Term

The majority of the winter term was spent researching steam, gas and refrigeration cycles to find out what the recent advancements in each cycle had been and to develop an opinion of how each technology is likely to evolve in the future. Extensive research was done into optimization methods used for the ORC and for the HRSG in a combined Brayton-Rankine cycle. This includes energy and exergy analysis which will be useful when optimizing a complete co/ tri-generation system. I have also seen examples of pinch analysis and found that in general it is important to reduce the pinch point temperature difference in order to reach optimal performance. Above, I have presented several examples of where such methods have been used for system optimization.

6.2. Work To Be Carried Out In The Spring Term

The main objective for the spring term will be to design a system for the optimization of an integrated CCHP system. The first step will be to select appropriate components and to obtain manufacturers' data. After this I will select an appropriate platform to perform the optimization eg: Matlab, Python, Fortran or C, and then perform the optimization. This process will also involve the analysis of the emissions from such a system and their environmental impact on a Smart City.

In the Gantt chart below I have presented my work plan for next term with a predicted duration for each of the tasks described above corresponding to the university week numbers.

underestimate   overestimate!

Select Components and Obtain Data	■												
Choose a platform and familiarise		■											
Perform optimization			■	■	■								
Write thesis						■	■	■	■	■			
Prepare Presentation									■	■	■	■	■
Week	29	30	31	32	33	34	35	36	37	38	39	40	41

7. Risk Assessment

What are the hazards?	Who might be harmed and how?	What are you already doing?	Do you need to do anything else to manage the risk?	Action by whom?	Action by when?
Prolonged periods of work at a computer	I may suffer repetitive strain injury	Avoiding long periods of work on computers	Assure that I continue to avoid working on computers for too long	Me	By the time I start to run simulations
Sitting at a desk with bad posture	I may suffer from back problems	Nothing	Make sure that my posture is always good when I am working	Me	By the time I start to run simulations

8. Works Cited

[1] Brown, J.S., Brignoli, R. and Daubman, S., "Methodology for estimating thermodynamic parameters and performance of working fluids for organic Rankine cycles," *Energy,* pp. 818-828, 2014.

[2] "About City Science," [Online]. Available: http://cities.media.mit.edu/about/cities. [Accessed 09 January 20115].

[3] "Digital Agenda For Europe," [Online]. Available: http://ec.europa.eu/digital-agenda/en/smart-cities. [Accessed 09 January 2015].

[4] "Smart cities," [Online]. Available: http://www.smart-cities.eu/index.php?cid=6&ver=3&city=68. [Accessed 09 January 2015].

[5] Singh, S., "Smart Cities- A $1.5 Trillion Market Opportunity," [Online]. Available: http://www.forbes.com/sites/sarwantsingh/2014/06/19/smart-cities-a-1-5-trillion-market-opportunity/. [Accessed 09 January 2015].

[6] "Typical Steam Cycle Thermodynamics," [Online]. Available: http://www.engineersedge.com/thermodynamics/typical_steam_cycle.htm. [Accessed 01 November 2014].

[7] Fu, B., Hsu, S. and Liu, C., "Trends in patent applications relating to organic Rankine cycles," *Procedia Engineering,* vol. 79, pp. 249-257, 2014.

[8] Yamamoto, T., Furuhata, T., Arai, N. and Mori, K., "Design and testing of the Organic Rankine Cycle," *Energy,* pp. 239-251, 2011. Vol ?

[9] Saleh, B., Koglbauer, G., Wendland, M. and Fischer, J., "Working fluids for low temperature organic Rankine cycles," *Energy,* pp. 1210-1221, 2007. Vol ?

[10] Tchanche, B.F., Lambrinos, G., Frangoudakis, A. and Papadakis, G., "Low-grade heat conversion into power using organic Rankine cycles-A review of various applications," *Renewable and sustainable energy reviews,* pp. 3963-3979, 2011. Vol ?

[11] Velez, F., Segovia, J.J., Martin, M.C., Antolin, G., Chejne, F. and Quijano, A., "A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation," *Renewable and sustainable energy reviews,* pp. 4175-4189, 2012. Vol ?

[12] "3.7 Brayton Cycle," [Online]. Available: http://web.mit.edu/16.unified/www/FALL/thermodynamics/notes/node28.html. [Accessed 02 November 2014].

[13] Desideri, U., Modern Gas Turbine Systems, Woodhead Publishing, 2013.

[14] Heppenstall, T., "Advanced gas turbine cycles for power generation: a critical review," *Applied thermal engineering,* pp. 837-846, 1998. vol ?

[15] "The Brayton cycle with, Regeneration, Intercooling and reheating," [Online]. Available: www.academia.edu/5467390/The_Brayton_Cycle_with_Regeneration_Intercooling_and Reheating. [Accessed 02 January 2015].

[16] "Open Gas-Turbine Cycle," [Online]. Available: www.sfu.ca/~mbahrami/ENSC%20461/Notes/Brayton%20Cycle.pdf. [Accessed 02 January 2015].

[17] Wu, C., Chen, L. and Sun, F., "Performance of a regenerative Brayton heat engine," *Energy,* pp. 71-76, 1996. vol ?

[18] Bracco, S., Pierfederici, A. and Trucco, A., "The wet compression technology for gas turbine power plants: Thermodynamic model," *Applied Thermal Engineering,* pp. 699-704, 2007. vol ?

[19] "Combined cycles in stationary gas turbine for power production," [Online]. Available: web.mit.edu/16.unified/www/FALL/thermodynamics/notes/node67.html. [Accessed 28 December 2014].

[20] "Combined cycles," [Online]. Available: www.che.boun.edu.tr/courses/che480/5.combined%20cycles2.pdf. [Accessed 28 December 2014].

[21] Mansouri, M.T., Ahmadi, P., Kaviri, A.G. and Jaafar, M.N.M., "Exergetic and economic evaluation of the effect of HRSG configurations on the performance of combined cycle power plants," *Energy conversion and management,* pp. 47-58, 2012. vol ?

[22] Kaviri, A.G., Jaafar, M.N.M., Lazim, T.M. and Barzegaravval, H., "Exergoenvironmental optimization of heat recovery steam generators in combined cycle power plant through energy and exergy analysis," *Energy Conversion and Management,* pp. 27-33, 2013. vol ?

[23] Mohagheghi, M. and Shayegan, J., "Thermodynamic optimization of design variables and heat exchangers layout in HRSG's for CCGT, using genetic algorithm," *Applied thermal engineering,* pp. 290-299, 2009. vol ?

[24] Franco, A., "Analysis of small scale combined cycle plants based on the use of supercritical HRSG," *Applied thermal engineering,* pp. 785-794, 2011. vol ?

[25] Yeh, R., "MIT," 1999. [Online]. Available: http://web.mit.edu/2.972/www/reports/compression_refrigeration_system/compression_refrigeration_system.html. [Accessed 04 November 2014].

[26] "Compression Refrigeration System," [Online]. Available: http://web.mit.edu/2.972/www.reports/compression_refrigeration_system/compression

_refrigeration_system.html. [Accessed 04 November 2014].

[27] "Alternative and Emerging Refrigeration Technologies for Food Refrigeration Applications," [Online]. Available: http://sites.brunel.ac.uk/_data/assets/pdf_file/0006/325572/Alternative_and_Emerging_Refrigeration_Technologies_for_Food_Refrigeration_Applications.pdf. [Accessed 07 January 2015].

[28] Gwadera, M. and Kupiec, K., "Adsorption Cooling As An Effective Method Of Waste Heat Utilization," *Technical Transactions,* pp. 61-70, 2011. ?

[29] Suzuki, M., "Application of adsorption cooling systems to automobiles," *Heat Recovery Systems and CHP,* pp. 335-340, 1993. ?

[30] Zhang, L.Z. and Wang, L., "Performance estimation of an adsorption cooling system for automobile waste heat recovery," *Applied Thermal Engineering,* pp. 1127-1139, 1997. vol ?

[31] Zhang, L.Z., "Design and testing of an automobile waste heat adsorption cooling system," *Applied Thermal Engineering,* pp. 103-114, 2000. vol ?

[32] Wang, R.Z., "Performance improvement of adsorption cooling by heat and mass recovery operation," *International Journal of Refrigeration,* pp. 602-611, 2001. vol ?

[33] "raee," [Online]. Available: http://raee.org/climatisationsolaire/gb/solar.php . [Accessed 09 January 2015].

[34] "Solar Cooling," [Online]. Available: http://raee.org/climatisationsolaire/gb/solar.php. [Accessed 08 January 2015].

[35] "Multi-effect absorption chillers," [Online]. Available: http://ac.els-cdn.com/014070079390002P/1-s2.0-014070079390002P-main.pdf?_tid=d7bda6b6-9744-11e4-92ec-00000aacb360&acdnat=1420728446_c6e864e59ae5f2112cca86f51d7372e4. [Accessed 08 January 2015].