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Feasibility of using Rankine power cycles for utilisation of medium to low temperature heat sources in the industry

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MASTER THESIS

for

Student Kjersti Røssland

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Feasibility of using Rankine power cycles for utilisation of medium to low temperature heat sources in the industry

Mulighet for bruk av Rankine varmekraftmaskiner for utnyttelse av varmekilder med mellom- til lav temperatur i industrien

Background and objective

There is an increasing concern related to climate change. This has initiated a focus on research and development related to increasing the energy efficiency in general, and specifically utilisation of surplus heat in the industry.

Surplus heat may be utilised for power production by conversion in a Rankine power cycle. Such processes are already implemented in the industry, but it is a large potential for a higher degree of implementation, especially for heat sources with medium (350'C) to low temperature (100'C) heat.

Conversion to environmentally benign working fluids in the Rankine cycles is also an important challenge, since many of the commonly used fluids are about to be phased out. Use of natural working fluids is long term robust from an environmentally perspective, but also introduces development needs.

The economic feasibility is related to a vast number of parameters, both technical and non-technical, such as incentives from the government.

The aim of this Project work is to perform theoretical, modelling and simulation efforts in order to understand how technical and non-technical parameters influence implementation of Rankine power cycles for utilisation of surplus heat in the industry.

The following tasks are to be considered:

1. Literature survey related to techno-economic evaluation of implementation of heat engines for utilisation of medium- to low temperature heat in the industry
2. Develop a model for techno-economic evaluation of the feasibility of implementing power cycles in the industry. Examples of elements that should be included:

    a. Technical elements
        i. Component efficiencies
        ii. System efficiency
        iii. Heat source temperature, and the possibilities to increase this
        iv. Constraints in utilisation of limited heat sources
    b. Non-technical
        i. Governmental incentives, e.g. by Enova
        ii. Energy cost
        iii. Investment cost
        iv. Operational cost
3. Use the model to try to exemplify the current status for selected applications and technologies based on available information
4. Pin-point important areas for further development and work, and quantify the potential of these

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The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

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☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 25. January 2016

Olav Bolland	Petter Nekså
Department Head	Academic Supervisor

Research Advisor:
Trond Andresen, SINTEF Energy Research

Declaration of Authorship

I, Kjersti Røssland, declare that this thesis titled, 'Feasibility of using Rankine power cycles for utilisation of medium to low temperature heat sources in the industry' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Abstract

In this paper, an overview of different ORC applications is presented, along with a market review that includes major manufacturers, application areas and cost estimates. Focus was laid upon low (100°C) to medium (350°C) temperature heat sources from industrial processes. Economic parameters that influence the implementation of an ORC was presented, and numbers from manufacturers was analysed to obtain realistic estimates. A techno-economic generic analysis was performed to investigate the payback period for different economic parameters, such as the effects of varying electricity prices, CO_2-tax savings and government incentives. The influence of heat source temperature and system efficiency on economic parameters was investigated, and how changes in these affected the payback period. It was discovered that the payback period decreased for increasing heat source temperature. Increased system efficiency also lowered the payback period, but to a smaller extent. The inclusion of CO_2-tax savings lowered the payback period significantly, especially for low electricity prices.

Abstrakt

I denne oppgaven gis det en oversikt over forskjellige ORC bruksområder, sammen med en markedsvurdering som omfatter store produsenter, forskjellige bruksområder og kostnadsestimater. Fokus i oppgaven ble lagt på varmekilder fra industrielle prosesser med lav (100°C) til medium (350°C) temperatur. Økonomiske parametere som har innflytelse på implementeringen av en ORC ble presentert, og tall fra produsenter ble analysert for å oppnå realistiske anslag. En teknoøkonomisk generisk analyse ble utført for å undersøke tilbakebetalingstiden. Innflytelsen av forskjellige økonomiske parametre på tilbakebetalingstiden ble undersøkt, disse inkluderte varierende strømpriser, CO_2-skatt besparelser og statlige incentiver. Påvirkning av varmekildetemperatur og system-effektivitet på økonomiske parametre ble undersøkt, og hvordan endringer i disse påvirket tilbakebetalingstiden. Det ble oppdaget at tilbakebetalingstiden ble redusert når varmekildetemperaturen økte. Høyere system effektivitet bidrog også til å minske tilbakebetalingstiden, men i mindre grad. Inkludering av CO_2-skatt besparelser minsket tilbakebetalingstiden, særlig for lave strømpriser.

Acknowledgements

I wish to acknowledge my supervisors Petter Nekså and Trond Andresen for valuable guidance, support and advice throughout my Master programme.

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Abbreviations

ALT	**A**tmospheric **L**ifetime
BWR	**B**ack **W**ork **R**atio
CHP	**C**ombined **H**eat and **P**ower
COP	**C**ost **O**f **P**ower
GHG	**G**reen **H**ouse **G**ases
GWP	**G**lobal **W**arming **P**otential
IC	**I**nvestment **C**osts
IRR	**I**nternal **R**ate of **R**eturn
NPV	**N**et **P**resent **V**alue
ODP	**O**zone **D**epletion **P**otential
O&M	**O**peration **&** **M**aintenance
ORC	**O**rganic **R**ankine **C**ycle
PBP	**P**ayback **P**eriod
ROT	**R**adial **O**utflow **T**urbine
SF	**S**ize **F**actor
SIC	**S**pecific **I**nvestment **C**osts
SME	**S**mall and **M**edium-Sized **E**nterprises
VAT	**V**alue **A**dded **T**ax
WHR	**W**aste **H**eat **R**ecovery

Symbols

C_0	total initial investment costs	NOK
C_t	net cash inflow during period t	NOK
C_p	specific heat capacity	$\frac{kJ}{kgK}$
$\dot{m}$	mass flow	$\frac{kg}{s}$
$\dot{Q}$	heat rate	W
r	discount rate	-
t	number of time period	years
$\dot{W}$	power output	W

η	efficiency	-

c	cold
is	isentropic
h	hot
hm	hot medium
wf	working fluid
wh	waste heat

Chapter 1

Introduction

1.1 Background

The implementation of power generating projects that are environmentally sound and non-hazardous for operating personnel, is fundamental for a sustainable development within the energy production industry. The modern world continues to require an increasingly higher energy supply, hence demanding higher energy production. Traditional, and more polluting, energy production industry have often been favored above renewable energy sources due to the lower costs associated with the use of fossil fuels. Meanwhile, the environmental effects of such industries has become increasingly evident. At the Paris climate conference in December 2015, 195 countries agreed to a new global climate deal in which the overall goal was to avoid negative environmental effects by limiting global warming well below 2°C. In order to accomplish this goal, greenhouse gas emissions must be severely reduced, which can be achieved through a shift toward renewable energies, and increased energy efficiency.

The majority of energy loss in industry is represented by low-grade heat that is released into the atmosphere. Surplus heat pose an environmental threat as it may disturb the environmental equilibrium, as well as representing a significant energy loss. The Organic Rankine Cycle (ORC) can be used to increase energy efficiency in industrial processes through utilization of waste heat and convert renewable energy sources into electricity. It is advantageous compared to the steam Rankine cycle, as it is able to utilize low-grade heat sources. However, most systems have up till now only been cost-effective for large-scale systems.

The successful implementation of economically feasible ORC projects depend on several factors, among other local electricity prices, heat source characteristics, net power output and location. There is a vast, unused potential for low-grade heat recovery in industry and especially for small-scale systems. This paper focuses on what is needed to successfully implement a economically feasible, small-scale ORC that utilizes a low-grade heat source.

1.2 Problem Description

As a result of the current focus on retrieving/obtaining more environmentally friendly solutions for power generation, the following problem formulation has been developed.

> "The aim of this Project work is to perform theoretical, modelling and simulation efforts in order to understand how technical and non-technical parameters influence implementation of Rankine power cycles for utilisation of surplus heat in the industry."

1.3 Objectives

The main objectives of this Master's thesis are

1. Literature survey related to techno-economic evaluation of implementation of heat engines for utilisation of medium- to low temperature heat in the industry

2. Develop a model for techno-economic evaluation of the feasibility of implementing power cycles in the industry. Examples of elements that should be included:

    (a) Technical elements

        i. Component efficiencies
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        iii. Heat source temperature, and the possibilities to increase this

   iv. Constraints in utilisation of limited heat sources

  (b) Non-technical

   i. Governmental incentives, e.g. by Enova
   ii. Energy cost
   iii. Investment cost
   iv. Operational cost

3. Use the model to try to exemplify the current status for selected applications and technologies based on available information

4. Pin-point important areas for further development and work, and quantify the potential of these

1.4 Approach

Include contact with manufacturers in combination with a generic representation

1. Perform a literature review

2. Contact manufacturers to obtain cost estimations and technical specifications

3. Create a generic model that considers technical and economical parameters for the implementation of an Organic Rankine Cycle

1.5 Structure of the thesis

Chapter 2 presents the literature review, concerning both technical and non-technical parameters necessary to perform the generic analysis.

Chapter 3 presents the specific case analysis, which includes information obtained from manufacturers. Estimates from this chapter is used as basis for the generic techno-economic analysis.

Chapter 4 presents the generic techno-economic analysis with information from the literature review and the specific case analysis in Chapter 3.

Chapter 5 presents propositions for continued work.

Chapter 6 presents the conclusion of the thesis.

Chapter 2

Literature review

2.1 The Organic Rankine Cycle

The Organic Rankine Cycle (ORC) is employed for power production. The operation principle is similar to the more conventional steam Rankine cycle (SRC), with the main difference being the choice of working fluid. Instead of water steam, organic fluids are utilized as working medium. These are characterized by a lower boiling point and a higher vapor pressure than water, which enables the ORC to use low temperature heat sources to produce electricity. An assortment of available heat sources is presented later. Extracting power from a low-temperature heat source offer difficulties regarding efficiency, hence optimizing each unit in terms of application and heat source temperature is decisive.

2.1.1 Working Principle

A simple version of the ORC is shown schematically in Figure 2.1. It is comprised of an expander, condenser, evaporator, pump and generator. Units might also include a recuperator, but it was not considered in this paper. Figure 2.2 presents a typical T-s diagram for the cycle.

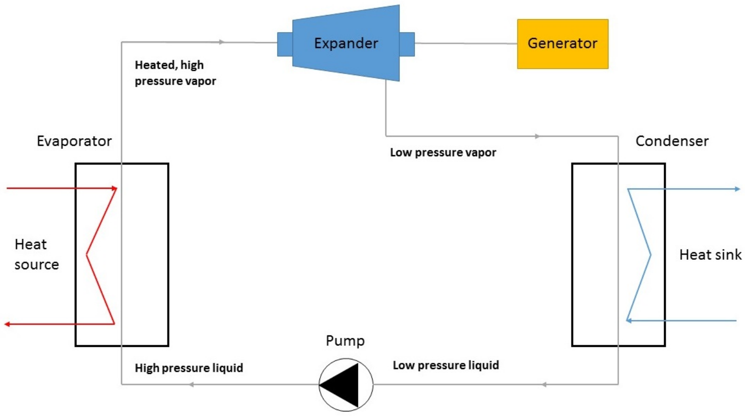

FIGURE 2.1: The Organic Rankine cycle

The working fluid is circulated in a closed loop, separating it from the heat source and heat sink medium. The condensate working fluid is pumped from a low pressure status after the condenser (1) to a higher pressure in the evaporator (2). In the evaporator, the working fluid extracts thermal energy from the heat source at constant pressure. The working fluid undergoes a phase change, entering the evaporator as saturated liquid and exiting as either saturated or superheated vapor (4). High pressure vapor expands through an expander (5), which in turn drives a generator and produces useful energy. During the expansion process, the pressure is lowered to the condenser pressure. The working fluid is returned to the condenser, where it is cooled down. During the cooling process, the working fluid changes phase from vapor to saturated liquid (1) and the process is repeated. In Figure 2.2, the ideal isentropic process in the pump and expander is denoted with an s. The real process will not be isentropic, and there will most likely be a pressure drop in the heat exchangers.

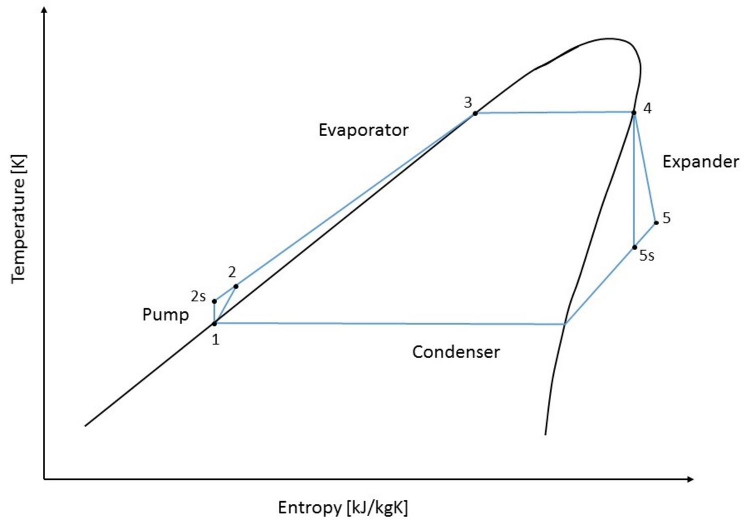

FIGURE 2.2: Temperature-entropy diagram for a subcritical ORC

2.1.2 Working Fluid

When choosing a working fluid, numerous considerations must be taken into account. The thermophysical properties of the fluid needs to be considered in relation to its intended application, as well as safety, environmental effects, availability and costs. For an ideal working fluid in a subcritical cycle, the following properties should be fulfilled [13].

- The critical temperature of the working fluid should be higher than the highest temperature of the proposed cycle.
- The freezing temperature of the working fluid should be lower than the lowest temperature of the proposed cycle.
- To avoid solidification in the process, the triple point should be well below the lowest projected temperature of the ambient air.
- The condensing pressure should not be lower than atmospheric pressure to avoid atmospheric air entering the system in case of sealing issues.
- The evaporator pressure should not be excessive to avoid design and operation difficulties as well as costly equipment.
- The working fluid should have a high density to ensure a low vapor and liquid specific volume. A low specific volume results in a low volumetric flow

rate, making the equipment smaller and less costly. Consequently, pressure losses are reduced for a low volumetric flow rate.

- The working fluid should have a low specific heat and a high latent heat to absorb more energy during the heating process, hence achieve high turbine work output.
- The working fluid should have a high thermal conductivity, a high convective heat coefficient and a low liquid viscosity.
- The slope dS/dT should be approximately zero or inhabit positive values to prevent excessive moisture.
  - $dS/dT < 0$: wet fluid with a negative saturation vapor curve
  - $dS/dT > 0$: dry fluid with a positive saturation vapor curve
  - $dS/dT \to \infty$: isentropic fluid with a vertical saturation vapor curve
- To avoid drop formation, superheat can be utilized to prevent corrosion when using wet fluids.
- The working fluid should have a low GWP, a low atmospheric lifetime (ALT) and an ODP equal to zero.
- The working fluid should be non-flammable and non-toxic, as well as not being explosive, corrosive or radioactive.
- The working fluid should be easily accessible and have low costs.
- The working fluid must be compatible with the materials used in the cycle.

The above-mentioned criteria describes an ideal working fluid in a subcritical cycle. For a transcritical and supercritical cycle, other criteria applies. For a transcritical cycle, the critical point is exceeded in parts of the process and the maximum temperature and pressure of a transcritical cycle is more related to the practical design of the cycle. Multiple studies have been executed to find optimal working fluids, [14] includes a screening of 31 pure working fluids, [6] includes a summary of 15 working fluid studies and [15] includes an extensive study of pure and mixture working fluid candidates, as well as recommendations for different applications, working conditions and performance indicators. Although having different approaches, the same conclusion is usually drawn. A universally optimal working fluid can not be determined and a screening is necessary to find the optimal working fluid for each unit. Despite there being multiple studies on the subject, few of the proposed fluids are used in commercial applications. Table 2.1 shows the most common working fluids used in commercial applications, arranged in terms of application [16].

Table 2.1: Working fluids used in commercial applications

Application	**Working fluids**
Geothermal	RE134, RE245, R245fa, R245ca, R600, R601, Ammonia, Propylene, R227ea, n-pentane
Waste heat recovery	Benzene, Toluene, n-pentane, R123, Solkatherm, R134a
Solar	R152a, R600, R290
Biomass	Alkylbenzenes, OMTS

For low-temperature applications, refrigerants are the most common, but higher temperatures demand other working fluids. Working fluids for different temperature ranges can be observed in Figure 2.3. Low to medium temperature applications can make use of refrigerants, hydrocarbons and siloxanes.

Conversion to environmentally benign working fluids is an important challenge, since many of the commonly used fluids are about to be phased out. Use of natural working fluids is long term robust from an environmentally perspective, but also introduces development needs. As no working fluid can be labeled as optimal, it follows that a screening of different working fluids should be a obligatory part of any ORC design process.

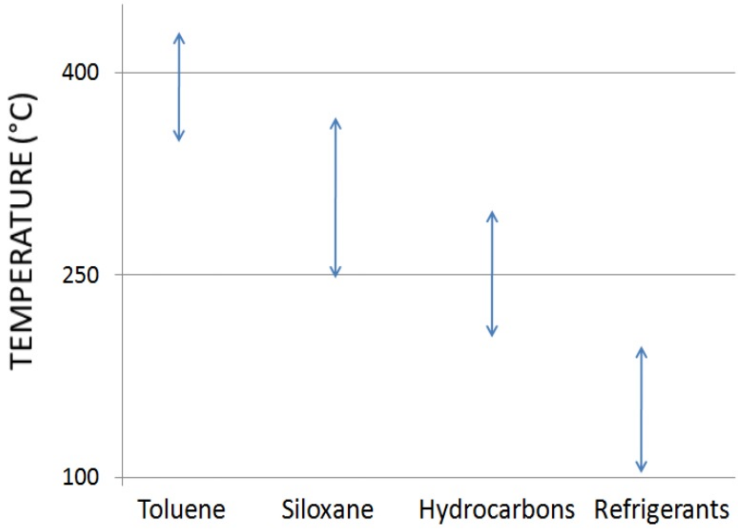

Figure 2.3: Working fluids for different temperature ranges [1]

2.1.3 Market

The first commercial applications became available in the late 70s and early 80s. Since then, the ORC market has experienced an exponential growth, which can be observed in Figure 2.4

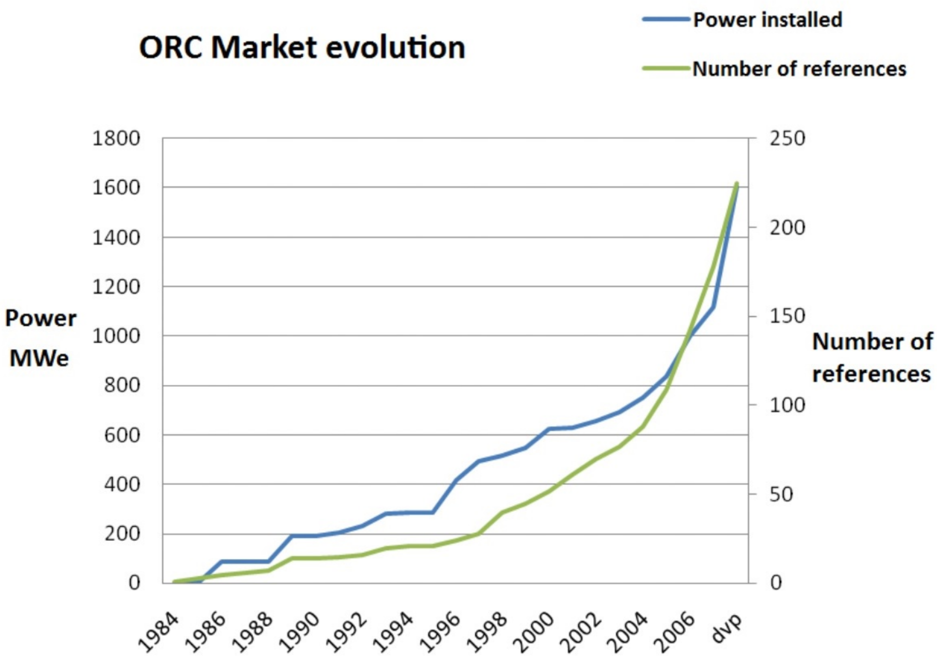

Figure 2.4: ORC market evolution [1]

The allocation of plants in terms of application can be viewed in Figure 2.5, with the majority of plants installed being biomass combined heat and power (CHP), followed by geothermal, waste heat recovery (WHR) and solar. Share of each application considering installed capacity can be seen in Figure 2.6. Geothermal dominates installed capacity with 76.5% despite accounting for only 31% of total installed units. This is a result of geothermal plants mainly being large-scale plants in the MW-range.

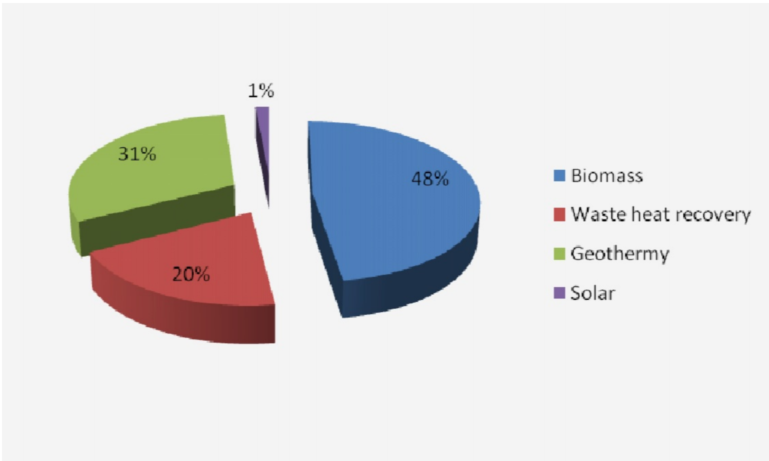

FIGURE 2.5: Share of each application considering number of units installed [2]

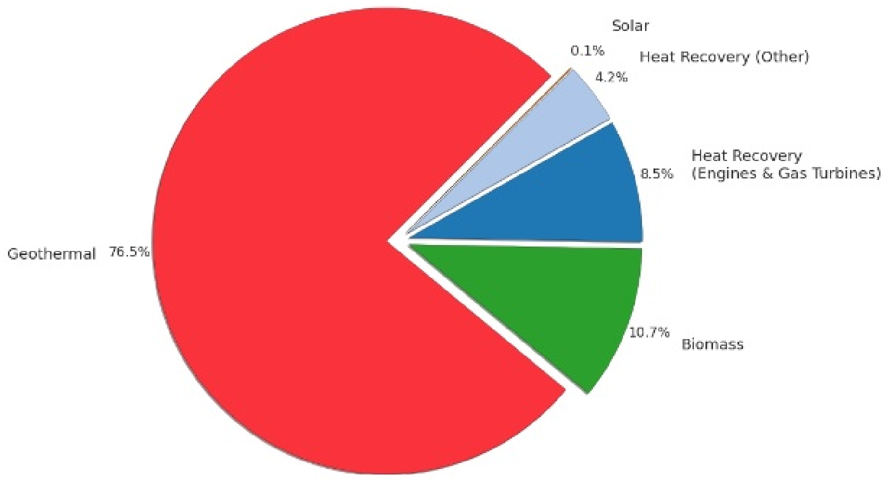

FIGURE 2.6: Share of each application considering installed capacity [3]

Main manufacturers worldwide are summarized in Table 2.2. Data was procured from manufacturer websites [17] and previous publications [18–20]. From [4], it is obvious that three players hold the major share of the market, but as the report was compiled in 2012, shifts might have occurred since then. Turboden dominates the market when share quantity is considered with a total of 45% of all installed units worldwide, but only 8.6% of accumulated power. ORMAT mainly produces large units, and accounts for the largest share of accumulated power with 86% and 24% of all installed units, while Maxxtec accounts for 23% of all installed units and 3.4% of accumulated power. Together, the three main manufacturers can be accredited 92% of all installed units and 98% of accumulated power.

Table 2.2: Main ORC manufacturers

Manufacturer	**Applications**	**Power range [kWe]**	**Heat source temperature [°C]**	**Technology**	**Working fluid**
ORMAT	1,2,4	200 - 70,000	100 - 300	Two stage axial turbine, synchronous generator	n-pentane
Turboden	1,2,3,4	200 - 15,000	100 - 320	Two stage axial turbine	OMTS Solkatherm,
Maxxtec	1,3		300 - 350		OMTS
Opcon	1,3	<800	55 - 160	Lysholm turbine	
ElectraTherm	1,2,3	<110	77 - 122	Twin-screw expander	R245fa
GE CleanCycle	1,3	50 - 140	155 >		R245fa
Tri-o-gen	1,3	<170	350 - 530	Direct evaporation	
Bosch	1,3,4	50 - 2,000			R245fa
Enertime	1,2,3,4	100 - 5,000	90 - 200		HFC
Exergy	1,2,3,4	<50,000	>90	Radial outflow turbine	

1. WHR 2. Geothermal 3. Biomass-CHP 4. Solar

2.2 Heat Sources

Surplus heat can be utilized through (1) direct use, (2) conversion to electrical power or (3) heat pumping to higher temperature levels. Heat sources at low-, medium- and high temperatures are available for utilization in accordance with the proper working fluid and optimization of the ORC system. When considering the implementation of an ORC, it is crucial that the process in question is not disturbed by the incorporation of the ORC. In the following sections, the main application areas from Figure 2.5 is presented in more detail.

Other potential application areas include food processing, ocean shipping and ocean thermal. Food processing may include beverage bottling, wineries, chip lines, bakeries and breweries, and ocean shipping can include factory ships, container ships and cruise ships. Ocean thermal energy conversion utilizes the thermal gradient between shallow, warmer seawater and deeper, cooler seawater to generate electricity. The warmer seawater may be used in the evaporator, while cooler seawater will function as cooling agent in the condenser. However, the temperature gradient is low, causing low efficiency. From [21], a minimum thermal gradient of 20°C is required. Ocean thermal energy recovery is still in the demonstration phase and is not considered as a commercial product at the present time.

2.2.1 Waste Heat Recovery

Waste to Energy

The concept of waste to energy is based on utilizing waste that cannot be recycled and would otherwise end up in a landfill. Categories of waste may include:

- Municipal solid waste
- Landfill gas
- Waste syngas

The extracted heat is directed to heat exchangers before being passed to the ORC, either through a heat carrier loop containing pressurized water, saturated steam or a thermal oil, or the heat is directly exchanged with the ORC. The ORC unit operates under the working principle presented in Section 2.1.1.

Industrial Processes

Industrial processes often produce an excessive quantity of heat, but the manufacturing industry is often unable to exploit this heat source and heat is therefore rejected to the atmosphere. Exhaust gases from industry contain pollutants such as CO_2, NO_x, SO_x and HC, which poses environmental and health concerns. Utilizing the waste heat can make the environmental effects less severe whilst generating electricity. There are several application areas that can be divided according to the heat source phase, either a gaseous, liquid or condensing heat source. Examples of each heat source is presented below.

- Gaseous sources
  - Internal combustion engines exhaust gas
  - Steel furnaces exhaust gas
  - Cement, glass and other non ferrous metal furnaces exhaust gas
- Liquid sources
  - Refineries hot streams
  - Cooling water loops in industrial processes
  - Jacket cooling water of reciprocating engines
- Condensing sources
  - Refineries organic vapours to be condensed
  - Surplus steam from production process
  - Steam from cooling loops in industrial processes

One industry that show promise is the cement industry, where one study [22] showed that as much as 40% of the energy used was rejected as waste heat with temperatures varying between 215 - 315°C.

In 2007, Enova conducted a detailed study to unveil the potential for energy efficiency in energy-intensive industries in Norway. These included aluminium industry, chemical industry, ferro-alloy industry and wood processing industry.

Aluminium industry is a promising industry for waste heat recovery, as close to 50% of the energy used is rejected as waste heat [23]. In 2007, aluminium industry in Norway represented 27% of total energy use in land-based industries, equivalent to 21.6 TWh. A potential energy reduction of 51% was considered plausible, meaning a possible reduction of 10.1 TWh/year. Measures to improve on energy efficiency include heat recovery from electrolysis cells, foundry, compressor installation and anode baking furnaces. Lack of capital or infrastructure and external risk usually represent the main barriers for initialization.

Chemical industry is another energy intensive industry with potential for heat recovery. In 2007, chemical industry represented 29% of total energy use in land-based industries, equivalent to 22.3 TWh. Potential reduction in energy use is set to 20%, where heat recovery is considered to have the largest potential with a possible reduction of 1.7 TWh/year. A detailed overview of possible energy efficiency measures within aluminium, chemical, ferro-alloy and wood processing industry can be found in Appendix B.

Although heat recovery from industrial processes represent a vast, unused potential, there are several barriers associated with implementation of heat recovery measures. Lack of capital and infrastructure, as well as external and internal risk represent some of the key challenges. Additionally, industry is often located in remote areas, providing few or no possibilities for direct use of surplus heat. Furthermore, the availability of waste heat and the need for heat are often poorly coherent. Electricity production either used on the site or sold to the grid would hence be the most viable option.

An overview of costs associated with energy efficiency measures in Norwegian industry can be found in Appendix A. Associated costs and total potential is included. Heat recovery from electrolysis cells in the aluminium industry was considered to be among the measures with the highest potential with a total of 26 000 GWh.

2.2.2 Renewables

Solar Thermal

The working principle of the solar ORC system is demonstrated in Figure 2.7. The solar field generates electricity and produces heat, which is transferred to a fluid and henceforth directed to the evaporator in the ORC. Solar thermal has traditionally been used in combination with the steam Rankine cycle or Stirling engine. The solar ORC system is still a immature technology with few installed units, mostly due to the high costs associated with installing small ORC units. If investment costs were to decrease, it would allow for smaller installations, hence making solar ORC system more attractive.

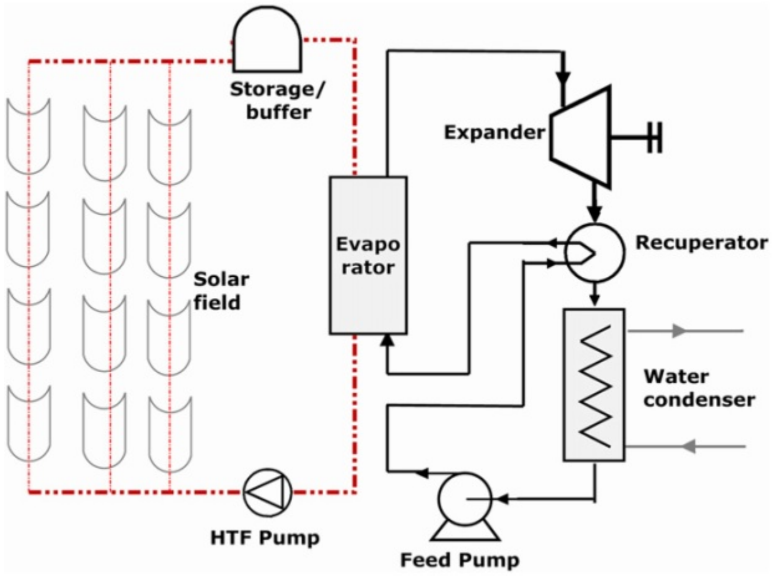

FIGURE 2.7: Working principle of a solar ORC system [4]

Geothermal

Geothermal energy is the designation given to the heat contained within the Earth that can be recovered and utilized. To utilize geothermal energy, it is necessary to drill wells and the geographical location and depth of these wells determine the temperature range that is available for heat extraction. Geothermal energy is therefore available over a large temperature range, from 65 - 350°C, but geothermal plants are currently not cost-effective below 80°C. Geothermal plants offer many advantages, among them high cycle efficiency, low O&M requirements, unattended operation and a choice between a variety of working fluids. At the present time, flash and binary technologies are considered mature and the main issues for geothermal energy is not related to the power-generation technology.

Previous to the GeoPower & Heat Summit in Instanbul, the CEO and MD of Turboden, Paolo Bertuzzi discussed, among others, the main challenges to stakeholders in the geothermal power industry. Financing was brought up as a main issue, as well as knowledge of the underground resource and optimization of the overall plant during its lifetime [24]. The financial issue is related to the initial investment cost, which can be quite high due to drilling costs. Depending on the depth required, drilling costs can account for 70% of the investment. A cost distribution proposal can be seen in Figure 2.8. From [18], a installation cost estimate of 1000 - 4000 €/kWe is given.

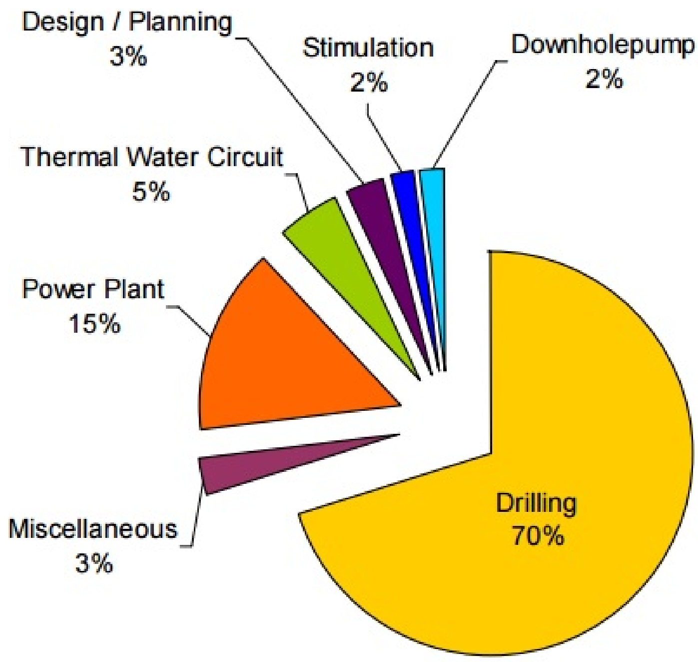

FIGURE 2.8: Geothermal Cost Estimation [5]

The working principle of a geothermal ORC plant can be observed in Figure 2.9. Two wells are drilled, one for production and one for injection. The hot brine is pumped from the production well, passed through an evaporator and injected back into the injection well at a lower temperature. The ORC operates under the same principles described in section 2.1.1.

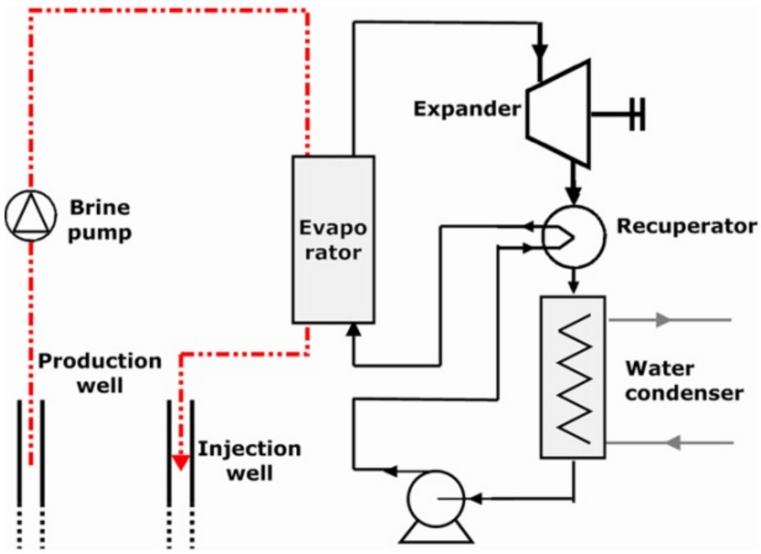

FIGURE 2.9: Working principle of a geothermal ORC system [4]

For low-temperature geothermal ORC plants, the pumps consume a large portion of the gross output power, in some cases as high as 30 - 50%, with the main consumer being the brine pump. Higher temperature geothermal plants permits the inclusion of CHP generation. The cooling water can be utilized in a district heating network, decreasing the electricity efficiency, but allowing for a higher overall energy recovery efficiency.

Biomass

An example of the working principle of a biomass CHP ORC system can be observed in Figure 2.10. A biomass burner supplies heat to the ORC unit by use of a thermal oil circuit. Biomass fuel is available through agricultural and industrial processes including, but not limited to, bi-products of wood industry, vine and green cutting, dried sewage sludge and waste material. The thermal power production can be used in a variety of applications, such as district heating networks, for drying purposes, refrigeration, in swimming pools and wine industry.

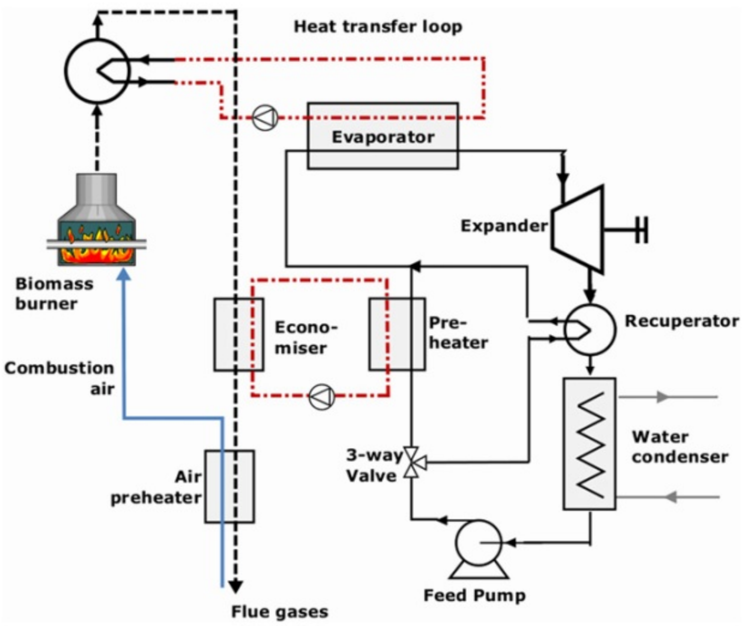

FIGURE 2.10: Working principle of a biomass CHP ORC system [4]

2.3 Technical Elements of the ORC

2.3.1 Turbine

The choice of turbine is essential both to the performance of the system, as well as the financial perspective. Depending on the application area, the turbine could be the most costly part of an ORC installation consisting of as much as 60% of the initial cost of the system.

When assessing which turbine that would be best suited, the following parameters must be evaluated [25].

- Capacity
- Rotational speed
- Degree of superheat/quality of inlet fluid
- Lubrication and sealing type
- Costs
- Choice of working fluid

Table 2.3 gives an overview of the various expanders types used in ORC units [20]. It can be observed that scroll and rotary vane expander is associated with the lowest costs and capacity. These are also characterized by high pressure ratios, low rotational speed and low flow rate, and are henceforth appropriate choices in small and micro-sized systems. Screw and reciprocating piston expander have higher costs, but also higher capacity, which makes them applicable for use in small and medium-sized systems. Finally, the radial-inflow turbine can be applied to large systems, but it is associated with high costs.

TABLE 2.3: Expanders available for use in ORC units

Type	Capacity range [kW]	Rotate speed [rpm]	Cost	Advantages	Disadvantages
Radial-inflow turbine	50 - 500	8000 - 80,000	High	Light weight, mature manufacturability and high efficiency	High cost, low efficiency in off-design conditions and cannot bear two-phase
Scroll expander	1 - 10	<6000	Low	High efficiency, simple manufacture, light weight, low rotate speed and tolerable two-phase	Low Capacity, lubrication and modification requirement
Screw expander	15 - 200	<6000	Medium	Tolerable two-phase, low rotate speed and high efficiency in off-design conditions	Lubrication requirement, difficult manufacture and seal
Reciprocating piston expander	20 - 100	-	Medium	High pressure ratio, mature manufacturability, adaptable in variable working condition and tolerable two-phase	Many moving parts, heavy weight, have valves and torque impulse
Rotary vane expander	1 - 10	<6000	Low	Tolerable two-phase, torque stable, simple structure, low cost and noise	Lubrication requirement and low capacity

The efficiency of the turbine depends on the above-mentioned parameters and the type of turbine. From literature, the isentropic efficiency of a turbine is stated to be in the range of 70 - 85% [2, 6, 9, 11, 25–28]. However, a prototype research conducted by [15] stated the isentropic efficiency for the various expander types mentioned in Table 2.3 to be much more dispersed. The stated isentropic efficiency for each machine was as follows.

- Radial-inflow turbine: 40 - 85%
- Scroll expander: 10 - 85%
- Screw expanders: 26 - 76%
- Reciprocating piston expander: 10 - 62%
- Rotary vane expander: 17 - 55%

An expander that was not mentioned in [20], is the radial outflow turbine. The radial outflow turbine (ROT) was introduced by Exergy as an alternative to the axial and radial inflow configurations usually applied in ORCs. The main advantage of the ROT is the high efficiency, which Exergy claims to be over 80%. The working principle of the ROT is as follows. "In ROT the fluid enters axially and is deviated by 90 degrees with a nose cone. The fluid expands radially through a series of stages arranged on a single disk. At the end the fluid is discharged in a radial diffuser to recover the kinetic energy and then is conveyed to the recuperator or the condenser" [29].

Some manufacturers claim efficiency over 80% [29] and up to 90% [17], but it is debatable whether these could be considered credible as it is in the manufacturers best interest to advertise high efficiencies. At design point, efficiencies of 80 - 90% might occur, but it is questionable at best to expect the same performance at off-design conditions.

2.3.2 Heat Exchangers

The main heat exchangers are the evaporator and the condenser. Depending on the system configuration, a recuperator and a preheater may be included as well. The heat exchangers account for a large share of the total module cost and should hence be considered carefully. They are sized according to key characteristics such as pressure drop and efficiency (or pinch point). Most common are the plate heat exchanger and the shell and tube heat exchanger. Due to the compactness of plate heat exchangers, these are usually applied to small-scale systems, while shell and tube is applied to larger-scale systems.

Heat exchangers may have to withstand high temperatures and be subject to fouling and/or corrosion. The pressure drop should be limited and its dimensions has to comply with the available space, as especially the condenser may take up considerable space. As an example, from [1], a 200 kWe ORC unit was expected to require 50 m^2, in which the cooling system required 25 m^2, and the ORC module 15 m^2. The choice of working fluid and the pressure has an impact on the size of the heat exchanger, which was studied in [14].

From Appendix G, the impact the recovery heat exchanger has on the costs may be observed. An intermediate loop resulted in much higher costs (21.2% of total costs), compared to direct heat exchange (3.7% of the total costs).

2.3.3 Pump

The pump is used to control the working fluid mass flow rate. A measure of the pump's performance is called the back work ratio (BWR), which shows the ratio of pump work required and turbine work generated.

$$BWR = \frac{W_{pp}}{W_{exp}} \tag{2.1}$$

where W_{pp} is the pump work and W_{exp} the expander work. A small value for BWR indicates a cycle in which the pumping work required is relatively small. For values equal to or larger than 1, the ORC experiences a net loss. Except for geothermal applications, the pump work usually represent a small share of the gross power output.

2.3.4 Cooling System

The choice of cooling system depends on the availability of resources. Water-cooling is more effective as water has more favorable thermodynamic properties compared to air. At 25°C, water has a thermal conductivity of 0.58 W/(mK), while atmospheric air equals 0.024 W/(mK). Air condensers require a larger area to achieve the same cooling abilities as water, hence demanding more space and higher costs. If water is available as cooling medium, it would be the best option when considering both thermodynamic and economical factors. Condensers using water as cooling medium is also more compact than an air condenser. However, in many locations, water is a scarce resource, making it an expensive choice. The choice of cooling also brings different challenges. Evaporative cooling towers produces vapor plumes and need makeup water, while air cooling produces a larger footprint and noise emissions [17].

2.3.5 Carnot and Trilateral Cycle Efficiency

To evaluate a systems efficiency and improve on its performance, an estimate of the theoretical maximum efficiency is a helpful tool. The isothermal efficiency for an ideal cycle can be described by Carnot efficiency.

$$\eta_{is,Carnot} = 1 - \frac{T_L}{T_H} \tag{2.2}$$

However, when extracting heat from a surplus heat source, the temperature of the heat source decrease. Hence, the efficiency will be lower than Carnot efficiency, which assumes a constant temperature heat source. The ideal efficiency for a gliding temperature heat source can be described by trilateral cycle efficiency (gliding temperature Carnot efficiency) [14].

$$\eta_{thermal,gliding} = 1 - \frac{T_L\, ln\left(\frac{T_H}{T_L}\right)}{T_H - T_L} \tag{2.3}$$

Equation 2.3 describes the maximum efficiency attainable from a heat source with a gliding temperature profile. As surplus heat is not a infinite heat source, which Carnot efficiency assumes, the gliding temperature Carnot efficiency is the ideal efficiency to strive for when optimizing an ORC.

2.3.6 Objective Functions

When optimizing an ORC, the thermodynamic objective functions are either efficiency or net power output, depending on application area. From [6], cycle efficiency is the objective function for CHP and solar applications, while net power output is the objective function in WHR applications.

For a thermo-economic optimization, the objective function can be the specific investment cost (SIC), which is investigated in more detail later. What is worth noting is that the thermodynamic and thermo-economic optimum rarely coincide, as stated in [6] and shown in Figure 2.11. The plot in Figure 2.11 was a result of a generic analysis of a 100 kW_{th} - scale WHR ORC, and shows the influence of T_{evap} on the thermodynamic and thermo-economic efficiency as well as the relationship between the two performance indicators [6].

The ORC efficiency is given by the simple formula,

$$\eta_{ORC} = \frac{\dot{W}_{net}}{\dot{Q}_{evap}} \tag{2.4}$$

with the net power output given by,

$$\dot{W}_{net} = \dot{W}_{exp} - \dot{W}_{pump} \tag{2.5}$$

and the heat rate to the evaporator is given by,

$$\dot{Q}_{evap} = \dot{m}_{hm} C_{p,hm} \left(T_{hm,in} - T_{hm,out} \right) \tag{2.6}$$

where hm stands for hot medium, including gas and liquid heat sources.

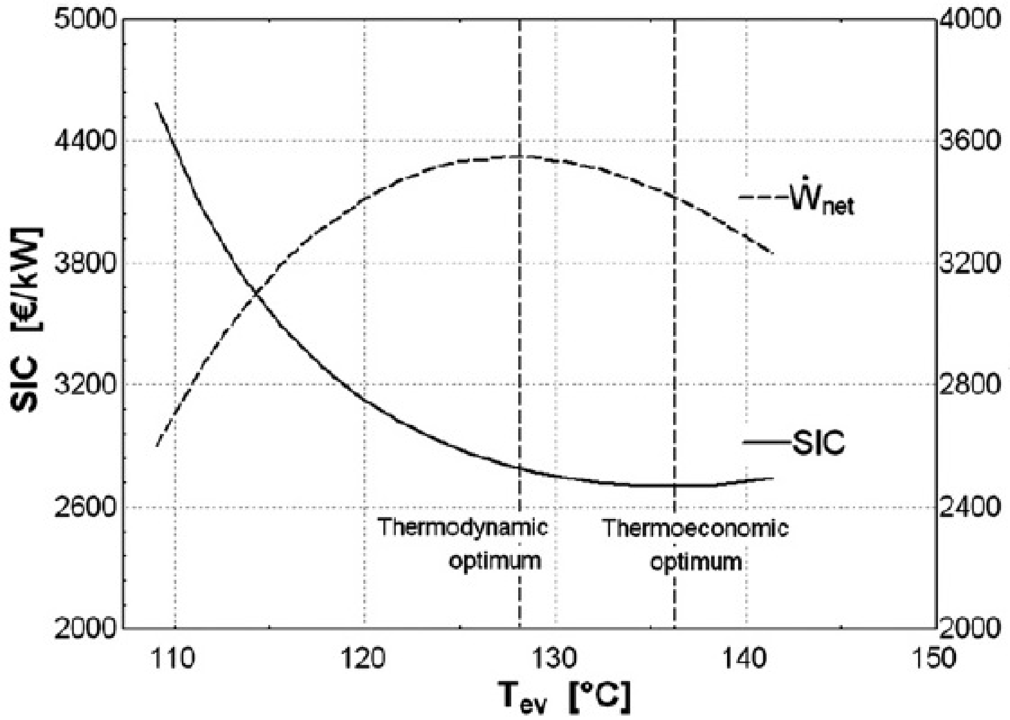

FIGURE 2.11: Effects of T_{evap} on thermodynamic and thermo-economic efficiency [6]

2.4 Non-Technical Data

2.4.1 Government Incentives

For technologies that struggle with high investment costs and long payback periods, government incentives may be the solution to lower these to an acceptable level. In Norway, government incentives is offered through targeted programmes by Enova.

Enova

Enova has chosen to organize its financial aid to businesses through various support programs. Regarding the exploitation of low-temperature waste heat to electric power, there are three support programs that are relevant:

- Support for the introduction of new technology
- Support for energy measures in industry
- Support for energy measures in construction

The size of the financial offering is determined based on various parameters, including innovation height, the profitability of the project and the size of the business. Generally, the financial support will be higher for small and medium-sized enterprises (SME).

> "The category of micro, small and medium-sized enterprises (SMEs) is made up of enterprises which employ fewer than 250 persons and which have an annual turnover not exceeding EUR 50 million, and/or an annual balance sheet total not exceeding EUR 43 million" [30]

A more extensive definition of the SME identification process can be found in the European Commission report "User Guide to the SME Definition". Based on correspondence with Enova, the size of the investment support would be in the range of 0 - 50% of the investment costs, based on the aforementioned requirements. Large enterprises that seek support for a proven technology will receive a maximum support rate of 30%, while SME that proposes a innovative project may receive a support rate up to 50%.

Enova operates with a electricity price that is based on the turnover of 3-year forward contracts on Nord Pool, with the price being a moving average from the last 6 months. As of 01.04.2016, the price of electric power was 0.1841 NOK/kWh. The price excludes transmission fee, VAT, consumption tax and electricity certificates fee. The end user electricity certificates fee is estimated at 0.0253 NOK/kWh, without including additional charges.

Currently, no applications have been filed to Enova regarding financial aid for a waste heat utilization project.

2.4.2 Investment Costs

The investment costs (IC) refers to the initial investment of the project. It occurs a single time at the beginning of the project. Costs that may be included in the IC for an ORC installation is cited below.

- Costs directly associated with the system
  - Equipment and materials
  - Working fluid
  - Labor required for the equipment and installation thereof
- Indirect costs
  - Engineering
  - Construction costs
  - Contingencies
- Transport
- Other outlays
  - Start-up costs
  - Working capital
  - Import tax

An investment cost allocation for two WHR projects can be viewed in Appendix G [1] and Appendix H shows the total cost allocation for a dual heat source ORC system. The cost of the ORC module proves to be the main investment for all three cases, comprising of 48%, 76% and 53% of the total costs respectively.

Some earlier studies have focused on estimating the IC through calculation of individual component costs using the six-tenth rule or the Chemical Plant Cost Index [11, 26, 31], but the main focus of this thesis will be on total IC and not the costs associated with each component.

When reviewing the IC for different project propositions, it might be most useful to look at the specific investment cost (SIC).

2.4.3 Specific Investment Costs

The SIC is the costs associated with producing 1 kW. A simple formula for calculating the SIC can be found below.

$$SIC = \frac{Cost_{Components} + Cost_{Labor}}{\dot{W}_{net}} \tag{2.7}$$

It is worth noting that the SIC is divided into two categories, one reflecting the specific costs associated with the components and one for labor, engineering etc. From [32], SIC estimates from several enterprises can be obtained, where some include reference cases with exact SIC, as well as operation and maintenance costs (O&M). These can be found in Table 2.4. From [16], the SIC was given as 1 800 - 2 857 \$/kW, [28] reported the SIC to be 1 500 - 2 500 \$/kW, [6] obtained values between 2 136 - 4 260 €/kW and [31] claims a general price estimate of 2 000 - 4 000 €/kW.

Table 2.4: SIC from different manufacturers

	General information		Specific case information		
Manufacturer	**SIC [NOK/kW]**	**Power range [kW]**	**Power [kW]**	**SIC [NOK/kW]**	**O&M [øre/kWh]**
Opcon	11,800 - 13,500	400 - 800	580	13,500	3 - 5
Turboden	8,100 - 16,200	280 - 15,000	3,000		
Viking Heat Engines	13,500	2 - 12	30	25,600	
ElectraTherm	15,000 - 26,000	40 - 110			
Ormat	10,260 - 11,400	100 - 25,000	5,000		<0.6
GE	11,400 - 20,000	130 - 140	102		<0.6
Enertime	13,100	600 - 1,000	850	19,000	4.7

When calculating the IC, the choice of heat source and the size of the unit determine the cost level of the direct and indirect costs. Figure 2.12 gives an indication of the cost differences between different applications [4]. For WHR applications, the trend appears to be that costs decrease with increasing nominal output power, with micro and small units having the highest costs. Few data points are available for geothermal and CHP applications, but the same trend can be observed. Overall, WHR applications seem to provide the lowest costs when discarding micro and small units. Geothermal and CHP costs seem to intertwine, but too few data points are included to form any conclusions. Target application is not included in Table 2.4, nor does it specify whether the SIC is for the module or the total cost of the system, but the SIC in Figure 2.12 and Table 2.4 have significant differences.

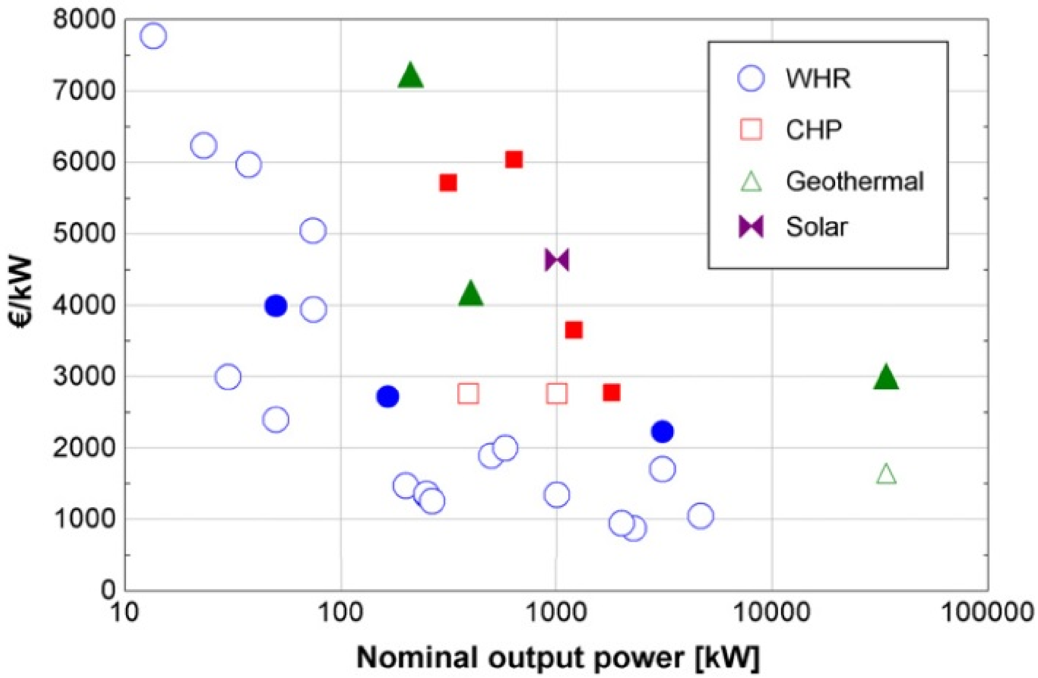

FIGURE 2.12: Module (empty dots) and total (plain dots) cost of ORC systems depending on the target application and on the net electrical power [4]

2.4.4 Operating Costs

A major advantage of the ORC is the low operation and maintenance (O&M) costs. This is a result of the system having few moving parts, being closed loop and operating at low speeds. The O&M costs can be divided into fixed and variable costs. Fixed costs include taxes and insurance. Variable costs include maintenance and labor. Since the system can be monitored and managed from a remote screen, labor cost associated with operation is minimal. From [9], labor requirement is estimated at a mere three hours per week. Maintenance include recharging working fluid, replace fans, filters and batteries, cleaning etc. In most cases, fuel costs will be zero since the system utilizes heat from an external source. However, fuel costs might occur in a biomass CHP system if additional biomass is necessary to make up for the extracted heat to the ORC [33].

From Table 2.4, O&M costs are stated to be in the range of 0.6 - 5 øre/kWh. From [1], O&M costs can be as low as 0.01 €/kWh (0.0835 NOK/kWh), but 0.03 €/kWh (0.2507 NOK/kWh) is considered to be a more conservative assumption. No information is provided concerning the content included in each cost estimation, hence making it difficult to assume a reasonable value. However, O&M represents a small rate of the total project cost, so despite considerable uncertainty in cost estimation rates, it will not have too great of an effect on the results.

2.4.5 Income

The income accrual from a potential plant installation includes the earnings obtained from selling electricity to the grid and potential savings originating from carbon emission taxes. Electricity prices and carbon emission taxes and quotas vary over time.

Cost of Power

The cost of power (COP) is a decisive factor when considering the feasibility of implementing a ORC. In countries where the electricity price is low, income or savings from an ORC may be limited and a potential project could rely on subsidies or tax-relief to be profitable. Depending on location, savings could be comprised of feed-in-tariff, white certificates or CO_2-tax.

An overview of the electricity prices for medium sized industry in the EU can be found in Appendix D, with Norway being in the lower price range. Low electricity prices are common in countries that are mostly self sufficient on power. The variation of electricity prices for industry in Norway from 2012 - 2016 can be viewed in Figure 2.13. Both energy-intensive industry and manufacturing industry excluding energy-intensive industry is included. Energy-intensive industry often purchase their electricity through fixed-price contracts, hence only small fluctuations in pricing are present. The average price of electricity for energy-intensive industry was 30.8 øre/kWh in the first quarter of 2016, excluding taxes and grid rent [7]. The service and manufacturing industry experience more frequent fluctuations in price as fixed-price contracts are more rare. The average price of electricity was 27.3 øre/kWh in the first quarter of 2016, somewhat lower than for energy-intensive industry.

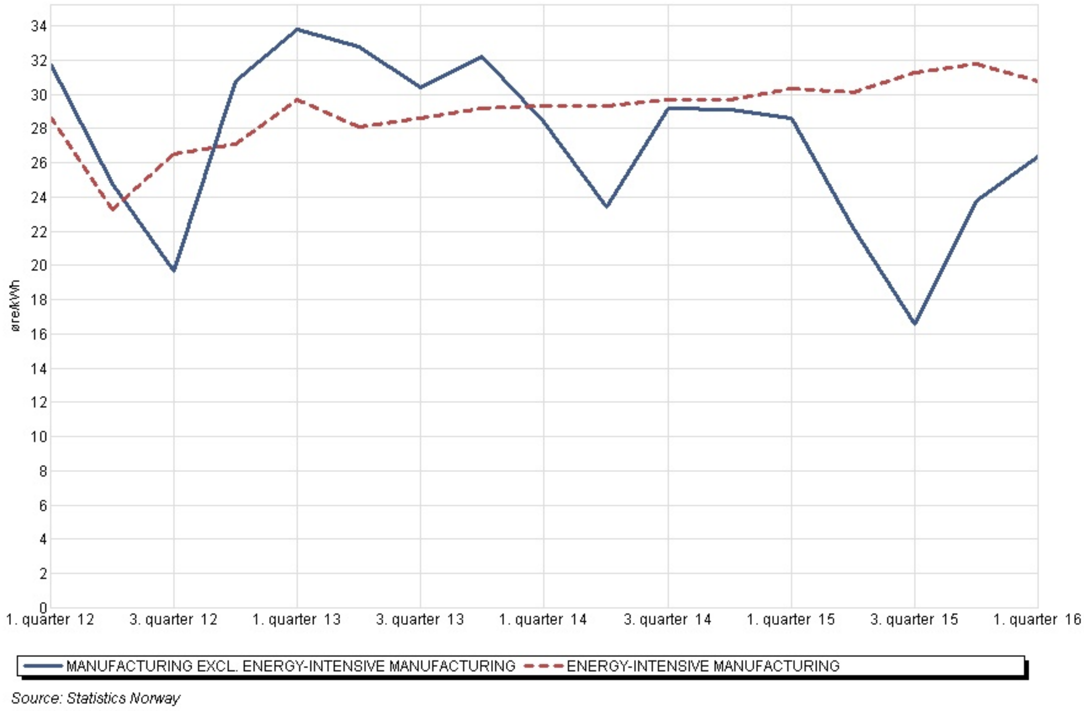

FIGURE 2.13: Electricity prices in the end-user market, by type of contract and time excl. taxes [7]

Carbon Emission Taxes

Carbon emission taxes are subject to energy taxes in EU-27 [34], which accounts for the largest share of environmental taxes with 76.5% in 2014 [35]. VAT is excluded from environmental taxes due to the special characteristics of the tax [34]. CO_2-taxes can be incorporated in the energy tax or be considered as a separate tax.

Carbon emission taxes, in combination with the emission trading scheme, are considered to be among the most important tools in the climate policy in Norway. More than 80% of Norway's total greenhouse gas emissions are covered by the emission tax or the European quota system. While the quota price is determined by the market, the emission tax rate is set by the Norwegian government. The emission trading scheme must be viewed in conjunction with the emission tax so that enterprises are not required to pay for their emissions multiple times. Approximately 45% of the total GHG-emissions in the EU are covered by cap and trade, while other industries are covered by carbon taxes.

Carbon emission taxes vary by country. Since this paper focuses primarily on Norway, the carbon emission taxes for Norway was investigated in more detail. The taxes on carbon emissions varies from 25 NOK per ton CO_2-equivalents to 427 NOK per ton CO_2-equivalents, depending on application area and fuel type [36, 37]. The CO_2-tax rates for the fiscal year of 2015 can be viewed in Table 2.5. Carbon taxes in the EU can be viewed in Appendix E.

TABLE 2.5: CO_2-tax rates for 2015

	NOK per l/Sm^3/kg	**NOK per ton CO_2**
Petrol	0,95	410
Mineral oil		
- Light oil	0,90	338
- Heavy oil	0,90	287
- Mineral oil imposed road use tax	0,63	237
- Mineral oil for domestic flights subject to quotas	0,57	223
- Mineral oil for other domestic flights	0,86	337
- Reduced rate light oil	0,31	116
- Reduced rate heavy oil	0,31	99
- Reduced rate fishing in shore waters	0,27	101
Domestic Use of Gas		
- Natural gas	0,67	337
- LPG	1,01	337
- Reduced rate natural gas	0,05	25
The Continental Shelf		
- Light oil	1,00	376
- Heavy oil	1,00	319
- Natural gas	1,00	427

2.4.6 Payback Period

Payback period is the simplest tool to investigate the profitability of a project. Payback period computes how fast an enterprise will be reimbursed on its initial cash investment. The calculation is based on cash flows and the measurement is made in years. Due to its simplicity, it is regarded as the analysis tool with the greatest shortcomings as it does not account for the time value of money, risk, financing and so on. Despite its shortcomings, it is a helpful tool when attempting to determine the payback.

$$Payback\ period = \frac{Cost\ of\ project}{Net\ annual\ cash\ inflows} \tag{2.8}$$

What is considered to be an acceptable payback period is determined by the firm. This is often called the cutoff period. The decision rules are as follows:

- If payback period $<$ the minimum acceptable payback period, the project is accepted
- If payback period $>$ the minimum acceptable payback period, the project is declined

Depending on industry, the cutoff period can be equal to or below five or three years.

2.4.7 Economic Tools

More sophisticated economic tools are needed when measuring the profitability of a specific project. This paper focuses on PBP, but for a more thorough analysis, the time value of money should be considered. Net present value and internal rate of return would be helpful tools when considering specific projects.

Net present value (NPV) is the sum of present values, which accounts for income minus costs in the economic lifetime of the project. It is often favored above the payback period as a method of analysis, as it considers the time value of money and risks associated with the project. The time value of money is incorporated in the NPV calculations through the discount rate. The discount rate represents the interest rate you need to gain on a specific amount of capital today to end up with a specific amount of capital in the future. A positive NPV indicates a net gain, while a negative NPV indicates a net loss. To initiate a project, the projected NPV must typically be positive and among several project propositions, the project with the highest NPV is usually chosen. The equation used to calculate the NPV is presented below,

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \tag{2.9}$$

where C_t is the net cash inflow during the period t, C_0 is the total initial IC, r is the discount rate and t the number of time periods.

Internal rate of return (IRR) is another tool for determining the profitability of a project. It computes the interest rate that is required to make the NPV equal to zero. Higher values for IRR equals a faster return on the investment.

2.4.8 Differential Costs

The term differential cost refers to the difference between multiple business decisions. It can also describe a change in output levels. When there are several options to pursue, the alternative that produces the most viable results will most likely be chosen. This is determined by the cost and profit of each alternative.

Chapter 3

Specific Case Analysis

The goal was to generate a generic representation considering both technical and economic elements. To ensure valid estimates, several ORC manufacturers were contacted to obtain actual price estimates for specific installations. As prices vary greatly according to application area, it was decided to limit the research to applications utilizing industrial waste heat. Hence, the price estimates requested were for waste heat recovery installations that would utilize a heat source with low to medium temperatures of 100 - 350°C. The heat exchange would occur via an intermediate heat carrier loop and proposed cooling medium was seawater or cold groundwater.

Data were procured from ElectraTherm, InfinityTurbine and Enertime, while a price estimate from a Turboden installation was obtained from [9]. Turboden price estimates can be viewed in Appendix C, together with price estimates for two additional installations of a larger scale. The price estimate for the Turboden installation was a large-scale unit with medium temperatures, but it was included to generate a SIC trend pattern. Price estimates from Infinity Turbine can be found in Appendix F. All together, seven cases were investigated with a net power output ranging from 50 kW - 1 MW. These will henceforth be referred to according to the notation in Table 3.1.

Table 3.1: Case information

Case number	Manufacturer	Net Power Output
1	ElectraTherm	59 kW
2	ElectraTherm	99 kW
3	Infinity Turbine	250 kW
4	Infinity Turbine	50 kW
5	Enertime	90 kW
6	Enertime	270 kW
7	Turboden	1 MW

3.1 Method

Microsoft Excel was used to create a model that would generate the PBP for each case. The PBP was calculated based on the approach mentioned in Section 2.4, via calculation of the cumulative cash flow. The procedure can be viewed in the flow diagram in Figure 3.1.

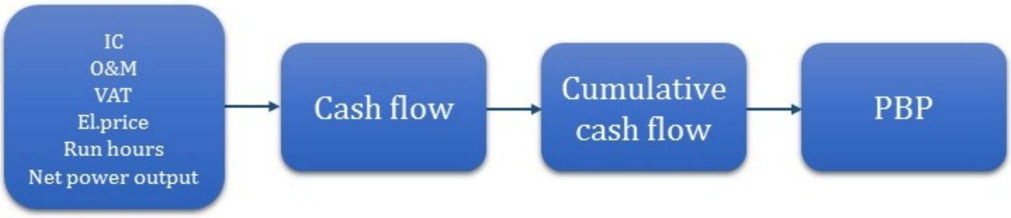

Figure 3.1: Flow diagram Excel procedure

A factor that proved decisive to the initial costs was the currency exchange. During the time span in which this thesis was written, the currency exchange was not favorable to the Norwegian kroner due to poor oil prices. To account for large fluctuations in the currency exchange, a weighted average from 2011-2016 was deployed [38].

Based on information from the manufacturers, economic lifetime was set to 20 years and annual run time was set to an optimistic 8497 hours, or 97% capacity. An exception was made for case 7, where 8000 hours annually was stated in the report. Regardless of incentives, each case was imposed a VAT of 25% based on the SIC of the module. A VAT was not added to the specific costs associated with labor, engineering etc. The costs associated with the VAT was considered to be covered by incentives as part of the total IC. Savings due to reductions in CO_2-emissions were not included, as the purpose of this analysis was to obtain SIC and PBP estimates, and not analyze case specific behavior.

3.2 SIC

From Table 2.4, the stated SIC ranges from 8 100 - 26 000 NOK/kW, depending on manufacturer and size. Figure 3.2 shows the calculated SIC for each case, which ranges from 23 000 - 47 000 NOK/kW. The plot was based on numbers obtained from the manufacturers directly. To investigate potential trend pattern, the cases were listed based on net power output.

Comparing the data in Table 2.4 with the results in Figure 3.2, the SIC is higher or in the upper range for all comparable cases. As [32] was drafted in 2014, deviations can be traced back to the difference in currency exchange, which in 2014 was more favorable to the Norwegian kroner. Also worth noting, is the difference in the given SIC estimate and the specific case SIC in Table 2.4, which might indicate a somewhat optimistic financial estimate from the manufacturers. The most significant deviation occur in cases 5 and 6, with the SIC given at 13100 NOK/kW in Table 2.4 and either 45975 NOK/kW or 91951 NOK/kW in Figure 3.2. Both cases concern the manufacturer Enertime. The data from Enertime also violates the apparent declining trend in the SIC with increasing installed power.

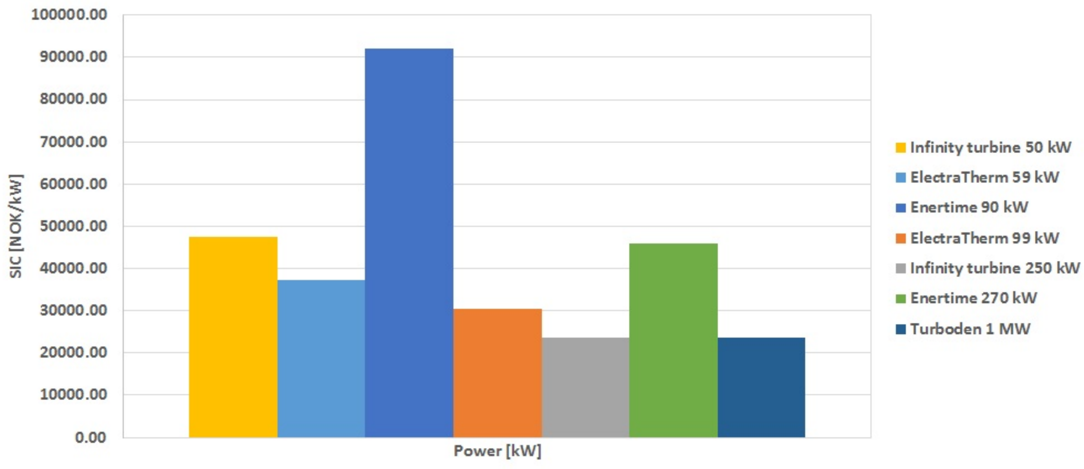

FIGURE 3.2: SIC with 0% Enova support

If the data from cases 5 and 6 were discarded from the statistic, the SIC plot would be a smooth curve with a decreasing trend, which can be observed in Figure 3.3. Assuming this curve can be acknowledged as a general representation of a SIC development, it shows that the SIC is considerably higher for smaller installations. This coincides nicely with the apparent cost trend from Figure 2.12. There seems to be a range where the SIC is leveling of and stabilizing. This occurs at 250 kW. To prove any form of generalization, more data would be necessary, but Figure 3.3 provides a starting point in which estimations can be based on. Without any incentives, the SIC obtained in this section ranges from 23 000 - 47 000 NOK/kW.

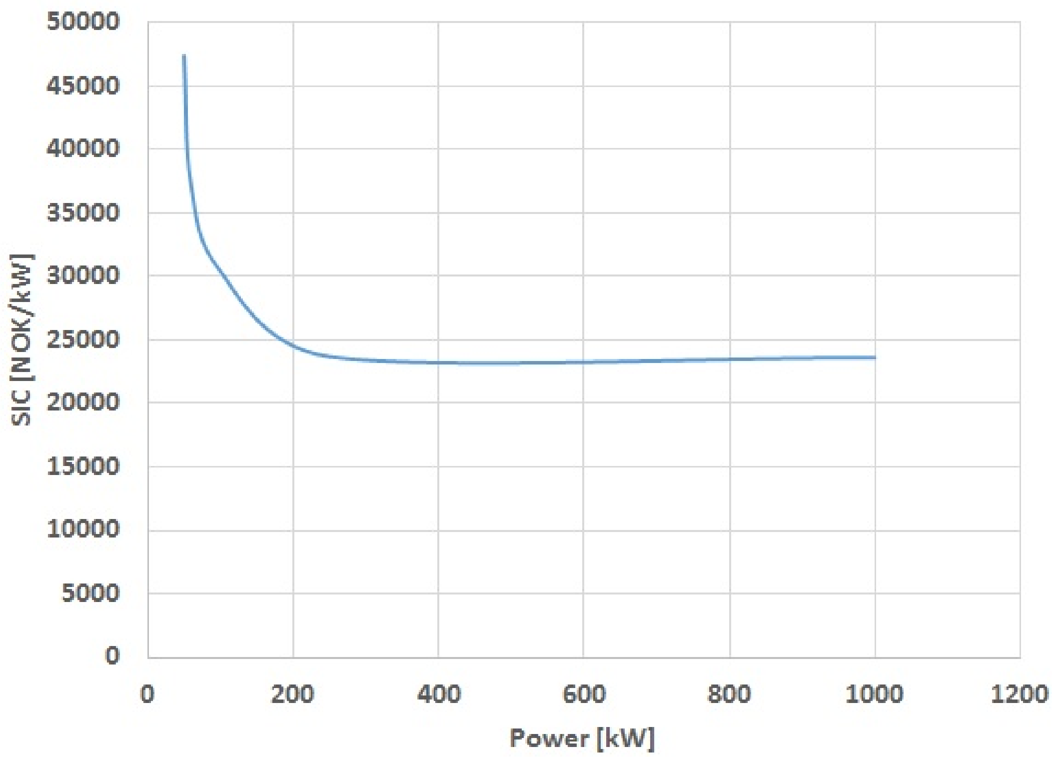

FIGURE 3.3: SIC trend plot

3.3 O&M Costs

O&M costs for each case was either provided by the manufacturer as a constant cost or as a share of the net power output. The rate for cases 5 and 6 were based on information from [1]. Infinity Turbine did not provide a operation cost rate, hence 2.7% was applied for cases 3 and 4. The estimate was based on the average O&M rate from the other five cases. The operation cost rates for each case can be found in Table 3.2.

TABLE 3.2: Operation cost rates for each case

Case	Obtained information	Percentage rate
1	0.011 \$/kWh	1.99%
2	0.012 \$/kWh	2.68%
3	None obtained	2.70%
4	None obtained	2.70%
5	0.03 €/kWh	2.73%
6	0.03 €/kWh	5.46%
7	40000 €/year	1.60%

3.4 Income

Income was calculated based on,

$$Income = R_{el} - C_{O\&M} \tag{3.1}$$

where R_{el} is revenue or savings from electricity production and $C_{O\&M}$ are the costs concerning O&M.

$$R_{el} = Net\,Power\,Output \times Annual\,Operation\,Hours \times El.\,Price \tag{3.2}$$

$$C_{O\&M} = O\&M\,rate \times Investment\,Cost \tag{3.3}$$

3.5 PBP with Different Incentives

The payback period was computed with varying electricity prices, which was determined based on statistics from SSB [7], Eurostat [10] and Enova [39]. The starting cost was set at 0.2 NOK. Considering inflation and prospects of higher electricity prices in the future, the electricity price range was extended as high as 0.8 NOK.

Three scenarios were investigated; the first with zero financial support, the second with 30% financial support and the third with 50% financial support. The financial support is a percentage rate of the IC of the project, corresponding to the maximum financial support provided by Enova for SMEs and large enterprises. To simplify, it was assumed that the financial support would be calculated based on the total initial IC, see section 2.4.2 for details.

Resulting payback period for each scenario can be found in Figure 3.4 - 3.6. If the PBP exceeded 15 years, it was discarded from the graphical representation.

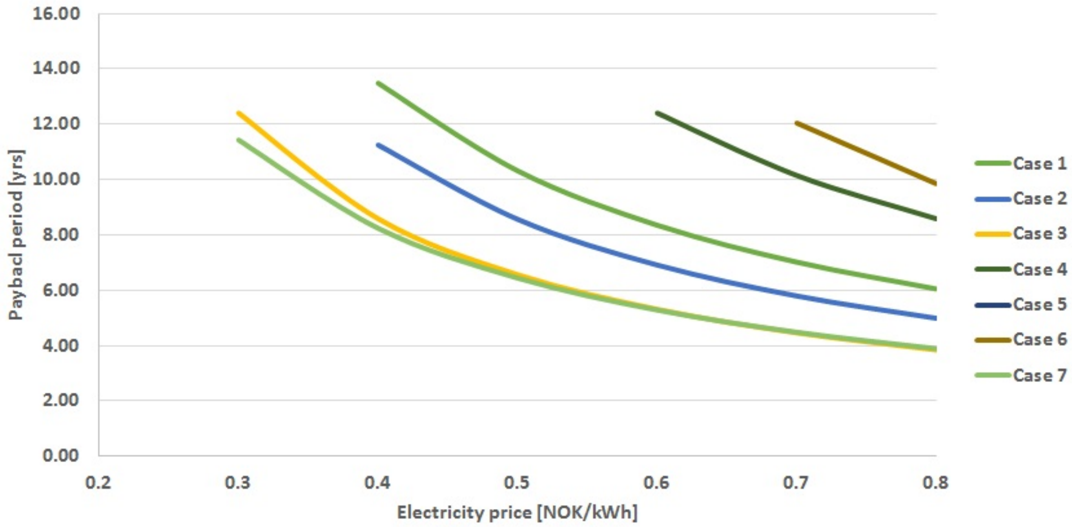

FIGURE 3.4: Payback period with 0% Enova support

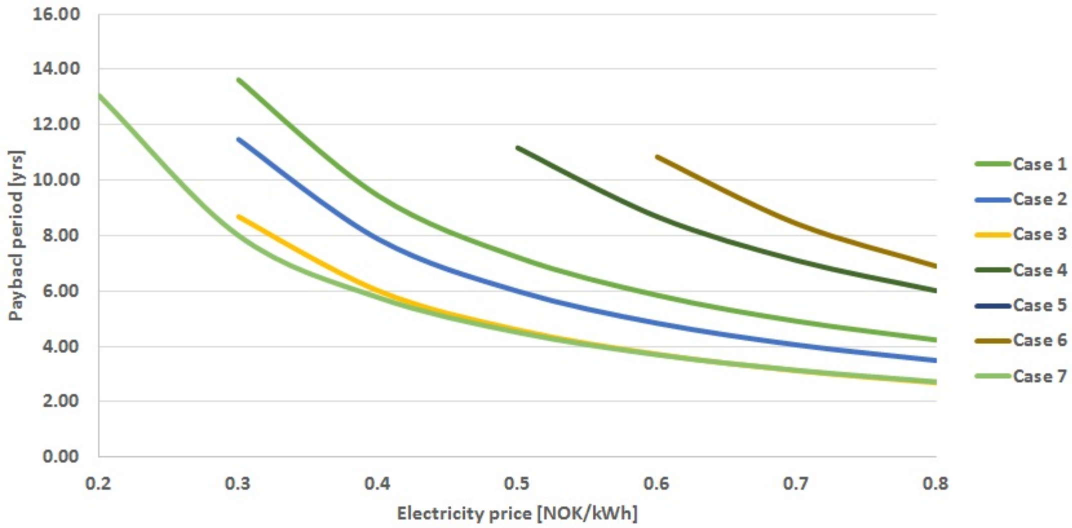

FIGURE 3.5: Payback period with 30% Enova support

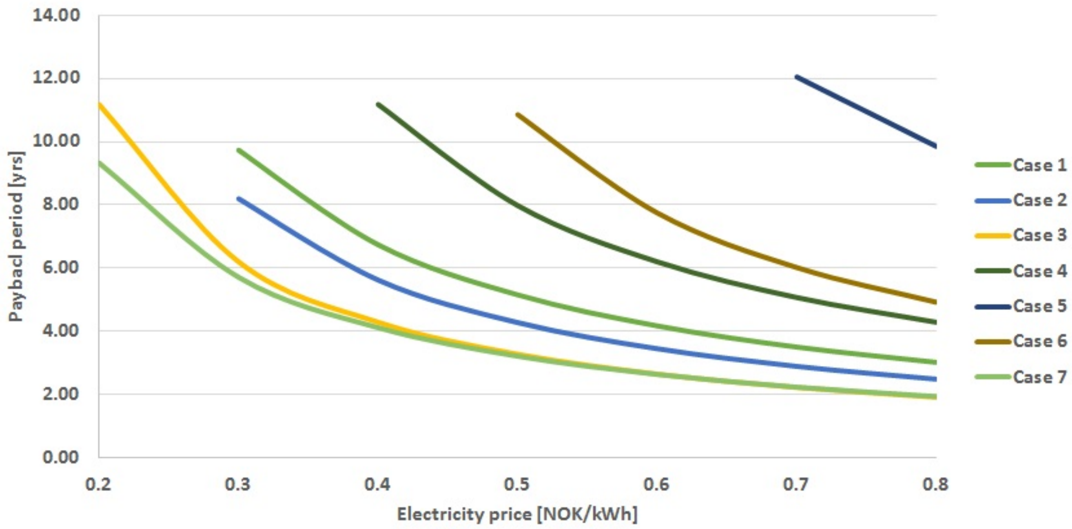

FIGURE 3.6: Payback period with 50% Enova support

From Figure 3.4 - 3.6, it is obvious that cases 3 and 7 provide the best results, having a net power output of 250 kW and 1 MW respectively. Case 7 obtained slightly lower PBP for lower electricity prices, but the curves intersect at a price of 0.4 NOK.

At 0.30 NOK/kWh and zero investment support, the best case scenario yielded a PBP of 11 years 5 months. With 30% investment support, the lowest PBP is 8 years at 0.30 NOK/kWh. Obviously, the best results were achieved with financial support of 50%. The lowest PBP was 5 years 6 months for 0.30 NOK/kWh. The costs associated with cases 5 and 6 were too high and was barely able to achieve a PBP less than 15 years for all three scenarios. Even with 50% investment support, a minimum electricity price of 0.50 NOK/kWh was required for case 6 to be within the upper limit of 15 years. Case 5 barely met the requirements concerning the upper PBP limit with 50% investment support.

Based on the assumptions made, none of the cases managed to yield a PBP of 3 years at 0.3 NOK/kWh. Above 0.5 NOK/kWh, the PBP was within 3 years with 50% investment support. Cases 3 and 7 almost made a payback of 5 years with an incentive rate of 50%. Higher incentive rates and electricity prices are required to lower the PBP.

Chapter 4

Techno-Economic Analysis

The purpose of the techno-economic analysis was to investigate the potential for profitability when implementing Rankine power cycles in Norway. The goal was to obtain a PBP that would be considered acceptable to investors. Information obtained in Chapter 3 was used as estimation basis. Electricity prices were investigated in the range of 0.2 - 0.9 NOK/kWh. The upper range of the considered prices were considerably higher than current electricity prices, but it was considered beneficial to examine the electricity price level necessary to make ORC projects profitable. Also, prognosis expect electricity prices to increase in the future, making projects like these more profitable. Electricity prices in the EU-27 are usually higher than the Norwegian price level, as can be seen in Appendix D, hence the model can, to some extent, be applied to other countries.

4.1 Method

The method applied for the specific case information in Chapter 3, was also used for the generic analysis.

Microsoft Excel was used to create a model for different PBP-scenarios via calculation of the cumulative cash flow. The SIC was considered to be more relevant than the IC for the generic analysis, hence SIC was computed against PBP. Equal to the specific case analysis, annual run time was set to 8497 hours and VAT at 25%.

4.2 SIC

Based on information from literature and Section 3, a range of 15 000 - 50 000 NOK/kW was investigated in the PBP analysis. The range was somewhat extended to account for flaws in previous work. When relating SIC to temperature, an approximation based on the trend pattern obtained in Figure 3.3 was used.

4.3 O&M Costs

Due to the variation in reported O&M costs, it was decided to calculate the O&M costs based on a percentage rate of the IC. Based on rates obtained in Chapter 2 and numbers attained from manufacturers in Section 3.3, a O&M rate of 2.7% was applied to the cash flow calculations.

4.4 Income

Income was calculated based on,

$$Income = R_{el} + S_{CO_2-tax} - C_{O\&M} \tag{4.1}$$

where R_{el} is revenue or savings from electricity production, S_{CO_2-tax} is savings concerning CO_2-taxes and $C_{O\&M}$ are the costs concerning O&M. Savings are given by,

$$S_{CO_2-tax} = EF \times Net\,Power\,Output \times Annual\,Operation\,Hours \times Tax\,Level \tag{4.2}$$

where EF is the emission factor. Whether to include savings from CO_2-taxes was subject to case scenario.

4.5 Payback Period

Payback period was computed for two scenarios; (1) excluding savings from CO_2-tax and (2) including savings from CO_2-tax. The rationale for investigating both scenarios is due to the fact that not all industries are covered by the carbon emission trading scheme or carbon emission-taxes.

The effect of governmental incentives were investigated for each scenario with incentive rates of 0 - 90% and SIC estimates of 23 000 NOK/kW and 47 000 NOK/kW. An overview of required incentive rates to obtain an acceptable payback was also included for each SIC estimate.

Finally, a comparison between the scenarios was executed for electricity prices of 0.4 NOK/kWh and 0.9 NOK/kWh. This to account for a present realistic price and a extremum. Figure 2.13 set present electricity prices for energy-intensive industry at approximately 0.30 NOK/kWh, but taxes and grid rent was not included in the estimates, hence 0.4 NOK/kWh was investigated.

4.5.1 Excluding CO_2 - Tax Savings

Figure 4.1 shows the PBP with respect to electricity price for a SIC ranging from 15 000 - 50 000 NOK/kW. It is apparent that an increasing SIC yields a longer PBP. To achieve a PBP of 5 years or less, the SIC had to be equal to or less than 25 000 NOK/kW. A minimum electricity price of 0.5 NOK/kWh was required.

Based on the SIC estimates obtained in Section 3.2, installed power would have to be approximately 200 kW to equal a SIC of 25 000 NOK/kW. Smaller units have higher SIC, making it increasingly difficult to achieve approval for project start ups. A SIC of 25 000 NOK/kW is in the lower SIC range and achievable, but it requires a minimum electricity price of 0.8 NOK/kWh to achieve a PBP of 5 years. That is considerably higher than current pricing level for industries. To be able to implement an ORC in the current market, incentives are necessary.

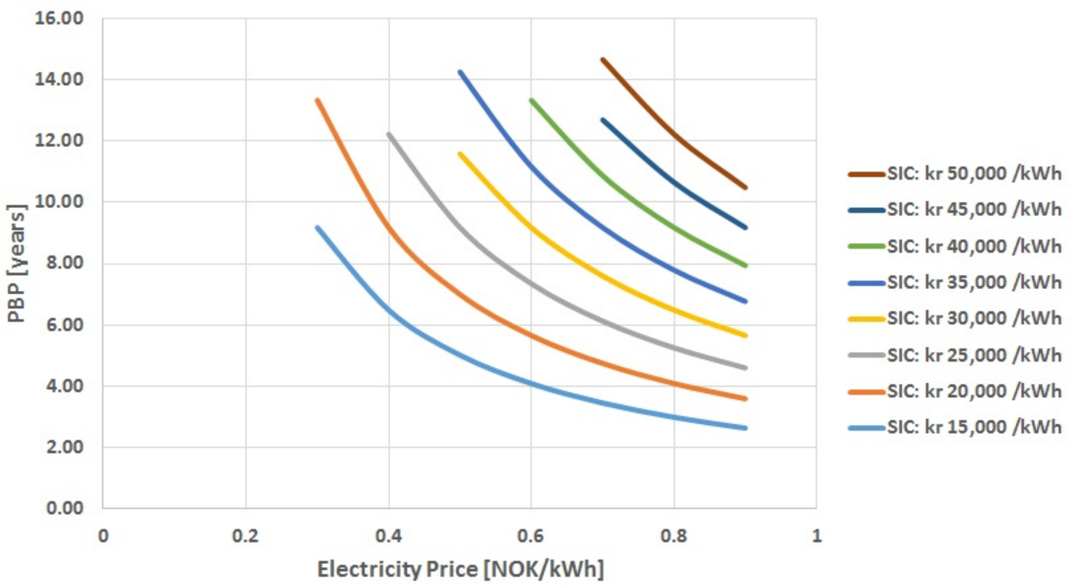

FIGURE 4.1: PBP vs electricity price for SIC ∈ [15.000, 50.000] NOK/kW excluding CO_2-tax

Effects of Incentives Excluding CO_2 - tax Savings

With the current support rates in Norway, up to 50% of the IC covered by Enova, lower electricity prices may yield an acceptable PBP. Installations smaller than 200 kW may also be available within the specific boundary conditions.

The lowest SIC obtained in Figure 3.3 was 23 000 NOK/kW, which occurred when net power output was 250 kW or higher. Without any incentives, the PBP would be 4.2 - 11 years, depending on electricity price. Figure 4.2 shows the PBP including incentive rates of 0 - 90%, where the PBP ranges from 0.4 - 14 years.

Table 4.1 shows the minimum required incentive rates to obtain a PBP of 3 years or less for 0.2 - 0.9 NOK/kWh. It is apparent that even at 23 000 NOK/kW, considerably higher support rates or electricity prices are necessary to yield a payback of 3 years or less. At the current pricing level of 0.3 NOK/kWh, a support rate of 80% would be required.

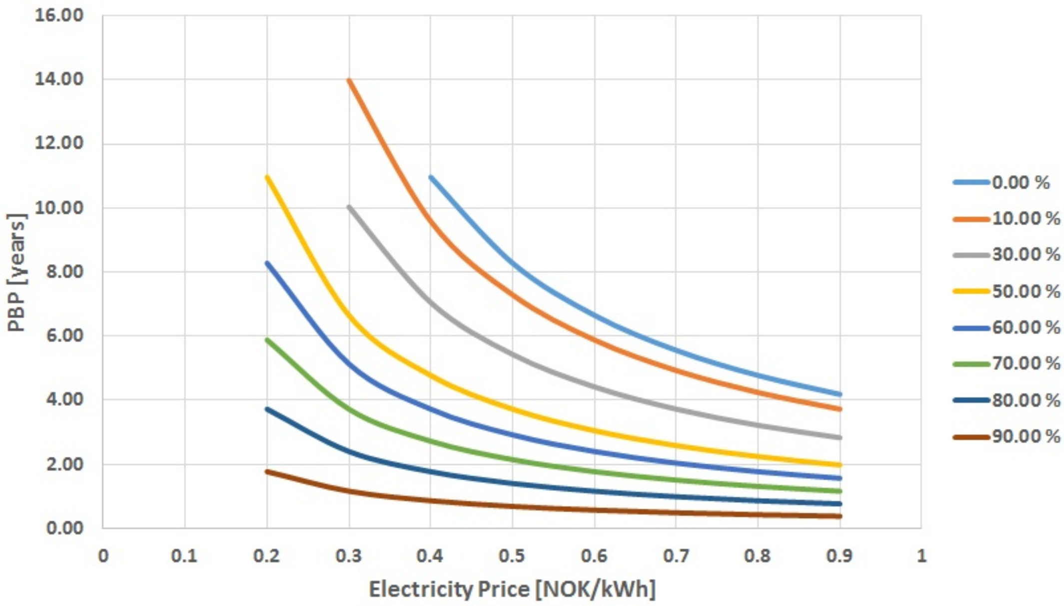

FIGURE 4.2: PBP for SIC = 23000 NOK/kW at incentive rates 0 - 90%

TABLE 4.1: Required incentive rate to obtain a PBP less than 3 years at 23 000 NOK/kW excluding CO_2-taxes

El.Price [NOK/kWh]	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Required rate [%]	90	80	80	70	70	60	60	50

Smaller units equal a higher SIC. From Figure 3.3, it appears to be in the range 25 000 - 47 000 NOK/kW. A SIC of 47 000 NOK/kW occurred when net power output was approximately 50 kW. Without any incentives, the PBP would be equal to or higher than 9.7 years, hence incentives are necessary.

Figure 4.3 shows the PBP including incentive rates of 0 - 90%, where the PBP ranges from 0.8 - 14.4 years. Table 4.2 shows the minimum required incentive rates to obtain a PBP of 3 years or less. At 0.3 NOK/kWh, the required support rate equals 90%, considerably higher than the current maximum rate of 50%.

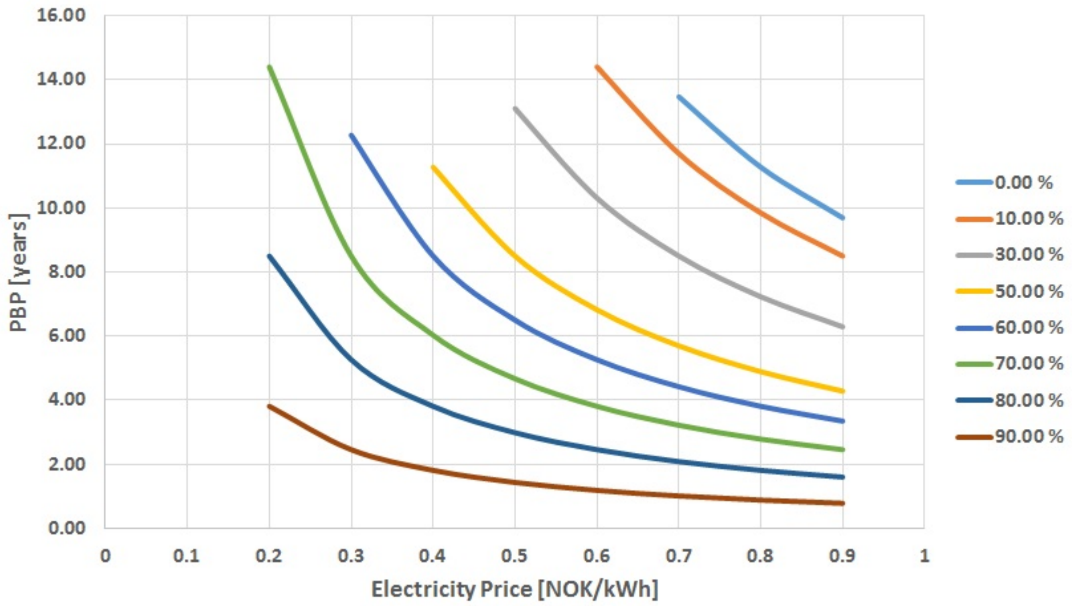

FIGURE 4.3: PBP for SIC = 47000 NOK/kW at incentive rates 0 - 90%

TABLE 4.2: Required incentive rate to obtain a PBP less than 3 years at 47 000 NOK/kW excluding CO_2-taxes

El.Price [NOK/kWh]	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Required rate [%]	>90	90	90	80	80	70	70	70

When excluding CO_2-tax savings, neither SIC estimates provided an acceptable PBP at present price levels or incentive rates. To ensure profitability for a small unit project, higher electricity prices or higher incentive rates are necessary. Either in combination with a slight increase, or individually with significant increase.

4.5.2 Including CO_2 - Tax Savings

When implementing a CO_2-tax in the model, the EU-27 was considered as one el-market with a standard emission factor of 0.460 t CO_2/MWh [40]. The emission factor was based on the EU power generation mix.

Due to varying tax rates within the EU-27, the Norwegian tax levels for CO_2-emissions was applied. Table 2.5 gives an overview of the Norwegian tax rates based on fuel source. To account for different fuel sources, an average based on the rates for petrol, NG (domestic use and on the continental shelf), LPG, light oil and heavy oil was computed. The resulting price was 367 NOK/ton CO_2, which is a high estimate in EU price context. See Appendix E for more details regarding tax information in the EU. Nonetheless, Norwegian electricity prices were used as basis for the analysis, hence carbon emission tax rates should be based on the same market. The resulting PBP including savings from CO_2-taxes is presented in Figure 4.4.

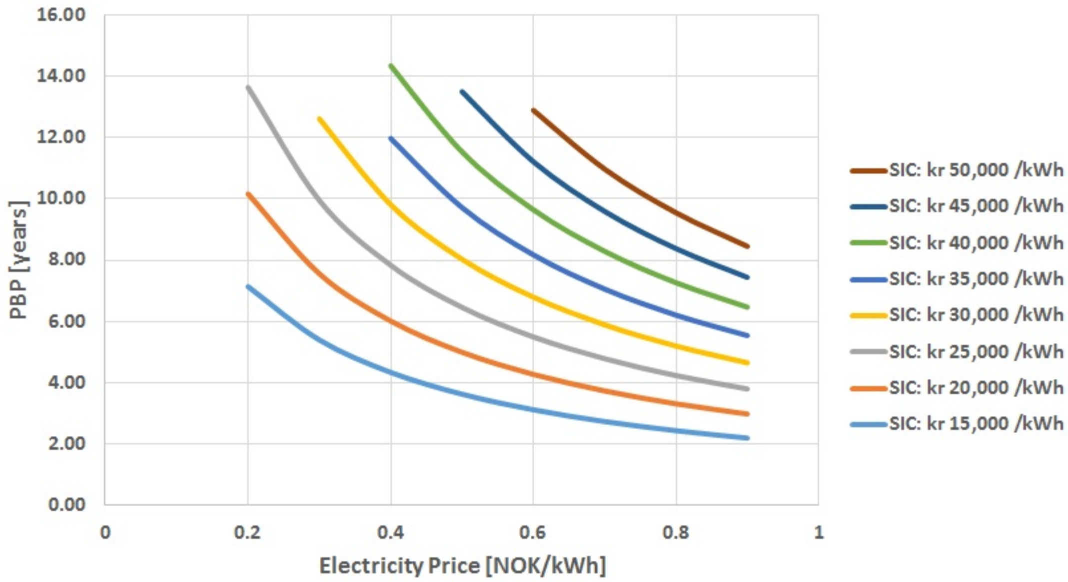

FIGURE 4.4: PBP vs electricity price for SIC $\in$ [15.000, 50.000] NOK/kW including CO_2-tax

Comparing this plot to Figure 4.1, PBP decreased and lower electricity prices can be considered compared to the previous scenario. To achieve a PBP of 5 years or less, the SIC can be equal to or lower than 30 000 NOK/kW. Minimum electricity price is set to 0.3 NOK/kWh. At 0.5 NOK/kWh, the SIC can be equal to or less than 20 000 NOK/kW, an increase of 5 000 NOK/kWh compared to the previous scenario.

Effects of Incentives Including CO_2 - Tax Savings

To visualize the impact of incentives including CO_2-tax savings, the same SIC estimates were considered as in the previous section.

At 23 000 NOK/kW, the PBP would be 3.5 - 12.2 years, discarding any incentives. Figure 4.5 shows the PBP with an incentive rate of 0 - 90%, where the PBP ranges from 0.3 - 12.2 years. Table 4.3 shows the required incentive rates to obtain a PBP of 3 years or less for 0.2 - 0.9 NOK/kWh. At 0.3 NOK/kWh, the required rate has decreased to 60%, compared to 80% in the previous scenario. The required rate is still above the current maximum support rate, but within a closer range than the previous scenario.

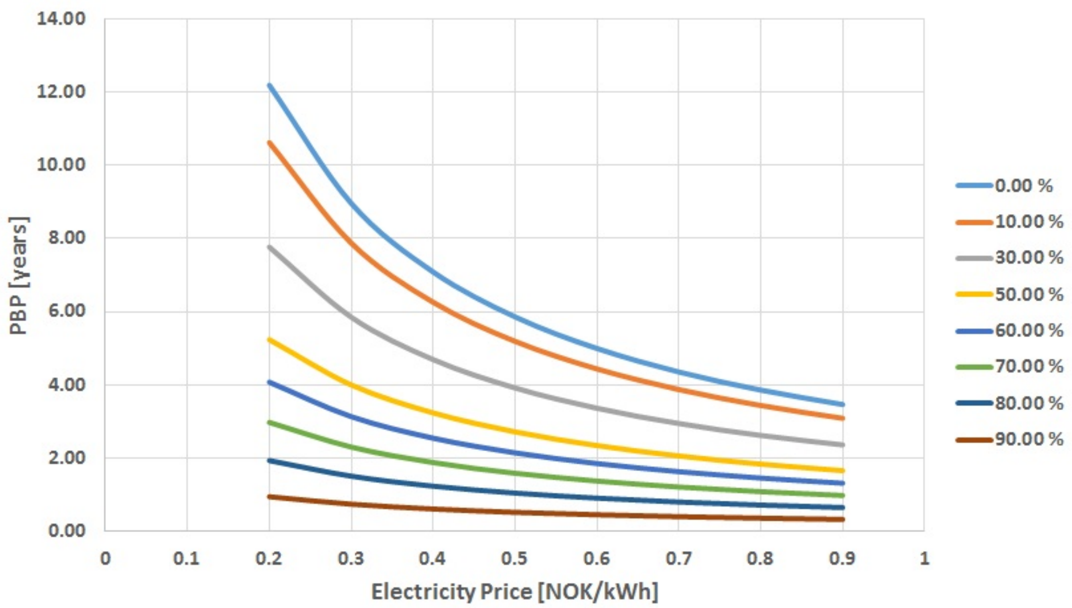

FIGURE 4.5: PBP for SIC = 23000 NOK/kW at incentive rates 0 - 90% including CO_2-tax savings

TABLE 4.3: Required incentive rate to obtain a PBP less than 3 years at 23 000 NOK/kW including CO_2-taxes

El.Price [NOK/kWh]	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Required rate [%]	70	60	60	50	50	30	30	10

For a SIC of 47 000 NOK/kW, the PBP would be 7.8 - 14.3 years, discarding incentives. When considering the lowest PBP from scenarios one and two, scenario two provides a two year decrease in PBP. An improvement, but still too high.

Figure 4.6 shows the PBP for an incentive rate of 0 - 90%, where the PBP ranges from 0.7 - 14.3 years. Table 4.4 shows the required incentive rates to obtain a PBP of 3 years or less for every electricity price. Despite including CO_2-tax savings, the required support rate is still as high as 80%, implying that any project involving a SIC up to 47 000 NOK/kW would be strongly dependent on high incentive rates.

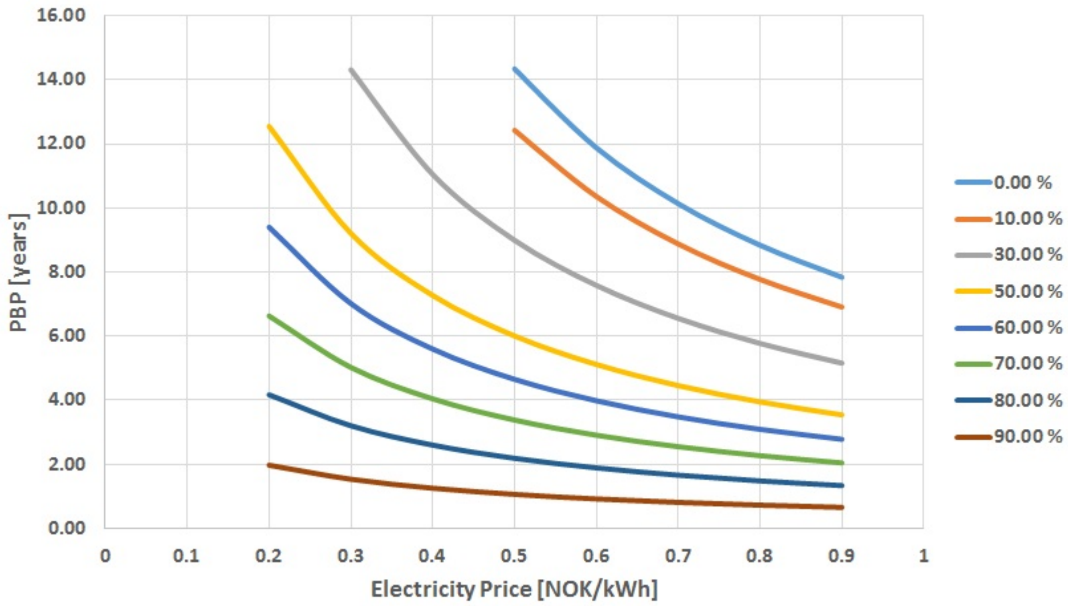

FIGURE 4.6: PBP for SIC = 47000 NOK/kW at incentive rates 0 - 90% including CO_2-tax savings

TABLE 4.4: Required incentive rate to obtain a PBP less than 3 years at 47 000 NOK/kW including CO_2-taxes

El.Price [NOK/kWh]	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Required rate [%]	90	80	80	80	70	70	60	60

4.5.3 Effects of CO_2 - Tax Savings

Table 4.5 present the percentage difference in PBP between the two scenarios under study. The upper and lower SIC obtained in Figure 3.3 was investigated with electricity prices of 0.4 and 0.9 NOK/kWh. The results show a PBP reduction of approximately 33 - 36% for a electricity price of 0.4 NOK/kWh and 14 - 19% for 0.9 NOK/kWh. It appears that the influence of CO_2-tax savings should be included in cost correlations when applicable, especially when considering low pricing levels where the PBP may be decreased significantly. The reason can be observed in Table 4.5, where it is obvious that the influence of CO_2-tax savings decrease with higher electricity prices. This is reasonable, as the CO_2-tax does not depend on the electricity price. Further, incentives prove to be necessary to achieve an acceptable PBP for lower electricity prices.

Table 4.5: Difference in PBP for scenario one and two at an electricity price of 0.4 NOK/kWh and 0.9 NOK/kWh

El.Price	**SIC**	**Support rate**	**PBP**$_{Scenario\,1}$	**PBP**$_{Scenario\,2}$	**% change**
0.4 NOK/kWh	**23000**		11 years	7.1 years	-36
	16100	30%	7 years	4.7 years	-33
	11500	50%	4.8 years	3.2 years	-33
	47000		>15 years	>15 years	-
	32900	30%	>15 years	11 years	≥-27
	23500	50%	11.3 years	7.3 years	-36
0.9 NOK/kWh	**23000**		4.2 years	3.5 years	-16.7
	16100	30%	2.8 years	2.4 years	-14.3
	11500	50%	2.0 years	1.7 years	-15.0
	47000		9.7 years	7.8 years	-19.6
	32900	30%	6.3 years	5.2 years	-17.5
	23500	50%	4.3 years	3.6 years	-16.3

4.6 Differential Costs

When considering a WHR system, differential costs may have a significant impact on the perception of the total costs of the project. Waste heat from industrial processes often reach high temperatures and are in need of cooling, which present an ongoing cost for the company. The introduction of a WHR system often struggle with high investment costs and a payback period that companies deem too long. However, if a WHR unit managed to lower other costs, for instance costs concerning cooling, a WHR project might come of as a more enticing investment to investors. Due to the different configurations of each WHR project, a generic cost estimation is not attainable, but it is a cost that should be considered and evaluated for every individual project.

An example could be aluminium industry. Utilizing surplus heat may reduce the size of treatment plants as well as lowering the main fans power consumption. Energy efficiency would henceforth increase, and expenses connected to cooling would be reduced.

4.7 Improve Real Cycle Efficiency

In Section 2.3.5, Carnot and gliding temperature efficiency was presented. In Figure 4.7 - 4.8, Equations 2.2 and 2.3 were computed for a heat source temperature of 0 - 600°C, with heat sink temperatures of 10°C and 30°C respectively.

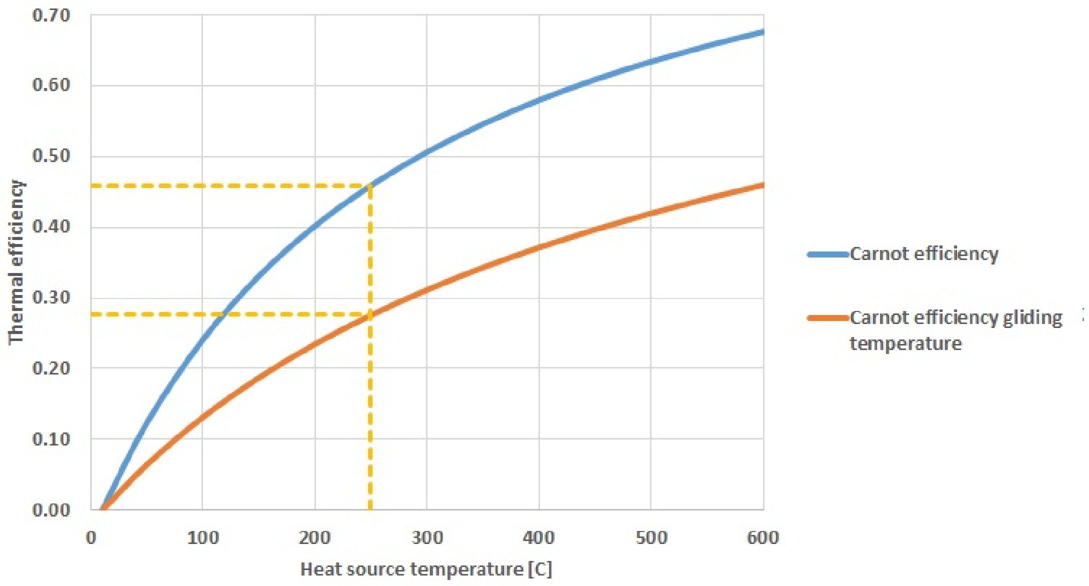

FIGURE 4.7: Efficiency with a heat sink of 10°C

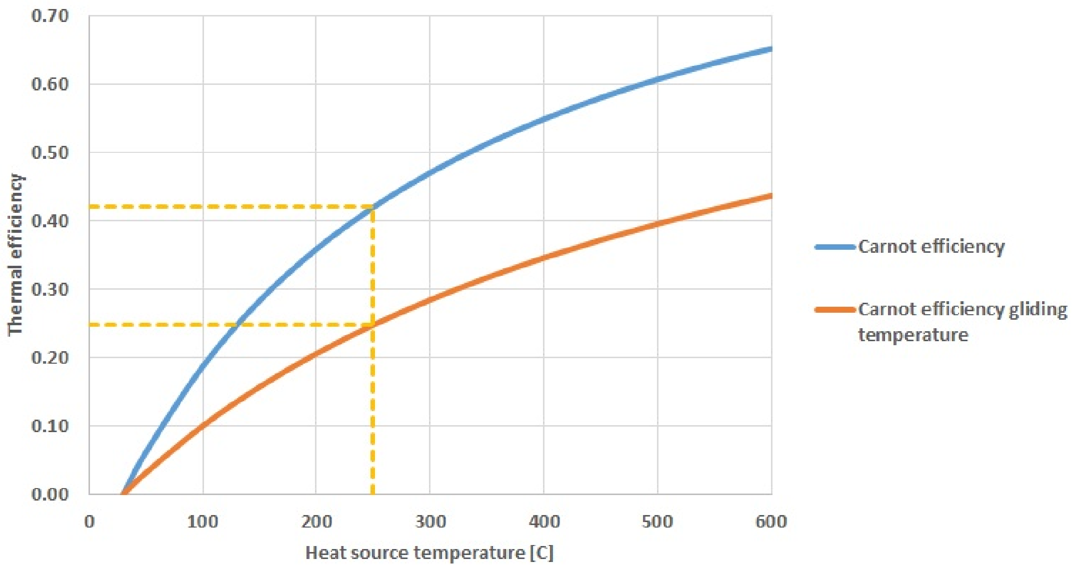

FIGURE 4.8: Efficiency with a heat sink of 30°C

From the plots, it is obvious that efficiency decreases with higher heat sink temperature and a gliding temperature profile causes further efficiency reductions. Low heat source temperature entails poor conversion efficiency.

For the particular case of a heat source with a temperature of 250°C, Carnot efficiency yielded 45.89% and 42.07% for heat sink temperatures of 10°C and 30°C respectively. Gliding temperature efficiency yielded 27.58% and 24.82% for heat sink temperatures of 10°C and 30°C respectively. Cycle efficiency is usually lower, which implies that there is potential for improvement.

According to Figures 4.7 and 4.8, measures that would increase efficiency are (1) an increase in heat source temperature and (2) a decrease in heat sink temperature. A constant heat source temperature profile would yield a higher potential maximum efficiency, but the nature of the process do not enable the possibility of a constant temperature heat source. Theoretically, both measures would increase efficiency, but the most promise is linked to an increase in heat source temperature.

Decreasing the heat sink temperature might not be practical or possible, as it depends on the ambient temperature and therefore the climate in the location. Ideally, the heat source would be cooled down to ambient temperature, hence taking full advantage of the available heat source. Obtaining temperatures below ambient would most likely decrease efficiency as it would demand additional energy use.

4.7.1 Increase in Heat Source Temperature

An increase in heat source temperature may require additional investments or changes to cooling methods. One option is to utilize a heat pump to increase the temperature of, for instance, cooling water and hence obtain a higher efficiency i.e higher power output. This requires additional investments, but may contribute to lowering the final PBP. This can be observed in Figure 4.9, where the PBP decreases with increasing heat source temperature. If PBP exceeded ten years, it was not included in the plot.

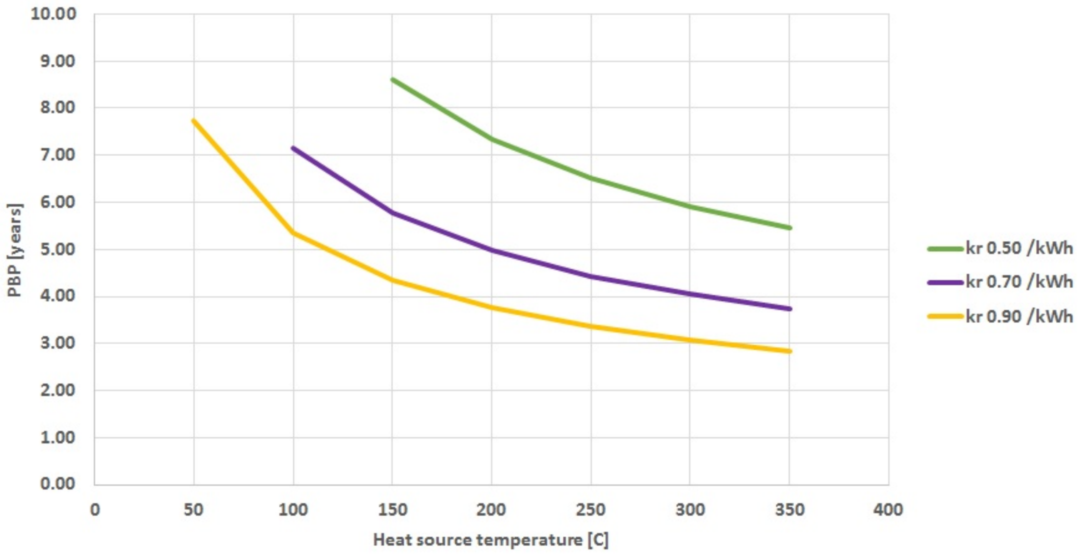

FIGURE 4.9: Payback period relative to heat source temperature at electricity prices of 0.3 - 0.9 NOK/kWh. Calculated without any incentives

The decrease in PBP at higher heat source temperatures is due to the SIC decreasing for increasing heat source temperatures, see Figure 4.10. Higher heat source temperature may also increase net power output.

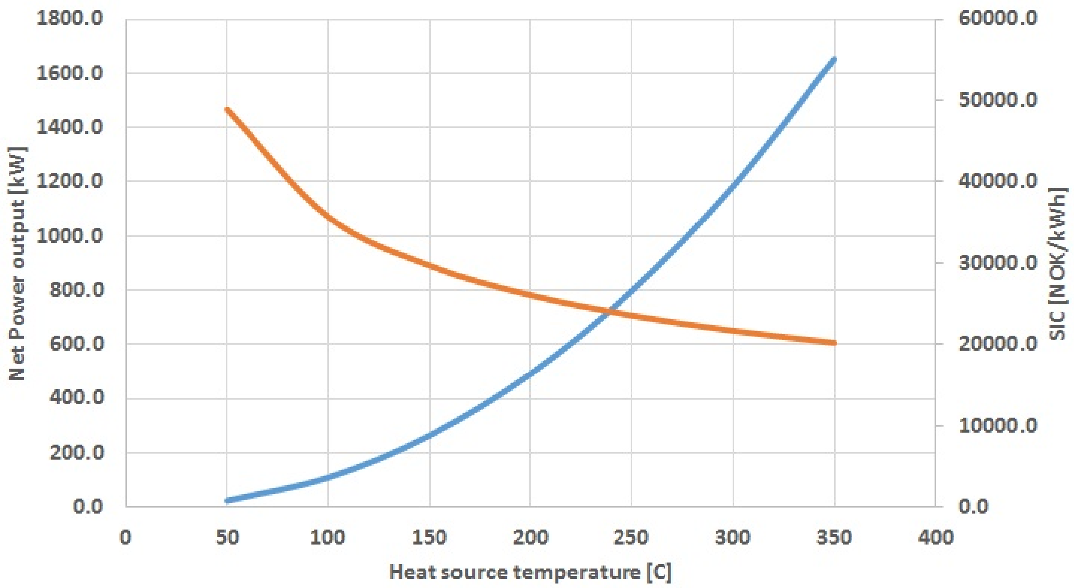

FIGURE 4.10: Net power output (blue) and SIC (orange) relative to heat source temperature

Figures 4.9 - 4.10 are trend patterns that were based on simple calculations combined with estimates from the specific case analysis. The heat source was set to be water with a mass flow of 10 kg/s, and a C_p that corresponded to the water temperature. The temperature drop over the evaporator was set to 20% of the heat source temperature. Gliding temperature Carnot efficiency was used as basis for the thermal efficiency, hence net power output is high considering the heat source temperature. The trend patterns give an indication of the ratio of the PBP, SIC and net power output to the heat source temperature.

4.7.2 The Effects of Component and System Efficiency

To demonstrate the influence of changes in thermal efficiency, a simple case was investigated. The heat source temperature was set to be constant at 250°C. Water was chosen as the hot working medium, with a C_p of 4.87 kJ/kgK, a mass flow of 10 kg/s and a temperature gradient of 50°C over the evaporator. The resulting thermal input was 2435 kW_{th}, and system efficiency was set to be 0 - 28%, which was the theoretical maximum thermal efficiency for a heat source of 250°C and a heat sink of 10°C. The trend patterns obtained for the SIC was used to calculate PBP. The resulting plot can be observed in Figure 4.11.

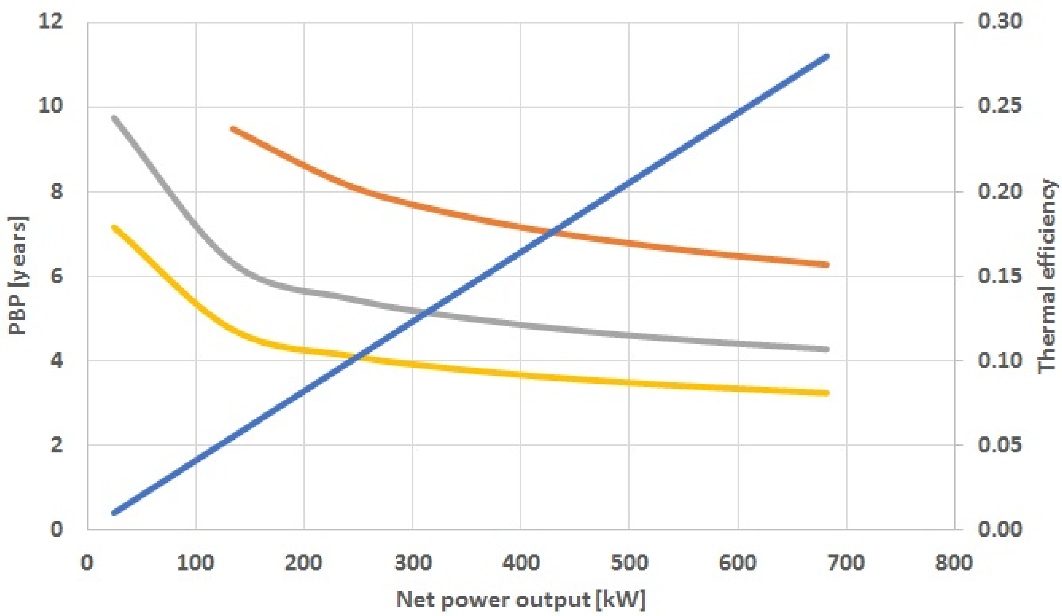

FIGURE 4.11: PBP in relation to net power output and thermal efficiency of the system. PBP at 0.5 NOK/kWh (orange), 0.7 NOK/kWh (grey), 0.9 NOK/kWh (yellow) and net power output (blue)

Net power output is a linear function of thermal efficiency and varies from 24 - 681 kW_{net}, corresponding to a thermal efficiency of 1 - 28%. It can be observed that the PBP drops significantly from 24 kW_{net} to approximately 200 kW_{net}, which corresponds to a system efficiency increase from 1% to approximately 10%. Henceforth, PBP appears to level of, and only minor decreases occur. This may indicate that the economic parameters are not heavily influenced by the efficiency over a certain efficiency level. It can be observed that for a electricity price of 0.7 - 0.9 NOK/kWh, the PBP is only reduced by one year when efficiency increases from 10% to 28%. At 0.5 NOK/kWh, a slightly higher difference in PBP can be observed, indicating that the economic sensitivity to efficiency may be directly affected by the electricity pricing level.

Increasing efficiency leads to a higher net power output, but from an economic perspective, it appears that increasing the efficiency don't have too much of an effect on the PBP. If increasing the efficiency is not related to significantly higher costs, it might be economically viable, but if ICs are notably higher, it might not be worth the additional investment. The configuration of each individual unit will determine the economical gain or loss associated with increasing efficiency.

As previously mentioned, the pump usually represents a low rate of the total energy use and improvements made to the pump will therefore not have too great of an effect on system efficiency in most cases. Increasing thermal efficiency will mostly be associated with improvements made to the heat exchangers and turbine design. Referring to Figure 4.11, minor adjustments will not affect the PBP noticeable. If the objective function was thermal efficiency or net power output, i.e thermodynamic, optimizing the design of the turbine and heat exchangers would be essential. From a economic perspective, it might not be of high importance.

4.7.3 Other Considerations

Additional to the above-mentioned measures, other factors need to be taken into consideration when utilizing waste heat from industrial processes. Industrial processes might experience downtime, decreasing the annual run-time of the ORC unit, hence lowering the annual electricity production. Downtime can be a result of seasonal demand or safety measures. Usually within the metallurgy industry, there is a set upper and lower temperature limit in which production is considered non-hazardous. Outside the temperature boundaries, unfortunate chemical reactions might occur, forcing production shutdown or other safety measures. For instance, in cases where flue gases contain sulfur, the temperature should be kept above the acid dew point. Depending on the sulfur content of the flue gas, exhaust gases are therefore not cooled below 120 - 180°C.

When considering waste heat recovery from industrial processes, heat source temperature profiles depend on the industrial process in question. As an example, an anode baking furnace process in a aluminium plant can be considered. Each step of the process demand different temperature levels, causing fluctuations in temperature, which results in a high temperature gradient for the fume gases. Since ORC units are optimized according to a constant temperature level, high fluctuations in temperature decreases efficiency.

Contaminants are often present in the raw materials used in the aluminium and ferroalloy industry, which lowers productivity and efficiency during production. Contaminants in raw materials result in exhaust gases including a lot of dust, so called dirty gases. Exploiting the full potential of dirty gases are difficult, but if such contaminants were to be removed prior to the melting process, it would increase productivity and efficiency. However, the raw materials are very fine-grained and difficult to handle, and it is therefore decisive that dirty gased are treated with caution to avoid productivity drop and efficiency loss.

4.8 Environmental Effects

Although the focus of this thesis has been on factors that influence techno-economic feasibility, potential environmental effects should also be considered. Figure 4.12 shows the potential for CO_2-emission reduction in tons per year relative to installed capacity. Savings were calculated from,

$$CO_2\, reduction = Net\, Power\, Output \times Operating\, hours \times Emission\, factor \quad (4.3)$$

where the emission factors were retrieved from the Department of Energy & Climate Change in the UK [41] and [40]. Both the standard and the LCA emission factor were considered.

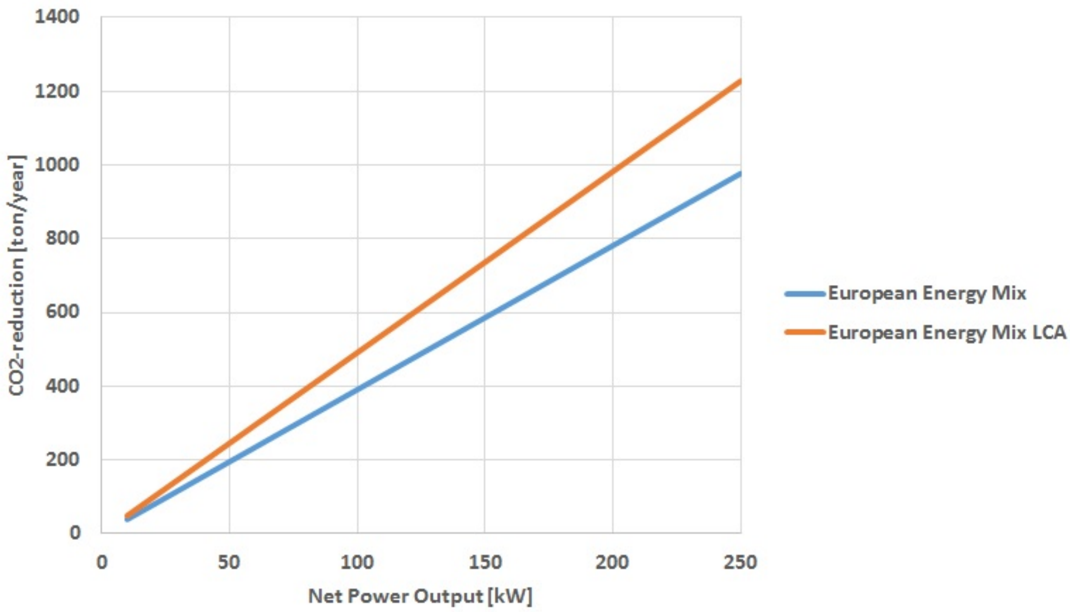

FIGURE 4.12: Potential for CO_2 reductions per year for the European energy mix

The resulting plot shows a linear correlation between the net power output and potential CO_2-reductions. In other words, the higher the net power output, the greater the CO_2-reduction. For a net power output of 250 kW, CO_2-emissions could be reduced with 1000 tons per year, or 1200 tons per year if the LCA-approach is considered. To put those numbers into perspective, an average car emits approximately 4.7 metric tons of CO_2 each year. Implementing a energy efficiency program, for example a ORC unit that produces 250 kW, would have the same impact as removing 213 vehicles from the road, or 255 vehicles when considering the LCA-approach.

Chapter 5

Further Work

The current state for the ORC portrays a maturity for the first generation ORC, which has a simple configuration, usually involving a pure working fluid and subcritical working conditions. Next-generation ORC could explore the use of transcritical and supercritical cycles, zeotropic mixtures as working fluid, and multiple evaporation pressures. Current ORC technologies rely heavily on state of the art units that are optimized for a specific set of operating conditions. Future configurations should take into consideration the variable nature of heat sources, allowing fluctuations in thermal input without the system exhibiting poor performance when deviating from the design point.

To achieve more accurate representations of the ratio between costs and technical parameters, the model should be extended and include more data to secure more precise ratios. To encourage implementation of ORC units in industry, possible measures to increase heat source temperatures should be investigated in detail, including the economic impact such measures would have.

To evaluate specific cases, a thermodynamic optimization process should be added to the model, to account for the relationship between thermodynamic optimization and cost minimization. As mentioned, these rarely coincide, but a optimal relationship can be obtained. Finally, when considering individual projects, economic analysis tools such as NPV and IRR should be evaluated to ensure financial viability as PBP is a simple tool with limitations.

Chapter 6

Conclusion

In this paper, an overview of ORC applications was presented with an emphasis on waste heat from industrial processes. Main manufacturers were presented, as well as market development and allocation of current plants according to application. The ORC market has increased exponentially, but it is dominated by large-scale plants in the MW-range. Low-capacity systems are under development, but experience difficulties with high investment costs.

A techno-economic feasibility study was performed to investigate the possibility of implementing a ORC plant. It was restricted to the Norwegian market in order to make use of set electricity prices, tax levels and emission constraints. The lowest SIC obtained occurred for a power output of a few hundred kWe at 23 000 NOK/kW, but the current electricity price level did not yield an acceptable payback. Smaller units offered higher SIC, making it increasingly difficult to achieve a quick payback. However, SIC numbers from literature deviate greatly, and many reports include SIC lower than 23 000 NOK/kW. Reductions in SIC could therefore generate a payback of 3 years or less.

The influence of incentives and CO_2-tax savings were investigated. Present incentive rates are from 0 - 50%. When excluding CO_2-tax savings, an incentive rate of 80% was necessary to obtain a payback of three years or less when the SIC was set to be 23 000 NOK/kW. CO_2-tax savings contributed to lowering the PBP. Low electricity prices gained a 33 - 36% reduction in PBP, while high electricity prices gained a 14 - 19% decrease.

Higher heat source temperatures proved to yield a lower PBP, while providing a higher net power output. Hence, configurations that deliver a higher heat source temperature will increase the likelihood of gaining a net profit and lowering the PBP. Additional investments leading to higher heat source temperatures may therefore prove cost-effective despite increasing total investment costs. Increased system efficiency gave higher net power output and lowered the payback period. However, the reduction was minor when thermal efficiency surpassed 10%, implying that it might not be cost effective to improve on system efficiency if it's associated with a significant increase in costs.

Presently, ORC projects in Norway depend heavily on incentives. The low electricity price level is making it difficult to achieve short paybacks, and year round operation is required for a unit to become economically feasible. However, Norway has low electricity prices compared to the rest of the EU, implying that it will be easier to implement a ORC that proves economically feasible in other EU countries. An increase in electricity prices would make more projects profitable, but it is possible to obtain a decent payback in Norway with present electricity price levels when CO_2-tax savings and incentive arrangements are accounted for.

Appendix A

Cost Curve for Energy Efficiency Measures

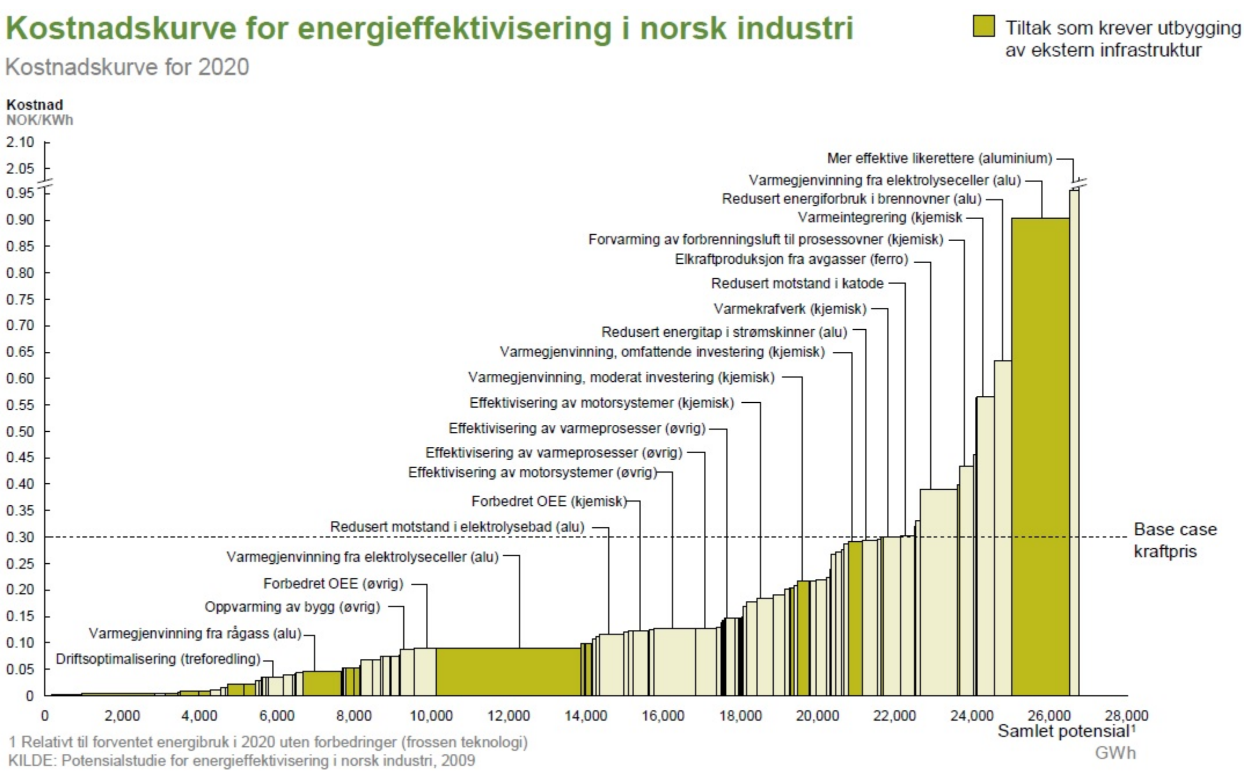

FIGURE A.1: Costs associated with energy efficiency in Norwegian industry [8]

Appendix B

Energy Efficiency Measures in Energy Intensive Industry

Tiltaksbeskrivelse	Potentsial (GWh/yr)	Beak-even energipris (NOK/kWh)	Spesifikk investeringskost (NOK/kWh)	Tilbake-betalings-tid (år)	Livstid (år)	Total CAPEX (MNOK)
Forbedring av transportsystem for damp - hindring av lekkasjer, isolasjon	227	0.04	0.31	2	20	28
Forbedring av transportsystem for trykkluft - hindring av lekkasjer, bedret vedlikehold	49	0.04	0.31	2	20	121
Effektivisering av dampsystemer (store anlegg) steg 1 - forbedret vedlikehold (rensing/blowdown), trykkontroll, optimalisering av vanninntak, forvarming av matevann	37	0.05	0.31	1	10	8
Effektivisering av dampsystemer (mindre anlegg) steg 1 - forbedret vedlikehold, trykkontroll, forvarming av matevann	48	0.05	0.31	1	10	15
Redusert energiforbruk ved nedetid på anlegg (mindre anlegg) - stenge ned så mye av anlegget som mulig ved driftsstand	205	0.07	0.59	3	20	15
Redusert energiforbruk ved nedetid på anlegg (store anlegg) - stenge ned så mye av anlegget som mulig ved driftsstand	47	0.07	0.59	3	10	12
Optimalisering av trykkluftproduksjon (ekskl. Transport) steg 1 - kombinering av nettverk (der samme trykk kreves I flere nettverk), splitting av nettverk (der ulikt trykk kreves innenfor samme nettverk), trykkontroll, tilpasning av produksjon og forbruk	13	0.10	0.59	2	20	70
Varmegjenvinning steg 1 - eksport av spillvarme fra eksotermiske prosesser, gjenvinning av varme fra trykkluft	154	0.10	0.59	2	10	52
Forbedret OEE i store anlegg - generell effektivisering av drift, vedlikehold, og kontroll (forbedret måling)	136	0.12	0.59	5	10	41
Forbedret OEE i mindre anlegg - generell effektivisering av drift, vedlikehold, og kontroll (forbedret måling)	384	0.12	0.59	5	10	13
Effektivisering av ovner gjennom driftsoptimalisering - bedret vedlikehold, isolering, forvarming av luft, oksygenkontroll, tilpasning av oppsett (åpningsstørrelse og timing)	45	0.12	0.59	2	20	27
Avpasning av dampforbruk og dampproduksjon - minimere variasjoner I produksjon og etterspørsel for damp, timing av eksoterme og endoterme prosesser	121	0.13	0.59	2	20	80
Effektivisering av dampsystemer (mindre anlegg) steg 2 - bytte/modifisering av kjel, gjenvinning av energi fra blowdown og "de-aeration" (fjerning av oksygen)	48	0.14	0.85	3	10	212
Effektivisering av dampsystemer (store anlegg) steg 2 - bytte/modifisering av kjel, gjenvinning av energi fra blowdown og "de-aeration" (fjerning av oksygen)	16	0.14	0.85	3	10	49
Redusert energiforbruk I elektromotorer I mindre anlegg (vifter, pumper, produksjonsbelter osv) ved å endre oppsett (frekvenskontroll) og forbedre vedlikehold	244	0.15	0.59	2	10	145
Redusert energiforbruk I elektromotorer I store anlegg (vifter, pumper, produksjonsbelter osv) ved å endre oppsett (frekvenskontroll) og forbedre vedlikehold	82	0.15	0.59	2	15	72
Implementering av system for kondensatretur	164	0.22	1.29	5	15	320
Optimalisering av trykkluftproduksjon (ekskl. Transport) steg 2 - bytte/modifisere kompressor	40	0.22	1.29	5	20	227
Varmegjenvinning steg 2 - kapitalkrevende vamegjenvinning, for eksempel ved varmeintegrasjon I deler av anlegg	271	0.22	1.29	5	5	94
Optimaliserte katalysatorer - generell forbedring, blant annet oppnåelse av lavere reaksjonstemperaturer	111	0.29	0.85	3	20	136
Varmeintegrering steg 3 - meget kapitalkrevende tiltak for varmegjenvinning, inkluderer komplett varmeintegrasjon ved større anlegg	372	0.29	2.10	10	15	780
Effektivisering av dampproduksjon gjennom etablering av kraftvarmeanlegg (mindre anlegg)	57	0.30	2.37	N/A	10	350
Effektivisering av ovner gjennom modifisering eller bytte av ovn	84	0.46	3.81	15	10	91
Total	**2 956.2**					**2 955.8**

Figure B.1: Energy efficiency measures in chemical industry [8]

Tiltaksbeskrivelse	Potentsial (GWh/yr)	Beak-even energipris (NOK/kWh)	Spesifikk investeringskost (NOK/kWh)	Tilbake-betalings-tid (år)	Livstid (år)	Total CAPEX (MNOK)
Forbedret effektivitet I spenning I elektrolysebad for å forhindre omvendt reaksjon (tilbake til alumina og carbon)	126	0.01	0.12	1	15	15
Var megjenvinning fra skorsteinene I støperiet (antatt at varme fra det smeltede metallet allerede benyttes til omsmelting av gjenvunnet metall)	441	0.02	0.18	1	15	15
Optimalisering av bruk av trykkluft. Dette innebærer både redusert bruk ved at man begrenser bruk til det nødvendige og gjør bruken mer effektiv.	63	0.03	0.25	1	15	15
Forbedrede operasjonelle rutiner (inkluderer generell forbedring som igjen fører til energibesparelser, ikke knyttet til ett spesifikt tiltak)	63	0.03	0.25	1	15	64
Optimalisering av andre støttesystemer (enn vifter, pumper og trykkluft) Tiltaket består I generell forbedring av bruk av støttesystemer, gjennom rutiner og prosessforbedringer	63	0.04	0.30	1	15	19
Optimalisering av bruk av vifter. Dette innebærer både redusert bruk ved at man begrenser bruk til det nødvendige og gjør bruken mer effektiv.	101	0.04	0.30	1	15	15
Optimalisering av bruk av pumper. Dette innebærer både redusert bruk ved at man begrenser bruk til det nødvendige og gjør bruken mer effektiv.	13	0.04	0.30	1	15	21
Reduserte tap fra anodeeffekt, dvs., mer effektiv innmating av alumina for å unngå at spenningen øker og elektrisitetsforbruket således går opp	44	0.04	0.35	2	15	21
Varmegjennvinning fra rågass som dannes I det anodene forbrukes. Denne varmen gjenvinnes I elektrolysehallen, varmebærer kan feks være vann eller luft	1 008	0.05	0.38	2	15	31
Varmegjenvinning fra sidevegger på elektrolysecellene. Varme gjenvinnes her fra sideveggene ved at man monterer varmegjenvinningsutstyr inne I cellen (kan også gjenvinnes fra utsiden, en effektivitetsgraden er da dårligere). Varme gjenvinnes fra ca 400 oC og gjenvinningsgraden er rundt 80%	3 730	0.09	0.36	2	15	154
Varmegjenvinning fra kompressorinstallasjon	95	0.10	0.82	3	15	30
Redusert spenning I cellen, dvs I elektrolysebadet og boblelaget I cellen, slik at mindre elektrisitet er påkrevd for å produsere samme mengde aluminium	630	0.12	0.98	4	15	4
Forbedrede rutiner og prosesser, feks at alle skift forbedres til beste skift I dag, forbedret instrumentbehandling mv.	13	0.15	1.23	5	15	15
Redusert elektrisk mostand I anoder, dvs at man produserer og utformer anodene slik at de gir minst mulig elektrisk motstand I det de forbrukes	290	0.19	1.60	7	15	214
Redusert energiforbruk I massefabrikken	38	0.20	1.70	8	15	463
Redusert energiforbruk I støpeformer	13	0.20	1.70	8	15	927
Varmegjenvinning fra anodebakeovnene I anodeproduksjonen	63	0.20	1.70	8	15	463
Redusert energiforbruk I forbindelse med homogenisering	13	0.20	1.70	8	15	1 814
Redusert energiforbruk ifm montering av anoder I elektrolysecellene.	18	0.21	1.75	8	15	618
Redusert energiforbruk I holde og smelteovner ved å holde temperatur konstant, ikke avkjøle for deretter å varme opp igjen m.v.	88	0.21	1.75	8	10	772
Utvide tverrsnitt I strømskinner I elektrolysehallen slik at den elektriske motstanden blir mindre. Dette tiltaket kan tenkes delt I to med en enkel og en vanskeligere del. Enkel del.	252	0.22	1.84	8	15	2 337
Utvide tverrsnitt I strømskinner I elektrolysehallen slik at den elektriske motstanden blir mindre. Dette tiltaket kan tenkes delt I to med en enkel og en vanskeligere del. Vanskelig del.	378	0.29	2.45	N/A	10	5 510
Redusert motstand I katode og foring. Redusert motstand I katoden er med å legge til rette for lavere spenning I elektrolysecellen som igjen muliggjør lavere elektrisitetsbruk.	378	0.30	2.04	10	15	107
Redusert energiforbruk I brennovner. Her er det ikke noe potensial I forbedring av dagens ovner, tiltaket forutsetter kjøp av nye ovner som er bedre enn de man finner på verkene I dag. Dette er en stor investering om man vil derfor ikke gjøre det før det trengs en ny ovn. Kan ikke forsvares på bakgrunn av energibesparelse.	441	0.63	5.30	15	15	77
Varmegjennvinning fra bunn og topp I elektrolysecellene. Gjenvinningsutstyr monteres inne I cellen og gjenvinner varme på ca 400oC. Dette er vanskeligere og mindre effektivt enn gjenvinning fra sidevegger I det det er større flater noe som virker svært fordyrende.	1 512	0.90	3.64	15	10	1 359
Installasjon av mer effektive likerettere enn det som I dag er I bruk. Dette tiltaket er ikke aktuelt ved alle verk da noen har relativt nye likerettere og man vil ikke bytte ut gamle likeretter som fortsatt fungerer for å spare energi grunnet høy investeringskort	227	0.96	8.00	15	15	386
Reduksjon av materialtap feks støv mv. Dette tiltaket gir ikke særlig energibesparelsee men gjøres av miljøhensyn	13	2.03	17.02	15	15	77
Total	**10 110**		**1.54**			**15 549**

FIGURE B.2: Energy efficiency measures in aluminium industry [8]

Tiltaksbeskrivelse	Potentsial (GWh/yr)	Beak-even energipris (NOK/kWh)	Spesifikk investeringskost (NOK/kWh)	Tilbake-betalings-tid (år)	Livstid (år)	Total CAPEX (MNOK)
Valg av optimal størrelse på utstyr slik at man unngår stor overkapasitet som krever mer energi, samt installere frekvensstyring på utstyret slik at det til enhver tid kjører på optimal intensitet. Dette gjelder feks pumper, vifter og motorer.	40	-	-	1	15	6
Redusert tap I halvferdige og ferdige produkter. I dette ligger for eksempel mindre feilkutt og mindre brukket papir.	32	-	-	1	15	-
Maksimal bruk av biofuels I eksisterende kjeler gjennom bruk av tallolje, såpe eller skogsrester	-	-	-	1	15	-
Energibesparelse ved å øke tørrstoff før tørking gjennom pressing slik at mindre energi kreves for å tørke	6	-	-	1	15	50
Salg av gjenvunnet varme til fjernvarmenettverk. Her kan man både benytte varme som genereres I dag og varme som kan genereres ved utnyttelse av ekstra kapasitet I biofuelskjeler.	357	0.00	0.03	1	15	120
Energibesparelse ved å øke brennverdien på brensel gjennom optimalisering av forbrenningsforhold (feks 02 innhold I luften)	218	0.00	0.03	1	15	8
Tilsetning av kjemikalier I raffinør sparer energi fordi flisen da trenger mindre behandling I raffinøren (den løses delvis opp på forhånd av kjemikaliene)	264	0.00	0.03	1	15	20
Redusert forbruk av vann gjennom tilsetning av mindre vann I masseproduksjonen. Dette sparer energi ved at mindre vann må varmes opp (vann brukt I masseproduksjon er ca 20 varmere enn starttemperaturen) og gjennom mindre behov for tørking av masse (for salg) og papir (integrert fabrikk).	274	0.01	0.10	1	15	100
Energibesparelse gjennom økt bruk av gjenvunnede fibre. Det krever mindre energi for å lage masse av gjenvunnede fibre enn nye fibre og økt andel vil derfor gjøre produksjonen mindre energiintensitiv.	10	0.03	0.20	1	15	100
Redusere energiforbruk gjennom automatisering, monitorering, visualisering av nøkkeltall, forbedret opplæring og styring av operasjoner, samt forbedret vedlikehold for å redusere variasjon og stans i produksjon.	400	0.04	0.30	1	15	-
Redusert energiforbruk ved redusert og optimalisert bruk av vifter.	16	0.06	0.51	2	10	2
Redusert energiforbruk gjennom installasjon av høyhastighet- eller dobbeldiscraffinør som er mer effektive enn tidligere typer. Mange anlegg har allerede innført dette, men det er fortsatt noe potensial igjen.	213	0.07	0.56	2	15	12
Optimalisering av varmegjenvinning fra mekaniske masseproduksjon. Varme kan her gjenvinnes fra damp og varmt vann.	160	0.07	0.63	3	15	75
Installasjon av mottrykksturbiner for å øke varmegjennvinning	80	0.07	0.63	3	15	27
Elektrisitetsproduksjon fra ekstra kapasitet I kjeler. Dette gir grønn elektrisitet da brensel er biofuels	80	0.11	0.94	4	15	50
Energibesparelse gjennom optimalisering av kontinuerlig kokeprosess for kjemisk masse.	12	0.12	1.00	4	6	67
Energibesparelse gjennom forvarming av vann med gjenvunnet varme. Dersom man klarer å bruke varme som genereres gjennom andre deler av prosessen til å varme vann vil man trenge mindre ekstra energi til dette formålet.	100	0.12	1.00	4	15	8
Bedre isolering av utstyr for å minske varmetap I alle prosessledd	112	0.13	0.60	3	15	110
Energibesparelse ved å øke tørrstoffandel I avlut før forbrenning. Dette gir avluten en høyere brennverdi og sparer således energi.	40	0.15	1.25	5	15	120
Energibesparelse gjennom økt bruk av fyllstoff. Fyllstoffer erstatter en del av massen, slik at man trenger å produsere mindre masse per tonn papir, og økt andel vil derfor gjøre produksjonen mindre energiintensitiv.	78	0.17	1.41	6	15	200
Energibesparelse ved forbehandlig av flis og defibrering I raffinør. Dette gjør at flisen trenger mindre behandling I raffinøren og prosessen blir dermed mindre energikrevende.	284	0.18	1.48	6	15	345
Energibesparelser ved optimalisering av vann- og konsitensforvaltning.	118	0.20	1.70	7	15	400
Energibesparelse gjennom å øke tørrstoff I slusj (ved bruk av polymer), og bark (ved å presse barken) før forbrenning slik at brennverdien øker	11	0.21	1.75	8	15	8
Energibesparelse ved høykonsistens bleking (bruk av peroxidbleking). Dette tiltaket er gjennomført på flere anlegg, men det er fortsatt noe potensial til stede.	4	0.24	2.00	10	15	420
Spart energi gjennom raffinering av masse på lav konsistens	152	0.27	2.27	N/A	15	9
Økt tørrstoff I presseseksjon (feks., skopresse, varmepresse, condebelt)	144	0.33	2.78	15	15	-
Total	3 206					2 256

Figure B.3: Energy efficiency measures in wood processing industry [8]

Tiltaksbeskrivelse	Potentsial (GWh/yr)	Beak-even energipris (NOK/kWh)	Spesifikk investeringskost (NOK/kWh)	Tilbake-betalings-tid (år)	Livstid (år)	Total CAPEX (MNOK)
Utnyttelse av termisk energi I kkølevann fra kjel som brukes til elkraftproduksjon (FeSi/SiMetal)	1 882	0.00	0.03	1	10	5
Utnyttelse av termisk energi I kjølevann fra kjel som brukes til elkraftproduksjon (mangan)	330	0.00	0.05	1	10	25
Termisk energi- kjølevann fra ovner føres gjennom ovn og ovnhette eksporteres (mangan)	465	0.01	0.08	1	10	43
Termisk energi - kjølevann fra ovner føres gjennom ovn og ovnhette eksporteres (FeSi/SiMetal)	303	0.01	0.08	1	20	245
Termisk energi fra slagg fanges og eksporteres med vann som medium (mangan)	302	0.02	0.21	1	20	69
Fanging og eksport av CO-gass som kjemisk energi (mangan)	168	0.04	0.41	2	20	3 500
Termisk energi fra varmt metall fanges og eksporteres med vann som medium (mangan)	152	0.05	0.50	2	20	350
Termisk energi fra varmt metall fanges og eksporteres med vann som medium (FeSi/SiMetal)	221	0.05	0.50	2	20	160
Forbedret effektivitet I trykkluftsystemer ved forbedret vedlikehold, avgrensning av kretser og trykkontroll	17	0.08	0.31	3	20	22
Redusert energiforbruk I elektromotorer (vifter, pumper, produksjonsbelter osv) ved å endre oppsett (frekvenskontroll) og forbedre vedlikehold (FeSi/SiMetal)	43	0.15	1.00	4	20	76
Redusert energiforbruk I elektromotorer (vifter, pumper, produksjonsbelter osv) ved å endre oppsett (frekvenskontroll) og forbedre vedlikehold (mangan)	25	0.15	1.00	4	20	111
Elkraftproduksjon fra forbrenning av CO-gass (mangan)	140	0.27	2.50	N/A	20	62
Reduserte energitap I transformer ved endring til nyere transformer (FeSi/SiMetal)	89	0.30	2.77	15	20	23
Elkraftproduksjon fra lavtemperert avgass (mangan). Varmeutveksling med annet medium enn vann, ekspansjon gjennom turbin	7	0.32	3.00	15	20	35
Elkraftproduksjon fra høytempererte avgasser (FeSi/SiMetal). Damp fra varmeutveksler føres gjennom dampturbin.	956	0.39	3.66	15	20	15
Reduserte energitap I transformer ved endring til nyere transformer (mangan)	30	0.56	5.27	15	20	60
Total	**5 131**					**4 801**

FIGURE B.4: Energy efficiency measures in ferro-alloy industry [8]

Appendix C

Turboden Price Estimates

Industry/application	Cement	Float glass	Steel: flat products (rolling mill)	Unit
Heat source	Kiln and clinker cooler gas	Oven exhaust gas	Preheating oven exhaust gas	
Plant capacity	2,500	500	6,000	Tons per day
Electricity cost [a]	0.09	0.095	0.06	€/kWh
Wasted thermal power in exhaust gas [b]	12	5	13	MW
Thermal power to ORC	11	4.7	13	MW
Thermal power to thermal users	1	0.3	0	MW
Net ORC electric production	1.6	1	2.4	MW
Net electricity production [d]	12,800	8,000	19,200	MWh/y
Capital expenditure indications				
ORC cost	1.8	1.3	2.4	Million €
Balance of plant [c]	2.6	1.1	1.5	Million €
Total cost (+10% project management)	4.8	2.6	4.3	Million €
Annual Cash flows [d]				
Operational expenditure	−40,000	−40,000	−40,000	€/y
Cash flow – electricity	1,152,000	760,000	1,152,000	€/y
Cash flow – heat [e]	240,000	72,000	0	€/y
Net cash flow	1,352,000	792,000	1,112,000	€/y
Results [f]				
Profit before tax	4	3.7	4.4	
Internal rate of return (10 years)	25%	27%	23%	
Net present value (10 years)	€5,333,129	€3,310,109	€4,091,971	
Avoided CO_2 emissions [g]	9,664	5,520	12,096	Tons per year

Notes:

a These values include incentives if any; differences are due to total power installed, nation, etc.
b Assuming to cool down the gas to 150/160°C
c Including heat recovery exchangers and civil works – estimated by reputable suppliers
d Assuming 8,000 operating hours/year
e Assuming a heat valorization of circa 0.03 €/kWh
f Assuming discount rate of 5%
g Assuming 0.63 kg of CO_2/kWh electric and 0.2 kg of CO_2/kWh thermal (from CH_4 combustion).

FIGURE C.1: Turboden prices estimates [9]

Appendix D

Electricity Prices by Country

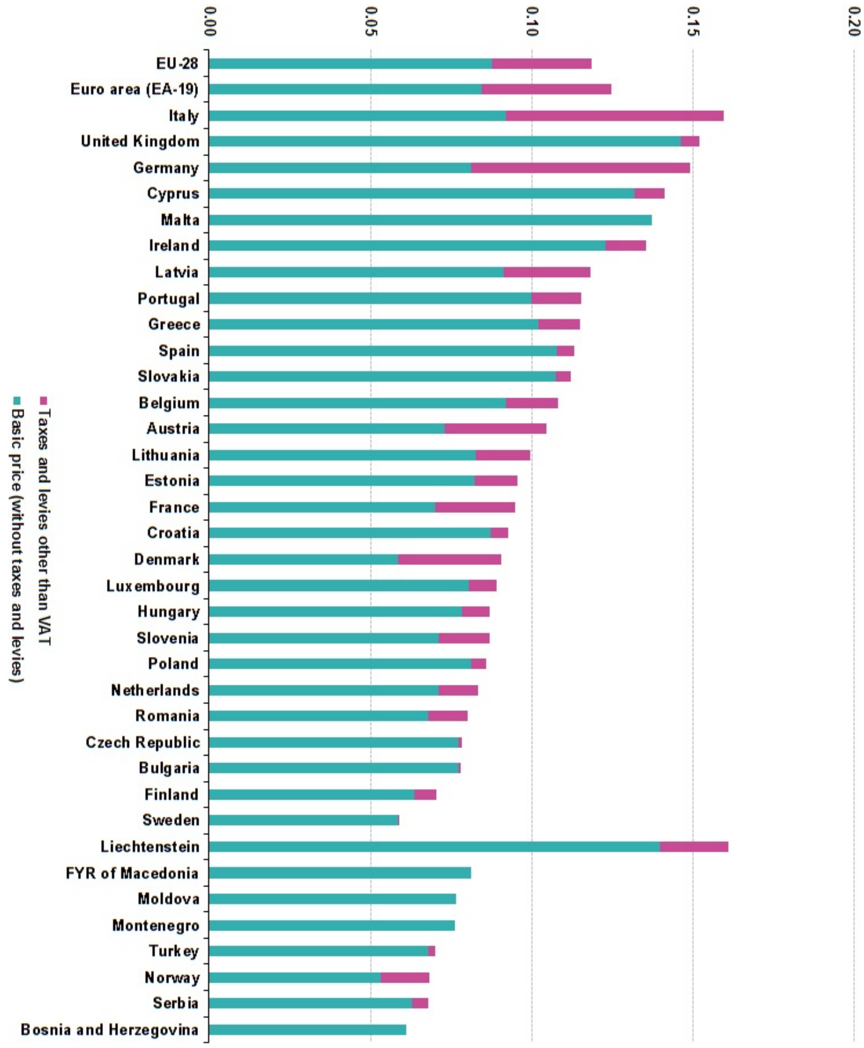

FIGURE D.1: Electricity prices by country in the EU for medium sized industry 2015, €/kWh [10]

Appendix E

Carbon Taxes in the EU

Table E.1: Carbon taxes by country [12]

Country	Tax Rate	Upcoming Changes
Denmark	31 \$/ton CO_2 (2014)	
Finland	35 €/ton CO_2 (2013)	
France	7 €/ton CO_2 (2014)	30 €/ton CO_2 (2017)
Iceland	10 \$/ton CO_2 (2014)	
Ireland	20 €/ton CO_2 (2013)	
Norway	4-69 \$/ton CO_2 (2014)	
Sweden	168 \$/ton CO_2 (2014)	
Switzerland	68 \$/ton CO_2 (2014)	
UK	15.75 \$/ton CO_2 (2014)	

Appendix F

Infinity Turbine Price List

Infinity Turbine LLC • Price List Prices Valid Until May 30, 2016 20160314 A

All Prices U.S. Dollars unless otherwise noted. Shipping and crating is not included.
Specifications are subject to change. Final data, dimensions, and specifications will be on invoice or contracts.
Any special prices will be given on formal quotes and invoices. Large systems require a grid-tie interconnection device to connect to the grid. All turbines, systems, and plans are sold "as-is."

ORC Turbine Generator Only • Working psi up to 200 psi • Compressed Air • R245fa

2015 Model	Mag Coupling Shaft Size - Max Power	Ports (NPT) Inlet/Outlet	Dimensions inches(metric)	Turbine With Generator
IT100	ROT 15 Turbine 50-75 kW direct drive	4" Input		$70,000 AC Gen
IT250	ROT 24 Turbine 300 kW direct drive	8-10" Input		$130,000 AC Gen

CO2 ORC Compete Systems • Uses Liquid CO2 not included • Working pressure up to 5,000 psi 30-65 C Temp
This is a ORC System - Not a Brayton Cycle System

Model	Power Output (turbine-generator)		Heat Exchanger	BTU input	Flow GPM	Price
IT10	Using IT10 CO2Turbine	DC up to 10 kW	Flat Plate	400,000	Up to 20 GPM	$100,000

ORC Compete Systems • Uses R245fa not included • Working pressure up to 200 psi 80-110 C Temp
ORCSystems with AC Generator require grid tie device for connection to grid and PLC for operation

Model	Power Output (turbine-generator)		Heat Exchanger	BTU input (kWt)	Flow GPM(lpm)	Price
IT50	Radial Outflow Turbine	AC Gen 50 kW	Shell / Tube	2.5 mmbtu (733 kWt)	140 gpm (530)	$200,000
IT100	Radial Outflow Turbine	AC Gen 100 kW	Shell / Tube	4 mmbtu (1172 kWt)	280 gpm (1060)	$250,000
IT250	Radial Outflow Turbine	AC 250 kW Net	Shell / Tube	11 mmbtu (3,224 kWt)	500 gpm	$500,000

ORC Turbine Only Plans

Model	Plans for ORC System	Consulting	Email/Skype Support	Additional Drawing	Price
ROT06 Turbine Only	ROT06 Turbine Blueprints		Optional	$60 /hr	$10,000
ROT15 Turbine Only	ROT15 Turbine Blueprints		Optional	$60 /hr	$20,000

Hourly Consulting: $300/hr. $1,600 per day on location plus all travel expenses. Monthly discounts available.

FIGURE F.1: ORC price list from Infinity Turbine

Appendix G

Investment Cost Allocation

	Ex-Works	Transport	Assembly	Total
Recovery heat exchanger	200	15	15	230
2 ORC modules	500	10	10	520
Cooling tower	100	5	5	110
Electrical auxiliaries	40	5	5	50
Mechanical auxiliaries	50	5	5	60
Civil works	0	0	40	40
Project costs	0	0	0	70
Total	890	40	80	1 080

FIGURE G.1: IC allocation for a 200 kWe net WHR from a coke plant with thermal input of 2,5 MWth. Heat of the exhaust gases are recovered through an intermediate loop. All prices are in k€[1]

	Ex-Works	Transport	Assembly	Total
Recovery heat exchanger	10	5	5	20
ORC module	400	5	10	415
Cooling tower	25	5	5	35
Mechanical auxiliaries	10	5	5	20
Civil works	0	0	20	20
Project costs	0	0	0	30
Total	445	20	45	540

FIGURE G.2: IC allocation for a 145 kWe net WHR from a biogas engine with thermal input of 760 kWth. Heat from the exhaust gases are recovered through direct heat exchange. All prices are in k€[1]

Appendix H

Dual Heat Source Cost Estimate

Cost Description	% of Purchased Equipment Cost	Amount USD	Amount GBP
Direct Costs			
Purchased Equipment Cost (ORC Module)	100.00	437,898.58	282,223.89
Cost of Charged R245fa Working Fluid	0.57	2,485.00	1,601.57
Cost of Installation, Material and Labour	4.78	20,928.98	13,488.64
Cost of Control System	2.65	11,591.43	7,470.63
Cost of Grid Connection	39.60	173,571.98	111,866.45
Indirect Costs			
Cost of Engineering	15.00	65,684.79	42,333.58
Cost of Freight	0.50	2,200.00	1,417.89
Import Duty & Tax	2.70	11,823.26	7,620.04
VAT = 20% (of ORC module + Import Duty & Tax)		89,944.37	57,968.79
Total Capital Investment		**816,128.39**	**525,990.59**

Exchange Rate GBP1 = USD1.5516= EUR1.1621[1]

FIGURE H.1: Estimation of total IC for a 199.40 kW dual heat source ORC system [11]

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