INDUSTRIAL CHARCOAL PRODUCTION WITH POWER GENERATION AT MULLY CHILDREN'S FAMILY YATTA, KENYA

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MASTER THESIS 30 CREDITS 2013

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May, 2013

Preface

This master thesis is the final work of my studies, a five year civil engineering degree in Environmental Physics and Renewable Energy at the Norwegian University of Life Sciences at Aas. When I was presented with the possibility of writing a thesis about renewable energy in a development country it was easy to accept the challenge. I would like to thank Erik E. Hohle at the Energy Farm for making this thesis possible by letting us work with them and arranging for a field study to Kenya. I would especially like to thank my advisor Petter H. Heyerdahl for good supervision and giving me motivation to finish this thesis.

As a part of the project a professor from the university, Petter Jenssen, and three students, Ragnhild Tjore, Ioannis Georgiadis and myself, went to Kenya to do a field study in February 2013. I would like to thank prof. Jenssen, Ragnhild and Ioannis for good company and support on our trip to Kenya.

Doing field study in a foreign country with a different culture was very interesting and motivating, even though it led to a few challenges. The main challenge was that everything took longer time than expected. Being at a child rescue center it was natural to be a part of activities, play with the children, listen to their moving stories and go to devotions in the evening. In addition to this we spent much time walking around to get a better understanding of their core activities.

The stay in Kenya gave me many impressions that I will carry with me for the rest of my life. I would like to thank Dr. Charles Mulli for letting us visit Mully Children's Family and for doing the great work he is doing. I would also like to thank Joshua Nyalita, Mully Children's Family and Paul Mbole, Norwegian Church Aid in Kenya for providing us with very useful information and arranging with meetings.

Finally, I would like to thank my wife for being understanding and supportive during my work with this thesis.

Abstract

This thesis examines the possibility for industrial charcoal production with power generation at Mully Children's Family (MCF) Yatta, located in rural Kenya. In Kenya, most of the population use firewood or charcoal for food preparation. In rural areas, where unsustainable firewood consumption is most common, it would be beneficial to use sustainably produced charcoal instead, due to health aspects and to reduce deforestation. With the forest biomass potential fully established MCF will annually have around 1000 ton dry biomass available.

Different technologies for industrial charcoal production have been described and the Pressvess twin retort is found to be a suitable design for MCF Yatta. This is a twin retort with two externally heated charge cylinders heated by a common combustion chamber. The annual potential for this type is 140 ton charcoal generating 520 MWh of accessible heat. However, it is a batch process which is not ideal to combine with power generation and therefore two alternative designs have been proposed.

One option is to have interchangeable charge cylinders, heated with the pyrolysis gas from the opposite charge cylinder, enabling the Pressvess twin retort to be semi continuous and generate smoother heat. The potential for this design is annually 340 ton charcoal and 1320 MWh of accessible heat. Another option is to have two Pressvess twin retorts ran in counter phase and in this way simulate a semi continuous process. This will require two units, giving higher heat losses, but it may be easier than enabling the unit to tolerate interchangeable charge cylinders. This option may annually produce 280 ton of charcoal and generate 1040 MWh of accessible heat.

Power generation technologies believed to be combinable with charcoal production have been described. Steam engine, steam turbine or an organic rankine cycle (ORC) turbine are closed cycle technologies that is suitable for the small scale production at MCF Yatta. Thermal efficiencies have been calculated for suitable working fluids for the ORC turbine and different parameters for steam. With a thermal storage, as a buffer between the charcoal production and the units utilizing the heat, a low temperature of the working fluid is preferable and with this in mind R245fa will be a good choice. An ORC turbine will be able to deliver a maximum of 27_e kW, with heat from two charcoal production units and 33 kW_e, with heat from a modified charcoal production unit. This will match the average electricity consumption of MCF Yatta well, which is 30 kW_e.

At MCF Yatta, one Pressvess twin retort may be install before the forest is fully established. The excess heat may be used to supply hot showers. When the biomass potential is reached the a semi continuous charcoal production should be established, and an ORC-turbine may be integrated.

Sammendrag

Denne masteroppgaven undersøker muligheten for industriell trekullproduksjon kombinert med strømproduksjon på Mully Children's Family (MCF) Yatta, som ligger på landsbygda i Kenya. I Kenya bruker de fleste ved eller trekull til matlaging. På landsbygda, der lite bærekraftig vedproduksjon er mest vanlig, vil det være fordelaktig å gå over til å bruke bærekraftig produsert trekull, på grunn av helsemessige aspekter og for å redusere avskoging. Med potensialet for skogsbasert biomasse fullt etablert vil MCF årlig ha rundt 1000 tonn tørr biomasse tilgjengelig.

Ulike teknologier for industriell trekullproduksjon har blitt beskrevet og tvillingretorten fra Pressvess vil være et egnet design for MCF Yatta. Dette er en tvillingretorte med to eksternt oppvarmede kullkamre oppvarmet av et felles forbrenningskammer. Potensialet for dette er årlig 140 tonn kull og 520 MWh tilgjengelig varme. Dette er en satsvis prosess som ikke er ideell å kombinere med strømproduksjon og derfor er to alternative design foreslått.

Et alternativ er å ha utskiftbare kullkamre, oppvarmet med pyrolysegass fra motsatt kullkammer, slik at tvillingretorten fra Pressvess vil være semikontinuerlig og generere en jevnere varme. Potensialet for denne utformingen er årlig 340 tonn trekull og 1320 MWh tilgjengelig varme. Et annet alternativ er å ha to tvillingretorter fra Pressvess kjørt i motfase, og på denne måten simulere en semikontinuerlig prosess. Dette vil kreve to enheter, noe som gir et høyere varmetap, men det kan være enklere enn å tilpasse enheten til å takle utskiftbare kullkamre. To enheter vil årlig produsere 280 tonn kull og generere 1040 MWh tilgjengelig varme.

Strømproduksjonsteknologier som antas å være kombinerbare med trekullproduksjon har blitt beskrevet. Dampmotor, dampturbin eller en organisk rankine-syklus(ORC)-turbin er teknologier med lukkede sykluser og de er egnet for småskala produksjon på MCF Yatta. Termiske effektiviteter har blitt beregnet for egnede arbeidsmedium for ORC-turbinen og for ulike parametere for damp. Med et varmelager, som en buffer mellom trekullproduksjonen og enhtene som skal utnytte varmen, vil en lav temperatur være å foretrekke, og med dette for øyet vil R245fa være et godt valg. En ORC-turbin, fylt med R245fa, vil være i stand til å levere et maksimum på 27 kW$_e$, med varme fra to enheter for trekullproduksjon og 33 kW$_e$, med varme fra en modifisert enhet for trekullproduksjon. Dette passer godt opp mot MCF Yattas gjennomsnittlige strømforbruk, som ligger på 30 kW$_e$.

På MCF Yatta kan en tvillingretorte fra Pressvess bli installert før skogen er fullt etablert. Overskuddsvarmen kan brukes til varmtvann til dusjing. Når biomassepotensialet er nådd kan semikontinuerlig trekullproduksjon etableres, og en ORC-turbin kan integreres.

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Nomenclature

Abbreviations and Latin Symbols

Symbol	Explanation	Unit
A	Area	m^2, ha
AC	Ash content	%
d.b	dry basis	
E	Energy	kWh, MWh, kJ
FC	Fixed carbon content	%
GCV	Gross calorific value	kJ/kg
h	Enthalpy	kJ/kg
h	Heat convection coefficient	$W/(m^2 °C)$
HCV	Higher calorific value	kJ/kg
L	Length	m
LCV	Lower calorific value	kJ/kg
m	mass	kg, ton
MC	Moisture content	%
MCF	Mully Children's Family	
NCA	Norwegian Church Aid	
OMTS	Octamethyltrisiloxane	
ORC	Organic rankine cycle	
P	Power	kW, MW
p,P	Pressure	MPa, kPa
rpm	Rounds per minute	
s	Entropy	kJ/(kgK)
T	Temperature	°C, K
V	Volume	m^3
VM	Volatile matter	%
w.b	wet basis	

Subscripts

Symbol	Explanation
e	Electric
con	Condensated
max	Maximum
p	Pump
s	Surface
$surr$	Surroundings
t	Turbine

Greek Letters

Symbol	Explanation	Unit
ϵ	Emissivity	
η	Efficiency	
σ	Stefan Bolztmann Constant	$W/(m^2K^4)$
ν	Specific volume	m^3/kg

1. Introduction

Kenya is a development country which have experienced a rapid growth and social development since the 1970s. One of the most important factors to continue developing is to ensure a stable and improved energy supply. Wooden biomass is the main source of energy used in Kenya and forms the basis of 70% of the total energy consumption. Firewood is the most common way for food preparation in rural areas while charcoal is most common in urban areas. Charcoal is more expensive than firewood, but since firewood is more space demanding, firewood is not a practical option in urban areas[1].

Often, firewood is cut from bush areas, and it may not be left to dry before being used for food preparation, resulting in a lot of smoke and low energy efficiency. There are less smoke issues connected to burning charcoal than firewood. Moving from a firewood based to a charcoal based society will be an important step in giving people of rural Kenya a better health[1, 2].

Out of the 2.4 million tonnes charcoal annually produced a large share is believed to be produced under non-sustainable circumstances. Firstly, the wood used for charcoal production may be harvested from areas which will not be replanted and hence this leads to deforestation. Secondly, the production method of the charcoal will be in small scale earth pit kilns which have low yields and generate a lot of unhealthy smoke. In order to guarantee charcoal as a clean and sustainable product, no more wood than the annual growth of an area should be harvested and industrial charcoal production methods should be used so that yield and emissions are kept at an acceptable level[1].

Norwegian Church Aid (NCA) in Kenya has initiated a project, which is the basis for this thesis. The overall goal for the project is to "promote learning and enable replication of "Best Practices" in the area of renewable energy, energy efficiency and climate adaption in Kenya and beyond" and the plan is to use Mully Children's Family's (MCF) farm Yatta as a demonstration facility[2].

1.1 Mully Children's Family

Mully Children's Family (MCF) is a Christian organization where the primary objective is to rescue street children by giving them a home, providing them with food, clothes, school and religious guidance. All this is done within the MCF facility. Other core objectives are sustainability and helping the nearby communities. To generate income and provide food for their children they have started with agriculture. In order to improve the micro climate MCF started with tree planting for almost 20 years ago and the facilities are now surrounded by growing forests. Recently they have established a tree nursery with an annual production of one million trees, for domestice use, for sale and for donations to the communities and others in need of trees so that they can change their own micro climate[5, 6].

1.1.1 MCF Yatta

MCF Yatta is located in the Yatta district in Machakos County in Kenya (coordinates -1.110537,37.359102) and the altitude is 1300m. The total area of MCF Yatta is 200 ha. The climate is semi arid and temperatures vary from around 12 ℃ to 30 ℃ [3], while the mean temperature of MCF Yatta is 25 ℃[4]. The annual precipitation at Thika weather station, which is located 30 km west for MCF Yatta, have in the last five years varied from 670 to 1170 mm[3]. MCF Yatta is believed to be a bit drier than Thika. Most of the precipiation comes in two rain seasons, one in the spring and one in the fall. Periods of drought may occur in between the rain seasons[5].

Figure 1.1: MCF Yatta seen from the south. Photo: K. A. Tutturen

Figure 1.1 shows MCF Yatta with school and dormitory buildings in the front and green houses in the back. MCF Yatta houses 350 former street girls and children. 60 staff are living there on a permanent basis and in the agricultural season the total number of workers may be up to 400[5].

1.1.2 MCF Ndalani

MCF Ndalani is another one of MCF's facilities. The location is approximately 12 km north east of MCF Yatta, but by road it is 30km away. It is expressed a wish to utilize the biomass resources from MCF Ndalani at MCF Yatta[5].

1.2 Research Question

The aim for this thesis is to find an appropriate technology for industrial charcoal production at MCF Yatta and look at the possibilities of combining this with electrical power generation and heat utilization. The size of the production facility should be designed to meet their future forest biomass potential. It should be a sustainable unit that match the needs of MCF Yatta.

1.3 Scope and Limitations

This thesis is part of a project, led by Norwegian Church Aid Kenya, and it is written for the Energy Farm in Norway. The objective of the project is to turn MCF Yatta sustainable and renewable in terms of energy usage. As a part of the project there are other thesis and papers being written. However, the focus on this thesis will be on the wooden biomass utilization and look upon this topic as a standalone project.

The focus lies in designing a unit that may be built in the near future and thus keeping focus on well proven and available technology. Research and development projects may be found to be more suited, but given that the time span of the project are until 2015 and that the units should be realized and built by then, those technologies are excluded in this thesis.

The focus will be on the technical solutions of the biomass, and the potential will be described and simplified to the extent suitable for this thesis. Matters of planting, harvesting and variation of tree species will be covered in other reports and as long as the matters do not affect the design or operation of the technical solutions they will not be emphasised in this thesis.

The heat utilization, from the industrial charcoal production, is considered for electrical power generation and water heating. Other options, for instance as a thermal compressor used in the cooling, is not discussed in this thesis. Those are topics that will be covered in other parts of the project work.

2. Energy Needs and Resource Mapping at MCF Yatta

2.1 Forest Biomass Resources at MCF Yatta and MCF Ndalani

The forest resources is primarily grown in two ways; conventional forest and agroforestry. In addition to the resources available at MCF Yatta it is a desire to include the resources of MCF Ndalani. In MCF Ndalani trees have been planted since 1996 with the purpose of changing the locale climate. At MCF Yatta tree planting began in 2001. A large 100 hectare forest area at MCF Yatta is scheduled to be planted in the near future and with this forest established the biomass resources will increase significantly. For this thesis the potential is calculated with an assumption that all the forest is fully established and with a relatively constant annual growth[5].

Agroforestry is shown in figure 2.1 and it is the growing of agricultural plants in between trees. This is being practised for most of the agricultural fields in both MCF Ndalani and MCF Yatta. The purpose of agroforestry is to give a better climate for the crops by reducing the wind, the solar radiation and by preserving moisture. The tree density of the agroforestry in MCF is estimated to be 100 trees per hectare.

Figure 2.1: Agroforestry at MCF Yatta, rows of grevillea robusta with green beans grown in between. Photo: K. A. Tutturen

Another type of agroforestry is planned for a 4 hectare corn field south of the largest dam. There trees in a grid with three metres between each tree are planned[5].

Areas available for forest production at MCF Yatta and MCF Ndalani have been estimated:

- 140 ha conventional forest
- 4 ha grid agroforestry
- 94 ha conventional agroforestry

2.1.1 Type of Trees

There is a range of tree types being planted at MCF Yatta. Several of these are planted for other purposes than forest, for instance as hedge. The most represented tree types suitable as forest will be used to represent the whole potential of MCF Yatta. These are described underneath[5].

Grevillea Robusta

Grevillea robusta (grevillea) is a fast growing medium weight hardwood tree originally from Australia, but common in tropical parts of the world. In agroforestry, grevillea is often chosen because the tree type is little competitive with the crop resources. Wood from the tree is common to use as firewood or in charcoal production. The higher calorific value of grevilla is 20.4 kJ/kg and the average annual growth, estimated in appendix A, is 7 ton per hectare. The density is 540-720 kg/m^3 at 15% moisture content (MC)[7].

Figure 2.2: Left: Grevillea seedlings in the tree nursery at MCF Yatta. Right: Young grevillea tree standing alone. Photo: K. A. Tutturen

Senna Siamea

Senna siamea (senna) is a medium to heavy weight hardwood which is well suited for charcoal production and as firewood. The higher calorific value of senna is 22.4 kJ/kg. At 15% MC the density varies from 600 kg/m^3 to 1010 kg/m^3. The annual growth of total above-ground biomass is 3.8 ton/ha[9]. Senna is able to re-grow when it is a cut, which makes it very suitable for firewood production. This enables many harvests from the same tree and for this reason the trees are planted dense, from 3300 trees/ha to 10000 trees/ha. For charcoal production it is beneficial with larger trees than for firewood and the trees should be planted a little less dense[10].

Figure 2.3: Grown senna in blossom. Photo: K. A. Tutturen

2.1.2 Biomass Potential Estimate

In estimating the forest biomass potential of MCF Ndalani and MCF Yatta the following assumptions were made[5]:

- All the potential forest is fully established.
- The mixture of species in the forest consist of 80% grevillea and 20% senna in planted trees
- Senna is planted with 2 metres (2500 trees/ha) distance between trees
- Grevillea is planted with 3 metres distance (1100 trees/ha) between trees in forest and in grid agroforestry
- In agroforestry, grevillea is used with a density of 100 trees per hectare. This gives an annual growth of 0.6 ton/hectare $\left(\frac{7 \text{ ton/ha}*100 \text{ trees/ha}}{1100 \text{ trees/ha}} = 0.6 \text{ ton/hectare}\right)$.

With a share of 80% planted grevillea with a tree density of 1100 trees per hectare and 20% senna with a tree density of 2500 trees per hectare the 140 ha with conventional forest will be represented with 125 hectare grevillea and 15 hectare senna. The forest biomass potential is given in table 2.1.

Table 2.1: Annual forest biomass potential estimate of MCF.

	Area (ha)	**Annual growth rate (ton/ha)**	**Total dry growth (ton/year)**
Forest - Grevillea	125	7	877
Forest - Senna	15	3.8	56
Conventional Agroforestry	94	0.6	60
Grid Agroforestry	4	7	28
Total			1021

2.1.3 Calorific Values

The two species system chosen for the estimation include two different HCV and these may be represented by a single one. The following assumptions were made in order to perform the estimates for the calorific values.

- Average ambient temperature is 25 ℃ [4]
- The forest biomass have this summarily composition: 50% carbon, 6% hydrogen, 44% oxygen[11].

From table 2.1 it may be calculated that the share of senna is 5.5% by dry weight and the share of grevillea 94.5%. The HCV of the mixture may be calculated by multiplying their respective HCV with their share of the total.

$$\begin{aligned} HCV_{wood} &= HCV_{grevillea} * \text{Share}_{grevillea} + HCV_{senna} * \text{Share}_{senna} \\ HCV_{wood} &= 20.4\text{ kJ/kg} * 94.5\% + 22.4\text{ kJ/kg} * 5.5\% = 20.5\text{ kJ/kg}_{dry} \end{aligned} \tag{2.1}$$

In order to calculate the lower calorific value (LCV) the enthalpy of evaporation of the water formed in the combustion must be subtracted from the HCV. Enthalpy of evaporation for water at 25 ℃ is 2442 kJ/kg[12]. Then the LCV may be calculated in equation 2.2[13].

$$\begin{aligned} LCV_{wood} &= HCV_{wood} - h_{evap,298K} * \text{Share}_{hydrogen} * \frac{M_{H_2O}}{M_{H_2}} \\ LCV_{wood} &= 20.5\text{ kJ/kg}_{dry} - 2442\text{ kJ/kg} * 0.06 * \frac{18\text{ g/mol}}{2\text{ g/mol}} \\ LCV_{wood} &= 19.2\text{ kJ/kg}_{dry} = 5.3\text{ kWh/kg}_{dry} \end{aligned} \tag{2.2}$$

The gross calorific value (GCV) takes into account the MC present in the biomass. GCV may be represented as a function of moisture content and LCV[13].

$$GCV_{wood,wet} = (1 - MC)LCV_{wood} - MC * h_{evap,298K} \tag{2.3}$$

Natural drying may dry the biomass down to 15%, giving a $GCV_{15\%MC} = 4,4$ kWh/kg. To get a lower MC in the feedstock a drying facility is needed. Figure 2.4 presents GCV for different MC, starting with LCV at 0% MC and reaching 0 kJ/kg around 88% MC[13].

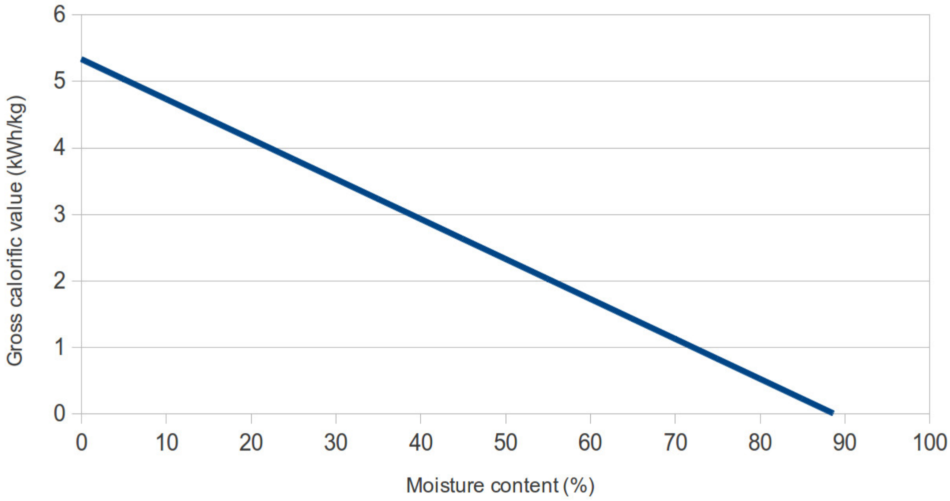

Figure 2.4: Gross calorific value as a function of moisture content, calculated with equation 2.3.

2.2 Electricity Consumption

At MCF Yatta there are three different electricity meters. The irrigation meter is mainly serving the irrigation of fields, a water borehole, lighting and other equipment in the office building. The dispensary meter serves the cooling rooms, the dispensary and two small houses. The central meter serves the rest of the buildings, including the workshop and a pump which pumps water from a water storage to the irrigation magazine[5].

2.2.1 Annual Mean Electricity Consumption

Table 2.2 shows power meter readings from MCF Yatta. The dispensary meter was replaced in 2012 and the first reading from this meter is inaccurate, but it will give a fairly good estimate. One reading from 2011 is included in the list and this reading may be used as a quality assurance of the average estimate[5].

Table 2.2: Power meter readings at MCF Yatta from selected dates.

Date	**Irrigation meter (kWh)**	**Dispensary meter (kWh)**	**Central meter (kWh)**
02.05.2011	80568	Not available	307685
30.08.2012	172456	914 (Estimated value)	417030
14.02.2013	216000	30400	457784
01.03.2013	221005	32331	461039

For the "central and irrigation" column in table 2.3 the average is calculated from 02.05.2011 For the total column in the same table the average is calculated from 30.08.2012. The purpose of the table is to estimate the long term average power consumption. Due to the fact that the dispensary meter have no long term reading a long term estimation of the other two meters are shown. The estimation from only the central and irrigation meter indicates that the average power consumption is quite constant. The main consumption from the dispensary meter is cooling, which is a relatively constant consumption throughout the day and year. Taking this into account it is safe to assume a total average electric power consumption at MCF Yatta of 30kW$_e$.

Table 2.3: Estimated average power consumption at MCF Yatta.

	Average power consumption estimate (kW)	
Date	**Central and irrigation**	**Total**
30.08.2012	23	NA
14.02.2013	22	30
01.03.2013	22	30

2.2.2 Daily Variation in Electricity Consumption

Figure 2.5 shows the daily variation in power consumption on a day in the end of February, 2013, which is during a dry season. The dip at around 15:00 is caused by a blackout in the grid.

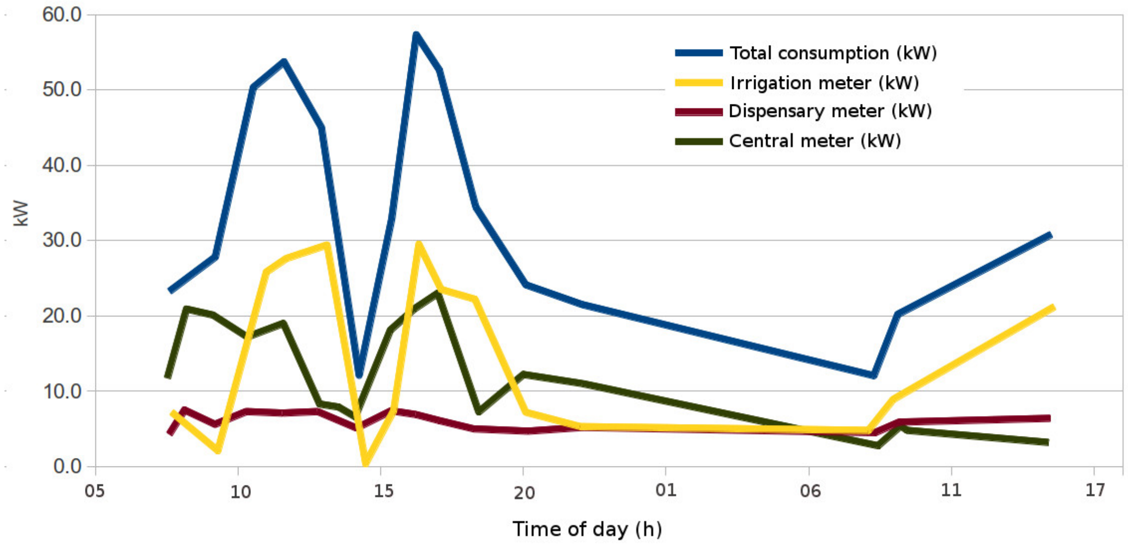

Figure 2.5: Power curve one day in February 2013.

The blackout is causing the curve to differ from a normal day. Therefore, figure 2.6, with two corrected values, shows the expected curve if the blackout had not occurred. This is not a real graph, but it illustrates a normal day at MCF Yatta better than figure 2.5. There is still at dip in the curve, which is due to a lunch break giving a reduction in the electricity consumption at the central meter.

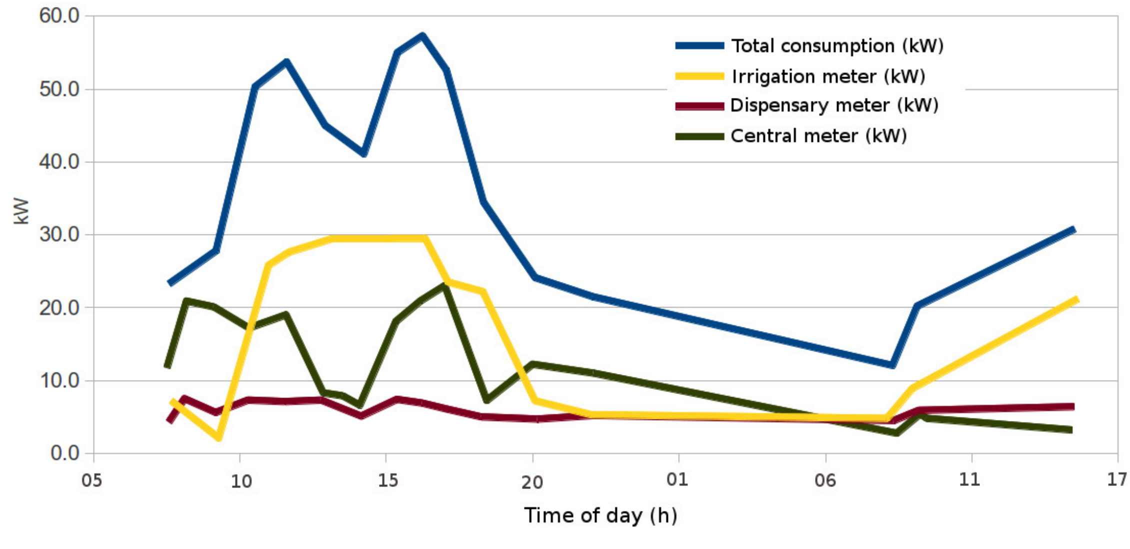

Figure 2.6: Power curve one day in February 2013 corrected for a blackout, affecting two values of the irrigation meter 15:30 and 16:20 the first day.

2.2.3 The Transformer at MCF Yatta

MCF Yatta is grid connected by a transformer located on their property. There are no other units connected to this transformer.

The transformer has the following properties:

- 200 kVA
- 11 kV high voltage
- 433 V / 250 V low voltage
- 10.4 A rated current
- 50 Hz frequency

Currently there is no system enabling small scale suppliers to feed electricity to the grid in Kenya. However, a system compensating electricity suppliers is likely to be established in the near future. For this thesis it will be assumed that such a system is established before the power generation unit is constructed[2].

Figure 2.7: The 200 kVa, 11 kV/400 V transformer, connecting MCF Yatta to the grid.

2.3 Hot Water Consumption

Except for two rarely used water heaters there are no systems for heating water, neither for washing of hands nor for showers. There is an expressed desire to establish a system with warm showers[5]. In order to estimate energy need to heat water for showering the following assumptions are made:

- Everyone living in Yatta takes 1-2 showers each day. There are mandatory showers in the morning[5]
- One shower lasts for 3-10 minutes
- Shower capacity is 6-12 litres per minute
- Water is stored above ground before heating and thus heated from ambient temperature, which in average is 25 ℃
- Shower temperature is 38 ℃

Under these assumptions the energy consumption for one shower becomes:

$$
\begin{aligned}
&Q = m * C_p * \Delta T \\
&Q = (6-12)\ \text{kg/min} * (3-10)\ \text{min/shower} * \frac{4.18\ \text{kJ/(kgK)}}{3600\ \text{kJ/kWh}} * (38-25)\ \text{K} \\
&Q = 0.3 - 1.8\ \text{kWh/shower}
\end{aligned}
\tag{2.4}
$$

With 60 staff, 350 girls and children living in Yatta the total energy needed on a daily basis will range from 120 kWh to 1500 kWh and on annual basis from 45 MWh to 540 MWh. The range in the annual heat need for hot water consumption reflects the uncertainty in the number. How many people that will shower more than once per day and for how long they will shower are quite uncertain values. The capacity of the aboveground water storage may not be high enough to ensure that the water keep 25 ℃ before being heated[5].

2.4 Firewood Consumption

Food preparation at MCF Yatta is mainly done in one central kitchen where the food is prepared in large pots on cooking stoves. In picture 2.8 the firewood based stoves are in use. These stoves have a low efficiency, around 10-15%. The annual firewood consumption is 120 ton naturally dried wood[5]. With an assumption of naturally dried firewood with 15% MC, this becomes 530 MWh in annual energy consumption.

Figure 2.8: Example of cooking stoves in use at the kitchen in MCF Yatta. Photo: K. A. Tutturen

3. Industrial Charcoal Production

3.1 Charcoal

Charcoal is carbonized biomass and it comes in many forms and qualities. Chaturverdi have made a statement that is almost a definition of good quality charcoal and he states that "charcoal of good quality retains the grain of the wood; it is jet black in color with a shining luster in a fresh cross-section. It is sonorous with a metallic ring, and does not crush, nor does it soil the fingers. It floats in water, is a bad conductor of heat and electricity, and burns without flame"[14].

This description of charcoal gives a good impression of what a piece of charcoal should look like and how it should behave. However, depending on the conditions of the production process the amount of carbon may vary from 50% to 80%. The ash content may vary from 2-10% depending on the type of biomass used and the calorific value range from 28 to 33MJ/kg[15, 11].

3.2 Pyrolysis of Wood, Giving Charcoal, Tar, Combustible Gases and Heat

Production of charcoal is done by heating biomass in an environment with little or no oxygen, a process called pyrolysis. At a temperature of 270 ℃ or higher the carbonization process begins and the absence of air prevents the biomass from combusting and it will form charcoal instead. In addition to charcoal, gases (mainly CO_2, CO and H_2O) and tarry vapours will be formed in the heating process. Charcoal production has been practised for centuries in traditional kilns with low efficiency and little control over the exhaust gases. The production has been modernised throughout the 19th and 20th century and industrial production is today mainly done with retorts[11].

The process of which charcoal is produced may be described in the following steps[16]:

(i) Drying stage - Temperature rises to 110 ℃ and is kept around 100 ℃ until MC is zero

(ii) Pyrolysis stage - Temperature raise to 270 ℃ giving an endothermic, a reaction which absorbs heat in order to run,decomposition of the wood

(iii) Final stage - Temperature raise to 500-600 ℃ to increase the quality of the charcoal

3.3 Properties of Charcoal

Many properties may be used in an attempt of defining charcoal and for this thesis the most relevant ones will be[11]:

- Volatile Matter (VM)
- Ash content (AC)
- Fixed carbon content (FC)
- Yield
- Moisture content (MC)

3.3.1 Volatile Matter

VM states how much of the charcoal that will turn it to combustible gases when it is heated. Typical values of VM range from 10-30% dry basis, where lowest percentage is considered to have the highest quality[17].

The amount of VM is estimated by analysing what happens when charcoal, $m_{charcoal}$, is heated and kept at 950 ℃ for 6 minutes. Then the remaining mass, $m_{char,remain}$, is measured and the VM will be[18]:

$$VM = \frac{(m_{charcoal} - m_{char,remain})}{m_{charcoal}} \tag{3.1}$$

The wanted and accepted level of VM depends on the use of the charcoal. For cooking purposes the amount of VM is not so critical, and 20-30% is acceptable. For metallurgic quality charcoal the less VM the better, and under 15% is wanted. The charcoal production at MCF Yatta will be for domestic applications and the level of VM is not so critical[18].

3.3.2 Ash Content

AC is determined by taking the charcoal used for establishing VM and heat it at 750°for 6 hours. The remains is considered to be ash. Between 0.5 - 5% is a typical value for ash content in charcoal[18].

3.3.3 Fixed Carbon Content

FC states how much pure carbon the charcoal consists of. FC will normally range from around 65-90%[17]. The FC is defined as[18]:

$$\text{FC}(\%) = 100 - \text{VM}(\%) - \text{AC}(\%) \tag{3.2}$$

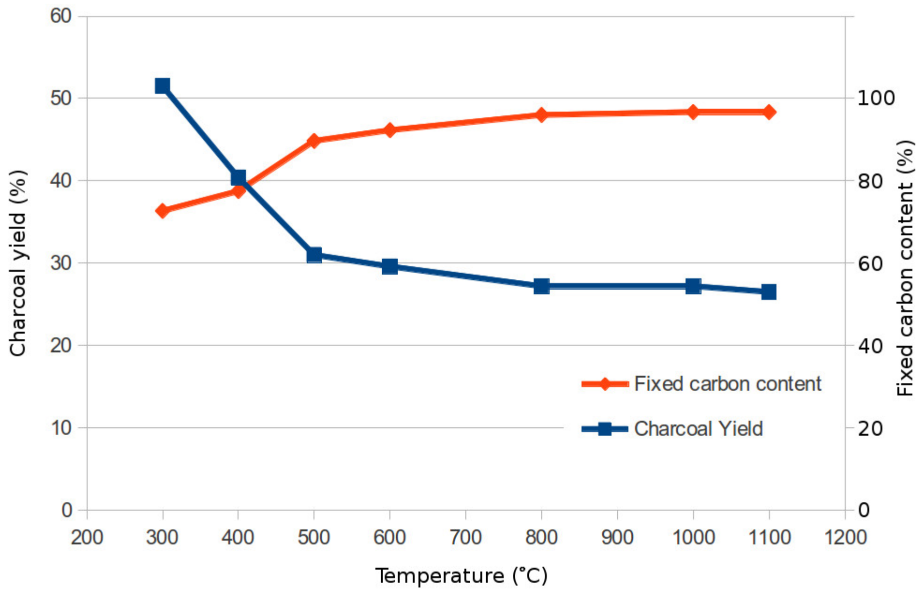

Figure 3.1: Effect of yield and fixed carbon content for different temperatures[16].

Figure 3.1 shows the effects of charcoal yield and FC as a function of temperature. The amount of FC increase with an increase in temperature, which implies that VM is evaporated from the charcoal giving an increase in FC. High FC will give a pure combustion and cleaner smoke[18].

3.3.4 Yield

The charcoal yield is defined in equation 3.3 as the amount of charcoal divided by the total amount of biomass fed. The yield decrease with an increase in the temperature used in the charcoal production process[18].

$$y_{charcoal} = \frac{m_{charcoal}}{m_{biomass}} \tag{3.3}$$

3.3.5 Moisture Content

Fresh biomass may have up to 60% MC and this is considered the limit for a combustion process to run. Natural drying can reduce the MC down to 15% and increase the calorific value. Natural drying takes time, requires space and reduces the total mass, but it will increase the calorific value and reduce the need for external heating in the charcoal production process. Mechanical drying may reduce the MC even further and thus give an additional reduction in the need for external heating[17].

Some studies show catalytic effects of the presence of water in charcoal production. Either having wet biomass or adding water will give higher yields than with dried wood. However, this will require additional heating and there will be less excess heat[11].

3.3.6 Effect of Temperature and Pressure

The temperature of the carbonization process has great influence on the charcoal properties. An increase in temperature seem to give a reduction in charcoal yield and tarry vapours. The lower the temperature the better the yield, but this will increase the production time of the charcoal, called cooking time[16, 18].

As the carbonization process is coming to an end, the energy fed to the reaction is used to evaporate VM and give a higher FC of the charcoal. The FC will increase with increasing temperature and give a higher quality of the charcoal. Higher temperature will give higher quality charcoal, but less charcoal. The temperature must thus be a balance between yield and quality[16].

Studies have shown increase in yield with elevated pressure in the carbonization process. The higher the pressure the better the yield[18, 16].

3.4 Industrial process

There are a many different designs of industrial charcoal production units. The most common one in historical terms is the charcoal kiln, while the most common unit to build today is a retort based one. Industrial charcoal production is a narrow branch, compared to other ways of converting biomass into other energy forms, and production units are often custom designed to each specific site, and seldom commercially available. The slight variations in design often result in different names of the charcoal kilns or retorts even though the principle is the same[17].

There are three different main principles for charcoal production[18]:

- Internal heating
- External heating
- Heating with recirculated gas

The last option with recirculated gas is only for large scale operations (typically over 5000 tonnes annual charcoal production) and will not be evaluated in this thesis[18].

3.4.1 Internal Heating

Internally heated charcoal production is based on letting some of the biomass being combusted in the same chamber as the charcoal is produced. Starved combustion is maintained by controlling the amount of air that is let into the chamber. This way of heating leads to good heat transfer between fuel and biomass since it is done within the chamber. The main challenges is to keep the flow of oxygen low enough to maintain high charcoal yield and get good quality charcoal[18].

The most common principles with internal heating are modern kiln, continuous process and internally heated retorts. With internally heated retorts several retorts are connected to a central combustion chamber. Both continuous process and internally heated retorts are more suited for large scale operations and the principles will not suit MCF Yatta[18].

The modern kiln, shown in figure 3.2, is a development from the traditional earth pit kiln where a pile of wood where stacked, ignited, and covered with soil in order to prevent combustion. Instead of building the kiln every time the modern charcoal kiln consists of a concrete or brick chamber which comes in a wide range of sizes. The chamber is filled with biomass and the biomass is ignited. The air inlets are choked so that starved combustion is preserved in a period from 7-30 days[11].

Figure 3.2: Picture of a Beehive charcoal kiln, located near Leadore, Idaho, USA. Photo: James A. McDonald. Public domain[19].

The kiln is internally heated with the pyrolysis gases produced by the process. If the kiln is run for too long or with excess air some of the charcoal will be combusted. Due to the internal heating the kilns are difficult to operate and the thus the yield is quite low with a range from 5-30%. The quality in terms of VM, FC and MC varies a lot from kiln to kiln. Afterburners are required in order to meet emission requirements in many countries[17].

Missouri Kiln

The principles are quite similar for the three most common types, Missouri kiln, Argentine kiln and the Brazilian Beehive kiln, and the Missouri kiln will be presented to represent all of them. The Missouri kiln varies in size from 4 m^3 to 350 m^3, and 180 m^3 is found to be the optimal size due to cost and operability. The kiln is constructed from bricks with metal doors and multiple air inlet and pipes. This enables the operator to adjust the inlets separately and optimize the temperature inside the kiln[18].

The yield varies from 20 - 30% and the cycle of one batch is from 25 to 30 days, due to a long cooling period. This simple design with a large variation in temperature throughout the long cycle seems difficult to integrate with a heat exchanger, at least for high quality heat[18].

3.4.2 External Heating

An enclosed retort is a chamber with valves for letting pyrolysis gases out of the chamber, but preventing air from flowing in. Charcoal production from retorts is the most common in modern facilities. The working principle of a charcoal retort may be seen in figure 3.3. The heating is external in the sense that there is no combustion in the same chamber as the charcoal, even though the fuel used most of the time is pyrolysis gas from the biomass in the same chamber. It is led through the valves and burned in a separate chamber. The pyrolysis gases are released in certain steps of the production process and by having more than one retort pyrolysis gas from one retort may be used to heat another[17].

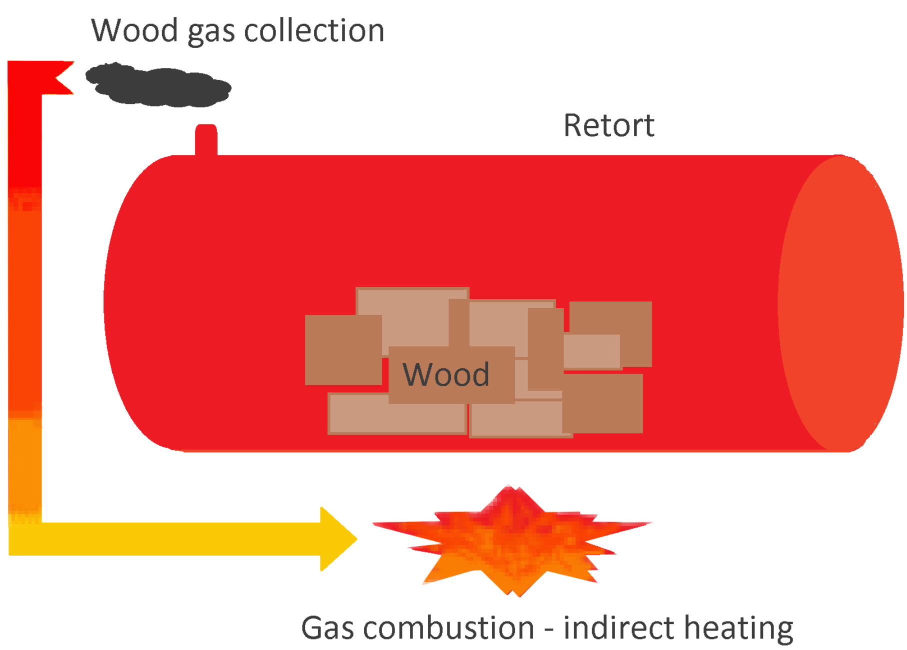

Figure 3.3: Principle of an enclosed charcoal retort.

The great advantage of using retorts compared to a kiln is that the retort is an air tight vessel. This prevents the biomass from combusting and the yields will be high, typically over 30%[17].

3.5 Enclosed Retort Designs

3.5.1 Van Marion Retort

The Van Marion retort (VMR) is a twin retort with two chambers for interchangeable cylinders. Each chamber has a volume of 4.5m^3 and the cooking time is 8-12 hours with a charcoal yield of 30-32%. A principle scheme may be seen in figure 3.4 and it is constructed to work in a cyclic manner where the heat from one enclosed retort is heating the other[11].

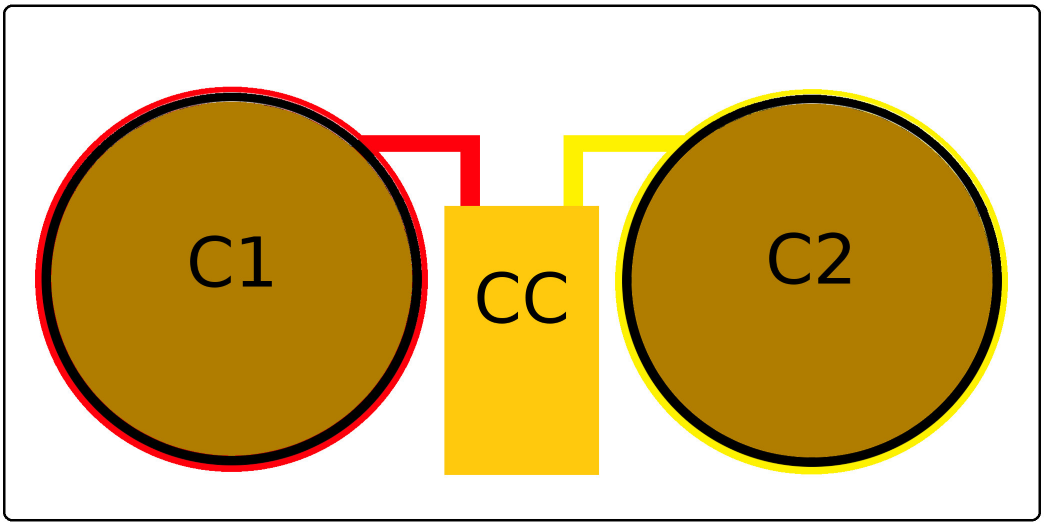

Figure 3.4: Principle scheme of the Van Marion Retort[18].

The VMR is a semi continuous process with the following working principle[11, 18]:

1 Wood is filled in cylinder C1, and heated with fuel in the combustion chamber (CC).

2 After half a duration enough wood gas have been produced in C1. A cylinder is put in C2 and heated with the wood gas from C1.

3 After one duration the cylinder in C1 is replaced with another one, filled with fresh biomass. Now the wood gas from C2 is used to heat the newly added cylinder.

4 The cycle is repeated from step 2.

The VMR is a an old design which is no longer available on the market. Therefore, this can not be used at MCF Yatta[18].

3.5.2 Pressvess Twin Retort

The Pressvess retort is a twin retort quite similar in design to the VMR, except for that the charge cylinders are not interchangeable. It is an externally heated batch process where air tight charge cylinders initially are heated with additional fuel before pyrolysis gas from the charges reheats the process. One cycle will take 24 hours if dry biomass with MC under 8% is used[20].

The Pressvess retort may be delivered with an internal steam coil and delivered with scrubbers, to clean the smoke, if this is necessary[20].

The whole unit measure 1.4 metre in height, 3.4 metre in width and 2.1 metre in depth. The two round charge cylinders are 1.8 metre deep and 1 metre in diameter. The retort is made from a 8mm thick carbon steel shell, insulated with 50 mm ceramic blanket. The cylinders are made of 12mm thick steel and the doors of the cylinders are made of two 4mm plates with 50 mm insulation in between. As inner construction material bricks and steel tubes are used[20].

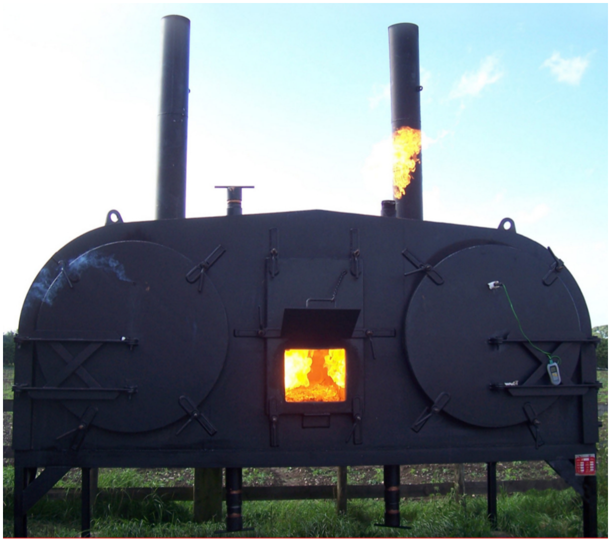

Figure 3.5: Picture of the Pressvess charcoal retort. Photo: Pressvess[20].

The principle of operation is quite similar to the VMR, but it is designed as a batch process and it needs to cool between every new load[20]:

- Fill the two cylinders with wood, around 1.5 m^3 in each charge cylinder. The solid mass percentage is reported to be 50%. Takes a little less than an hour
- Load central chamber with additional fuel and burn until approximately 300 ℃ is reached, takes 1-1.5 hours
- Pyrolysis gas from the charge cylinders will be released and heat the retort for the rest of the cooking period. Temperature of the outer surface is 85 ℃ during the cooking time
- When cooking is finished, afer 8-10 hours, let the retort cool
- Empty the charcoal from the cylinders and repeat the process

A MC of 7-8% is the limit for preburning and it is preferable to use wood as dry as this or drier. Preburning means to fill the cyldiners with biomass, light up the combustion chamber and preserve a temperature between 80 - 120 ℃until the wood have reached 7-8% MC. This may take several hours and will reduce the capacity of the retort. It is preferable to use dried wood in order to have maximum capacity of the retort, but this require a facility for drying[20].

If the wood is dried in advance the preburning step may be skipped. This will require a drying facility that will be able to dry the wood more than natural drying. Waste heat may be used for this purpose[20].

Yield

The maximum charcoal production for every batch is reported to be 400 kg in total for the two cylinders, but this number varies a lot with MC and type of tree. Different yields, based on information given from Pressvess[20] and on estimates from appendix B, are given in table 3.1[20].

Table 3.1: Charcoal batch estimate for MCF Yatta[20].

	7 % MC	20 % MC
Total input fraction	1	1
Retort input fraction	0.83	0.80
Combustion chamber fraction	0.17	0.20
Total charcoal yield (%)	0.37	0.25

Temperatures

The process is started by heating from the combustion chamber. A various range of fuel may be used, oil, coal, waste, biomass, etc. For this project using biomass in form of scrap wood, bad quality charcoal or wood not suitable for charcoal production will be the most probable. When the biomass inside the chamber reach a temperature of 275 ℃ decomposition begins and pyrolysis gas is released. This gas is then led out of the chamber and into the combustion chamber. From this point the retort is self fuelled[20].

Once fired on pyrolysis gas temperature rise and may reach 1100 ℃in the combustion chamber, and the retort is run with an ambition of keeping the temperature in the charge cylinders close to 600 ℃. If temperature exceeds 604 ℃a safety vent opens and reduce the temperature. This is in order to prevent cracking of the charcoal and risking yield reduction[20].

Cooling

When the cooking process is finished the retort needs to cool down to a temperature of 40 ℃before letting air into the charge cylinders. After 8-10 hours depending on the MC of the biomass and type of wood there is no more gasification and the retort may be let to cool. At this point the retort will have a temperature close to 600° C and all the heat is now considered excess heat, which still may be still used in a heat exchanger[20].

Heat Loss During Cooking

The Pressvess twin retort will have a radiation loss, a natural convection loss and a forced convection loss due to wind when during the cooking process. The heat convection coefficients and backgrounds for the calculations may be found in in appendix D[21].

With a known temperature of 85 ℃ on the surface of the retort the radiation and convection losses may be calculated. Radiation is given by Stefan-Boltzmann law. The retort is black painted and the emissivity (ϵ) will be 0.98[21].

$$\begin{aligned} P_{rad} &= \epsilon \sigma A_s \left(T_s^4 - T_{surr}^4\right) \\ P_{rad} &= 0.98 * 5.67 * 10^{-8}\ \mathrm{W/(m^2K^4)} 29.7\ \mathrm{m}^2 \left(((85+273)\ \mathrm{K})^4 - ((25+273)\ \mathrm{K})^4\right) \\ P_{rad} &= 14.1\ \mathrm{kW} \end{aligned} \tag{3.4}$$

Natural convection is given by Newton's law of cooling. The sides, the top and the bottom have different heat convection coefficients[21].

$$\begin{aligned} &P = hA_s(T_s - T_\infty) \\ &P_{top} = h_{top} * w * d(T_s - T_\infty) = 4.7\ \mathrm{W/(m^2{}^\circ C)} * 3.4\ \mathrm{m} * 2.1\ \mathrm{m} * 60^\circ\mathrm{C} = 2.0\ \mathrm{kW} \\ &P_{bottom} = h_{bottom} * w * d(T_s - T_\infty) = 1.4\ \mathrm{W/(m^2{}^\circ C)} * 3.4\ \mathrm{m} * 2.1\ \mathrm{m} * 60^\circ\mathrm{C} = 0.6\ \mathrm{kW} \\ &P_{sides} = h_{sides} * 2 * (w * h + d * h)(T_s - T_\infty) = \\ &P_{sides} = 0.3\ \mathrm{W/(m^2{}^\circ C)} * 2 * (3.4\ \mathrm{m} * 1.4\ \mathrm{m} + 2.1\ \mathrm{m} * 1.4\ \mathrm{m}) * 60^\circ\mathrm{C} = 0.3\ \mathrm{kW} \end{aligned} \tag{3.5}$$

The total heat loss from forced convection, wind, is given below[21].

$$P_{conv,forced} = h_{forced} A_s (T_s - T_\infty) = 5.4\ \mathrm{W/(m^2{}^\circ C)} * 29.7\ \mathrm{m}^2 * 60^\circ\mathrm{C} = 9.6\ \mathrm{kW} \tag{3.6}$$

The total heat loss of the Pressvess twin retort during the cooking process then becomes 27 kW.

4. Thermal Power Generation from Biomass

Thermal power generation is a widely used technology and most of the electrical power in the world is generated in this way. Coal, natural gas, oil and nuclear reactions are all common fuels in such power stations. Power generation from biomass will use the same technology, only with biomass as fuel. The basic principle is to use the energy in the fuel to create mechanical work, which is used to run a electric generator. Typical generator efficiency is 90%[13].

When describing thermal power generation technologies it is natural to distinguish between closed cycle and open cycle operation. A closed cycle implies that the working fluid in the engine is only heated by the conversion process and no biomass components are present inside the engine. This enables the engine cycle to run with a clean working fluid at all times and the likelihood of a failure is small. Open cycles implies the opposite, that parts of the converted biomass, combustible gases and liquids, are used in the engine to generate power[13].

The use of solid fuels in operation with open cycle power generation is generally not feasible, with the exception of gas and micro turbines ran. These are run on flue gases from the biomass, and these contain a lot of small particles, metals and chlorine components which require purification. Such systems are still at the research and development stage and they are not yet commercial. Open cycle systems will not be described further and the focus will be on closed cycle systems[13].

Table 4.1 shows the status of the different biomass based closed thermal cycle technologies.

Table 4.1: Table of closed thermal cycle for biomass based power generation[13, 22, 23, 11, 30].

Technologies with phase change		
Type of technology	**Size range**	**Status**
Steam turbine	50 kW$_e$ – 250 MW$_e$	Commercial technology
Steam piston engine	25 kW$_e$ – 1.5 MW$_e$	Commercial technology
Steam screw engine	Not available,	One demonstration plant, size 730 kW$_e$
Organic rankine cycle turbine	1 kW$_e$ – 1.5 MW$_e$	Commercial technology
Technologies without phase change		
Type of technology	**Size range**	**Status**
Hot air turbine	Not available	Development
Stirling engine	1 kW$_e$ – 100 kW$_e$	Development and pilot

4.1 Without Phase Change

Stirling engines and hot air turbines are externally heated through high temperature heat exchangers and there is no phase change in the cycle. Hot air turbine is not a commercial technology and will not be evaluated further[13].

The stirling engine comes in a size range from 1 kW$_e$ and upwards and this would suit the MCF Yatta well. However, the temperature of the flue gas in a stirling engine is high and may typically range from around 600 ℃ and up to around 1000 ℃. Considering the effects of what happens with the carbonization process at such high temperatures this would not be beneficial for the charcoal yield. This makes the stirling engine unsuitable in combination with charcoal production[13, 24].

4.2 With Phase Change

From table 4.1 it may be read that the steam screw engine is not a commercial technology and thus not suitable for MCF Yatta. The technologies which will be described in det ail will thus be steam turbine, steam piston engine and an organic rankine cycle (ORC) turbine[13].

Common for all the technologies with phase change in table 4.1 is that they are based on the same thermodynamic cycle, the rankine cycle. The ORC turbine uses a different working fluid than water, but the principle of the thermodynamic cycle is the same. Therefore, the rankine cycle will be described before the different technologies are described[12, 13].

4.3 The Rankine Cycle

The rankine cycle is the thermodynamic cycle which applies for the steam turbine, steam engine and the ORC turbine. By studying how the rankine cycle works, equations for how the efficiency of the cycle varies with working fluid, temperature and pressure may be established[12].

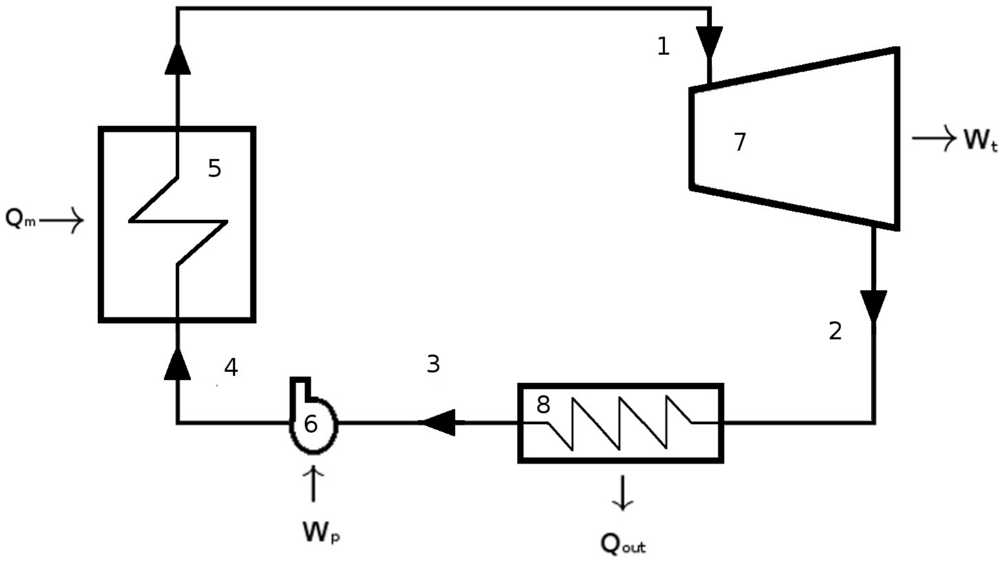

Figure 4.1: Schematic illustration of a steam turbine[12].

From figure 4.1 it may be seen that there are both work input and work output. These may be formulated by using the principles of mass and energy conservation . Certain assumptions are made in order to simplify these equations[12]:

- The direction of the arrows define the positive direction
- Neglecting stray heat transfer between plant components and surroundings
- Ignoring change in potential and kinetic energy
- Steady state within each component

At point 1 in figure 4.1 the working fluid, water in a rankine cycle, is pressurized by the pump (6) and the temperature has been raised in the boiler (5). The working fluid expands through the turbine (7) and releases energy to be left as work ($\dot{W}_t$). The energy and mass is conserved and this gives the following equation for the turbine work[12]:

$$0 = \dot{Q}_{sur} - \dot{W}_t + \dot{m}\left[h_1 - h_2 + \frac{V_1^2 - V_2^2}{2} + g(z_1 - z_2)\right]$$
$$\dot{Q}_{sur} = 0,\ V_1 = V_2,\ z_1 = z_2 \tag{4.1}$$
$$\Rightarrow \frac{\dot{W}_t}{\dot{m}} = h_1 - h_2$$

This equation states that the work per unit of mass of steam is equal to the difference in enthalpy at point 2 and point 1. The enthalpy states how much energy it is in the working fluid. Depending on the parameters of the boiler and the turbine the steam may be saturated or superheated vapour at point 1. Higher pressure is needed to obtain superheated vapour, but the enthalpy will be higher[12].

At point 2 the fluid may be superheated or saturated vapour or two phase. The vapour quality is used for two phase substances in order to tell how much energy is left in the gas after leaving the turbine[12]:

$$x = \frac{s_1 - s_{2f}}{s_{2g} - s_{2f}} \tag{4.2}$$

Similar reasoning as for the turbine work may be used for the condenser, pump and boiler since they are all assumed to be at steady state and there is no change in volume or altitude. The heat taken out ($\dot{Q}_{out}$) of the condenser (8) per unit of mass of working fluid then becomes[12]:

$$\frac{\dot{Q}_{out}}{\dot{m}} = h_2 - h_3 \tag{4.3}$$

The pump work ($\dot{W}_p$) required per unit of mass of working fluid becomes[12]:

$$\frac{\dot{W}_p}{\dot{m}} = h_4 - h_3 \tag{4.4}$$

The heat input of the boiler ($\dot{Q}_{in}$) per unit of mass of working fluid then becomes[12]:

$$\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4 \tag{4.5}$$

4.3.1 The Ideal Rankine Cycle

In the ideal rankine cycle all processes are assumed to be reversible and without losses. This is, obviously not entirely the case in the real rankine cycle, but ideal calculations will show the same tendencies as the real cycle. In figure 4.2 the cycle is shown in temperature-entropy diagram (TS) and it has the following process steps[12]:

1-2 Constant entropy, called isentropic, expansion through the turbine from stage 1 to stage 2. The entropy is a measure of disorder in a substance. At stage 1 the working fluid is either a saturated or superheated vapour

2-3 Constant pressure, called isobaric, heat transfer from the working fluid through the condenser. At stage 3 the working fluid is a saturated liquid

3-4 Isentropic compression in the pump

3-4 Isobaric heat transfer to the working fluid in the boiler. The cycle is complete and repeated

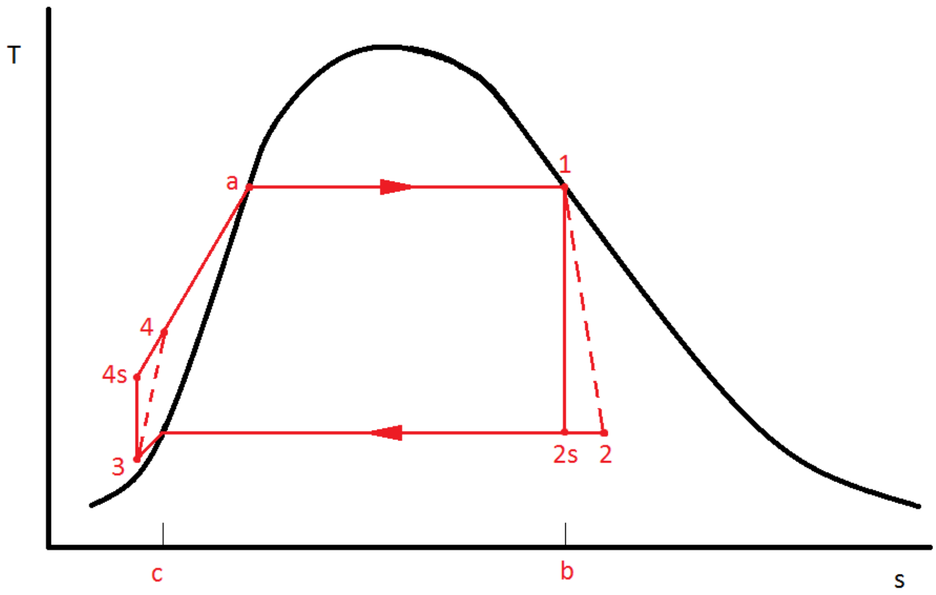

Figure 4.2: Temperature-entropy diagram for a rankine cycle, with ideal cycle in points 2s and 4s and real cycle in stapled line[12].

Assuming that the specific volume is approximately equal before entering and after leaving the pump the ideal pump work per unit of working fluid may now be expressed in terms of specific volume and pressure[12]:

$$\begin{aligned} \left(\frac{\dot{W}_p}{\dot{m}}\right)_{\substack{internally\\reversible}} &= \int_3^4 v dp \quad \mid \; v_4 \simeq v_3 \\ \left(\frac{\dot{W}_p}{\dot{m}}\right)_{\substack{int\\rev}} &= v_3 \int_3^4 dp \\ \left(\frac{\dot{W}_p}{\dot{m}}\right)_{\substack{int\\rev}} &= v_3(p_4 - p_3) \end{aligned} \tag{4.6}$$

4.3.2 Thermal Efficiency of the Cycle

The thermal efficiency of the cycle tells how much mechanical output is being done compared to the heat input[12].

$$
\begin{aligned}
\eta_{t,ideal} &= \frac{\text{Wanted energy out}}{\text{Energy input}} = \frac{W_{net,out}}{Q_{input}} \\
\eta_{t,ideal} &= \frac{\frac{\dot{W}_t}{\dot{m}} - \frac{\dot{W}_p}{\dot{m}}}{\frac{\dot{Q}_{in}}{\dot{m}}} = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)} \\
\eta_{t,ideal} &= \frac{h_1 - h_2 - h_4 + h_3}{(h_1 - h_4)} = \frac{(h_1 - h_4) - (h_2 - h_3)}{(h_1 - h_4)} \\
\eta_{t,ideal} &= 1 - \frac{(h_2 - h_3)}{(h_1 - h_4)}
\end{aligned}
\tag{4.7}
$$

According to Loo and Koppejan[13] the ”efficiency of the Rankine cycle depends on the enthalpy difference before and after the turbine and therefore on the difference between inlet and outlet pressure and temperature”. Thus, the higher inlet temperature and pressure the better, but this will increase the cost of the turbine so the gain in increased efficiency must be compared to the increase in cost[13].

4.3.3 Effect of Temperature and Pressure

The thermal efficiency of an ideal rankine cycle is the net heat input divided with the total heat input. In the ideal cycle the heat inputs are equal to the areas under their curves. The total heat input is[12]:

$$
\begin{aligned}
\left(\frac{\dot{Q}_{in}}{\dot{m}}\right)_{\substack{int\\rev}} &= \int_4^1 T ds \\
\left(\frac{\dot{Q}_{in}}{\dot{m}}\right)_{\substack{int\\rev}} &= \overline{T}_{in}(s_1 - s_{4s})
\end{aligned}
\tag{4.8}
$$

The total heat output is[12]:

$$
\begin{aligned}
\left(\frac{\dot{Q}_{out}}{\dot{m}}\right)_{\substack{int\\rev}} &= \int_3^2 T ds \\
\left(\frac{\dot{Q}_{out}}{\dot{m}}\right)_{\substack{int\\rev}} &= T_{out}(s_{2s} - s_3) \\
\left(\frac{\dot{Q}_{out}}{\dot{m}}\right)_{\substack{int\\rev}} &= T_{out}(s_1 - s_{4s})
\end{aligned}
\tag{4.9}
$$

T_{out} refers to the temperature on the steam side of the condenser. Now these two equations may be put in to the formula for efficiency[12]:

$$
\begin{aligned}
\eta_{ideal} &= \frac{\left(\frac{\dot{Q}_{in}}{\dot{m}}\right)_{\substack{int\\rev}} - \left(\frac{\dot{Q}_{out}}{\dot{m}}\right)_{\substack{int\\rev}}}{\left(\frac{\dot{Q}_{in}}{\dot{m}}\right)_{\substack{int\\rev}}} = 1 - \frac{\left(\frac{\dot{Q}_{out}}{\dot{m}}\right)_{\substack{int\\rev}}}{\left(\frac{\dot{Q}_{in}}{\dot{m}}\right)_{\substack{int\\rev}}} \\
\eta_{ideal} &= 1 - \frac{T_{out}(s_1 - s_{4s})}{\overline{T}_{in}(s_1 - s_{4s})} = 1 - \frac{T_{out}}{\overline{T}_{in}}
\end{aligned}
\tag{4.10}
$$

This result show that high inlet temperature of and low outlet temperature will give high thermal efficiency[12].

The greater the area of the cycle loop in figure 4.2, the greater work is being done. This implies that increasing the boiler pressure and/or decreasing the condenser pressure will increase the thermal efficiency. The condenser pressure is limited by the saturation pressure corresponding to the ambient temperature, leaving an increase in the boiler pressure as the only practical option to get an increase in the thermal efficiency. However, having a high pressure will require stronger materials and thus represent an increase in the construction costs[12].

4.3.4 Irreversibilities and Losses

The irreversible processes in a real rankine cycle are the ones including work. The isentropic processes are not entirely isentropic due to some change in entropy, as illustrated in figure 4.2. In order to deal with this efficiencies are introduce for the pump and for the turbine. The real turbine work will include an increase in entropy and reach point 2 instead of 2s, which is the ideal point. This introduce a turbine efficiency[12]:

$$\eta_t = \frac{\left(\frac{\dot{W}_t}{\dot{m}}\right)}{\left(\frac{\dot{W}_t}{\dot{m}}\right)_s} = \frac{h_1 - h_2}{h_1 - h_{2s}} \tag{4.11}$$

In a similar fashion the pump work leads to an increase in entropy and reach point 4 instead of 4s in figure 4.2. A pump efficiency may be introdued[12]:

$$\eta_p = \frac{\left(\frac{\dot{W}_p}{\dot{m}}\right)_s}{\left(\frac{\dot{W}_p}{\dot{m}}\right)} = \frac{h_{4s} - h_3}{h_4 - h_3} \tag{4.12}$$

Except for stray heat transfer in all the components other losses are related to external losses. This includes irreversibilities in the combustion process and heat loss in the heat exchangers[12].

4.4 Steam Turbine

A steam turbine uses steam as working fluid and the ideal thermodynamical cycle is the rankine cycle. There are three main type of steam turbines; back-pressure, condensing and extraction turbines. In condensing plants and extraction plants the efficiencies of the cycle is not at an acceptable level before reaching a size of respectively 29 MW_e and 5 MW_e. This is too large scale for MCF Yatta. This leaves the back-pressure plant for further elaboration, since this one exists from around 50 kW_e and upward[13].

Small scale turbines often require dry steam after the turbine, compared to large scale turbines where small droplets are acceptable. This will give a lower efficiency for a smaller turbine since partially condensed water have released more of its internal energy than dry steam[13].

Steam turbine systems consists of a boiler, the steam turbine, a condenser and a pump. The steam turbine unit is considered competitively priced per kW compared to other ways of generating power. The steam turbine system is considered quite expensive, and this is mainly due to the boiler unit. At MCF Yatta the charcoal production unit will work as a boiler and the additional cost of adding a steam coil will represent the cost of a boiler, which will be lower than installing a conventional boiler[22].

The charcoal production unit may deliver some variation in the quality of the heat and this is a potential risk of getting low quality steam with water droplets. If a steam turbine should be chosen as the power generation method it should be a steam expander that allows water droplets in the steam. A steam turbine with dry steam would require higher pressures and will not be an interesting option due to safety aspects with high pressures[13].

4.5 Steam Engine

The steam engine is a piston engine with the rankine cycle as the ideal cycle of the engine. It utilize the difference in steam energy with high pressure and temperature steam entering the piston and low pressure and temperature steam leaving the piston. Early steam engines used to be single stage, but today most engines are two stage engine. High pressure steam enters at one side to push the piston to the other side. When the piston has reached the other side high pressure steam enters there and push the piston back[13].

The range of electrical power output is typically from 25 kW_e to 1.5 MW_e. Mechanical efficiencies range from 6-10% for single stage engines, and 12-20% for multi stage engines. Boiler pressure may typically range from 0.6 to 6 MPa, and the condenser pressure is usually 2.5 MPa or lower. The efficiencies of a steam engine is equal or slightly better than for a steam turbine with equal steam properties[13].

Steam engines designed with old principles requires oil in the steam as a lubricant. These will need an oil separator and an active carbon filter placed before the boiler. High concentrations of oil may cause problems with heat exchange, due to poorer heat transfer capability of oil than steam. Even after separation there is too much oil in the water in order to use the water directly for other purposes. State of the art engines do not consume oil[13].

Water droplets in the outlet steam is acceptable, up to 12%. This makes the steam engine less sensitive regarding steam quality, in contrary to steam turbines that often require dry steam. The part load efficiency is often quite good for a steam engine, giving 90% of the maximum efficiency down to 50% of its nominal power. Both these factors make the steam engine require less of the boiler. For small scale operations, with fewer options of controlling the boiler and condenser environment, a steam engine will be preferred before a steam turbine[13].

4.5.1 Mike Brown Solutions 20hp Steam Engine

In order to demonstrate the thermodynamic properties of a steam engine using an existing engine will give a more realistic picture than with assumptions. Mike Brown Solutions offer a two piston double acting steam engine. At 1.4 MPa and 700 rpm it can deliver 15 kW mechanical output. The steam engine is oil consuming and 1 litre of oil is consumed per 50-60 hours[25].

4.6 Organic Rankine Cycle Turbine

An organic rankine cycle (ORC) turbine is based on the rankine cycle with a different working fluid than water. There is a wide range of working fluids available with a great variety in properties. This allows the turbine system to be designed to suit the conditions on site[27].

The reason for choosing an ORC turbine lies with the high efficiency at low temperatures and pressures. At high temperatures and pressure steam turbines are well suited. For small scale applications it is often not economically feasible and often unwanted from a security aspect to construct a system able to withstand the high pressures required for a regular steam turbine. This makes the ORC more suitable for small scale operations than the conventional steam turbine[27].

Figure 4.3 shows the different components of an ORC unit. However, this shows a rather sophisticated unit and the design may vary from the simplest design in figure 4.1 to this design. The necessary components are a feed pump, a heat exhanger for heat input, representing the preheater and the evaporator, a turbine and a condenser[27].

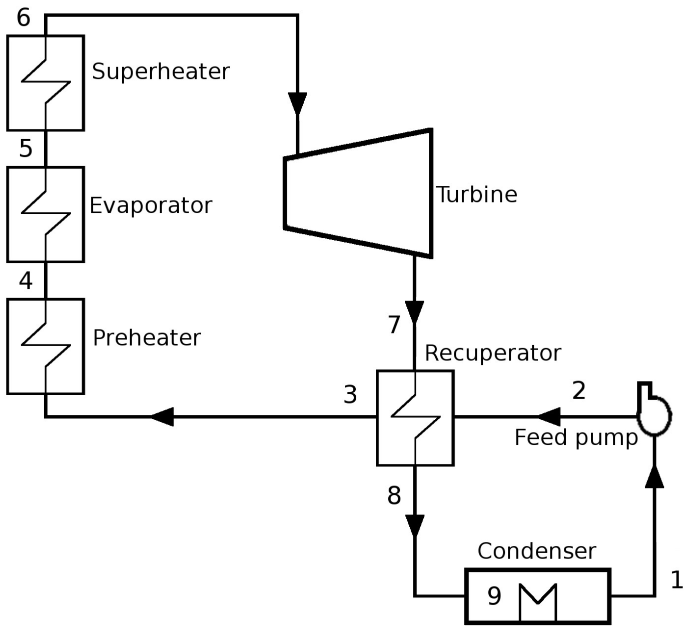

Figure 4.3: Principle scheme of an organic rankine cycle unit[27].

In choosing a working fluid, the following features are important[27]:

- Thermodynamic properties of the fluid
- Compatibility and stability with the materials in contact with the fluid
- Safety, health and environmental related to the fluid
- The cost and availability of the fluid

All these aspects are important and in order to give a valid comparison with the other technologies the thermodynamic properties will be the focus in this thesis. The other topics will be discussed to the extent they are relevant.

Many ORC applications are designed for waste heat recovery and the typical high temperature in the cycle is around 100 ℃. For biomass combustion the temperature may be higher than this and this will make it natural to use another working fluid for biomass than for waste heat recovery. Even though a combustion process may reach temperatures up to 700 ℃ the nature of the organic fluids limit the maximum temperature of the ORC to be approximately 300 ℃. The fluids would at higher temperatures become chemically unstable[27].

Biomass combustion is a process that varies a lot in power output and to even out these variations the working fluid is often coupled with the heat source through thermal oil. This enables also the heat exchanger to be operated at atmospheric pressure[27].

4.6.1 R134a as Working Fluid

Tetrafluoroethane, R134a, is a much used refrigerant, initially developed as a non-ozone-depleting refrigerant to replace chlorofluorocarbons. In addition to be a refrigerant with many purposes R134a may also be used as an ORC working fluid. Its low boiling point makes it suitable for low temperature waste heat recovery[28].

For normal operating conditions R134a is stable. For high temperatures it is not stable and it may decompose and form toxic compounds. Abraded aluminium and active metals should therefore be avoided in combination with R134a. At atmospheric pressure and ambient temperature R134a is not combustible, but with elevated pressures and in mixture with air the combustibility increases. Therefore, it is not advise to store R134a in combination with anything containing oxygen or oxides. Table 4.2 shows some general properties of the fluid[28].

Table 4.2: Physical and chemical properties of R134a[28].

Chemical formula	CH_2FCF_3
Freezing point	−96.6 ℃ at 0.1 MPa
Boiling point	−26.1 ℃ at 0.1 MPa
Flash point	None
Liquid density	1207.0kg/m^3 at 25 ℃
Liquid heat capacity	1.43 kJ/kgK
Critical temperature	101.06 ℃
Critical pressure	4.06 MPa℃

4.6.2 R245fa as Working Fluid

R245fa, or pentafluoropropane, is mainly used as a plastic foam insulation, but it may also be used as a working fluid in refrigeration cycles and for ORC system applications. It is a non-flammable, non-ozone depleting and colourless hydrofluorocarbon. The fluid is known as practically non-toxic, only minor effects are reported, such as mild inflammation of the heart. This is only on repeated exposure, and since the fluid is supposed to be in a closed cycle this is no big issue. Table 4.3 shows general properties of R245fa[29].

Table 4.3: Physical and chemical properties of R245fa[29].

Chemical formula	$CF_3CH_2CHF_2$
Freezing point	-107 ℃ at 0.1 MPa
Boiling point	15.3 ℃ at 0.1 MPa
Flash point	None
pH	Neutral
Specific gravity	1.32 at 20 ℃
Liquid heat capacity	1.36 kJ/kgK

R245fa is often preferred in new ORC applications where it was common to use R134a earlier. According to Honeywell[29], a manufacturer of R245fa, it "has the most favorable properties for low temperature heat recovery systems". It is considered to be stable in thermal and hydrolytic terms. However, the stability may be influenced when in contant with metals, air, moisture or a lubricant[29].

4.6.3 Biomass Working Fluids

A study of around 700 compounds found suitable for biomass ORC applications has been performed by Drescher and Brüggemann[27]. They presented the five most suitable options which is presented in table 4.4. These compounds are all highly flammable which introduce a new safety aspect compared to the previous compounds described. All have quite high condenser temperatures as they are designed to deliver heat in addition to power[27].

Drescher and Brüggemann found that "biomass plants operating with a maximum process temperature of [300℃], a maximum pressure between 0.9 and 1.5 MPa is best. The family of alkylbenzenes shows highest efficiencies"[27]. They also found a 2.5% increase in effieciency when they raised the maximum temperature from 300 ℃ to 350 ℃[27].

Table 4.4: Parameters of selected biomass working fluids[27].

Working fluid	T_{max}(℃)	p_{max}(MPa)	T_{con}(℃)	p_{con}(kPa)	**Thermal efficiency**(%)
OMTS	287	1.34	90	13.8	22.5
Toluene	263	2.00	90	54.1	23.2
Ethylbenzene	297	2.00	90	24.3	24.3
Propylbenzene	300	1.41	90	11.4	24.9
Butylbenzene	300	0.92	91	5.0	25.3

4.6.4 Honeywell - R245fa Parameters

Honeywell is a manufacturer of refrigerants, among others they produce R134a and R245fa. In their brochure "working fluids ORC systems"[29] they state parameters where R245fa is used as working fluid in an ORC turbine. The parameters are[29]:

- High pressure: 2.8 MPa
- Boiler temperature: 150℃
- Condenser temperature: 45℃
- Turbine efficiency: 0.85
- Pump efficiency: 0.75

4.6.5 Infinity Turbine - ORC Turbine Manufacturer

Infinity Turbine LLC, located in the United States of America, is a company specialized in small scale ORC units ranging from 600 W - 1 MW electric output. Thermal oil, water or glycol solutions is used to utilize the heat and the temperature range is from 80-130 ℃. Infinity Turbine use either compressed air, R134a or R245fa as working fluid, with the latter the most common in new installations. In addition they have started developing systems using the brayton cycle with CO_2 as working fluid, which at the moment is at the experimental stage[30].

For the evaporator Infinity Turbine report an expected 15-20 ℃ temperature decrease in the thermal oil in the boiler. For the condenser a 5-10 ℃ increase in the condenser water is expected. The turbines are tested for pressures up to 2 MPa. The systems are delivered with a direct current generator, running at 5000-20000 rpm, and an inverter to convert the power to alternating current. In USA, the turbines are considered economically viable if the heat is at free cost, in the sense that the heat is a waste product from another process[30].

Test Parameters of the IT50

The 50kWe unit from Infinity Turbine, IT50, filled with R134a as working fluid, was tested with the following parameters[30]:

- High pressure: 0.9 MPa
- Turbine inlet temperature: 83 ℃
- Low pressure: 0.5 MPa
- Turbine outlet temperature: 17 ℃

5. Method

This thesis being part of a project in Kenya a visit to the local organization was natural in conducting the necessary data mapping. This has been a central part in getting the information and background for the thesis. Apart from the field study the information relevant for this thesis is retrieved through scientific articles, books and internet pages.

5.1 Field Study in Kenya

The stay in Kenya lasted four weeks and the main objectives was to:

- Get to know MCF as organization
- Learn general practises and routines of how things work in Kenya
- Map the forest biomass resources
- Map the energy needs of MCF Yatta
- Discuss ideas with key people from MCF and NCA.
- Get an idea of what is realistic to achieve in terms of technology, economy and human resources.

The first week consisted mainly of getting to know the people and the sites. NCA in Kenya is running the project and it was natural to begin with a meeting there, before heading to MCF. The base of the field study was at MCF Ndalani with frequent trips to MCF Yatta. The remaining weeks were used to data mapping.

The data mapping of energy needs and biomass resources were accomplished by data collection and estimation based on the data collection. Different types of data being used:

- Electricity bills
- Fuel usage logs
- Tree planting logs
- Maps
- Satellite pictures

Additional data was supplied through discussions with key people at MCF Yatta.

During the field study there were several meetings. Most of the meetings were used to get answers to factual questions. Some meetings were used to discuss the focus of the project and our topics. A seminar was arranged where we presented our preliminary findings and thought. After each presentation key people from MCF and NCA shared their thoughts and asked questions.

Working in a different culture may lead to some complications. Things were more time consuming than expected and this was mainly due to cultural differences. For instance, reading power measurements from the power meters in order to construct figure 2.5, was initially planned to be done more than once. The power meter readings were supposed to be done by some workers at MCF Yatta, but they misinterpreted us and too few readings were done. We ended up doing the readings ourselves and there was too little time to do more than one day with readings. Ideally, a few more days with readings would give a better figure and a day without a blackout would also be preferable. However, figure 2.6 gives a representable picture of how a normal day at MCF Yatta looks like in terms of power consumption and we did not prioritize to spend another day doing readings.

5.1.1 Area Estimation of MCF Yatta and MCF Ndalani

In order to determine the biomass potential, estimates for areas suitable for forest growing have been established. Measuring different sections of MCF Yatta and MCF Ndalani on satellite images and topographical maps have made it possible to estimate the areas used in section 2.1.2. The agroforestry is practised with different tree densities in the different fields. As a simplification, the agroforestry area of Yatta has been used to represent all the agroforestry. In this area the number of rows of trees and the distance between the trees was estimated and this is the basis for the 100 trees per hectare given in section 2.1.2.

5.2 Tree Planting Mixture

At MCF Yatta some forest is planted and large areas will be planted in the years to come. The biomass potential estimate is based on the maximum potential when all the planned forests are fully grown.

From records of tree plantings in recent years, a mixture of different trees planted was established. Some of these trees have been planted for agricultural purposes, for instance papaya, and some, like kei apple, have been planted to be used as a hedge. Such trees were natural to exclude from the forest biomass potential. After excluding those trees a mixture of suitable trees showed that two species, grevillea and senna were represented more than the other species. Grevillea represented 60% of the forest trees while senna represented 13%. 7 other species had also been planted that could be considered forest trees, with a representation of 6% and lower.

The two most dominant tree species are chosen to represent the biomass potential. Given their respective fractions it was assumed a mixture where 80% of the planted trees is grevillea and the remaining 20% is senna.

5.3 The Charcoal Production Unit

In chapter 3 and in chapter 4 a range of technologies are described. The purpose of these chapters is to narrow down the number of technologies and describe these. Only technologies that are considered feasible in a sustainable and practical sense for MCF are described in detail.

The charcoal production chapter consists of one part describing how charcoal is made and the different qualities of charcoal. This is meant to give a better understanding of the second part where different ways of producing charcoal are described. By considering sustainability, efficiencies, practical issues with the concept and to what extent the technology is combinable with heat utilization the different concepts are described in detail if they are found suitable.

5.3.1 Charcoal Potential

The charcoal potential in section 6.1 is based on the Pressvess retort. This retort is considered the most suitable design for MCF Yatta.

For operation time two values are chosen. 100% operation time is chosen to illustrate the maximum potential. However, all such units do have some maintenance time and some days where running is not possible and 100% operation time is not a realistic value. Real operation time values for the Pressvess twin retort is not stated by the manufacturer and the value may vary from year to year. 90% operation time is chosen to represent a realastic operation time.

5.4 Thermal Power Generation Unit

In order to be able to determine which power generation technology is most suitable to combine with charcoal production, thermal efficiencies of different working fluids under different conditions were determined. During the thermal power generation chapter the number of working fluids was narrowed down to include only those considered feasible. The main constraints in a thermal efficiency is pressure and temperature and their lower and higher values.

In order to compare the different technologies thermal efficiency may be an appropriate selection factor. At least it is a selection factor suitable for discussion and then comparing it to other factors such as economy and safety. The different calculations on different working fluids are based on real parameters given from manufacturers. There may exists parameters that will give higher thermal efficiencies for the working fluid, but in this thesis it is considered best to stick to the real values.

Thermodynamic properties tables from Moran et. al[12] have been used to determine the properties of steam. Properties of R134a and R245fa were retrieved from NIST Chemistry Web Book. The selected working fluids for biomass ORC thermal efficiencies were stated in Drescher and Brüggemann[27] under conditions suitable for this thesis and the discussion is based on these calculations.

5.4.1 NIST Chemistry Web Book

National Institute of Standards and Technology Chemistry Web book is a public database with thermodynamical and chemical properties of a wide range of reference data available.

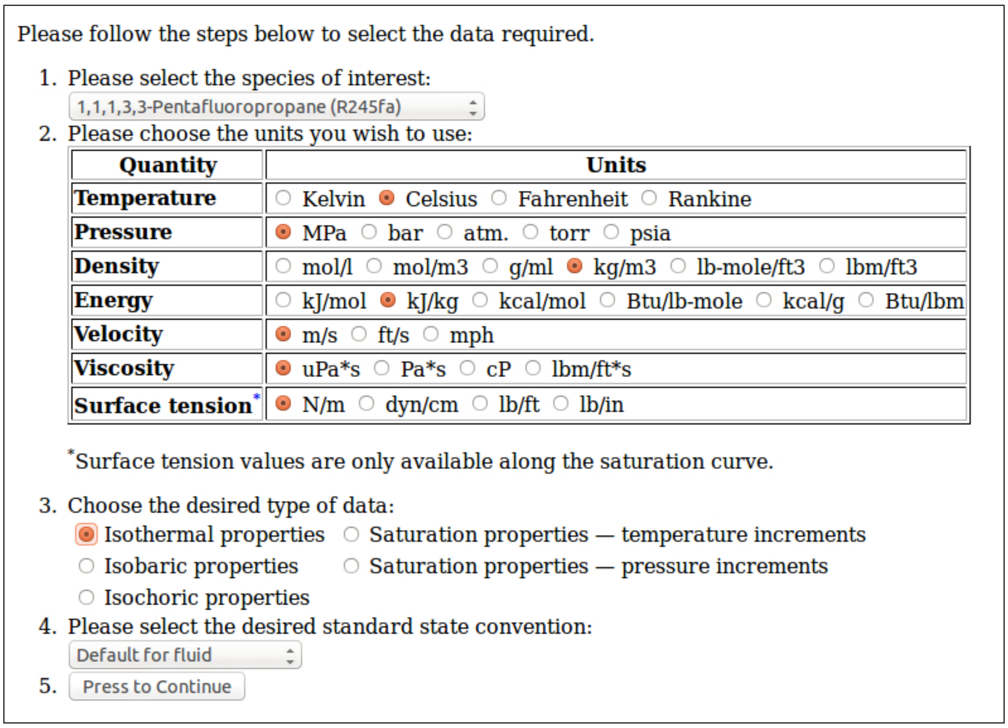

Figure 5.1: NIST Chemistry Web Book first page[31].

The first page of NIST Chemistry Web Book is shown in figure 5.1. Fluid, units and the desired type of data are chosen. After entering temperature and pressure at the next step, a graph and a table with properties are presented. These are the properties used in the calculations.

The properties of the steps from section 4.3.1 were found by the following method:

Stage 1 Temperature and pressure was given and both isothermal and isobaric properties may be used to get the enthalpy and entropy.

Stage 2s Temperature was given and with an isentropic process in the turbine the entropy should match the entropy of stage 1. Isothermal properties were chosen as "desired type of data" and the pressure matching the entropy and temperature was found.

Stage 3 ”Saturation properties - temperature increments” was chosen for the low temperature to find the corresponding specific volume for saturated liquid.

5.4.2 Water as Working Fluid

Both steam turbines and steam engines use water as a working fluid. With reference to the reasoning in section 4.4 the steam turbine should be able to accept the same quality steam as the steam engine. Then the thermodynamic calculations will be similar and the steam engine parameters will be used to represent both technologies.

The lower and higher temperature was not given in the parameters from Mike Brown Solutions. A lower temperature of 45 ℃ was chosen. This is the same lower temperature as for R245fa and the water is still warm enough to be utilized as tap water at this temperature.

With water as working fluid a high pressure value from Mike Brown Solutions[25] and a high pressure value from Infinity Turbine[30] were tested. A vapour quality check was conducted in order to figure out which high temperatures that would give an acceptable vapour quality at the given pressure of 1.4 MPa. A higher pressure of 2 MPa was also tested in order to see if increasing the pressure to the same level as the other working fluids would be beneficial. From theory it was given an acceptance up to 12% waters droplets in steam engine steam.

The vapour quality check revealed that temperatures below 400 ℃ for 1.4 MPa and below 440 ℃ for 2 MPa gave insufficient vapor qualities. Taking into account the temperature of the retort being held at 600 ℃, it was chosen to test 400 ℃ and 500 ℃ for 1.4 MPa as high pressure and 440 ℃ and 500 ℃ for 2 MPa as high pressure.

6. Results

6.1 Industrial Charcoal Production

An externally heated twin retort offers a design which is relatively easy to operate and to obtain a high yield of good quality charcoal. The external combustion chamber may be operated with a range of fuels and it is well suited for biomass. Internally heated charcoal kilns, retorts or earth pits are much more difficult to operate in a manner that gives a high yield and high quality of the charcoal. Implementation of a heat exchanger for heat utilization is easier with an externally heated unit with a combustion chamber, and it will not affect the charcoal production process[20, 11].

For these reasons the Pressvess charcoal twin retort is chosen and will be used to demonstrate the potential of charcoal production and heat utilization at MCF Yatta. The original design of the Pressvess retort is a batch process. The long period of cooling makes the Pressvess retort unsuitable for electricity generation. In order to deal with this matter the following designs will be assessed:

- One Pressvess twin retort run as batch process
- Two Pressvess twin retort, giving four charge cylinders. Running as batch processes in counter phase to enable high quality heat utilization
- One modified Pressvess twin retort, with interchangeable charge cylinders, running as a semi continuous process.

6.1.1 Charcoal Produced per Batch

The potential estimates are based on 20% MC, which is naturally dried, and 7% MC. The following assumptions are made in order to conduct the estimate:

- One batch takes 24 hours, including loading, firing, cooking, cooling and unloading
- 90% operational time
- 50% solid mass percentage (SM%) when a charge cylinder is filled
- High quality charcoal produced, thus giving a high calorific value

Equation 6.1 implies that 480 kg of biomass is required for every filling per charge cylinder.

See appendix A for detailed estimation of the retort input and the charcoal output.

$$\begin{aligned}
m_{\text{charge cylinder}} &= \text{Volume}_{\text{charge cylinder}} * \text{Density}_{\text{tree mixture}} * \ \text{SM}(\%) \\
m_{\text{charge cylinder}} &= 1.5 \text{ m}^3 * 640 \text{ kg/m}^3 * 0.50 \\
m_{\text{charge cylinder}} &= 480 \text{ kg}
\end{aligned} \tag{6.1}$$

Table 6.1 shows the potential of one batch of the Pressvess twin retort.

Table 6.1: Charcoal potential per batch for one Pressvess twin retort[20].

	7% MC		**20% MC**	
	w.b	d.b.	w.b.	d.b.
Charge cylinder input (kg) (2 * 480 kg)	960	890	960	770
Combustion chamber input (kg)	200	190	240	190
Total input (kg)	1160	1080	1200	960
Charcoal output (kg)	430		300	
Yield (%)	0.37		0.25	

6.1.2 Annual Potential From One Twin Retort

The annual potential from one Pressvess twin retort in terms of tonnage and energy is given in table 6.2.

Table 6.2: Annual potential for one Pressvess twin retort in terms of energy and tonnage[20].

	7% MC		**20% MC**	
Operation time (%)	100	90	100	90
Biomass consumption (ton)	350	315	350	315
Biomass dry matter consumption (ton)	330	290	280	250
Charcoal production (ton)	160	140	110	100
Biomass energy input (MWh)	1720	1550	1450	1300
Charcoal production (MWh)	1010	910	700	630
Heat generated (MWh)	710	640	750	670

6.1.3 Annual Potential From Two Twin Retorts

Running two equal retorts as in the previous section. Same assumptions as for one twin retort. Running with two units instead of one will give the double amounts but if they are run in counter phase the heat will be more evenly distributed. The annual potential from two Pressvess twin retorts in terms of tonnage and energy is given in table 6.3.

Table 6.3: Annual potential for two Pressvess twin retorts in terms of energy and tonnage[20].

	7% MC		20% MC	
Operation time (%)	100	90	100	90
Biomass consumption (ton)	700	630	700	630
Biomass dry matter consumption (ton)	650	590	560	500
Charcoal production (ton)	320	280	220	200
Biomass energy input (MWh)	3440	3090	2890	2600
Charcoal production (MWh)	2020	1820	1400	1260
Heat generated (MWh)	1420	1270	1490	1340

6.1.4 Annual Potential From Modified Continuous Design

Modifying the design will give much more constant heat generation. Assuming 10 hour between replacing charge cyliners will give 2.4 batches per day. The annual charcoal potential and total heat generation will from the modified continuous design is given in table 6.4.

Table 6.4: Annual potential for the modified continuous design[20].

	7% MC		20% MC	
Operation time (%)	100	90	100	90
Biomass consumption (ton)	840	760	840	760
Biomass dry matter consumption (ton)	780	700	670	610
Charcoal production (ton)	380	340	260	240
Biomass energy input (MWh)	4130	3710	3470	3120
Charcoal production (MWh)	2420	2180	1680	1510
Heat generated (MWh)	1710	1530	1790	1610

6.2 Heat Loss From Charcoal Production

6.2.1 Heat Loss Per Batch

In order to be able to say how much heat is available for power generation an estimate of the heat losses from the Pressvess twin retort unit will be useful. In section 3.5.2 the heat loss from one Pressvess twin retort during cooking is calculated to be 27 kW.

The cooking period of the Pressvess twin retort is from 8-10 hours and 10 hours is used for this estimate. Loading and unloading will take two hours and with 24 hours between every batch this leaves 12 hours of cooling.

The following assumptions are made to conduct the estimate for heat loss during cooling

- The ambient temperature is the average temperature of 25 ℃.
- The temperature of the unit is 600 ℃ when the cooking is finished.
- The temperature of the unit is 40 ℃ when cooling is finished.

The temperature difference between the retort and the a decrease exponentially:

$$\Delta T(t) = \Delta T_0 * e^{-(t/\tau)} \tag{6.2}$$

ΔT_0 is the initial temperature difference,
t is the time in hours,
τ is the rate of temperature decrease, given in hours.

The temperature of the unit is 40 ℃, a temperature difference of 15 ℃, after 12 hours of cooling. This may be used to determine the decrease rate, τ, by inserting in equation 6.2.

$$\begin{aligned}
&\Delta T_1 = \Delta T_0 * e^{-(t_1/\tau)} \\
&\frac{\Delta T_1}{\Delta T_0} = e^{-(t_1/\tau)} \\
&\ln\left(\frac{\Delta T_1}{\Delta T_0}\right) = \ln\left(e^{-(t_1/\tau)}\right) \\
&\ln\left(\frac{\Delta T_1}{\Delta T_0}\right) = \frac{-t_1}{\tau} \\
&\tau = \frac{-t_1}{\ln\left(\frac{\Delta T_1}{\Delta T_0}\right)} = \frac{-12\ \text{h}}{\ln\left(\frac{15\ \text{K}}{575\ \text{K}}\right)} \\
&\tau = 3.3\ \text{h}
\end{aligned} \tag{6.3}$$

The heat loss rate will decrease with a decrease in temperature. For this estimate it will be sufficient to assume that the heat loss rate is proportional the temperature decrease rate. This will give a heat loss rate as a function of time.

$$\begin{aligned} \Delta P(t) &= \Delta P_0 * e^{-(t/\tau)} \\ \Delta P(t) &= 27 \text{ kW} * e^{-(t/3.3h)} \end{aligned} \tag{6.4}$$

Equation 6.4 is presented in figure 6.1 showing how the heat loss rate decreases with time. The heat loss rate decreases rapidly in the beginning and towards the end of the cooling period the heat loss is small.

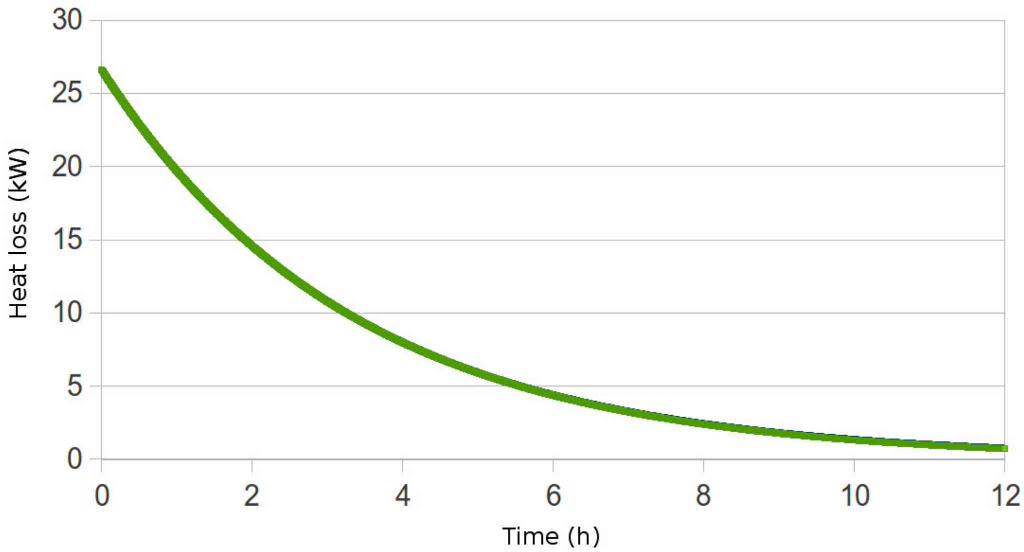

Figure 6.1: Heat loss rate as a function of time.

The total heat loss per batch of the Pressvess twin retort will be the integral of equation 6.4.

$$\begin{aligned} Q &= \int_{0h}^{12h} P(t)dt = \int_{0h}^{12h} 27 \text{ kW} * e^{-(t/3.3h)}dt \\ Q &= \left[27 \text{ kW} * (-3.3 \text{ h}) * e^{-(t/3.3h)}\right]_{0h}^{12h} \\ Q &= 27 \text{ kW} * (-3.3 \text{ h}) \left[e^{-(12h/3.3h)} - e^{-(0h/3.3h)}\right] \\ Q &= 27 \text{ kW} * (-3.3 \text{ h})(0.026 - 1) \\ Q &= 87 \text{ kWh} \end{aligned} \tag{6.5}$$

The total heat loss per batch may now be calculated:

$$\begin{aligned} Q_{batch} &= Q_{running} + Q_{cooling} \\ Q_{batch} &= P_{running} * t_{running} + Q_{cooling} \\ Q_{batch} &= 27 \text{ kW} * 10 \text{ h} + 87 \text{ kWh} \\ Q_{batch} &= 357 \text{ kWh} \end{aligned} \tag{6.6}$$

With one twin retort the daily heat loss will be the same as Q_{batch}. With two twin retorts it will be the double. The modified continuous will have a high temperature the whole period it is running and the daily loss will be:

$$Q_{modifiedcontinuous,daily} = P_{running} * t_{running} = 27 \text{ kW} * 24 \text{ h} = 648 \text{ kWh} \tag{6.7}$$

6.2.2 Heat Available for Utilization

The following table summarizes how much heat annually lost and annual heat available for other utilization for the different designs.

Table 6.5: Annual heat loss and accessible heat[20].

	One batch		Two batch		Continuous	
Operation time (%)	100	90	100	90	100	90
Heat loss (MWh)	130	120	260	230	240	210
Excess heat 7% MC (MWh)	580	520	1160	1040	1470	1320
Excess heat 20% MC (MWh)	620	550	1230	1110	1550	1400

6.3 Thermal Efficiency Calculations of the Different Working Fluids

The different thermal efficiencies for different working fluids are presented in this section. In table 6.6 thermal efficiencies for R134a, R245fa and steam based on parameters given from manufacturers in chapter 4 are given. Reasoning and calculations for values of entropy, vapour quality and enthalpy may be found in Appendix C.

Table 6.6: Properties of different working fluid, showing high and low pressure, high and low temperature and corresponding thermal efficiency[12, 30, 25].

	High pressure (MPa)	**High temperature (°C)**	**Low pressure (MPa)**	**Low temperature (°C)**	**Thermal efficiency (%)**	
					Ideal	**Real**
R134a	0.9	83	0.5	17 (55)	10.9	9.1
R245fa	2.8	150	0.08	45	26.5	22.2
Steam	1.4	400	0.01	45	30.8	26.2
Steam	1.4	500	0.01	45	32.5	27.6
Steam	2.0	440	0.01	45	33.1	28.1
Steam	2.0	500	0.01	45	34.0	28.9

In table 6.7 the real thermal efficiencies for all the suitable working fluids are summarized, including efficiencies presented in table 4.4 and in table 6.6.

Table 6.7: Thermal efficiencies of the different working fluids[12, 25, 30, 27].

Working fluid	Thermal efficiency (%)
R134a	9.1
R245fa	22.2
Steam - 1.4 MPa, 400 °C	26.1
Steam - 1.4 MPa, 500 °C	27.5
Steam - 2 MPa, 440 °C	28.1
Steam - 2 MPa, 500 °C	28.9
OMTS	22.5
Toluene	23.2
Ethylbenzene	24.3
Propylbenzene	24.9
Butylbenzene	25.3

6.4 Power Generation

The one batch design is not suitable for power generation, but the two batch design and the modified continuous design may produce heat suited for generating power. Assumptions made in this calculation:

- 90% operation time of the system
- 90% efficiency of the generator
- 7% MC in the biomass used in the charcoal production
- Negligible heat loss in heat exchangers

The annual electrical energy production will be:

$$\begin{aligned}&E_e = Q_{generated} * \eta_{thermal} * \eta_{generator}\\&\text{where,}\\&Q_{generated} - \text{Heat available from charcoal production}\\&\eta_{thermal} - \text{Thermal efficiency}\\&\eta_{generator} - \text{Generator efficiency}\end{aligned} \tag{6.8}$$

The average electrical power delivered will be:

$$P_{e,average} = \frac{E_e}{\text{Operation time} * \text{Hours in a year}} \tag{6.9}$$

To illustrate this, a turbine filled with R245fa generated from a two batch design the annual electrical energy production will be:

$$E_{R245fa,twobatch} = 1320\ \text{MWh} * 22.2\% * 90\% = 260\ \text{MWh} \tag{6.10}$$

The average electrical power will be:

$$P_{R245fa,twobatch} = \frac{260\ \text{MWh}}{90\% * 8760\ \text{h}} = 33\ \text{kW} \tag{6.11}$$

Similar calculations are done for all the selected working fluid for two batch design and modified continuous design. The results are presented in table 6.8.

Table 6.8: Maximum electrical power output for different working fluids[12, 25, 30, 27].

	Two batch design		**Modified continuous**	
	Annual (MWh)	Average (kW)	Annual (MWh)	Average (kW)
R134a	90	11	110	14
R245fa	210	27	260	33
Steam - 1.4 MPa, 400 ℃	250	32	310	39
Steam - 1.4 MPa, 500 ℃	260	33	330	42
Steam - 2 MPa, 440 ℃	260	33	330	42
Steam - 2 MPa, 500 ℃	270	34	340	43
OMTS	210	27	270	34
Toluene	220	28	280	36
Ethylbenzene	230	29	290	37
Propylbenzene	230	29	300	38
Butylbenzene	240	30	300	38

7. Discussion

7.1 Biomass Utilization

MCF will in a few years time have a large forest biomass resource. The main purpose for MCF is to change the local climate to improve living conditions. Since the trees are worth more to them alive than chopped down a sustainable harvest comes natural to them. The harvested forest will primarily be used to cover the internal needs and the excess will be sold to generate income for MCF[6].

The different options for biomass utilization at MCF Yatta is timber, firewood, charcoal and heat for power generation or other purposes. Timber should be given priority to the extent it is necessary and possible. Grevillea is a good tree type for timber production. This will probably not be a major part of the forest resource and it is estimated from MCF key people that 10% of the resource will be used as timber[6, 5].

Both firewood and charcoal is primarily used for food preparation in Kenya. With charcoal, the overall efficiency will increase and there are fewer health issues related to charcoal. There is less smoke and the smoke contains fewer contagious components. The benefits of charcoal compared to firewood are so clear that a charcoal production unit should be established instead of selling firewood[1, 6].

Using forests for heating purposes is a common option worldwide, but in this region of Kenya, the temperature only occasionally is so low that heating of buildings is needed and establishing a system for heating buildings is not necessary. There is a demand for hot showers and this may be delivered as a waste heat product from either power generation or charcoal production.

Power generation from biomass is a feasible option. Considering the average electrical power consumption throughout the year, the size of the generator will not be bigger than what is combinable with utilizing the waste heat from charcoal production.

For these reasons a good option for utilizing the forest biomass resources would be an industrial charcoal production unit with heat recovery. The heat may be used for power generation and to heat tap water for showers.

7.2 Charcoal Production Method

There are many different designs when it comes to producing charcoal. The design chosen with enclosed twin retorts was chosen due to a range of reasons. The most important reason for choosing the externally heated retort is the high yield and high quality charcoal that relatively easily may be obtained. With internally heated charcoal production there is a risk of burning some of the charcoal in the heating process and thus reducing the yield. The internally heated kiln are often large since a lot of charcoal is produced over a long period of time, and keeping the heating conditions similar in the whole kiln at all times is difficult. It requires a highly skilled and trained operator to maintain proper heating conditions and to get a high yield[18, 11].

With external heating the combustion may be kept under proper conditions at all times and there will be less problems with unclean smoke. There is a minor difference in accessible heat whether 7% MC or 20%MC biomass is used, but there is a major increase in the amount of charcoal produced using 7% MC compared to using 20% MC biomass. Therefore, a biomass drying facility should be established so that the charcoal yield is maintained as high as possible[11].

The size of the selected twin retort does not require more than the expected biomass potential at MCF Yatta. In fact, since it does not even require half the potential it may be a good option to begin with one unit and then extend with another one when more of the total biomass potential is reached. Another option is to modify the design to include interchangeable charge cylinders when there is enough biomass.

The twin retort principle is easier to combine with heat recovery than a kiln. A kiln is much larger and keeps a lower temperature, while with the externally heated twin retort the heat is focused in the combustion chamber. The Pressvess Twin Retort, which is delivered with a steam coil, is excellent in combination with heat recovery[20, 18].

Another aspect with having a separate combustion chamber enables MCF Yatta to process a wide range of fuels. There are certain issues with how the municipal waste is treated at the site and certain types of this waste may be burned in the combustion chamber instead of being burned in open treatment pits combined with all sorts of waste.

7.3 Different Twin Retorts

The Pressvess twin retort is chosen as technology for the charcoal production. It is easy to operate and one twin retort will be able to utilize approximately 30% of the annual biomass potential. The unit is available for purchase, which somehow is rare for industrial charcoal production units. However, the Pressvess twin retort does not fully meet the ideal design, which more or less is the design of the Van Marion retort.

In order to deal with this, two alternative designs were suggested. One design, just having two of the Pressvess unit and run these to simulate a semi continuous design, and another design to modify the Pressvess retort to have interchangeable charge cylinders and thus making it semi continuous.

All of the different designs are believed to be able to deliver enough heat to meet the demand for hot water at MCF Yatta, even with loss in storage and with an increase in consumption. The hot water consumption is estimated to be between 45 MWh and 540 MWh.

7.3.1 Modified Continuous Retort

The ideal twin retort for heat recovery should have interchangeable charge cylinders. Then the cylinders would be taken out when cooking was over and let to cool instead of the whole unit having to cool down before a new batch could be started. Ideally, this finished cylinder could cool so that the air used to cool the cylinder was used as inlet air in the combustion chamber in the twin retort. In this way the cooling of the cylinder would work as preheating of the combustion process and reduce the need of excess heat.

The semi continuous design will be able to utilize almost 70% of the total biomass potential and it will have less heat loss per unit produced charcoal, compared to the other designs, since it does not need to cool the whole unit, only the charge cylinder, when the cooking is finished.

The greatest concern with the semi continuous design is that it is not in the portfolio of the Pressvess company. Even if the design is possible the cost of having a custom made design may be so high that another design should be considered.

7.3.2 Two Batch Design

The fact that the previous design is not available on the market may make it easier and cheaper to combine two Pressvess twin retort units and run these in counter phase and in this way simulate semi continuous. This will enable high temperature heat production during most of the running period. This design will be able to utilize almost 60% of the annual biomass potential.

No facility for treatment of charge cylinders will be required and a large production may be established without any great obstacles. If one unit should fail, then some production and heat generation may be maintained and there will not be necessary to have a backup unit to produce the required heat for hot showers.

7.4 Thermal storage as a Buffer

Having several units it may be wise to regulate it all with a thermal storage, principally shown in figure 7.1. This enables the possibility of having several charcoal production units without having to modify the design of the heat utilization and several heat consuming units may be connected. All the units are connected to the thermal storage with separate heat exchanger.

How a thermal storage should be constructed is an important task for further work, but in general terms it should consist of a thermal mass, for instance stone, that may withstand high

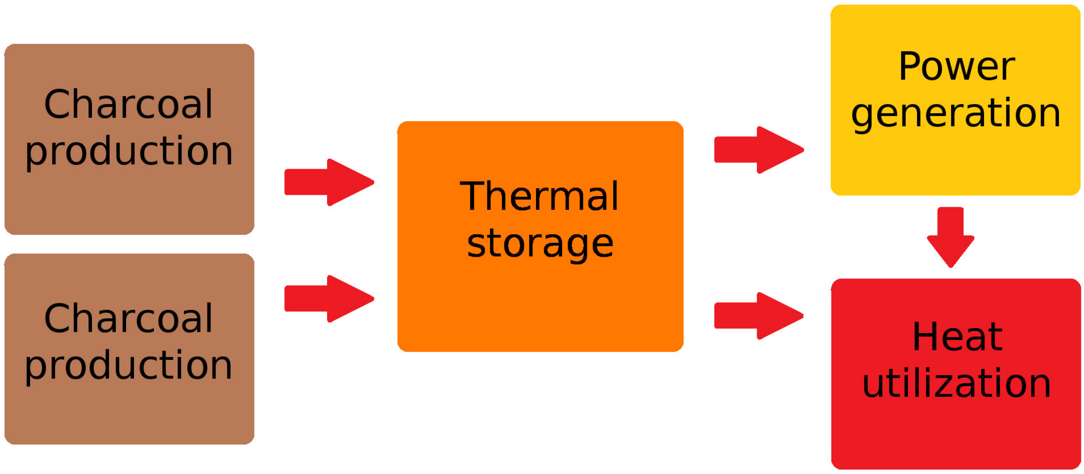

Figure 7.1: Proposed charcoal and power generation system.

temperatures without causing any issues with pressure, which water would have done. The outside should be covered with insulation to limit the heat loss from the storage.

The thermal storage will increase the flexibility of the total system. Minor stops in the charcoal production will then not affect power generation and with major stops in the charcoal production the storage will be able to serve tap water for showers a long time afterwards.

A thermal storage will give a more constant temperature output, but it will give a lower maximum temperature than if the power generation unit was directly coupled to the charcoal production unit. Keeping the thermal storage at a higher temperature will also give a higher heat loss.

7.5 Selection of Working Fluid for the Power Generation Unit

A thermal storage should be the basis for heat utilization and the lower temperature the better in order to reduce thermal losses from this unit. Therefore a balance between thermal efficiency and high temperature of the fluid should be the selection criteria. R134a has a significantly lower efficiency than the other fluids and this one should not be selected.

Steam as a working fluid gives the best thermal efficiencies, but steam operates at the highest temperatures. Additionally, if the temperature drop slightly the vapour quality will be less than 88% and this may damage the engine or turbine.

With a thermal storage installed the safety issues related to the flammability of the biomass working fluid in section 4.6.3 will have less relevance. The biomass working fluids operate at a temperature around 300 ℃ which will reduce the losses from the thermal storage significantly compared to using steam.

R245fa maintains an efficiency of 22.5%. This is the same efficiency as the OMTS and almost as good as toluene and the different benzenes. The R245fa requires an upper temperature of 150 ℃ and this will give less than half the heat losses in the thermal storage compared to using one of the biomass working fluids. For those reasons R245fa will be the preferable working fluid.

Using R245fa an average power of respectively 27 kW$_e$ or 33 kW$_e$ may be obtained if two batch design or modified continuous design is chosen. This is close to the 30 kW$_e$ average consumption of MCF Yatta.

8. Conclusion

Industrial charcoal production will be a good way of utilizing the biomass potential at MCF Yatta and MCF Ndalani. There will be a few years time before the biomass potential is fully established and it may be wise to invest in one Pressvess twin retort, or similar design, to begin with. Using biomass with 7% MC this will annualy give 140 ton of charcoal and 520 MWh of excess heat available for other purposes. The excess heat could be used to provide hot showers and to dry the biomass. A thermal storage should be built to maintain a flexibility in the charcoal production and the heat utilization.

When the biomass potential is fully established the facility may be expanded to a semi continuous process. If it is possible to modify the design to semi continuous by having interchangeable retorts this is a good way of getting constant quality heat. The potential for the modified continuous design is annually 340 ton charcoal and 1320 MWh of accessible heat. If modification of the design is not possible having two Pressvess retorts will be a good substitute. If these are run in counter phase combined with a thermal storage relatively constant heat generation may be obtained. The two batch design may annually produce 280 ton of charcoal and generate 1040 MWh of accessible heat.

Implementing a semi continuous design combined with a thermal storage will be a good way of getting heat to supply an ORC turbine, with R245fa as working fluid. The condenser temperature of the ORC turbine will be 45 ℃ and this will be a temperature sufficient to supply the heat for hot showers. Depending on the design of the charcoal twin retort the ORC turbine may be able to supply 200 MWh electricity annually with an average of 27 kW_e with two batch design or 260 MWh electricity annually with an average of 33 kW_e with a modified continuous design. This is close to the average electrical consumption of MCF Yatta at 30 kW_e.

Beginning with one Pressvess twin retort before the forest is fully established will be a good way of reducing economic risk. The construction costs will be spread out in time and the people of MCF Yatta will learn how to operate the charcoal retort. This will give a good understanding of the charcoal production and prepare them for the implementation of a semi continuous process. People of MCF Yatta will have the opportunity to send feedback to the manufacturer of the charcoal production unit. By the time the semi continuous production should be implemented, they will know how they want their power generation unit and have a good understanding of what size would be most suitable.

9. Further Work

In the work with the thesis a few factors give rise to some recommended further work. This thesis being part of a project involving other topics, the further work will only be relevant if it is decided that charcoal production should be implemented at MCF Yatta. If so, the implementation of the charcoal production and the power generation in the manner proposed in the conclusion will be a natural progression.

In order to get low enough MC in the forest biomass, a drying facility should be established. The details of this facility needs further investigation, which should include the size of the unit, the amount of heat needed and the time span for drying a batch of wood.

A thermal storage, as a buffer for the heat producing and heat consuming units, came up as an idea during the work of this thesis. This idea should be investigated further, with focus on the size of the storage, which material to use as storage, how much insulation and what temperature that should be the basis of the storage. What temperature is chosen will be of great relevance to how much heat loss there will be and to what working fluid should be used in the power generation.

In addition to this a more thorough examination of the scale of the power generation unit should be performed. In the project other sources of power generation will be evaluated, for instance from solar panels, which will generate power when there is sunlight. The power generation unit should be seen in context with other power generating units.

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Appendix A.

Grevillea Robusta Properties

The HCV for grevillea is given as 20.1 kJ/kg for sapwood and 20.7 kJ/kg for heartwood. Assuming 50% share of each the total HCV for grevilla will be 20.4 kJ/kg[7].

The annual growth of grevillea has been estimated based to be 7 ton per hectare. This estimate is based on the average annual growth the first four years from figures in Lott et al.[8], and an assumption that the annual growth the remaining years equal the growth the fourth year and that the tree will be cut after ten years. Table A.1 shows the assumed annual growth per year and an average total growth[8].

Table A.1: Annual growth for grevillea robusta[8].

Year after planting	**Annual growth (ton / ha)**
1	0
2	2
3	8.5
4	8.5
5	8.5
6	8.5
7	8.5
8	8.5
9	8.5
10	8.5
Average	7

Appendix B.

Charcoal Potential Calculation

B.1 Calorific Values

In section 2.1.3 the GCV for the biomass as given as a funtion of LCV. In table B.1 GCV for 7% MC and 20% MC are shown[12].

Table B.1: GCV for 7% MC and 20% MC for the given mixture of species[12].

Moisture content (%)	**Gross Calorific Value (kWh/kg)**
7	4.9
20	4.1

B.2 Density of the Tree Mixture

In literature a range of densities are given for the two tree types. The density of the tree mixture may be estimated with the following assumptions:

- The middle value of the stated range is used
- The density will vary with MC, but this is neglected in this estimate.

The density of grevillea range from 540-720 kg/m^3[7] with a middle value of 630 kg/m^3. The density of senna is 600-1010 kg/m^3[10] giving a middle value of 805 kg/m^3. The density of the tree mixture then becomes:

$$\begin{aligned}\text{Density}_{wood} &= \text{Density}_{grevillea} * \text{Share}_{grevillea} + \text{Density}_{senna} * \text{Share}_{senna} \\ \text{Density}_{wood} &= 630\ \text{kg/m}^3 * 94.5\% + 805\ \text{kg/m}^3 * 5.5\% = 640\ \text{kg/m}^3\end{aligned} \tag{B.1}$$

B.3 Combustion Chamber Input

In the information given from Pressvess[20] some data is given but not all in order to fully calculate the potential and some estimatation is needed. There are two given situations[20].

Table B.2: Charcoal batch information from Pressvess[20].

Type of biomass	Retort input	Retort output	Combustion chamber input
Pine, 7% MC	400 kg	180 kg	Not given
Pine, 20% MC	1 part	$\frac{1}{4}$ of total input	$\frac{1}{5}$ of total input

If a batch of 400 kg, 20% MC biomass is being put in the charge cylinders this will give 125 kg of charcoal and require 100 kg of 20% MC biomass as external heat. The energy in these 100 kg of additional heat is 416 kWh, based on the GCV from table B.1. Ignoring the difference in MC it may be assumed that the same amount of energy is required as external heat for the batch with 7% MC. Accounting for a higher calorific value in the 7% MC biomass, 84 kg will be required to give 416kWh[20].

Assuming that the mixture of biomass given at MCF Yatta will behave in the same manner as pine from the UK a table for use in MCF Yatta may be established:

Table B.3: Charcoal batch estimate for MCF Yatta[20].

	7 % MC	20 % MC
Total input fraction	1	1
Retort input fraction	0.83	0.8
Combustion chamber fraction	0.17	0.2
Total charcoal yield (%)	0.37	0.25

Appendix C.

Thermal Efficiencies Calculations

This appendix shows the enthalpies used for the thermal efficiency calculations and the reasoning for these. The values may have been interpolated.

All calculations are based on a turbine efficiency $\eta_t = 0.85$. The pump efficiency is $\eta_p = 0.85$, except for with R245fa where it is 0.75[30, 29].

C.1 R134a

The thermal efficiency calculation for R134a is based on the parameters given by Infinity Turbine in section 4.6.5. At stage 1, recalled from section 4.3.1, there is either saturated or superheated vapour. With a pressure of 0.9 MPa and temperature of 83 ℃ this gives an entropy $s_1 = 1.86$ kJ/(kgK). Ideally, there is an isentropic expansion in the turbine, and since the irreversibility of the turbine is covered in the efficiency, the calculation is done ideally. This gives an entropy of $s_{2s} = s_1 = 1.86$ kJ/(kgK). With a pressure of 0.4 MPa this corresponds to a temperature of 55 ℃[31]. This value will be used as the lower temperature, even though it does not correspond to the given temperature of 17 ℃[30].

With the knowledge of pressures, entropies and thus temperatures a table of relevant enthalpies may be formulated[12, 31].

Table C.1: Relevant enthalpies for R134a in order to calculate the thermal efficiency[12, 31].

Stage	State	Equation	P (MPa)	T (C)	h (kJ/kg)	h_f (kJ/kg)	h_{fg} (kJ/kg)	h_g (kJ/kg)
1	Superheated vapour		0.9	83	466.9			
2s	Superheated vapour		0.4	55	446.1	278.8	146.2	425.0
2	Superheated vapour	$h_2 = h_1 - \eta_t(h_1 - h_{2s})$	0.4	55	449.2			
3	Saturated liquid	$p_3 = p_2$ $\nu_3 = 0.93 * 10^3$ m^3/kg	0.4		278.8	278.8	146.2	425.0
4s	Saturated liquid	$h_4 = h_3 + \frac{\dot{W}_p}{\dot{m}} = h_3 + \nu_3(p_4 - p_3)$	0.9		279.2			
4	Saturated liquid	$h_4 = h_3 + \frac{1}{\eta_p}\nu_3(p_4 - p_3)$	0.9		279.3			

With all the enthalpies known the ideal and real thermal efficiency may be calculated with equation 4.7:

$$\begin{aligned}
\eta_{ideal} &= 1 - \frac{(h_{2s} - h_3)}{(h_1 - h_{4s})} = 1 - \frac{(446.1 - 278.8)}{(466.9 - 279.2)} = 10.9\% \\
\eta_{ideal} &= 1 - \frac{(h_2 - h_3)}{(h_1 - h_4)} = 1 - \frac{(449.2 - 278.8)}{(466.9 - 279.3)} = 9.2\%
\end{aligned} \tag{C.1}$$

C.2 R245fa

The thermal efficiency calculation for R245fa is based on the parameters given by Honeywell in their brochure[29]. A pressure of 2.8MPa and a temperature of 150 ℃ gives an entropy $s_1 = 1.85$ kJ/(kgK). This gives an entropy of $s_{2s} = s_1 = 1.85$ kJ/(kgK). With a temperature of 45 ℃ this corresponds to a pressure of 0.08MPa[29, 31].

With the knowledge of pressures, entropies and temperatures a table of relevant enthalpies may be formulated[12, 31].

Table C.2: Relevant enthalpies for R245fa with parameteres given from the Honeywell brochure[29, 31].

Stage	State	Equation	P (MPa)	T (C)	h (kJ/kg)	h_f (kJ/kg)	h_{fg} (kJ/kg)	h_g (kJ/kg)
1	Superheated vapour		2.8	150	512.1			
2s	Superheated vapour		0.08	45	443.6	259.9	160.8	420.7
2	Superheated vapour	$h_2 = h_1 - \eta_t(h_1 - h_{2s})$	0.08	45	453.9			
3	Saturated liquid	$p_3 = p_2$ $\nu_3 = 0.78 * 10^3$ m^3/kg	0.08		259.9	259.9	160.8	420.7
4s	Saturated liquid	$h_4 = h_3 + \frac{\dot{W}_p}{\dot{m}} = h_3 + \nu_3(p_4 - p_3)$	2.8		262.0			
4	Saturated liquid	$h_4 = h_3 + \frac{1}{\eta_p}\nu_3(p_4 - p_3)$	2.8		262.7			

With all the enthalpies known the ideal and real thermal efficiency may be calculated with equation 4.7:

$$\begin{aligned} \eta_{ideal} &= 1 - \frac{(h_{2s} - h_3)}{(h_1 - h_{4s})} = 1 - \frac{(443.6 - 259.9)}{(512.1 - 262.0)} = 26.5\% \\ \eta_{ideal} &= 1 - \frac{(h_2 - h_3)}{(h_1 - h_4)} = 1 - \frac{(453.9 - 259.9)}{(512.1 - 262.7)} = 22.2\% \end{aligned} \tag{C.2}$$

C.3 Water

The thermal efficiency calculations are based on the parameters given by Mike Brown Solutions in section 4.5.1 and on the high pressure parameter from Infinity Turbine in section 4.6.5.

C.3.1 Vapour Quality Check

Vapour quality above 88% is required in order to use the steam in a steam engine. All vapour qualities are calculated with reference to 45 ℃ and its saturated pressure. The vapour quality is given in equation 4.2 and in this case it will be[12]:

$$x = \frac{s - s_f}{s_g - s_f} = \frac{s_{superheated} - s_{f,45^\circ C}}{s_{g,45^\circ C} - s_{f,45^\circ C}} \tag{C.3}$$

All states in table C.3 is superheated steam except for the one at 45 ℃ which is saturated liquid.

Table C.3: Vapour qualities for selected properties[12].

Pressure (MPa)	**Temperature (℃)**	**Entropy (kj/(kgK))**	**Vapour quality (%)**
0.01	45	$s_f = 0.64$, $s_g = 8.17$	
1.4	500	7.61	92.6
1.4	400	7.31	88.6
1.4	360	7.18	86.9
2.0	500	7.43	90.3
2.0	440	7.25	87.9
2.0	400	7.13	86.2

This table concludes that the 500 ℃ and 400 ℃ for with 1.4 MPa pressure is worth investigating, together with 500 ℃ and 440 ℃ for 2 MPa pressure.

C.3.2 Superheated Steam, 1.4 MPa, 400 ℃

With the knowledge of pressures, entropies and temperatures a table of relevant enthalpies may be formulated[12].

Table C.4: Relevant enthalpies for superheated water at 400 ℃ and 1.4 MPa[12].

Stage	State	Equation	P (MPa)	T (C)	h (kJ/kg)	h_f (kJ/kg)	h_{fg} (kJ/kg)	h_g (kJ/kg)
1	Superheated vapour		1.4	400	3257.4			
2s	Two phase	$h_{2s} = h_f + x * h_{fg}$	0.01	45	2310.6	188.5	2394.8	2583.2
2	Two phase	$h_2 = h_1 - \eta_t(h_1 - h_{2s})$	0.01	45	2452.7			
3	Saturated liquid	$p_3 = p_2$ $\nu_3 = 1.01 * 10^3$ m^3/kg	0.01		188.5	188.5	2394.8	2583.2
4s	Saturated liquid	$h_4 = h_3 + \frac{\dot{W}_p}{\dot{m}} = h_3 + \nu_3(p_4 - p_3)$	1.4		189.9			
4	Saturated liquid	$h_4 = h_3 + \frac{1}{\eta_p}\nu_3(p_4 - p_3)$	1.4		190.1			

With all the enthalpies known the ideal and real thermal efficiency may be calculated with equation 4.7:

$$\begin{aligned} \eta_{ideal} &= 1 - \frac{(h_{2s} - h_3)}{(h_1 - h_{4s})} = 1 - \frac{(2310.6 - 188.5)}{(3257.4 - 189.9)} = 30.8\% \\ \eta_{real} &= 1 - \frac{(h_2 - h_3)}{(h_1 - h_4)} = 1 - \frac{(2452.7 - 188.5)}{(3257.4 - 190.1)} = 26.2\% \end{aligned} \tag{C.4}$$

C.3.3 Superheated Steam, 1.4 MPa, 500 ℃

With the knowledge of pressures, entropies and temperatures a table of relevant enthalpies may be formulated[12].

Table C.5: Relevant enthalpies for superheated water at 500 ℃ and 1.4MPa[12].

Stage	State	Equation	P (MPa)	T (C)	h (kJ/kg)	h_f (kJ/kg)	h_{fg} (kJ/kg)	h_g (kJ/kg)
1	Superheated vapour		1.4	500	3474.2			
2s	Two phase	$h_{2s} = h_f + x * h_{fg}$	0.01	45	2406.1	188.5	2394.8	2583.2
2	Two phase	$h_2 = h_1 - \eta_t(h_1 - h_{2s})$	0.01	45	2566.3			
3	Saturated liquid	$p_3 = p_2$ $\nu_3 = 1.010 * 10^3$ m^3/kg	0.01		188.5	188.5	2394.8	2583.2
4s	Saturated liquid	$h_4 = h_3 + \frac{\dot{W}_p}{\dot{m}} = h_3 + \nu_3(p_4 - p_3)$	1.4		189.9			
4	Saturated liquid	$h_4 = h_3 + \frac{1}{\eta_p}\nu_3(p_4 - p_3)$	1.4		190.1			

With all the enthalpies known the ideal and real thermal efficiency may be calculated with equation 4.7:

$$\begin{aligned} \eta_{ideal} &= 1 - \frac{(h_{2s} - h_3)}{(h_1 - h_{4s})} = 1 - \frac{(2406.1 - 188.5)}{(3474.2 - 189.9)} = 32.5\% \\ \eta_{real} &= 1 - \frac{(h_2 - h_3)}{(h_1 - h_4)} = 1 - \frac{(2566.3 - 188.5)}{(3474.2 - 190.1)} = 27.6\% \end{aligned} \tag{C.5}$$

C.3.4 Superheated Steam, 2.0 MPa, 440 ℃

With the knowledge of pressures, entropies and temperatures a table of relevant enthalpies may be formulated[12].

Table C.6: Relevant enthalpies for superheated water at440 ℃ and 2.0 MPa[12].

Stage	State	Equation	P (MPa)	T (C)	h (kJ/kg)	h_f (kJ/kg)	h_{fg} (kJ/kg)	h_g (kJ/kg)
1	Superheated vapour		2.0	440	3335.5			
2s	Two phase	$h_{2s} = h_f + x * h_{fg}$	0.01	45	2293.4	188.5	2394.8	2583.2
2	Two phase	$h_2 = h_1 - \eta_t(h_1 - h_{2s})$	0.01	45	2449.7			
3	Saturated liquid	$p_3 = p_2$ $\nu_3 = 1.010 * 10^3 \mathrm{m}^3/\mathrm{kg}$	0.01		188.5	188.5	2394.8	2583.2
4s	Saturated liquid	$h_4 = h_3 + \frac{\dot{W}_p}{\dot{m}} = h_3 + \nu_3(p_4 - p_3)$	2.0		190.5			
4	Saturated liquid	$h_4 = h_3 + \frac{1}{\eta_p}\nu_3(p_4 - p_3)$	2.0		190.8			

With all the enthalpies known the ideal and real thermal efficiency may be calculated with equation 4.7:

$$\begin{aligned} \eta_{ideal} &= 1 - \frac{(h_{2s} - h_3)}{(h_1 - h_{4s})} = 1 - \frac{(2293.4 - 188.5)}{(3335.5 - 190.5)} = 33.1\% \\ \eta_{real} &= 1 - \frac{(h_2 - h_3)}{(h_1 - h_4)} = 1 - \frac{(2449.7 - 188.5)}{(3335.5 - 190.8)} = 28.1\% \end{aligned} \tag{C.6}$$

C.3.5 Superheated Steam, 2.0 MPa, 500 ℃

With the knowledge of pressures, entropies and temperatures a table of relevant enthalpies may be formulated[12].

Table C.7: Relevant enthalpies for superheated water at 500 ℃ and 2.0 MPa[12].

Stage	State	Equation	P (MPa)	T (C)	h (kJ/kg)	h_f (kJ/kg)	h_{fg} (kJ/kg)	h_g (kJ/kg)
1	Superheated vapour		2.0	500	3467.6			
2s	Two phase	$h_{2s} = h_f + x * h_{fg}$	0.01	45	2349.9	188.5	2394.8	2583.2
2	Two phase	$h_2 = h_1 - \eta_t(h_1 - h_{2s})$	0.01	45	2517.6			
3	Saturated liquid	$p_3 = p_2$ $\nu_3 = 1.010 * 10^3$ m^3/kg	0.01		188.5	188.5	2394.8	2583.2
4s	Saturated liquid	$h_4 = h_3 + \frac{\dot{W}_p}{\dot{m}} = h_3 + \nu_3(p_4 - p_3)$	2.0		190.5			
4	Saturated liquid	$h_4 = h_3 + \frac{1}{\eta_p}\nu_3(p_4 - p_3)$	2.0		190.8			

With all the enthalpies known the ideal and real thermal efficiency may be calculated with equation 4.7:

$$\begin{aligned}\eta_{ideal} &= 1 - \frac{(h_{2s} - h_3)}{(h_1 - h_{4s})} = 1 - \frac{(2349.9 - 188.5)}{(3467.6 - 190.5)} = 34.0\% \\ \eta_{real} &= 1 - \frac{(h_2 - h_3)}{(h_1 - h_4)} = 1 - \frac{(2517.6 - 188.5)}{(3467.6 - 190.8)} = 28.9\%\end{aligned} \tag{C.7}$$

Appendix D.

Heat Convection Coefficients of the Pressvess twin retort

In order to calculate the heat loss of the Pressvess twin retort during cooking, estimates for the different heat convection coefficient was needed. The following assumptions were made to conduct the estimates:

- Steady operating conditions
- Air is ideal gas
- Local atmospheric pressure is 1 atm
- Critical Reynolds number is $5 * 10^5$
- The surrounding temperature is uniform

The average ambient temperature is 25 ℃ [4]. With a hot surface temperature of 85 ℃ the temperature defining the properties will be[21]:

$$T_f = \frac{T_s + T_\infty}{2} = \frac{85℃ + 25℃}{2} = 55℃ \tag{D.1}$$

Properties at 50 ℃ and 60 ℃ is given in tables and interpolation is required[21]:

Table D.1: Properties of air[21].

Temperature T (℃)	Thermal conductivity k (W/(m ℃))	Kinematic viscosity ν (m^2/s)	Prandtl number Pr
50	0.02735	$1.798 * 10^{-5}$	0.7228
60	0.02808	$1.896 * 10^{-5}$	0.7202
55	0.02772	$1.847 * 10^{-5}$	0.7215

Recall the dimensions of the Pressvess retort:

w - width - 3.4 m

h - height - 1.4 m

d - depth - 2.1 m

For the heat loss calculations the retort is treated as a box with rectangular sides. This gives the following area estimation:

$$
\begin{aligned}
&A_s = A_{front} + A_{back} + A_{top} + A_{bottom} + 2A_{side} \\
&A_s = 2A_{front} + 2A_{top} + 2A_{side} \\
&A_{front} = h * w \\
&A_{top} = d * w \\
&A_{side} = h * d \\
&\Rightarrow A_s = 2(hw) + 2(dw) + 2(hd) \\
&A_s = 2 * 1.4 \text{ m} * 3.4 \text{ m} + 2 * 2.1 \text{ m} * 3.4 \text{ m} + 2 * 1.4 \text{ m} * 2.1 \text{ m} \\
&A_s = 29.7 \text{ m}^2
\end{aligned}
\tag{D.2}
$$

D.1 Natural Convection Coefficient

The natural convection coefficient is dependent on the angle and position of the plate and it will therefore be natural to divide into three different coefficients[21]:

h_{top} - For the horizontal top plate

h_{bottom} - For the horizontal bottom plate

h_{side} - For the vertical side walls

D.1.1 The Top and Bottom Plate

For the top and bottom plate the characteristic length will be the same and it will be[21]:

$$
L_C = \frac{A_{plate}}{\text{Perimeter}} = \frac{w * d}{w + d} = \frac{3.4 \text{ m} * 2.1 \text{ m}}{3.4 \text{ m} + 2.1 \text{ m}} = 1.3 \text{ m} \tag{D.3}
$$

The rayleigh number is given by the following formula[21]:

$$
\begin{aligned}
&Ra_D = \frac{g\beta(T_s - T_\infty){L_C}^3}{\nu^2} Pr \\
&Ra_D = \frac{g\frac{1}{T_f}(T_s - T_\infty)L^3}{\nu^2} Pr \\
&Ra_D = \frac{9.81 \text{ m/s}^2 \frac{1}{(273+55)\text{ K}}(85 - 25) \text{ K}(L_C)^3}{(1.847 * 10^{-5} \text{ m}^2/\text{s})^2} * 0.7215 \\
&Ra_D = 1.458 * 10^9 L_C^3
\end{aligned}
\tag{D.4}
$$

For the top and bottom plate this becomes[21]:

$$Ra_D = 1.458 * 10^9 * (1.3\text{ m})^3 = 3.19 * 10^9 \tag{D.5}$$

The nusselt number then becomes[21]:

$$\begin{aligned} Nu_{top} &= 0.15Ra^{1/3} = 0.15 * (3.19 * 10^9)^{1/3} = 221 \\ Nu_{bottom} &= 0.27Ra^{1/4} = 0.27 * (3.19 * 10^9)^{1/4} = 64 \end{aligned} \tag{D.6}$$

This gives natural convection coefficients for top and bottom[21]:

$$\begin{aligned} h_{top} &= \frac{Nu_{top} * k}{L_C} = \frac{221 * 0.02772\text{ W/(m℃)}}{1.3\text{ m}} = 4.7\text{ W/(m}^2\text{℃)} \\ h_{bottom} &= \frac{Nu_{bottom} * k}{L_C} = \frac{64 * 0.02772\text{ W/(m℃)}}{1.3\text{ m}} = 1.4\text{ W/(m}^2\text{℃)} \end{aligned} \tag{D.7}$$

D.1.2 The Side Walls

For the side walls the characteristic length will be the height of the walls. The rayleigh number is[21]:

$$Ra_D = 1.458 * 10^9 * (1.4\text{ m})^3 = 3.98 * 10^9 \tag{D.8}$$

The Nusselt number then becomes[21]:

$$\begin{aligned} Nu &= \left[0.825 + \frac{0.387 * (Ra_D)^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}}\right] \\ Nu &= \left[0.825 + \frac{0.387 * 3.98 * 10^{9^{1/6}}}{[1 + (0.492/0.7215)^{9/16}]^{8/27}}\right] \\ Nu &= 15 \end{aligned} \tag{D.9}$$

This gives natural convection coefficients for the sides[21]:

$$h_{sides} = \frac{Nu_{sides} * k}{L_C} = \frac{15 * 0.02772\text{ W/(m ℃)}}{1.4\text{ m}} = 0.3\text{ W/(m}^2\text{℃)} \tag{D.10}$$

D.1.3 Natural Convection Heat Loss

The natural convection heat losses will then be[21]:

$$\begin{aligned} &Q = hA_s(T_s - T_\infty) \\ &Q_{top} = h_{top}w * d(T_s - T_\infty) = 4.7\text{ W/(m}^2\text{℃)} * 3.4\text{ m} * 2.1\text{ m} * 60\text{℃} = 2.0\text{ kW} \\ &Q_{bottom} = h_{bottom}w * d(T_s - T_\infty) = 1.4\text{ W/(m}^2\text{℃)} * 3.4\text{ m} * 2.1\text{ m} * 60\text{℃} = 0.6\text{ kW} \\ &Q_{sides} = h_{sides}2 * (w * h + d * h)(T_s - T_\infty) = \\ &Q_{sides} = 0.3\text{ W/(m}^2\text{℃)} * 2 * (3.4\text{ m} * 1.4\text{ m} + 2.1\text{ m} * 1.4\text{ m}) * 60\text{℃} = 0.3\text{ kW} \end{aligned} \tag{D.11}$$

D.2 Forced Convection Coefficient

In order to know how much the wind at MCF Yatta leads to forced convection the forced convection coefficient must be estimated. The average wind speed at Yatta is 3.4 m/s. The reynold number will be used to establish if there is laminar or tubular flow[21].

$$Re_L = \frac{VL}{\nu} = \frac{3.4 \text{ m/s} * 3.4 \text{ m}}{1.847 * 10^{-5} \text{ m}^2/\text{s}} = 6.26 * 10^5 \tag{D.12}$$

This is higher than the critical value ($5 * 10^5$) and the flow is turbulent. Then the nusselt number will be[21]:

$$\begin{aligned} Nu &= \frac{hL}{k} = (0.037 Re_L^{0.8} - 871) Pr^{\frac{1}{3}} \\ Nu &= (0.037 * (6.26 * 10^5)^{0.8} - 871) * 0.7215^{\frac{1}{3}} \\ Nu &= 658 \end{aligned} \tag{D.13}$$

The expression in equation D.13 may be turned around and the convection coefficient may be calculated[21]:

$$h_{forced} = \frac{kNu}{L} = \frac{(0.02772 \text{ W/(m℃)})(658)}{3.4 \text{ m}} = 5.4 \text{ W/(m}^2\text{℃)} \tag{D.14}$$

The total heat loss then becomes[21]:

$$Q_{conv,forced} = h_{forced} A_s (T_s - T_\infty) = 5.4 \text{ W/(m}^2\text{℃)} * 29.7 \text{ m}^2 * 60\text{℃} = 9.6 \text{ kW} \tag{D.15}$$