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

Review of the *Winter Report* ‘Optimisation of Energy Systems in Smart Cities’ by Don Stuart

The manuscript reports initial literature review and analysis of power, heating and cooling systems. An overview of the existing thermodynamic power cyle technologies relevant to (C)CHP was undertaken by Mr Stuart including: (a) organic Rankine, (b) gas-turbine Brayton and (c) vapour-compression 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. My main concern is that there is no clear indication of actual objectives (project’s and report’s) in the paper, except by generic sentences in *Introduction* and *Conclusion* sections. In summary, the report outlines (in a very superficial way) a few developments on thermodynamic cycles with no clear links with the main subject areas, sustainability (a crucial concept and motivation for ‘*smart cities*) and optimisation (energy integration coupled with low GHG emissions). A few general comments,

1. Dissertations and thesis are divided into chapters, reports however are always divided into sections.

2. 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. In this report, there is **no** *Abstract*.

3. 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 always 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) and (ii) (in part) above but lacked explain/summarise the main state-of-the-art aspects of the subject areas. In fact, the *Introduction* section barely introduces the main motivation for the work – optimal use of energy resources for sustainable cities.

4. Quality of figures are very poor. Also, figures **must** be referenced in the main text – they can not just ‘float around’! Also, figure/table captions should be self-contained, i.e., with a good description of the figure/table highlighting the most relevant aspects/information that the author wants to convene.

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

6. You must avoid use *colloquial (informal)* writing.

7. The main objectives of the Winter report are:

   (a) Student can get familiar with:

i. fundamental science and technologies of the main subject areas (through an in-depth literature review);

ii. main techniques to assess/investigate the problem that will be used during the Spring term.

(b) Student can narrow the project towards his main interests. With this in mind he can plan his research activities during the Spring.

The paper is a superficial review of power and refrigeration thermodynamic cycles that can be used in combined power, heating and cooling systems.

In the attached scanned document:

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

Date received:

SCHOOL OF ENGINEERING

COVER SHEET FOR CONTINUOUSLY ASSESSED WORK

Course Code ....EG4013....................................

SECTION 1: **Student to complete**

SURNAME/FAMILY NAME: ...DON..

FIRST NAME: ...STUART.....................................

ID Number: ....51119767...............................

Date submitted: ....20/01/15...........................

Please:

- *Read the statement on "Cheating" and definition of "Plagiarism" contained over page. The full Code of Practice on Student Discipline, Appendix 5.15 of the Academic Quality Handbook is at:* *www.abdn.ac.uk/registry/quality/appendices.shtml#section5*
- *attach this Cover Sheet, completed and signed to the work being submitted*

SECTION 2: Confirmation of Authorship

The acceptance of your work is subject to your signature on the following declaration:

I confirm that I have read, understood and will abide by the University statement on cheating and plagiarism defined over the page and that this submitted work is my own and where the work of others is used it is clearly identified and referenced. I understand that the School of Engineering reserves the right to use this submitted work in the detection of plagiarism.

Signed: ______________________

Date: 20/01/15

Note: Work submitted for continuous assessment will not be marked without a completed Cover Sheet. Such work will be deemed 'late' until a completed cover Sheet is submitted and will be subject to the published penalty for late submission.

Cheating in any assessment, whether formative or summative, can result in disciplinary action being taken under the University's Code of Practice on Student Discipline. For these purposes "Cheating" includes:

(a) Possession in an examination of material or electronic device which has not been authorised in writing by the relevant Course Co-ordinator. Students whose first language is not English may, however, refer to a dictionary where this is approved by the Head of the School responsible for the examination;

(b) Copying from another student in an examination;

(c) Removing an examination book from an examination room;

(d) Impersonating another candidate in relation to any assessment;

(e) Permitting another person to impersonate oneself in relation to any assessment;

(f) Paying or otherwise rewarding another person for writing or preparing work to be Submitted for assessment;

(g) Colluding with another person in the preparation or submission of work which is to be assessed. This does not apply to collaborative work authorised by the relevant course coordinator.

(h) Plagiarism. Plagiarism is the use, without adequate acknowledgment, of the intellectual work of another person in work submitted for assessment. A student cannot be found to have committed plagiarism where it can be shown that the student has taken all reasonable care to avoid representing the work of others as his or her own.

Optimisation of Energy Systems in Smart Cities: Winter Term Report

Stuart Don

51119767

Supervisor: Dr Jefferson Gomes

Contents

Abstract ? ×

Nomenclature

C(C)HP	Combined (Cooling,) Heating, and Power
ORC	Organic Rankine Cycle
TIT	Turbine Input Temperature
$T_{critical}$	Critical Temperature
$P_{critical}$	Critical Pressure
COP	Coefficient of Performance

Chapter 1 - Introduction

Motivation

Since 1950, the world's population has nearly trebled from 2.53 billion to around about 7 billion today. With this growth the amount of energy being used has also increased but the number of open spaces found in modern day cities has decreased to make way for houses and offices to account for the influx of people. The extra energy now required to power our cities is such that the need for more sustainable and efficient energy systems are of the upmost importance. This work will examine traditional thermodynamic gas, steam and compression refrigeration cycles and their optimisation and will also study co- and tri-generation technologies and how their implementation and optimisation could reduce the amount of waste energy produced by storing and recycling heat and power to be re-used to improve fuel efficiency and reduce CO_2 emissions.

linkage?

actions/tasks

? THESE ARE GENERIC TASKS NOT OBJECTIVES

The main objections of the project are as follows:

- A Literature Review on Thermodynamic steam, gas and refrigeration cycles;
- A Study of co-/tri-generation technologies;
- Perform an Energy and Exergy analysis for process integration (including pinch analysis);
- Perform optimisation methods often used in energy/exergy process integration and;
- To design a system (in Matlab, Python, Fortran or C) for optimisation process of an integrated CCHP with manufactured data
- An analysis of CO_2 emissions in C(C)HP processes and the environmental impact in 'Smart Cities'
- A Case study: Sheffield and Masdar City

obj of report ?

This winter term report focusses mainly on the background theory of thermodynamic cycles and their optimisation for use in modern day situations where fuel efficiency and environmental impact are of high importance. The development of CCHP technology is also looked at, and the combination of the thermodynamic cycles and trigeneration is also investigated briefly.

Chapter 2 - Background Theory

2.1

1. Thermodynamic Cycles

2.1.1

1.1 The Rankine Cycle

The Rankine cycle is a thermodynamic vapour cycle where the working fluid undergoes a series of processes to turn thermal energy into mechanical energy through the use of a pump, evaporator, turbine and condenser. The evaporated high pressure steam is allowed to expand through the turbine resulting in mechanical energy which is used to generate electricity and power before it is cooled through the condenser and returned to its original state. This process however proves to be highly inefficient at lower temperature and the use of a high-grade heat source (>600°C) is required. To make this efficient therefore a large amount of fuel is required which in turn will lead to CO, CO_2, NO_x and various other air pollutants being produced. In traditional Rankine cycles the turbine input temperature (TIT), turbine pressure ratio and turbine input mass flow rate were the most important factors in turbine efficiency and increasing the value of TIT increases the efficiency but in the case of an Organic Rankine Cycle (ORC) this is not true.

ORCs use ~~an~~ organic substances with lower latent heat and a higher density than that of water and as such can be operated using low-grade heat sources (solar, geothermal, biomass, waste industrial heat) which are more sustainable and environmentally safer than high-grade heat sources. ORCs and their configurations are discussed by Branchini et al. [1] where the variables of ORC lay-out, operating conditions, working fluid and heat source grade are compared to give optimal conditions. It is noted by Branchini et al. that an increase in evaporation pressure leads to increased ORC efficiency in almost all cases with only the recuperated supercritical cycle showing the opposite trend in the case where toluene is the working fluid. Despite the improved performance gained when using supercritical conditions with ORCs it can often not be an economically viable option as keeping the plant at these higher pressures presents danger, and a higher

SC/PE

? SC/PE

maintenance and operational cost to the process. Graphs plotting the performance obtained by Branchini et al. [1] are shown in figure 1.

SC

The inclusion of a heat recuperation stage in the ORC cycle has been shown to increase the overall efficiency but (DOES) not have any effect on the volumetric expansion ratio, and the work of the ORC as this does not affect expansion. However an even greater effect can be obtained from the inclusion of an additional regenerative heat exchanger. Superheating the fluid also shows some improved performance with or without the regenerative phase as it gives the highest value of work and higher values for efficiency than the cycles which do not use a superheating stage.

Obj of the paragraph ??

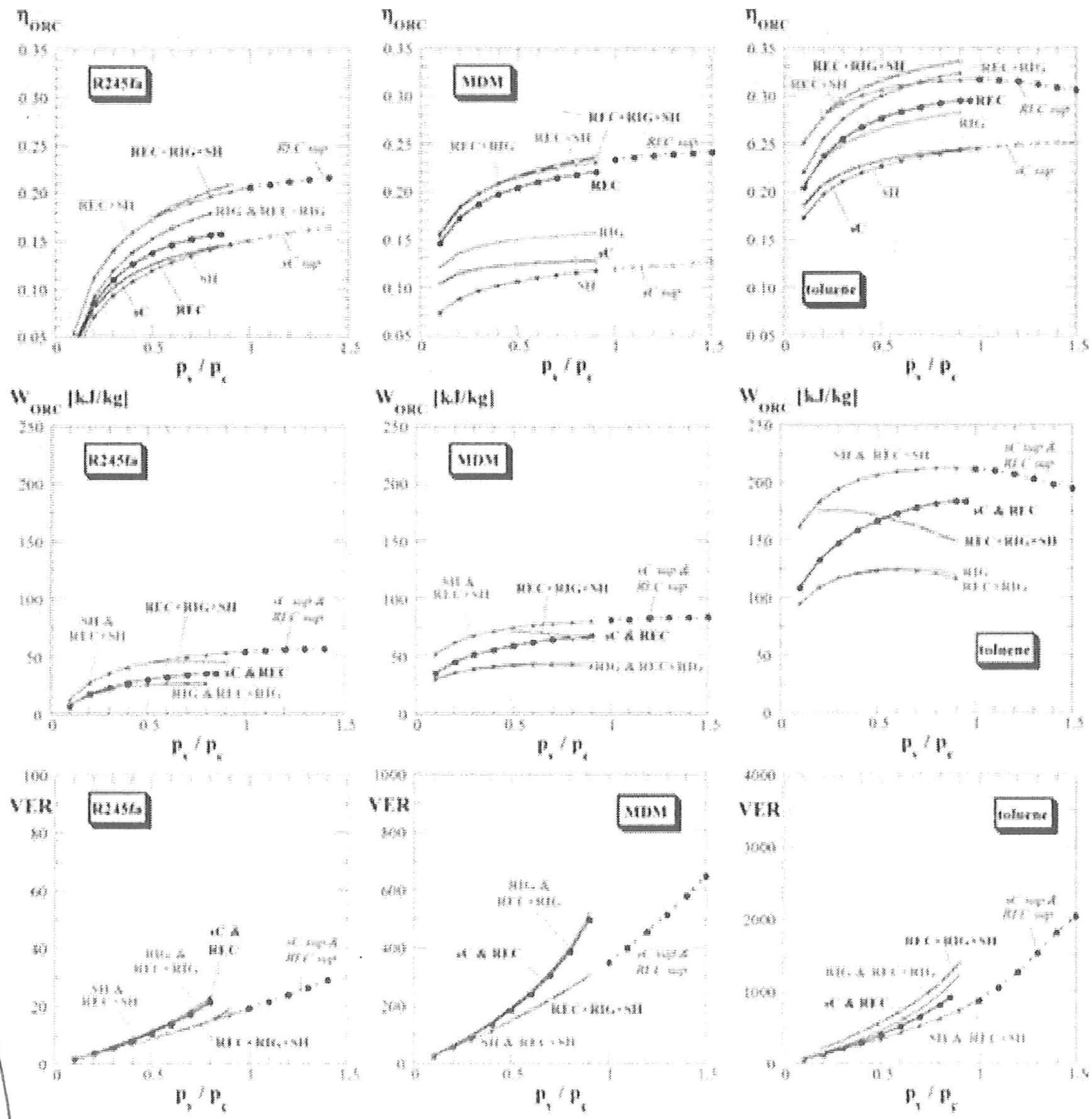


Figure 1 - Graphs from Branchini et al. [1] showing the performance of various ORC configurations

Poor Quality !! Floating Pics!

Despite this, it is shown by Mago et al. [2] that the superheating of organic fluids has little effect on the thermal efficiency of the cycle ~~using organic fluids~~ and even lead to a decrease in efficiencies in some cases (This is the opposite for the case of the cycle using water where increased TIT leads to greater efficiency). In their study it is suggested that a regenerative heat exchanger is used to increase the first and second law of thermodynamic efficiencies whilst also decreasing the amount of heat required to operate the system, and the system specific irreversibility. ??

Floating Pic

COLLOQUIAL

RIG VAP ECO REC ?

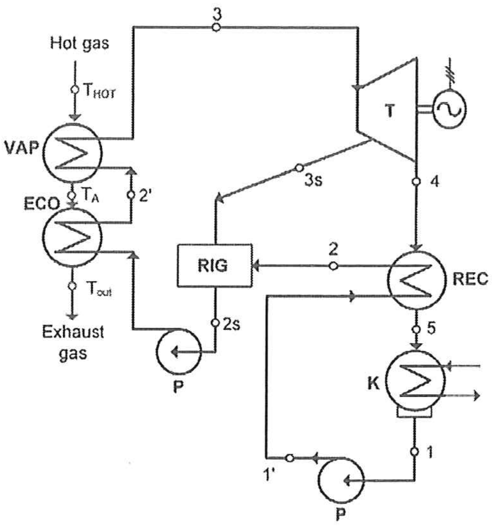


Figure 2 - Regenerative and Recuperated ORC cycle from Branchini et al. [1]

Branchini et al. [1] then go on to compare the performance of ORCs for both high and low temperature applications concluding that simple cycle and the temperature recuperated cycles give the most advantageous results for high temperature. However in low temperature cases (gained from the likes of geothermal, solar heat sources etc.) the use of a superheated stage is advised with or without a recuperation stage if possible to give the optimal results. However since the ORC is primarily aimed at the use of low-grade heat sources it would be impractical to include a superheating stage as stated by Hung [3] and instead the regenerative cycle as investigated by Mago et al. [2] appears to offer improved efficiency without the impracticality of superheating the fluid.

Hung [3] states that the efficiency of the organic Rankine cycle is limited by the irreversibility which in turn is dependent on the working fluid and working conditions such that an acceptable level of efficiency can only be reached through ~~thorough~~ selection of an optimal working fluid. Studying temperature-entropy graphs gives three classifications for working fluids - Dry, wet and isentropic – and each give a different plot. Dry fluids give a positive gradient on their saturation vapour curves, wet fluids display a negative gradient and isentropic fluids display nearly vertical slopes. When subject to a large enthalpy drop as occurs when passing through a turbine, wet fluids will often condense and as a result cause damage to the turbine, and it is for this reason that

ORCs should be operated only with dry or isentropic fluids. It also explains why traditional Rankine cycles using water require much higher temperatures to prevent this potential of damage to the turbine from occurring.

2.2

~~1~~.2 The Brayton Cycle

The Brayton Cycle is a thermodynamic cycle where gases are used as the working fluid. The gas undergoes compression before it is mixed with fuel, ignited and the work gained through the fluid expansion is used to drive a piston. The Brayton cycle can also be operated as a closed system as the working fluid is recycled from turbine to compressor with the use of an additional heat exchanger instead of an internal combustion chamber. It offers a simpler and more robust cycle because the working fluid used never undergoes a phase change and as a result the cycle is cheaper to design and operate due to the use of one-phase compressors and turbines. However, because of irreversibility in the compression and expansion and pressure drops in the heat exchangers, the efficiency is often limited to unacceptable values in moderate-low temperature applications [4]. It is suggested that the inlet of the compressor is operated close to the critical point of the gas being used as the working fluid, as this allows for lower compressor irreversibility and compression work which improves the efficiency of the cycle. The selection of the gas therefore is of paramount importance again in the Brayton cycle with importance on critical pressure temperature of the fluid. With $T_{critical}$ being kept lower than ambient temperature if possible, and thus $P_{critical}$ also as low as possible to reduce the compressor irreversibility further when working at supercritical pressures by allowing the low pressure threshold of the regenerator to be overcome easier.

As stated by Rovira et al. [4] The most efficient configuration for a Brayton cycle is one with additional intercooling, regenerative and reheating stages however the effect on cycle efficiency these stages have when operating close to the critical point as above is minimal, and such the simplest configuration should be used in this situation, but ensuring that the cycle is kept above the fluid critical temperature at all times. This simple configuration allows for use with a solar thermal source as the equipment works with very moderate pressure ratios and are small in size due to the specific volumes of the working fluid compared to other thermodynamic cycles.

The Brayton cycle can be run in reverse with the purpose of moving heat instead of producing work which is instead put into the system and is known as the Bell Coleman cycle and is used in various applications including domestic heating. For this to be worthwhile though the system losses must be maintained at less than 1% and even when using recuperation to improve the system the benefits gained are only significant in cases when losses are already high and efficiency (ratio of heating/cooling provided to work consumed (coefficient of performance (COP))) is low [5] which tends to mean more expensive operation.

~~1.3~~ 2.1.3 The Vapor Compression Refrigeration (VCR) Cycle

The vapor compression refrigeration cycle is a thermodynamic cycle where a refrigerant is used as the working fluid. This refrigerant is used to absorb heat as it flows through the cycle, cooling the desired area as it evaporates before rejecting this heat elsewhere. The cycle requires an evaporator, compressor, condenser and an expansion valve.

?

Recently great efforts have been put into the discovery of methods to optimise the operation of vapour-compression refrigeration systems but due to the large number of unknown variables this has proved difficult. Bejan however assumed that refrigeration systems are a combination of Carnot cycles and heat transfer processes between two constant-temperature heat resources in both condensers and evaporators [6]. Despite this reducing the complexity of the system this assumption had proved too general to as it over simplifies the internal components.

PE/SC

Air conditioning units are often the combination of ORC cycles with the vapour compression cycle (as shown in figure 3). To reduce losses the shafts of the ORC expander and VCR compressor are coupled. Wang et al. [9] state that an advantage of this system over other types of cooling cycles is that electrical power can still be generated without the use of the cooling function, in this case all thermal energy is be converted to power and any excess returned to the electrical grid.

Poor quality

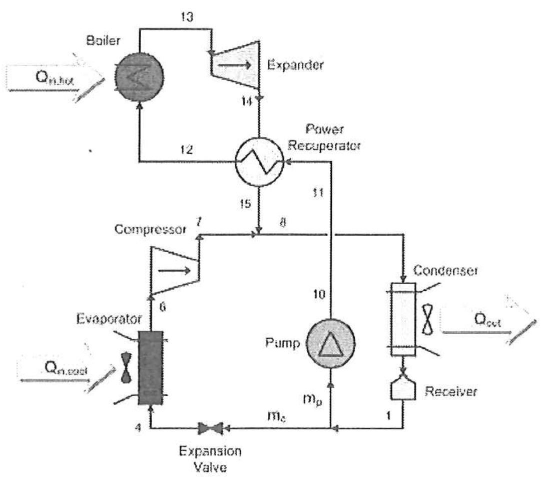


Figure 3 - From Wang et al. [9] Shows basic schematic of ORC-VCR combined cycles with recuperation

2.2

2. C(C)HP Technology

Combined Cooling, Heating and Power generation (CCHP) technologies have been developed to make the way that energy is used more efficient and reduce the amount of pollution being produced in our cities. CCHP decentralises electricity generation to smaller community generators using both renewable or fossil fuels to completely satisfy the energy requirements of communities by recycling waste heat to generate power and provide heating to residential and communal buildings.

Wu et al. [6] suggest that CCHP systems can be classified into two categories;

1. Traditional large scale CCHP applications in centralised power plants or large industries
2. Relatively small capacity distributed CCHP units with advanced prime mover and thermally activated technologies (Technologies capable of using waste heat as a fuel) to meet multiple energy demands in commercial, institutional, residential and small industrial sections.

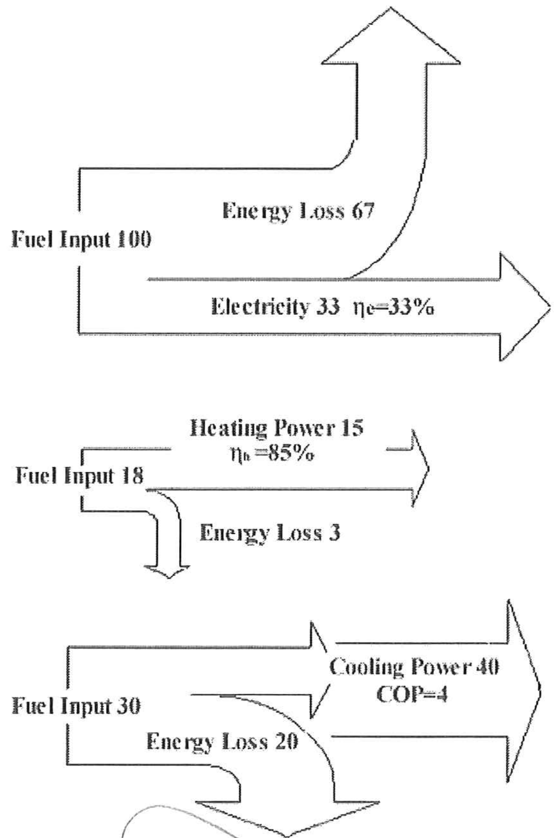


Figure 4 - From Wu et al. [6]

NON-DESCRIPTIVE CAPTION

Figure 3 shows a theoretical break down of the fuel input and power output gained from category 1 CCHP systems.

Figure 4 shows the same type of breakdown for a category 2 CCHP system.

As it can be seen the distributed system using only 100 units of fuel input can gain the same power output as the traditional system can gain from 148 units of fuel input making the system more fuel efficient.

Type 2 also only wastes 19 units of energy which gives a fuel efficiency of 81% compared to 39% for the traditional system meaning less pollution as well.

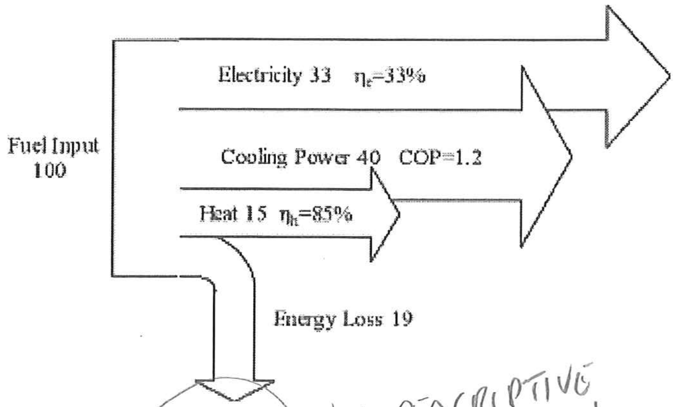


Figure 5 - from Wu et al. [6]

NON-DESCRIPTIVE CAPTION!

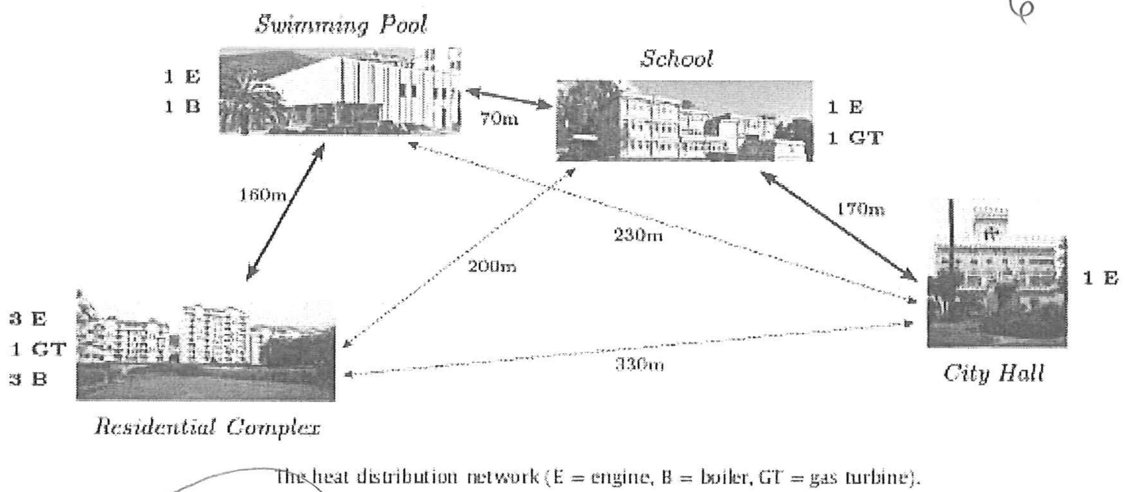
The newer type 2 also hold significant reliability advantages over type 1 due to quicker repairs, a more flexible system and a significantly reduced terror threat.

?

Due to their ability to be used with low grade heat sources it is possible to also operate decentralised CCHP systems using renewable and sustainable energy sources (biomass and municipal waste) providing low cost energy to local houses and businesses.

Bracco et al. [7] developed a mathematical optimisation model to provide guidelines which were followed in the case of an urban area located in the city of Arenzano, a provice of Genova in Italy. This experiment paid particular attention to the energy needs of four buildings; a residential complex (RC), a swimming pool (SP), a school (S), and the city hall (CH). The optimisation method suggested the need for 3 pipelines and a total of six engines, two gas turbines and four boilers distributed as shown in figure 5 below.

6



E
B
GT
?

Poor Quality

Figure 6 - From Bracco et al. [7]

NON-DESCRIPTIVE CAPTION

The optimisation model was run to simulate the average daily electrical and thermal demands in every season of the year. Figures 6 and 7 show some of the results of the

7 8

Arenzano experiment including the energy break down and comparison to a traditional system.

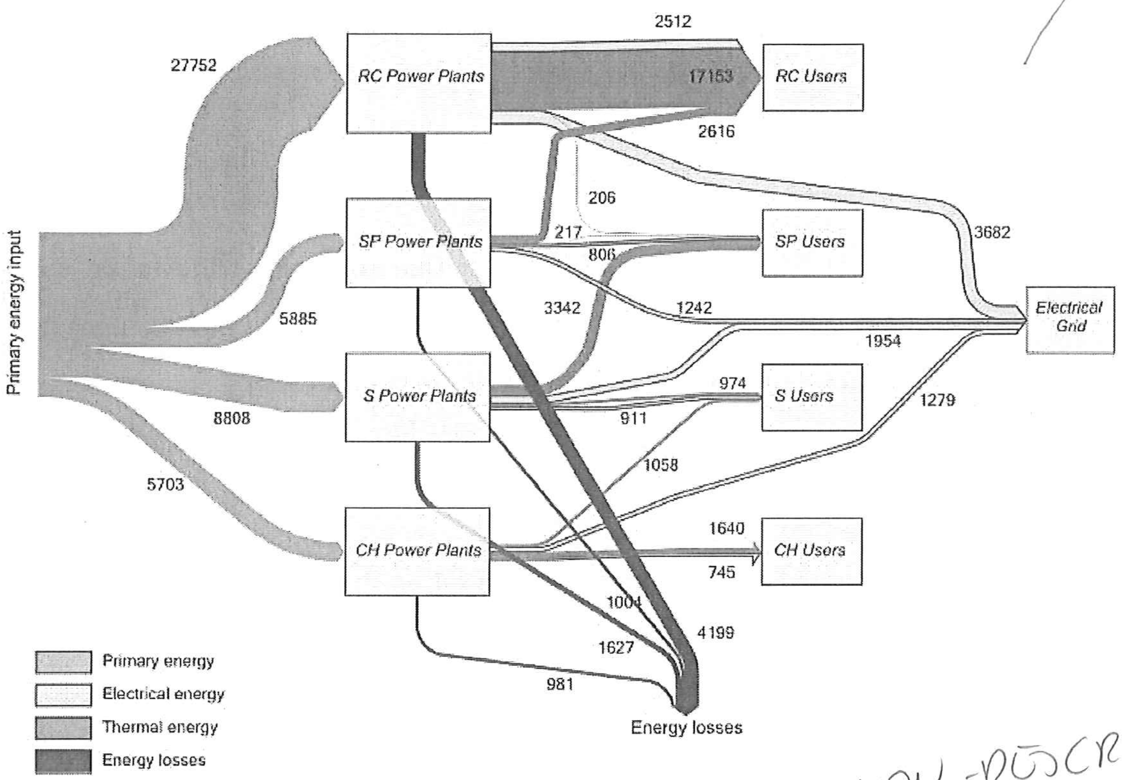


Figure 7 - From Bracco et al. [6] Shows the daily energy balance of the system NON-DESCRIPTIVE CAPTION

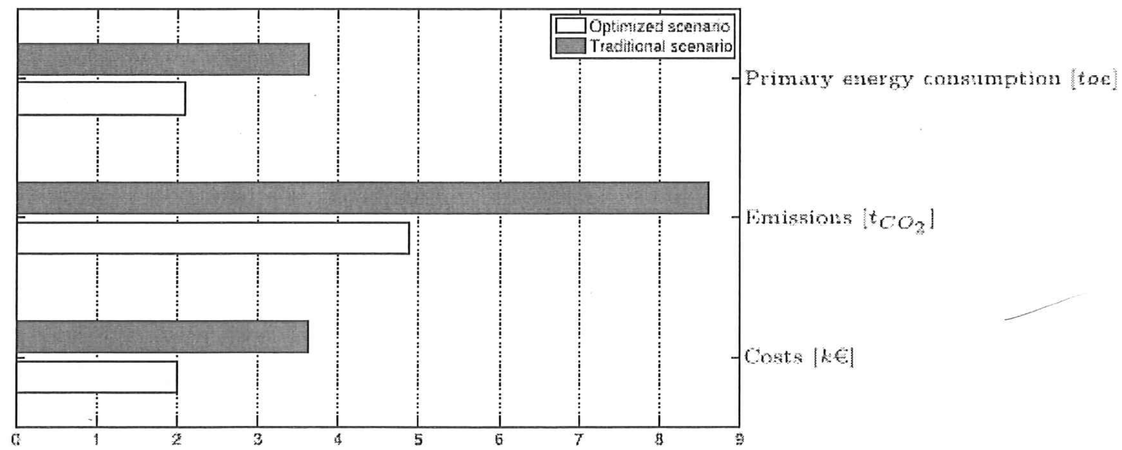


Figure 8 - From Bracco et al. Shows the comparison between optimised and traditional results

Figure ~~6~~ 17 displays the breakdown of the energy used throughout each day in the CCHP system and shows an overall efficiency of 84% with only 7,811 units of energy being wasted from 48,148 units of input. Figure ~~7~~ 8 displays the key advantages of the optimised cycle in that it has nearly halved; the amount of energy being used, the amount of CO_2 emitted and the cost of the operation of the system.

COLLOQUIAL

Very long sentence

Al-Sulaiman et al. [8] go on to investigate the combination of tri-generation systems and ORCs stating that when combined with a Solid Oxide Fuel Cell (SOFC) and an ORC system, trigeneration improved the efficiency from 46% to 74% and similarly from 13% to 84% when a biomass combustor and ORC system was combined with a tri-generation system and an increase from 15% to approximately 90% is experienced for the solar-trigeneration system. This justifies the research and development of CCHP technologies as it is shown just how large a difference they can make to the efficiency of the low-grade heat source systems like biomass combustion which is a sustainable source of energy.

SC/PE

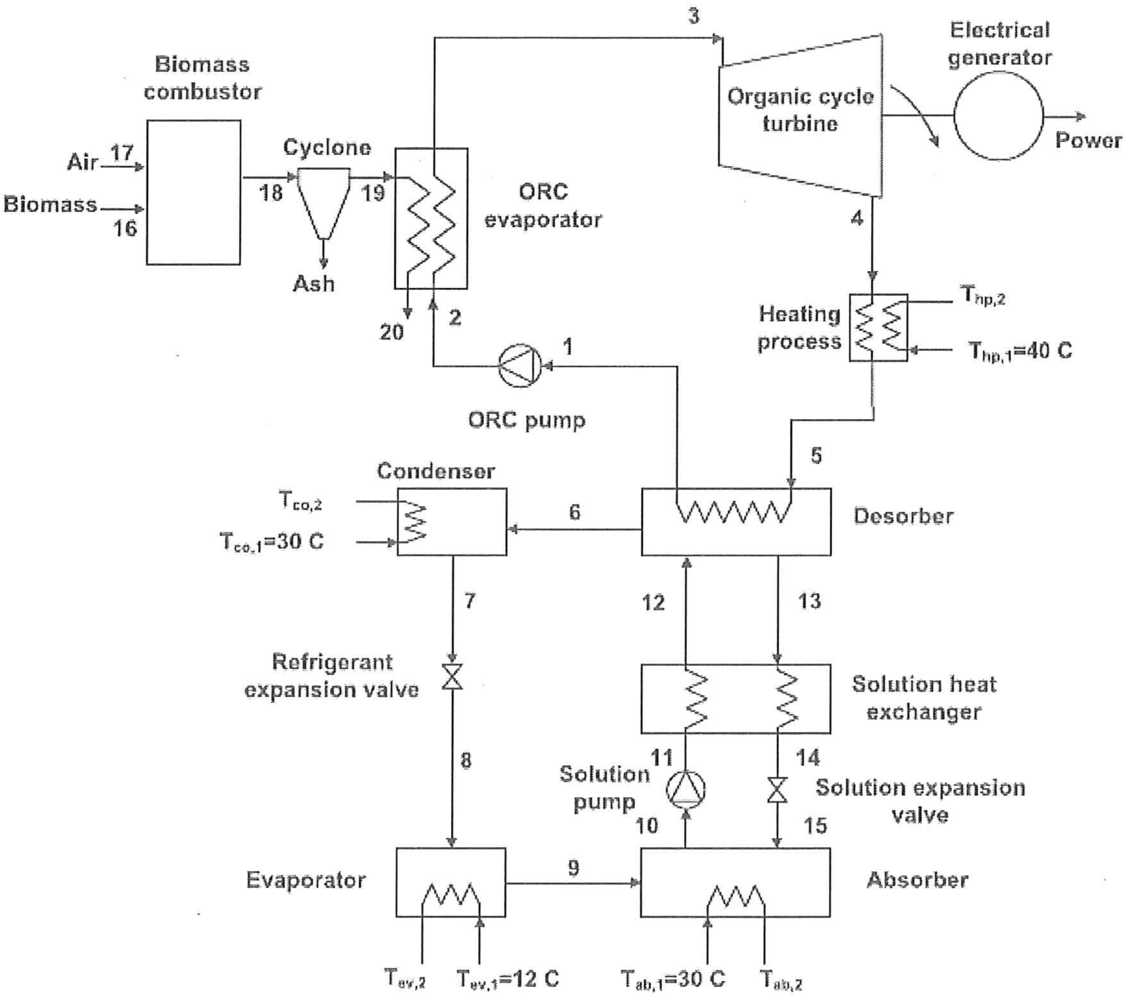


Figure 9 - From Al-Sulaiman et al. [8] Biomass-trigeneration system schematic

↳ NON-DESCRIPTIVE CAPTION

Paragraph is not fully linked with the previous one!

WHICH OTHER 2?

The solar system emits no CO_2 at all, however these other two systems are high pollutants when operated on their own. The integration of a tri-generation unit however reduces the pollution greatly making them a more environmentally viable option.

Chapter 3 – Conclusion

obj

This work has focussed on obtaining a background knowledge on which to build upon throughout the remainder of the project and to allow for further investigation into the development of more efficient and environmentally friendly ways to produce power in modern day cities.

The development and optimisation of thermodynamic cycles for use with low-medium grade heat sources has been looked at with a view to also reducing CO_2 and other pollutant emission to improve the quality of air in urban areas. Combined Cooling, Heating, and Power generation systems have also been investigated as a potential technology to improve the efficiency of our use of fuels and when combined with ORCs can even allow for the use of more sustainable, and renewable energy sources such as biomass, solar, geothermal, and waste industrial heat.

Future Work

With the objectives of the project as stated earlier and due to the theoretical nature of the project throughout the winter term it was vitally important to gain a comprehensive understanding of the topic. This involved a large amount of literature reading on all of the topics discussed above; Rankine, Brayton and Compression Refrigeration cycles and working fluids, Combined Cooling, Heating, and Power generation technology and energy/exergy analysis for process integration.

Due to the time constraints of the winter term, the workload for the spring term should be planned better to allow for a more thorough investigation into the subject in hand as it was in this aspect I feel that I struggled. Due to the nature of the spring term timetable being less demanding a large amount of time should be able to be dedicated to working on this project each week rather than the inconsistent reading and work schedule which at times lead to a lack of direction and disjointed work.

The plan for the spring term is as follows:

- Continue to improve knowledge and understanding of the thermodynamic cycles investigated above, specifically a deeper investigation into the compression refrigeration cycle.
- Studying the optimisation methods often used in energy/exergy process integration
- Designing a CCHP system and investigating its optimisation using computational software
- An analysis of the CO_2 emissions and the environmental impact co- and tri-generation systems have in 'Smart Cities' and a case study on Sheffield and Masdar City as they implement these systems to improve their use of energy and reduce their emissions.

Due to the theoretical and computational nature of this project, a timeline for completion of tasks is difficult to produce however a consistent effort should be made each week to continue and improve the work already started in the winter term, and begin and develop an optimisation model of a CCHP system.

Bibliography

*FULL LIST OF AUTHORS

[1] Brancini et al. (2013). Systematic comparison of ORC configurations by means of a comprehensive performance indexes. *Applied Thermal Engineering*. 61, p129-140.

[2] Mago et al. (2007). An examination of regenerative organic Rankine cycles using dry fluids. *Applied Thermal Engineering*. 28, p998-1007.

[3] Hung, T. (2001). Waste heat recovery of organic Rankine cycle using dry fluids. *Energy Conversion and Management*. 42, p539-553.

[4] Rovira, A; Muñoz-Antón, J; José Montes, M; Martínez-Val J M. (2013). Optimization of Brayton cycles for low-to-moderate grade thermal energy sources. *Energy*. 55 ~~(2013)~~, p403-416.

[5] White, A.J. (2009). Thermodynamic analysis of the reverse Joule-Brayton cycle heat pump for domestic heating. *Applied Energy*. 86 (11), p2443-2450.

[6] Wu, D.W.; Wang, R.Z.. (2006). Combined cooling, heating and power: A review. *Progress in Energy and Combustion Science*. 32, p459-495.

[7] Bracco, S; Dentici, G; Siri, S. (2013). Economic and environmental optimization model for the design and the operation of a combined heat and power distributed generation system in an urban area. *Energy*. 55 (1), p1014-1024.

[8] Al-Sulaiman, F.A.; Hamdullahpur, F; Dincer, I. (2011). Performance comparison of three trigeneration systems using organic Rankine cycles. *Energy*. 36 (1), p5741-5754.

[9] Wang, H; Peterson, R; Herron, T. (2011). Design study of configurations on system COP for a combined ORC (organic Rankine cycle) and VCC (vapor compression cycle). *Energy*. 36 (8), 4809-4820.