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Waste Heat Recovery System for The Dolphin Concept Car

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By

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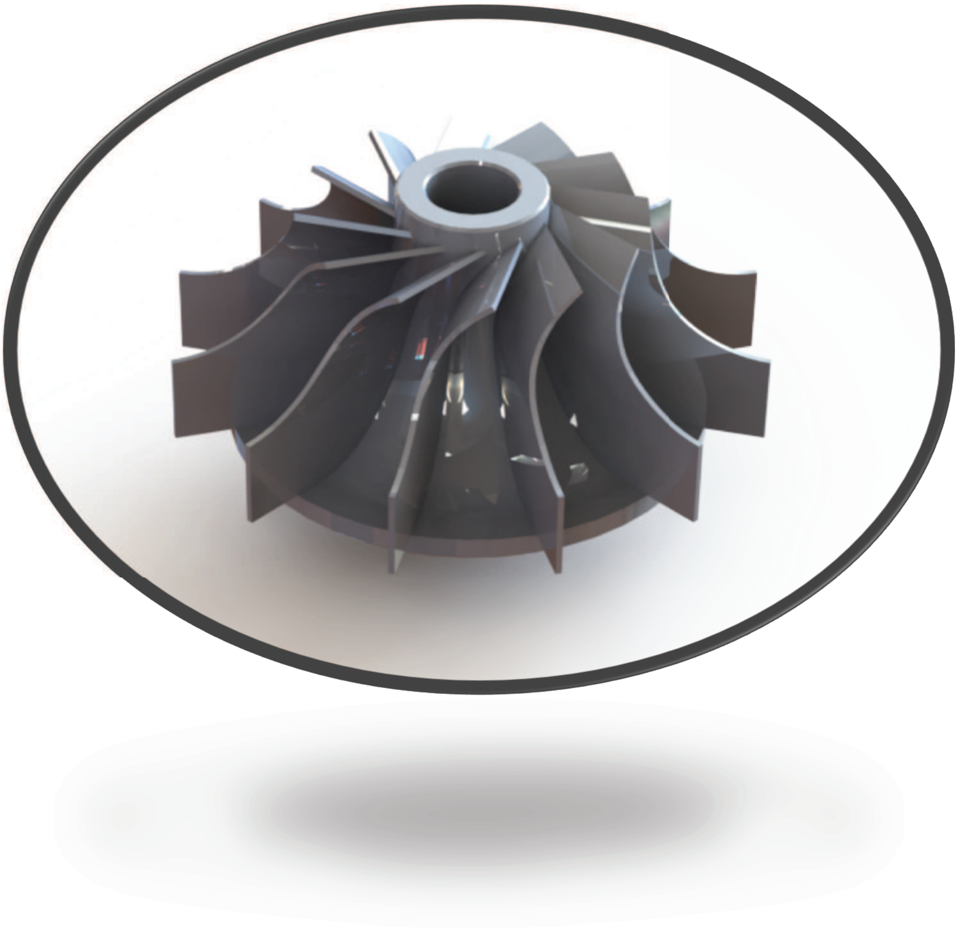

Master thesis at The University of Life Sciences
Department of Mathematical Sciences & Technology

2014

Foreword

This thesis is my study of a waste heat recovery system for the Dolphin concept car. The thesis is written for the Department of Mathematical Sciences and Technology (IMT) at University of Life Sciences (NMBU).

I would like to thank my supervisor, Associate Professor Jan Kåre Bøe for excellent help and guiding along the way, and Associate Professor Jorge Mario Marchetti for help with the thermodynamic calculations.

Motivation

Nils N. Finnøy, my great great grandfather, started producing naval low-pressure diesel engines as the first producer in 1902. He was a self-made man without any technical degree, but with experience and knowledge as a blacksmith he produced his first low-pressure diesel engine. Later on his factory, Nils N. Finnøy Motorfabrikk, he produced a 4-stroke engine with glow plug. It is also common knowledge that Finnøy Motorfabrikk produced the first 100HK engine in Norway in 1913. In other words, my interest for engines is inherited through many generations.

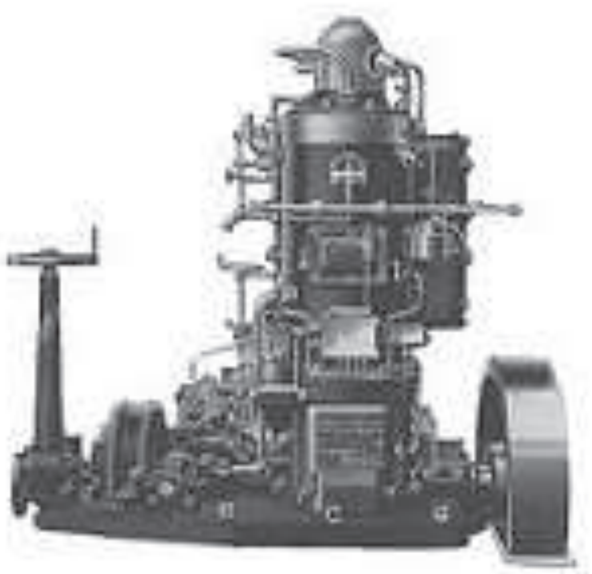

Figure 1: 100HK low pressure diesel engine (semi diesel) produced by Nils N. Finnøy Motorfabrikk (1)

Ås May15th 2014

Sigve Eikrem Finnøy

Abstract

Technological advances in the transportation industry have considerable potential to reduce air pollution and greenhouse gas emissions. Technology deployments, whether in the form of changes in conventional vehicles or through the introduction of radically different vehicle and fuel technologies could give the necessary reduction in greenhouse gas emission for the next several decades.

One of the main engineering tasks today is to gain higher thermal efficiency to conventional power plants already in use. One of the most popular innovative methods of modification involves a gas power cycle on the top of a vapor power cycle. Because the disadvantageous characteristic of a gas turbine cycle exhausting about 60% of its energy, it is possible to take advantage of this high temperature exhaust gases as energy source for a bottoming cycle such as a steam power cycle.

Exhaust heat from a gas turbine can be recovered externally or internally to the cycle itself. Of the technology options for external recovery, the combined gas-steam plant is by far the most effective and commonly used worldwide. For internal recovery conventional solutions are based on thermodynamic regeneration (Preheat of combustion air).

The primary objective in this project was to examine different ways of recovering heat, choose a concept, and to calculate and develop a system design proposal.

First, a Brayton cycle gas turbine from Thue & Sundquist was considered input to this thesis. Second, a Rankine cycle was modeled theoretically with temperature and pressure boundaries from industrial literature to investigate the work output and the thermal efficiency as a function of the maximum pressure and temperature in the steam cycle. All of these relationships were modeled in Microsoft Excel for convenience to do several iterations. A thorough study led to a concept, which was calculated and tested with different inputs. Cost calculations were made for a prototype and series production, and a system solution was proposed.

It was shown in this thesis that a waste heat recovery system (WHRS) has great potential in increasing the overall system efficiency of a gas turbine driven vehicle, and that it is doable concerning space constraints in the Dolphin concept car. It is however many uncertainties realizing a project since this study was done theoretically.

Results that were achieved, with the given input, is that a WHRS adds 21,9kW to the system. That means an increase in overall system efficiency by 19%. The overall system efficiency is now 46%. That is about the same efficiencies you get from a conventional diesel engine.

The calculations were done with several assumptions that cause uncertainties in the result. They were based on the literature study and consultation with GreenTurbine. It is also mentionable that the calculations were done ideally, meaning that losses in components such as friction and heat flux are not considered, except in the steam turbine. Combined it gives a good impression of what to expect in the future when a project is optimized and realized.

Sammendrag

Teknologiske fremskritt innen transportindustrien har et betydelig potensial med å redusere luftforurensing og klimagassutslipp. Tiltak, enten i form av endring av konvensjonelle biler eller gjennom innføringen av radikalt annerledes bilteknologi og drivstoffteknologi, kan stå for det meste av de nødvendige reduksjoner i klimagassutslipp de neste tiårene.

En av de viktigste ingeniøroppgavene i dag er å oppnå høyere termisk virkningsgrad i konvensjonelle typer kraftverk som allerede er i bruk. En av de mest populære innovative metodene involverer en gasskraftsyklus (Brayton) på toppen av en dampkraftsyklus (Rankine). På grunn av at gassturbiner har høyt tap gjennom avgass er det mulig å dra nytte av den store andelen høylatent eksos som slippes ut som en energikilde til en dampkraftsyklus.

Eksosen fra en gassturbin kan gjenvinnes eksternt eller internt tilbake i selve syklusen. Av de teknologiske mulighetene for ekstern gjenvinning er et kombinert gass- og dampkraftsystem uten tvil det mest effektive og populære brukt verden rundt. For intern gjenvinning er det pre-oppvarming av forbrenningskammerluften som er det mest vanlige.

Målet med dette prosjektet var å undersøke ulike måter å gjenvinne eksosvarme, velge et konsept og å beregne og utvikle et systemforslag.

Først ble en gass turbin fra Thue & Sundquist som opererer på en Brayton syklus regnet som input til denne studien. Deretter ble en dampturbin som opererer på en Rankine syklus utviklet med temperatur- og trykkgrenser hentet fra industrilitteratur. Dette for å undersøke kraften den kan levere, og termisk virkningsgrad som en funksjon av maksimalt trykk og temperatur i dampsyklusen. Utregningene på dette ble utført i Microsoft Excel for lettere å kunne gjøre flere iterasjoner. En grundig studie ledet til et konsept som ble testet og beregnet med forskjellige input. Kostnadskalkyle for prototyping og for serieproduksjon ble utført, samt en systemløsning ble foreslått.

Det ble vist i denne avhandlingen at et varmegjenvinningssystem har stort potensial i å øke den totale virkningsgraden på et gassturbindrevet kjøretøy, og at det er gjennomførbart med tanke på plassmangel i Dolphinbilen. Det er i midlertidig mange usikkerhetsmomenter, siden denne studien er utført teoretisk.

Resultatene som ble oppnådd, med gitt input, var at et varmegjenvinningssystem tilfører 21,9kW til systemet. Det er en økning i total virkningsgrad på 19%. Den totale virkningsgraden på system er da 46%. Det er noenlunde det samme man får på en konvensjonell diesel motor.

Utregningene ble gjort med flere antagelser som gir usikkerhet i resultatene. Utregningene er basert på litteraturstudien og i konsultasjon med GreenTurbine. Det er også verdt å nevne at alle utregninger er gjort ideelle, noe som betyr at tap i komponenter som friksjon og annet varmetap ikke er medregnet, for utenom i dampturbinen. Legger man sammen dette gir det et godt inntrykk på hva man kan forvente seg av ytelse når et prosjekt er optimert og realisert.

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1 Introduction

1.1 Background

Emissions from greenhouse gases have increased by 10 percent over the past ten years and now accounts for 33% of total greenhouse gas emissions in Norway. Conventional road traffic is the main source of emissions. (2)

Concerns about environmental quality, social equity, economic vitality, and the threat of climate change have converged to produce a growing interest in the concept of sustainable development.

Vehicles must be smaller and lighter and you have to consider other engine- and chassis solutions to reduce consumption and emissions. Such a lightweight vehicle concept is being developed by IMT under the name “Dolphin”.

The dolphin concept car is a result of several master theses from NMBU. A small, practical and environmental friendly car with high efficiency and low emissions. The point is to show how engineering principles is used to reduce emissions in all different areas of the car. The design, aerodynamics, interior, engine solutions are all being thoroughly researched.

Figure 2: Dolphin concept car front view, back view and side view. (3)

Today’s society is leaning more and more towards eco-friendly ways of living. Especially in public transportation this is in constant improvement. Cars, airplanes, trains and public transportation are all looking for alternatives that can contribute to the overall target; lower emissions. Even though transportation sector stands for about 30% of the overall greenhouse gases in total, it is a subject that everyone can relate to and is something everybody can contribute to.

In many ways combustion engines are not efficient enough and have high CO2 emissions. Electric cars are not an adequate alternative since it has limited range. A hybrid that combines combustion engines and electric technology is a better alternative, but its efficiency still needs improvement and has to high emissions.

This thesis will discuss and analyze different alternatives of recovering any waste heat that leaves Dolphins gas turbine concept.

Turbine engines have existed for a long time and are very reliable because of its limited number of moving parts. However, the efficiency is only about 20-30% depending on the technology. The remaining 70% is lost due to heat loss and friction.

Exploiting waste heat is the newest source of clean energy. But it is rarely included as a renewable energy source, because waste heat derives from factories, plants and energy sources that run on fossil fuels.

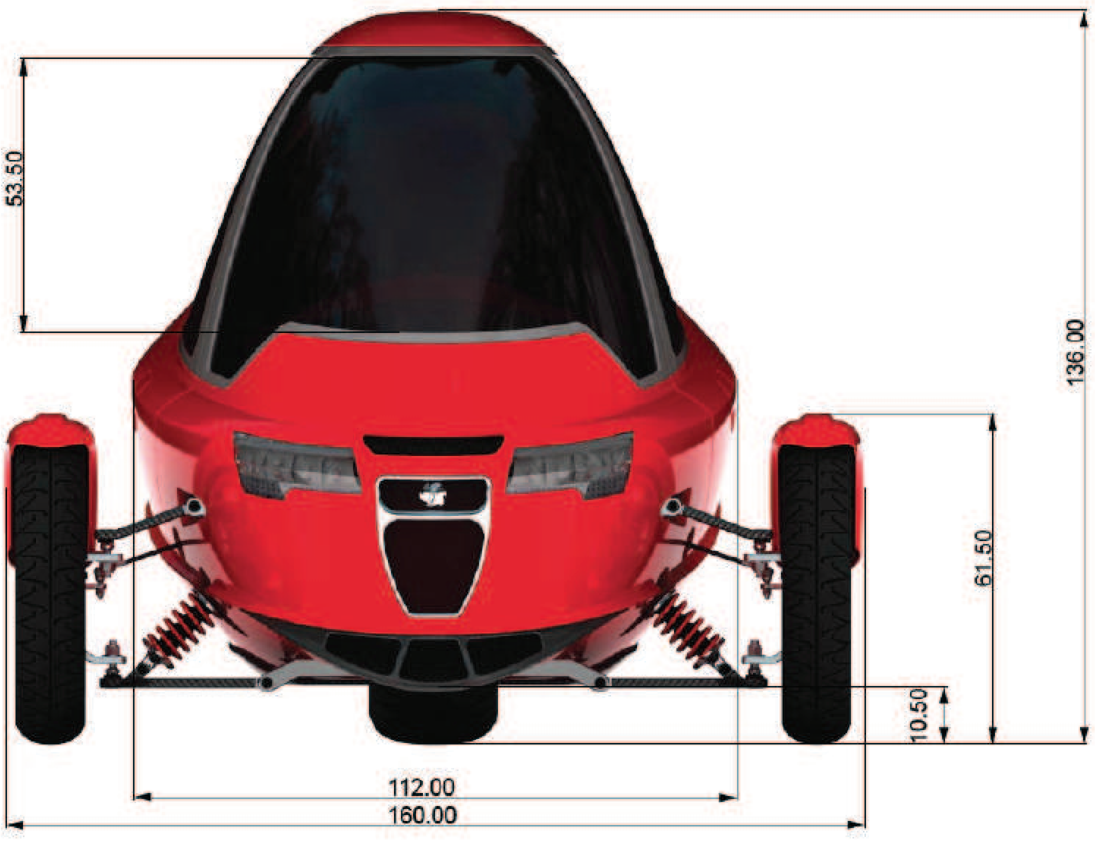


Figure 3: Dolphin concept car front view. The figure shows external dimensions in centimeters. (4)

Several students are currently developing the Dolphin concept car. The main goal of the project is to show how engineering principals and technological enhancements can contribute to lower emissions.

1.2 Historical review

A turbine is any kind of spinning device that uses the action of a fluid to produce work. Typical fluids are: air, wind, water, steam and helium.

As the oldest trace of the steam turbine, we might consider the "Aeolipile" used by the Egyptian priests, and which was described by Hero of Alexandria about the year 120 B.C. (Figure 4) It consisted of a hollow ball placed over a fire, and made to rotate by the reaction of a steam jet exhausting from two bent tubes. (5) The steam turbine is a prime mover in which the potential energy of the steam is transformed into kinetic energy and the latter in its turn is transformed into the mechanical energy of rotation of the turbine shaft.

Figure 4: Hero's jet engine with a boiler and steam exit nozzles (6)

In the history of energy conversion, however, the gas turbine is relatively new. The first practical gas turbine used to generate electricity ran at Neuchatel, Switzerland in 1939, and was developed by the Brown Boveri Company. The first gas turbine powered airplane flight also took place in 1939 in Germany, using the gas turbine developed by Hans P. von Ohain. In England, the 1930's invention and development of the aircraft gas turbine by Frank Whittle resulted in a similar British flight in 1941. (7)

The name "gas turbine" is somewhat misleading, because to many it implies a turbine engine that uses gas as its fuel. Actually a gas turbine Figure 5 has a compressor to draw in and compress gas (most usually air); a combustor (or burner) to add fuel to heat the compressed air; and a turbine to extract power from the hot air flow. The gas turbine is an internal combustion (IC) engine employing a continuous combustion process. This differs from the intermittent combustion occurring in diesel and automotive IC engines. (7)

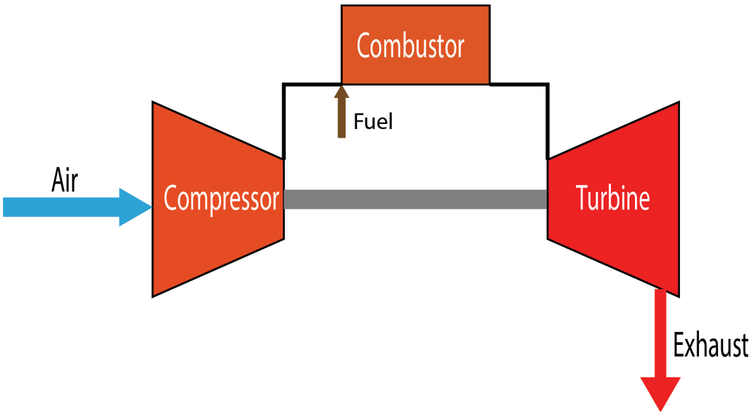


Figure 5: Gas turbine system with compressor, combustor and turbine

Submarines

Most of US submarines use steam turbines to propel the ship, and gets its energy from nuclear reactors. Nuclear reactors are basically heat engines. As uranium fissions, the breaking apart of atoms releases energy, much of it in the form of heat, which can then be used to do work.

Figure 6: U.S.S Louisiana commissioned in 1997 (8)

U.S. submarines rely on nuclear power for both propulsion and life support. The nuclear reactor heats water to make steam that drives a turbine to turn the propeller. The same system also provides steam for the boat's turbine generators, the source of electricity for all submarine systems, including oxygen makers.

U.S. Navy future

The U.S. Navy is betting its future of its submarine force on a secret and revolutionary nuclear drive system that aspires to be more efficient and quieter than anything under the water today. (8)

Current submarines have a direct mechanical connection to the propellers that drive the boat. Energy from steam turbines driven by the nuclear power plant goes through a series of mechanical gears that translate the high RPM output of the turbines into lower torque energy needed to propel the ship. All of those mechanical connections can generate noise, the bane of the submariner. Mowing forward, the Navy wants to use the power from the reactor to create an elaborate electrical grid inside of the submarine. The reactor power would feed the grid and in turn the electric motors that would drive the boats. Eliminating the mechanical connection would mean less noise under water. The set up would also free up power previously devoted to driving the ship.(8) Not unlike the engine solution this thesis will analyze and discuss.

Military ships (Destroyers, battleships and warships)

Figure 7: USS Nimitz Aircraft Carrier commissioned in 1975. (9)
USS Nimitz is propelled by:
- 2 x Westinghouse A4W nuclear reactors
- 4 x Steam turbine
- 4 x Shafts
- Total power: 194MW

USS Nimitz (CVN-68)

USS Nimitz is a super carrier of the United States Navy, and the lead ship of its class. One of the largest warships in the world was launched and commissioned as CVN 68 (nuclear powered multimission aircraft carrier) on June 30th 1975. (9)

Nuclear power plants
A nuclear reactor produces and controls the release of energy from splitting the atoms of uranium. Uranium-fuelled nuclear power is a clean and efficient way of boiling water to make steam, which drives turbine generators. The big challenge with nuclear power plant is the handling of the radioactive by-products (waste).

Figure 8: Nuclear Power Plant in Grafenrheinfeld, Germany (10)

Nuclear energy supplies some 12% of the world’s electricity. Today 31 countries use nuclear energy to generate up to three quarters of their electricity, and a substantial number of these depend on it for one-quarter to one-third of their supply. It exist about 440 nuclear power reactors today. The number of reactors powering naval vessels is about the similar amount.

1.3 Environmental challenges

Figure 9: Conventional road traffic is the main source of greenhouse gas emissions (11)

Emissions from greenhouse gases have increased by 10 percent over the past ten years and now accounts for 33 percent of total greenhouse gas emissions in Norway. Conventional road traffic is the main source of emissions. (2)

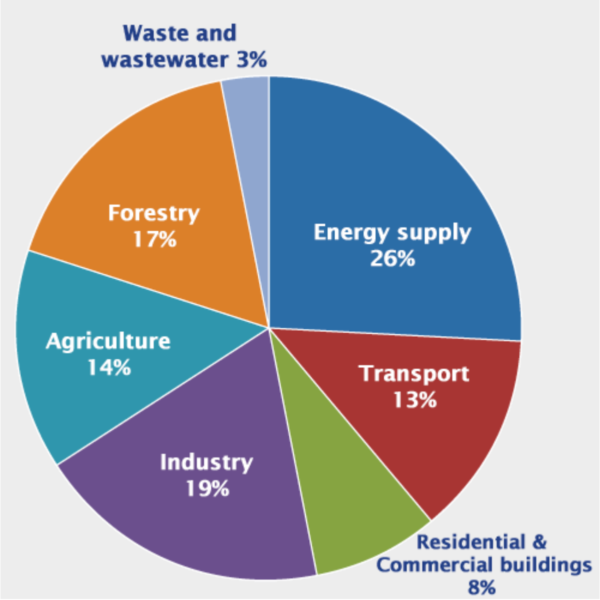


Figure 10: Global Emissions by source (12)

1.3.1 Transportation

Greenhouse gas emissions from this sector primarily involve fossil fuels burned for road, rail, air, and marine transportation. Almost all (95%) of the world's transportation energy comes from petroleum-based fuels, largely gasoline and diesel. (2)

Should climate change be limited sufficiently, the trends of increasing greenhouse gases have to change. Extensive reduction in emissions will be necessary. This require that we change both production and consumption patterns. It has been difficult to agree on such global emissions reductions. In 2015, countries are going to try to agree on a comprehensive global climate agreement. (2)

Norway has undertaken to reduce emissions in the Kyoto Protocols second commitment period. In 2020, the Norwegian emissions should not exceed 84 percent of emissions in 1990. To achieve these objectives, Norway has introduced a CO2 tax and a national system of emissions trading.

The European Emissions Trading System (EU ETS)

The EU emissions trading system (EU ETS) is a cornerstone of the European Union's policy to combat climate change and its key tool for reducing industrial greenhouse gas emissions cost-effectively. The first - and still by far the biggest - international system for trading greenhouse gas emission allowances, the EU ETS covers more than 11,000 power stations and industrial plants in 31 countries, as well as airlines. (13)

1.3.2 Transportation management

"*A sustainable transportation system is one that allows the basic access and development needs of individuals, companies and societies to be met safely and in a manner consistent with human, and promotes equity within and between successive generations. It has to be affordable, operate fairly and efficiently, offers choice of transport mode, and supports a competitive economy, as well as balanced regional development. Limit emissions and waste within the planet's ability to absorb them, uses renewable resources at or below their rates of generation, and uses non-renewable resources at or below the rates of development of renewable substitutes, while minimizing the impact on the use of land and the generation of noise*". (14)

This definition by the Centre for Sustainable Transport (15) has been widely accepted in Europe and North America.

Important uncertainties persist about the nature and severity of many environmental problems, including transportation related air pollutants, greenhouse gas emissions and even noise. (For example, what are the health effects of long-term low-dose exposures?) Uncertainties also persist concerning the economic benefits of transportation infrastructure investments. Such uncertainties make it difficult to have a clear story about the need for change of the likely results of intervention and, coupled with the high stakes involved, make it hard to muster the political support needed for action. (16)

Another issue is that in the absence of public policy direction the technological changes that do emerge may or may not be directed to environmental improvements or other socially beneficial ends. For example, in the US at present many advances in the automotive technology are being applied to increase acceleration and performance or strengthen vehicle bodies, not to boost efficiency or cut greenhouse gas emissions. (16)

In Norway, a variety of interventions are already in motion to deal with this. Higher fuel taxes, but also higher taxes on the less efficient automotives. In Oslo in particular more and more parking spots are reserved for electrical vehicles, and you can recharge them for free. Another incentive to buy electrical vehicles is that you pay no road toll, parking fee, vehicle tax, ferry tickets etc.

Changes in travel behavior resulting from changes in land use and location, modes offered and chosen, and overall activity patterns also would depend on public support for policy changes, along with individual, household, and business decisions consonant with those changes. Here, the increasing interest in "liveable communities" and "sustainable development" suggests a growing movement favoring broad policy reform. It remains to be seen, however, whether these new initiatives can develop enough support to significantly change the patterns of settlement and transportation consumption. Here, the long time frame of greenhouse gas reduction efforts is an advantage; since there is enough time that land use policies could take hold. (16)

1.4 Market potential analysis

1.4.1 World energy supply and waste heat recovery

All forecasts of future world energy supply anticipate an increase across the globe. The projection shows (Figure 11) almost doubling of the world primary energy supply between 2000 and 2020. (17)

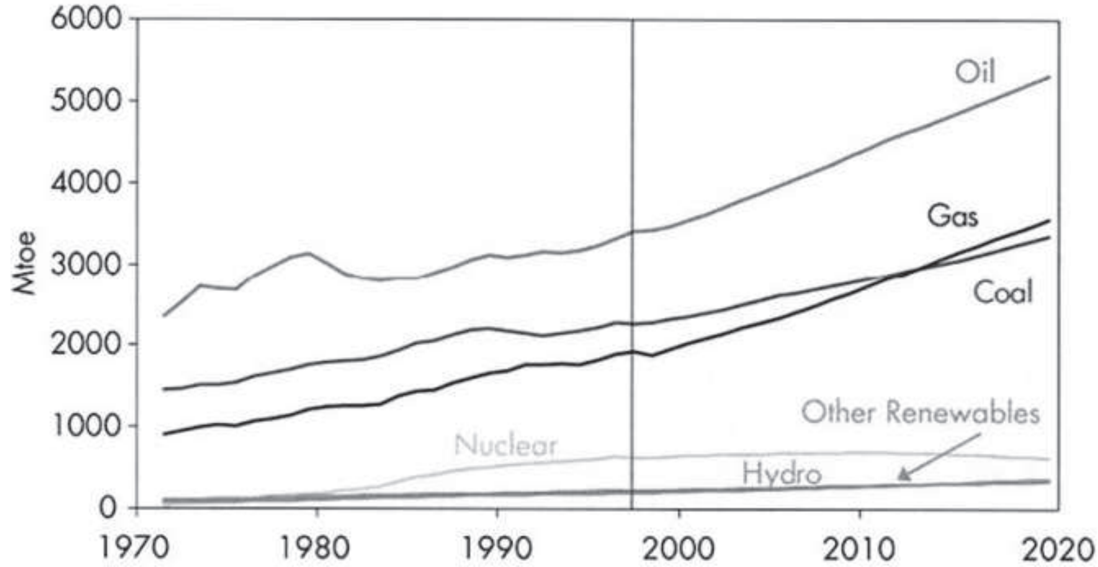


Figure 11: World primary energy supply by fuel, 1970 – 2020 (17)

The demand for waste heat recovery systems will continue to surge with the growing requirement for energy efficiency and rising environmental concerns regarding industrial waste heat emissions. The waste heat recovery systems offer energy savings and ensure effective utilization of the waste heat operations. These are the best solutions to the concerns over increasing energy and electricity prices. Technological improvement is as a major opportunity for the waste heat recovery systems market.(18)

The primary consideration in the R&D effort of this market lies in minimizing economic costs of waste heat recovery technologies.

The factors driving waste heat recovery market are increased growth in government regulatory requirement, increasing concern towards environmental protection, rising concern for energy prices, and the reluctant use of waste heat management. (18)

Waste heat recovery equipment finds their usage in various industries for one or more applications. Enhancing process heat recovery efficiency provides significant and immediate cost savings. The waste heat recovery systems are used in various end-user in industries such as petroleum refining, heavy metal production, cement, chemical refining and other industries. (18)

The waste heat recovery market will reach $53.12 billion by 2018. Europe dominates the market, accounting for a major share of about 38% in 2012. Asia-Pacific will experience highest growth rate of 9.7% in the next five years from 2013-2018. Key regions in Asia-Pacific market are China and India, which will experience the highest installations of waste heat recovery systems. (18)

1.4.2 Micro WHRS for vehicles

In the market for micro waste heat utilization, there is hardly any competition. The same goes for the market of micro combine cycle applications. However, the potential is great considering that traditional piston engines have almost reached its potential in lowering emissions and high efficiency.

This gives way for alternatives that have potential in becoming even more efficient, have lower emissions. Gas and steam turbines have high kW/kg and since it consists of only rotational parts, it has very low need of maintenance. A gas turbine can utilize almost everything as fuel, the most common being gasoline, diesel, paraffin and industrial waste ethanol. It is a well-known problem getting rid of industrial waste ethanol today, and maybe that can be the solution in fueling future gas turbines.

Using a WHRS in a hybrid car or a hydrogen/fuel cell car, can improve fuel efficiency with another 20-30%. As waste heat is about 60% of the total energy input of a car, a 10% recover of heat is substantial.

1.5 Advantages and disadvantages comparing CHP with reciprocating engines

Micro-turbine offers a number of potential advantages compared to other technologies for small-scale power generation. The already mentioned compact size and low-weight per unit power leading to reduced civil engineering costs, a small number of parts, lower noise, multi-fuel capabilities as well as opportunities for lower emissions.(17)

Compared to diesel engines micro turbines have high-grade waste heat, low maintenance cost and low vibration level. The absence of reciprocation and friction components means that balancing problems are few, and the use of lubrication oil is very low.

Reciprocating engines in the lower power range have higher efficiencies, but they are challenged from the increasing efficiency of both gas and steam turbine individually, and even more when they are put together in combined cycles.

A challenge with CHP systems is the power delay. It is a 1-2 second power delay from when your foot steps on the gas pedal. That problem doesn't apply when the gas turbine and CHP system output is directed to a generator. If so, the system becomes a backup for the electrical battery when the power is running low.

Main non-technical barriers to the implementation of CHP systems are that the investment payback period could be high, access to the gas network is not always possible and there are still administrative and institutional barriers to CHP in several countries. (17)

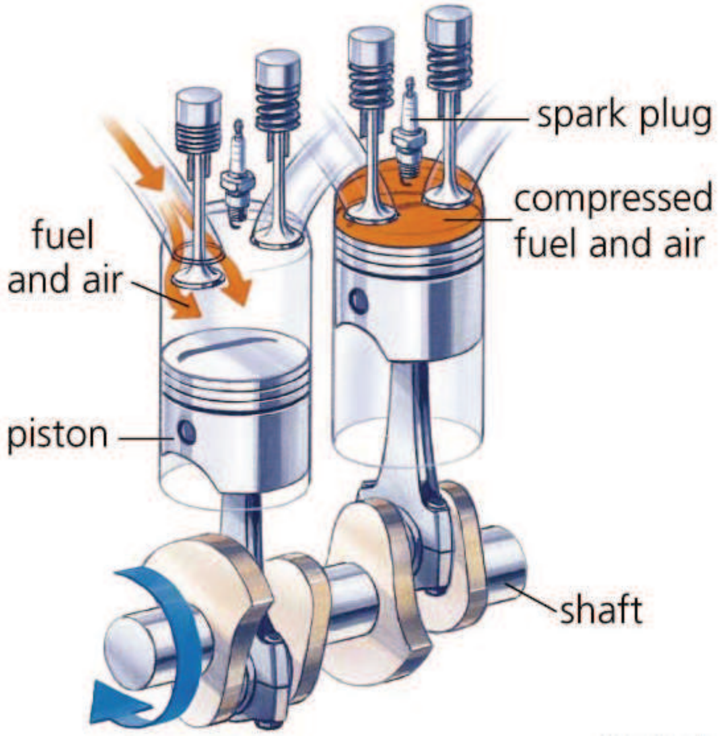


Figure 12: Traditional reciprocating piston engine (19)

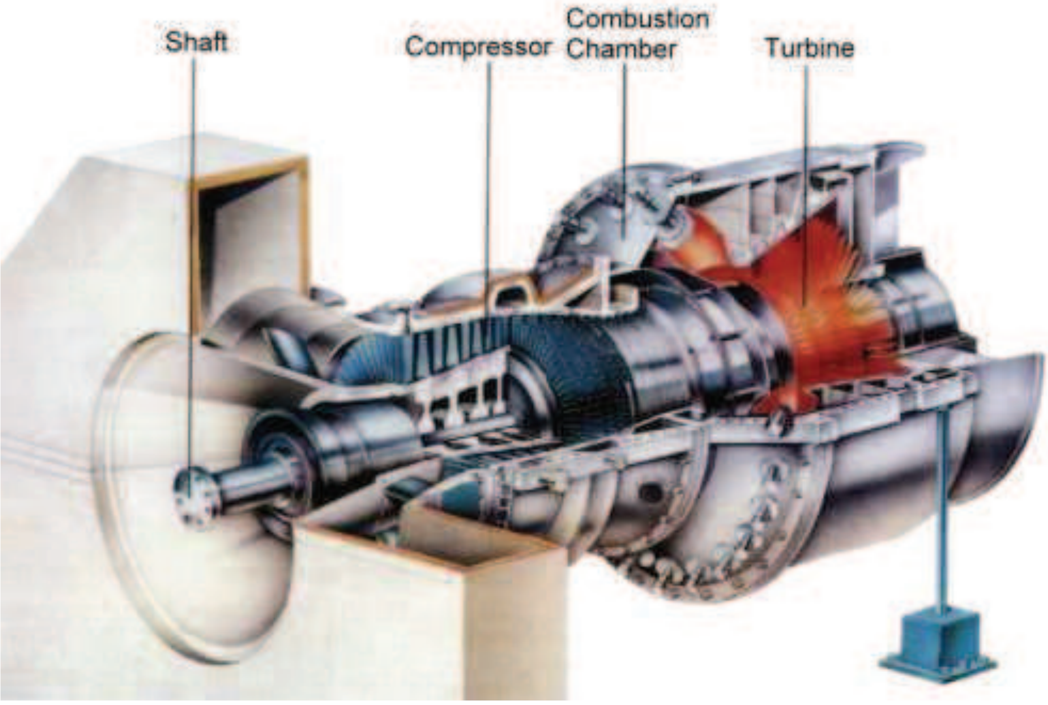


Figure 13: Gas turbine with only rotating parts (20)

Some of the principle advantages of the gas turbine are:

- It is capable of producing large amounts of useful power for a relatively small size and weight.
- Since motion of all its major components involve pure rotation (unlike reciprocating), its mechanical life is long and corresponding maintenance cost is relatively low.
- Although the gas turbine must be started by some external means (a small external motor or other source, such as another gas turbine), it can be brought up to full-load (peak output) conditions in minutes.
- A wide variety of fuels can be utilized. Natural gas is commonly used in land-based gas turbines while light distillate (kerosene-like) oils power aircraft gas turbines. Diesel oil or specially treated residual oils can also be used, as well as combustible gases derived from blast furnaces.
- The usual working fluid is atmospheric air. As a basic power supply, the gas turbine requires no coolant (e.g. water).

1.6 Problem and technological challenges

To examine, calculate and develop a system design and design basis for the recycling and utilization of waste heat based on the micro gas turbine from Thue & Sundquist (4), and to increase the overall system efficiency.

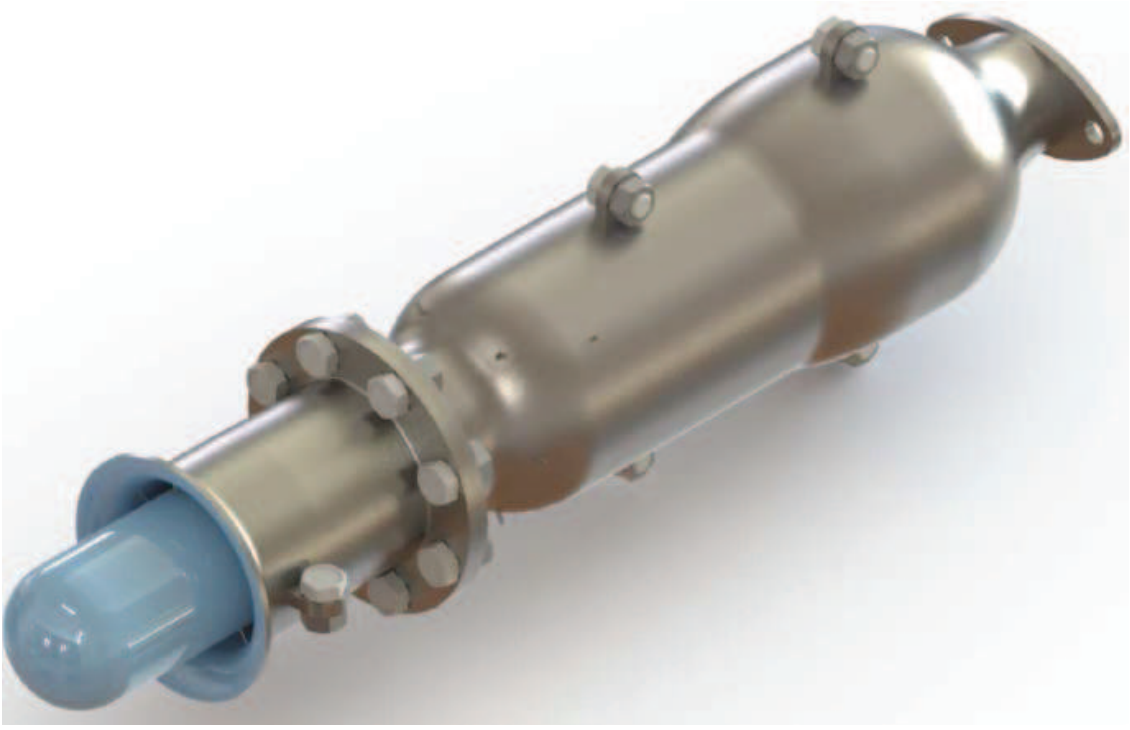


Figure 14: Thue & Sundquist gas turbine, rendered. (4)

Technological challenges

- Waste heat recovery systems for micro gas turbines are somewhat a new technology and it exists little or nothing information about it
- Thermodynamic calculations with several assumptions
- High rpm and temperature as design criteria's are demanding
- Space constraints in the Dolphin concept car
- Micro components have less efficiency than bigger components, such as in a power plant
- Selection of desired design characteristics

2 Project planning

2.1 Assignment

This master thesis will discuss different opportunities in exploiting and recycling the thermodynamic energy from multi fuel micro gas turbines, together with development of a system design for an efficient engine solution.

The thesis is based on several research projects, especially a master thesis from the students Thue & Sundquist. (4)

2.2 Objective

To examine, calculate and develop a system design and design basis for the recycling and utilization of waste heat from the micro gas turbine and to increase overall system efficiency.

- Evaluate potential in available waste heat recovery methods
- Calculate and recommend preferable system design and engine solution

2.3 Subsidiary objectives

The following subsidiary objectives will help to fulfill the main goal:

- Overall system efficiency >= 50 %
- Research existing literature to enhance the necessary knowledge on gas and steam turbines
- Describe alternatives and configurations available in waste heat recovery
- Develop a concept for a simple waste heat recovery system
- System selection
- Calculate the WHRS with different temperature/pressure input
- Material, production and cost comments
- Report contains conceptual drawings and presentation of the result

2.4 Limitations

The following limitations is set due to the limitation of 900 hours available:

- Limited to the steam turbines main components
- Conceptual design
- The calculations will be done ideally
- Main components are not designed for optimized strength, materials or production method
- All components are treated as black boxes in the design

The following are not considered in this thesis:

- Flow of air/exhaust
- FEM analysis
- Fatigue analysis
- Other components then Turbine, compressor, pump and heat exchanger
- The utilization of electric output power
- SolidWorks model

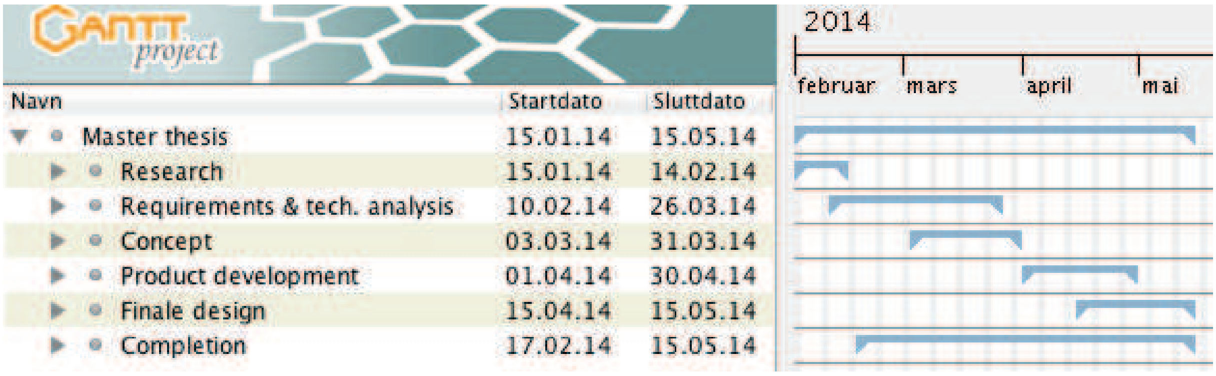
2.5 Gantt scheme

Underneath the milestones for the project is presented. The full gantt scheme can be found in appendix 1.

Table 1: Project milestones

Date	Number	Description
15.feb	1	Literature study
20.mars	2	Concept
20.apr	3	Design of WHRS
05.mai	4	System proposal
15.mai	5	Project deadline

Preview of gantt scheme



Navn	Startdato	Sluttdato
Master thesis	15.01.14	15.05.14
Research	15.01.14	14.02.14
Requirements & tech. analysis	10.02.14	26.03.14
Concept	03.03.14	31.03.14
Product development	01.04.14	30.04.14
Finale design	15.04.14	15.05.14
Completion	17.02.14	15.05.14

Figure 15: Preview of gantt scheme

3 Method & terminology

3.1 Overview of methodology

An extensive study that included traditional textbooks, science journals and digital libraries has been conducted. The study includes system alternatives, costs, configurations, power and temperature ranges and special considerations related to waste heat recovery technology.

During the study, development cost of WHRS, quality and quantity of produced energy and WHRS properties as well as initial cost has been taken into account. The components of the WHRS have been examined and some recommendations proposed. To reach the aforementioned goals, the thermodynamic cycle with its components have been analyzed with respect to heat exchanger size and space constraints in the Dolphin concept car. Issues including the working fluid, degree of superheat, working minimum and maximum temperature and pressure have been considered.

A computational model for thermal efficiencies, fluid properties, heat exchanger size and heat transfer and has been developed. The model output include information on cycle performance with different temperature and pressure configurations as well as heat exchanger size that works as dimensioning component regarding space constraints in this thesis.

The results is presented in a simple excel chart.

3.2 Terminology

3.2.1 Acronyms

Table 2: Acronyms used in this thesis

Term	Description
NMBU	Norges miljø- og biovitenskapelige Universitet / University of Life Sciences
IMT	Department of Mathematical science and Technology
CHP	Combined heat and power
WHRS	Waste heat recovery system
WHRU	Waste heat recovery unit
IC	Internal Combustion
R & D	Research & Development
Micro Turbine	Turbine that delivers output between 1-100kW
CRGT	Chemically recuperated gas turbine
EU ETS	European Union Emissions Trading System

3.2.2 Symbols and units

Table 3: Symbols and units used in thesis

Symbol	Description	SI-Unit
$\boldsymbol{P}$	Pressure	kPa
$\boldsymbol{V}$	Volume	m^3
$\boldsymbol{v}$	Specific volume	m^3/kg
$\boldsymbol{T}$	Temperature	℃ $or\ K$
$\boldsymbol{l, w, h}$	Length, width & height	m
$\boldsymbol{A}$	Area	m^2
$\boldsymbol{r}$	Radius	m
ø	Diameter	m
$\boldsymbol{N}$	Rounds per minute	rpm
$\boldsymbol{\dot{m}}$	Mass flow	m^3/s
$\boldsymbol{h}$	Enthalpy	kJ/kg
$\boldsymbol{s}$	Entropy	$kJ/kg * K$
$\boldsymbol{q}$	Received/Rejected heat	kJ/kg
$\boldsymbol{\dot{W}}$	Component effect	kW
$\boldsymbol{W}$	Work	kJ/kg
$\boldsymbol{\eta}$	Efficiency	$\%$
$\boldsymbol{C}$	Heat capacity	kW/K
$\boldsymbol{c_p}$	Specific heat capacity	$kJ/kg * K$
$\boldsymbol{U}$	Heat transfer coefficient	$W/m^2/K$
$\boldsymbol{\Delta T}$	Mean temperature	℃
$\boldsymbol{\Delta T_{lm}}$	Logarithmic mean temperature	℃

3.2.3 Formulas and equations

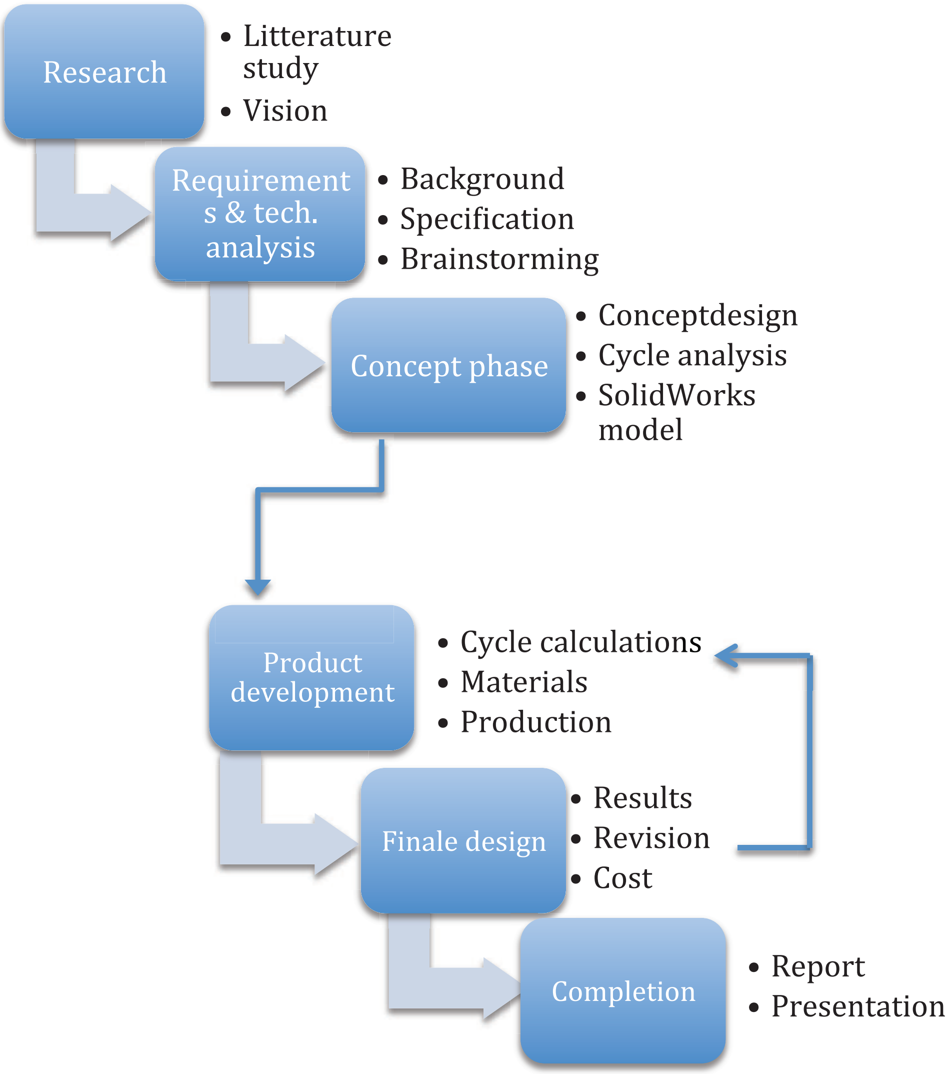
Table 4: Formulas used in thesis (21)

Description	Formula	Index
Conservation of energy	$E_{in} - E_{out} = \Delta E$	[1]
Work by pump	$W_{pump} = h_2 - h_1 = v_1 * (P_2 - P_1)$	[2]
Entropy state 4	$s_4 = s_3 = s_f + s_{fg} * x_4$	[3]
Quality of steam state 4	$x_4 = \frac{s_4 - s_f}{s_{fg}}$	[4]
Enthalpy state 4	$h_4 = h_1 + x_4 * h_{fg,4}$	[5]
Work by pump	$W_{pump} = h_2 - h_1$	[6]
Work by turbine	$W_{turb} = h_3 - h_4$	[7]
Heat added by heat exchanger	$q_{in} = h_3 - h_2$	[8]
Heat rejected in condenser	$q_{out} = h_4 - h_1$	[9]
Thermal cycle efficiency	$\eta_{TH} = \frac{W_{net}}{q_{in}} or\ 1 - \frac{q_{out}}{q_{in}}$	[10]
Net work in cycle	$W_{net} = W_{turb} - W_{pump}$	[11]
Actual turbine work	$\dot{W}_{net} = \dot{m}_s * W_{net} * \eta_{TH,turbine}$	[12]
Overall system efficiency	$\eta_{TH,overall} = \frac{\dot{W}_{net,\ gas\ turbine} + \dot{W}_{net}}{Energy\ added\ in\ gas\ turbine}$	[13]
Mass balance in system	$\dot{m}_{in} - \dot{m}_{out} = \Delta\dot{m}_{system}$	[14]
Energy balance in system	$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}$	[15]
Temperature of outbound exhaust	$T_{exh,out} = \frac{m_s * (\dot{h}_2 - h_3)}{\dot{m}_{exh} * C_{p,exh}} + T_{exh,in}$	[15]
Heat capacity of exhaust	$C_{exh} = \dot{m}_{exh} * c_{p,exh}$	[16]
Rate of heat transfer	$\dot{Q} = C_{exh} * (T_{exh,in} - T_{exh,out})$	[17]
Rate of heat transfer	$\dot{Q} = U_{HE} * A_{HE} * \Delta T_{lm}$	[18]
Logaritmic mean temperature	$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$	[19]
Area of a tube (sylinder)	$A_{tube} = 2 * \pi * r_{tube} * l_{tube}$	[20]
Height of tube	$h_{HE} = \left(\frac{A_{tube}}{w_{HE}/\emptyset_{tube}}\right) * \emptyset_{tube}$	[21]

3.2.4 Tools & Resources

Dropbox replaces project file in this study. All materials are synced with dropbox. Supervisor is given access to dropbox if needed. Microsoft Word is used as text editor in this report, together with endnote as reference tool. All figures and graphics are edited with Adobe Illustrator. GanttProject is used as gantt scheme software.

3.2.5 Process chart



Process chart
The process chart shows the development steps in this thesis and follows the classic staircase principal. If necessary changes have to be done, revisions are possible.

4 Theory

Conservation of energy

One of the most fundamental laws of nature is the conservation of energy principle. In physics, the law of conservation of energy states that the total energy of an isolated system cannot change. Energy can be neither created or destroyed, but can change form. In this thesis case, chemical energy can be converted to mechanical energy. (21)

Energy balance is expressed as:

$$E_{in} - E_{out} = \Delta E \qquad [1]$$

The first law of thermodynamics is simply an expression of he conservation of energy principle, and it asserts that energy is a thermodynamic property. (21)

The terms steady is used frequently in engineering, and thus it is important to have a clear understanding of their meanings. The term steady implies *no change with time*. A large number of engineering devices operate for long periods of time under the same conditions, and they are classified as *steady-flow devices*. A process involving such devices can be represented reasonably well by a somewhat idealized process, called the *steady-flow process,* which can be defined as a "process during which fluid flows through a control volume steadily". Therefore, the volume V, the mass m, and the total energy content E of the control volume remain constant during a steady flow process.(21)

Devices that are intended for continuous operation such as turbines, pumps, boilers, condensers and heat exchangers or power plants can closely be approximated by the steady-flow conditions. Some cyclic devices, such as reciprocating engines or compressors, do not satisfy any of the conditions stated above since the flow at the inlets and the exits will be pulsating and not steady. (21)

Internal energy

Internal energy is defined as the sum of all the microscopic forms of energy of a system. It is related to the molecular structure and the degree of molecular activity and can be viewed as the sum of the kinetic and potential energies of the molecules. (21)

The internal energy is also associated with various binding forces between the molecules of a substance, between the atoms within a molecule, and between the particles within an atom and its nucleus. The forces that bind the molecules to each other are, as one would expect, strongest in solids and weakest in gases. (21)

"*If sufficient energy is added to the molecules of a solid or liquid, the molecules overcome these molecular forces and break away, turning the substance into a gas*".(21)

Because of this added energy, a fluid in gas form contains higher energy levels than a fluid in solid or liquid phase. This is a phase-change process that is going to analyzed and calculated later.

Mechanical energy

The mechanical energy can be defined as *the form of energy that can be converted to mechanical work completely and directly by an ideal mechanical device such as an ideal turbine.* Kinetic and potential energies are the familiar forms of mechanical energy. (21)

Energy transfer by heat

Energy can cross the boundary of a closed system in two distinct forms: heat and work. Heat is defined as *the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference.* *(21)*

In other words an energy transfer is only heat if it's because of a temperature difference. The energy transfer cases that will be analyzed in this thesis are heat addition and heat rejection. That is transfer of energy from one fluid to another because of a temperature difference.

A process during which there is no heat transfer is called an *adiabatic process*. There are two ways a process can be adiabatic. Either the system is well insulated so that only a negligible amount of heat can pass through the boundary, or both the system and the surroundings are at the same temperature and therefore there is no driving force (temperature difference) for heat process. (21)

Energy transfer by work

Work is an energy interaction between a system and its surroundings. Then, an energy interaction that is not caused by a temperature difference between a system and its surroundings is work. An example of a work interaction is a rotating shaft. (21)

"*The heat transfer is zero for adiabatic systems, the work transfer is zero for systems that involve no work interactions, and the energy transport with mass is zero for systems that involve no mass flow across their boundaries".(21)*

Enthalpy & Entropy

In the analysis of certain types of processes, particularly in power generation and refrigeration, we frequently encounter the combination of properties $(u + Pv)$. For the sake of simplicity and convenience, this combination is defined as a new property, *enthalpy,* and designated h. The widespread use of the property enthalpy is due to professor Richard Mollier, who recognized the importance of the group $(u + Pv)$ in the analysis of steam turbines and in the representation of the properties of steam in tabular and graphical form (as in the famous Mollier chart). (21)

Entropy is an extensive property of a system and sometimes is referred to as total entropy. Entropy per unit mass, designated s, is an extensive property and has the unit $kJ/kg * K$. (21)

A process during which the entropy remains constant is called an *isentropic process.* Many engineering systems or devices such as pumps, turbines, nozzles, and diffusers are essentially adiabatic in their operation, and they perform best when irreversibilities, such as friction associated with the process, are minimized. Therefore an isentropic process can serve as an appropriate model for actual processes. (21)

Steam

Steam (superheated steam) is a state where water is in a gas phase. As mentioned before heat transfer is necessary in order to change phase from liquid to gas.

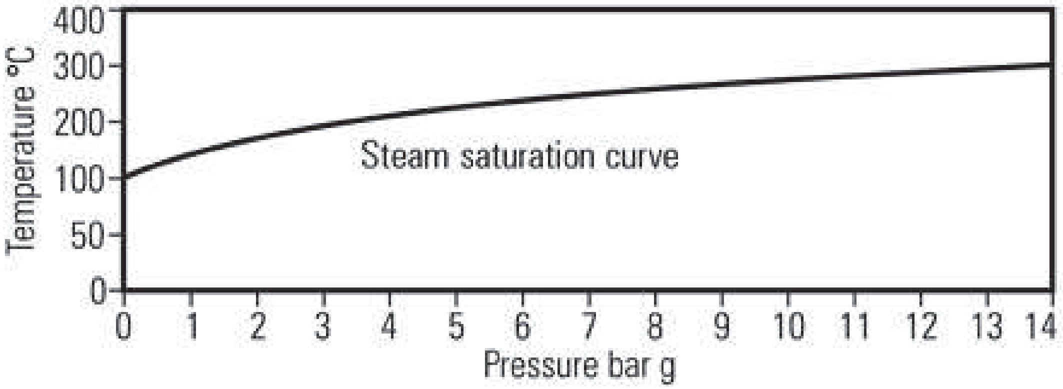


Figure 16: Steam saturation curve with respect to temperature and pressure (22)

The relationship between saturation temperature and pressure is shown in Figure 16. It is called the steam saturation curve. At atmospheric pressure the saturation temperature is 100°C. If pressure is increased, this will allow the addition of more heat and an increase in temperature without change of phase. (22)

5 Description

5.1 Previous work

As mentioned in chapter 1.2 it exist different combined heat and power systems all over the world in nuclear reactor power plants, warships, small power plants, factories and hospitals. However, in the market for micro waste heat utilization, there is hardly any competition. The same goes for the market of micro combine cycle operation.

Most of the previous work done on this subject in micro level is theoretical analysis of combined heat and power cycles. Some producers have done major research projects on increasing efficiency of micro gas turbines (Capstone, Jaguar etc.) but very few, if any, have come up with an actual working solution for vehicles.

There is still a lot of work maximizing regular CHP that takes place at manufacturing plants, hospitals, universities, and the like. It has not reach its potential regarding thermal efficiency. EPA and DOE estimates that between CHP and waste energy recovery U.S. could slash the greenhouse gas emissions by 20%. That’s as much as if every passenger vehicle were taken off the road.

Science daily (23) recently posted an article that says that Yanliang Zhang, a professor in the Department of Mechanical and Biomedical Engineering, is given $8 million funding in his research project were he wants to make cars more efficient by utilizing waste heat. The goal is to develop and test a thermoelectric waste heat recovery system capable of enhancing the fuel efficiency of a light-duty vehicle by 5 percent.

It is safe to say that you can notice some movement in the engineering world that focuses on waste heat recovery in vehicles.

Some manufacturers have come up with components that can fit in a CHP system, but virtually no complete solution exists. Here are some examples of existing products:

GreenTurbine

Green turbine is a very small (slightly larger than a football) steam driven turbo generator that converts waste heat into electricity. As the temperature of the needed steam is relatively low (200 °C), waste heat without supplementary firing can often be used to fire the turbine as second stage in a micro CHP system. The energy output is 1,2kW, but GreenTurbine have prototypes of 15kW steam turbines currently being developed.

Figure 17: 1,2kW Steam turbine from GreenTurbine (24)

Micro Turbine Technology Bv (MTT)

MTT's micro CHP system solution is a system for small business and households. The highly cost efficient system produces 3 kW electric power and reduces the energy bill by 20-25%. Environmental standards are met with low noise and exhaust emissions. The micro CHP can be fired using a wide range of fuels including natural gas, propane, heating oil and biogas. (25)

Figure 18: MTT Bv CHP system (25)

Nesjavellir geothermal power plant

Nesjavellir is a geothermal power station in Iceland. The Nesjavellir power plant is a CHP plant wherein it produces electricity and hot water for district heating. The mixture of steam and geothermal brine is transported from the wells to the power plant where it is separated. The steam resulting in 120MW electrical power, and the brine resulting in 1100 liters of hot water per second, servicing the space heating and hot water needs of the Greater Reykjavik.(26)

Figure 19: Nesjavellir geothermal power plant, 120MW (26)

5.2 System overview

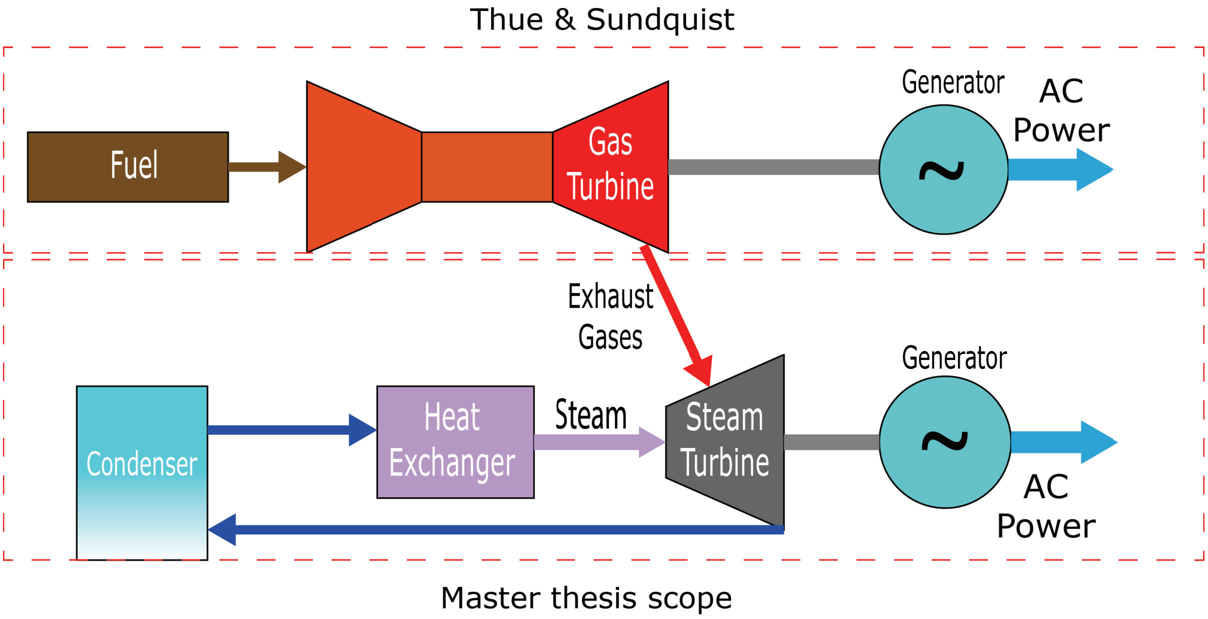


Figure 20: Combined Heat and Power Cycle - System Overview

The system above is a Combined Heat and Power system. The upper red square, is the result of a Master thesis from Thue & Sundquist, designing a multi fuel gas turbine. The lower red square represents the scope of this thesis. The intention is to create a waste heat recovery system.

The cogeneration technology is designed to combine electrical and mechanical equipment into a operating system converting fuel energy into both electric power and useful thermal energy. The electrical power gives mechanical shaft power to move the vehicle, and the thermal energy is being guided into a waste heat recovery system.

By arranging a series of thermodynamic processes into a cycle, the CHP systems are designed to convert heat to work on a continuous basis.

The combined cycle of greatest interest is the gas-turbine (Brayton) cycle topping a steam-turbine (Rankine) cycle, which has a higher thermal efficiency than either of the cycles executed individually.

Recent developments in power plant gas-turbine technology have made the combined gas-steam cycle economically very attractive. The combined cycle increases the efficiency without increasing the initial cost greatly. The challenge in the micro CHP is to downscale it without decreasing thermal efficiencies.

5.3 Energy source – Gas turbine exhaust heat

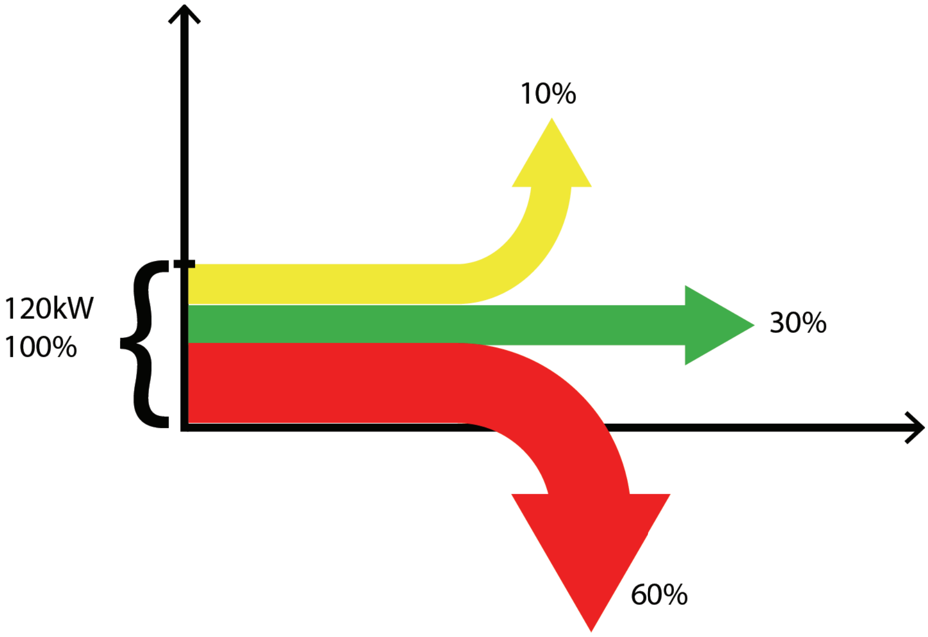


Figure 21: Losses in a gas turbine

Approximately 60% of the total energy added is exhausted from the gas turbine as heat. Gas turbines produce high-quality exhaust heat that can be used in CHP configurations. 10% is lost due to heat loss through the material of the gas turbine. 30% off the added energy goes directly to the generator. (27)

5.3.1 Gas turbines

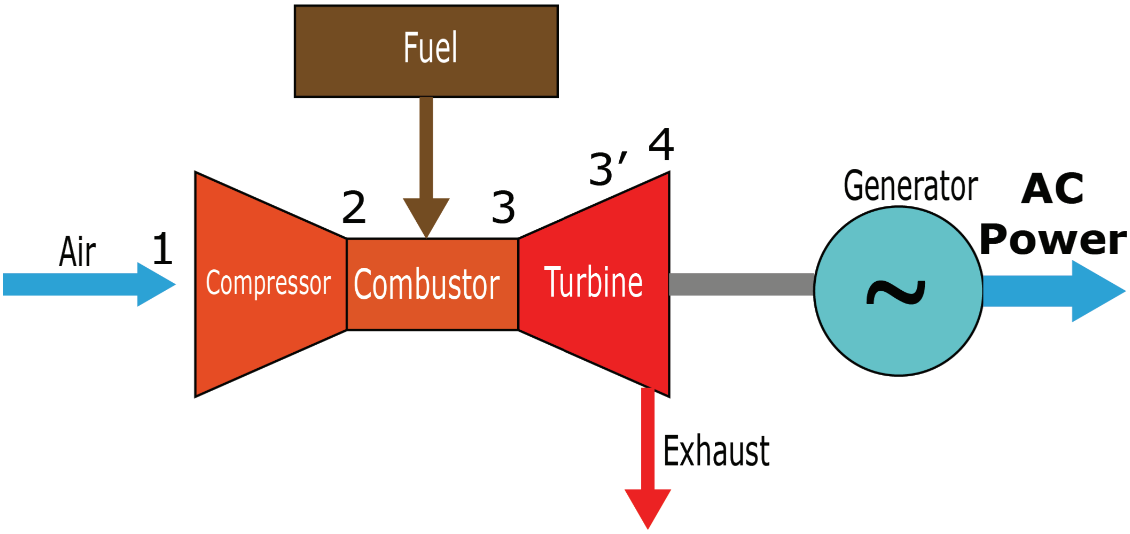


Figure 22: Gas turbine cycle with numbered cycle steps: 1-2: Air compression. 2-3: Heat added through combustion. 3-3': Flow through turbine to run compressor. 3'-4: Flow through turbine to rotate shaft (useful work).

Gas turbine systems operate on the thermodynamic cycle known as Brayton. Atmospheric air is compressed, heated with the help from a chosen fuel, and then expanded. The excess of power produced by the turbine over that consumed by the compressor is utilized for power generation.

The power produced by an expansion turbine and consumed by a compressor is proportional to the absolute temperature of the gas passing through the device. Consequently, it is advantageous to operate the expansion turbine at the highest practical temperature consistent with economic materials and internal blade cooling technology and to operate the compressor with inlet air flow at as low a temperature as possible. (28)

5.3.2 Gas turbine cycle

A cycle describes what happens to air as it passes into, through, and out of the gas turbine. The Brayton cycle (1876), shown in graphic form in (Figure 23) as a pressure-volume diagram, is a representation of the properties of a fixed amount of air as it passes through a gas turbine in operation. These same points are also in the schematic in (Figure 22). A gas turbine that is configured and operated to closely follow the Brayton cycle is called a simple cycle gas turbine.

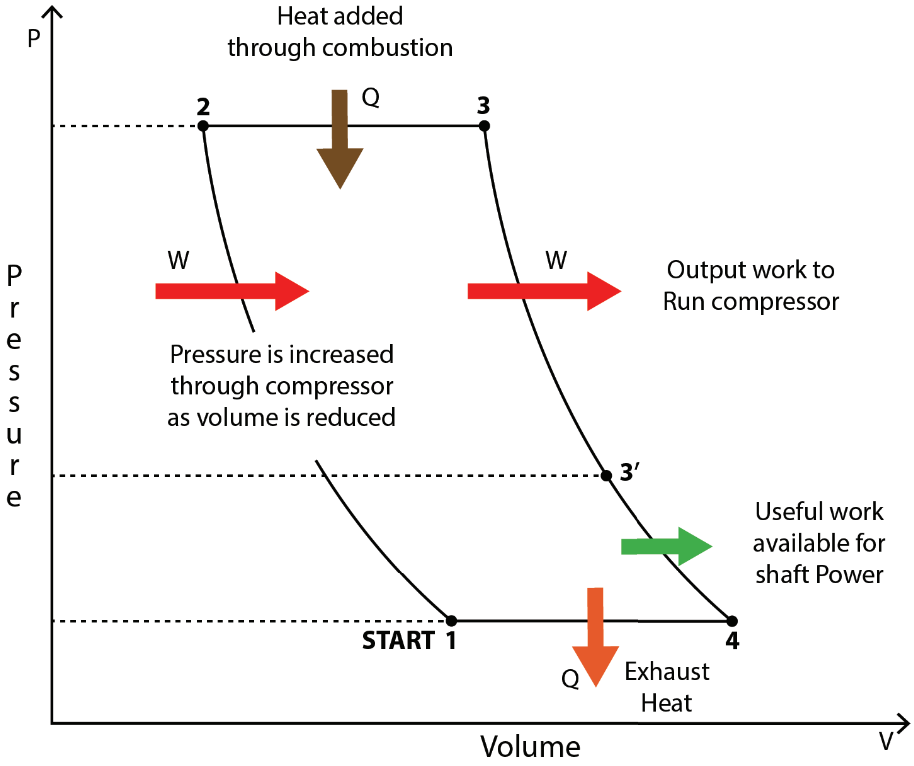


Figure 23: Brayton cycle in a gas turbine

Air is compressed from point 1 to point 2. This increases the pressure as the volume of space occupied by the air is reduced. The air is then heated at constant pressure from point 2 to point 3. The heat is added by injecting fuel into the cumbostor and igniting it on continuous basis. The hot compressed air at point 3 is then allowed to expand (from point 3 to 4) reducing the pressure and temperature and increasing its volume. In the engine in (Figure 22), this represents flow through the turbine to point 3’ and then flow through the power turbine to point 4 to turn a shaft. The "useful" work in (Figure 23) is indicated by the curve 3'- 4. This is the energy available to generate power. (7)

5.4 Heat recovery - Master thesis scope

5.4.1 Potential of waste heat energy

Industrial waste heat refers to energy that is generated in industrial process without being put to practical use. Sources of waste heat include hot combustion gases discharged to the atmosphere, heated products exiting industrial processes, and heat from equipment surfaces.(29)

Waste heat losses arise both from equipment inefficiencies and from thermodynamic limitations on equipment and processes. Exhaust gases immediately leaving the furnace can have temperatures as high as 1200-1300°C. Consequently, these gases have high-heat content, carrying away as much as 60% of the furnace input. (29)

Evaluating the achievability of waste heat recovery requires evaluating the waste heat source and the stream to which heat will be transferred.

5.4.2 Recovery of exhaust heat from gas turbines

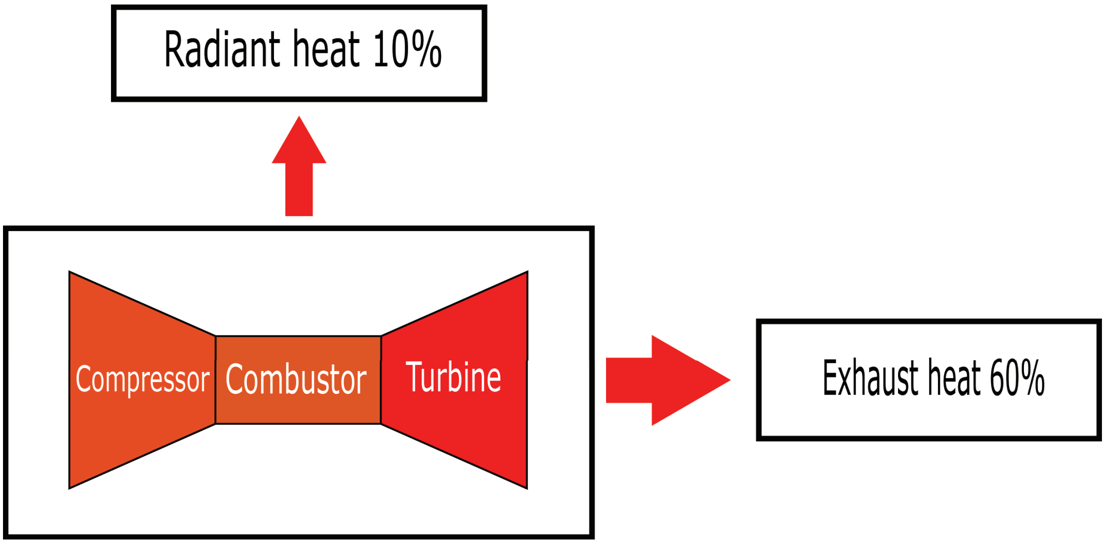


Figure 24: Gas turbine system that shows waste heat recovery potential

There are different ways of recovering heat from a gas turbine:

1. **Externally:**
    a. Steam turbine (CHP)
    b. Steam turbine w/Fired boiler
    c. Heat flux
2. **Internally:**
    a. Reusing the thermal energy exiting the turbine, and use it for preheating the combustion air. (Or unconventional techniques such as humid air regeneration and steam fuel reforming)

More advanced methods such as steam injection and chemically recuperated gas turbine (CRGT) are not covered in this thesis, as its focuses on a simple concept.

Externally

Combined Heat and Power (CHP)

A combined heat and power system is a system that combines the Brayton cycle of the gas turbine with Rankine cycle of the steam turbine. In a typical layout (Figure 25) exhaust heat from the gas turbine, passing through a heat recovery steam generator (Usually a heat exchanger) produces steam that evolves in the bottoming steam cycle.

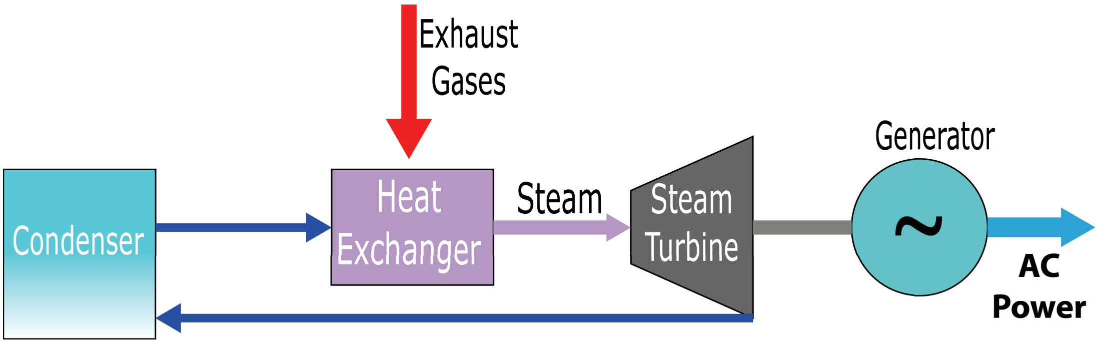


Figure 25: Steam turbine concept

Combined Heat and Power (CHP) with Boiler

Waste heat boilers are water boilers that use high-temperature exhaust gases to generate steam. In cases where the waste heat is not sufficient for producing desired levels of steam, auxiliary burners or an afterburner can be added to attain higher steam output. (29)

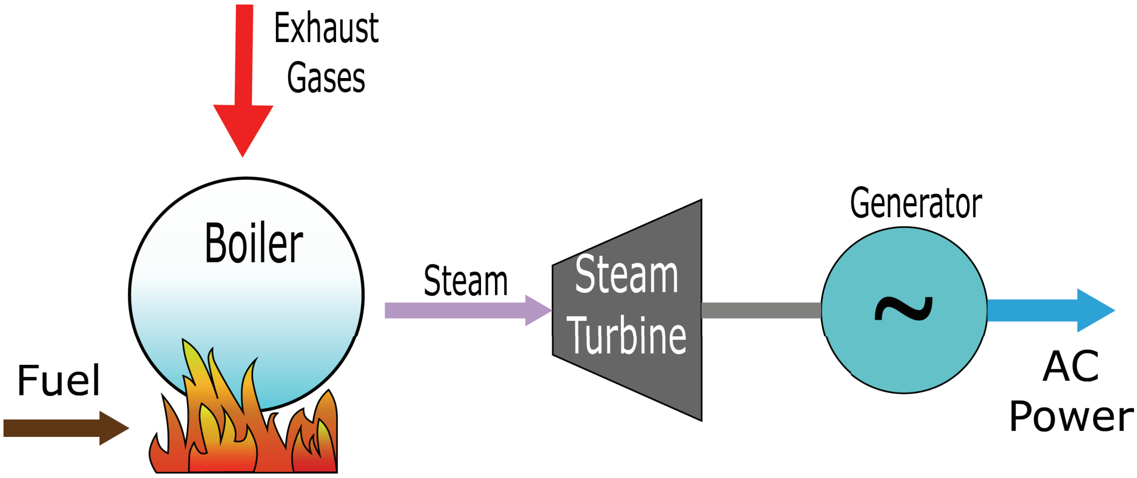


Figure 26: Gas turbine system with supplementary firing of received exhausts gas in a boiler to achieve desirable superheated steam.

Heat flux through combustor walls

To exploit heat through the gas turbines walls, the turbine is wrapped in water. In other words, a heat exchanger that creates steam for a steam turbine.

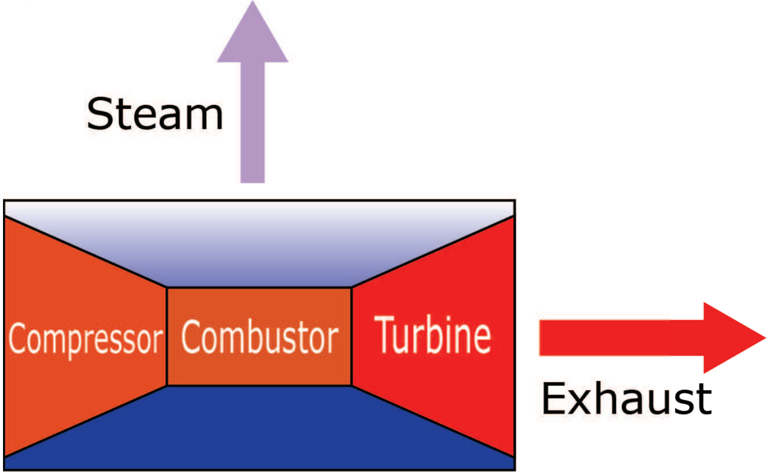


Figure 27: Gas turbine system wrapped in water, works as a heat exchanger

The amount of heat flux through the combustor walls depends on the combustor wall temperature, which in turn is a function of the compressor inlet gas temperature, the distance between turbine and compressor impeller, the conductivity of the material and the heat transfer coefficient. It is different ways of exploiting energy from heat flux. Turbine wrapped in water or air is probably the most efficient.

Internally

The need to combine the high efficiency of combined cycles with low cost simple cycles has raised the interest in low technologies that enable internal waste heat recovery from the gas turbine. Internal heat can be recovered through the working fluid such as fuel or air.

Regeneration

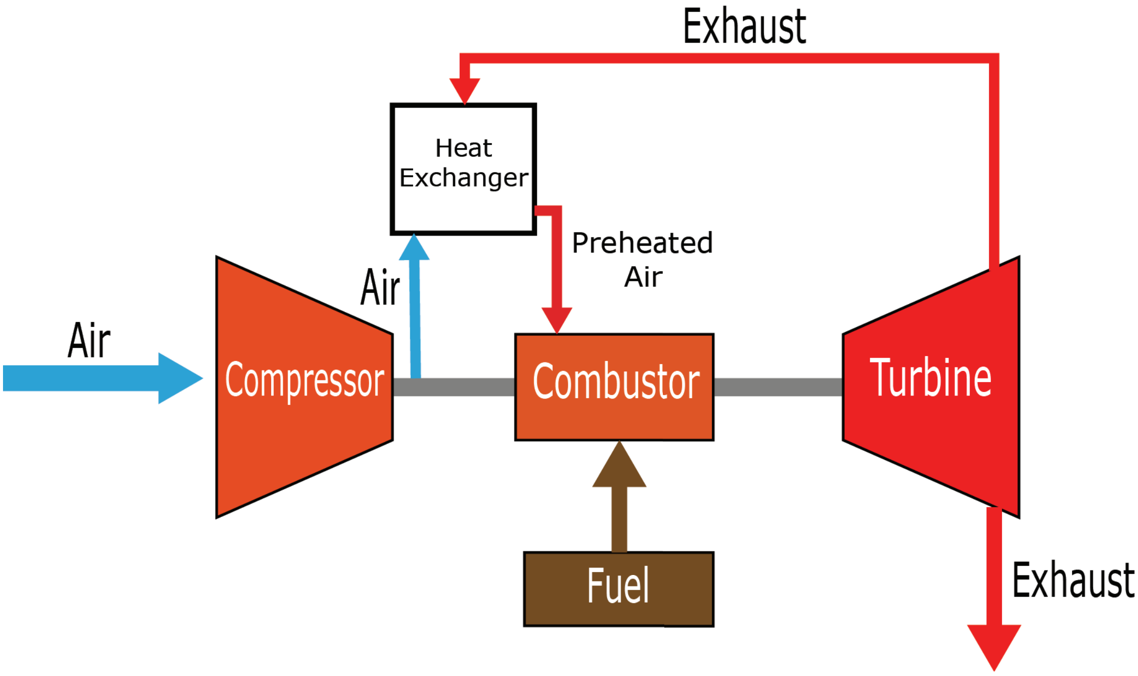


Figure 28: Gas turbine system with recuperator. Air is preheated before combustion.

Regeneration involves the installation of a heat exchanger (recuperator) through which the turbine exhaust gases pass (Figure 28). The compressed air is then heated in the exhaust gas heat exchanger, before the flow enters the combustor. If the regenerator is well designed (i.e., the heat exchanger effectiveness is high and the pressure drops are small) the efficiency will be increased over the simple cycle value.

Intercooling

Intercooling also involves the use of a heat exchanger. An intercooler is a heat exchanger that cools compressor gas during the compression process. For instance, if the compressor consists of a high and low pressure unit, the intercooler could be mounted between them to cool the flow and decrease the work necessary for compression in the high pressure compressor. The cooling fluid could be atmospheric air or water. It can be shown that the output of a gas turbine is increased with a well-designed intercooler. (7)

5.5 Energy conversion - Steam turbine

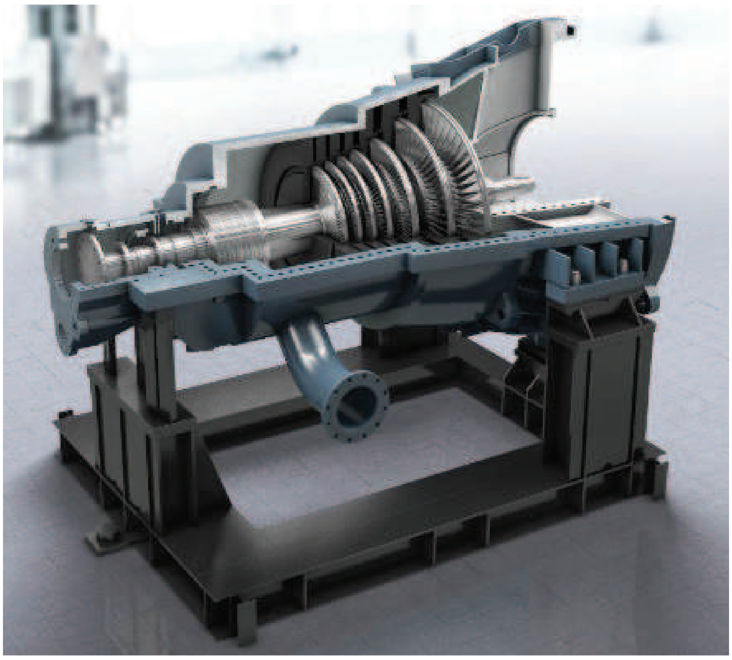


Figure 29: Siemens 60MW steam turbine (30)

5.5.1 Steam turbines

A steam turbine is a unit that converts thermal energy from fluid to mechanical energy. More precisely as rotational energy of rotors on a shaft. Waste heat to power works by capturing industrial waste heat and converting it into electricity.

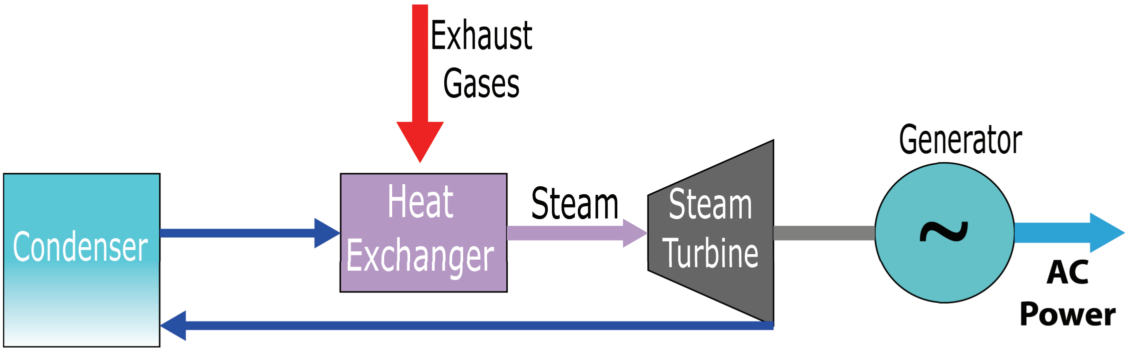


Figure 30: Steam turbine that uses exhaust gases as source for steam generation

The steam turbine consists of a heat source (Heat Exchanger) that converts water to low pressure steam. The steam flows through the turbine to produce power by rotating the shaft. The steam exiting the turbine is condensed and returned to the heat exchanger to repeat the process.

A steam turbine is highly customizable, and can be designed to match the CHP design pressure and temperature requirements. It is also capable of operating over a broad pressure range. Steam turbines offer the best fuel flexibility using a variety of fuel sources including nuclear, coal, oil, and natural gas, wood and in our case; waste heat. (28)

In this thesis the steam turbine is defined as a heat recovery device. Producing electricity in a steam turbine from the exhaust of a gas turbine (combined cycle).

Since gas turbine exhaust is oxygen rich, it can support additional combustion through supplementary firing. A duct burner is usually fitted within the heat recovery steam generator to increase the exhaust gas temperature if necessary at efficiencies of 90% and greater. (28)

5.5.2 Steam turbine cycle

Superheating the steam, and condensing it completely in the condenser can eliminate many of the impracticalities associated with the Carnot cycle. The cycle that results is the Rankine cycle (Figure 31), which is the ideal cycle for vapor power plants. (21)

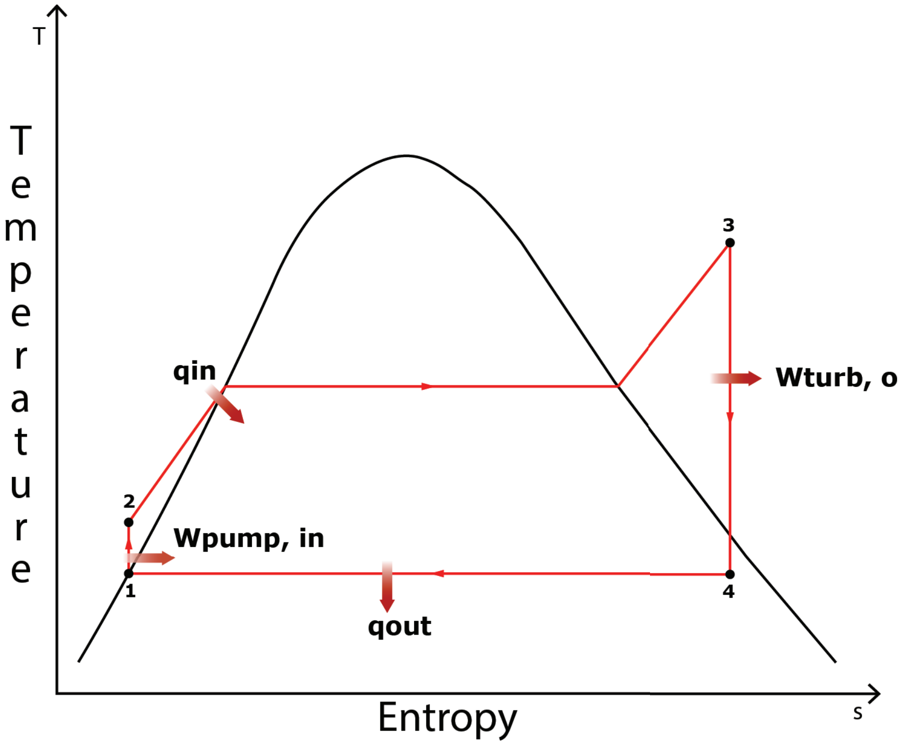


Figure 31: Rankine cycle for a steam turbine

The ideal Rankine cycle does not involve any internal irreversibilities and consists of the following four processes:

1-2: Isentropic compression in a pump
2-3: Constant pressure heat addition in a boiler/heat exchanger
3-4: Isentropic expansion in a turbine
4-1: Constant pressure heat rejection in a condenser

Losses in a non-ideal Rankine cycle system

The losses in a non-ideal Rankine cycle can be as follows:

1. Losses due to cylinder condensation (surface loss).
2. Losses due to the volume of the clearance space (clearance volume loss).
3. Loss due to throttling or wire drawing.
4. Friction loss.
5. Loss due to leakage.
6. Loss due to heat radiation and convection.
7. Loss due to incomplete expansion.

5.5.3 Heat exchanger

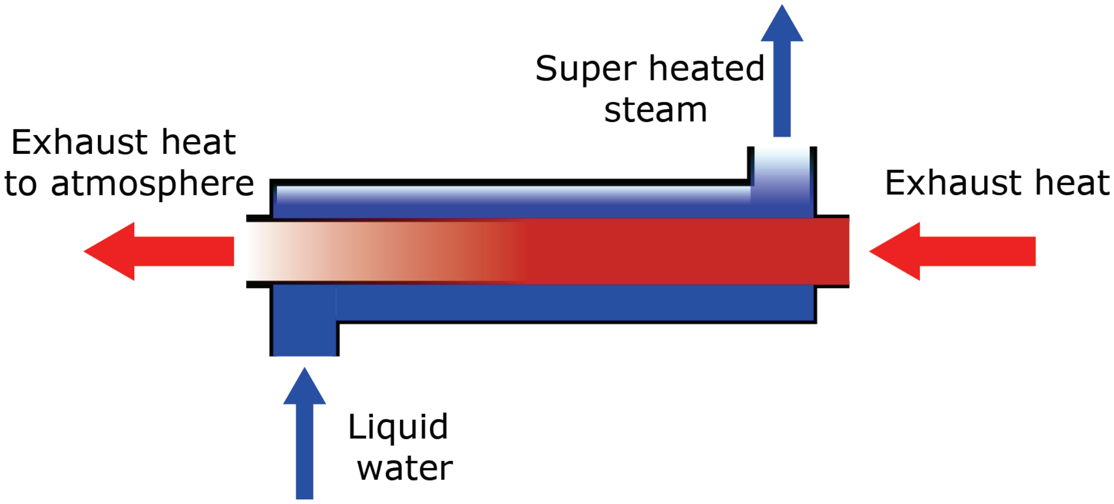


Figure 32: Counter flow tube-and-shell heat exchanger with exhaust heat on the hot side and water on the cold side

High quality exhaust heat enters the counter flow heat exchanger from the gas turbine. In a counter direction water enters from the condenser at a given temperature. As it flows through the heat exchanger it changes phase and exits preferably as superheated steam.

6 Concept description

The goal of this project is to develop a system design for the recycling and utilization of waste heat based on the micro gas turbine from Thue & Sundquist and design constraints and space requirements from the Dolphin concept car. A detailed literature study and thermodynamic cycle analysis was performed, resulting in a concept selection.

6.1 Concept selection

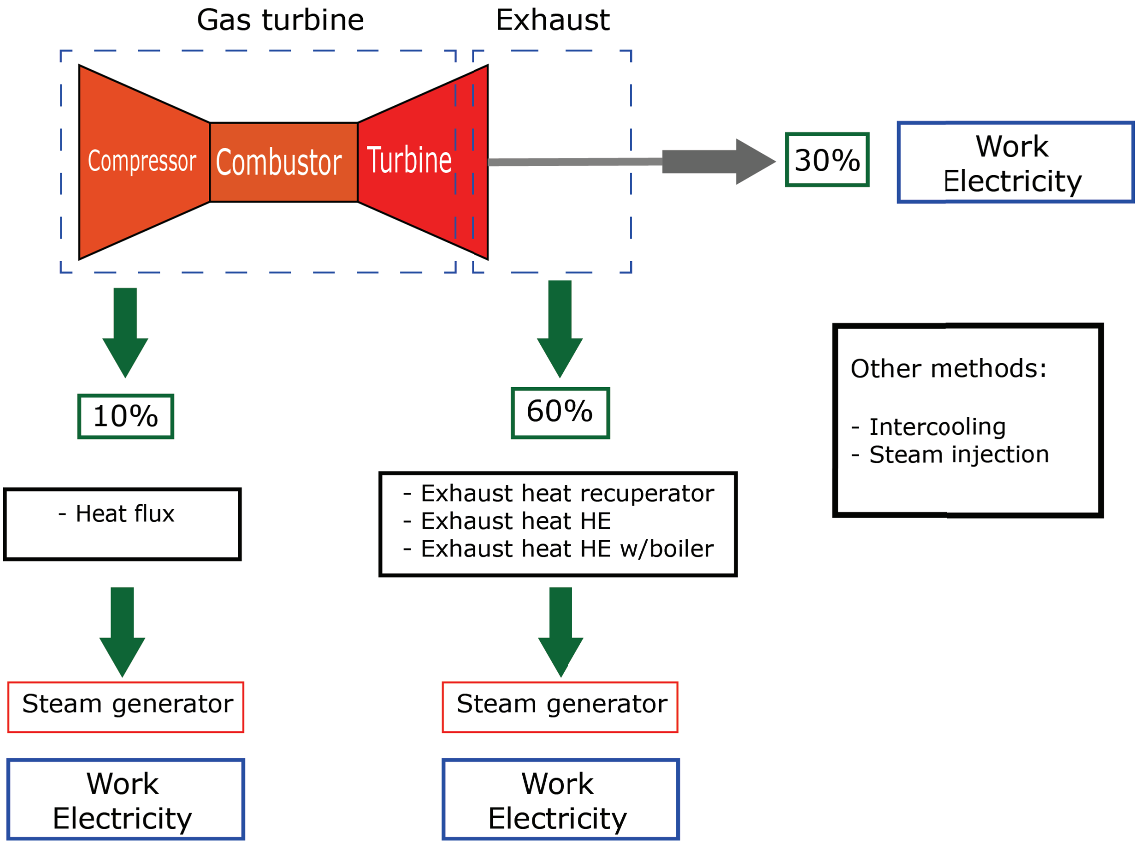


Figure 33: Concept selection matrix

The selection matrix shows different alternatives on how to achieve the goal of increasing the overall system efficiency. Due to limitations, this thesis will only consider the exhaust of the gas turbine, where the heat recovery potential is higher. Using the gas turbines heat flux is an interesting subject, but not studied in this thesis. It is also reason to believe that if you wrap the gas turbine in water, the effect will be significant noise reduction. Designing a system that uses a exhaust heat recuperator involves a change in gas turbine design, consequently it becomes a limitation in this thesis.

As much as 60% of the energy input is exhausted, thus as little as 10% heat recovery can be substantial increase in the overall system efficiency. The three ways of exploiting thermal energy in exhaust heat discussed in this thesis is:

1. *Exhaust heat recuperator:* Recover a little part of the exhaust heat and guide it into the combustor for preheating of the air, resulting in less amount of energy needed to reach desirable temperatures, therefore less fuel consumption and increase in overall system efficiency.

2. *Exhaust heat HE*: Guide the exhaust through a heat exchanger where the exhaust heat is on the hot side and water on the cold side, resulting in steam generation. The thermal energy is routed through a steam turbine, and as a result much of its thermal energy is converted to electrical energy. The result is increase in overall system efficiency.

3. *Exhaust heat HE w/boiler*: Guide the exhaust into a heat exchanger/boiler where additional firing is done to reach satisfying steam temperatures. The thermal energy is converted to electrical energy. The result is increase in overall system efficiency.

6.2 Chosen WHRS concept

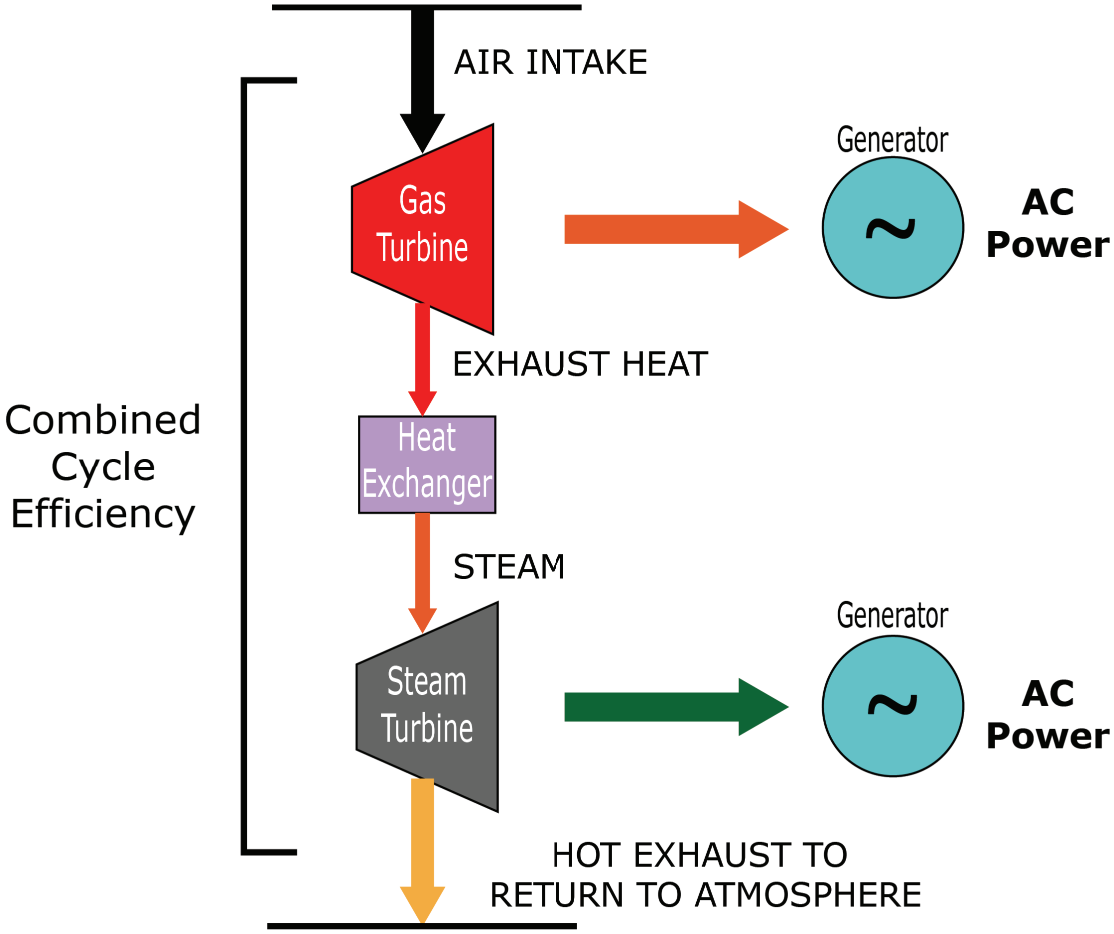


Figure 34: Chosen WHRS concept. Rankine cycle steam turbine topped of Brayton gas turbine cycle

The chosen concept is based on Thue & Sundquist's gas turbine. The thermal energy from exhaust is guided through a heat exchanger working as a steam generator. The energy is translated into mechanical energy by expanding the steam through a steam turbine. An addition of electrical power in the system will increase the overall system efficiency. In order to return the steam to the high-pressure of the steam generator to continue the cycle, the low-pressure steam leaving the turbine is first condensed to a liquid state, and then pressurized in a feedwater pump, ready for its next pass through the heat exchanger. In other words a Brayton cycle topping a Rankine cycle.

The chosen concept has several opportunities in choosing component configurations, and pressure/temperature configurations. A thorough system design and selection follows next.

7 System design

7.1 System design goal specifications

Table 5: Design goal specifications

Description	Value
Thermal efficiency	30 %
Electrical output effect	27kW
Overall system efficiency	50 %
Total weight	30kg
Heat exchanger volume	$1m^3$
Fuel	None

7.2 Desired WHRS design characteristics

Custom design
The WHRS should be designed to match the Dolphin concept cars requirements and constraints.

Thermal output
The steam turbine is capable of operating on a very broad range of steam pressures.

Fuel flexibility
Many WHRS systems have a boiler instead of a heat exchanger to produce the desired steam for the steam turbine. This thesis will only discuss a system with a heat exchanger without supplementary firing.

Reliability and life
A steam turbine life should last extremely long due to very few moving parts and rotational parts compared to a reciprocating engine. Overhaul interval are often measured in years.

Emissions
Emissions are dependent upon the fuel used by the energy source (gas turbine), the combustion design and operation.

7.3 Function analysis

The function analysis describes the main components of the WHRS.

Table 6: Description of functions in a WHRS

Function	Description
Exhaust air intake	The exhaust air intake leads the hot exhaust from the gas turbine to the heat exchanger.
Heat exchanger	The heat exchanger will be functioning as a steam generator. The two moving fluids, exhaust and water, will exchange heat without mixing, resulting in steam generation.
Disposal of Exhaust	The exhausts function is to guide the remaining gases to the atmosphere, noise reduction, as well as temperature and speed reduction.
Turbine	Steam flows to the turbine where part of its energy is converted to mechanical energy that is transmitted by rotating shaft to drive an electrical generator.
Condenser	The reduced energy flowing out of the turbine condenses to liquid water in the condenser. It is important that it is designed to correspond with the heat exchangers requirements.
Feedwater pump	A feedwater pump returns the condensed liquid to the steam generator. It is important that it is designed with minimal friction so it does not “steal” energy from the steam turbine output.
Generator	Its function is to transfer the rotational mechanical energy from the output shaft of the turbine, to electrical energy.

7.4 Selection

Instead of making one big selection matrix where the functions are being weighted, the functions are divided into several simple tables. Advantages and disadvantages are listed and a selection is made.

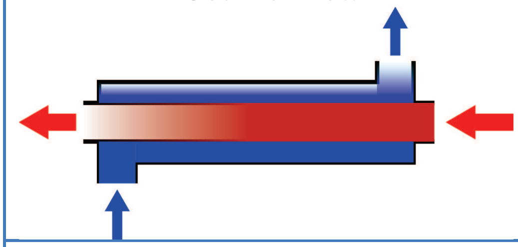
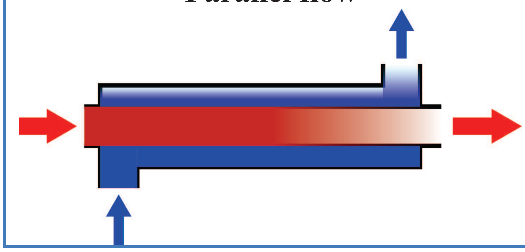
7.4.1 Exhaust air intake

One of the constraints on the amount of waste heat that could be extracted is the limit on excessive backpressure. Avoiding backpressure in the gas turbine is important, since it will decrease the gas turbine efficiency. Design considerations will be necessary. It means that the heat exchanger will have a bigger cross section in the beginning, than in the end. Limitations in this thesis limit the design to only major components of WHRS.

7.4.2 Heat exchanger

On the hot side of the heat exchanger are the combustion gases from the gas turbine. On the cold side it is feedwater, which is heated to saturated liquid, then evaporated to saturated vapor and then superheated steam. In a well-designed heat exchanger both fluids pass through with little pressure loss. The shell-and-tube heat exchanger is the most common, so to simplify this thesis it has been selected as heat exchanger.

Table 7: Heat exchanger selection

Component	Description	Selection
Counter flow 	+ Cheap design + Uniform temperature difference + Heat exchange potential is higher + Area of tube is less	✔
Parallel flow 	+ Cheap design + Exit temperature of water can never exceed the lowest temperature of the exhaust – Area of tube is bigger – Less heat transfer rate	

7.4.3 Disposal of exhaust

Due to limitations this will not be considered in this thesis. It is however important that the exhaust is guided to a place where it doesn't effect other parts of the car due to high temperatures, usually on the back of a car. If it is necessary, a noise reduction unit (muffler) can be added to the exhaust.

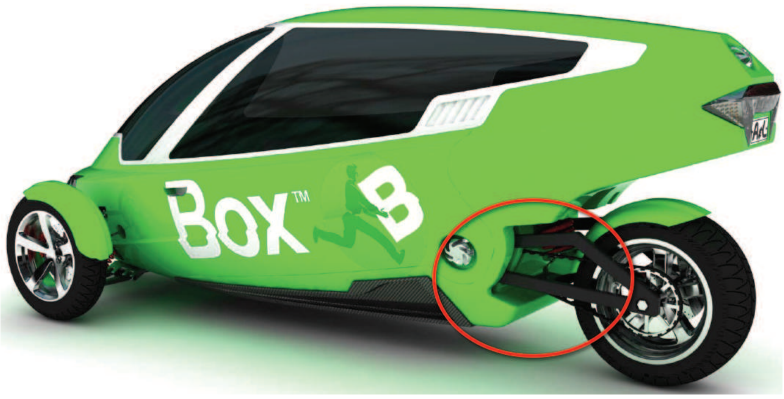


Figure 35: Dolphin concept car disposal of exhaust (3)

7.4.4 Turbine

Due to simplicity in the Rankine cycle and convenience in the calculations, a single stage expansion is assumed.

Table 8: Steam turbine concept selection

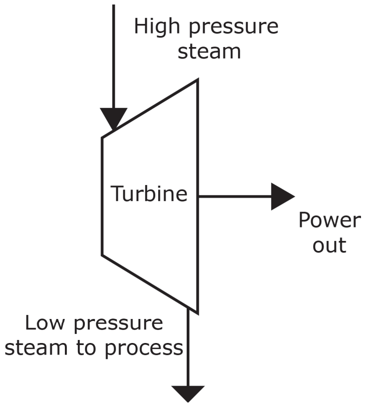
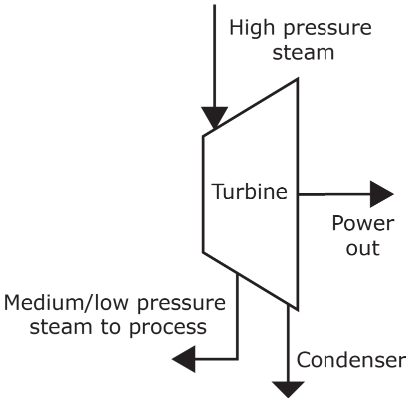
Component	Advantages/Disadvantages	Selection
Non-Condensing steam turbine  	+ Simplest configuration + Avoided expensive costs of low-pressure stages of turbine + Low capital cost + Reduced need of cooling water – A small amount of air is known to leak into the system – Sensitive to ambient conditions	✔
Extraction condensing steam turbine  	+ Portion of steam available for process purposes + Increased thermal efficiency – Possible steam leakage – Demands regulation of steam extraction pressure – Higher capital cost	

Table 9: Shaft to power selection

Component	Advantages/Disadvantages	Selection
Shaft-to-shaft power (Rotating shaft on the turbine is coupled directly on the drive shaft)	+ Less components – Delay from when the foot is on the pedal to reaction in turbine – Start up time – A turbine is not well suited for dynamic power demand	
Shaft-to-generator electrical power	+ No power delay + Fuel savings when the system is on idle, when the battery capacity is full. – Increase in components	✔

7.4.5 Working fluid

As a result of the turbine conversion of much of its thermal energy into mechanical energy, or work, steam leaves the turbine at a pressure and temperature well below the turbine entrance values. At this point steam could be released into the atmosphere. But since Dolphin is a vehicle and haven't unlimited amount of water available it is not possible to allow the luxury of one-time use. The water tank is approximated to need refill every 3weeks due to condensation. Water is chosen as working fluid due to convenience since water is available everywhere.

The mass flow of the steam in the circuit is set to 0,04 kg/s. When consulting with Greenturbine, they recommended using 0,04 kg/s calculating for ideal situations in a micro steam turbine.

7.4.6 Condenser

The condenser usually is a large shell-and-tube heat exchanger positioned below or adjacent to the turbine in order to directly receive the large flow rate of low-pressure turbine exit steam and convert it into liquid water. External auxiliary is pumped through the tubes in the condenser to transport the heat of condensation of the steam away from the plant. The heat is rejected to the surroundings.

Table 10: Condenser selection

Component	Advantages/Disadvantages	Selection
Shell-and-tube condenser (Surface condenser)	+ Simplicity + Less expensive + Allows higher temperatures and pressures + Pressure drop across tube is less – Heat transfer efficiency is less – Requires more space	✔
Plate-and-tube condenser	+ Compact + Heat transfer efficiency is more + Easy maintenance – Initial cost is high (Titanium plates) – Higher pressure drop than shell-and-tube	

7.4.7 Feedwater pump

The feedwater pump moves the condensed liquid from low pressure to high pressure. Work and power must be supplied to operate the pump, resulting in decrease in power delivered by the Rankine cycle. One of the significant advantages of the Rankine cycle is that the pump power is usually quite small compared with the turbine power. Compared to a gas turbine where the "back work" to rotate the compressor can be 60-80%, it is approximately 0-8% to rotate the feedwater pump in a Rankine cycle.

7.4.8 Generator

The rotating shaft of the electrical generator usually is directly coupled to the turbine drive shaft. One of the big advantages with a CHP system is that it allows unattended operation and interfacing with the commercial grid. Automatically power switching excludes the need for synchronization with the power grid. Thus, the generator can be directly coupled with the turbine shaft.

Table 11: Generator selection

Component	Advantages/Disadvantages	Selection
Shared generator with gas turbine	+ Less components – RPM difference complexity	
Separate generators	+ Simplicity – Higher cost	✔

7.5 Metrical boundaries

Table 12: Design variation

Description	Parameter	Min	Max
Rankine cycle steam turbine	Thermal efficiency	10%	30%
Electrical output effect of WHRS	Electrical effect	5kW	50kW
Overall system efficiency	Thermal efficiency	30%	60%

Table 13: Metrical boundaries of WHRS cycle components

Component	Parameter	Min [mm]	Goal [mm]	Max [mm]
Steam turbine	Diameter	250	300	350
	Length	450	500	550
Condenser	Width	700	750	800
	Height	50	150	250
	Length	800	900	1000
Pump	Diameter	250	300	350
	Length	450	500	500
Heat exchanger	Width	800	900	1000
	Height	50	150	250
	Length	1000	1100	1200

8 Calculations

8.1 The Brayton-Rankine cycle

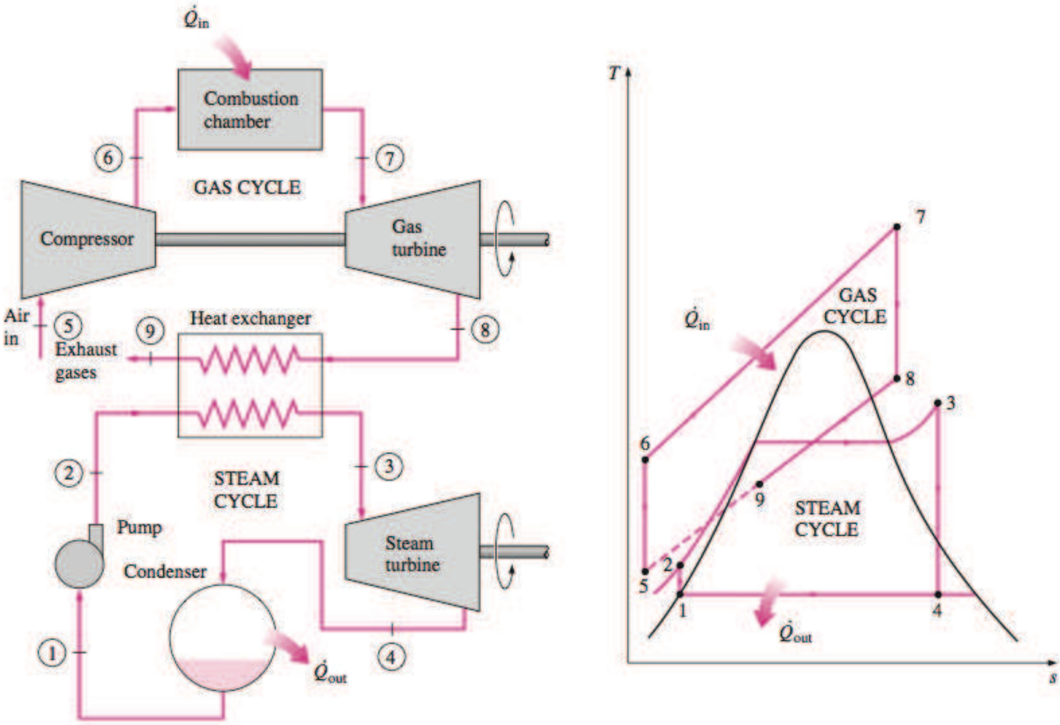


Figure 36: A CHP system. A Brayton cycle topping a Rankine cycle. Numbered with cycle steps. (21)

The modification showed in Figure 36 is a gas power cycle topping a vapor power cycle. (CHP) Since the gas turbines have the disadvantage of exhausting gas at 500°C+. The situation can be improved by recovering that heat.

It makes engineering sense to take advantage of the very desirable characteristics of the gas turbine cycle at high temperatures and to use the high-temperature exhaust gases as the energy source for the bottoming cycle such as a steam power cycle. (21)

Input from Thue & Sundquist gas turbine:

Table 14: Input from Thue & Sundquist gas turbine

Description	Unit	Notation	Value
Gas turbine thermal efficiency		$\eta_{TH,gas\ turbine}$	27%
Exhaust gas temperature	℃	$T_{exh,in}$	1018
Mass flow of exhaust	kg/s	$\dot{m}_{exh}$	0,256
Exhaust pressure	kPa	P_{exh}	102,694

8.2 WHRS calculations

Assumptions:

1. Steady-flow process since there is no change with time
2. The heat exchanger is well insulated so that heat loss to the surroundings is negligible and thus heat transfer from the hot exhaust is equal to the heat transfer to the cold fluid.
3. There are no work interactions
4. Changes in kinetic and potential energies of fluid/gas streams are negligible.
5. Fluid/gas properties are constant.
6. Exhaust gases are assumed to have air properties with constant specific heats.

Cycle analysis

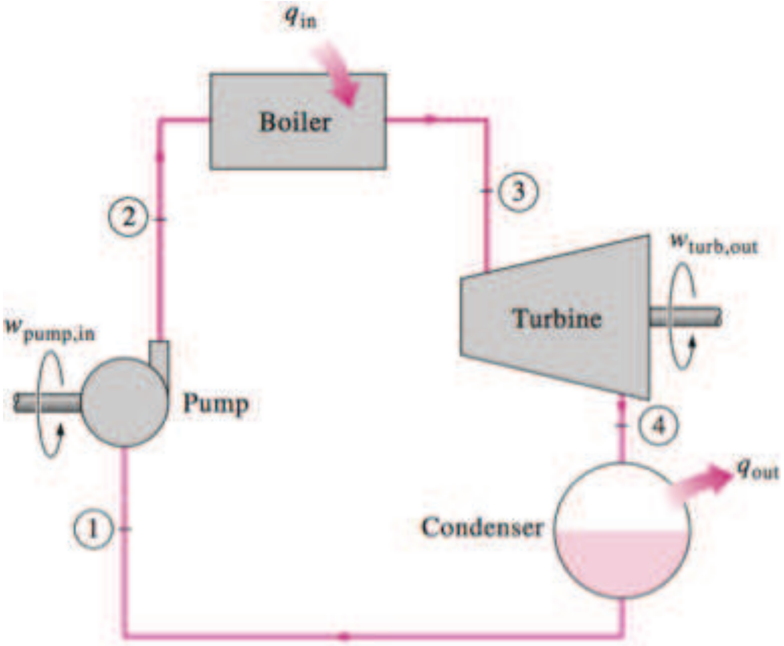


Figure 37: Ideal Rankine cycle ⁽²¹⁾

In this analysis it is assumed that the components of the WHRS system are joined by conduits that allow transport of the working fluid from the exit of one component to the entrance of the next, with no intervening state change.

- All flows of mass and energy are steady, so that steady state conservation equations are applicable
- The kinetic and potential energy changes of the steam are usually small relative to the work and heat transfer terms and are therefore neglected.

This is appropriate to most situations because power plants usually operate at steady conditions for significant lengths of time. Thus, transients at startup and shutdown are special cases that will not be considered. In the ideal Rankine cycle shown in (Figure 37) steam expands adiabatically and reversibly, or/and isentropically, through the turbine to a lower temperature and pressure at the condenser entrance. (21)

In order to calculate efficiencies, some conditions, such as the steam generator in and outlet temperatures T_2 and T_3, the turbine inlet and outlet pressure T_3 and T_3 are assigned at each calculation. The power output is determined by circulating mass flow rate $\dot{m}_s$, which is fixed in thesis. The main factors affecting the efficient operation of a Rankine cycle are the maximum steam temperature, the maximum pressure, the amount of heat input (fixed), and work output from the system. In order to compare how efficient a cycle operates at these different conditions the thermal efficiency can be calculated for each condition and compared.

Due to space constraints in the Dolphin concept car, the volume of the heat exchangers that works as dimensioning component is also calculated in order to validate that the components of the Steam turbine Rankine cycle can fit.

The cycle was analyzed for four different turbine pressure states, wherein all four was iterated three times with different max temperatures. The table below shows the number of iterations and the parameters altered for each pressure and temperature. T_{max} and P_{max} refer to the temperature and the pressure inlet of the steam turbine (throttle conditions).

Table 15: Iterations and altered parameters for theoretical analysis

Iteration	P_{max}	500kPa	800kPa	1000kPa	1200kPa
1	T_{max}	$T_{sat} + 5°C$	$T_{sat} + 5°C$	$T_{sat} + 5°C$	$T_{sat} + 5°C$
2	T_{max}	$T_{sat} + 25°C$	$T_{sat} + 25°C$	$T_{sat} + 25°C$	$T_{sat} + 25°C$
3	T_{max}	$T_{sat} + 50°C$	$T_{sat} + 50°C$	$T_{sat} + 50°C$	$T_{sat} + 50°C$

In order to calculate the specified state points within the cycle the following calculations were made. The numbers on each value and state refers to numbers on (Figure 37). The analysis began with state one, the inlet to the pump.

State 1:

$$h_1 = h_{f\ @\ P_1} = Table\ (A-5)$$

$$v_1 = v_{f\ @\ P_1} = Table\ (A-5)$$

State 2:

The pump is assumed to be isentropic. Then the conservation of energy relation for each device can be expressed as follows:

$$W_{pump} = h_2 - h_1 = v_1 * (P_2 - P_1) \qquad [2]$$

$$h_2 = v_1 * (P_2 - P_1) + h_1$$

State 3:

$$h_3 = h_{f\ @\ P_3,T_3} = Table\ (A-6)$$
$$s_3 = s_{f\ @\ P_3,T_3} = Table\ (A-6)$$

State 4:

$$s_4 = s_3 = s_f + s_{fg} * x_4 \quad [3]$$

where

$$s_f = s_{f\,@\,P_4} = Table\ (A-5)$$
$$s_{fg} = s_{fg\,@\,P_4} = Table\ (A-5)$$

Quality of steam:

$$x_4 = \frac{s_4 - s_f}{s_{fg}} \quad [4]$$

$$h_4 = h_1 + x_4 * h_{fg,4} \quad [5]$$

where

$$h_{fg,4} = h_{fg\,@\,P_4} = Table\ (A-5)$$

Further Calculations:

The steady-flow first law of thermodynamics is obtained to calculate the work and power to drive the pump to raise the condensate to the high-pressure liquid water entering the steam generator.

Pump (q = 0): $$W_{pump} = h_2 - h_1 \quad [6]$$

When the small kinetic and potential difference between the inlet and the outlet are neglected we apply the steady-flow form of First law of thermodynamics for an isentropic turbine:

Turbine (q = 0): $$W_{turb} = h_3 - h_4 \quad [7]$$

Applying the steady-flow first law of thermodynamics to the heat exchanger (steam generator), we obtain the heat transfer:

Heat exchanger (w = 0): $$q_{in} = h_3 - h_2 \quad [8]$$

The rejection of heat to the surroundings by the cooling water is essential to maintaining the low pressure in the condenser. Applying the stead-flow first law of thermodynamics to the condensing steam we obtain:

Condenser (w = 0): $$q_{out} = h_4 - h_1 \quad [9]$$

Thermal efficiency of the Rankine cycle:

$$\eta_{TH} = \frac{W_{net}}{q_{in}} or\ 1 - \frac{q_{out}}{q_{in}} \quad [10]$$

Where

$$W_{net} = W_{turb} - W_{pump} \quad [11]$$

Actual turbine work:

$$\dot{W}_{net} = \dot{m}_s * W_{net} * \eta_{TH,turbine} \qquad [12]$$

Overall system efficiency:

$$\eta_{TH,overall} = \frac{\dot{W}_{net,\ gas\,turbine} + \dot{W}_{net}}{Energy\ added\ in\ gas\ turbine} \qquad [13]$$

Heat exchanger dimensions:

The conservation of mass principle for heat exchangers in steady operations requires that the sum of the inbound mass flow rates the equals the sum of outbound mass flow rates. Steady-flow. The heat exchanger involves no work interactions (w = 0) and neglecting kinetic and potential energy changes ($\Delta ke = 0, \Delta pe = 0$) for each fluid stream. (21)

Mass balance (For each fluid stream)

$$\dot{m}_{in} - \dot{m}_{out} = \Delta\dot{m}_{system} = 0 \qquad [14]$$

Where

$$\dot{m}_{exh,1} = \dot{m}_{exh,2} = \dot{m}_{exh}$$

$$\dot{m}_{s,1} = \dot{m}_{s,2} = \dot{m}_s$$

Energy balance (for the heat exchanger)

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system} = 0 \qquad [15]$$

Where

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}_{exh} * h_{exh,in} + \dot{m}_s * h_2 = \dot{m}_{exh} * h_{exh,out} + \dot{m}_s * h_3 + Q_{out}$$

No heat loss to the surroundings ($Q_{out} = 0$)

$$\dot{m}_{exh} * C_{p,exh} * T_{exh,in} + \dot{m}_s * h_2 = \dot{m}_{exh} * C_{p,exh} * T_{exh,out} + \dot{m}_s * h_3 + Q_{out}$$

Substitution gives:

$$T_{exh,out} = \frac{m_s * (\dot{h}_2 - h_3)}{\dot{m}_{exh} * C_{p,exh}} + T_{exh,in} \qquad [15]$$

Assuming that the exhaust has the properties of air we obtain:

Specific heat capacity of exhaust

$$c_{p,exh} = c_{p,air\ @\ T_{exh,in}}\ \ Table\ (A-2)$$

Heat capacity of exhaust

$$C_{exh} = \dot{m}_{exh} * c_{p,exh} \qquad [16]$$

Rate of heat transfer from exhaust to water

$$\dot{Q} = C_{exh} * (T_{exh,in} - T_{exh,out}) \qquad [17]$$

$$\dot{Q} = U_{HE} * A_{HE} * \Delta T_{lm} \quad [18]$$

Logarithmic mean temperature

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \quad [19]$$

Where

$$\Delta T_1 = T_{exh,out} - T_2$$
$$\Delta T_2 = T_{exh,in} - T_3$$

Necessary heat transfer area in the heat exchanger from equation: [18]

$$A_{HE} = \frac{\dot{Q}}{U_{HE} * \Delta T_{lm}}$$

Where U_{HE} is the heat transfer coefficient in the heat exchanger. Assumed a heat exchanger with steam-mild steel-air. (31)

$$U_{HE} = W/m^2/K$$

Area of tube:

$$A_{tube} = 2 * \pi * r_{tube} * l_{tube} \quad [20]$$

Size of "black box" heat exchanger with 0,01m walls. The Length is fixed at 1.1m, and width is given from a ratio of the length. Thus, the height is a floating value that varies with cycle values.

Width/Length ratio: $\frac{w_{HE}}{l_{HE}} = 0{,}8$

Height/Length ratio: $\frac{h_{HE}}{l_{HE}} = 0{,}164$

Dimensions:

$$l_{HE} = l_{tube} + 0{,}01m$$
$$w_{HE} = l_{HE} * 0{,}8 + 0{,}01m$$

$$h_{HE} = \left(\frac{A_{tube}}{w_{HE}/\emptyset_{tube}}\right) * \emptyset_{tube} \quad [21]$$

8.3 Results

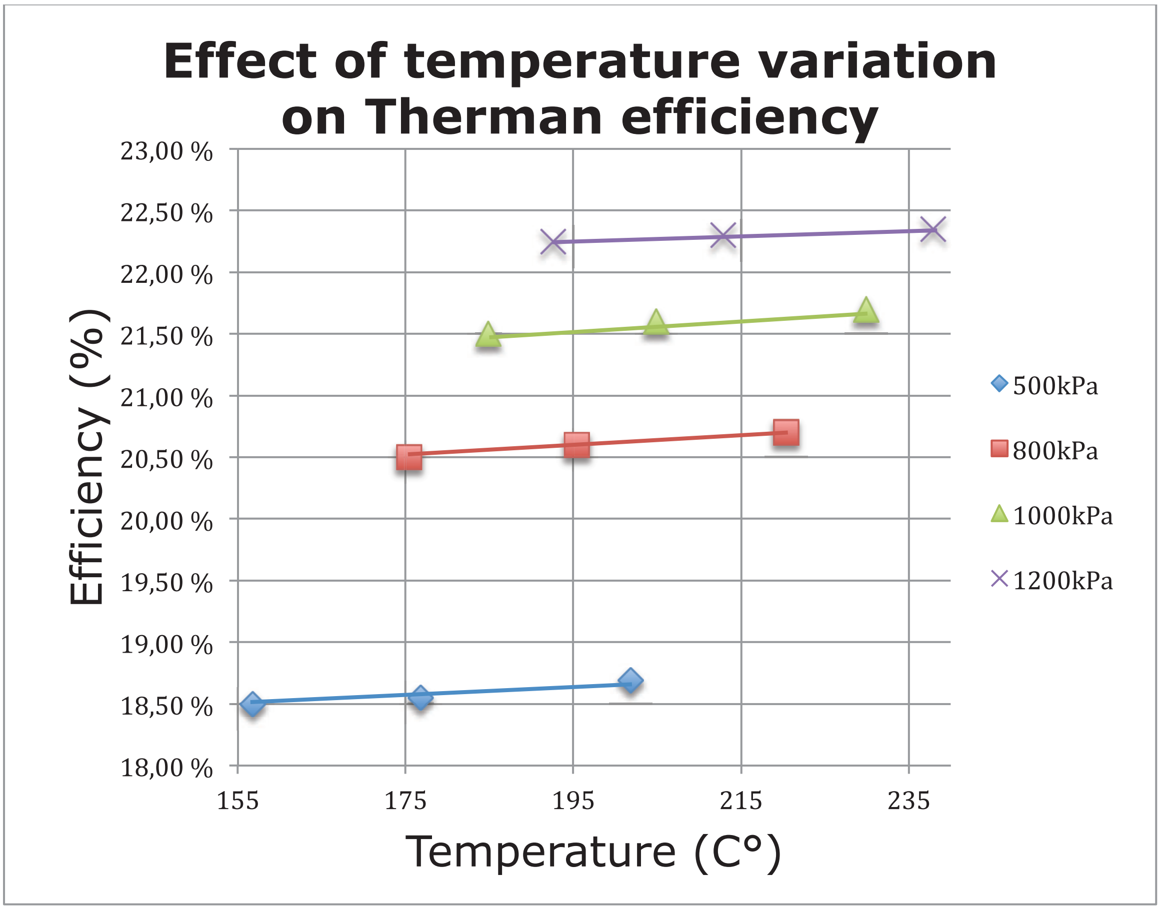


Figure 38: Efficiency graph for the calculated Rankine cycle

The graph in Figure 38 shows the thermal efficiency variation for a 0.04 kg/s mass flow rate Rankine cycle, using water as working fluid. The thermal efficiency was calculated for four different pressures at three different temperatures. It shows that the higher pressure, with associated higher saturation temperature, leads to higher thermal efficiency. Since the pressure is proportional to the temperature in a Rankine cycle, it was expected that lower pressure would have lower temperatures, which means a decrease in heat absorption (less latent heat), and thus have lower thermal efficiencies. Figure 38 shown above supports the claim.

All the four pressures show approximately linear increase in thermal efficiency, with linear increase in maximum pressure.

In a real micro CHP system (real Rankine) the compression in a pump and the expansion in a turbine are not isentropic. This will decrease the power generated by the turbine and increase the power required by the pump

Table 16: Inlet conditions and results from case with P_{max} = 1000kpa & $T_{max} = T_{sat} + 25$℃ from the ideal Rankine cycle.

Inlet conditions	Unit	Notation	Value
Mass flow of steam	m^3/s	$\dot{m}_s$	0,04
Turbine pressure	kPa	P_3	1000
Turbine temperature	℃	T_3	205
Condenser pressure	kPa	P_4	10
Steam turbine efficiency	-	$\eta_{TH,overall}$	80%

State	Temperature (°C)	Pressure (kPa)	Enthalpy (kJ/kg)	Phase
1	40	100	191,81	sat.liquid
2	40	1000	192,81	comp.liq
3	205	1000	2835,30	sup.steam
4	-	100	2120,39	sat.mix

Results	Unit	Notation	Value
Actual turbine output	kW	$\dot{W}_{net}$	22,88
Thermal efficiency	%	η_{TH}	21,6 %
Overall system efficiency	%	$\eta_{TH,overall}$	46 %
Overall power increase	%	-	19 %

Heat exchanger			
Length (m)	Width (m)	Height (m)	Volume (m2)
1,11	0,89	0,07	0,07

The case shown above is a case from the line market in green in Figure 38. The inlet conditions is $P_{max} = 1000kPa$, $T_{max} = T_{sat} + 25$°C, and $\dot{m}_s = 0{,}04\, m^3/s$. The thermal efficiency of the steam turbine was set to $\eta_{TH,overall} = 80\%$. The condensing temperature was fixed at 40°C. It is assumed that the temperature difference from the cooling fluid circulating on the cold side of the condenser is satisfying, when the cooling fluid have ambient temperature ($T = 20$°C). The condenser pressure P_1 was then obtained from thermodynamic tables for saturated liquid at $T_{sat\ @\ 40\ °C}$.

The result was that the WHRS recovery system is adds 21,9kW to the system. That means an increase in overall efficiency by 19%. The overall system efficiency is now 46%. That is about the same overall system efficiencies you get from a traditional modern diesel engine.

8.4 Increasing efficiency

Condenser:

To increase the thermal efficiency you can decrease the average temperature at which heat is rejected from the condenser. Since steam exists at saturated mixture in the condenser at a saturation temperature corresponding to condenser operating pressure, it is preferable to lower the condenser pressure, resulting in a lower temperature. Hereby the rejection temperature will decrease also. The saturation pressure cannot be lower than the saturation pressure corresponding to the temperature of the cooling fluid, which would cause leakage into the condenser. (21)

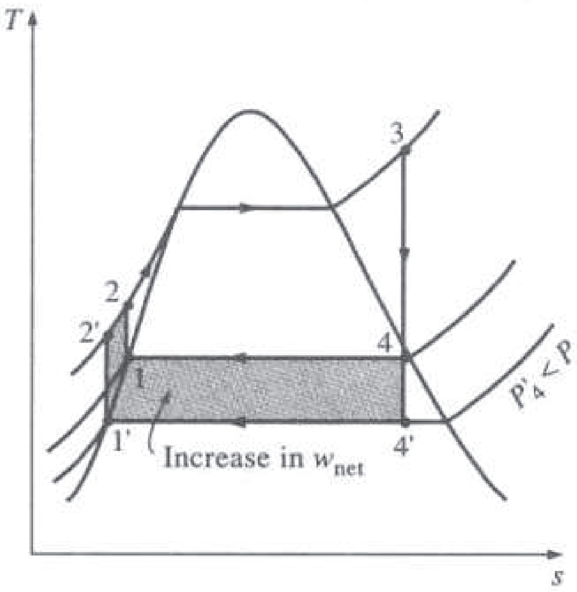


Figure 39: Increasing efficiency in Rankine cycle condenser *(32)*

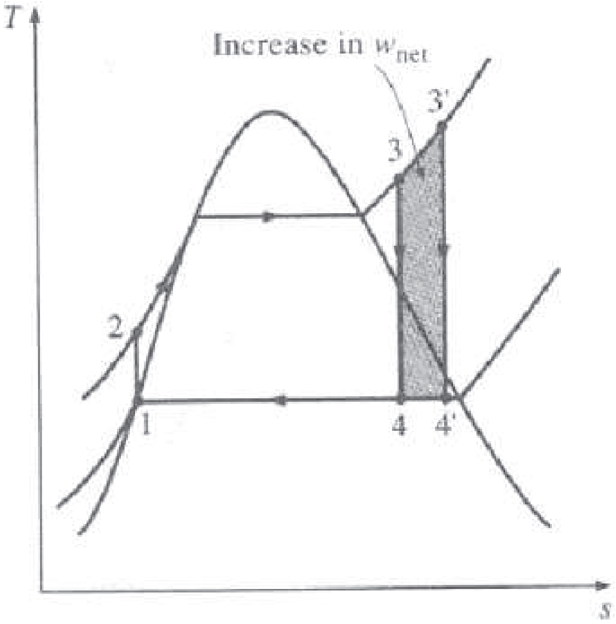


Figure 40: Increasing efficiency in a Rankine cycle heat exchanger/boiler *(32)*

Heat exchanger:

The average temperature at which heat is added to the steam can be increased without increasing the boiler pressure by superheating the steam to high temperatures. From 3 to 3’ on Figure 40. Superheating the steam to higher temperatures has another very desirable effect: it decreases the moisture content of the steam at the turbine exit. Increasing the operating pressure of the heat exchanger/boiler, automatically raises the temperature at which boiling takes place. This raises the average temperature at which heat is added to the steam and thus raises the thermal efficiency of the cycle.

Materials:
New technology were the inside of the turbine is coated with ceramics is an interesting subject. Especially inside the gas turbine, that would allow higher combustion temperatures.

9 System proposal

Based on industrial literature, consultation with GreenTurbine, assumptions and results the following system solution is proposed.

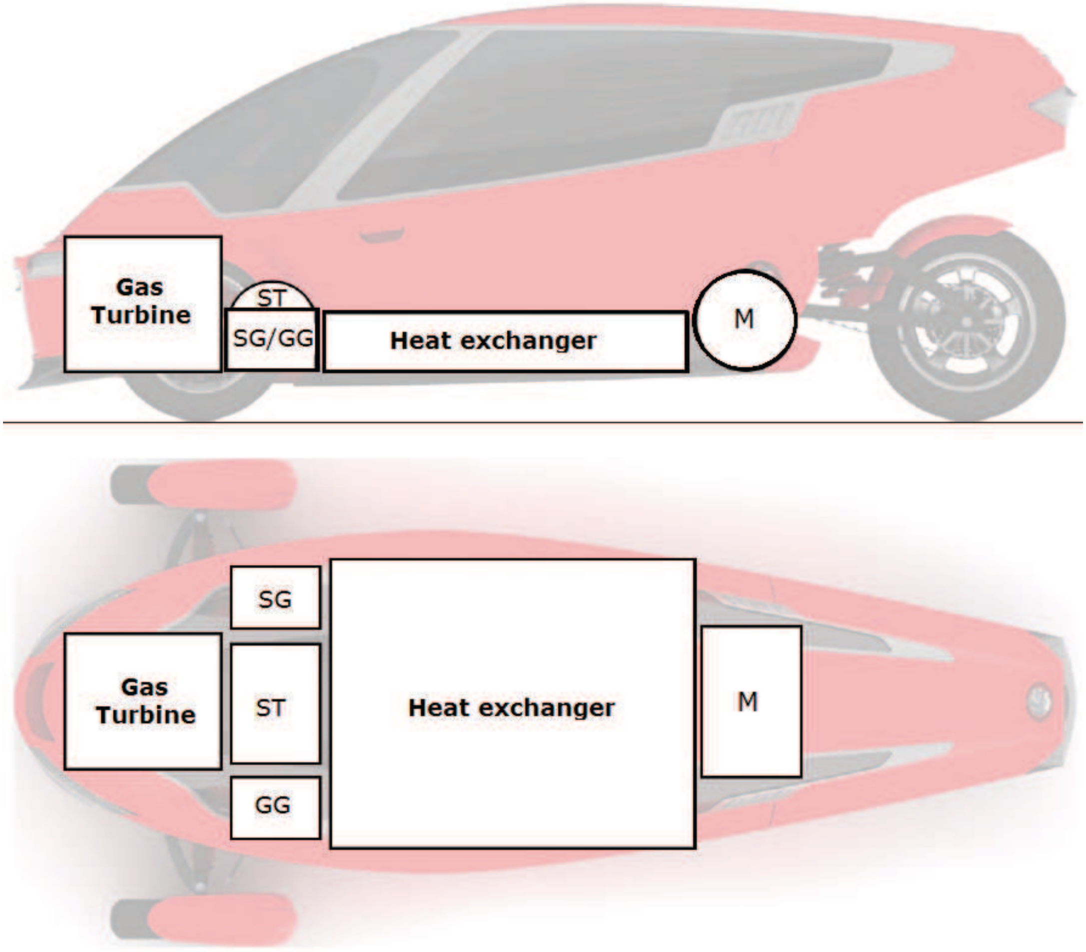


Figure 41: System solution proposal (3)

The solution proposed (Figure 41) shows the different components placed in the Dolphin concept car. The gas turbine is located close to the air intakes in the front. The two separate generators for both the steam turbine generator and gas turbine generator (SG and GG) are placed on each side of the steam turbine. The heat exchanger is placed in the bottom of the car, giving it a low center of gravity. The electric motor (M) is placed in the back. The small sized pump and the condenser is placed within the heat exchangers area. See appendix 3 for available dimensions.

10 Material, production & cost

The total cost to install the WHRS system includes the costs associated with the waste heat recovery equipment (Heat exchanger/Condenser), the power generation equipment (Turbine, pump), power conditioning and interconnection equipment. It would also include the soft costs associated with analyzing, designing and constructing the system. Consultation with the steam turbine producer Greenturbine, gave tips on what costs to expect.

10.1 Production & Cost

Table 17: Cost calculation on building a WHRS prototype

1. Concept development	Hours	Quantity	Rate/Hour	Sum NOK
Research	300		650	195000
Concept development	100		650	65000
Design	100		650	65000
3-D model	40		650	26000
Project report	300		650	195000
Sum:	840			546000
2. Prototyping	**Hours**	**Quantity**	**Rate**	**Sum NOK**
Complete steam turbine		22000W	1€/W	179300
Working cost	400		650	260000
Sum:				439300
Sum total:	1240			985300

After consultation with Greenturbine they recommended using a production cost of 1€/Watt.

Table 18: Cost calculation on series production of WHRS

1. One-time cost	Hours	Quantity	Rate/Hour	Sum NOK
Sum R & D				546000
Special tools	50		650	32500
Sum:				578500
2. Ongoing costs	**Hours**	**Quantity**	**Rate**	**Sum NOK**
Complete steam turbine		22000W	0.8€/W	143500
Working cost	200		650	130000
Sum:				273500

Table 19: Cost calculation on series production of 100, 1000 and 10000 units

1. Series production 100 units	Quantity	Price NOK	Sum NOK
One-time costs	1	578500	578500
On going costs	100	273500	273550000
Sum:			274128500
Unit cost:			279285
2. Series production 1000 units	**Quantity**	**Price NOK**	**Sum NOK**
One-time costs	1	578500	578500
On going costs	1000	273500	2735500000
Sum:			274078500
Unit cost:			274078
3. Series production 10000 units	**Quantity**	**Price NOK**	**Sum NOK**
One-time costs	1	578500	578500
On going costs	10000	273500	27355000000
Sum:			2735578500
Unit cost:			273558

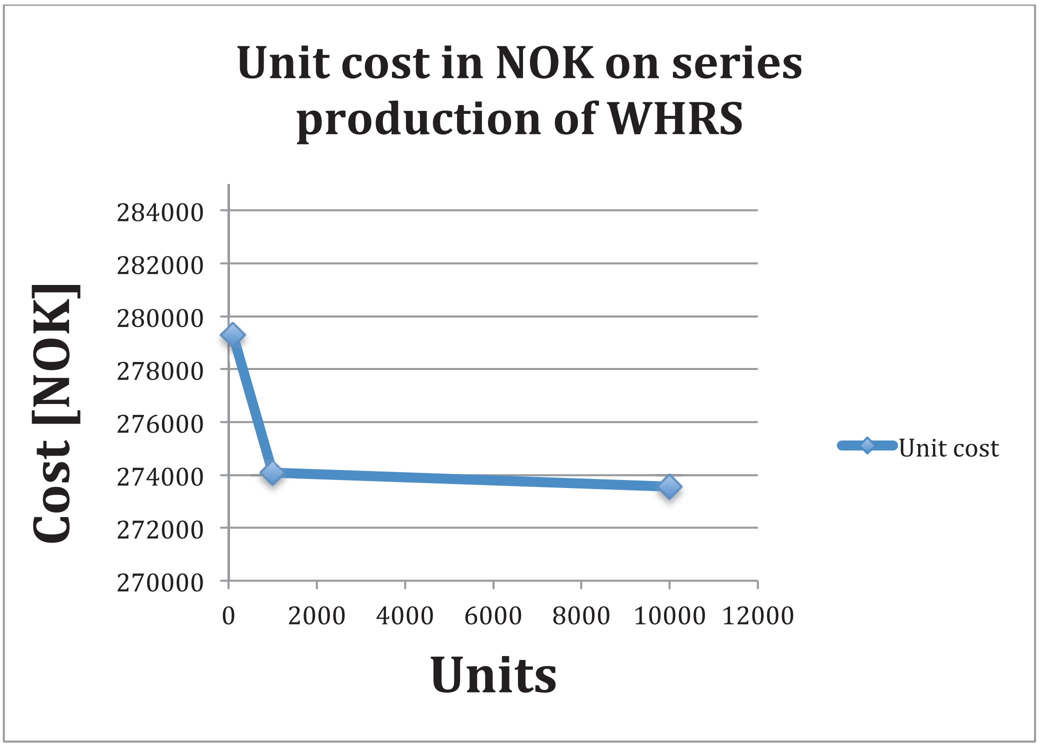


Figure 42: Unit cost in NOK on series production of WHRS. Stabilizes after 1000 produced units.

10.2 Materials

Table 20: Preliminary material selection on main components

Material	Advantages/Disadvantages	Selection
Aluminum	+ Little corrosion + Good heat conduction – Lower melting temperatures – Lower strength – Expensive	
Construction steel	+ Good strength + Less expensive – High corrosion – Medium heat conduction	
Stainless steel	+ Little corrosion + High strength + Withstands high heat – Medium heat conduction – Expensive	✔

The selection ends up with stainless steel. It can withstand high heat and corrosion as well as high strength. This material selection is just suggestion on the main components such as the outer casing of the heat exchanger, condenser and steam turbine. Detailed selection of materials is a limitation in this thesis.

11 Discussion

11.1 Process discussion

The time estimates for the thesis was relatively precise. In retrospect it is clear that the literature study on previous work and existing waste heat recovery solutions was more time consuming than planned, and could advantageously been shorter, allowing more time on design. However, the importance of understanding gas and steam turbines as well as general thermodynamics was based on these chapters, so the real problem was too little time.

The thesis ended up becoming more of a guide through a difficult jungle of literature and data, rather then e development of a product. I hope this thesis can contribute and be a show-starter for a future design project, and that it can build on my assumptions and recommendations.

It is also mentionable that thermodynamics is a subject that is difficult in general, and that made the learning process longer than expected.

The selection of design functions was done with a thought of making good choices and keeping the concept design as simple as possible, so that actual results could be possible to calculate. A selection matrix was evaluated as unnecessary because most of the functions have so many clear advantages and disadvantages that a matrix would make it too complicated.

Surprisingly many assumptions were made before the calculations could come to an end, and some significant results could be presented. The assumptions made are however qualified guesstimates done by Greenturbine, my supervisors and my self. The input is given with respect to what I expect it to be in a real case of building a WHRS.

From the beginning this thesis scope was underestimated, so it became difficult to reach the main objective without making limitations along the way.

11.2 Discussion of results

First it is necessary to emphasize that the results were satisfying. With a WHRS it is possible to add about 20kW to the engine solution without burning any more fuel. With further work on the subject it is possible to even gain more by optimizing the temperature and pressures in the cycle. One of the subsidiary objectives was to get an overall system efficiency of 50% or higher. That objective was not fully met, but overall system efficiency of 46% is very good. Compared with a conventional diesel engine it is about the same. Considering the low emissions, low weight and low maintenance, it is a very good result.

The results are reliable concerning formulas and calculations since it pretty straightforward, when you calculate everything in ideal situations. The present work includes literature study, cycle analysis, efficiency calculations for different parameters, and device design.

In a real micro CPH analysis it is necessary to account for non-ideal effects such as fluid friction, turbulence, and flow separation in components otherwise assumed to be reversible. In this thesis calculation this is only accounted for in the turbine where the thermal efficiency of 80% was added in the equation. That is a relatively conservative choice since it is achievable with efficiencies of 95% in well-designed machines.

Work must be supplied to a pump to move liquid from a low pressure to a high pressure. Some of the work supplied is lost due to irreversibilities. The amount of work supplied is only about 2-8%. That is one of the big differences from a gas turbine where the “back pressure” rotating the compressor shaft is about 60%.

The results don’t necessarily show that a WHRS project is doable for the Dolphin concept car. It shows theoretically that with the gas turbine as heat source it possible to recover about 20% of the heat.

Key restrictions preventing heat recovery in a particular application can include cost, temperature restrictions, chemical composition of heat streams and application-specific constraints. These constraints have challenges for heat recovery that include material costs, maintenance cost, environmental concerns, and the need for process and product control.

It is already technology for waste heat recovery, but constraints mentioned above may prevent the technology to reach its potential. The principal hurdle for a WHRS is the heat recovery itself. Power generation equipment is commercially established and relatively standardized except the micro steam turbine, were it exists little or nothing on the market.

12 Conclusion

This study evaluated technologies and current waste heat recovery practices in a variety of applications. The present work focuses on power generation by a micro gas turbine with a waste heat recovery system for additional power. The study gives a clear path to future design projects based on acquired knowledge, literature study and existing technology. It is shown that the potential of recovering heat from a gas turbine is possible, with results that increase the overall system efficiency. Consequently, implementing a micro CHP system will contribute to the main goal; making human beings reduce their environmental footprint.

I have developed a WHRS capable of running on pressurized steam. Because of that, full advantage can be made in the application areas of waste heat and combined cycle. It adds between 18kW and 24kW of electrical power to the system, and increases the overall system efficiency to 46%. If a future project shows results comparable to this thesis theoretical result, micro CHP applications can become a very good alternative as energy source for a vehicle.

In a large scale, CHP in power plants already are, and will in the future, reduce the gap between demand of supply and electricity. In the micro scale, a CHP system in the Dolphin concept car can be a pioneer project and make way for a more environmental friendly and sustainable transportation. The issue is to carry out a search for a transportation strategy, which can simultaneously support economic development and increase the environmental footprint of human beings.

There is an opportunity for CHP when there is a simultaneous requirement for power and heat. Integrating cogeneration technology into a new or existing gas turbine installation has the potential to save fuel resources. However, there is no assurance of economic benefits due to factors such as the varying nature of fuel and electricity prices, financial environment, and regulatory requirements that are beyond control of micro CHP manufacturers. Although economic benefit is often primary condition for project acceptance, other factors such as the reliability of the energy supply may be equally or more important.

My recommendations are to proceed with further studies until it’s necessary to go from theory to practice. My thoughts on what the next steps are presented in further work.

Further work

The Dolphin concept car study is in early development phase. It is necessary with several reports and optimization before the project can be realized. Further work:

- Further literature studies and knowledge enhancement
- Calculate the cycle non-ideal to make the results closer to reality.
- SolidWorks component design
- Study on wrapping the gas turbine in water for both heat recovery and noise reduction
- FEM-analysis
- Flow analysis
- Component selection and manufacturing
- Include the constraints of a human being regarding space, noise and temperature comfort.
- Extend the range of temperatures over which heat recovery can be performed, both low temperature and high temperature. (Ceramic coating etc.)
- Material selection for all the included components
- A study on the Kalina cycle for low-temperature power generation. (Efficiencies comparable to combined cycles with less complexity)
- Production methods

Key factors that should be considered when assessing CHP projects economics include:

- Initial investment and cost of capital
- Operating and maintenance cost
- Purchase price of fuel and electricity

13 Bibliography

References

3. Brevik, A. & Lundheim, L. T. (2007). Dolphin - Formkonsept for Trike. Ås: NMBU. 96 pp.

4. Thue, A. M. & Sundquist, P. (2012). *Development, dimensioning and construction of multi fuel gas turbine engine*: Norges miljø- og biovitenskapelige Universitet, Institutt for Matematisk realfag og Teknologi. 174 pp.

5. Stodola, A. & Loewenstein, L. C. (2012). *Steam Turbines: With an appendix on Gas Turbines and the future of Heat Engines*. Polytechnikum Zurich: Ulan Press. 978-1146908238

7. Langston, L. S. & Opdyke, G. (1997). Introducton to Gas Turbines for Non-Engineers. *Global Gas Turbine News*, 37 (2): 9.

14. Goldham, T. & Gorham, R. (2006). Sustainable urban transport: Four Innovative directions. *Technology in Society*. 261-273 pp.

16. Deaking, E. (2001). Sustainable Development and Sustainable Transportation: Strategies for Economic Prosperity, Environmental quality, and Equity: University of California, Berkeley. 42 pp.

17. Pilavachi, P. A. (2002). Mini- and micro-gas turbines for combined heat and power. *Applied Thermal Engineering*. ScienceDirect. 26 pp.

18. MarketsandMarkets. (2014). Waste Heat Recovery Market by application (Pre-heating, Steam Generation, Electricity & others), and Industry (Petroleum, Refining, Heavy Metal, Cement, Chemical, Natural Gas Compression, Pulp/Paper Inustry & Others) - Global Trends & Forecast to 2018.

21. Çengel, Y. A. & Boles, M. A. (2007). *Thermodynamics: An engineering approach*. 6th ed. 978-007-125771-8

27. Shlyakhin P. (1970). *Steam Turbines: Theory and Design*. University Press of the Pacific, Hawaii. 1-4102-2348-5

28. Corporation, O. S. E. (1999). Review of Combined Heat And Power Technlogies. California: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. 32 pp.

29. Energy, U. S. D. o. (2008). Waste Heat Recovery: Technology and opportunities in U.S. Industry: Industrial Technologies Program. 112 pp.

Weblinks

1. Semidiesel. (2014). *100HK Finnøy Motor*. Available at: http://www.semidiesel.no/engines/finnoy/finnoy_b.htm.
2. Miljøverndepartementet. *Utslipp fra veitrafikk*. Available at: http://www.miljostatus.no.
6. Wikipedia. (2014). *Aelopyle*. Available at: http://en.wikipedia.org/wiki/Aeolipile.
8. Lagrone, S. (2013). *Secret Nuclear Redesign*. Available at: http://www.wired.com/2013/01/secret-sub-design/.
9. Wikipedia. *USS Nimitz*. Available at: http://en.wikipedia.org/wiki/USS_Nimitz_(CVN-68).
10. Wikipedia. *Nuclear Power Plant*. Available at: http://en.wikipedia.org/wiki/Nuclear_power_plant.
11. Miljøstatus. *Kilder til utslipp av klimagasser - Transport*. Available at: http://www.miljostatus.no.
12. Agency, U. S. E. P. *Greenhouse Gas Emissions*. Available at: http://www.epa.gov/climatechange/ghgemissions/.
13. Commission, E. *Emissions Trading System (EU ETS)*. Available at: http://ec.europa.eu/clima/policies/.
15. EMBARQ. *Centre for sustainable transport*. Available at: http://embarq.org/.
19. Yourdictionary. *Traditional piston enginge*. Available at: http://www.yourdictionary.com/piston.
20. Wartsila. *Gas turbine engine*. Available at: http://www.wartsila.com.
22. SpiraxSarco. *Steam theory*. Available at: http://www.spiraxsarco.com/.
23. ScienceDaily. (2013). *Using waste heat to make cars more efficient*. Available at: http://www.sciencedaily.com/releases/2013/11/131118120037.htm.
24. GreenTurbine. (2014). *micro Steam turbine*. Available at: http://www.greenturbine.eu/.
25. Bv, M. *Micro CHP system*. Available at: http://www.mtt-eu.com/en/applications/micro-chp.
26. Mannvit. *Geothermal Powerplants*. Available at: http://www.mannvit.com/GeothermalEnergy.
30. Renewbl. (2014). *Steam turbine*. Available at: http://www.renewbl.com/category/geothermal.
31. Engineeringtoolbox. *Heat transfer coefficient*. Available at: http://www.engineeringtoolbox.com/.
32. Indian Institute of Technology. *Lecture on Rankine cycles*. Kanpur. Available at: http://www.iitk.ac.in/.

14 Appendix

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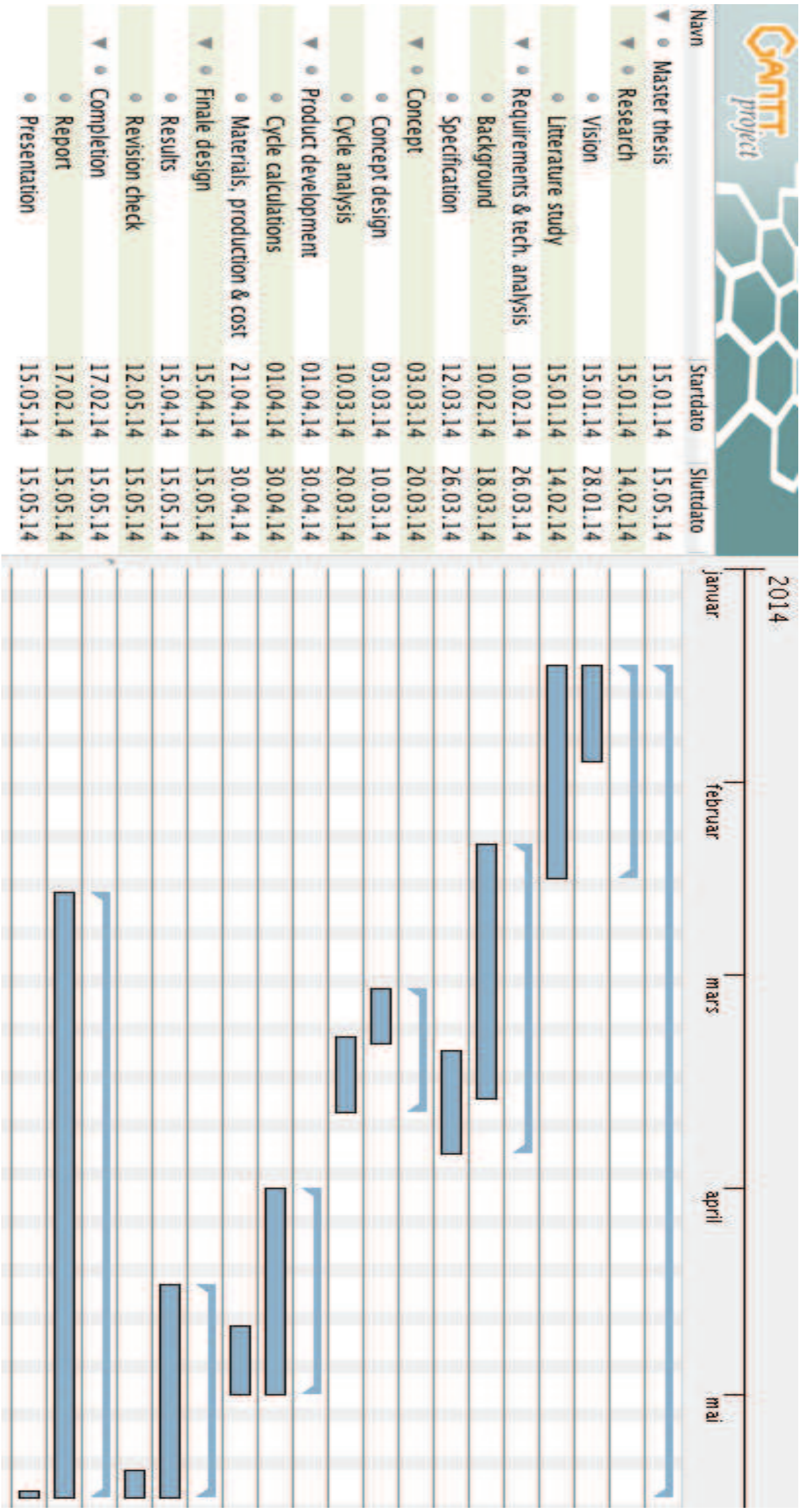
Appendix 1: Gantt scheme



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Research	15.01.14	14.02.14
Vision	15.01.14	28.01.14
Literature study	15.01.14	14.02.14
Requirements & tech. analysis	10.02.14	26.03.14
Background	10.02.14	18.03.14
Specification	12.03.14	26.03.14
Concept	03.03.14	20.03.14
Concept design	03.03.14	10.03.14
Cycle analysis	10.03.14	20.03.14
Product development	01.04.14	30.04.14
Cycle calculations	01.04.14	30.04.14
Materials, production & cost	21.04.14	30.04.14
Finale design	15.04.14	15.05.14
Results	15.04.14	15.05.14
Revision check	12.05.14	15.05.14
Completion	17.02.14	15.05.14
Report	17.02.14	15.05.14
Presentation	15.05.14	15.05.14

Appendix 2: Calculation sheet from excel

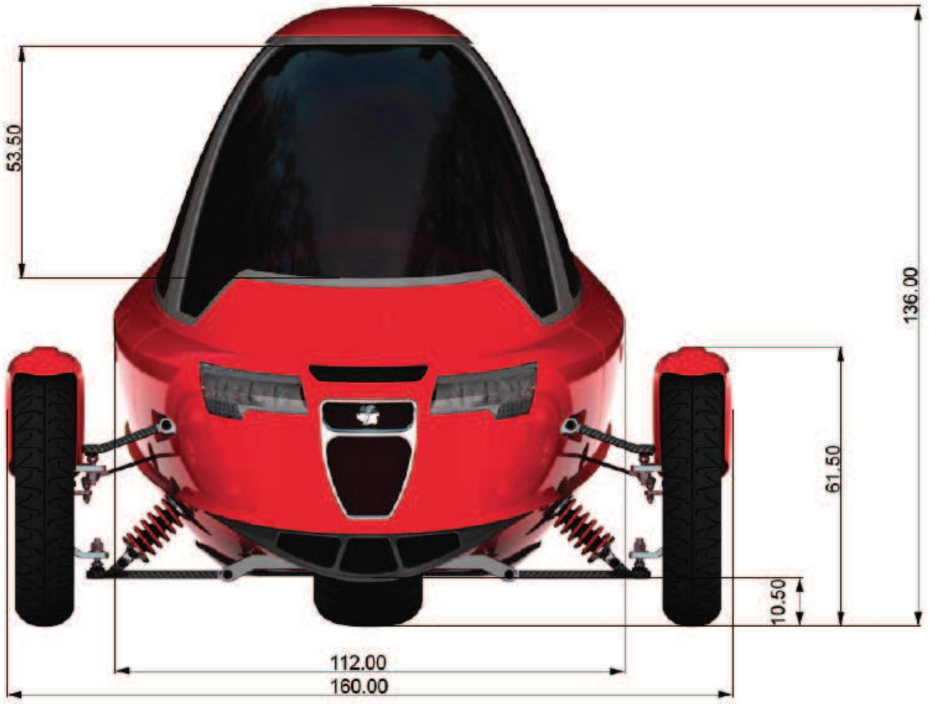
The following table is the calculation sheet from excel. Values marked green is manually input, while values market in white is calculated.

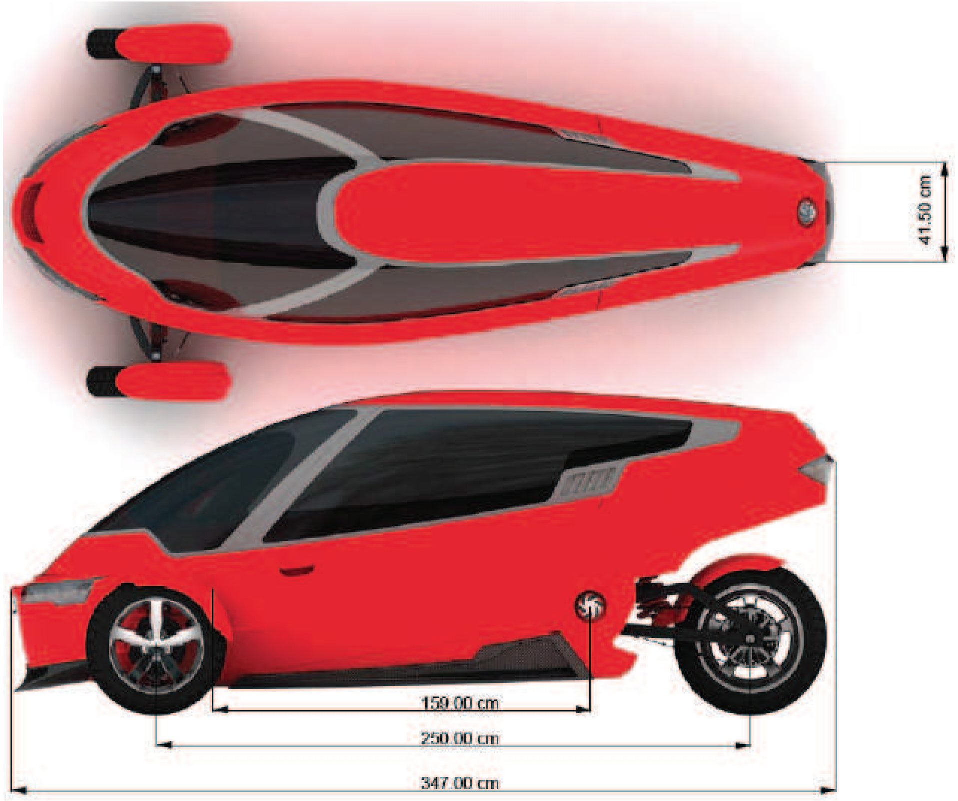
Initial conditions	Unit	Notation	Value
Steam			
Mass flow	m^3/s	$\dot{m}_s$	0,04
Specific volume steam state 1	m^3/kg	v_1	0,00101
Entropy of saturated liquid state 4	$kJ/kg*K$	s_4	0,6492
Entropy of vaporization state 4	$kJ/kg*K$	s_{fg}	7,4996
Entropy state 3	$kJ/kg*K$	s_3	6,6956
Enthalpy of vaporization state 4	kJ/kg	$h_{fg,4}$	2392,1
Exhaust			
Temperature inlet	$^\circ C$	$T_{exh,in}$	1018
Specific heat capacity	$kJ/kg*K$	$C_{p,exh}$	1,081
Mass flow	m^3/s	$\dot{m}_{exh}$	0,256
Turbine			
Pressure	kpa	P_3	1000
Steam temperature inlet	$^\circ C$	T_3	200
Turbine thermal efficiency		$\eta_{TH,turbine}$	0,8
Condenser			
Pressure	kpa	P_4	10
Heat exchanger			
Heat transfer coefficient	$W/m^2/K$	U_{HE}	14,3
Tube diameter	m	$\emptyset_{tube}$	0,02
Steam temperature in	$^\circ C$	T_2	40
Steam temperature out	$^\circ C$	T_3	205
Length of tube	m	l_{tube}	1,1
Width/length ratio		w_{HE}/l_{HE}	0,8
Height/width ratio		h_{HE}/w_{HE}	0,164

Calculations sheet from excel cont.

Calculations	**Unit**	**Notation**	**Value**
Enthalpy state 2	kJ/kg	h_2	192,81
Quality of steam state 4		x_4	0,81
Enthalpy state 4	kJ/kg	h_4	2120,39
Turbine work	kJ/kg	W_{turb}	714,91
Added heat in heat exchanger	kJ/kg	q_{in}	2642,49
Work by pump	kJ/kg	W_{pump}	1,00
Rejected heat in condenser	kJ/kg	q_{out}	1928,58
Thermal efficiency		η_{TH}	0,27
Actual turbine work	kW	$\dot{W}_{net}$	22,88
Exit temperature of exhaust	$°C$	$T_{exh,out}$	636,05
Heat exchanger			
Heat capacity exhaust	kW/K	C_{exh}	0,28
Rate of heat transfer	kW	$\dot{Q}$	105,70
Mean temp 1	$°C$	ΔT_1	541,05
Mean temp 2	$°C$	ΔT_2	818,00
Logarithmic mean temperature heat exchanger	$°C$	ΔT_{lm}	670,01
Area of heat exchanger	m^2	A_{HE}	11,03
Area of tube	m^2	A_{tube}	159,62
Length	m	l_{HE}	1,11
Width	m	w_{HE}	0,89
Height	m	h_{HE}	0,07

Appendix 3: Dolphin concept car available dimensions (3)





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