NTNU – Trondheim
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Life Cycle Assessment of Electricity Generation from Low Temperature Waste Heat

The Influence of Working Fluid

Lijun Bai

Master in Industrial Ecology
Submission date: July 2012
Supervisor: Edgar Hertwich, EPT
Co-supervisor: Yves Ladam, SINTEF Energy Research

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Acknowledgments

This thesis would not have been possible without the support of many people. Many thanks to my supervisor Edgar Hertwich, Co-supervisor Thomas Gibon and external contact Yves Ladam for their academic and technical guidance. Thanks to the Industrial Ecology Programme and Sintef Energy for their generous support. And thanks to my family members and classmates, their support is important for the completion of this thesis.

Abstract

With the increasing demand for clean energy to reduce the consumption of fossil fuel and to limit the environmental burden, the research towards the utilization of waste heat from various sources is growing in recent years. In this thesis, environmental impacts of electricity generation from low temperature waste heat using organic Rankine cycle (ORC) power plants have been evaluated. Using the Life Cycle Assessment (LCA) as the evaluation method, the environmental impacts of NH_3, R134a, CO_2 and n-Pentane as working fluids in ORC power plants have been calculated. Comparing with wind power, the results show that the overall environmental impacts from low temperature waste heat ORC power plants are comparable with wind power. And the working fluids have significant effects to the entire environmental impacts of electricity production from ORC power plants.

Abstrakt

Wed den økende etterspørselen etter ren energi for å redusere forbruket av fossilt brensel og for å begrense miljøbelastningen, er forskningen mot utnyttelse av spillvarme fra ulike kilder økende de siste årene. I denne oppgaven har miljøkonsekvenser av elektrisitet fra lav temperatur spillvarme hjelp organic Rankine cycle (ORC) kraftverkene blitt evaluert. Bruke livssyklusanalyser som metode for evaluering, de miljømessige konsekvensene av NH_3, R134a, CO_2 og n-pentan som arbeider væsker i ORC kraftverk er beregnet. Sammenligning med vindkraft, viser resultatene at de samlede miljøkonsekvensene fra lavtemperatur spillvarme ORC kraftverk er kompatible med vindkraft. Og arbeidsforholdene væsker ha betydelige effekter på hele miljøkonsekvensene av strømproduksjon fra ORC kraftverk.

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Nomenclature

ORC	Organic Rankine Cycle
LCA	Life Cycle Analysis
LCIA	Life Cycle Inventory Analysis
WHR	Waste Heat Recovery
NPO	Net Power Output
WF	Working Fluid
T	Temperature
P	Pressure
s	Entropy
h	Enthalpy
η_{th}	ORC Thermal Efficiency

Chapter 1

INTRODUCTION

With the increasing demand for clean energy to reduce the consumption of fossil fuel and to limit the environmental load, while increasing the quality of life, the research towards the utilization of waste heat from various sources is growing in recent years. It is an interesting topic to do the research for evaluating the environmental impacts of electricity generation from low temperature waste heat concerning the influence of working fluids in the power plants.

In Norway, there are enormous waste energy sources from metallurgical industry, refineries and process industries that produce exhaust heat which are currently wasted. The researchers of Sintef Energy have been collaborating with other international industry and research institutes ,working on improving energy efficiency and developing cost-effective, environmentally- friendly waste heat recovery and electricity generation technology based on the utilization of surplus heat (Sintef Energy, 2011). One of the key points of this project is to identify the new energy technologies which can be applied to the related industries for converting the waste heat into useful electricity from low-temperature sources.

In European industry, it is estimated that over 300 TWh of waste heat could be available, which can be used either in district heating systems or for production of electricity. Almost all production or consumption of energy loses large portion of input energy. One example is in a standard combustion engine, for which only 35% of the energy input is utilized, while the remaining 65% is lost as waste heat (Öhman & Hedebäck, 2008). Finding ways to convert this enormous amount of energy which are both thermodynamically efficient and technically practical is a top priority.

In conventional thermal energy conversion in power plants, impacts connected to constructing the power plant or manufacturing the equipment are not important for the overall environmental impact of the electricity produced. A large portion of the environmental impact is connected to the production of electricity. For the developing of new technologies, given the energy source is waste heat, the question is what are the environmental impacts caused by the equipment needed for producing energy from the waste heat? What is the environmental benefit of using waste heat, compared other technologies for producing one unit of electricity?

Much industrial waste heat is in the low-temperature range: around 60% of unrecovered waste heat is low quality with the temperatures below 232^0C (U.S. Dep. of Energy, 2008). Based on the thermodynamic principle of Rankine cycle, the low-temperature waste heat can actually be used for electricity generation. Power plants based on the organic Rankine cycle (ORC) have been employed to produce power from various heat sources; the size range of these power plants of a few kilowatts to more than several megawatts have demonstrated the success of this technology (Quoilin & Lemort, 2009).

With the increased demand for fossil fuels, the progress of clean energy technologies research and their applications is making impressive pace in recent years. For the application of new technologies, evaluating their overall environmental impacts is necessary. LCA as one of the important environmental tools has been applied to evaluate the environmental impacts of photovoltaic and wind power (Jungbluth, Bauer, Dones, & Frischknecht, 2005), hydropower

(Varun, Bhat, & Prakash, 2008), solar power (Kannan, Leong, Osman, Ho,& Tso, 2006), etc.. For ORC power plant, there are no LCA researches that have been performed. It should be a challenged topic to do for evaluating the environmental impacts through the approach of LCA.

The environmental impacts of ORC power plants are closely related with the scale of power plants, configuration of the ORC cycle, equipments chosen for those power plants, and the working fluids. The choice of working fluids is important for system performance, since they influence the system efficiency, operation, and environmental impact (Liu, Chien, & Wang, 2004). The aim of this research is to provide a life-cycle environmental impact evaluation of electricity from low-temperature heat, comparing thermal cycles based on different working fluids suitable for low-temperature heat sources.

Chapter 2

BACKGROUND AND LITERATURE REVIEW

2.1 OVERVIEW OF WASTE HEAT RECOVERY

In general, industrial waste heat refers to energy that is generated from industrial processes without being put into practical use. Various studies have estimated that as much as 20% to 50 % of industrial energy consumption is ultimately discharged as waste heat (U.S. Dep. of Energy). The main aim to seek and adopt alternate renewable energy sources as well as converting technologies is to replace the consumption of fossil fuels, which could get the environmental benefit through the reduction of greenhouse gases and gain the economic benefit by using the power produced from waste heat for district utility.

For waste heat recovery (WHR) , there are three necessary components: source of waste heat, recovery technology and end use of the recovered energy. For utilizing the waste heat source, both the quantity and quality (typically exhaust temperatures) need to be considered. The technologies used should maximize the heat recovery, expand application constrains and improve the economic benefit.

Waste heat source temperatures have no standard classifications based on the operation temperatures of power plants. In general, according to the temperature ranges, the waste heat sources can be categorized as high temperature heat source; medium temperature heat source; and low temperature heat source. U.S. Department of Energy (2008) classified the temperature ranges as:

High Temperature: 650^0C and higher
Medium Temperature: 230^0C to 650^0C
Low Temperature: 230^0C and lower

The barriers for utilizing the vast amount of waste heat:

1). Cost: the cost concern rising from the long payback periods; material constraints and costs; economics-of-scale; and operation and maintenance.

2). Temperature Restrictions: low-temperature power generation is currently in development; material constraints and costs mechanical and chemical properties in high temperature and corrosion of materials in low temperature.

3). Chemical Composition: temperature restrictions; heat transfer rates;

material constraints and costs; operation and maintenance costs; environmental concerns and product/process control.

4). Application-specific Constraints: equipment designs must be adapted to the needs of a given process; heat recovery can complicate process control systems.

5). Limited Space and Inaccessibility.

Waste heat temperature is a key factor for the adaption of technologies in the waste heat recovery power plants. The theoretical (Carnot) efficiency is limited when the temperature of heat source is low, and the net work is proportional to the source temperature drop between the heat source and heat sink (Nekså & Ladam, 2009). Based on the Carnot efficiency, the maximum efficiency at given heat source and heat sink is defined as:

$\eta_{th} = 1 - T_L/T_H$

T_H is the waste heat temperature, T_L is the heat sink temperature.

The efficiency η_{th} is higher at the higher heat source temperature and the efficiency η_{th} is lower at the lower heat source temperature.

Mostly depending on the temperature, the technologies for WHR include:

1). Steam Power Cycle

Steam power plant which uses the waste heat to produce steam and then drives a steam turbine for producing output work is the most frequently used power cycle. Historically, steam power plants have been used for medium to high temperature waste heat recovery.

2). Organic Rankine Cycle

At lower temperature, instead of steam power cycle, organic Rankine cycle with organic substances as working fluids has been employed, since at the low-temperature waste heat may not provide sufficient superheating for the running of turbine.

3). Other Technologies

CO_2 transcritical power cycle with CO_2 as working fluid has getting increased attention for the conversion of low-temperature waste heat and recently developed Kalina cycle is a suitable technology for the low – to medium-temperature waste heat sources.

2.2 ORGANIC RANKINE CYCLE AS THE TECHNOLOGY FOR WASTE HEAT RECOVERY

ORC is an environmentally friendly technology with no emissions such as CO, CO_2, NOx, SOx and other atmospheric pollutants to the environment. The most important advantage for ORC as one of the renewable energy technologies is that

ORC can be used in various kinds of low-grade heat sources for power generation including industrial waste heat recovery from industrial waste heat streams, biomass, geothermal, and solar energy.

ORC in Industrial waste heat recovery:

- Gas compressor stations: recover energy from pipeline compressor stations.
- Gas processing plants: transfer waste heat from gas turbine exhaust.
- Power generation: heat recovery on internal combustion engines.
- Steel and aluminum industries: utilize the vast amount of waste heat from steel and aluminum refineries.
- Other industrial processes: pulp and paper mills; chemical plants; cement factories; glass plants; etc.

ORC in other areas:

- Biomass application represents important portion of ORC applications --- around 48% of market share of ORC is from Biomass (Quoilin & Lemort, 2009).
- There is significant geothermal market potential in the EU and in global regions, which could be used for electricity generation based on ORC technology.

- ORC technology also can be used to generate electricity from solar energy transferred from solar collectors --- an alternative to photovoltaic cells and solar plants.

2.2.1 Thermodynamic Principle of Organic Rankine Cycle and ORC Configuration

Based on Rankine cycle, organic Rankine cycle (ORC) uses organic substances as working fluids to recover heat from low temperature heat sources. The thermodynamic principle of Rankine cycle is the first law of thermodynamics, which states that the output work can be produced by expanding working fluids from high pressure state to low pressure state.

An ideal Rankine cycle includes four processes [Fig. 1]:

A. Heat transferred from waste heat source to working fluid, the working fluid phase is changed from liquid to gas (2-2’-3).

B. High temperature and pressure gas expanded and the output work produced(3-4);

C. Working fluid condensed in the constant pressure(4-1);

D. Liquid working fluid compressed by the pump to form high pressure liquid (1-2).

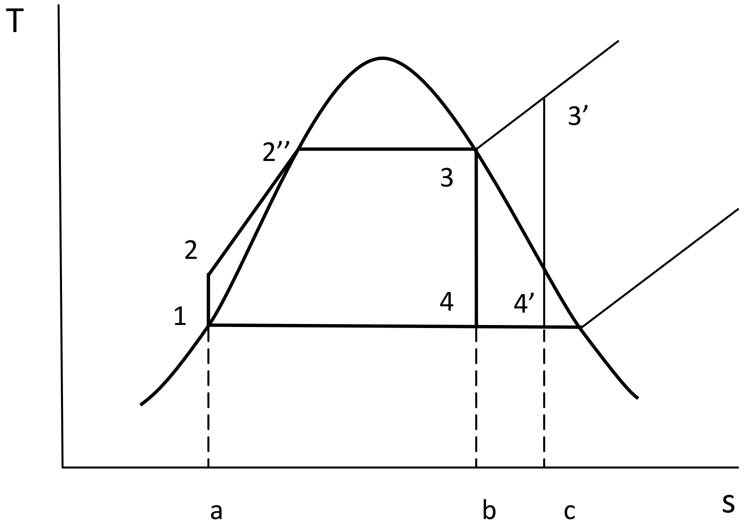


Fig. 1: T - S Diagram of an Ideal Rankine Cycle

A basic organic Rankine cycle consists of four main components: evaporator, condenser, turbine, and working fluid pump.

In the evaporator and preheater, the heat is transferred to the working fluid from the heat source, liquid working fluid is heated and evaporated; output work is produced in turbine and the synchronous generator; steam from the outlet of turbine is condensed in the condenser by the cold source, which could be the local lake water or other cold water; and the working fluid pump to raise the pressure of liquid working fluid to the required operation pressure.

A typical ORC power cycle has been demonstrated in Fig. 2:

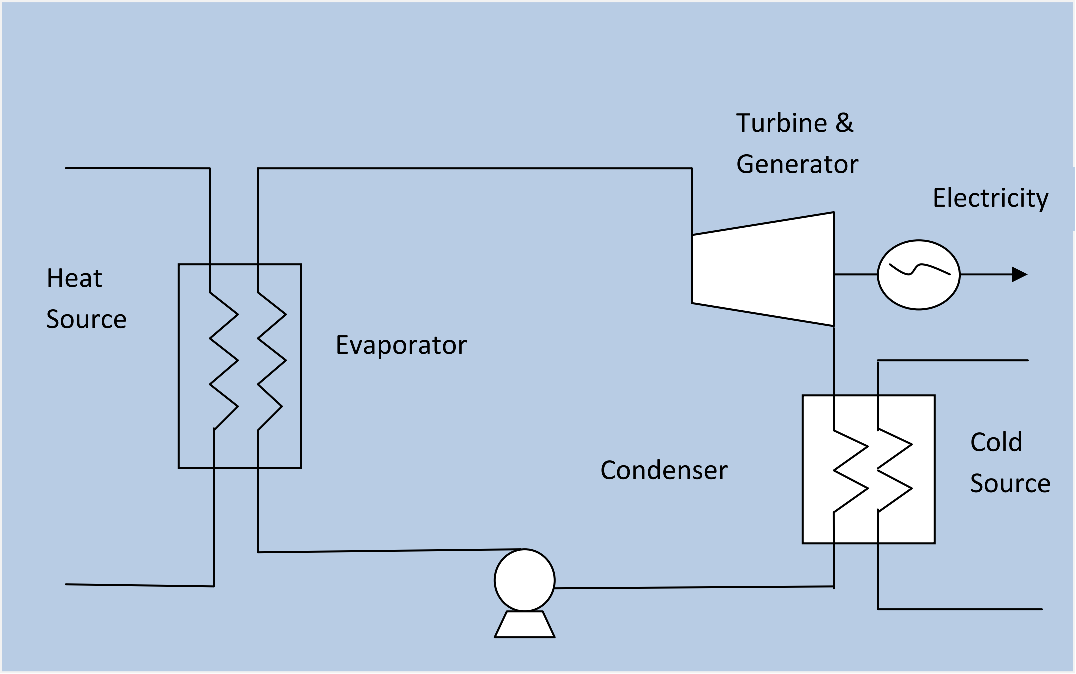


Fig. 2: ORC Power Cycle Configuration

Other configurations such as regenerative ORC power cycles with internal heat exchanger and the ORC power cycle with superheating are frequently used in ORC power plants (Mago, P. J., Chama, L. M., Srinivasan, K., & Somayaji, C., 2008); (Roy & Mstra, 2012); and (Roy, Mishra & Misra, 2011).

The efficiency of ORC for converting heat to work can be expressed as:

$\eta_{th} = (W_t - W_p) / Q_{in} * 100$

W_t: turbine output work

W_p: work consumed by the pump

Q_{in}: heat transferred from heat source

The efficiency of ORC is related with the configuration of power cycle, operation pressure, temperature of heat source and heat sink, working fluid properties, efficiency of turbine and pump, etc.. Wei et al. (2007) in their paper Performance analysis and optimization of organic Rankine cycle for waste heat recovery analyzed the thermodynamic performances of an ORC system using R245fa as working fluid. They concluded that maximizing the usage of exhaust heat as much as possible and the higher grade of heat source can improve system output net power and efficiency and the condenser should be cooled properly to reach the peak system efficiency (Wei, Lu, Lu, & Gu, 2007). The research from Roy et al.(2011) revealed that non-regenerative ORC during superheating using R123 produces the maximum efficiencies and turbine work output for constant as well as variable heat source temperature conditions among four working fluids R12, R123, R-134a and R717 (Roy, 2011). Kuo, Chang, & Wang (2011) analyzed a 50 kW organic Rankine cycle system for the effect of heat exchangers. The results indicate that the dominant thermal resistance in the shell-and-tube condenser is on the shell side and the dominant thermal resistance is on the refrigerant side for the plate evaporator (Kuo, 2011). And Yamamoto, Furuhat, Arai, & Nori (2001) in their paper " design and testing of a organic Rankine cycle" did the research for the optimal operation conditions of ORC theoretically and experimentally. They found that there are optimum operating conditions between the rotation speed and the turbine outlet and R-123 improves the cycle performance in the large extent comparing with traditional working fluid water (Yamamoto, 2001).

2.2.2 Working Fluids in ORC Power Cycle

Considering the environmental impacts of ORC power plants, one of the disadvantages is the working fluid. Traditional organic working fluids used in ORC such as silicone oil, R245fa and R134a suffer from being excessively priced as well as suffering environmental drawbacks. Researchers are investigating the use of naturally occurring substances such as hydrocarbons, NH_3 and CO_2.

In general, good working fluids should satisfy the following criteria:

- High thermal efficiency for the given heat source and heat sink temperatures;
- Low specific volumes;
- Moderate pressure in the heat exchangers;
- Low liquid viscosity and high liquid thermal conductivity;
- High latent heat of vaporization;
- Low toxicity; No –flammable and non-corrosive;
- Low ODP and low GWP;
- Low cost and good availability;

The selection for working fluids varies with types of ORC power plants, manufacturers, heat sources, availability, etc.. Except the direct environmental impacts, working fluids also have significant influence to the environmental impacts considering the thermal efficiency of ORC power plant. With higher efficiency, the consumption of working fluid could be lower, and areas required for the heat exchangers could be lower, both factors contribute lower environmental impacts from the life cycle assessment point of view.

ORC manufacturer Ormat uses n-pentane as the working fluid for heat source temperature range of 150^0C – 300^0C, and the output power range is from 200 kWe to 72 MW_e. ORC manufacturer Turboden used OMTS as the main working fluid with the temperature range of 100^0C – 300^0C, and the output power range is 200 KWe to 2 MWe. The working fluids of other manufacturers include hydrocarbons, R245fa, R134a, etc.(Quoilin & Lemort, 2009).

The working fluid can be classified on three categories of working fluids: dry, isentropic and wet depending on the slope of the T –S diagram of working fluids [Fig. 3].

An isentropic fluid has nearly infinitely large slopes, examples are R11, R12, R134a --- illustrated in diagram (a); a wet fluid has negative slope, examples are water and ammonia --- illustrated in diagram (b). Wet types of working fluids often have low molecular weight; a dry fluid has positive slopes, examples for dry fluids are benzene, R113, R245fa, R123, isobutane --- illustrated in diagram (c).

Dry and isentropic fluids have better thermal efficiencies considering the droplet in turbine. Isentropic fluids are most suitable for recovering low-temperature waste heat with the property of vapor saturated at the turbine inlet will remain saturated throughout the turbine exhaust without condensation, so the regenerator is not necessary. Research also indicates that dry fluids can reach efficiencies if a regenerator is added to the cycle (Saleh, Koglbauer, Wendland, & Fischer, 2007).

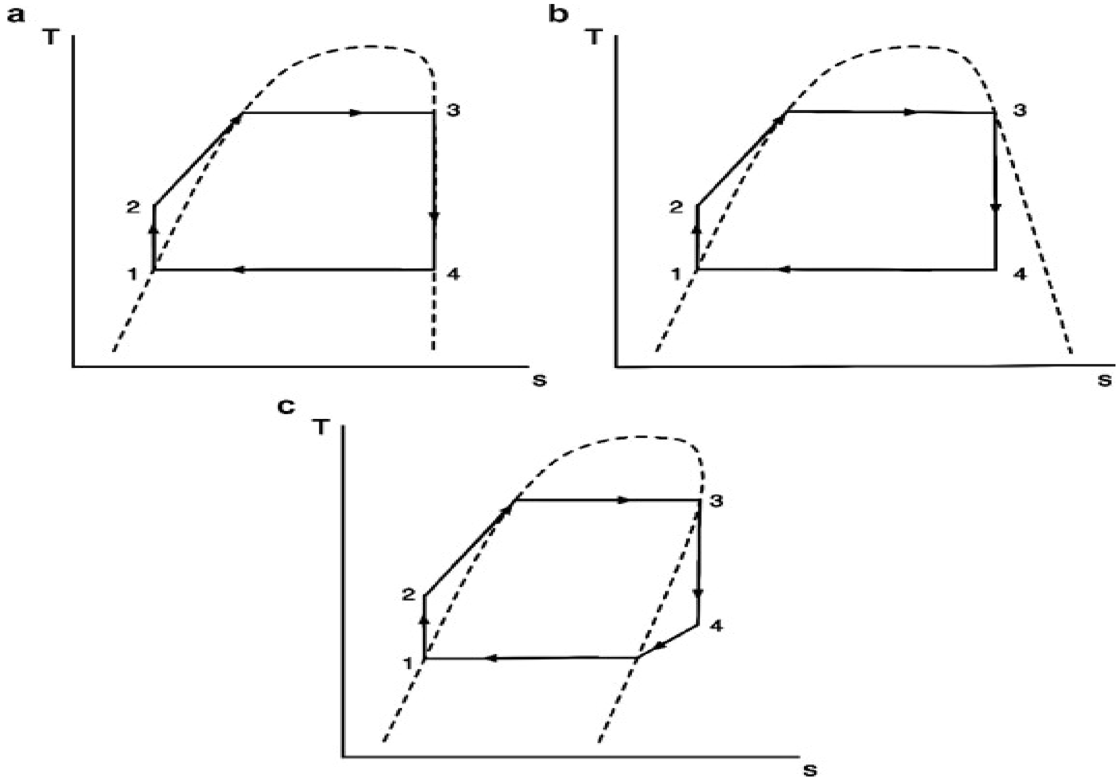


Fig. 3: Classification of Working Fluids (Mego et al, 2008)

2.2.3 Working fluids and their properties

Table 1: Properties of typical ORC working fluids

Parameters	R-12	R-123	R134a	R717	R747
Chemical formulae	CF_2Cl_2	CF_3CHCl_2	CF_3CH_2F	NH_3	CO_2
Molecular weight(g/mol)	120.92	152.93	102.03	17.031	44.01
Boiling point(^{0}C)	-29.8	27.85	-26.15	-33.35	-57
Critical Temperature(^{0}C)	112.04	183.79	101.06	133.0	33.1
Critical pressure(bar)	41.15	36.74	40.56	112.97	73.8
Atmospheric lifetime(yrs)	100	1.40	52.0	---	N/A
Ozone depletion potential	0.82	0.012	0.00	---	0
Global warming potential (at 100 years)	1060	120.0	1300.0	0	1

Source: (Roy, Mishra & Misra, 2011)

2.3 CO2 AS WORKING FLUID IN ORGANIC RANKINE CYCLE

With the non-toxic and non-combustible natural properties, and inexpensive cost of CO_2, as well as non-explosive and abundance in the nature, CO_2 as a working fluid is getting increased attention in the industrial applications.

CO_2 has following special properties as working fluid in ORC:

1). Low critical temperature is suitable for the low temperature heat source.

2). Ozone depletion potential (ODP) is zero and global warming potential (GWP) 100 years is 1.

3). Abundant, non-flammable, non-toxic and low cost.

4). Favorable thermodynamics and transports properties.

The basic principle of CO_2 power plant is still the Rankine cycle. The CO_2 power cycle includes four principle processes: compression, heat transferred from heat sources, expansion and condensation and at least five components: evaporator, condenser, turbine, pump and working fluid. Since CO_2 has a low critical temperature of CO_2, the CO_2 power cycle is a transcritical cycle: Part of the cycle is located in the supercritical region which could affect the configuration of CO_2 power cycle (Cayer, Galanis, & Nesreddine, 2010). The configuration of CO_2 power cycle includes regenerator (or internal heat exchanger) because of its special supercritical property [Fig. 4].

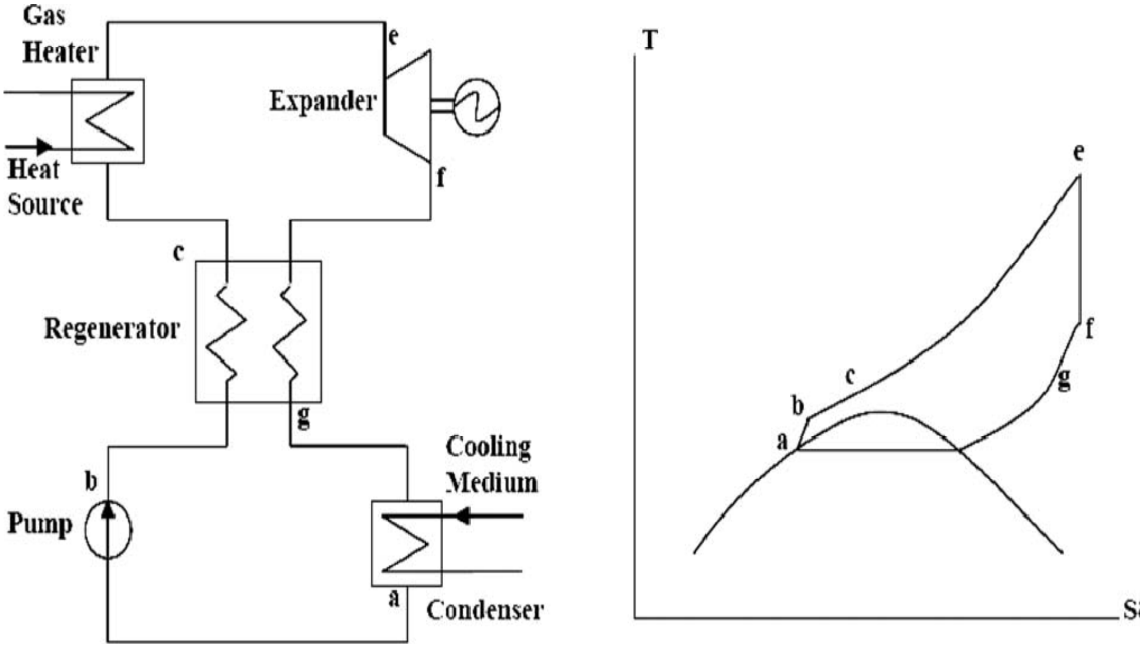


Fig. 4: Configuration of CO_2 Supercritical Power Cycle (Chen at el , 2010)

CO_2 as a promising working fluid of ORC is getting more and more attention. Chen, Lundqvist, Johansson, & Platell (2006) carried on the research for the comparison of CO_2 transcritical power cycle with ordinary organic working fluid R123 in waste heat recovery. The results show that with the same temperature of heat source, the CO_2 transcritical power system gives a slightly higher power output than R123 as working fluid. Further, the power system with carbon dioxide as a working fluid is also more compact and more environmental friendly than the one with organic working fluid. Cayer et al (2010) analyzed a CO_2 transcritical power cycle for an industrial low-grade stream of process gases as its heat source.

By varying the high pressure of the cycle and its net power output with fixed temperatures and mass flow rates of the heat sources, he concluded that the existence of optimum high pressure of the cycle. Andresen, Ladam, & Nekså, (2011) investigated the simulation optimization of the power cycle and heat exchanger parameters, this methodology can be adapted to analyze and compare cycles of different complexity, working fluids and boundary conditions. Ladam & Skaugen(2007) in their technical report "CO_2 as working fluid in a Rankine cycle for electricity production from waste heat sources on fishing boats" showed that performances for low temperature waste heat are significantly improved(25%) with a CO_2 technology. Energy (fuel) savings up to 10% can be achieved.

Chapter 3

METHODOLOGY

In this paper, Life Cycle Assessment methodology is used to evaluate the environmental impacts for producing electricity from low temperature waste heat sources in the situations of different working fluids.

3.1 INTRODUCTION OF LIFE CYCLE ASSESSMENT

A life-cycle Assessment(LCA) method systematically assesses and evaluates environmental aspects associated with all the stages of a product’s life from raw material acquisition to final disposal (from “cradle to grave”). Life cycle assessment can be used in a wide range of products and activities, from agriculture to energy system, from packaging products to transportation vehicles, and which could integrated into strategic levels of firms and corporate, and further for the reference of different decision makers.

3.1.1. Life cycle assessment

Traditionally, the LCA method consists of four main steps [Fig. 5]:

Goal and scope definition; Inventory analysis; Impact assessment; and Interpretation.

Step 1). Goal and scope definition:

The purpose of the LCA analysis is decided. The goal definition includes stating the intended application of the study, the reason for carrying it out and to whom the results are intended to be presented. In the phase of goal and scope definition, the functional unit and system boundary are defined. Inventory analysis is to build a systems model according to the requirements of a goal and scope definition.

Step 2). Inventory analysis:

1). Construction of the flow model: the flow model is usually a flowchart which shows the activities within the analyzed system and the flows between those activities.

2). Data Collection for all those activities such as raw materials, energy consumption, products, and waste and emissions to air and water.

3). Calculation of the amount of resource use and pollutants of the system with related to the functional unit.

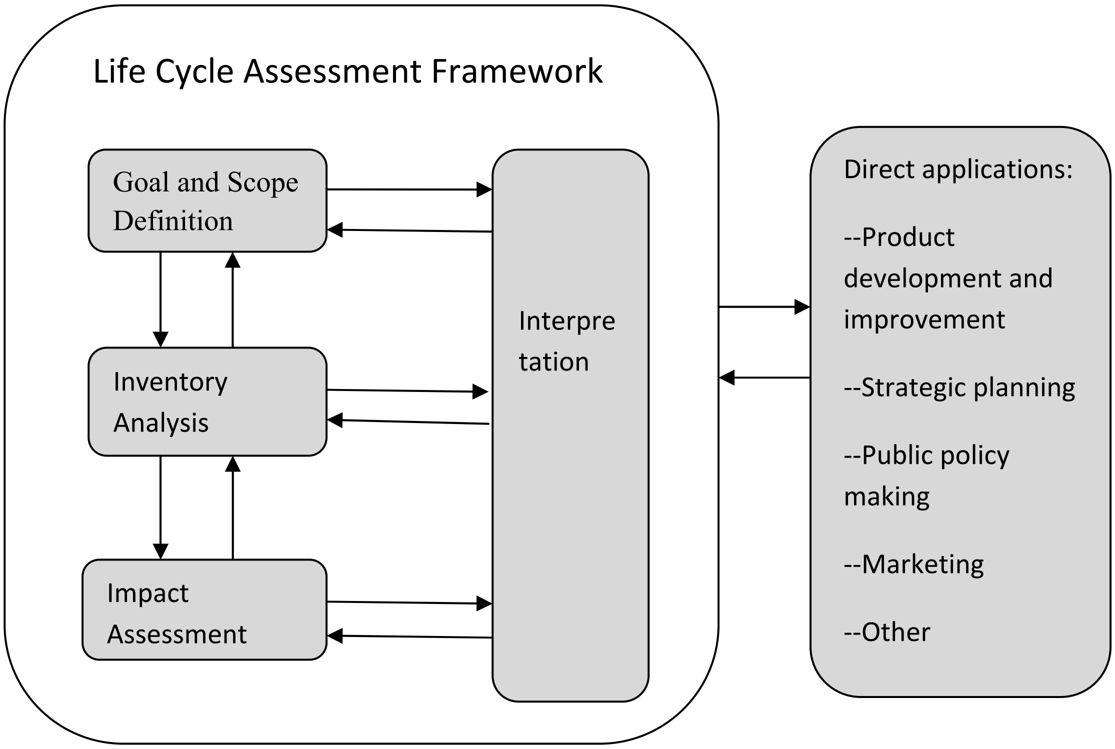


Fig. 5: Illustration of LCA Phases (ISO 2006a)

Step 3). Impact assessment or Life Cycle Assessment (LCIA): the procedure to quantify the environmental impacts loads in the inventory analysis.

Step 4). Interpretation: the process of refining the raw results into useful, presentable and final results. Most often method is to present only the most important inventory result parameters in a bar diagram and weighted impact assessment results.

3.1.2 Life cycle inventory database

Publicly available high quality life cycle inventory (LCI) databases have been known as Franklin US98, Idemat 2005, Buwal 250, ETH-ESU 96, and Ecoinvent. Among them, Ecoinvent database developed by the Ecoinvent Center has been recognized as the most recent, comprehensive and best quality LCA database available. The first launch of Ecoinvent data v1.01 was in 2003, and the latest version is Ecoinvent v.2.2 leased in 2009. The version used in this research for life cycle inventory assessment(LCIA) is Ecoinvent v2.1, which includes about 4000 datasets for products, services, and processes often used in LCA case studies(Ecoinvent, 2007) , covering energy, transport, building materials, chemicals, mechanicals, electronics, waste treatment and agricultural products.

3.1.3 Basic mathematics of LCA

Considering LCA is the calculation of emissions from the entire production value chain, the total emissions include direct emission from the production and service and the indirect emissions from related production and service activities.

1) Production output equation

$x = A * x + y$

x : output

$$x = \begin{pmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{pmatrix}$$

A: intermediate demand matrix

$$A= \begin{pmatrix} a_{11}\ a_{12}\ \dots\ a_{1n} \\ a_{21}\ a_{22}\ \dots\ a_{2n} \\ \dots.. \\ a_{n1}\ a_{n2} \dots\ a_{nn} \end{pmatrix}$$

y: external demand

$$y = \begin{pmatrix} y_1 \\ y_2 \\ \dots \\ y_n \end{pmatrix}$$

2) Leontief inverse matrix

$$x = (I - A)^{-1} y \leftrightarrow x = L y$$

I : unit matrix

$L = (I-A)^{-1}$: Leontief inverse matrix

$$L = \begin{pmatrix} 1-a_{11} & -a_{12} & \dots & -a_{1n} \\ -a_{21} & 1-a_{22} & \dots & -a_{23} \\ \dots & & & \\ -a_{n1} & -a_{n2} & \dots & 1-a_{nn} \end{pmatrix}^{-1} = \begin{pmatrix} l_{11} & l_{12} & \dots & l_{1n} \\ l_{21} & l_{22} & \dots & l_{2n} \\ \dots & & & \\ l_{n1} & l_{n2} & \dots & l_{nn} \end{pmatrix}$$

3) Calculation of total emissions for a given external demand

$$e = S * x = S * L * y$$

S: stressor intensity matrix

$$S = \begin{pmatrix} s_{11} & s_{12} & \dots & s_{1, pro} \\ s_{21} & s_{22} & \dots & s_{2, pro} \\ \dots & & & \\ s_{str,1} & s_{str,2} & \dots & s_{str, pro} \end{pmatrix}$$

e: vector of stressors generated for a given external demand

$$e = \begin{pmatrix} e_1 \\ e_2 \\ \dots \\ e_{str} \end{pmatrix}$$

4). Impact evaluation of different categories

$$d = C*e = C*S*(I-A)^{-1}*y$$

C: Characterization factor matrix

$$C = \begin{pmatrix} c_{11} & c_{12} & \dots & c_{1,str} \\ \dots & \dots & & \\ \dots & \dots & & \\ c_{imp,1} & c_{imp,2} & \dots & c_{imp,str} \end{pmatrix}$$

$$d = \begin{pmatrix} d1 \\ . \\ . \\ d_{imp} \end{pmatrix}$$

LCIA interpretation calculation:

1. Characterization

   $d = C*e$

   d = category indicator vector(potentials)

   C = characterization factor matrix

   e = LCI vector

2. Normalization

   $n = N* d$

   n = normalized category indicator vector

   N = normalization matrix

3. Weighting

   $t = w*n$

   t = single aggregated indicator

   w = vector of weighting factors

3.2 LIFE CYCLE INVENTORY ASSESSMENT

From the life cycle inventory data, the steps for evaluating the environmental impacts are illustrated in [Fig. 6]:

1). Classification:

Assigning the inventory items to different environmental impact categories.

2). Characterization:

Multiplying the inventory items by characterization factors to obtain the category indicator values.

3). Normalization (optional)

Expressing the required category indicators as the portion of given type of total impact.

4). Weighting (optional)

Multiplying the category factors to get the social importance of responding categories.

3.3 CALCULATION METHODS

3.3.1 Midpoint and endpoint approaches

Generally, there are two calculation methods: midpoint methods and endpoint methods. In the midpoint approach, environmental impacts from products or processes are related to damage categories such as climate change, ecotoxicity acidification. In endpoint approach, the final social and health consequences such

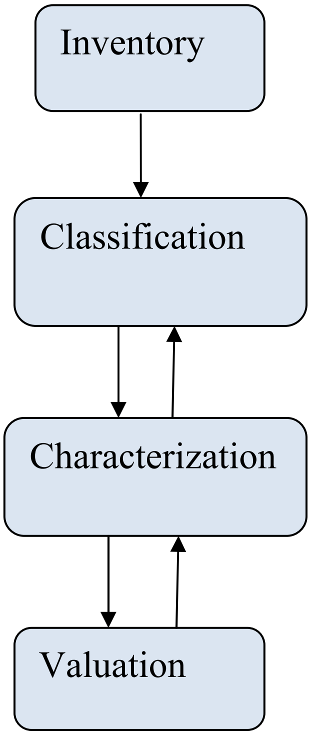


Fig. 6: The Structure of Life Cycle Inventory Assessment

as damage to human health and damage to ecosystem quality are obtained based on a common attribute ($ or DALY).

Midpoint methods

- CML-method
- EDIP 2003
- Impact 2000 (CMIL2)

- TRACI

Endpoint methods:

- Ecoindicator 99
- Environmental Priority System
- Ecoscarcity method

3.3.2 ReCiPe method

Newly developed ReCiPe comprises of two sets of impact categories: midpoint level and endpoint level.

There are eighteen impact categories at the midpoint level of ReCiPe. Ten of them have been chosen for reporting (ReCiPe 2008, 2009):

1. Climate Change

   Characterization factor is Global Warming Potential (GWP), the environmental impact effect is the amount of kg CO_2 equivalent to air.
2. Ozone Depletion

Characterization factor is Ozone Depletion Potential (ODP), the environmental impact effect is the amount of kg CFC-11 equivalent to air.

3. Terrestrial Acidification

   Characterization factor is Terrestrial Acidification Potential (TA), the environmental impact effect is the amount of kg SO_2 equivalent to air.

4. Freshwater Eutrophication

   Characterization factor is Freshwater Eutrophication Potential (FE),

   the environmental impact effect is the amount of kg P equivalent to freshwater.

5. Marine Eutrophication

   Characterization factor is Marine Eutrophication Potential(FE), the environmental impact effect is the amount of kg N equivalent to freshwater.

6. Human Toxicity

   Characterization factor is Human Toxicity Potential (HT), the environmental impact effect is the amount of kg 1,4-DCB equivalent to urban air.

7. Photochemical Oxidant Formation

   Characterization factor is Phtochemical Oxidant Formation Potential (POF), the environmental impact effect is the amount of kg NMVOC to air.

8. Particulate matter formation

   Characterization factor is Particulate Matter Formation Potential (PMF), the environmental impacts effect is PM_{10} equivalent to air.

9. Terrestrial Ecotoxicity

   Chracterization factor is Terrestrial Ecotoxicity Potential (TET), the environmental impacts effect is kg 1,4-DCB equivalent to industrial soil.

10. Freshwater Ecotoxicity

    Charaterization factor is Freshwater Ecotoxicity Potential (FET), the environmental impacts effect is kg 1,4 –DCB to freshwater.

And other categories:

11. Marine Ecotoxicity
12. Ionizing Radiation
13. Agricultural Land Occupation
14. Urban Land Occupation
15. Natural Land Transformation
16. Water Depletion
17. Mineral Resource Depletion
18. Fossil Fuel Depletion

And three endpoint categories at the endpoint level of ReCiPe method:

1. Damage to human health

   Indicator is Disability-adjusted Loss of Life Years (DALY) in years (yr).

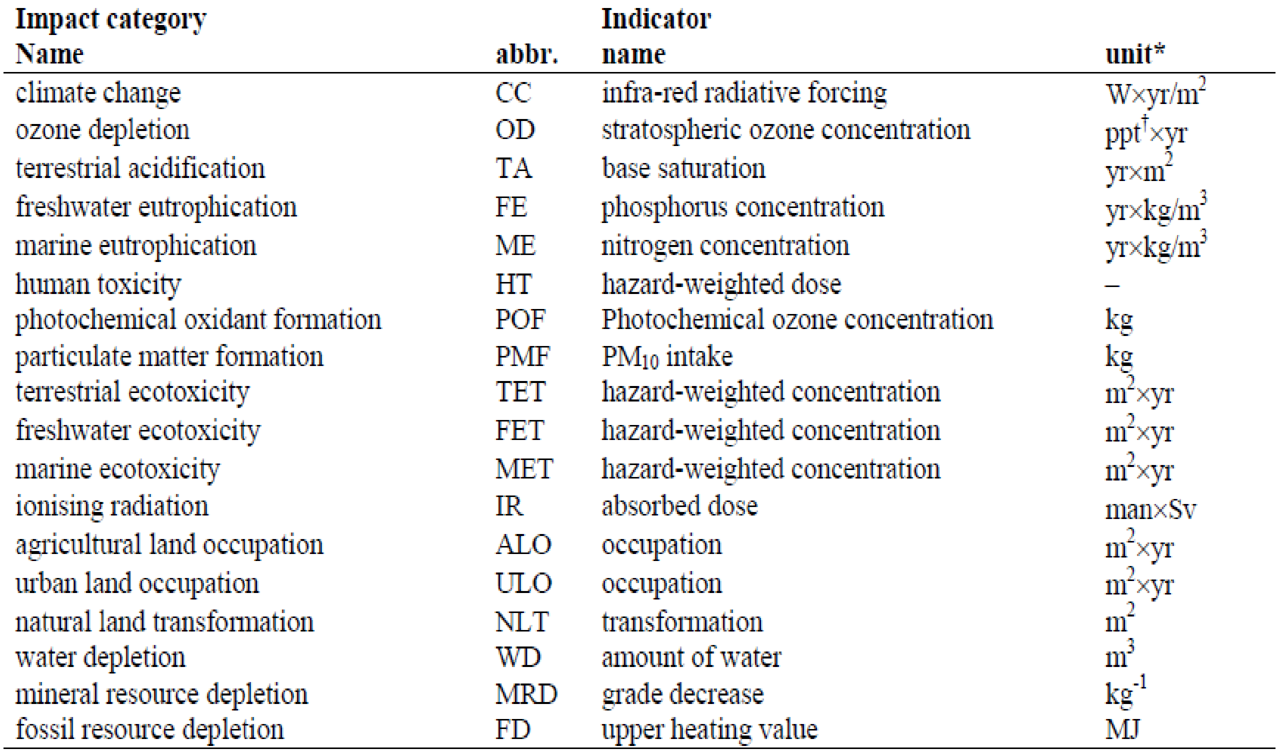
2. Damage to ecosystem diversity

   Indicator is Loss of Species during a year in years (yr).

3. Damage to resource availability

   Indicator is Increased Cost in dollars ($)

Table 2: List of ReCiPe Midpoint Impact Categories



Impact category		**Indicator**	
Name	**abbr.**	**name**	**unit***
climate change	CC	infra-red radiative forcing	$W \times yr/m^2$
ozone depletion	OD	stratospheric ozone concentration	$ppt^{\dagger} \times yr$
terrestrial acidification	TA	base saturation	$yr \times m^2$
freshwater eutrophication	FE	phosphorus concentration	$yr \times kg/m^3$
marine eutrophication	ME	nitrogen concentration	$yr \times kg/m^3$
human toxicity	HT	hazard-weighted dose	–
photochemical oxidant formation	POF	Photochemical ozone concentration	kg
particulate matter formation	PMF	PM_{10} intake	kg
terrestrial ecotoxicity	TET	hazard-weighted concentration	$m^2 \times yr$
freshwater ecotoxicity	FET	hazard-weighted concentration	$m^2 \times yr$
marine ecotoxicity	MET	hazard-weighted concentration	$m^2 \times yr$
ionising radiation	IR	absorbed dose	man×Sv
agricultural land occupation	ALO	occupation	$m^2 \times yr$
urban land occupation	ULO	occupation	$m^2 \times yr$
natural land transformation	NLT	transformation	m^2
water depletion	WD	amount of water	m^3
mineral resource depletion	MRD	grade decrease	kg^{-1}
fossil resource depletion	FD	upper heating value	MJ

Source: ReCipe 2008 (2009)

There are three perspectives are concerned in ReCiPe:

- Individualist perspective (I): technology optimist based on short-term interest. The individualist perspective assumes a short time frame of 20 year time frame.
- Hierarchist perspective (H): problem solver based on the most common policy principles. The hierarchist perspective seeks consensus for the 100 year timeframe.
- Egalitarian perspective (E): extreme sustainability considering the longest time-frame, assuming 500 years. For the substances with short lifetime, the results will be the same.

3.3.3 Software and method used in this research

In this research, software used for LCA assessment is SimaPro 7.3.2 from Pré Consultants, Neitherland and the method used here is the ReCiPe midpoint method, Hierarchist version(European normalization) created by RIVM, CML, Pre Consultants, Radboud Universitert Nijmegen and CE Delft(SimaPro 7.3.2).

Chapter 4

LIFE CYCLE ANLAYSIS OF NPO 210 kW_e ORC POWER PLANT

4.1 POWER PLANT DESCRIPTION

The power plant used for LCA analysis is the Geothermal Power Plant at Chena Hot Springs, Alaska with the power capacity of 210 kW_e NPO. The higher temperature heat source is the hot water from local geothermal hot spring and the low temperature heat sink is the local river water. The purpose of this project is to generate electricity from the available geothermal resource for local power supply, usually this power is generated by diesel generation sets. Manufactured by Turboden, this power plant is a successful application case for the R134a as working fluid in organic Rankine cycle. The model used in Chena project is the same as the Turboden PureCycle 280 model, which has been installed for electricity generation from waste heat recovery in various situations (Turboden, 2012)

4.1.1 Configuration of the power plant

The power plant produces electricity using ORC power cycle with R134a as working fluid. For the LCA, other working fluids Ammonia, CO2 and Pentane have been included. Same as other ORC power plants, this power plant consists of evaporator and preheater set, turbogenerator, condenser, working fluid pump and working fluid itself.

In evaporator and preheater set, heat is transferred from waste heat source to working fluid for evaporating, the liquid working fluid becomes higher pressure vapour to enter into the inlet of turbine. In turbogenerator, this higher pressure vapour is expanded to generate electricity. In condenser, the working fluid from the outlet of turbine is condensed into liquid. Then the liquid working fluid is pressured in the working fluid pump and then enters into the evaporator to complete the power cycle.

4.1.2 Parameters in the power cycle

In this power plant, the gross output power of turbine is 250 kW and the net power produced is 210 kW. In the evaporator/preheater side of the ORC system, the flow rate of 33,44 l/s hot water enters the unit at the temperature of 85^0C and leaves at the temperature of 70 ^{0}C, transferring 2,58 MW of themal energy to the working fluid. In condenser, 5^0C of cooling water is heated to 10^0C transferring 2,36 MW energy from the working fluid. In pump, the working fluid pressure is raised from 4 bar to 15 bar. The efficiency of this power plant is 8.2%. With the same heat source and heat sink temperature, a completely reversible thermodynamic cycle would have a thermal efficiency nearly 18%. Efficiency improvement in this power plant is not critical from the economic point of view since the heat source and then the fuel is essentially free.

4.1.3 Equipments used and the power plant layout

The sizes of this power plant unit are roughly estimated, around 5.1 meters length and 1.75 meter height. The basic layout of this power plant is illustrated in Fig. 7 below:

Equipments:

Evaporator/Preheater:

Evaporator is the type of shell-and-tube heat exchanger which integrated evaporator and preheater into one unit. The material used in this unit is Cupro-Nickel 90-10. In boiler region, there are 1-pass 260 tubes; in preheater region, there are 1-pass 90 tubes.

Condenser:

Condenser is a standard two pass shell-and-tube heat exchanger. There are 602 fin types tubes and the material used is copper.

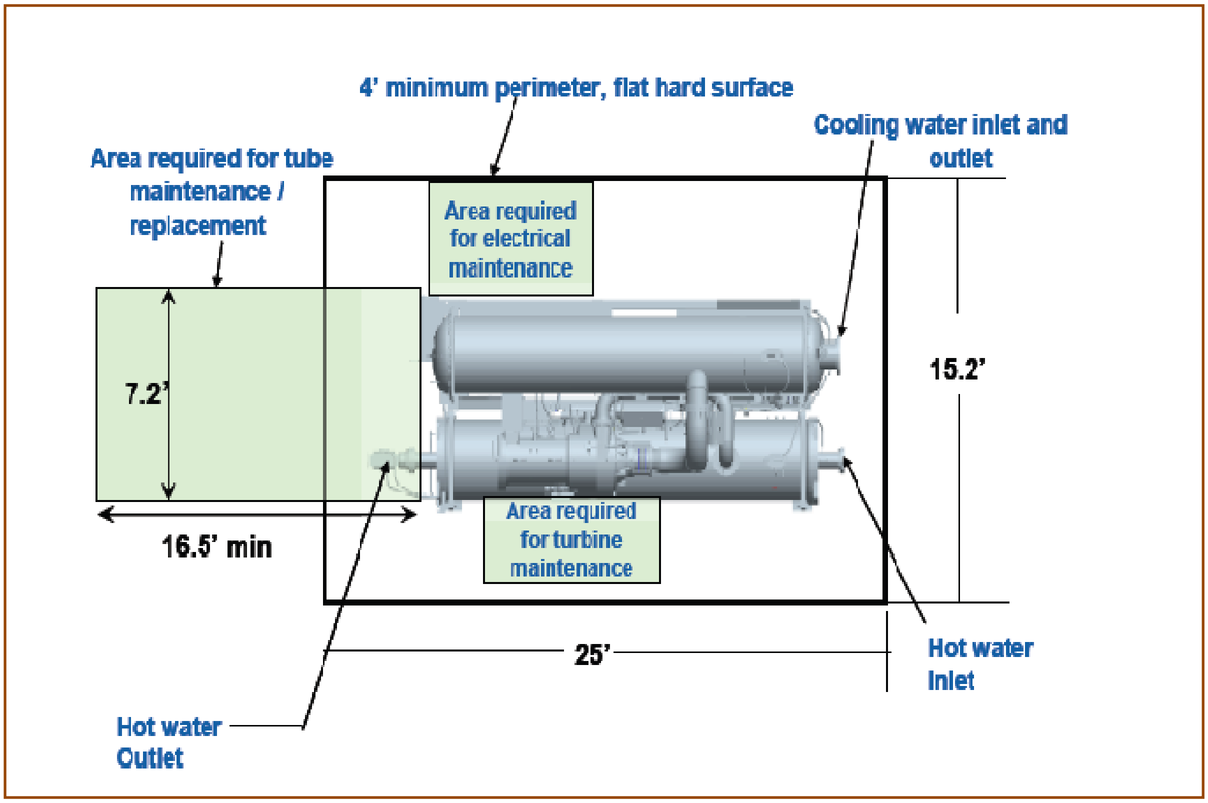


Fig. 7: Layout of NPO 210 kWe ORC Power Plant (LLC, 2007)

Turbogenerator:

Manufactured by United Technology Corporation, the turbogenerator combines a radial inflow turbine with an internal gearbox and an induction generator in a single hermetically sealed unit. Generator cooling is provided by the working fluid and the turbine is internally lubricated by high temperature lubricant which is compatible with the working fluid.

Working Fluid Pump:

The pump used in this power cycle is a regenerative pump manufactured by Roth Pump Company.

Working Fluid: the built-in working fluid of this power plant is R134a. R134a is frequently used in ORC power plant. With the chemical formula of CH_2FCF_3, the molecular weight of R134a is 102,03 kg/kmol and the boiling point of R134a is -26,15 at atmosphere pressure. Following the initial charge of liquid R134a in the assembling stage of power plant, the working fluid is also supplied considering the leakage in the maintenance and repair.

Other three potential working fluids for LCA analysis are $NH_{3,}$ CO_2 and n-Pentane. NH_3 and CO_2 are well-known substances in the nature. For the n-Pentane, the critical temperature of n-Pentane is 96,68 ^{o}C, critical pressure is 42,47 bar.

4.2 LIFE CYCLE ANALYSIS OF THE POWER PLANT

4.2.1 Goal and scope

The goal of this study is to evaluate the environmental impacts associated with the production of 210 kW$_e$ NPO electricity for the ORC power plant with organic R134a as working fluid. The sizes of the power plant are relatively small, but considering the increased demand for the fossil fuel energy, it is necessary to pay attention for the small scale power plants. The LCA evaluation of this ORC power plant will give the quantitative amounts of environmental impacts considering the effects to human health, ecosystem health, and the damage to nature resources. Through the performance of Life Cycle Analysis, the environmental impacts of electricity production from ORC power plants have been determined, which have been the basic data for comparing with other renewable energy technologies. Also the environmental impacts of other potential working fluids NH_3 and CO_2 for ORC power plants have been performed by the LCA.

4.2.2 Functional unit

The functional unit of this analysis is 1 kWh electricity generated from this R134a power plant. This is based on the lifetime of 25 years and accounting for all the mechanical and electrical losses for operating this power plant.

4.2.3 Flowchart of NPO 210 kW$_e$ power plant

The process flowchart of this power plant has been illustrated in Fig. 8 below:

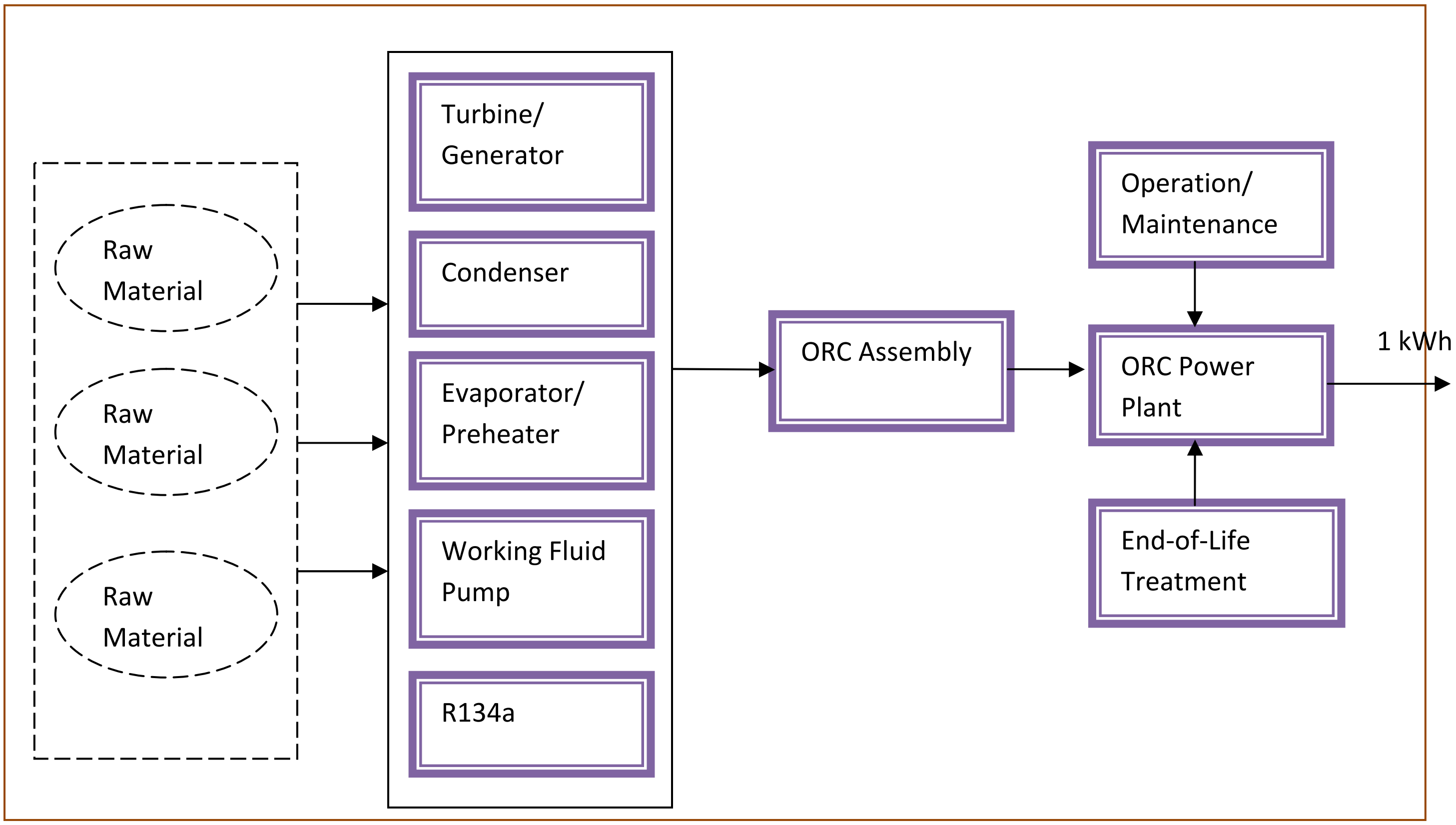


Fig. 8: Process Flowchart of NPO 210 kW_e Power Plant

4.2.4 Data collection

The principal manufacturing data of equipments have come from the a project description of 400kW Geothermal Power Plant at Chena Hot Springs(LLC, 2007), the information of given manufacturers, and from the SimaPro database.

4.2.5 Life cycle inventory of the power plant

The Life Cycle Inventory include the raw materials extraction and production, energy consumption, transport, assembly of ORC components, construction of ORC power plant, operation and routine maintenance, and disposal. For the assembly, included for process inputs are evaporator/preheater; condenser; turbine/generator; pump; and the assmbly of all those components and the entire assemly of ORC power plant; For operation and maintenance; included are all the operation and maintenance of all above equipments and the raw materials inputs; For disposal, included are all the solid and liquid end-of - treatment considering their environmental effects.

4.3 RESULTS AND DISCUSSION

4.3.1 Overall characterization impacts from the ORC power plant

The total characterization impact amounts of chosen categories have been calculated which include all the life cycle stages of this ORC power plant: ORC and components assembly, plant construction, operation and maintenance, and end-of-life treatment. Results have been listed on Table 3.

Typically, for producing 1 kWh electricity from the ORC power plant of 210 kWe using R134a as working fluid, the impact amount for climate change is 9,253 g CO_2 eq; for ozone depletion is 0,0007817 g CFC-11 eq; amount for human toxicity is 2,686 g 1,4-DCB eq; etc..

Table 3: Total Impacts of 210 kW_e ORC Power Plant from Chosen Categories

Impact categories	Unit	Total Amount
Climate Change	kg CO2 eq	0,009253
Ozone Depletion	kg CFC-11 eq	7,817E-7
Human Toxicity	kg 1,4-DCB eq	0,002686
Photochemical Oxidant Formation	kg NMVOC	8,914E-6
Particulate Matter Formation	kg PM10 eq	8,993E-6
Ionising Radiation	kg U235 eq	0,000585
Terrestrial Acidification	kg SO2 eq	2,64E-5
Freshwater Eutrophication	kg P eq	1,801E-6
Marine Eutrophication	kg N eq	5,856E-6
Terrestrial Ecotoxicity	kg 1,4-DCB eq	3,498E-7

4.3.2 Percentage contribution of different life cycle stages

In the life cycle analysis stage, the environmental impacts from assembly, operation, setup construction and disposal have been calculated. Fig. 9 below shows the percentage distribution from those stages.

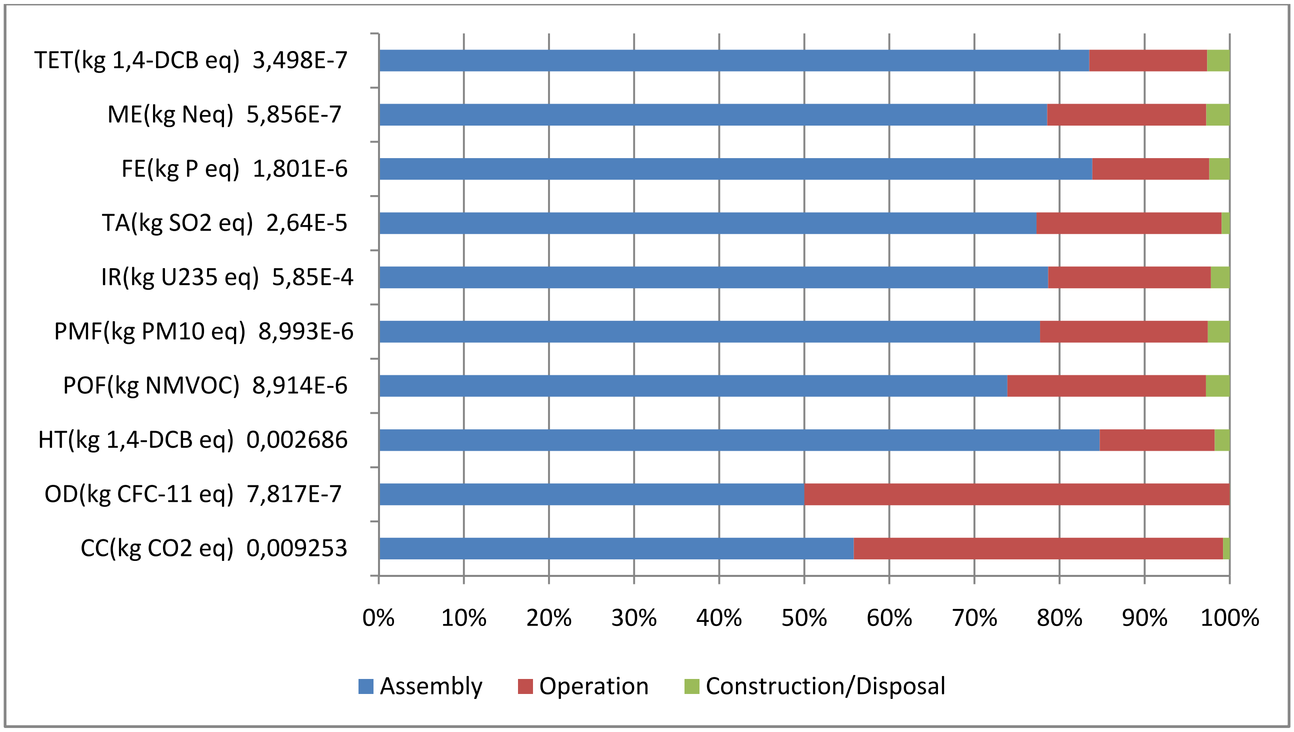


Fig. 9: Percentage Contribution of Different Life Cycle Stages

4.3.3 Components percentage contribution for ORC assembly in chosen categories

Fig. 10 below illustrates the percentage contribution from the main components of ORC power plant for the chosen categories. For climate change and ozone depletion, the most important contribution comes from the working fluid R134a; for other categories, power output device turbine and generator has significant contribution to the total amounts; and heat exchangers have large portion of contribution to the total amounts.

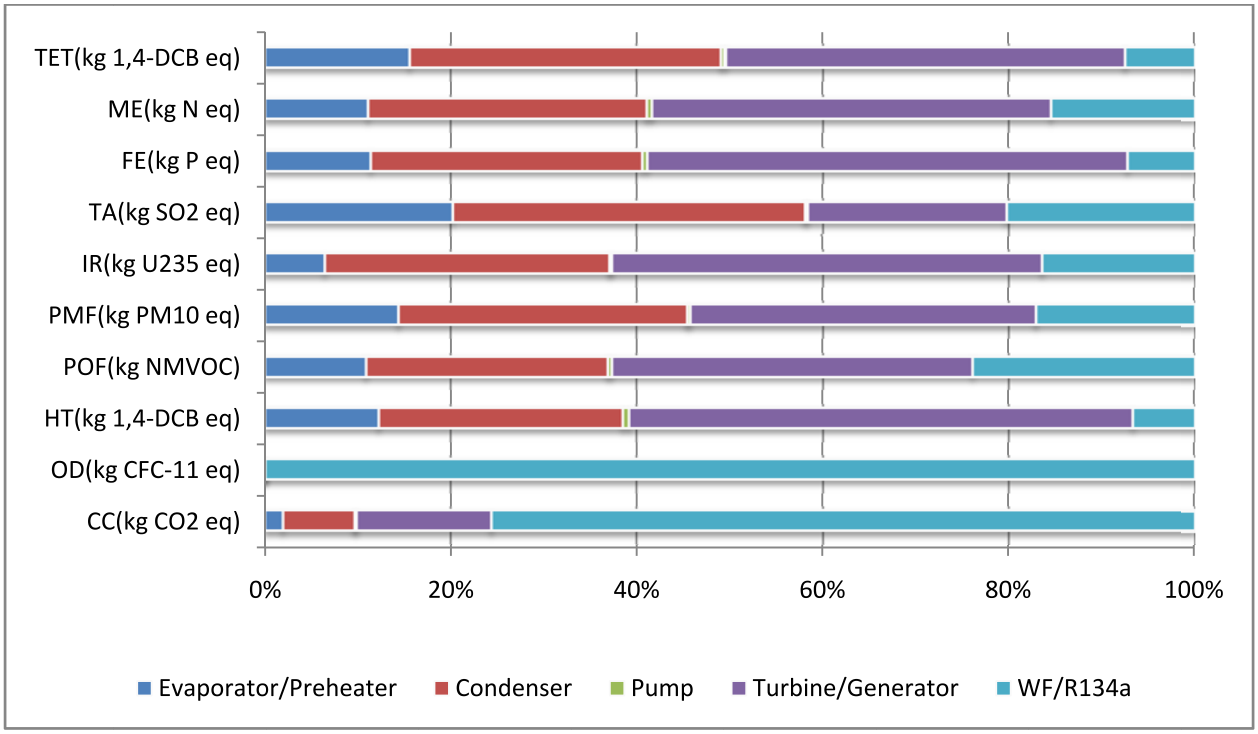


Fig. 10: Percentage Contribution of ORC Components

4.3.4 Total impact amounts from the scenarios of four different working fluids

The total impact amounts from chosen categories for the different working fluids have been listed on the table below [Table 4]:

Table 4: Total Impact Amounts from Chosen Categories of 750 kWe Power Plant from Four Working Fluids Scenarios

	R134a	Ammonia	CO2	Pentane
Climate change(kg CO2 eq)	0.009253	0.0006764	0.002639	0.0012785
Ozone depletion(kg CFC-11 eq)	7.82E-07	5.26E-11	1.85E-10	8.41E-11
Human toxicity(kg 1,4-DCB eq)	0.002686	0.0009877	0.004109	0.0019423
Photochemical oxidant formation(kg NMVOC)	8.91E-06	2.50E-06	1.06E-05	5.09E-06
Particulate matter formation(kg PM10 eq)	8.99E-06	2.79E-06	1.17E-05	5.48E-06
Ionising radiation(kg U235 eq)	0.000585	0.000182	0.0007903	3.68E-04
Terrestrial acidification(kg SO2 eq)	2.64E-05	7.61E-06	3.36E-05	1.51E-05
Freshwater eutrophication(kg P eq)	1.80E-06	6.56E-07	2.77E-06	1.29E-06
Marine eutrophication(kg N eq)	5.86E-07	1.73E-07	1.85E-10	3.36E-07
Terrestrial ecotoxicity(kg 1,4-DCB eq)	3.50E-07	1.38E-07	5.66E-07	2.50E-07

4.3.5 Results from the different working fluids

With the different physical and thermodynamic properties, the results of environmental impacts are different for the working fluids. Fig. 11

below shows the environmental impacts comparison for the scenarios of all the four working fluids: R134a, Ammonia, CO_2 and n-Pentane. Fig. 11(a)includes the categories of climate change, human toxicity and ionizing radiation; Fig. 11(b) includes the categories of ozone depletion, marine eutrophication and terrestrial ecotoxicity; Fig. 11(c)include all other four categories: photochemical oxidant formation, particulate matter formation, terrestrial acidification and freshwater eutrophication.

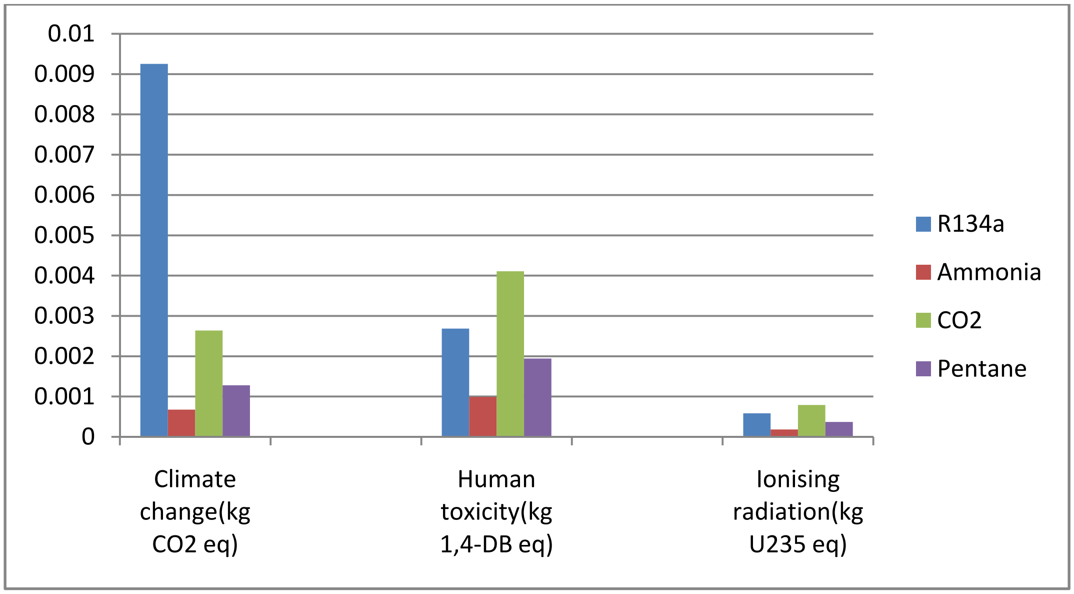


Fig. 11(a): Comparison of Working Fluids Effect

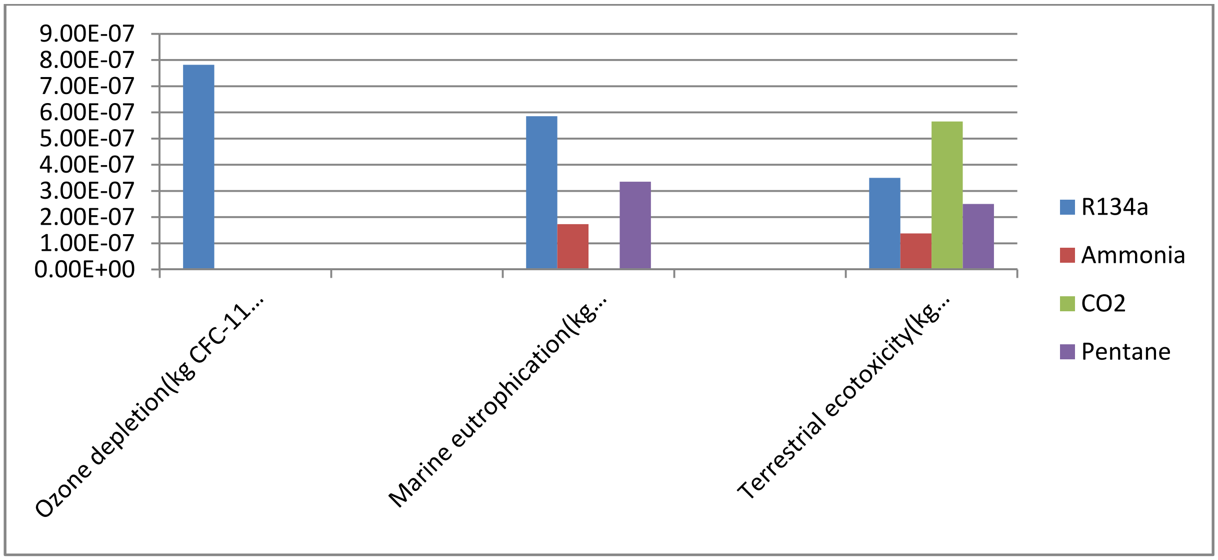


Fig. 11(b): Comparison of Working Fluids Effect

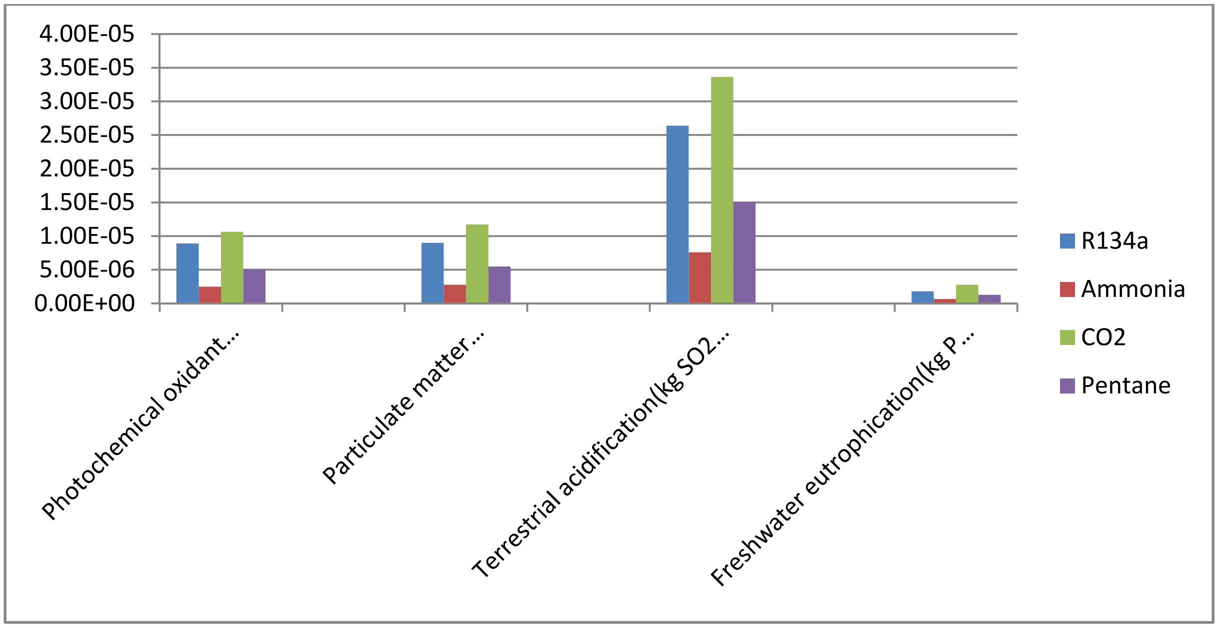


Fig. 11(c): Comparison of Working Fluids Effect

4.3.6 Discussion on the effect of working fluids

Climate change has harmful effect on a number of environmental mechanisms on human health and ecosystem health. With the characterization factor of CO_2 equivalency, R134a has quite larger CO_2 equivalent amount over other three working fluids, the relative scale comparing with NH_3 is about 10 times higher and several times over CO_2 and n-Pentane.

Ozone Depletion

Ozone is formed by the action of sunlight and chemical reactions in the stratosphere, and the stratospheric ozone is vital for life because it hinders solar ultraviolet UV-B radiation. R134a has overcoming amount of ozone depletion potential over other three working fluids represented by CFC-11 equivalent.

Eutrophication

Aquatic eutrophication is caused by the nutrient enrichment of the aquatic environment. Eutrophication leads to environmental problems which affect the speices diversity at varying levels. R134a has dominant emission amount of N in the category of marine eutrophication and CO_2 has highest score for P in the category of freshwater eutrophication.

Acidification

CO_2 has the highest impact on the acidification among these four working fluids.

Toxicity

The human toxicity and ecotoxicity account for the fate (environmental persistence), exposure, and toxicity effect of a chemical. CO_2 as working fluid has highest amount of 1,4-DCB both on human toxicity and terrestrial ecotoxity.

Chapter 5

LIFE CYCLE ANALYSIS OF NPO 750 kWe ORC POWER PLANT

5.1 POWER PLANT DESCRIPTION

The power plant used in this research for LCA analysis is the ORC power plant with NH_3 as working fluid. The heat source of this ORC power plant comes from a paper mill located at Aspa, Sweden, which produces bleached and unbleached pulp at a capacity of 200,000 tons/year (Öhman, 2012). The waste heat comes from several parts of the manufacturing processes and the cooling source is local lake water. With the output power of 750 kW_e, this ORC power plant could supply at least 3133 MWh/year electricity to the local utility (Öhman, 2012). Without the installation of the ORC power plant, all of the mill's process water reaches the local lake. With the installation of ORC power plant, the waste heat water is transformed into emission free electricity. Furthermore, the waste heat with higher temperature has been cooled in the ORC power plant before it is finally diverted into treatment.

5.1.1 Process scheme of the power plant

This ORC power plant uses typical organic Rankine cycle configuration to convert the waste heat into electricity. The powe plant consists of boiler, turbine and generator, condenser, and pump[Fig. 10]. Working fluid used in this power plant is commercially available Ammonia (NH_3).

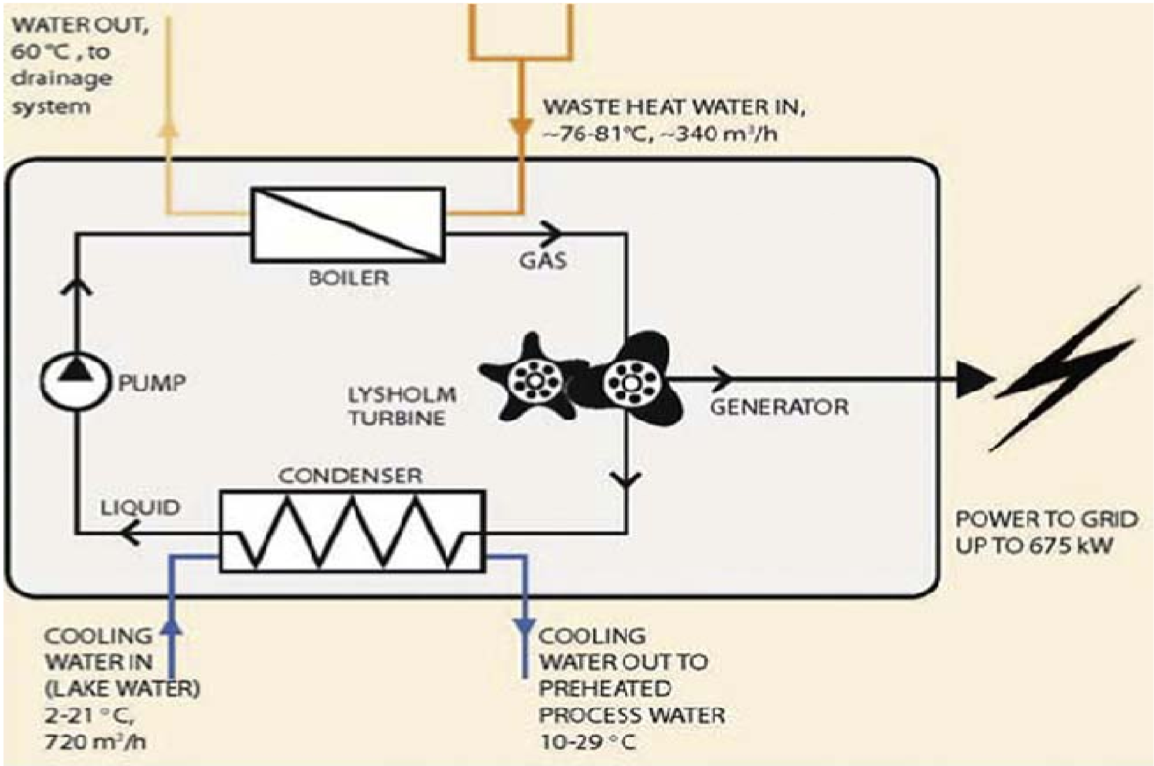


Fig. 12: Process Scheme of NH_3 Power Plant (Öhman, 2012)

After the waste heat entering the power plant, heat from is transferred from the heat source to pressurized working fluid liquid for preheating and boiling; The NH_3 vapour is expanded to a lower pressure in a turbine to produce shaft work; The output mixture of liquid and gas from turbine is condensed by the cooling water heat sink; After condensing, the liquid is pumped back to the boiler for the required higher pressure and then the power cycle completed. Operation of the plant is 24h per day typically two weeks yearly maintenance.

5.1.2 Technical data of the 750 kWe power plant

Model used:	Opcon ORC Powerbox Model
NPO:	750 kW_e
Waste heat water in:	around from 76^0C to 81^0C
Waste heat water flow rate:	around 340 m^3/h
Cooling water in:	around from 2^0C to 21 ^{0}C
Cooling water flow rate:	around 720 m^3/h
Thermal efficiency:	8 – 9 %

5.1.3 Equipments used in this power plant

The overall sizes of the power plant are 11m in length, 4m in height, and 3,5m in width. Total amount of the equipments of this power plant is 27,000 kg.

Turbine:

Turbine is a key component for the operation of ORC power plant. For expansion of working fluid, the equipment used in this ORC power cycle is Lysholm Turbine designed and manufactured by Svenska Rotor Makiner AB, Sweden, which is a positive displacement type, twin rotary, helical body machine (Fig. 11 below shows the images of this particular type of Lysholm turbine):

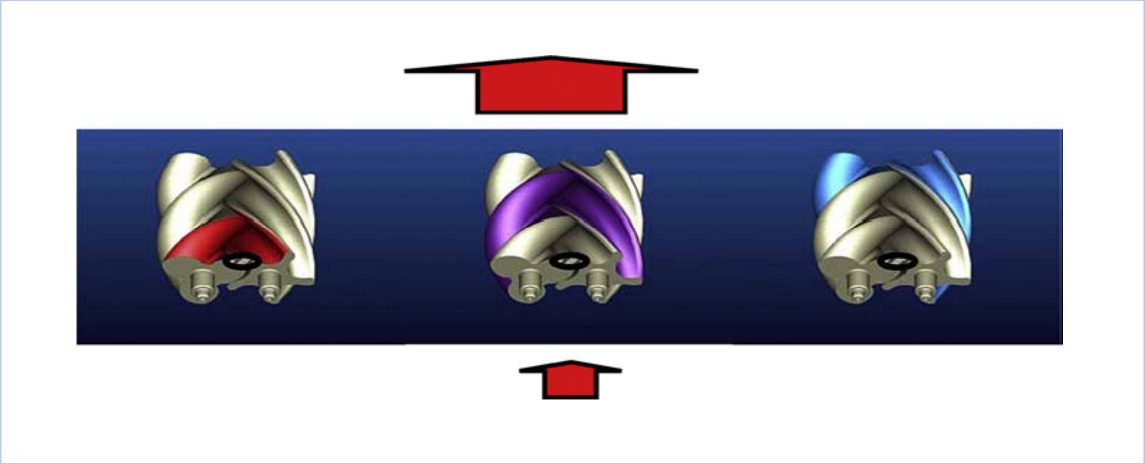


Fig. 13: Images of Lysholm Turbine (Öhman, 2012).

The advantage of the Lysholm turbine is that its preferred operating condition is the mixture of liquid and gas. This property allows ORC to operate without superheating and guarantees the mechanical reliability of the turbine since traditional diesel and gas turbine suffers from low efficiency and erosion problems in the two phase area. The main material used for manufacturing the Lysholm turbine is Iron.

Heat Exchangers:

Boiler and condenser are the shell and tube type of heat exchanger, those are the most frequently used type of heat exchangers in the ORC power plants.

Working Fluid Pump:

Without furthermore information from the manufacturers, the power of working fluid pump is 60 kW_e.

Working Fluid: working fluid in this LCA analysis is Ammonia (NH_3).

5.2 Life Cycle Analysis of the Power Plant

5.2.1 Goal and scope

The purpose of this study is to evaluate the environmental impacts for producing electricity from 750 kW_e ORC power plant with Ammonia as working fluid. Based on the calculation of 210 kW_e ORC power plant, the calculation results from this 750 kW_e power plant will be used for another source of data considering the environmental impact evaluations of ORC power plants. The heat source is a typical low temperature waste heat source.

5.2.2 Functional unit

The functional unit for this study is 1 kWh electricity produced from this power plant. This is based on the designed 30 years lifetime of power plant considering all the energy consumed by the power plants.

5.2.3 Process flowchart of NPO 750 kW_e power plant

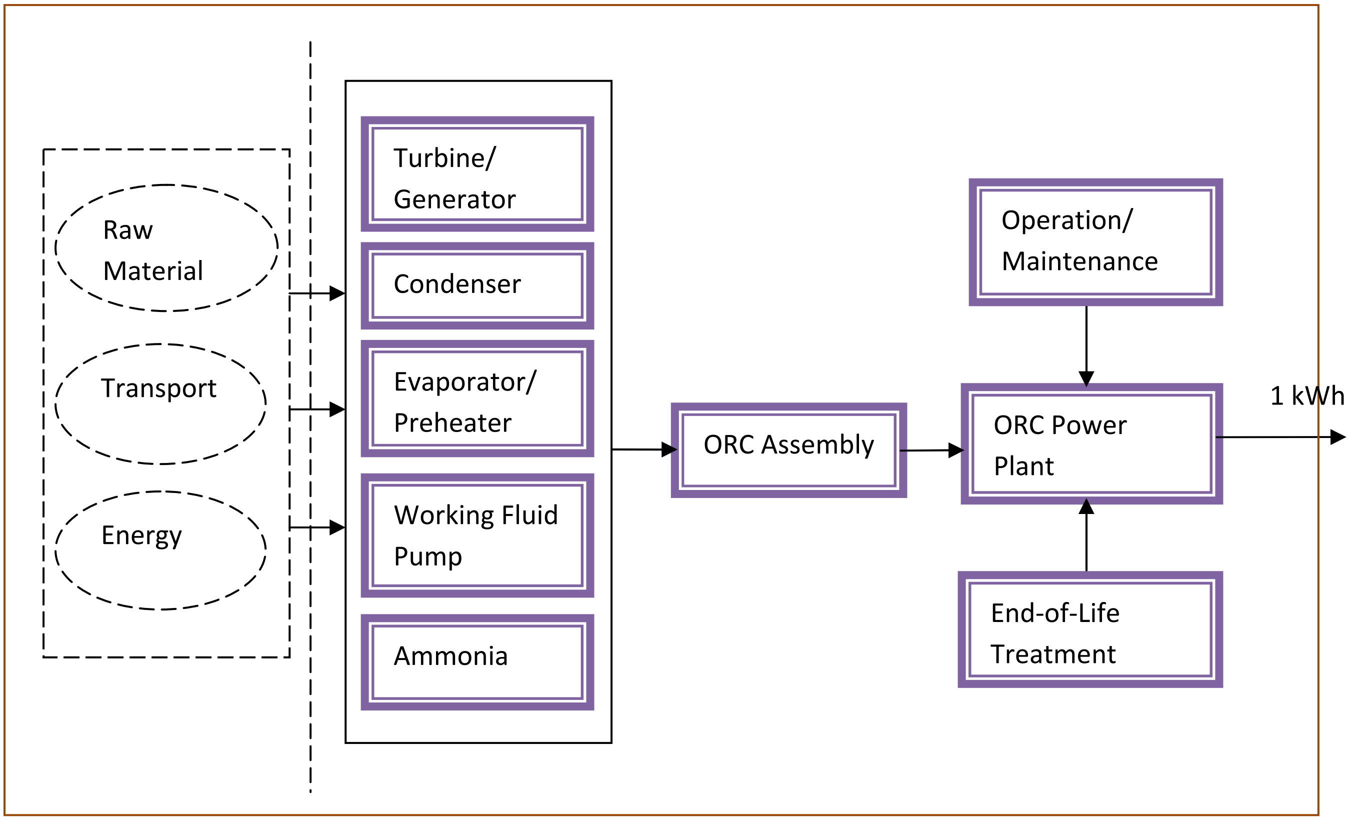


Fig. 14: Process Flowchart of Ammonia Power Plant

5.2.4 Data collection

The primary data used for LCA analysis is from the information of power plant manufacturer, and from built-in SimaPro dataset.

5.2.5 Life cycle analysis inventory

The Life Cycle Inventory include all the inputs of ORC power plant from raw material extraction to the end-of-life treatment.

5.3 Results

5.3.1 Total impact amounts of 750 kW_e power plant

The total characterization impact amounts of chosen categories have been calculated from the life cycle stages of the 750 kW_e ORC power plant . The results for chosen categories are listed on Table 5 below:

Table 5: Total Caracterization Impacts of 750 kW_e Power Plant from Chosen Cagegories

Categories	Unit	Total Amount
Climate Change	kg CO2 eq	0,0009024
Ozone Depletion	kg CFC-11 eq	7,2866E-11
Human Toxicity	kg 1,4-DCB eq	0,0009767
Photochemical Oxidant Formation	kg NMVOC eq	3,5313E-6
Particulate Matter Formation	kg PM10 eq	4,3429E-6

Ionising Radiation	kg U235 eq	0,0003073
Terrestrial Acidification	kg SO2 eq	1,5383E-5
Freshwater Eutrophication	kg P eq	7,9649E-7
Marine Eutrophication	kg N eq	2,4247E-7
Terrestrial Ecotoxicity	kg 1,4-DCB eq	1,9901E-7

5.3.2 Life cycle stage contributions to the total amounts

The percentage contributions from the stages of assembly, operation and maintenance, and construction and disposal have been shown on Fig. 15 below.

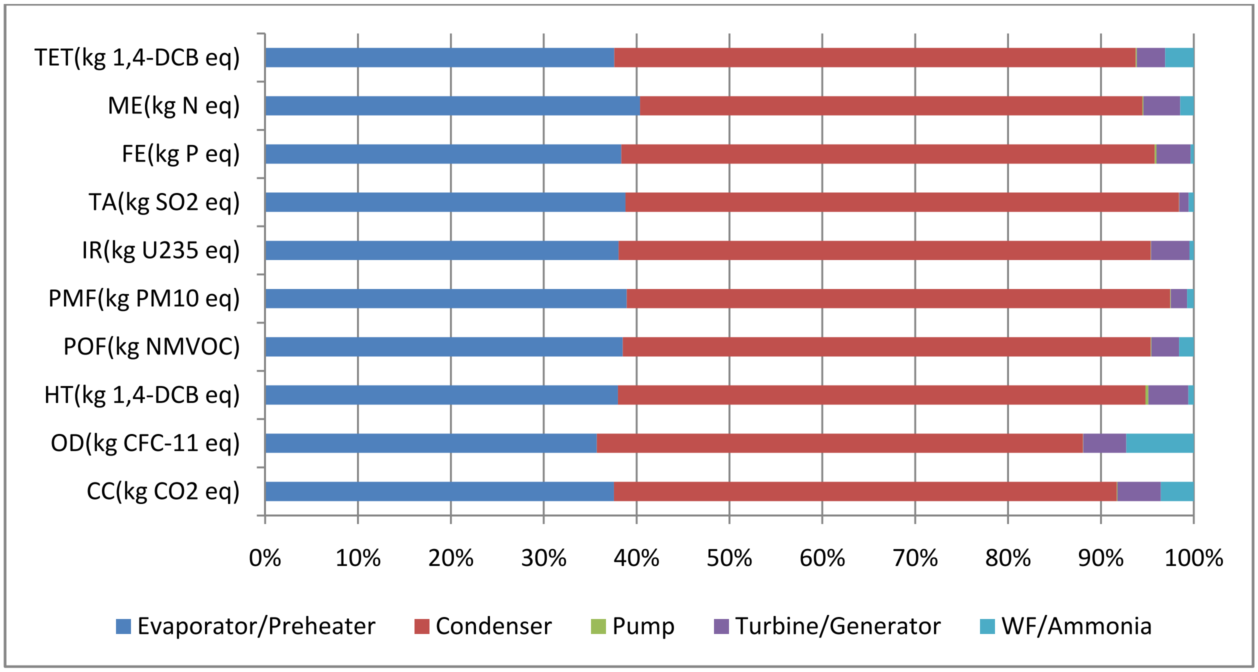


Fig. 15: Percentage Contributions from Life Cycle Stages of 750 kW$_e$ ORC Power Plant

5.3.3 Comparison between 210 kW_e ORC power plant and 750 kW_e ORC power plant with NH_3 as working fluid

Table 6: Comparison of characterization results from two ORC power plants

Categories	Unit	Total Amount (210 kW_e)	Total Amount (750 kW_e)
Climate Change	kg CO2 eq	0,0006764	0,0009024
Ozone Depletion	kg CFC-11 eq	5,257E-11	7,2866E-11
Human Toxicity	kg 1,4-DCB eq	0,0009877	0,0009767
Photochemical Oxidant Formation	kg NMVOC eq	2,503E-6	3,5313E-6
Particulate Matter Formation	kg PM10 eq	2,785E-6	4,3429E-6
Ionising Radiation	kg U235 eq	0,000182	0,0003073
Terrestrial Acidification	kg SO2 eq	7,612E-6	1,5383E-5
Freshwater Eutrophication	kg P eq	6,56E-7	7,9649E-7
Marine Eutrophication	kg N eq	1,735E-7	2,4247E-7
Terrestrial Ecotoxicity	kg 1,4-DCB eq	1,380E-7	1,9901E-7

The results from these two ORC power plants are consistent with regard to the working fluids for those chosen categories.

Chapter 6

THE ENVIRONMENTAL IMPACTS OF ORC POWER PLANTS COMPARING WITH OTHER RENEWABLE TECHNOLOGIES

6.1 Comparison with Wind Power

Garrett & Rende (2012) in their paper " Life cycle assessment of wind power: comprehensive results from a state-of-the-art approach" have conducted with three LCA analysis of 2-MW wind turbines. These lCAs assess all stages in the life cycle from cradle to grace, including raw materials; production of all parts of the wind plant; manufacturing; all transport stages; installation; operation and end-of-life treatment. The functional unit is 1 kWh electricity produced from these 2-MW wind turbines and the software used for analysis is GaBi DfX software.

The results from this research show that for these wind turbines, to produce 1 kWh electricity, the global warming potential is 7 to 10 g CO_2 equivalent; acidification potential 37 to 45 mg SO_2 equivalent; human toxicity potential 1,150 to 1,400 mg DCB equivalent (Garrett & Rende, 2012).

Considering the NPO 210 kW_e ORC power plant , to produce 1 kWh electricity, the impact amount for climate change is 9,253g CO_2 eqivalent; acidification potential 26,4 mg SO_2 equivalant; and human toxicity 1,4-DCB eqivalent. The environmental impacts of these two types of power plants are at the same level of amounts.

6.2 COMPARISON WITH HYDROPOWER

Varun, Bhat, & Prakash (2008) in their paper “Life Cycle Analysis of Run-of-River Small Hydropower Plants in India” investigated the environmental impacts of three small scale hydropower plants by LCA. The capacities of these three run-of-river power plants are 50 kW_e, 100 kW_e, and 300 kW_e , and their greenhouse gases emissions vary from 74,88 g, 55,42 g, to 35,29g CO_2
equivalent respectively for 1 kWh electricity production from these hydropower plants. The software used in this research is EIO-LCA software. The CO_2 equivalent amounts are higher than the results from ORC power plant with 1 kWh electricity generation.

From the above comparison and discussion, the conclusion is that the electricity generation from ORC power plant is a promising type of energy generation technology comparing with other renewable technologies.

Chapter 7

CONCLUSION

The LCA evaluation of electricity generation from 210 kW_e ORC power plant has been performed in this research and the environmental impact amounts of producing 1 kWh electricity from low-temperature waste heat ORC power plant with R134a have been calculated. And furthermore the environmental impacts from ORC power plants using alternative ORC working fluids scenarios have been calculated by LCA.

The results show that from the LCA point of view, using natural substances of NH_3, CO_2 and n-Pentane as working fluids in ORC power plants is more environmentally favourable than the refrigerant working fluid R134a. And the further investigation for the LCA environmental impact evaluation on the ORC power plants considering power plant sizes, working fluids, etc. would be challenging topics to do the research.

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Appendix I:

Life Cycle Inventory of NPO 210 kW$_e$ ORC Power Plant

Raw Materials		
Evaporator/Preheater		
Copper tube, technology mix	842,7	kg
Nickel, 99,5%	96,2	kg
Iron and steel, production mix	13,5	kg
Condenser		
Steel, low-alloyed	1142	kg
Chromium	294	kg
Nickel, 99,5%	163	kg
Pump		
Stainless steel hot rolled coil, prod. mix	44	kg
Copper	14,7	kg
Turbine/Generator		
Reinforcing steel	2596	kg
Steel, low-alloyed	4276	kg
Chromium steel 18/8	932	kg
Copper	252	kg
Aluminium, production mix	143	kg
Iron-nickel-chromium alloy	76	kg
Polyethylene, HDPE, granulate	63	kg

Working Fluid		
Refrigerant R134a	1392	kg
Ammonia, liquid	1392	kg
Carbon dioxide, liquid	1392	kg
Pentane	1392	kg

Operation/Maintenance		
Oil and grease	350	kg
Refrigerant R134a	1392	kg
Ammonia, liquid	1392	kg
Carbon dioxide, liquid	1392	kg
Pentane	1392	kg

Transport		
Transport, passenger car	912,5	personkm
Transport, lorry > 28t	2688	tkm
Transport, lorry > 16t	130	tkm
Transport, freight	1296	tkm

Energy		
Light fuel oil	18000	MJ
Natural gas	32130	MJ
Electricity, medium voltage	4452	kWh
Electricity, low voltage	2668	kWh

Appendix II:

Life Cycle Inventory of NPO 210 kW$_e$ ORC Power Plant

Raw Materials		
Evaporator & Preheater		
Steel, low-alloyed	4103	kg
Chromium	1172	kg
Nickel, 99,5%	587	kg
Condenser		
Steel, low-alloyed	6395	kg
Chromium	1827	kg
Nickel, 99,5%	913,5	kg
Pump		
Copper	3,75	kg
Polyvinylchloride	0,45	kg
Synthetic rubber	0,105	kg
Cast iron	18	kg
Turbine/Generator		
Cast iron, at plant	1000	kg
Working Fluid		
Ammonia, liquid	2500	kg

Operation/maintenance		
Lubricant	850	kg

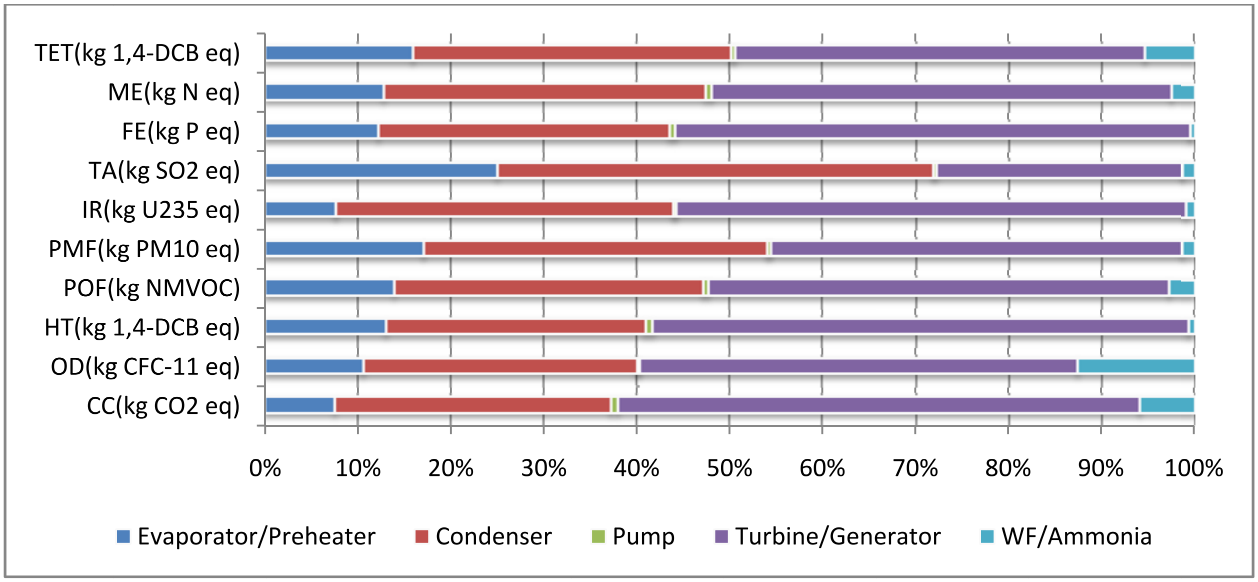
Transport		
Transport, lorry > 28t	1200	tkm
Transport, lorry > 16t	750	tkm
Transport, passenger car	1095	personkm
Freight, rail	7498	tkm

Energy		
Light fuel oil	24900	MJ
Natural gas	15300	MJ
Electricity, medium voltage	2120	kWh
Electricity, low voltage	4348	kWh

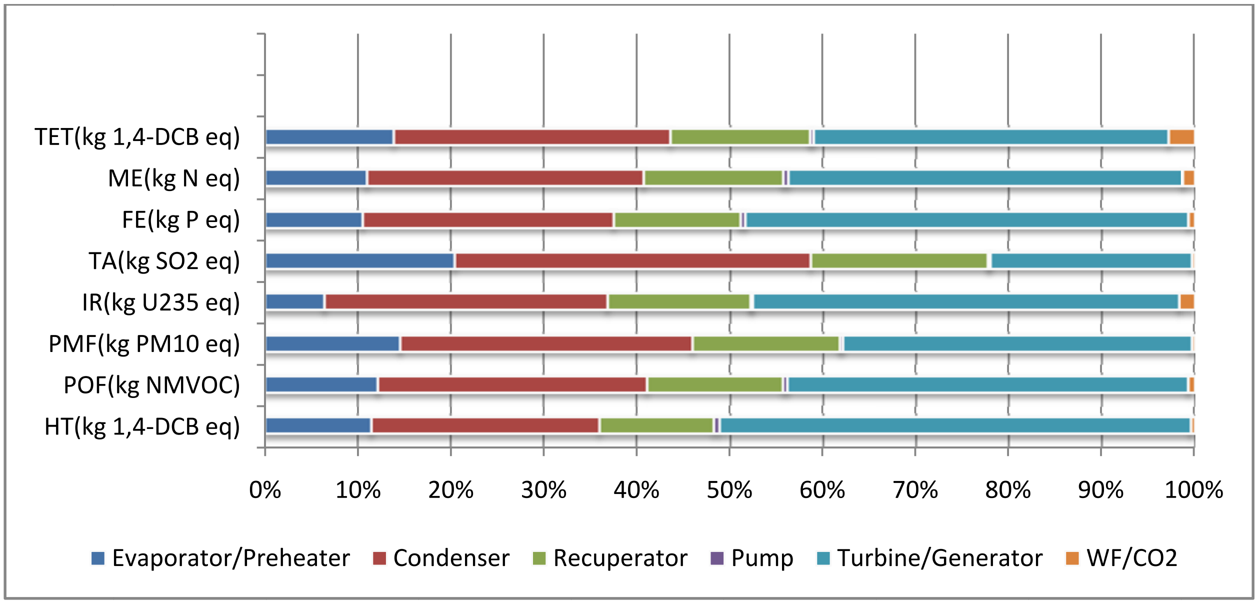
Appendix III:

Components Contribution to the Assembly of ORC Power Plant

Ammonia as Working Fluid



CO_2 as Working Fluid



n-Pentane as Working Fluid