

EXECUTIVE SUMMARY

The aim of this project is to study the viability of a 1MW waste heat power plant. There is a lot of waste heat available in the port of Rotterdam and it is usually released into the environment. Alternatively, it is used for a District Heating network. If we can manage to produce electricity (with profits), we then have a CO₂-free power plant.

The design conditions are: a hot source of 100°C temperature and the ocean as cold source. The temperatures of the ocean change throughout the year so we will use 2 models: one for summer and the other for winter.

The two most suitable technologies are Rankine cycle (using organic fluids) and the Kalina cycle. The first is also called Organic Rankine Cycle (ORC) and it uses organic fluids with lower boiling points (compared to water) which is appropriate for this application.

The working fluid for the Kalina cycle is a water/ammonia mixture and this is the key to its superior performance: its adjustable boiling point allows for a better exchange of heat, both in the condenser and the heat exchanger.

Regarding the ORC working fluids, we were left with three potential candidates after eliminating the compounds with non-suitable boiling points and the candidates that can damage the environment. The three candidates were R123, isopentane and pentane, in decreasing order of efficiency. However, we chose the second best (isopentane) because it contributes 7 times less to global warming.

We achieved similar results with the thermodynamic analysis: less than 10% thermal efficiency and around 35% exergetic efficiency. It is important to use the concept of exergy because it allows us to compare magnitudes of different quality: electricity is first-grade energy while heat is second-grade energy.

The economic methodology that was used was estimation from prior projects or other studies. Both ORC and Kalina systems achieved similar results: 6% IRR and around 200 k€ of NPV. The analysis was performed using 85 €/MWh as the price of electricity but we also found that we could sell it cheaper, up to 82 €/MWh. The idea of selling electricity close to the generation site is aligned with a decentralized generation strategy that seems to be the trend for the future.

In conclusion, this project is profitable and it would save around 2500 tons of CO₂ per year.





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GLOSSARY

AETEG	Automotive Exhaust ThermoElectric Generator
CHP	Combined Heat and Power
COE	Cost of Electricity produced
CS	Cold Source
GWP	Global Warming Potential
HICP	Harmonised Index of Consumer Prices
HS	Hot Source
ICSC	International Chemistry Safety Card
IRR	Internal Rate of Return
NPV	Net Present Value
O&M	Operation & Maintenance
ODP	Ozone Depletion Potential
OTEC	Ocean Thermal Energy Conversion
ORC	Organic Rankine Cycle
RES	Renewable Energy Sources
SST	Surface Sea Temperature
TEG	ThermoElectric Generator
WF	Working Fluid
η_I	First law efficiency
η_{II}	Second law efficiency (or exergetic efficiency)



List of units used

Dimension	Abbreviation	Name
Energy	toe	tons of equivalent oil
	TWh	TeraWatts-hour
	GWh	GigaWatts-hour
	MWh	MegaWatts-hour
	kWh	kiloWatts-hour
	GJ	GigaJoule
Enthalpy	kJ/kg	kiloJoule per kilogram
Money	€	Euros
	c€	Euro cents
	k€	Thousand euros
	M€	Million euros
	\$	Dollars
	c\$	Dollar cents
	k\$	Thousand dollars
M\$	Million dollars	
Temperature	°C	grades Centigrade
Pressure	bar	Bar
Mass	kg	Kilogram
	Mton	Million tons
	lb	Pound

Comment on notation: a comma will be used to separate decimals and a dot to separate thousands.



INTRODUCTION

In Rotterdam there is a lot of waste heat available due to the large amount of industries that operate there: power plants, chemical industries, refineries, etc. This heat has low temperature and it is usually rejected to the surroundings (via water or air). There is District Heating network already in place in the city of Rotterdam that redirects some waste heat into heating the buildings of the city. But the demand varies greatly throughout the year so that in summer there is more waste heat available than in winter. Is there any other way of using the excess heat? Could we use it to produce first-grade energy?

The conventional methods of electricity production through a thermal cycle require high temperatures due to the law of Carnot's efficiency: the higher the difference of temperatures, the higher the efficiency. There is, however, a type of power plant that operates in a narrow range of temperatures: OTEC (Ocean Thermal Energy Conversion), which uses the difference of temperatures between the surface and the depths of the ocean.

The idea for this Master Thesis originated with the following question: could OTEC technology be used in Rotterdam in order to produce electricity from waste heat? If we formulate this idea in a more formal way, we have our research question:

Under which conditions would it be feasible to use waste heat of the companies in Rotterdam in order to produce 1 MW of electricity?

We will use thermodynamics in order to determine the optimum parameters and the efficiencies of the heat-electricity conversion.

And the same industries that produce waste heat could easily be our clients, wanting to buy our carbon-free electricity. Therefore, we will also perform an economic analysis in order to determine whether this type of investment would be profitable.

Finally, we will analyse the impact of such a project into the environment: a heat recovery plant would save carbon dioxide emissions but maybe the working fluids pose a higher threat to the environment.





1 PROJECT BACKGROUND

1.1 Electricity production in the Netherlands

The Netherlands is aiming to comply with the EU directive on renewable energy: 20% share energy from renewable sources in the EU by 2020 [Ref. 1]. However, the directive takes into account that every country has different resources for electricity generation so that every country has a specific target. The EU as a whole will achieve the 20% share by 2020 and the specific target for the Netherlands is 14% (see table 1.1 below).

Year	Share of renewable energy
2007	6,01%
2008	7,46%
2009	8,91 %
2010	9,07 %
2020 target	14%

Table 1.1 – Share of renewable energy in the Netherlands [Ref. 2]

They are progressing towards the target at a very fast pace but so far most of the renewable energy is wind and biomass (see table 1.2, [Ref. 2]).

Hydro energy	105 GWh	0,09 %
Wind energy	3.995 GWh	3,49 %
Incinerators	1.328 GWh	1,16 %
Biomass	3.986 GWh	3,50 %
Biogas (agriculture)	547 GWh	0,48 %
Solar energy	(negligible)	(negligible)
TOTAL	10.390 GWh	9,07%

Table 1.2 – Breakdown of renewable energy in the Netherlands in 2010

We believe that electricity production from waste heat has been overlooked and that it has a great potential that will help to move towards the EU target at an even faster pace.

1.2 Rotterdam: world capital for CO₂-free energy

Rotterdam has a population of around 600.000 people, the second largest city of Netherlands. But it is most famous because of its port. The Port of Rotterdam is the first in Europe and the fourth in the world. The importance of the port does not only lay in the number of tons moved but also in the cluster of industries around it, mostly chemical and petrochemical. The Rotterdam Port Authority describes it as follows:



Rotterdam is one of the main ports and the largest logistic and industrial hubs of Europe. With an annual throughput of 430 million tons of cargo in 2010, Rotterdam is by far the largest seaport of Europe. The port is the gateway to an European market of more than 350 million consumers.

Rotterdam thanks its position to the excellent accessibility via the sea, the hinterland connections and the many companies and organisations, active in the port and industrial complex. The port stretches out over 40 kilometres and is about 10.500 ha (excluding Maasvlakte 2). [Ref. 3]

Annex A.1 contains a list of the extensive industries located in the port area.

These industries release a lot of heat into environment and this waste heat is not used. It has been roughly estimated as of 2 GW of heat production at 100°C [Ref. 4] which would have the potential to save 1 million tons of CO₂. Another more optimistic approach estimates that the amount of recuperable industrial waste heat is up to 29 million GJ (or 8,1 million MWh) in the greater Rotterdam area [Ref. 5].

This aspect (and many others) is being considered by the Rotterdam Climate Initiative (RCI), a programme that intends to align all stakeholders of the Rotterdam-Rijnmond region with the following goals:

Improving the climate for the benefit of people, the environment, and the economy; that is the challenge confronted by the collective initiators; [...]The Rotterdam Climate Initiative creates a movement in which government, organizations, companies, knowledge institutes, and citizens collaborate to achieve a fifty per cent reduction of CO₂ emissions, adapt to climate change, and promote the economy in the Rotterdam region. [Ref. 6]

Some of the other projects of the RCI are: promotion of electric transport, promotion of biofuels, implementation of sustainable city lighting, CO₂ capture and storage, green roofs, environmental education and awareness, etc. Ultimately, Rotterdam aims to be the world capital for CO₂-free energy.

Summing up, Rotterdam is the perfect place to re-use waste heat because:

- There is plenty of waste heat due to the intensive industry
- The city has a comprehensive programme (RCI) that promotes “green” projects

Annex A.2 tells the story of an original use of waste heat: a shrimp farm.



1.2.1 Warmte Bedrijf (the Heating Company)

One could think that the easiest way of using waste heat is to use it as heat. That's why there is already an organisation that collects waste heat from the industry areas and it uses for homes and other businesses (e.g., hospitals) [Ref. 7]. This is the easiest way to handle waste heat but it has a main inconvenience: the demand of heat varies greatly between winter and summer. Therefore, the idea of using waste heat to produce electricity should be regarded as complementary to the work that Warmte Bedrijf is already doing. Moreover, the return temperature of the hot source (after being used to produce electricity) is around 80°C, so it could still be used for domestic heating.

1.3 OTEC as inspiration

The idea for this project came from Ocean Thermal Energy Conversion (OTEC) technology. OTEC is feasible in tropical areas around the equator, where the sea surface temperature (SST) can be as high as 28°C all year round. However, the water temperature several meters below is much colder, around 4°C. From the temperature difference of these two sources, we can generate work and thus, electricity. One of its most interesting features is that it can be a base-load energy source: it does not depend on the weather or any other source of supply – it produces power 24/7.

Obviously, Rotterdam is not located anywhere near the Equator and its water temperature would not allow any OTEC plant. However, Rotterdam has an abundant supply of heat at 100°C (at least) so we should be able to use this potential to produce carbon-free electricity.

There are mainly two types of OTEC plants:

- **Open-cycle OTEC** uses warm seawater as working fluid in a flash evaporation process and its by-product is desalinated water.
- **Closed-cycle OTEC** uses a thermodynamic cycle with an intermediate working fluid.

For our application, we will look into closed-cycle technology because open-cycle presents more technical difficulties [Ref. 8] and desalinated water is not a desirable by-product in the Netherlands. There are basically three thermodynamic cycles that have been proposed for closed-cycle OTEC: Rankine, Kalina and Uehara, each of them named after its inventor.



- **Rankine cycle** is used with organic fluids which have a lower boiling point than water. Therefore, it is called Organic Rankine Cycle (ORC).
- **Kalina cycle** is only 30 years old although it is already in place for commercial power plants. It uses a mixture of water and ammonia as working fluid. Theoretically, its efficiency is over 20% higher than ORC:
- **Uehara cycle** was invented in 1994 and it also uses water and ammonia as working fluid though its theoretical efficiency is higher than Kalina's. [Ref. 9]

Due to the experimental state of the Uehara cycle, we will only look into ORC and Kalina cycle for the waste heat recovery application.

More information about OTEC can be found in Annex B.1: the main milestones. And see Annex B.2 for schematic of Uehara cycle.

1.4 Introduction to Organic Rankine Cycle

ORC is a Rankine cycle that uses organic fluids instead of water/steam as working fluid. These organic fluids usually have lower boiling points so they are used for systems where the hot source temperature is lower than in the normal Rankine applications. Since the temperature of the hot source is lower, the efficiency is also lower than the usual for Rankine cycles. We can see an schematic of ORC in Figure 1.1, extracted from [Ref. 10].

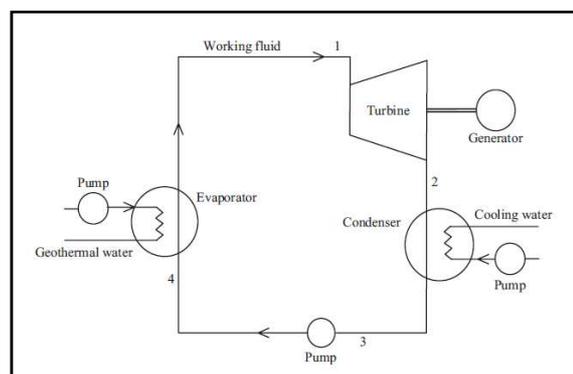


Figure 1.1 – Schematic of Organic Rankine Cycle

Waste heat recovery is only one of the many applications of the ORC. Other current applications are: geothermal power plants, biomass power plants, solar thermal power, Ocean Thermal Energy Conversion (OTEC), solar ponds, micro CHP (Combined Heat and Power), etc.



Figure 1.2 from [Ref. 11] shows a comparison between ORC and other common technologies for heat-to-power conversion.

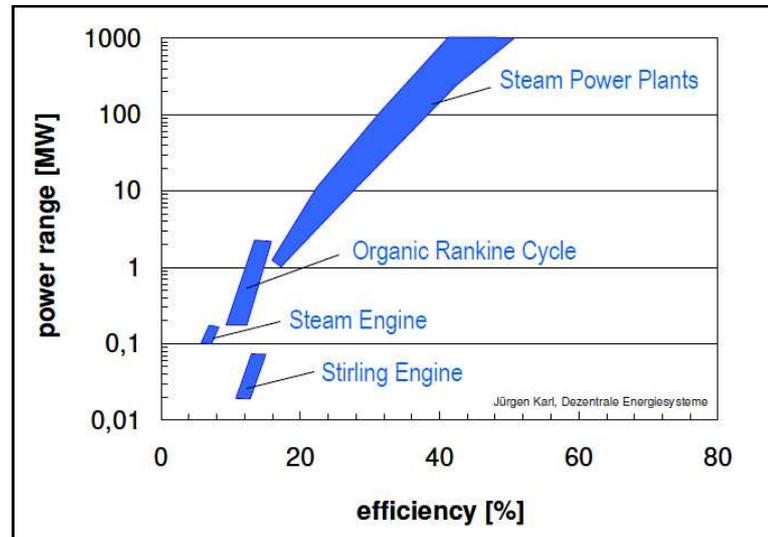


Figure 1.2 – Power range and efficiency of common power machines

We can see that ORC technology is adequate for our objective power: 1MW. And we will address the Stirling engine later, in Chapter 1.7.2.

Annex B.3 contains a list of companies that work with ORC and their range of applications.

1.5 Introduction to Kalina cycle

This cycle is based on the Rankine cycle and uses a mixture of ammonia and water as a working fluid. The simplified diagram of the cycle can be found in figure 1.3 [Ref 12].

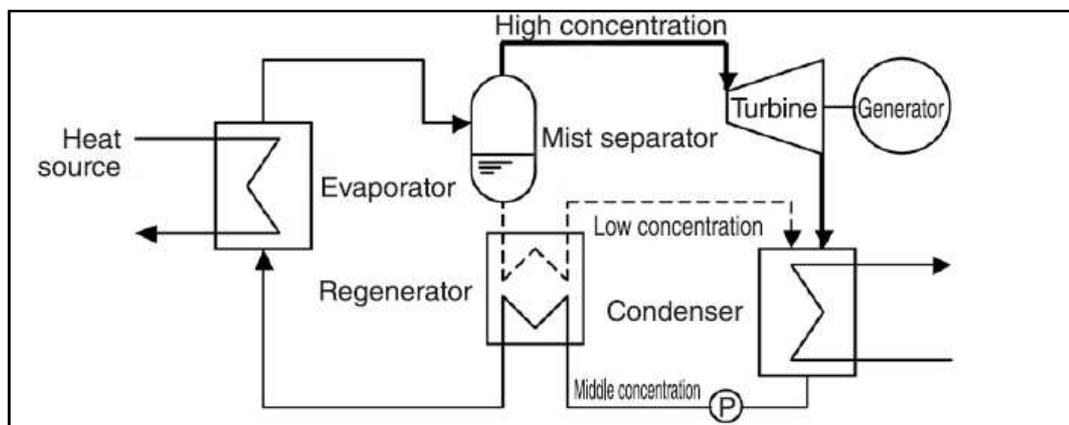


Figure 1.3 – Simplified diagram of Kalina cycle



The working fluid is boiled using the heat given out by the hot source. Next, the fluid enters the separator and divides it into two streams: the stream with high ammonia concentration in vapour phase will expand in the turbine and the stream with low concentration in liquid phase will be used in the regenerator. The two streams merge in the condenser, where the fluid condenses by giving out heat to the cold source. The stream with the middle concentration is heated in the same regenerator and the cycle starts again.

1.5.1 Superior performance compared to ORC

The Kalina cycle uses a mixture of water and ammonia as a working fluid and this is the main reason why it has better performance than ORC. In plain words, it “follows” better the T-Q curve (temperature vs heat) and the T-H (temperature vs entropy) so that it is able to extract more heat from the same source. Figures 1.4 and 1.5 accurately reflect this fact, extracted from [Ref. 13] and [Ref. 14].

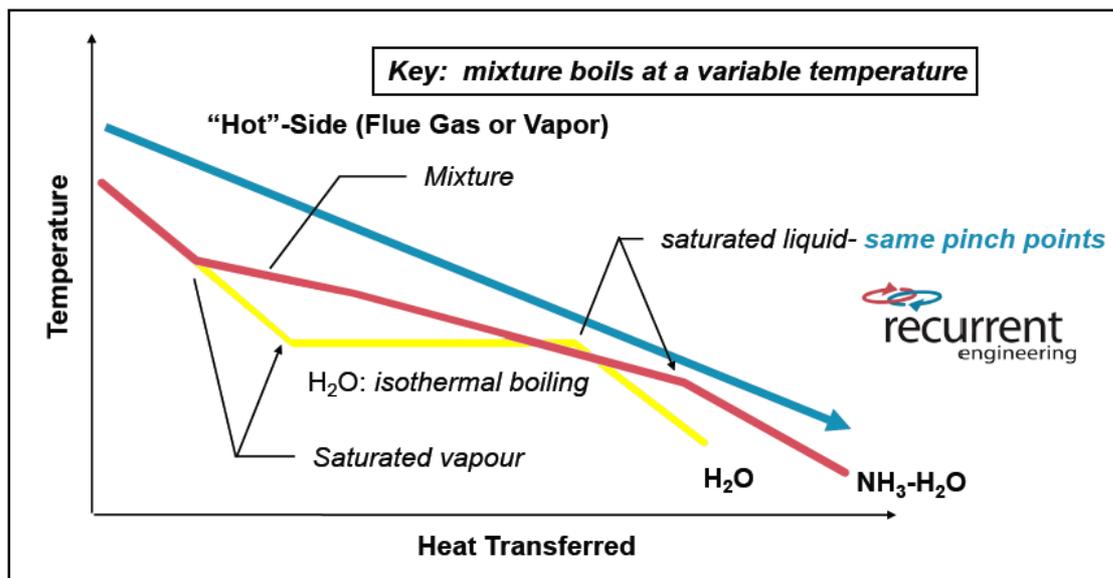


Figure 1.4 – Improved heat transfer of Kalina compared to ORC



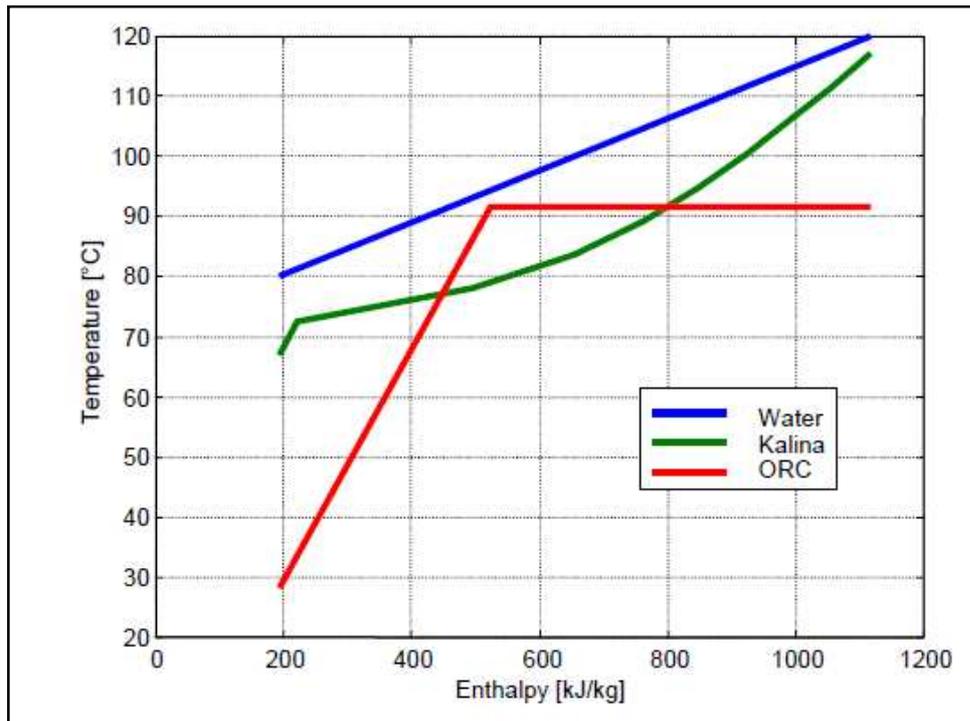


Figure 1.5 – Boiling curves for Húsavik

The same happens in the condenser, as shown in Figure 1.6 from [Ref. 15].

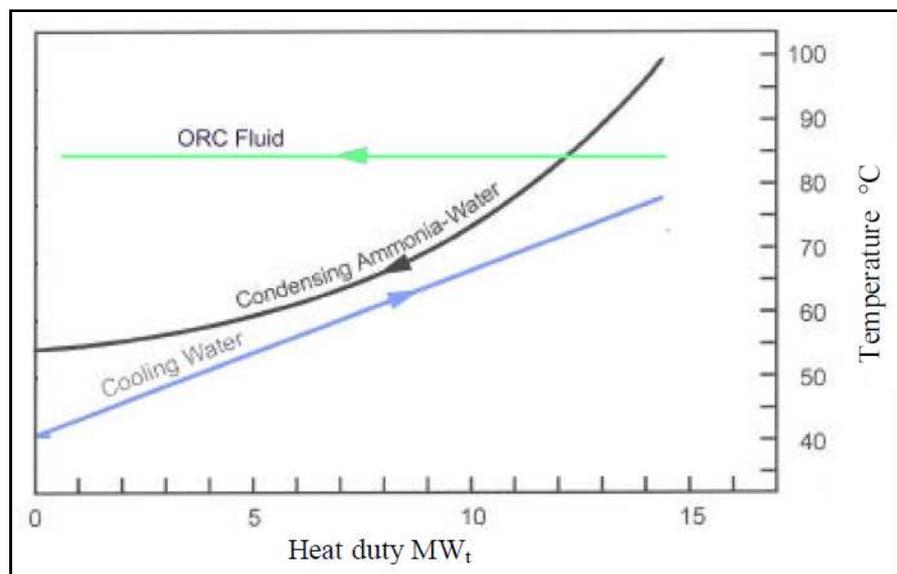


Figure 1.6 – The condense process of ammonia-water mixture and an ORC fluid

Several literature sources agree that Kalina cycle is 10-40% more efficient than ORC: higher power output with the same conditions [Ref.10, 16, 17 and 18]. The latest field experiment to confirm this superior performance was carried out by the Industrial Technology Institute (belonging to Taiwan’s Bureau of Energy) in the geothermal field of Qingshui [Ref. 19].



1.6 History and development of Kalina cycle

The Kalina cycle was developed by Dr. Alexander Kalina; it was first published in 1984 and it was patented in 1987 by the company that he created, Exergy Inc.

The Canoga Park Demonstration Plant in California was the first plant using the Kalina cycle. It ran between 1991 and 1997 for a total amount of 9.000 h of operation [Ref.16]. It used turbine inlet vapor at 515°C, which is much higher than the usual waste heat available. It proved, however, the viability of the cycle.

Another demonstration was carried out in Fukuoka (Japan) where the Kalina cycle was used in an incineration plant. 200 tonnes of municipal solid waste are burnt daily and it supplied 4.5MW of electric power between 1998 and 1999 [Ref. 20].

The first commercial plant was also built in Japan in 1999 by Sumitomo Metals Kashima Steelworks. It produces 3.1 MW using waste heat from the steel plant. The hot source is water at 98°C [Ref 12 and 13].

The first geothermal power plant was built in 2000 in Húsavík, Iceland. It uses hot homoeothermal water at 124°C and cold water at 4°C and the net electrical power is 2,0 MW. It is a Combined Heat and Power plant so the remaining heat from the hot source (at 80°C) is used for District Heating of the town [Ref. 17].

In 2002 another Waste Heat Recovery plant was built inside the Tokyo Bay Fuji Oil refinery and it yields up to 3,9 MW of electric power [Ref. 16].

In 2009 Siemens built a geothermal plant in Germany, in the town of Unterhaching and the electrical power output is 3 MW. As in the Húsavík case, the rejected hot water was used for District Heating [Ref. 21].

In December 2009 another geothermal plant was built in Germany, in Bruchsal. The operator is EnBW and the contractor was Siemens. The electrical power is 500 kW , the hot source is at 120°C and the mass flow is 24 litres per second of water [Ref. 22].

In 2010 another Kalina pilot plant was built in Taiwan, in the Qingshui geothermal field. It is owned by Shanghai Shenghe New Energy and Resources and it produces 60 kW from a 110°C hot source [Ref. 19].



There is more information of Kalina cycle in the annexes: a list of the current companies involved in Kalina technology (Annex B.4) as well as a list of other Kalina plant projects planned for the coming years (Annex B.5).

1.7 Alternative technologies for waste heat recovery

1.7.1 Thermoelectric generator (TEG)

A thermoelectric generator is a piece of equipment that uses the Seebeck effect to generate electricity from a temperature difference. It is the opposite of the thermocouple, that uses electricity to determine temperature differences.

Although the discovery of the Seebeck effect dates from 1821, its application in thermogenerators (an alternative way of naming them) is still in a very experimental state. A lot research is currently focused in AETEGs (Automotive Exhaust ThermoElectric Generators) – they want to use the high temperatures of the exhaust gas of automobiles to produce electricity and thus reduce fuel consumption [Ref. 23, 24, 25]. The advantages of TEGs are that they use very little space and that there are no rotating parts because the conversion is direct from heat to electricity. The main disadvantage is its high price and its low efficiency, around 5%.

This type of technology will not be considered in this study due to its experimental state.

1.7.2 Stirling engine

It is named after its inventor, Robert Stirling, who patented it in 1816. They present good efficiencies – in fact, they are the closest that we can get to an ideal Carnot cycle.

However, as already shown in Figure 1.2, Stirling engines have much lower power output ranges. For example, GenoaStirling s.r.l. offers models ranging 0,35 kW to 7 kW [Ref. 26]. One of its most popular applications are solar dishes and in these have individual Stirling engines between 5 and 50 kW of power. If we want 1MW, we would need many small Stirling engines or a big one; but Stirling engines are more competitive below 100kW. In addition, their capital costs are much higher than ORC or Kalina's.

In conclusion, Stirling engines will not be considered in this study.



1.8 Reliability of supply

In this study we are supposing that we have an unlimited supply of waste heat. In reality, we would have to reach an agreement with industrial plants; their waste heat becomes our hot source. Therefore, the plant output depends on the availability of waste heat.

We do not foresee any major issue here because most big industrial companies work uninterruptedly; usually the stop/start-up sequence is very expensive, so it is avoided by never stopping. Moreover, there is plenty of waste heat available in the Rotterdam area (as already discussed in Chapter 1.2) so we can assume that the supply of waste heat is very reliable.

This reveals an advantage in front of fossil fuel power plants. Europe has to import most of the fossil fuels and it is at the mercy of the prices that other people set.

The main advantage in front of wind and solar power is that waste heat is not weather-dependent. Wind and solar power outputs vary greatly depending on the weather conditions; we would not have this problem.



2 PROJECT DEFINITION

2.1 Initial conditions

The original research question was formulated in the Research Proposal as:

Under which conditions would it be feasible to use waste heat of the companies in Rotterdam in order to produce 1 MW of electricity?

We have already announced that the objective electric power is 1MW and we now need to define other variables that will be representative of the chosen location, Rotterdam. And we also need to define the efficiencies of the equipment. Therefore, we are going to define a set of fixed (or initial) conditions.

1) The objective power generated will be 1MW.

Borgert and Velásquez realized an exergoeconomic optimization of a Kalina absorption power cycle [Ref. 27] and they determined that the optimum power output in order to minimize costs was 977,875 kW. We will round this figure up to 1MW.

Another reason to choose 1MW is that it is easy to compare.

- When compared to wind power, we find that a regular wind turbine produces around 1MW electric power as well.
- When compared to nuclear power plants, we see that those easily reach 1GW of installed power; so our 1MW power plant would produce 0,1% of a nuclear plant.
- When compared to household electricity consumption, we can see that a 1MW plant would supply electricity for around 2.000 Dutch households (see Annex C for more detail).

2) The pressures for the Hot Source (HS) and Cold Source (CS) will be atmospheric: 1 bar.

We chose this to avoid complications like adding pumps to increase the pressure of the HS or the CS.

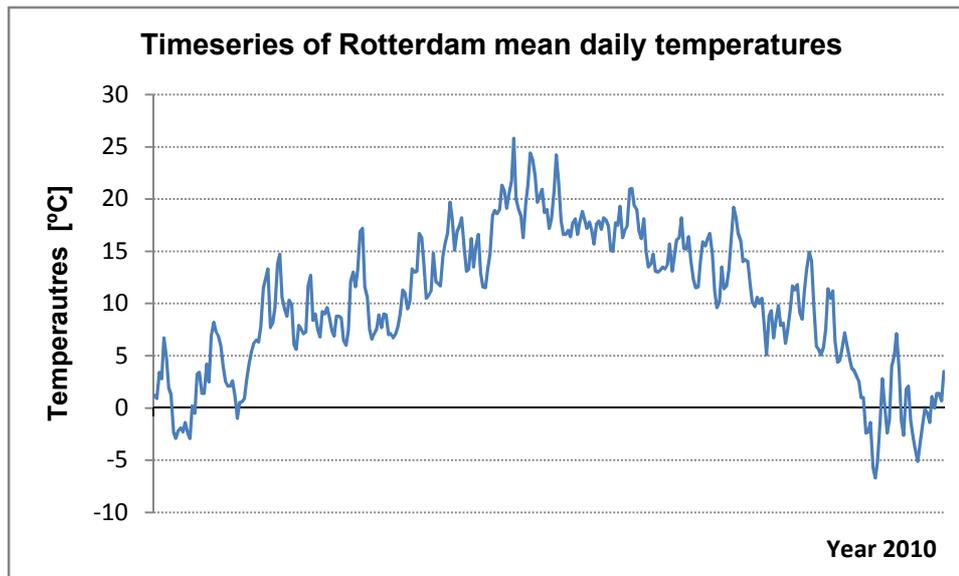
3) The hot source temperature will be 100°C.

The reason for this value is the above mentioned estimation about the available heat source at 100°C in the Rotterdam area [Ref. 4].



4) The air temperature (of the environment) will have two values: -2°C for winter and 20°C for summer.

This data was extracted from the KNMI¹ [Ref. 28] database, from the Rotterdam weather station (number 344) and we have plotted it in two graphs. Graph 2.1 shows the daily mean temperatures of year 2010: we can see that the lowest was -6,7°C on December the 2nd and the highest value was 25,8°C on July the 2nd.



Graph 2.1 – Rotterdam mean daily temperatures in year 2010

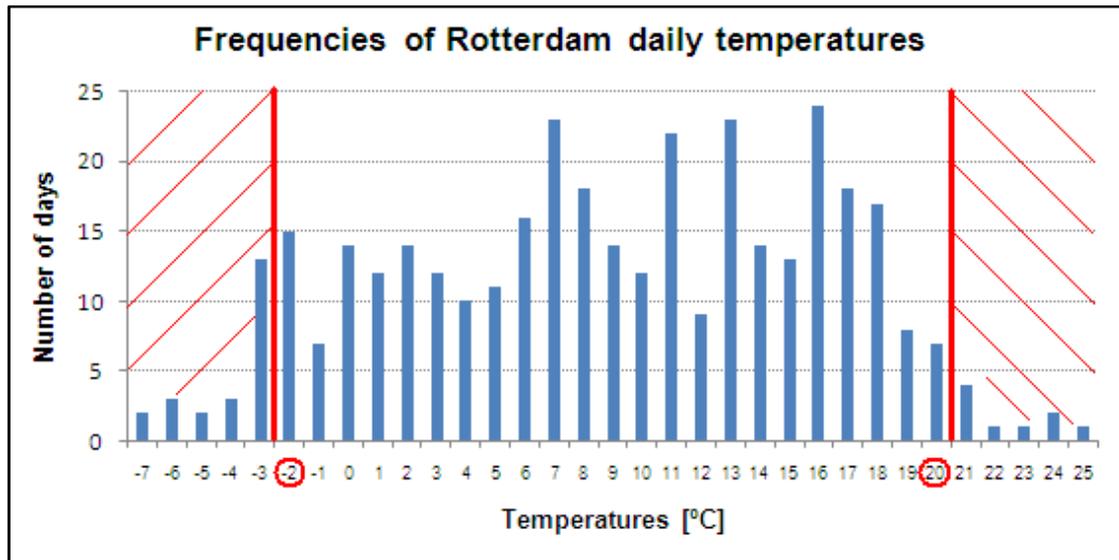
We want to find a representative temperature for winter and summer so we decided to find values that would exclude the 5% coldest days and the 5% warmest days. These values are -2°C for winter and 20°C for summer (see table 2.1 and graph 2.2).

Number of days over 20°C	16	4,4%
Number of days below -2°C	23	6,3%

Table 2.1 – Temperatures that eliminate (approx.) 5% on the sides

¹ KNMI: Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)





Graph 2.2 – Distribution of temperatures in year 2010

The reason why we need to define the temperatures of the environment is that we will calculate the exergy values in our thermodynamic simulation. And exergy is always calculated in relation to the conditions of the environment.

5) The cold source temperature will have two values, corresponding to the average winter and summer Sea Surface Temperatures (SST): 4°C and 20°C.

The data was retrieved through the KNMI, from the NOAA (National Oceanic and Atmospheric Administration) weekly archives [Ref. 29].

- The hottest week of the year was the 34th and the average value was 21,1°C; it is rounded down to 20°C.
- The coldest week of the year in 2010 was the 6th and the average value was 3.3°C; it is rounded up to 4°C.

6) The equipment used will have losses.

The values of the losses have been taken from three articles of the literature [Ref. 10, Ref. 30 and Ref. 31]:

- The mechanical efficiency of the rotating equipment is 90%.
- The isentropic efficiency of the pump is 75%.
- The isentropic efficiency of the turbine is 85%.
- The generator efficiency is 95%.
- The pressure loss in the heat exchanger and condenser is 5%.
- The pipes losses are 5kJ/kg for the WF and 10 kJ/kg for HS and CS.



The summary of this conditions can be found in table 2.2:

CONDITIONS	Value	Dimension
Objective power	1	MW
Hot Source Pressure	1	bar
Cold Source Pressure	1	bar
Hot Source temperature	100	°C
Air temperature – summer	20	°C
Air temperature – winter	-2	°C
Cold Source temperature – summer	4	°C
Cold Source temperature - winter	20	°C
Equipment losses	(several)	%

Table 2.2 – Summary of initial conditions

2.2 Thermodynamic simulation

For every possible technology (and working fluid) we will simulate twice: one with summer conditions and another with winter conditions. The mass flow of the HS and WF will remain the same regardless of the season but the CS mass flow will always be higher in summer because the temperatures of the ocean are higher – we need more mass flow to retrieve the same amount of power with lower temperature differences.

2.2.1 Software: Cycle-Tempo

Cycle-Tempo is a computer program developed by TU Delft (Delft University of Technology). The program is, as described by their authors, “a modern tool for the thermodynamic analysis and optimization of energy systems” [Ref. 32]. Cycle-Tempo is used with a built-in database called FluidProp, also developed by TUDelft [Ref. 33]

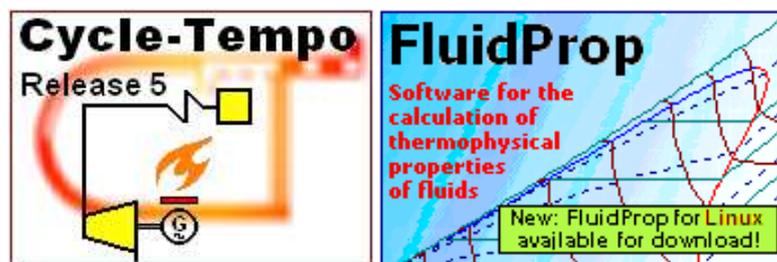


Figure 2.1 – Cycle-Tempo and FluidProp logos



The source of the fluid data is as follows:

- For water/steam, the International Association for Properties of Water and Steam (IASPWS)
- For refrigerants and organic fluids, the National Institute of Standards and Technologies (NIST), see Annex D for more details.
- For ammonia/water mixtures, the Equations of State for Ammonia-Water Mixtures by Ziegler and Trepp [Ref. 34].

As per the history of the software, it was created in 1975 and it has been updated regularly; the last update was release 5.0 in 2002. [Ref. 35] contains a list of references and published works that cite one or more components of Cycle-Tempo: a total of 86 since year 1991.

2.2.2 Optimisation method

No optimisation function will be used. We will use a first set of conditions using previous studies that allow for a successful simulation. Then, we will proceed to find the local optimums by combining a couple of variables: an independent with a dependent variable.

An example is given with the variables for the ORC (it is much simpler than Kalina cycle because it has less elements). First, we list all the variables of the simulation (Table 2.3).

Mass flows	HS	
	CS	
	WF	
Temperatures	HS	Outlet
		Inlet
	CS	Outlet
		Inlet
	WF	T1 (Turbine outlet)
		T2 (Pump inlet)
		T3 (Pump outlet)
T4 (Turbine inlet)		
Pressures	HS	
	CS	
	WF	High (pump to turbine)
		Low (turbine to pump)
Electric power		

Table 2.3 – List of thermodynamic variables for the ORC system



- The fixed variables are shown in grey – these correspond to the initial conditions that we had already set in Chapter 2.1.
- The variables that we will control are shown in red.
- The variables that will be auto-calculated by the program are shown in orange.

2.2.3 Sankey diagrams

Sankey diagrams are very useful to represent flows and we will use them to show energy and exergy flows of the systems. The program that was used to draw them is *e!Sankey*.



Figure 2.2 – Logo of *e!Sankey*®

2.3 Evaluation criteria

In order to decide whether the project is worth being implemented and then, which technology is better, we need to define a set of evaluation criteria. We will not only consider the thermodynamic aspect, but also the economic aspect and the safety of the project.

1) First law efficiency

This is the most common way of evaluating projects: the ratio between useful power and gross power (Eq. 2.1).

$$\eta_I = \frac{\dot{W}_{OUT}}{\dot{Q}_{IN}} = \frac{\dot{W}_e}{\dot{Q}_H} \quad (\text{Eq. 2.1})$$



The downside of this ratio is that it compares energies of different quality: electric energy is first-grade energy while heat is second-grade energy. Plus, there is no way of knowing how useful is the available heat. This is why we will also use a second efficiency ratio.

2) Second law efficiency

The second law efficiency is also called exergetic efficiency because it compares the useful exergy with the gross exergy input (Eq. 2.2)

$$\eta_{II} = \frac{EX_{OUT}}{EX_{IN}} = \frac{\dot{W}_e}{EX(\dot{Q}_H)} \quad (\text{Eq. 2.2})$$

We should remember that the value of the exergy of electric power is equal to the value of the electric power because electricity is the highest quality of power. And when calculating the exergy of the hot source, we will be taking into account the temperature of the hot source in relation to the temperature of the environment.

3) IRR, NPV and payback

We will also look into the financial aspects because this is an investment: Internal Rate of Return (IRR), Net Present Value (NPV) and the payback time. The criteria used to evaluate the profitability are: positive NPV, an IRR higher than the interest rate and the lowest payback time.

4) Safety of working fluids

There are several aspects to take into account regarding safety: flammability, toxicity (for humans and for the environment), explosiveness, etc. In the end it is difficult to say whether one fluid is safer than another so we will just characterize them.

The summary of the above-mentioned criteria can be found in Table 2.4:

Criteria	Target
First law efficiency (η_I)	As high as possible
Second law efficiency (η_{II})	As high as possible
NPV	Positive
IRR	Higher than the interest rate
Payback	As low as possible
WF safety	As safe as possible

Table 2.4 – Summary of evaluation criteria



Chapter 7 is a comparison of the two proposed technologies: ORC and Kalina. We will use these evaluation criteria and also some other characteristics.

2.4 Economic analysis methodology

2.4.1 Power plant costs

The best way to calculate the cost of the project is bottom-up: calculating the cost of the individual components and the contracting. However, this requires a level of detail that is not needed in this preliminary study. The methodology that was then used to estimate the cost of the 1MW power plant is extrapolation. The sources for the extrapolation are:

- costs of previous plants (both ORC and Kalina)
- capital costs (€ per kW power installed) from articles and other studies

In conclusion, we will be dealing with a very rough estimate of the costs of the plant.

And since we will be dealing with economic data that dates several years back, we will need to update this figures and/or convert them if they are expressed in dollars. The details of the update and/or conversion can be found in Annexes E.1 and E.2.

2.4.2 O&M costs

We will also estimate the Operation and Maintenance (O&M) costs for the power plant. We will use the same value for both power plants (ORC and Kalina) because it does not differ much and it is .

The first source is Lovekin [Ref. 36], who estimated in 2005 that geothermal power plants have O&M costs of 2,5 c\$/kWh. Once converted and updated, the costs would be of 2,2 c€/kWh. We established that our plant would have a 75% utilisation factor, so it would produce 6.570 MWh. The O&M cost would then be around 150.000 € annually.

We have a second “source”: a rule of thumb - O&M costs equal to around 2% of the total power plant costs [Ref. 38]. We will later see that the estimated plant costs are 1,5 and 2,25 M€, so the O&M costs would be between 300 k€ and 450 k€.



The third and last source is [Ref. 38] that an ORC plant would spend \$200.000 per year in maintenance. This figure becomes around 150.000 k€/year once converted.

Table 2.5 shows a summary of the sources used for O&M average cost calculation:

Reference number	Source	O&M costs [k€/year]
[Ref. 36]	Lovekin	150
[Ref. 37]	Rule of thumb (1)	300
	Rule of thumb (2)	450
[Ref. 38]	Leslie	150
Average		262

Table 2.5 – Summary of O&M costs by different sources

The average of these four values is 262 k€/year. However, we should consider the fact that Kalina cycle is quite a new technology so our O&M costs might be higher than the costs of ORC. Therefore, we will establish O&M costs of **250 k€/year for ORC** and **300 k€/year for Kalina**.

2.4.3 Electricity price

When considering options to sell our product (in this case, electricity) we could choose to sell it in the wholesale market. However, we believe it would be smarter to sell the electricity in the same place where it was produced, the port of Rotterdam. There are many industries located in the port or close to it, and surely the electricity can be sold there. This way, we can sell the electricity at a final consumer price, not at the wholesale price.

Another advantage of selling electricity close to the place where it has been produced is that it reduces transport losses. This strategy is called decentralized electricity generation, as opposed to the huge power plants that produce a lot of electricity in one location. Other ways of naming it are: on-site generation, distributed generation or dispersed generation. This strategy is favorable to renewable energy because it tends to be more small-scale, like wind power or solar power.

According to Eurostat [Ref 39], the average electricity price in 2010 for industrial consumers was 85 €/MWh while for the domestic consumers it was 126 €/MWh. Since our client(s) will be industrial, the estimated price will be **85 €/MWh**.

More information about electricity prices in the EU area can be found in Annex E.3.



2.4.4 Other economic variables

- Apart from the O&M costs, we will also account for the administration costs. These are estimated to be 60.000 €, which would account for some expenses plus the salary of a full-time worker.
- We have chosen a timespan of 15 years because the equipment is likely to last this much. Energy-related projects would usually have a much longer timespan (e.g. 40 years for nuclear or 30 years for a gas-fired power plant). However, this technology is quite new and the total installed power is also quite low.
- The interest rate has been taken at 5% - it has been rounded up from the 12-month Euribor [Ref. 40] plus 1% (see Annexes E.4 and E.5 for more detail).
- The inflation rate has been taken at 2% because the Bank of Netherlands has been and currently is complying with the ECB directive of keeping inflation below 2% [Ref. 41]
- The corporate tax in the Netherlands is 20% for the first 200 k€ of income [Ref. 42]. In no case our yearly incomes will be higher than this figure.
- The utilisation factor of the power plant has been estimated at 75%². Therefore, the plant will be producing electricity 6.570 hours every year.
- We also have to think about the start-up of the plant. The first year the power plant will be working at 75% of its usual capacity and the second year, at 85%. From the third year on, the plant will be working at 100% capacity, 6.570 hours annually.
- The Netherlands, as most governments of the EU, has several programs to promote “green” technologies. This will not be considered in the body of the project but a more detailed study can be found in Annex E.6.

² Geothermal power plants have utilisation factors up to 90%. The proposed power plant has the potential to achieve this figure but since this is not a widely used technology, we have used a conservative estimate.



3 ORGANIC RANKINE CYCLE

3.1 Cycle-Tempo modelling

Figure 3.1 shows the modelling of the ORC in Cycle-Tempo software:

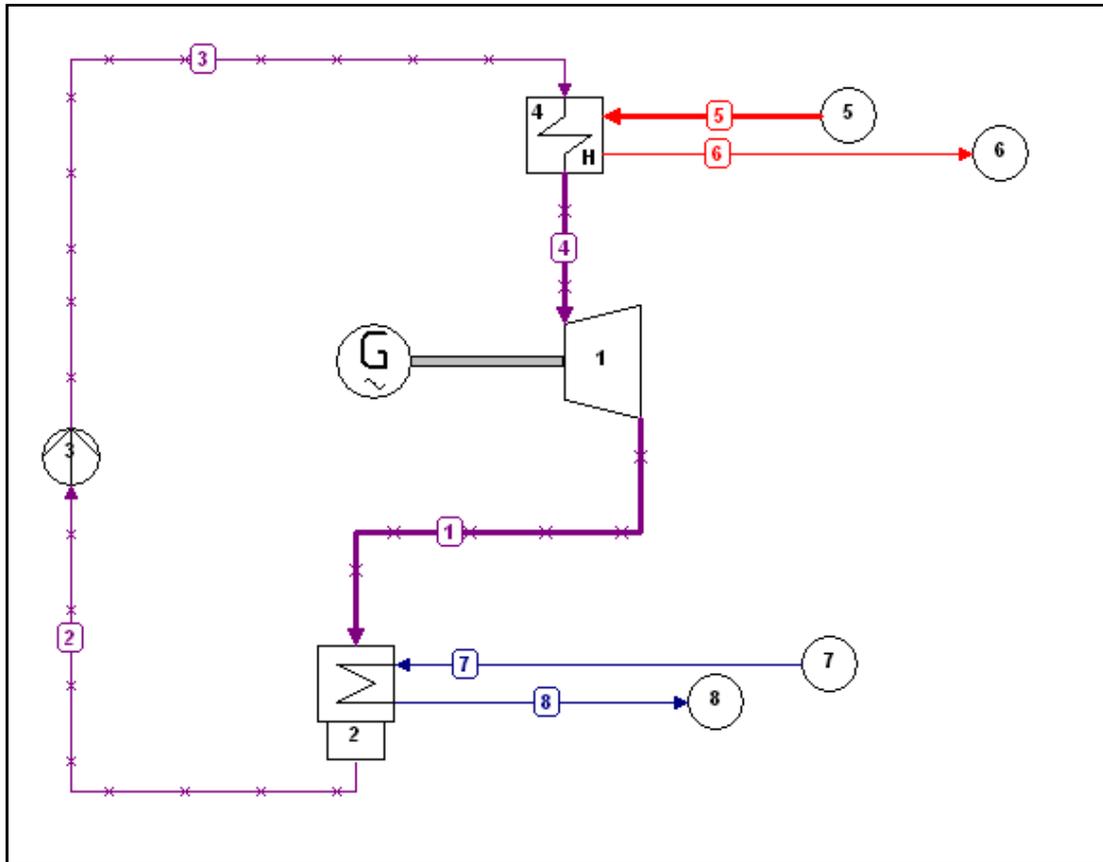


Figure 3.1 – Diagram of the ORC as modelled in Cycle-Tempo

There are four sink/sources (numbers 5 to 8) and their symbol is a circle. The rest are the following apparatus (1 to 4 plus the generator):

- Apparatus 1 is the turbine
- Apparatus 2 is the condenser
- Apparatus 3 is the pump
- Apparatus 4 is the heat exchanger
- Apparatus G is the generator

Colours have been used to differentiate the three circuits:



- The circuit in red is for the Hot Source: source 5 is the HS outlet and source 6 is the HS inlet. Pipe 5 looks thicker because it is a steam pipe (as pipes 4 and 1). The rest are pipes for liquids.
- The circuit in blue is for the Cold Source: source 7 is the CS outlet and source 8 is the CS inlet.
- The circuit in purple is for the Working Fluid (WF).

After the simulation has been done, we can see the thermodynamic state of the system. It shows four properties: pressure, temperature, specific enthalpy and mass flow. At the bottom of Figure 3.2 we can see the legend:

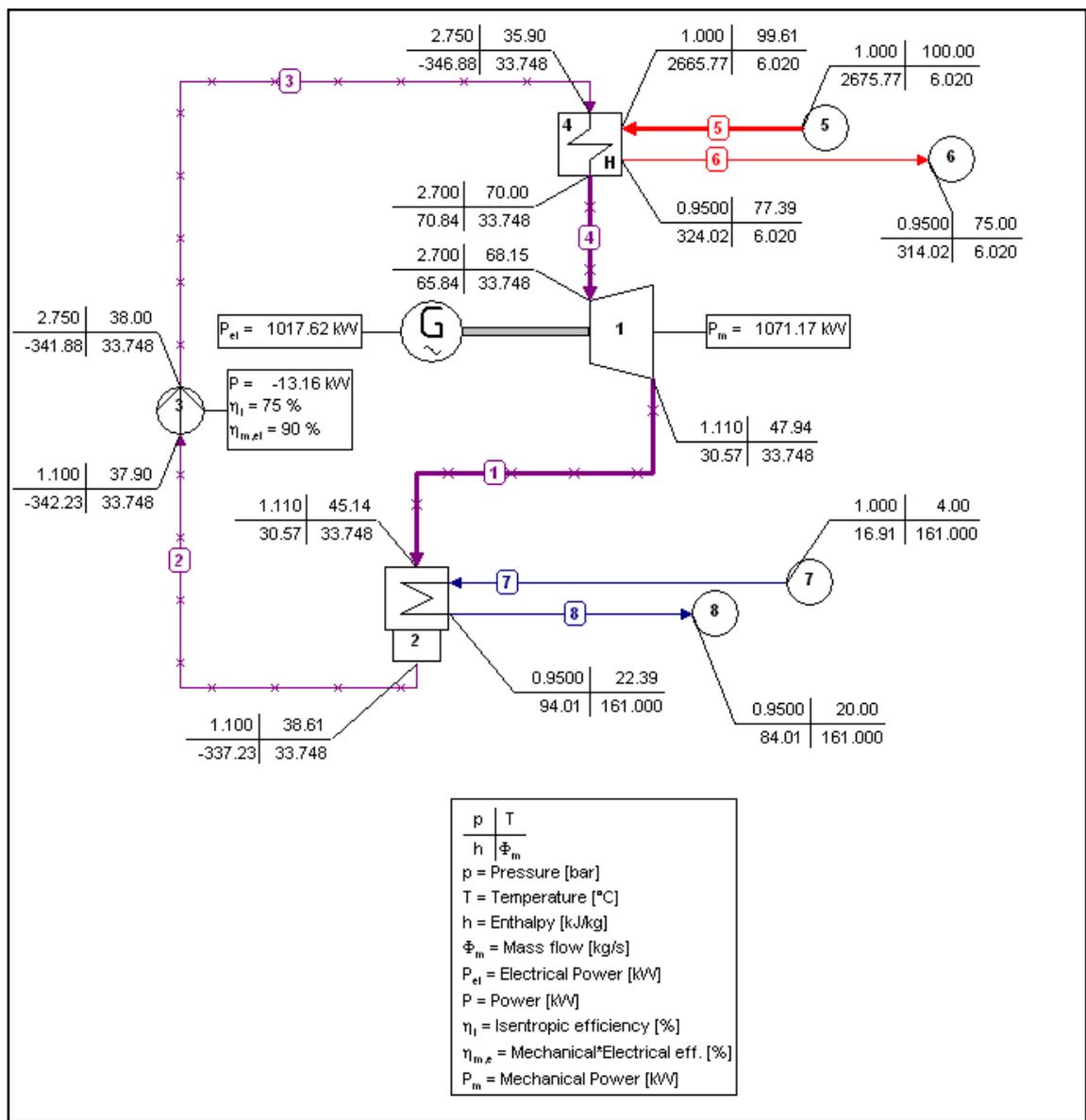


Figure 3.2 – Diagram of ORC with results



3.2 Simplifications

3.2.1 Circulation pumps for HS and CS

In order to simplify the diagram and thus the number of variables, we decided to study whether the circulating pumps for the HS and CS could be neglected. Their only function is to circulate the fluids of the HS and CS and there is no pressure increase. We studied a case of ORC (with n-pentane as working fluid) with pumps and the results are shown in Figure 3.3:

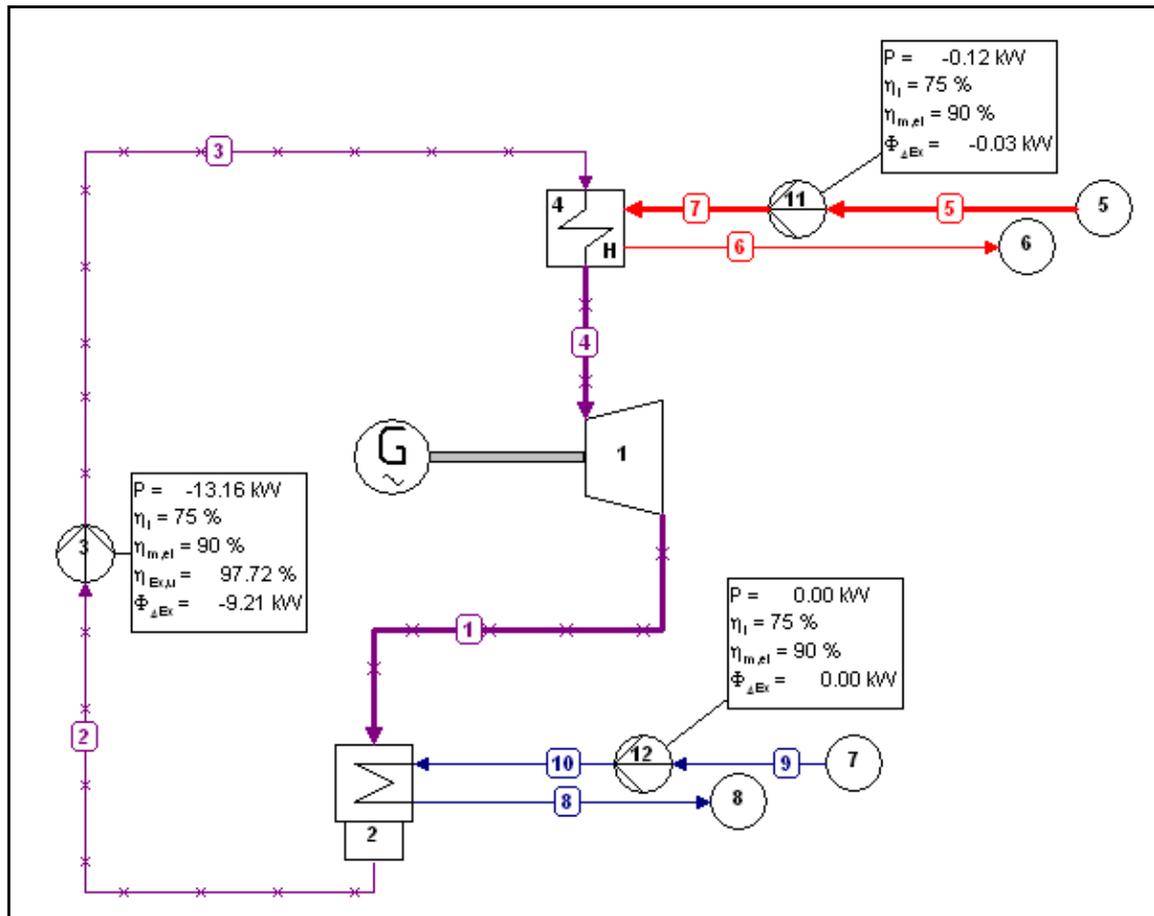


Figure 3.3 – ORC diagram in Cycle-Tempo with circulating pumps for HS and CS

Almost no power was consumed: 0,12 kW for the HS (pump 11) and 0,00 kW for the CS (pump 12). This is negligible compared to the 13,16 kW of the working fluid pump (pump 3) because it is two orders of magnitude inferior.

Almost no exergy was lost: only 0,03 kW for the HS (pump 11) - again two orders of magnitude inferior than pump 3.

In conclusion, these two pumps will be neglected.



3.2.2 Internal Heat Exchanger

The use of an internal heat exchanger has been considered because it usually improves the efficiency of the cycle. It allows for a heat transfer between the turbine outlet flow and the pump outlet flow – it cools the low-pressure flow that needs cooling and it heats the high-pressure flow that needs heating.

However, Dai et al. realized a study of ORC for low grade waste heat recovery and concluded the following:

Adding the internal heat exchanger would not improve the performance of the ORC system under this waste heat condition. [Ref. 30]

Given that the waste heat condition of this study is similar to ours (145°C and around 16 kg/s), we consider this conclusion to be valid for our study as well. Therefore, no internal heat exchanger will be used in the ORC design.

3.3 Selection of ORC working fluid

First of all, we have made a list of all organic working fluids that have been previously used for ORC studies [Ref. 43 to Ref. 49]. These are shown in table 3.1 (next page).

Hung et al. [Ref 45] identified seven important factors of the ORC working fluid: toxicity, chemical stability, boiling temperature, flash point, specific heat, latent heat and thermal conductivity. We will use as first criterion the boiling point.

We need fluids whose boiling point is close to the temperatures in the condenser: approx. 25°C to 40°C. All these potential working fluids have been classified in three categories:

- Fluids with boiling points between 15°C and 55°C (the range of the condenser plus/minus 15°C) will be considered good candidates – they are highlighted in green in table 3.1.
- Fluids with boiling points higher than 60°C and lower than 0°C will be discarded (shown in orange in table 3.1).

The data for the compounds has been taken from the NIST Chemistry Webbook, a comprehensive database [Ref. 50].



Name	Molar mass [g/mol]	Boiling point [°C]
Benzene	78,11	80,4
Butane	58,12	-0,5
Cyclohexane	84,16	353,9
Ethane	30,07	-88,6
Ethylbenzene	106,2	136
Hexane	86,18	69
Isobutane	52,12	-11,7
Isopentane	72,15	27,7
Octane	114,2	125,52
Pentane	72,15	36
Propane	44,1	-43
o-Xylene	106,2	144,4
m-Xylene	106,2	139
p-Xylene	106,2	138,4
R11	137,4	23,6
R113	187,4	47,6
R114	170,9	3,7
R115	154,5	-38,9
R116	138	-78,3
R12	120,9	-29,8
R123	152,9	27,9
R124	136,5	-12,1
R125	120	-48,3
R134a	102	-26,2
R152a	66,05	-24,02
R22	86,45	-41,2
R23	70	-82,1
R236	152	6,19
R245fa	134,1	14,9
R32	52,02	-51,7
R401A	94,44	-32,97
R401B	92,8	-34,67
R401C	101	-28,4
R402B	94,71	-47,4
R404A	97,6	-46,45
R407C	86,2	-43,56
R500	99,31	-33,5
R502	111,6	-45,4
Toluene	92,14	110,6

Table 3.1 – Molar mass and boiling point of ORC working fluids



Now we will look closer into these six (green) best candidates. Chart 3.1 and chart 3.2 show the saturation curves for this six fluids.

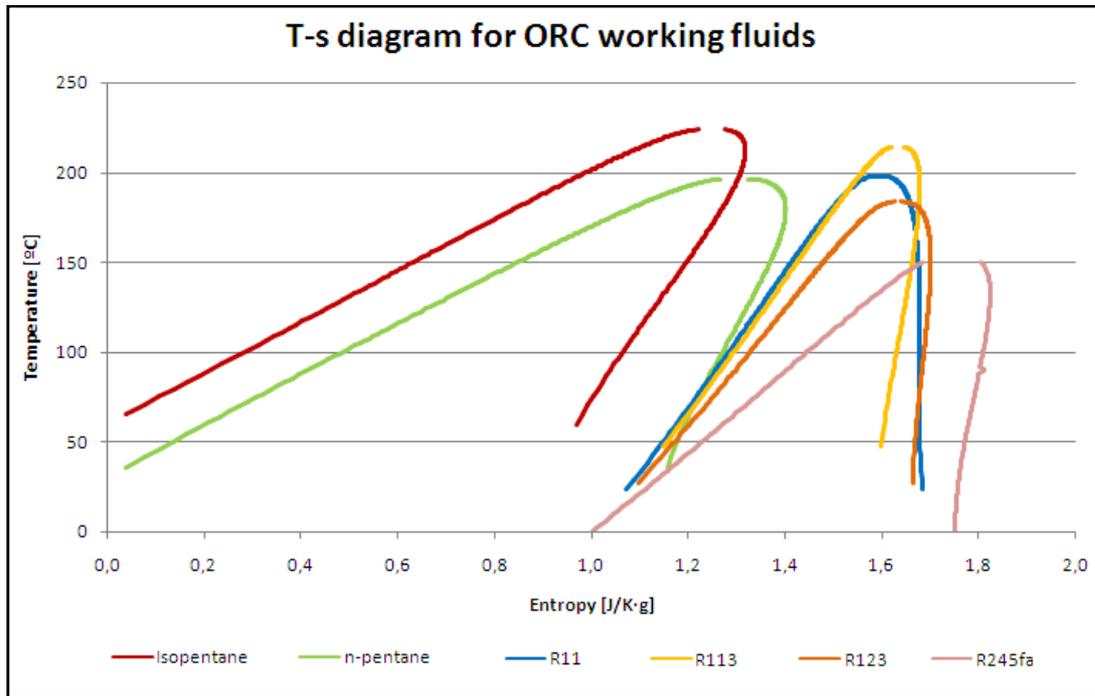


Chart 3.1 – Temperature vs entropy diagram for common ORC working fluids

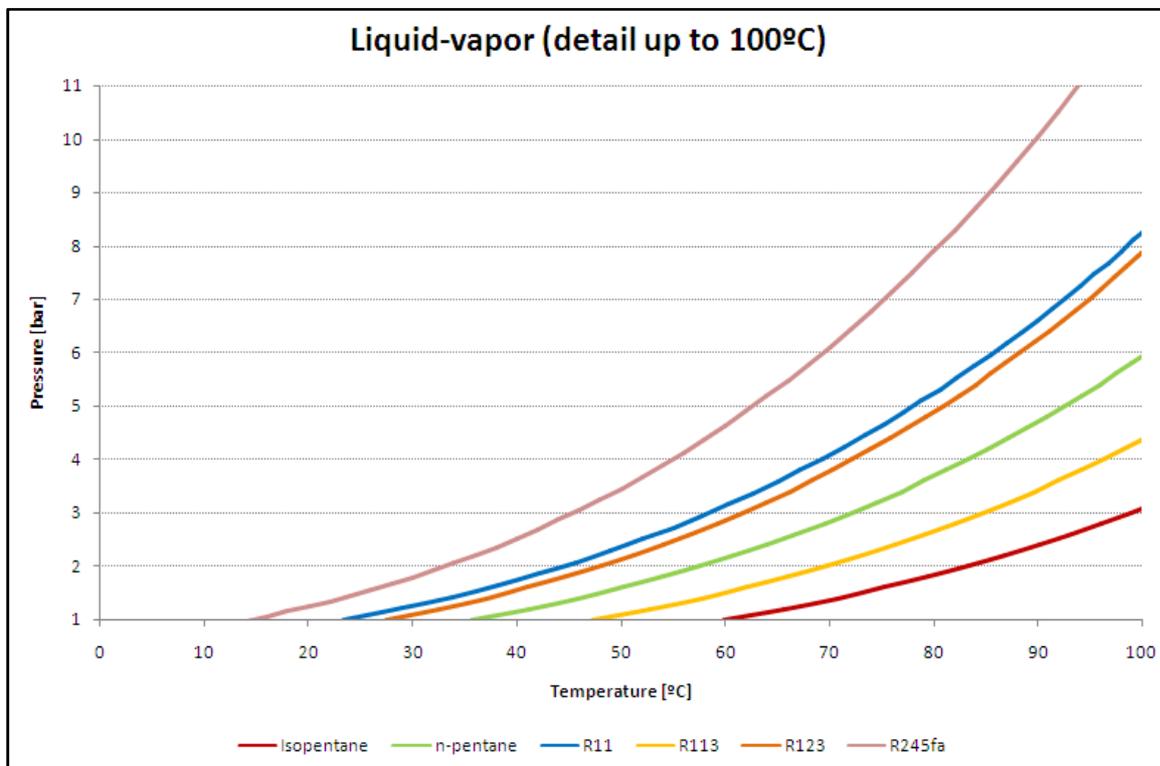


Chart 3.2 – Pressure vs Temperature diagram for common ORC working fluids



Fluids can be classified into dry, isentropic or wet according to the slope of the vapor saturation curve (dT/ds): positive for dry fluids, negative for wet fluids and isentropic when the curve is almost vertical. According to Chart 3.1, pentane and isopentane are dry fluids while the refrigerants (R11, R113, R123 and R245fa) are isentropic. Liu et al. already established that dry and isentropic fluids are suitable for this type of applications:

The working fluids of dry or isentropic type are more appropriate for ORC systems. This is because dry or isentropic fluids are superheated after isentropic expansion, thereby eliminating the concerns of impingement of liquid droplets on the turbine blades. Moreover, the superheated apparatus is not needed. [Ref. 46]

Figure 3.4 shows this phenomena more adequately [Ref. 51]:

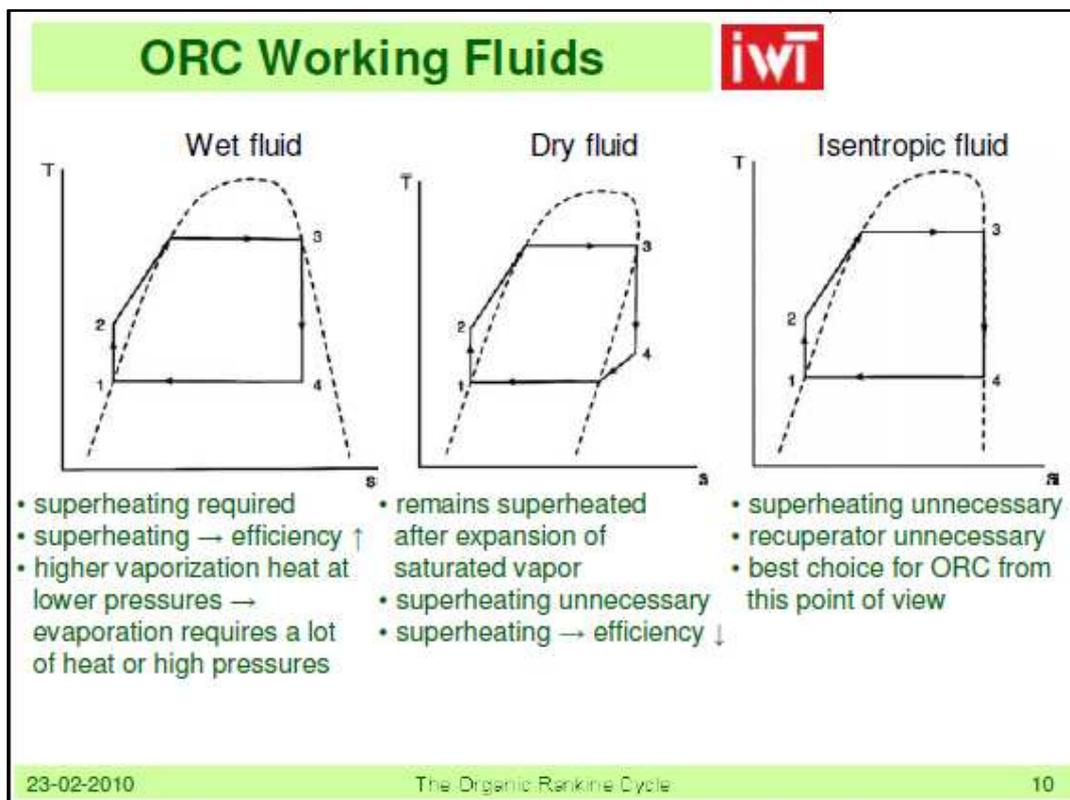


Figure 3.4 – Ts diagram for wet, dry and isentropic fluids

Therefore, the six candidates are appropriate for the ORC system.

Next, we should consider how harmful they are to the environment; it does not make much sense to build a CO₂-free power plant if some of its components are also dangerous to the environment. We will use two different measures:



- **ODP** stands for **Ozone Depleting Potential** and it shows how harmful the compound is in relation to R-11. The amount of degradation of the ozone layer of R-11 is indexed to 1. Ideally, our WF of choice should have a ODP value of zero.
- **GWP** stands for **Global Warming Potential**. The concept is similar to ODP but it is referenced to carbon dioxide, which contributes with a relative value of 1 to the Global Warming. Recently the EU has banned refrigerant in mobile applications with a GWP higher than 150 [Ref. 52] so we shall take this value to exclude WF candidates.

Fluid	Boiling point	ODP	GWP
Isopentane	27,2	0	11
Pentane	36	0	11
R11	23,6	1	-
R113	47,6	1	-
R123	27,9	0,02	76
R245fa	14,9	0	1020

Table 3.2 – ODP and GWP of 6 candidates for ORC working fluid

If we exclude R11 and R113 because of their ODP, and we also exclude R245fa because of its high GWP, we are only left with three candidates: isopentane, pentane and R123 for the simulation.

3.4 Results of simulation

The most important parameters of the simulation are summarized in table 3.3 below:

		HS flow [kg/s]	CS flow [kg/s]	WF flow [kg/s]	Thermal efficiency	Exergetic efficiency	Carnot ratio
pentane	summer	6,0	170	33,609	7,125%	33,27 %	33,236%
	winter		161	33,748	6,748%	26,58 %	26,230%
Isopentane	summer	4,52	289	25,56	9,54 %	44,48 %	44,529%
	winter		133		9,54 %	35,53 %	37,082%
R123	summer	3,94	211	43,4	10,95 %	46,44 %	51,09 %
	winter		131		10,95 %	20,09 %	42,57 %

Table 3.3 – Summary of simulation results for ORC



The only parameter that has not been explained yet is the Carnot ratio. This is the ratio between the thermal efficiency and the Carnot efficiency.

As we can see, the best results are achieved with R123 as working fluid. It has the best efficiencies (both energetic and exergetic). However, R123 has an ODP of 0,012 and its GWP is the seven times higher than isopentane/pentane's (as previously shown in table 3.4). The second best results are achieved by isopentane and its thermal efficiency is only 1% lower than the efficiency of R123.

In conclusion, we will choose **isopentane as a working fluid for the ORC system**. The Cycle-Tempo diagram with the full set of results can be found in Annex E.1 and E.2.

Regarding the cost of the working fluid, we obtained a range of prices for the isopentane family, which includes pentane and cyclo-pentane. The indicative prices of [Ref. 53] show a range of 50–90 c\$/lb, which equal to 80-150 c€/kg.

3.4.1 Energy and exergy diagrams

Firstly, we will show the energy diagrams, for both summer in Figure 3.5 and winter in Figure 3.6. And then the exergy diagrams in Figure 3.7 for summer and Figure 3.8 in winter.

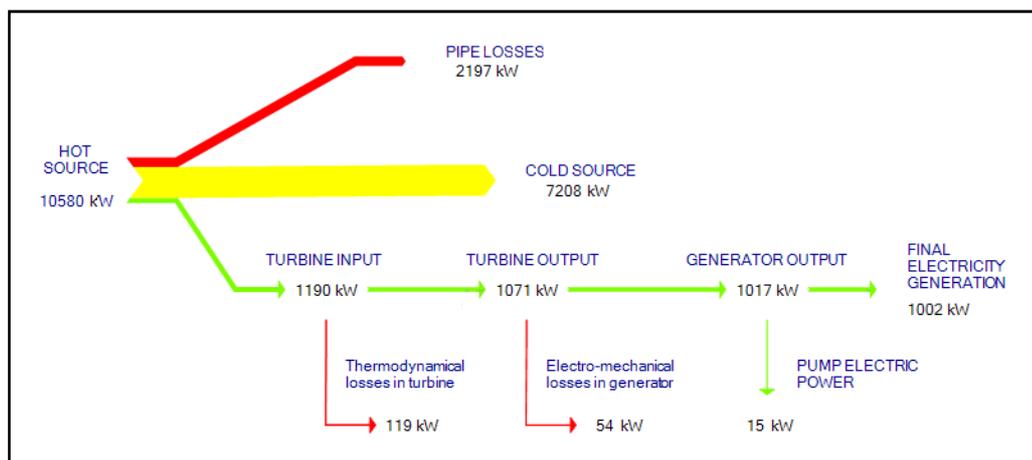


Figure 3.5 – ORC Sankey energy diagram with summer conditions

We can see that most of the energy transmitted by the HS ends up in the CS (yellow arrow). Another significant flow is the cumulated losses in all pipes (red arrow). Regarding the first law efficiency, we can see that it is the ratio between the FINAL ELECTRICITY GENERATION (1.002 MW) and the HOT SOURCE (10.580), which is the 9,5% we already showed in Table 3.5.



The difference in winter is that the pipe losses diminish while the power transmitted to the CS increases. However, the power transmitted by the HS and the final electricity generation are the same. Therefore, the first law efficiency is also the same: 9,5%.

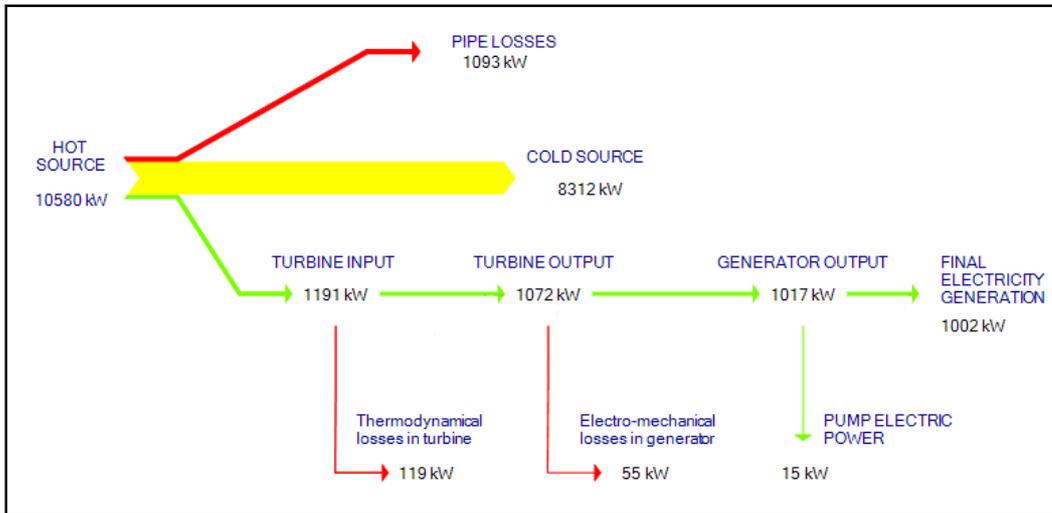


Figure 3.6 – ORC Sankey energy diagram with winter conditions

We can see that the width and distribution of the arrows significantly change when we look at the exergy diagrams. The second-law efficiency is the ratio between FINAL ELECTRICITY GENERATION and HOT SOURCE (same as before) but this time we are comparing exergies, not energies. And the values are much higher than for the first law efficiency: 35% for winter and 45% for summer.

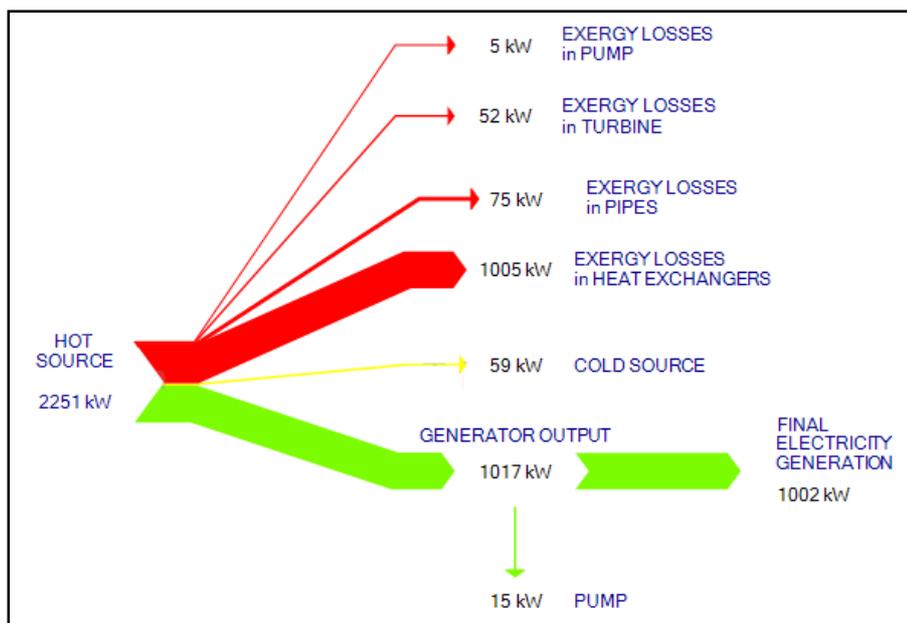


Figure 3.7 – ORC Sankey exergy diagram with summer conditions



We can see that the HS exergy value is higher in winter than in summer; more work can be obtained from 100°C when it is winter because the environment temperature is lower.

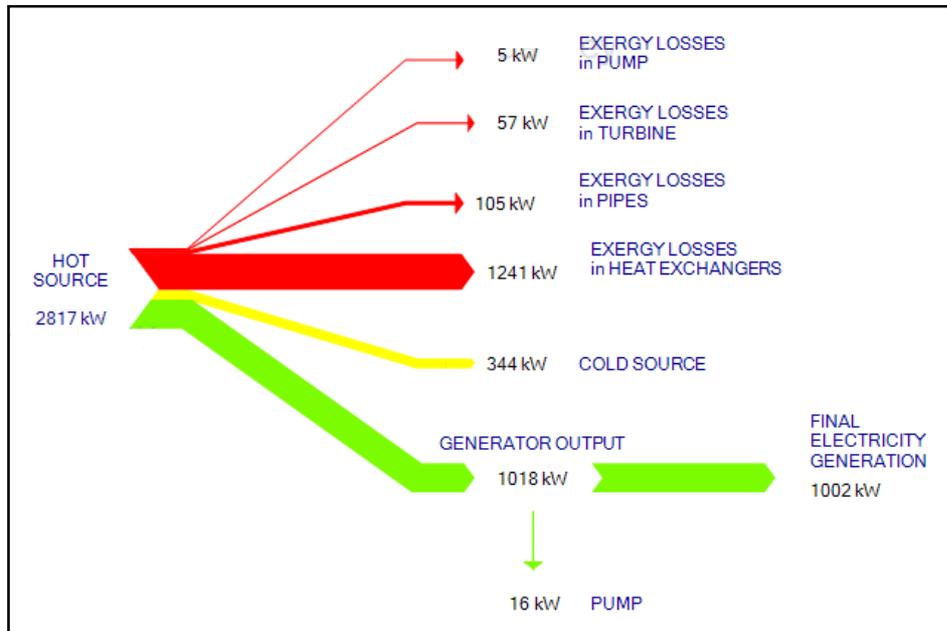


Figure 3.8 – ORC Sankey exergy diagram with winter conditions

3.5 Cost estimation

As already said in Chapter 2.4.1, we will use literature references to estimate the capital costs of an ORC power plant. The details of the calculations (how to update and convert the figures) can be found in Annexes E.1 and E.2.

Reference number	Author	Conditions	Capital costs [€/kW]
[Ref. 54]	U.S. Dep. of Energy	2.500 \$/kW of 2008	1.750
[Ref. 55]	Pernecker	1.580 €/kW in 1995	2.090
[Ref. 38]	Leslie	2.500 \$/kW in 2009	1.830
[Ref. 37]	Schuster	3.755 €/kW of 2009	3.820
[Ref.56]	Theunki	3.500 \$/kW of 2007	2.700
[Ref. 51]	Vanslambrouck	1.350 €/kW of 2010	1.350
Average			2.250

Table 3.4 – Estimation of ORC capital costs

The estimation for the average capital costs are around 2.250 €/kW. Therefore, our 1MW plant with ORC technology would cost **2,25 M€**.



3.5.1 Alternative ORC costs: several units

Alternatively, we could buy ORC units with a defined power. We have data from Pratt&Whitney and TransPacific Energy [Ref. 57].

Feature	Pratt&Whitney (UTC)	TransPacific Energy
Unit power	280 kW	115 kW
Unit price	350 k\$	250 k\$
Number units needed	4	9
Price (\$ 2009)	1,4 M\$	2,25 M\$
Price (€ 2010)	1,15 M€	1,85 M€

Table 3.5 – ORC cost by installing several units

On the plus side, by having several units we increase the reliability of the system because if one fails, the rest are still available. On the other hand, they are not adjusted to the specific conditions of the waste heat, so the efficiency will be lower. Also, more units means that the control system will be much more complex.

In conclusion, this is a valid alternative, but we will not consider it further because the objective of this study is a tailor-made installation.

3.6 Economic analysis

First, we will summarize the input variables in Table 3.6.

Description	Value	Unit
Investment	2.250	k€
O&M costs	250	k€/year
Administration costs	60	k€/year
Operational hours	6.570	h/year
Electric power	1	MW
Generated electricity	6.570	MWh/year
Electricity price	85	€/MWh
Timespan	15	years
Interest rate	5	%
Inflation rate	2	%
Corporate tax	20	%
Start-up of first year	75	%
Start-up of second year	85	%

Table 3.6 – Conditions for economic analysis of ORC



Chart 3.3 shows the Cash Flows of the ORC project: we have positive Cash Flows from year 1 onwards although the profits of year 1 and 2 are much lower than for the rest of the years. The payback time comes between year 9 and 10.

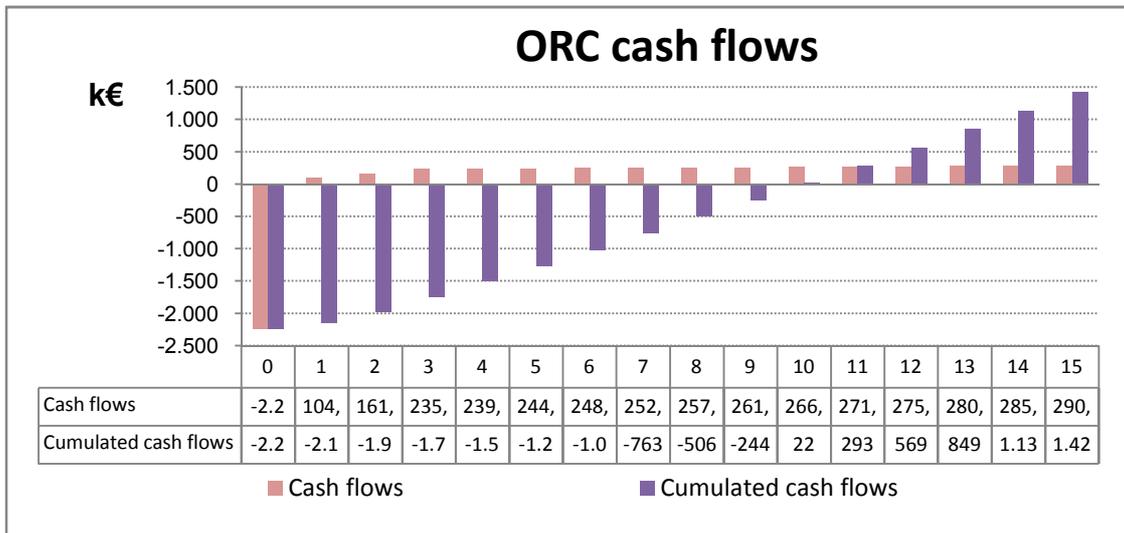


Chart 3.3 – Cash flows and cumulated cash flows for the ORC project

Regarding the incomes, they are negative in the first year, quite low in the second year and then they slowly grow from 100 k€ to 175 k€ (before taxes). This growth is due to the increase of the electricity price in prevision of the 2% inflation.

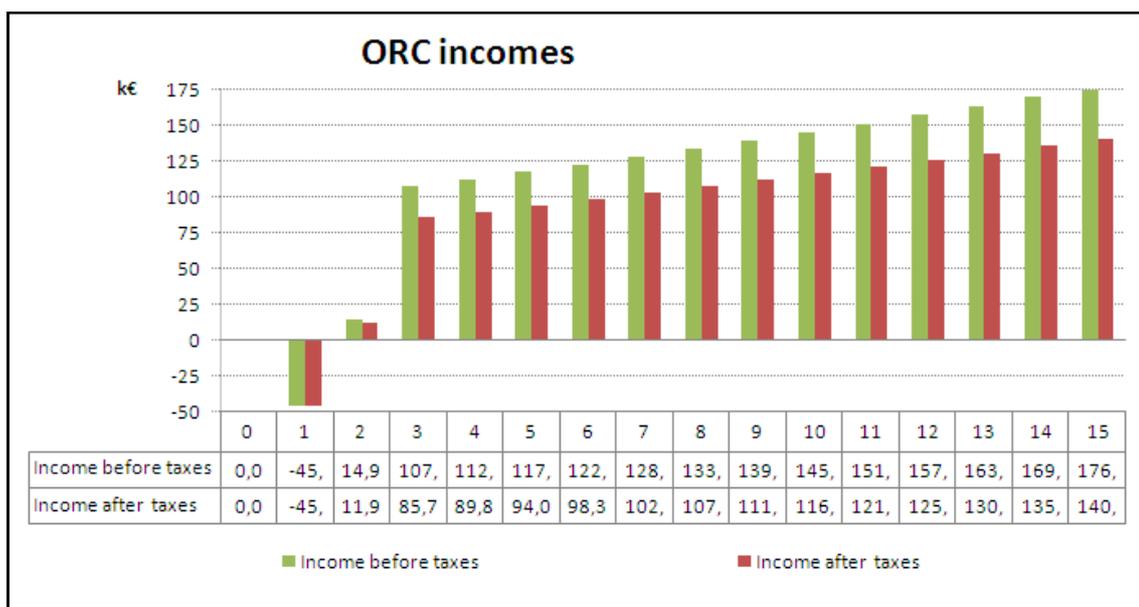


Chart 3.4 – Incomes before and after taxes for the ORC project



But the three most important parameters are the ones we already defined in Chapter 2.3, the economic evaluation criteria:

- The IRR is 6,18%.
- The NPV is 195 k€.
- The payback is 9,9 years.

As we can see, IRR is higher than the interest rate of 5% and the NPV is positive, so we can say that the project is profitable.

The economic analysis has been performed under the supposition that we sell the electricity at the average electricity price. However, it would be advisable to perform a sensibility analysis on the electricity price. If we can sell it at a lower price and still be profitable, we would have more leverage.

Electricity price [€/MWh]	IRR	NPV
80	4,4%	-103 k€
81	4,7%	-43 k€
81,72	5,00 %	0 k€
82	5,1%	17 k€
83	5,5 %	77 k€
84	5,8%	136 k€
85	6,2%	195 k€
86	6,5%	256 k€
87	6,9%	313 k€

Table 3.7 – Sensibility analysis on electricity price

We find that the minimum price at which we can sell electricity is 81,72 €/MWh. And, obviously, if we managed to sell it above 85 €/MWh, we would make even more profit.



4 KALINA CYCLE

4.1 Pre-selection of cycles

There are several variations on this cycle: in his patent, Dr. Kalina proposed several different cycles (named KCS-#) [Ref. 58] and the company Kalex developed some others (named SG-#) [Ref. 59]. Table 4.1 below shows the application range for some of this cycles.

	Cycle name	Application range
ORIGINAL KALINA CYCLES	KCS-1	Sources between 200-400°C
	KCS-5	Direct-fired applications
	KCS-6	Bottoming cycle in a combined cycle
	KCS-11	Sources between 100-200°C, low-temperature geothermal (high-end)
	KCS-34	Sources between 100-200°C, low-temperature geothermal (low-end). Used in Húsavik
KALEX NEW CYCLES	SG-2a	Low temperature heat sources, with an initial temperature of up to 310 °F (155 °C.)
	SG-2c	It is a simplified version of SG-2a
	SG-2d	Wide range of heat sources, with initial temperatures of geofluid up to 400 °F (205 °C.)
	SG-4d	Range of initial temperatures from 310 °F to 400 °F or higher

Table 4.1 – Kalina cycles and application ranges

The schematics of the SG cycles can be found in Annex B.6.

Our application with the Rotterdam waste heat is comparable to the low-end range of geothermal applications. Therefore, we will use the **KCS-34**, the same used in Húsavik and thus we will use the same values as a starting point for our simulation. The details of the Húsavik operating conditions can be found in Annex B.7.

4.2 Cycle-Tempo modelling

The diagram of this system in Cycle-Tempo is shown in Figure 4.1:



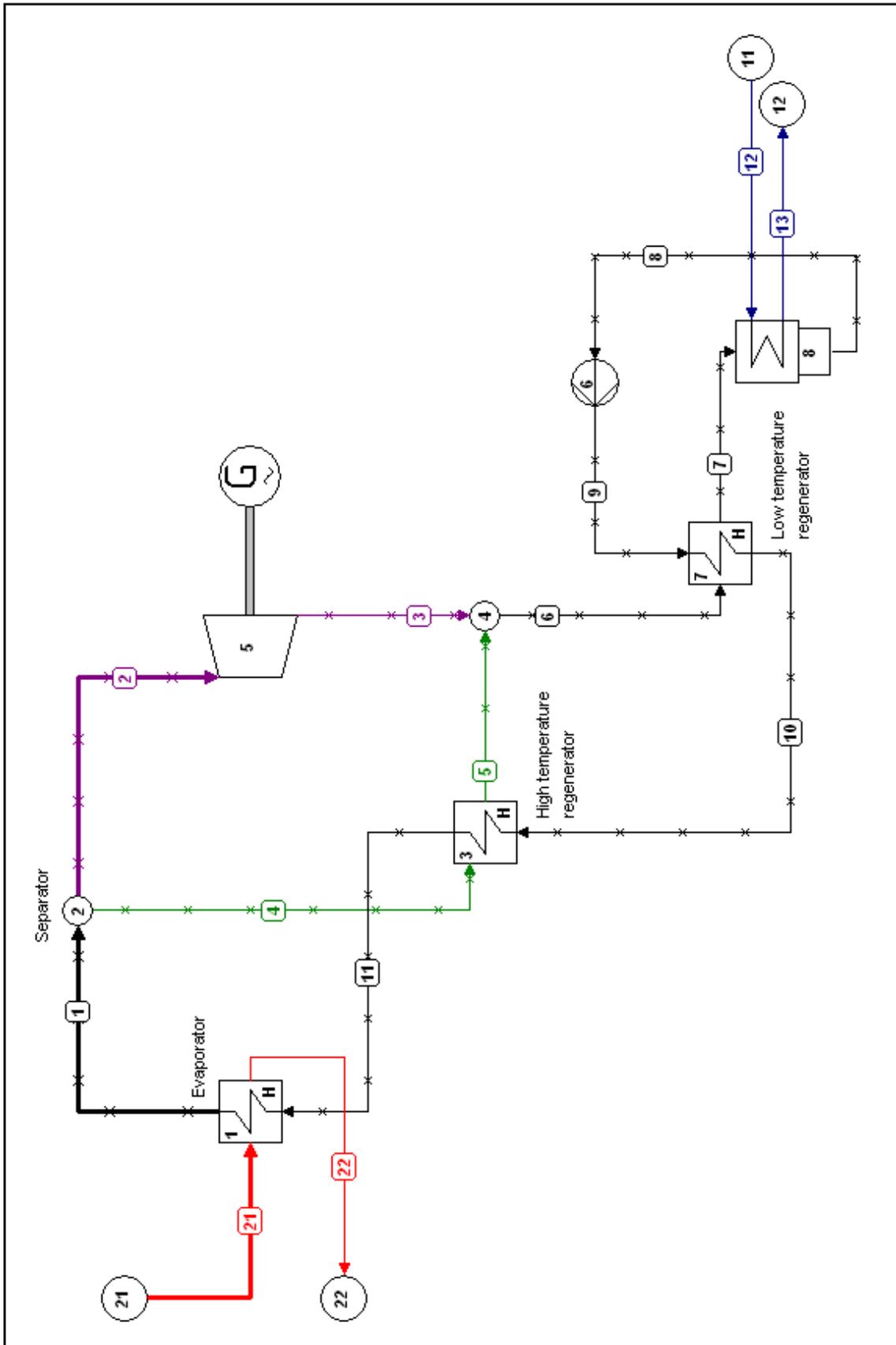


Figure 4.1 – Kalina system model in Cycle-Tempo



We can see that this cycle is more complex because it contains more elements:

- Apparatus 1 is the heat exchanger
- Apparatus 2 is a node, the separator
- Apparatus 3 is the high-temperature regenerator
- Apparatus 4 is a node, the mixer
- Apparatus 5 is the turbine
- Apparatus 6 is the pump
- Apparatus 7 is the low-temperature regenerator
- Apparatus 8 is the condenser
- Apparatus G is the generator

There are also 3 circuits (as in the ORC) although the WF circuit is more complicated due to the existence of the separator (apparatus 2):

- The circuit in red is for the HS: source 21 is the HS outlet and sink 22 is the inlet
- The blue circuit is for the CS: source 11 is the CS outlet and sink 12 is the inlet.
- The circuit in black represents an ammonia/water mixture with an 80% concentration. In the separator, the flow is divided into two streams: the stream in green represents the poor mixture (around 50% ammonia) while the circuit in purple represents the rich mixture (around 98% ammonia) that will action the turbine. After the turbine, the two streams are mixed again into an 80% concentration mixture.

4.3 Results of simulation

The Cycle-Tempo diagram with the full set of results can be found in Annex F.3 and F.4, while the summary of the results is shown in Table 4.2 below:

		HS flow [kg/s]	CS flow [kg/s]	WF flow [kg/s]	Thermal efficiency	Exergetic efficiency	Carnot ratio
Ammonia/ water	summer	5,6	356	16,1	7,69%	36,09%	35,88 %
	winter		256			28,88 %	29,93 %

Table 4.2 – Summary of results for Kalina simulation

Finally, we obtained a range of prices for ammonia, which is the expensive component of the water/ammonia mixture. The indicative prices of ICIS.com [Ref. 60] show a range of 380–780 \$/ton, which equals to 28-60 c€/kg.



4.3.1 Energy and exergy diagrams

Figure 4.2 shows the energy diagram for Kalina cycle in summer and Figure 4.3 shows the same diagram with winter conditions. We can see that there are losses in the exchangers that did not appear for the ORC; these refer to the internal heat exchangers, the high-temperature regenerator number 3 and low-temperature regenerator number 7.

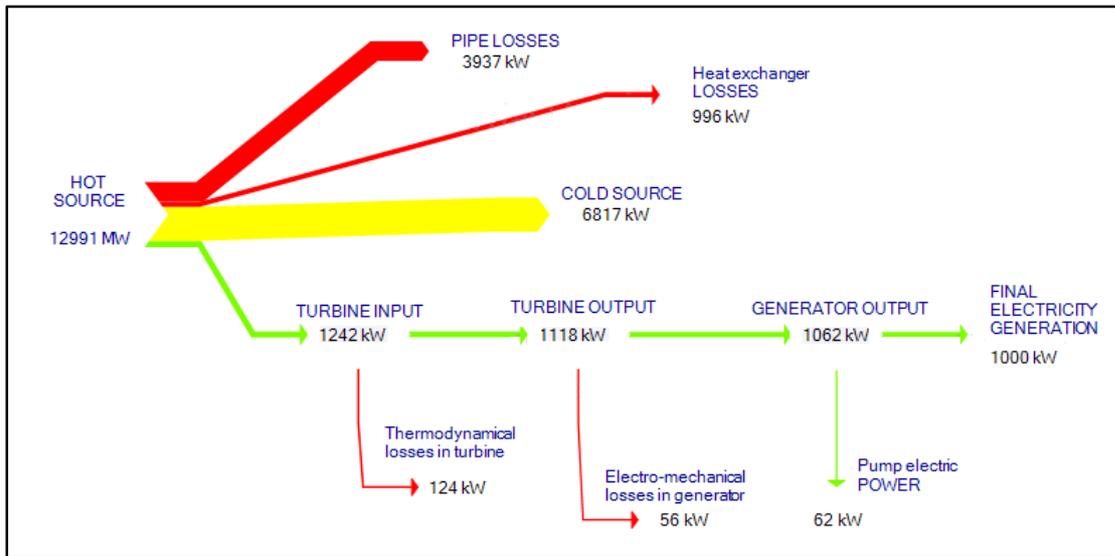


Figure 4.2 – Kalina Sankey energy diagram with summer conditions

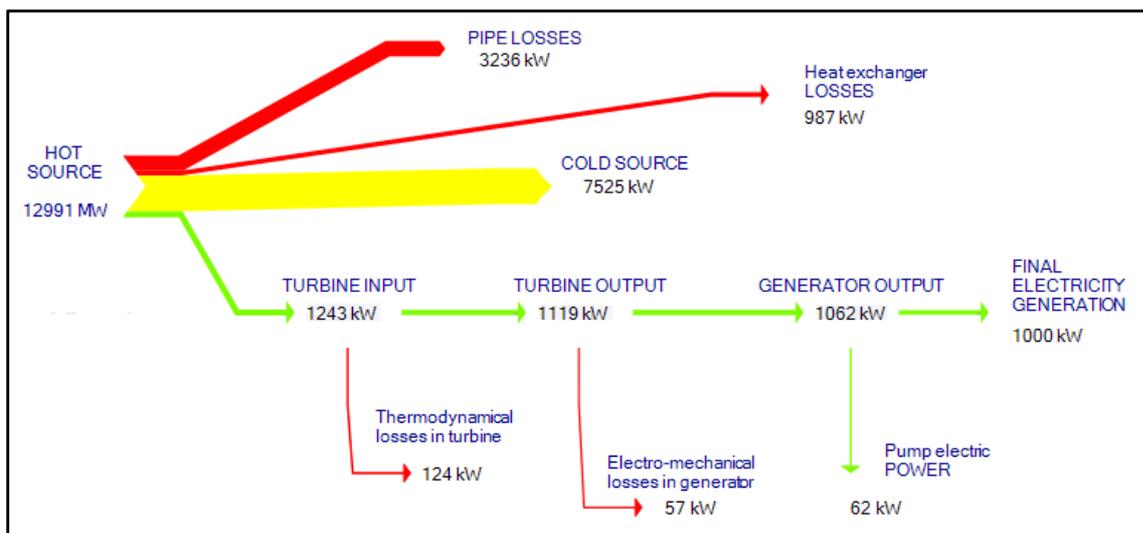


Figure 4.3 – Kalina Sankey energy diagram with winter conditions

Now we can see the exergy diagrams: Figure 4.4 for summer and Figure 4.5 for winter. A new component appears: the exergy losses in the nodes. These refer to nodes 2 and 4 which are respectively used to separate the main stream and to recombine it.



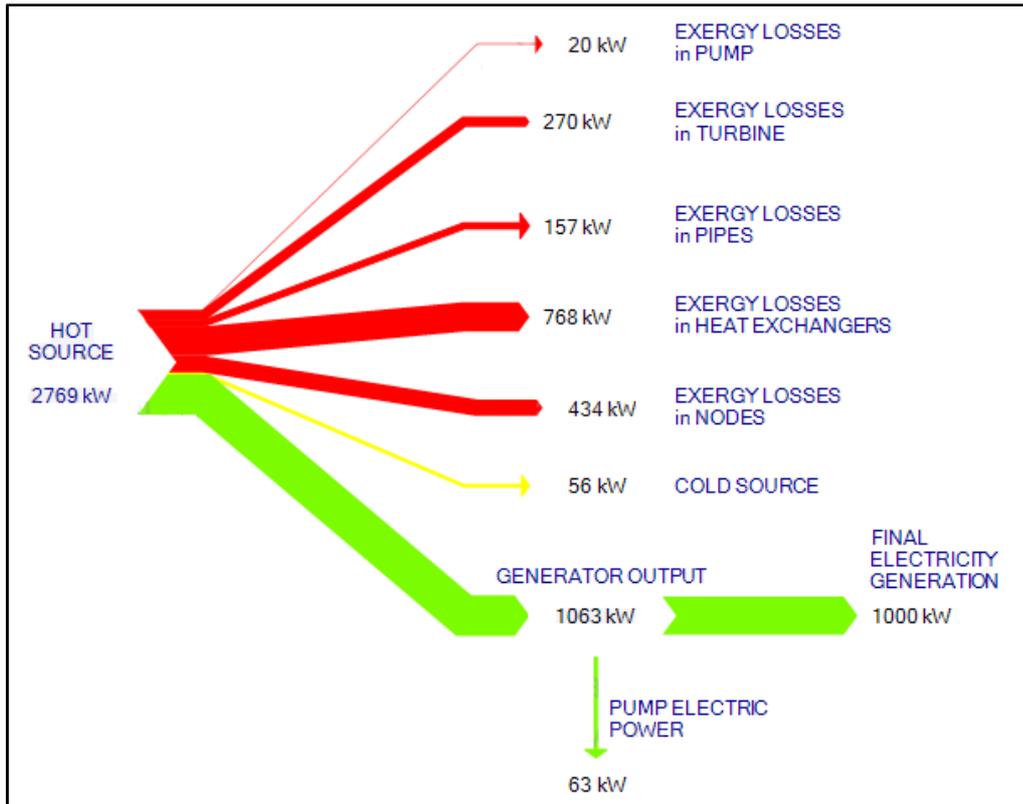


Figure 4.4 – Kalina Sankey exergy diagram with summer conditions

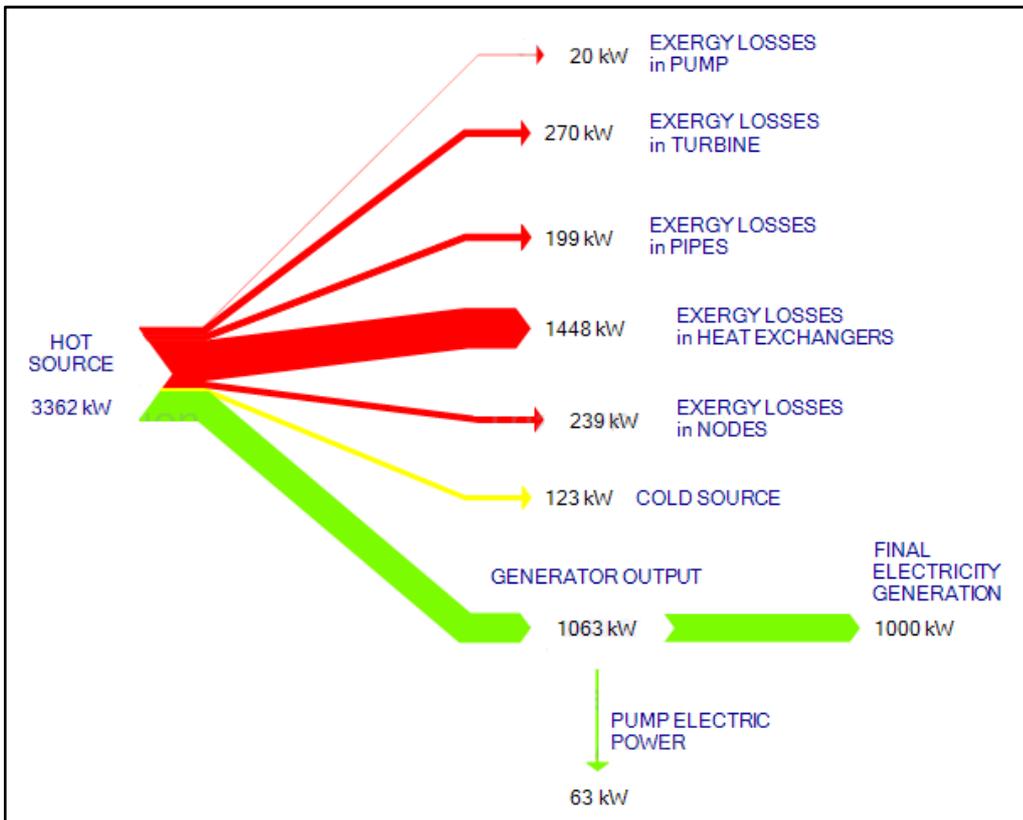


Figure 4.5 – Kalina Sankey exergy diagram with winter conditions



4.4 Cost estimation

Kalina technology is not as popular as ORC cycles so the cost estimation will be based on two studies and three completed projects of which financial data has been made available to the public.

1) Study for the application on Kalina cycle in Hawaii

A workshop was carried out in Hawaii in 2003 to look at alternative energy sources since their petroleum dependence is 78% of the total produced electricity. In this study several scenarios were devised which included a 11 MW Kalina bottoming cycle to re-use waste heat from Diesel engines [Ref. 61]. The estimation of the Kalina capital costs were 1.200 \$/kW at the time (year 2003). If we apply the 2003 conversion rates and update it through EU inflation, we obtain 1.214 €/kW.

2) Húsavík power plant

It was built in 2000 so the costs will be updated with the inflation since 1999. The plant commissioning was awarded to Exergy Inc. for 1,874M\$. The installed power is 2MW so the capital costs are 937 \$/kW [Ref. 62]. Once converted and updated, the capital costs are 1.150 €/kW.

3) Unterhaching in Germany

The power plant costs 16 M€ (plus the maintenance for 10 years) and the whole CHP system around 80 M€ [Ref. 63]. If we discount this 10 years of maintenance (at 250 k€/year as previously estimated in Chapter 2.4.2), the cost of the power system would be 14,5 M€ and it yields 3,36 MW.

It is also a geothermal power plant, so only a fraction of these 14,5 M€ belongs to the power plant. Hance [Ref. 64] estimated in that 54% costs of the costs of a geothermal power project belong to the power plant while the remaining correspond to exploration, confirmation, permitting, drilling, steam gathering and transmission. Figure 4.6 (also from Hance's report) shows the cost distribution:



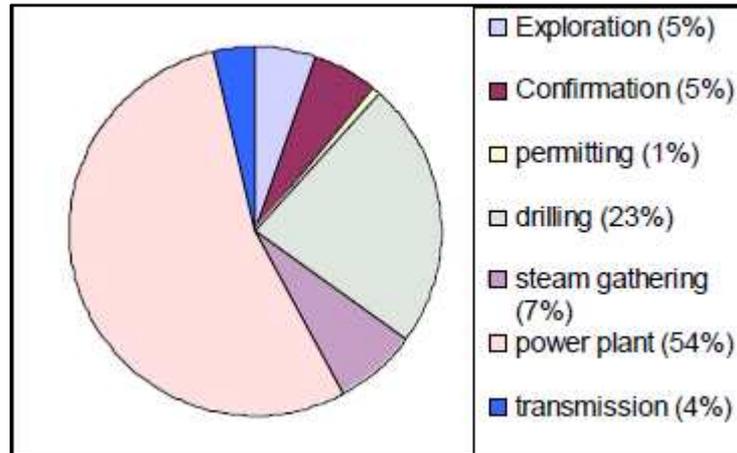


Figure 4.6 – Typical cost breakdown of geothermal projects

Therefore, we estimate that the Kalina power plant built in Unterhaching cost around 7,29 M€, so the specific capital costs would be around 2.170 €/kW and once transformed, 2.210 €/kW.

4) Bruchsal in Germany

The project cost 17 M€ and provides 0,55 MW electric power for 1.200 households. However, the commissioning for the plant was given to Siemens for 9,81 M€. If we make the same considerations as before (only 54% of the costs belong to the power plant) then it cost 5,3 M€ or 9.600 €/kW. After updates, it becomes 9.780 €/kW.

The capital costs for Bruchsal are much higher than the rest and it can probably be explained by the fact that the installed power is the lowest. One possible conclusion is that economies of scale affect the capital cost of the power plant so we would not recommend to build a plant with such a low electric power. Despite this, the Bruchsal project is profitable because of two facts:

- it is CHP, so heat is also sold to the households and additional profit is made
- the German Government subsidizes renewable energy considerably

In conclusion, the capital costs for Bruchsal will not be taken into account.

5) Report of Dr. Arvin C. Thedki

In this report, an estimation is given for Kalina capital costs: between \$2.000 and \$3.000 per kW power installed [Ref. 55]. We will take the upper figure of this range: 3.000 \$/kW from 2007. Once converted and updated, it becomes 2.310 €/kW.

The summary of this projects can be found in the table 4.3 below:



Source	Conditions	Capital cost [€/kW]
1) Hawaii study	1.200 \$/kW of 2003	1.214
2) Húsavík geothermal plant	973 \$/kW of 1999	1.150
3) Unterhaching geothermal plant	2.170 €/kW of 2009	2.210
4) Bruchsal geothermal plant	9.600 €/kW of 2009	9.780
5) Thedki report	3.000 \$/kW of 2007	2.310
Average		1.721

Table 4.3 – Summary of capital costs for Kalina cycle projects

The capital cost estimation is 1721 €/kW so the total cost (rounded down) is **1,7 M€**.

4.5 Economic analysis

First, we will summarize the input variables.

Description	Value	Unit
Investment	1.500	k€
O&M costs	300	k€/year
Administration costs	60	k€/year
Operational hours	6.570	h/year
Electric power	1	MW
Generated electricity	6.570	MWh/year
Electricity price	85	€/MWh
Timespan	15	years
Interest rate	5	%
Inflation rate	2	%
Corporate tax	20	%
Start-up of first year	75	%
Start-up of second year	85	%

Table 4.4 – Conditions for economic analysis of Kalina

Chart 4.1 shows the cash flows of the Kalina project: we have positive cash flows from year 1 although the cash flows of year 1 and 2 are much lower than for the rest of the years. The payback time comes between year 8 and 9.



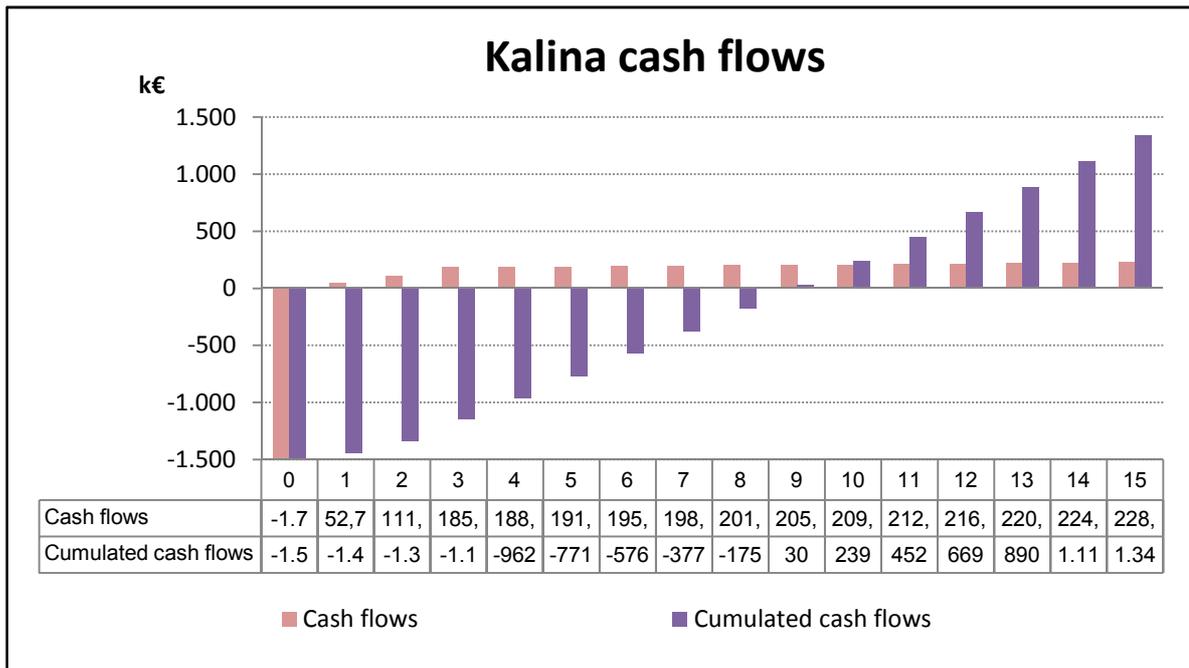


Chart 4.1 – Cash flows and cumulated cash flows for the Kalina project

As for the incomes (shown in Chart 4.2), they start being positive from year 3 onwards; they start at 75 k€ and they rise until 115 k€ after taxes. We confirm that we are below the 200 k€ threshold for the corporate tax accounting.

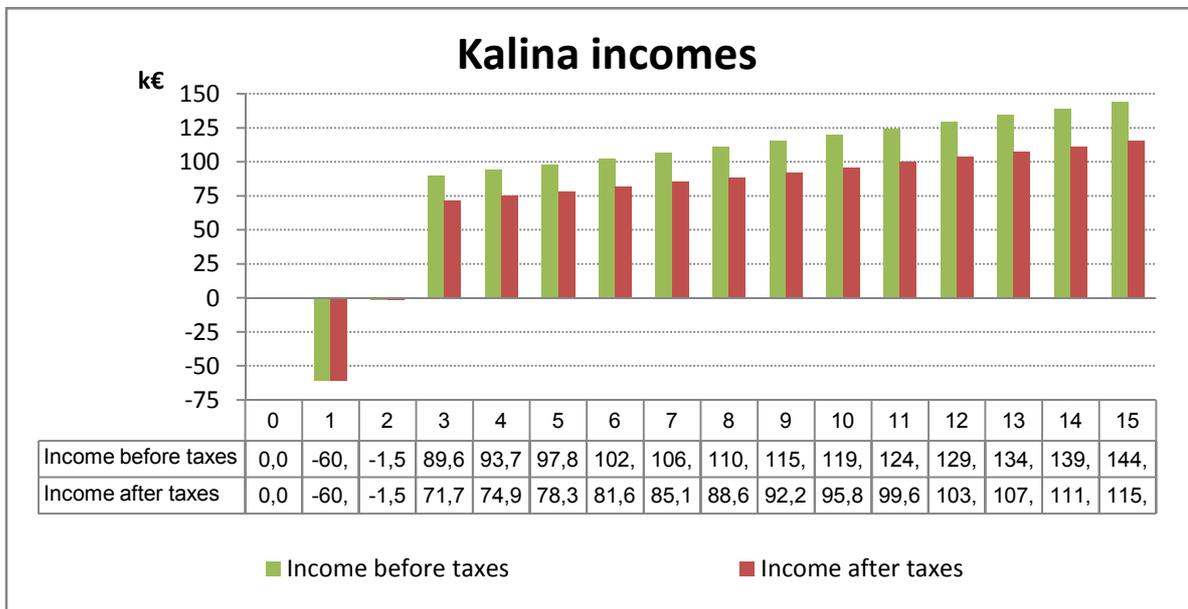


Chart 4.2 – Incomes before and after taxes for the Kalina project

Again, the three most important parameters are the ones we already defined in Chapter 2.3, the economic evaluation criteria:



- The IRR is 6,39%.
- The NPV is 177 k€.
- The payback is 8,85 years.

As we can see, IRR is higher than the interest rate of 5% and the NPV is positive, so we can say that the project is profitable.

The economic analysis has been performed under the supposition that we sell the electricity at the average market electricity price. However, it would be advisable to perform a sensibility analysis on the electricity price.

Electricity price [€/MWh]	IRR	NPV
80	4,0%	-123 k€
81	4,5 %	-63 k€
82	5,0%	-3 k€
82,05	5,0%	0 k€
83	5,5 %	57 k€
84	5,9%	117 k€
85	6,4%	177 k€
86	6,8%	236 k€
87	7,3%	295 k€

Table 4.5 – Sensibility analysis on electricity price

We find that the minimum price at which we can sell electricity is 82,05 €/MWh. And, obviously, if we managed to sell it above 85 €/MWh, we would make even more profit.



5 ENVIRONMENTAL IMPACT

5.1 CO₂ savings

Electricity produced from waste heat is not polluting because we are using heat that would otherwise be released into the environment. The amount of emissions saved depends on the structure of electricity production of every country. For the Netherlands, the average CO₂ emissions are 392 g CO₂ per kWh in 2008 according to the International Energy Agency [Ref. 65]. This value is very close to the value for gas-fired power plants because in the Netherlands the greatest source of electricity production is gas. Table 5.1 presents a summary of the calculations.

Description	Value	Dimension
Specific CO ₂ emissions from electricity generation	392	g CO ₂ per kWh
Estimated utilisation factor of the plant	75	%
Annual hours of electricity production	6.570	h
Annual energy produced	6.570	MWh
Annual CO ₂ emissions saved	2.575	tons CO ₂

Table 5.1 – Summary of calculations for annual CO₂ savings

In conclusion, we estimate that **2.575 tons of CO₂** could be saved annually. A more detailed study of the possible CO₂ savings can be found in Annex G.

5.2 Nuclear waste savings

In average, every kWh of electricity generated by a nuclear power plant produces 0,010 g of high-radioactivity nuclear waste [Ref. 66]. Table 5.2 shows the calculation of the total nuclear waste savings:

Description	Value	Dimension
Nuclear waste per kWh from electricity generation	0,010	g per kWh
Share of nuclear power in Netherlands [Ref. 1]	4,07	%
Estimated utilisation factor of the plant	75	%
Annual hours of electricity production	6.570	h
Annual energy produced	6.570	MWh
Annual high-radioactivity waste saved	2,46	kg

Table 5.2 – Summary of calculations for annual nuclear waste savings



5.3 Safety of working fluids

Below we will list some of the safety-related features of the two chosen working fluids: ammonia for Kalina cycle and isopentane for ORC. The description of these features (the legend) can be found in Annex H.1.

The main sources are: NIOSH (National Institute for Occupational Safety and Health) [Ref. 67] and the ICSC (International Chemistry Safety Card) provided by the International Labour Organization, from the U.N.

5.3.1 Ammonia

NIOSH	Flash point	11°C
	Autoignition temperature	651°C
	Explosive limits	15% – 28%
	REL: TWA	25 ppm / 18 mg/m ³
	REL: STEL	35 ppm / 27 mg/m ³
	IDLH	300 ppm
UN Hazard Class	2.3 – Toxic gas 8 – Corrosive (as subsidiary risk)	
European Classification	T – Toxic C – Corrosive N – Dangerous to the Environment	
NFPA (fire diamond) 	Health (blue)	3 : Short exposure could cause serious temporary or moderate residual injury
	Flammability (red)	1 : Must be heated before ignition can occur
	Instability/Reactivity (yellow)	0 : Normally stable, even under fire exposure conditions, and is not reactive with water
Effect on global warming	ODP	0
	GWP	0

Table 5.3 – Summary of ammonia hazards

Summing up, ammonia is not a danger from the flammability point of view. Moreover, it is not a threat for global warming because its ODP and GWP are zero. On the other hand, it is, corrosive and toxic for humans and the environment. We could also argue that it is a widely used compound and that there is great expertise on how to handle it.

The Safety Sheets can be found in Annex H.2.



Despite its toxicity, Recurrent Engineering makes the case for ammonia safety in Figure H.3 [Ref. 13]:

Environmental and Safety



- Less hazardous and flammable than organic cycle working fluids
- Environmentally benign, the most common compound found in nature
- Ammonia vents easily, and is self-alarmed
- Ammonia is the 6th largest chemical produced in the U.S.
- Proven safety record in ammonia synthesis, power plants and refrigeration plants

Ammonia-Water is safe and environmentally friendly

Figure 5.1 – Environmental and safety traits of ammonia

5.3.2 Isopentane

NIOSH	Flash point	-51 °C
	Autoignition temperature	420 °C
	Explosive limits	1,4% – 7,6%
	REL: TWA	600 ppm
	REL: STEL	750 ppm
	IDLH	1.500 ppm
UN Hazard Class	3 – Flammable liquid	
European Classification	F: Highly flammable	
	Xn: Harmful	
	N: Dangerous to the environment	
NFPA (fire diamond) 	Health (blue)	1: Exposure would cause irritation with only minor residual injury
	Flammability (red)	4: Will rapidly or completely vaporize at normal atmospheric pressure and temperature, or is readily dispersed in air and will burn readily
	Instability/Reactivity (yellow)	0: Normally stable, even under fire exposure conditions, and is not reactive with water
Effect on global warming	ODP	0
	GWP	11

Table 5.4 – Summary of isopentane hazards



The main safety issue with isopentane is its flammability – it scores a 4 on the red box of the fire diamond, which is the highest score possible.

It also presents an issue with the GWP: it contributes to the global warming 11 times more than carbon dioxide. However, it is a closed cycle and (as long as there are no leaks) we should only be concerned with the way of disposing it.

The Safety Sheets can be found in Annex H.3.



6 PROJECT COST

The amount of time dedicated to this project was 600h. The recommended hourly wage for an engineering student is between 8 and 15 €, according to ETSEIB [Ref. 68] and we will choose 10 €/h because it is a common value used in internships. Therefore, 600 hours would cost 6.000 €.

We should also account for the license of the thermodynamics simulation software, *Cycle-Tempo* and the license for the Sankey diagram software, *e!Sankey*.

Finally, we will also include 600 € of travelling expenses between Delft and Barcelona. These are the costs of two trips, each of them consisting of two flights, two nights, train tickets and food expenses.

Table 6.1 shows the summary of all the expenses and that the **total cost of this study is 11.499 €**.

Concept	Expense
600 hours (at 11,5 €/h)	6.000 €
Cycle-Tempo license	4.800 €
e!Sankey license	99 €
Travelling expenses	600 €
TOTAL	11.499 €

Table 6.1 – Summary of calculations for cost of this study





7 COMPARISON

Now we will present the two alternative technologies, ORC and Kalina cycle, according to the evaluation criteria already defined in Chapter 2.3 and other features.

		ORC (isopentane)	Kalina cycle
EVALUATION CRITERIA	First law efficiency	9,54 %	7,69 %
	Second law efficiency	36%-44%	30%-36%
	IRR	6,18 %	6,39 %
	NPV	195 k€	177 k€
	Payback	9,9 years	8,85 year
	Safety of WF	Toxic & corrosive	Highly flammable
Investment		2,25 M€	1,7 M€
O&M costs		250 k€/year	300 k€/year
Minimum electricity selling price		81,72 €/MWh	82,05 €/MWh
CS mass flow		133-289 kg/s	256-356 kg/s
HS mass flow		4,52 kg/s	5,6 kg/s
WF mass flow		26,56 kg/s	16,1 kg/s
WF cost		80-150 c€/kg	28-60 c€/kg
Turbine inlet pressure		27 bar	3,75 bar
HS return temperature		80 °C	85 °C
Complexity		Simple	Complex

Table 7.1 – Evaluation criteria of ORC and Kalina cycle

Regarding the efficiencies of the cycle, ORC seems better because they are higher. This is in contradiction with most of the results of the literature - Kalina cycle is more efficient at a 100°C source temperature. One possible explanation is that the Kalina cycle has more exergy losses because it has more components (2 internal regenerators and 2 nodes).

Regarding the required mass flows, we cannot point out which one is better: the WF mass flow is higher for ORC system but the CS mass flow is higher for Kalina cycle.



From the economic point of view there is not much difference between both projects: their IRR is quite similar and so is the NPV. This is due to the fact that the initial investment is higher for ORC but its O&M costs are lower. The payback time comes one year sooner for Kalina and this might be a differentiating factor. However, the cost of the working fluid is considerably higher for isopentane.

Also, from the point of view of safety of the working fluid, ammonia seems to be a better choice: it is less flammable and it is a widely-used chemical all around the world.

From the construction point of view, ORC is probably a better choice: it is more simple and the highest pressure is 3,75. With Kalina cycle we would have to dimension heat exchangers and pipes to withstand 27 bar of pressure. And it has more elements than the ORC system.

As we explained in Chapter 1.2.1, if the HS return temperature is still high we can use it for District Heating. Although Kalina's return temperature is slightly higher than ORC's, we can still use the HS afterwards in both alternatives.

Finally, there is an additional consideration: the Kalina cycle is a fairly new technology with great potential. Using it in Rotterdam would increase the expertise and would help its promotion. Plus, it would be aligned with will of the Netherlands of being at the head of the innovation in Europe (and the world).



CONCLUSIONS

After having considered several waste heat conversion technologies, we realized the two most suitable for this application are ORC and Kalina cycle.

Several working fluids were considered for the ORC and the one with the best performance (first law efficiency of almost 11% and second law efficiency of 20% to 46%) is R123. However, it is a compound that contributes to the deterioration of the ozone layer (ODP is 0,02) and its global warming effect is 76 times the effect of carbon dioxide. Therefore, we suggest that isopentane (it has the second best performance) should be the working fluid for the ORC system.

We have also seen that using the thermal efficiency (or first law efficiency) is not good enough because it compares energies with different quality. Also, it gives a misguided idea that only 9% of the available energy is retrieved. When we use the exergetic efficiency (or second law efficiency) we see that at least 20% of the exergy is retrieved. We should also note that Sankey diagrams are a very useful tool to show how the energy and exergy are used and/or lost.

The return temperature of the hot source is 80-85°C so it is still hot enough to be used in a residential district heating network.

Financially speaking, both projects offer similar revenues, with IRRs between 6% and 6,5% with a 15 year timespan. Financial data does not help us to choose which is better. It proves, however, that the project is profitable despite the chosen technology. The average electricity price for industrial consumers is 85 €/MWh but we could even sell it at around 82 €/MWh and still be profitable. This shows us the price negotiation range.

Regarding the environmental benefits, we have calculated that this waste heat recovery power plant of 1MW could save 2.575 tons of CO₂ and 2,46 kg of high-radioactivity nuclear waste annually.

It is my recommendation that this idea should be pursued further because we can produce electricity from waste heat and make profit.





ACKNOWLEDGEMENTS

This has been a co-located project since it started in the Delft, in the Netherlands. Therefore, I will acknowledge first the Dutch people and then the Spanish people.

The original idea came from Dr. Kas Hemmes, from the TDSD section (Technology Dynamics & Sustainable Development) of TU Delft. He has worked with me during my Thesis Proposal and he has been giving plenty of ideas.

Dr. Hemmes also helped me by introducing me to Berend Jan Kleute, co-founder of Bluerise BV. Bluerise is working with OTEC technology, specially with Kalina cycle and they were most helpful by sharing their expertise.

I would also like to thank José M. Salla Tarragó, from the Department of Màquines i Motors Tèrmics in UPC – not only for carefully overseeing the entire Thesis but also for pointing out my weak points and helping me improve it.

Finally, I want to thank my dearest and beloved sister Blanca, who pressed me to work harder and faster by constantly asking: “Why haven’t you finished yet?”.





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ANNEXES

A Annexes related to Rotterdam

A.1 Industries in the port of Rotterdam

We have stated many times that there is a lot of waste heat available due to the amount of industries located there. Figure A.1 shows the number of extensive industries located in the port area in 2008 [Ref. 3].

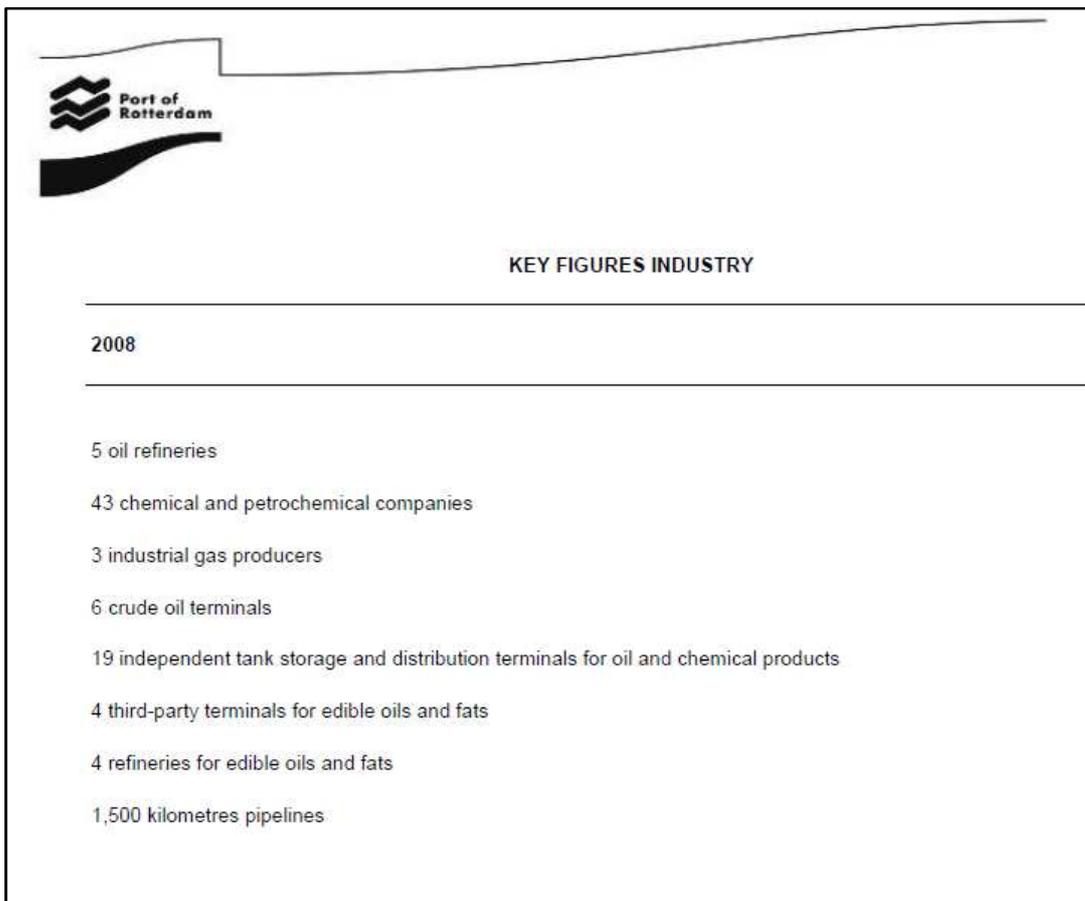


Figure A.1 – Key figures about the industry in the port of Rotterdam



A.2 The shrimp farm

Sustainable tropical shrimps from Rotterdam

THE INDUSTRIAL AREA OF ROTTERDAM HARBOUR IN THE NETHERLANDS DOES NOT SEEM TO BE AN OBVIOUS LOCATION TO FIND TROPICAL SHRIMPS. HOWEVER, BY USING THE WASTE HEAT FROM A NEIGHBOURING POWER PLANT, THIS AREA TURNED OUT TO BE THE PERFECT SPOT FOR THE HAPPY SHRIMP FARM, HOME TO TWO MILLION PACIFIC WHITES. EMMY KOELEMAN TALKED TO GILBERT CURTESSI, MANAGING DIRECTOR AND SHRIMP FANATIC.

Everything at the Happy Shrimp Farm is done in the spirit of sustainable development, of which re-use of residual heat is the main part. An idea that Gilbert Curtessi and commercial director Bas Greiner picked up in 2002 when they were both studying the possibilities of co-siting: sustainable production by using the available nearby utilities, waste and space. Looking at the industrial area of Rotterdam, their attention was drawn to the power plant of E.ON Benelux. "We both like fish and our travels to Japan, China and Brazil inspired us to start a fish farm that could use the residual heat from E.ON. This is not only cheaper, it also is more sustainable because normally the heat is lost as the power plant releases it into the air," states Curtessi.

FINDING THE RIGHT SPECIE

After learning that aquaculture was possible by using the residual heat from their neighbours, the next question was then: what kind of fish will be used? "Possible candidates were the Red Snapper and Tuna," explains Curtessi. However, Red Snapper is a carnivore and cannibalistic and therefore not suitable for housing in basins. In addition, they need 5-6 kg of feed to grow one kg of fish. To grow one kg tuna you even need 16 kg of feed.

"For shrimps it is a different story," says Curtessi.

Shrimp have a far better feed conversion rate; for one kg shrimp you approximately need 1.5 kg of feed. In addition, it takes seven months to grow an adult shrimp, a process that can take two years in Red Snappers, for example. Eventually, the search for the ideal shrimp led the Dutch duo to the Pacific White Shrimp (*Penaeus vannamei*). This shrimp specie eats more algae than other tropical shrimps, which makes this specie more



Trained as an environmental geographer, Gilbert Curtessi has turned himself into a shrimp expert and sustainable entrepreneur.

efficient in terms of feed. In addition, they are more vegetarian than its fellow specie Tiger Shrimp, which makes it easier to use vegetable ingredients (soy, corn and starch) instead of fish meal (an ingredient that is getting scarcer and more expensive).

Curtessi explains that the White Shrimp variety is also very popular in the market, because it has a better taste and texture than the Tigerprawn (*Penaeus monodon*).



Aqua meets horti

The innovative ideas from Curtessi and Greiner are endless. The wastewater, containing feed waste and nitrogen rich shrimp manure turned out to be a very useful medium for certain vegetables to grow on. Curtessi and Greiner therefore have recently started a new chapter in the race for innovation: the company Green & Blue. This saltwater vegetable nursery is a cooperation between Taste of Nature BV, Kappert Cress and Happy Shrimp Farm. It is located above the existing shrimp basins and uses an infrastructure and its resources to produce salty vegetables such as sea lavender and glasswort. "This approach shows that certain types of fish and shrimps can be grown in combination with agricultural vegetables or plants. This makes an existing production facility more efficient because water and heat can be re-used", explains Curtessi. The steady climate conditions of the farm during every season of the year, makes it possible to produce the salty veggies all year-round.



Glasswort is naturally found in the Wadden Sea and along the coastal area of Southern Holland.

SUSTAINABLE APPROACH

As mentioned before, the farm is co-sited with the power plant from E.ON, right in the middle of the industrial area of Rotterdam.

"We installed a 2.5 km pipeline to the E.ON plant and we recover the residual heat (60°C) from the industrial process," says Curtessi. The waste heat is used to warm the farm's basins to a constant 30°C (the optimal temperature for the tropical shrimps). This efficient use of energy resources is a main issue for the Happy Shrimp Farm.

"But we also want to raise our shrimps in a sustainable and ecological way", comments Curtessi. The tropical shrimps found on the menus in European restaurants are primarily imported frozen from Asia and Latin America. According to Curtessi, these imported tropical shrimps have two major disadvantages; firstly they are not fresh and secondly these shrimps are often produced at farms that largely pollute natural mangroves –threatening the coastal wetlands where many fish live and breed. "We produce fresh (or even live) shrimps for the local market. This is not only better for the environment and more sustainable; we also make the customers happy because we can offer them fresh shrimps, every day, the whole year round.

Sustainable production also means that Happy Shrimp does not use any antibiotics or other growth promoting or water improving additives and chemicals on the farm. The larvae (the size of a pin-head) are bought from a SPF (Specific Pathogen Free) farm that raises these larvae on land (instead of catching them from the sea). This makes the larvae free of diseases, which is very important for Happy Shrimp to minimise the risk of importing shrimp viruses. Each batch of larvae can be tested for viruses at the CIDC in Lelystad, the Netherlands. After that, the larvae are kept in quarantine tanks for one month before they are placed in one of the 24 basins. Happy Shrimp aims to grow its own larvae soon. "In

theory you could say that we are an ecological shrimp farm, but there is simply no label for ecological shrimps," Curtessi explains.

However, he and Greiner are working with the European Union to create such an Eco-label for tropical shrimps, which is expected to be ready in 2009.

ALGAE PRODUCTION

Algae are an important ingredient for the Happy Shrimp Farm. Firstly, they keep the water clean, because they take up CO₂ and produce oxygen, which is taken to every corner of the basins by an ingenious recirculation system. Secondly, the algae serve as a valuable feed ingredient for the shrimp.

The algae are currently bought from different suppliers, but next year the Happy Shrimp Farm will host a pilot



The search for the ideal shrimp led the Dutch duo to the Pacific White Shrimp (*Penaeus vannamei*). This type of shrimp eats more algae than other tropical shrimps, which makes this specie more efficient in terms of feed.





The farm covers an area of 5,000m² and is located next to the power plant of E.ON Benelux. A 2.5 kilometre connecting pipe enables Happy Shrimp Farm to re-use the waste heat from the power plant to keep the 24 basins at a tropical temperature of 30°C.

plant for its own algal production system. In this system, waste from the Happy Shrimp Farm and the E.ON power plant will be used to grow the algae. "But using the algae only for Happy Shrimp is too limited," says Curtessi. He explains that algae are a very interesting type of vegetation. Because they are able to consume large quantities of CO₂, they are a powerful weapon against global warming. In the future, CO₂ can be isolated from the air and injected in [created] algae ponds to neutralise them. "Furthermore, algae biomass can be used as a source for bio diesel, food supplements, natural colorants, cosmetics and even pharmaceutical applications", Curtessi continues. In addition, algae are about ten times more effective as a bio-diesel producer than other energy crops. That is of particular interest now that world supplies of feed and food crops are becoming more limited.

MORE FARMS IN EUROPE

The ideas of Curtessi and his partner Greiner are endless. "At our current location in Rotterdam, we can easily double or triple the production capacity," says Curtessi.

Furthermore, the shrimp farmers are planning to build three farms in Germany (Berlin, München and Hamburg), which all located near power plants from E.ON. "All we need are big cities where you can find both residual industrial heat and a consumer market for fresh shrimp," explains Curtessi.

The aim is to have 25 Happy Shrimp Farms up and running across Europe within five to ten years, but also non European countries are being looked at. Regarding competition, the Dutch are optimistic. Since their kick-off in 2006, there have been a few small other initiatives. However, their production output of those small companies is a fraction of the Happy Shrimp Farm's output. "Our approach is different and we have learned a lot from the first (pilot) farm in Rotterdam. In July of this year, the first adult shrimps have been delivered. An event that did not go along silently. The first catch was auctioned during a festive ceremony (called Night of the Prawns) of which the proceeds (€25,000!) will go to the World Wildlife Fund (WWF).

"This is just the beginning," says Curtessi. "The next step is expanding the happy shrimp concept to the rest of the planet and we hope that other companies become enthusiastic about co-siting and that more consumers will eat shrimp; Happy shrimps of course". <-



B Annexes related to technology

B.1 Development of OTEC

This is list of major OTEC milestones [references in Complementary Bibliography]:

- 1870 Jules Verne proposed in *Twenty Thousand Leagues Under the Sea* the use of ocean temperature differences to produce electricity
- 1881 Jacques Arsene D'Arsonval was a French physicist who first formulated the principles of the closed-loop OTEC (with ammonia as WF)
- 1930 George Claude (a former student of D'Arsonval) proposed the open-cycle OTEC and attempted to demonstrate it in Cuba
- 1974 Establishment of NEHLA (Natural Energy Laboratory of Hawaii)
- 1977 Saga University succeeds with 1kW experimental plant
- 1979 State of Hawaii and a consortium US companies succeeded in providing 50kW gross power and 18kW of net power with a mini-OTEC barge-off Hawaii; 2km off Keahole point.
- 1980s US DOE (Department of Energy). OTEC-1 on board a Navy tanker
- 1981 Nauru. Japanese companies (Tokyo Electric Co) yield 100kW gross power with a land-based plant. It operated for a few months
- 1990 IOA (International OTEC/DOWA³ Association) was created:
<http://140.96.175.55/about.htm>
- 1993-1998 Open-cycle OTEC operation in Hawaii. It yielded 103kW net power and 0.41s⁻¹ of desalinated water
- 1999 250kW pilot closed-cycle plant

³ DOWA stands for Deep Ocean Water Application



B.2 Schematic of Uehara cycle

Figure B.1 is an schematic of the Uehara cycle, from [Ref, 69]. As we can see, it is more complex than Kalina cycle.

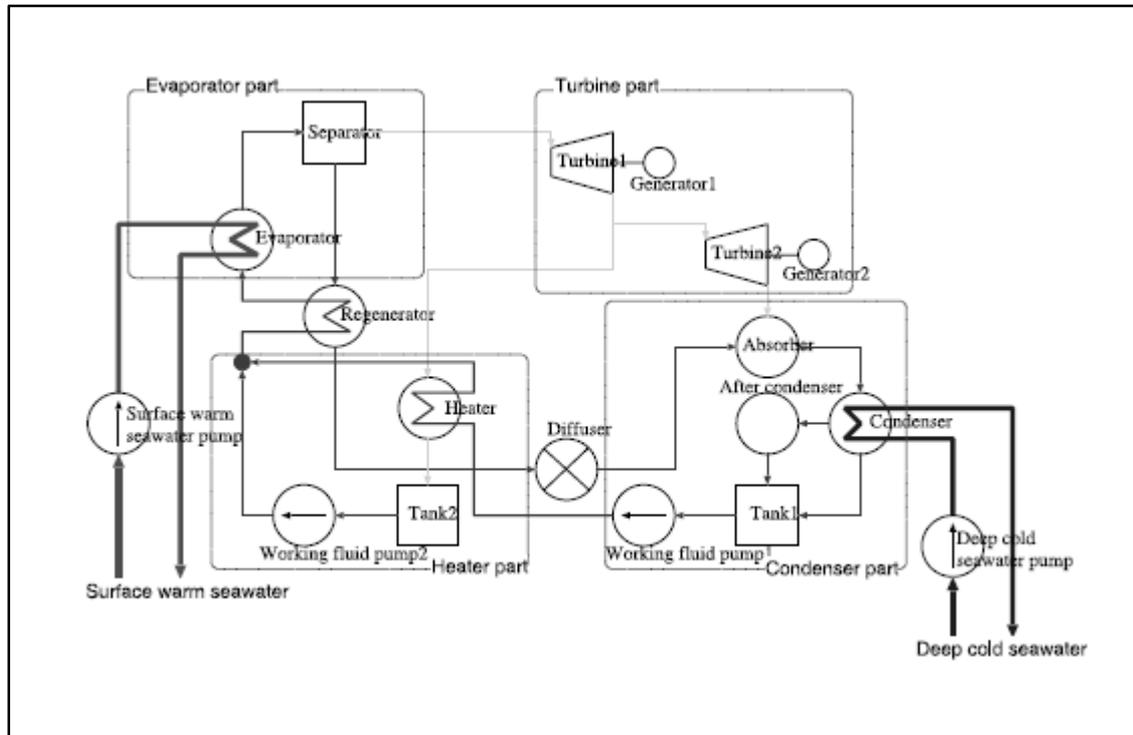


Figure B.1 – Schematic of Uehara cycle



B.3 Companies that work with ORC

Ormat Technologies Inc.

The OEC is a field-proven, mature commercial product used in 71 countries worldwide. Ormat has successfully manufactured and supplied about 1100 MW of geothermal power plants, based on its proprietary technology, logging millions of hours of operating experience.

The ORMAT® ENERGY CONVERTER (OEC) is a power generation unit, which converts low, medium and high temperature heat into electrical energy. A single OEC may range in size from 250 kW to 20 MW

<http://www.ormat.com/oec>

Maxxtec AG

The vapour phase organic fluid allows the use of low temperatures to generate electrical power from a few kW to 2.5 MW module.

ORC modules up to an electrical output of 500 kW are delivered pre-assembled on a skid. All main equipment parts of the turbo generator e.g. heat exchanger, feed pump, turbine, generator piping, instruments/wiring and other auxiliary equipment are pre installed and allow cost effective transport and installation at site.

<http://en.maxxtec.net/products/renewable-energies/orc-module/>

Pratt&Whitney

Pratt & Whitney Power Systems (PWPS) developed the PureCycle® power system (280 kW) for low-to-moderate temperature heat streams, particularly in the smaller (1 MW or lower) size range. Turboden, a PWPS company, is an ORC manufacturer based in Italy with more than 30 years of experience. It manufactures ORC product lines suitable for moderate and higher temperature heat streams, particularly in the larger (1 MW – 12 MW, and up) size range.

http://www.pw.utc.com/products/power_systems/organic_rankine_cycle.asp

Infinity Turbine LLC

Of the very small number of ORC manufactures, most focus on above 500 kw/hr output. The few big players focus on above 1 MW/hr output. Yet more than 90 percent of the availability of waste heat world wide is available to the 10-400 kw/hr system size. For this reason, we are focussing on small ORC systems which allow the ORC user to capture and profit from low grade heat. [...], Infinity Turbine provides any size turbine from the IT01, IT10, IT50 and IT400.

http://www.infinityturbine.com/ORC/ORC_Waste_Heat_Turbine.html

GMK - Gesellschaft für Motoren und Kraftanlagen mbH



INDUCAL-, „industrial caloric" describes our **organic rankine cycle-waste heat recovery** product line that makes it possible to recover **waste heat** efficiently from industrial plants, such as glass and steel mills or big engines for the generation of electricity.

The primarily named **waste heat** sources nowadays are mainly not recovered since most of the time they are only available on low temperature levels (up to 300°C/572°F) with small power outputs. Based on these reasons such waste heat potentials can not be converted into electricity with the water steam cycle, because of the high investment costs of such plants and physical properties of water.

http://www.gmk.info/ORC_waste_heat.523.html?

Barber-Nichols Inc.

Barber-Nichols, Inc. (BNI) specializes in the design and manufacture of Waste Heat Recovery Systems & Geothermal Power Generation Equipment. Thermodynamic Cycle Systems including Organic Rankine Cycles (ORC) and Steam Rankine Cycles are a core competency at BNI. These systems are used to turn industrial waste and geothermal heat, as low as 115° C (240° F), into electrical energy.

http://www.barber-nichols.com/products/waste_heat_power_generation_equipment/



B.4 Companies that work with Kalina

Kalex: They have developed the second generation: SG-2a, SG-2c, SG-2d and SG-4d

<http://kalexsystems.com>

X-Orka: Exorka International Limited is the result of the merging of Exorka (who has been licensed for Iceland, Central America and some part of Western Europe) and GeoDynamics (who has the license for Australia and New Zeland).

www.exorka.com

Global Geothermal: It owns the patents for over 200 Kalina cycles

www.globalgeothermal.com

Recurrent Engineering: The subsidiary company of Global Geothermal

www.recurrentengineering.com

Wasabi Energy: They own 96% of Global Geothermal

www.wasabienergy.com

Shanghai Shenghe New Energy Resources Science and Technology Co. Ltd: The patents have been licensed to them and they are developing several projects in China.

www.shanghaishenghe.com

Siemens: They have been licensed for Kalina technology in Germany up to 10 MW

Raser Technology is a US company that has been licensed both for geothermal and waste heat applications.

www.rasertech.com

Energent: they manufacture turbines and they seem to be involved in every major Kalina project.

www.energnet.net



B.5 Some current Kalina projects

Figure B.2 is extracted from a Global Geothermal presentation [Ref. 16] and it shows the current projects of this company (dated May 2009) involving a Kalina cycle.



Figure B.2 – Kalina Cycle current project

Figure B.3 is also an extraction from a presentation of Wasabi (the owner of Global Geothermal) and it shows the revenue targets for Global Geothermal [Ref. 70]

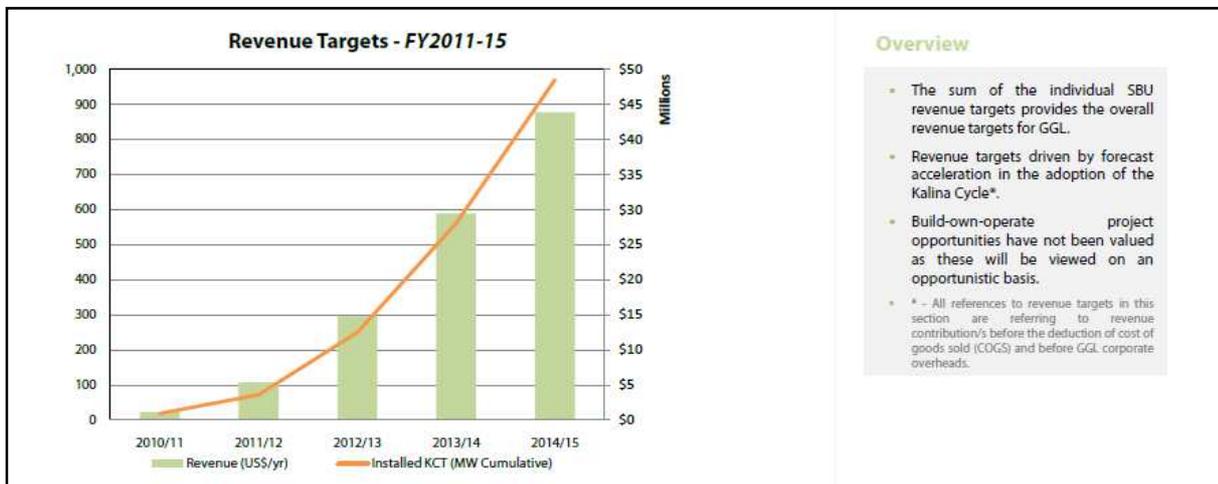


Figure B.3 – Revenue targets of Global Geothermal Ltd. for the next 5 years

The target revenues for the next 5 years increase exponentially and so does the cumulative installed power. Despite the fact that this slide is only a projection, it shows the great expectations for the Kalina cycle technology in the near future.



B.6 Kalex Kalina cycles: SG series

Below we will show in Figures B.4 to B.7 the schematics of the four Kalex cycles: SG-2a, SG-2c, SG-2d and SG-4d [Ref. 59].

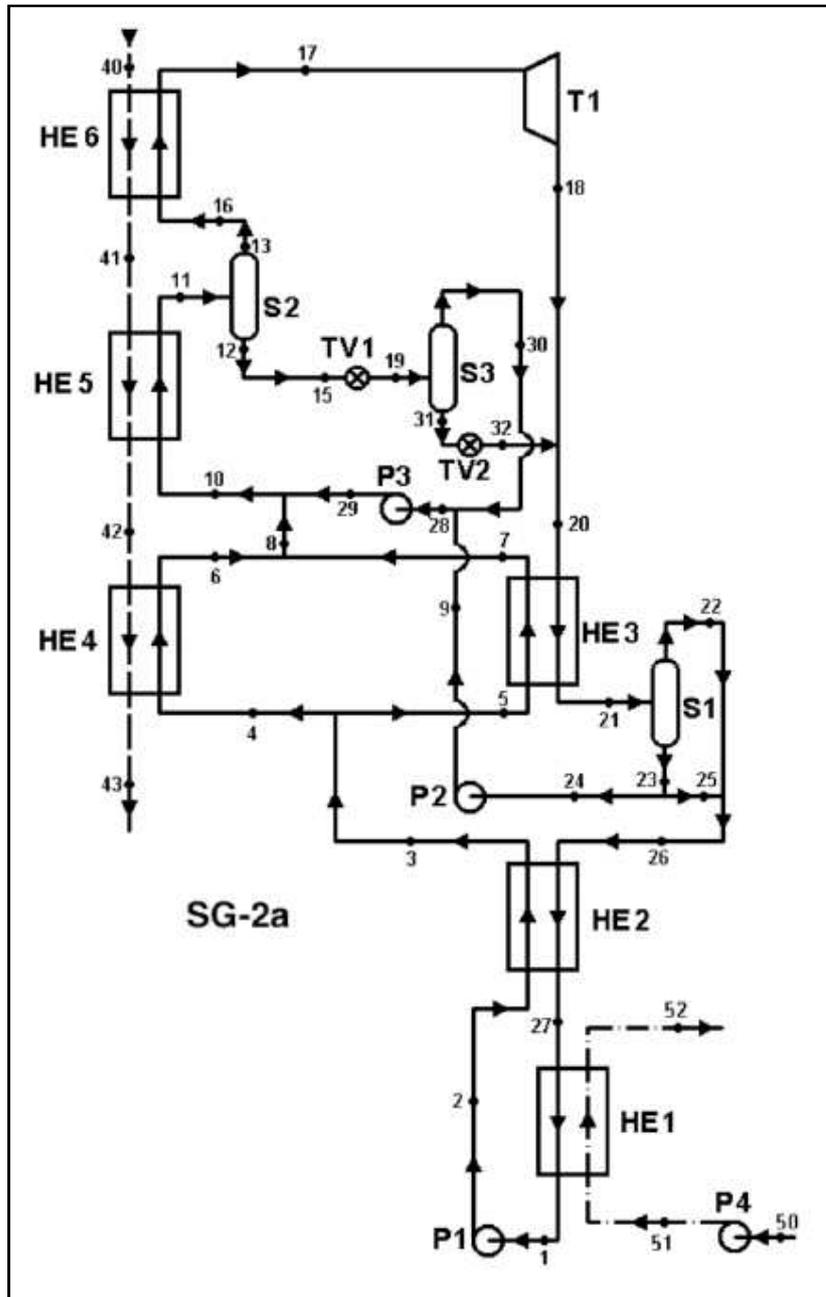


Figure B.4 – Kalex Kalina cycle SG-2a schematic



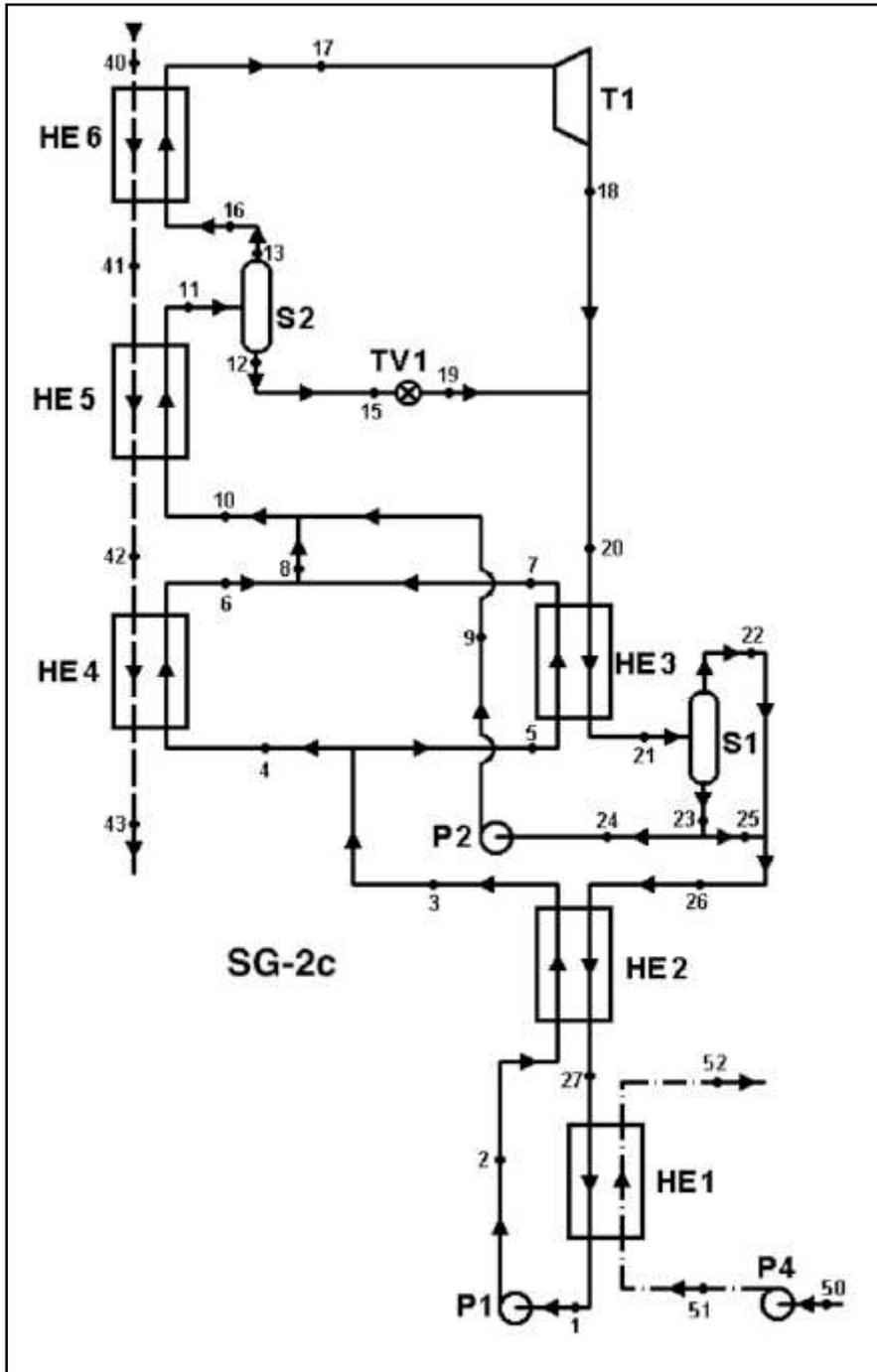


Figure B.5 – Kalex Kalina cycle SG-2c schematic



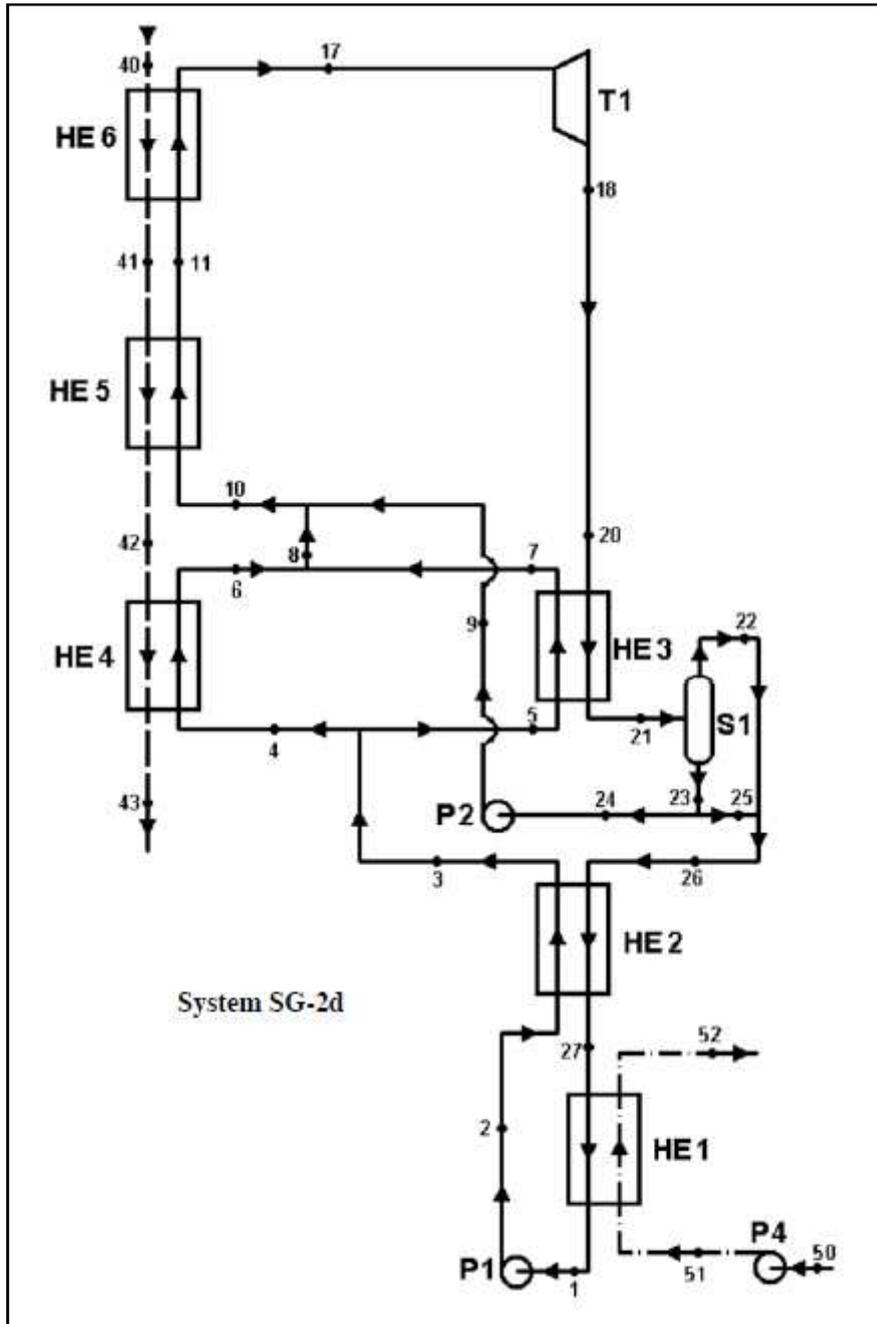


Figure B.6 – Kalex Kalina cycle SG-2d schematic



C Household electricity calculation

This chapter describes the calculation steps taken in order to determine how many households could be provided with electricity with a 1MW power plant.

Description	Value	Unit
Total electricity consumed by Dutch households in 2009, Ref. [72]	2.077	Mtoe
Conversion factor from toe to MWh	11,63	MWh/toe
Total electricity consumed by Dutch households in 2009, converted	24.155	TWh
Number of household in the Netherlands in 2008, Ref. [73]	7.242.202	households
Average annual electricity consumption for households	3,335	MWh/household
Utilisation factor	75	%
Annual electricity production	6.570	MWh
Number of household that could be provided for	1.970	households

Table C.1 – Details of households electricity calculation



D Properties of fluids in REFPROP

Below you can find a reproduction of Chapter 4.7.1 from the *Cycle-Tempo Reference Guide*:

This database (REFrigerant PROPERTIES) concerns Version 4.01 of the Standard Reference Database 23 of NIST (National Institute of Standards and Technology) from the U.S.A. The database contains 38 different refrigerants (see the table below).

Table 4-1: pure refrigerants

Nr.	Type	Critical point		
		pc (bar)	Tc (°C)	vc (m ³ /kg)
1	R11	44.7	198.1	179.81E-05
2	R12	41.8	111.8	179.47E-05
3	R13	38.7	28.9	173.27E-05
4	R13B1	40.2	67.1	134.31E-05
5	R14	38.0	-45.6	160.23E-05
6	R21	51.7	178.5	191.59E-05
7	R22	50.5	96.2	195.44E-05
8	R23	49.0	26.0	189.97E-05
9*)	R32	57.9	78.2	231.43E-05
10	R113	34.6	214.4	175.58E-05
11	R114	32.5	145.7	179.62E-05
12	R115	31.5	79.9	163.14E-05
13*)	R123	36.7	183.8	181.78E-05
14	R123a	37.4	188.0	183.87E-05
15*)	R124	36.4	122.5	178.65E-05
16*)	R125	36.3	66.2	174.84E-05
17	R134	45.6	119.0	185.24E-05
18*)	R134a	40.7	101.2	195.04E-05
19	R141b	41.2	204.2	185.57E-05
20	R142b	41.2	137.2	229.87E-05
21	R143	45.2	156.8	226.08E-05
22	R143a	38.1	73.1	230.37E-05
23	R152a	44.9	113.6	274.03E-05
24	R218	26.8	72.0	159.23E-05
25*)	R290 (propane)	42.5	96.7	498.90E-05
26	RC270 (cyclopropane)	55.8	125.2	461.03E-05
27	RC318	27.8	115.2	162.36E-05
28	R227ea	29.5	101.9	168.78E-05
29	R236ea	35.3	139.3	175.14E-05
30	R245cb	31.4	106.9	203.79E-05
31*)	R600 (n-butane)	38.0	152.0	438.72E-05
32*)	R600a (i-butane)	36.3	134.7	440.44E-05
33*)	n-C5 (n-pentane)	33.6	196.4	408.32E-05
34*)	i-C5 (i-pentane)	33.7	187.4	424.12E-05
35*)	CO2 (R744)	73.8	30.9	217.45E-05



36	E134	42.3	147.1	189.78E-05
37	E245	34.2	170.9	199.94E-05
38	NH3 (R717)	113.3	132.3	425.72E-05

For all refrigerants, except for ammonia, a simple as well as a more complex thermodynamic model is available.

The simple model is the equation of state according to Carnahan-Starling-DeSantis (CSD). This equation represents the properties of refrigerants quite well between certain limits. The model can easily be extended to mixtures of refrigerants. However, the model is not suited to calculate properties over wide ranges of pressure and temperature.

There are two different thermodynamic models available, which are more complex and can predict the properties of refrigerants more accurately over wide ranges of pressure and temperature. The MBWR-model (Modified Benedict-Webb-Rubin) for the calculation of thermodynamic properties is available for 11 refrigerants. These refrigerants are marked with an asterisk *) in the table shown below. For the remaining refrigerants the ECS-model (Extended Corresponding States) is available.

The properties of ammonia can be calculated with the high-accuracy equation of state developed by Haar en Gallagher (see: *J. Phys. Chem. Ref. Data* 7, 635-792 (1978)).

The transport properties of refrigerants are always calculated with the ECS-model.

Besides the pure refrigerants listed in Table 4-1 a large number of commercially available refrigerant mixtures is available. Table 4-2 lists the mixtures presently available in Cycle-Tempo and their corresponding compositions. The thermodynamic properties are calculated with the CSD-model, and the transport properties with the ECS-model.

Table 4-2: refrigerant mixtures

Mixture	Components	Composition (mass %)
R401A	R22/R152a/R124	53/13/34
R401B	R22/R152a/R124	61/11/28
R401C	R22/R152a/R124	33/15/52
R402A	R22/R290/R125	38/2/60
R402B	R22/R290/R125	60/2/38
R403A	R22/R218/R290	75/20/5
R403B	R22/R218/R290	56/39/5
R404A	R125/R134a/R143a	44/4/52
R405A	R22/R152a/R142b/RC318	45/7/5.5/42.5
R406A	R22/R142b/R600a	55/41/4
R407A	R32/R125/R134a	20/40/40
R407B	R32/R125/R134a	10/70/20
R407C	R32/R125/R134a	23/25/52



R407D	R32/R125/R134a	15/15/70
R408A	R22/R125/R143a	47/7/46
R409A	R22/R124/R142b	60/25/15
R409B	R22/R124/R142b	65/25/10
R410A	R32/R125	50/50
R410B	R32/R125	45/55
R412A	R22/R218/R142b	70/5/25
R413A	R218/R134a/R600a	9/88/3
AM DI36	R22/R124/R600	50/47/3
AM DI44	R22/R125/R143a/R290	50/42/6/2
Daikin	R32/R134a	30/70
EA FX40	R32/R125/R143a	10/45/45
EA FX220	R23/R32/R134a	4.5/21.5/74
Hoec HX4	R32/R125/R134a/R143a	10/33/21/36
HOTSHOT	R22/R124/R600a/R142b	50/39/1.5/9.5
NARM 22	R23/R22/R152a	5/80/15
NARM 502	R23/R22/R152a	5/90/5
OZ 12	R290/R600a	50/50
Isceon59	R125/R134a/R600a	46/50/4
Isceon89	R125/R290/R218	86/5/9
R500	R12/R152a	73.8/26.2
R501	R22/R12	75/25
R502	R22/R115	48.8/51.2
R503	R23/R13	40.1/59.9
R504	R32/R115	48.2/51.8
R507	R125/R143a	50/50
R509A	R22/R218	44/56

With regard to the validity range of the models the following can be said:

CSD-model

$0.6 * T_c < T < T_c$ (T in K) for pressures up to the saturation pressure, thus not for compressed liquid.

$T > T_c$ (T in K) for densities (ρ) below the critical value (the critical density ρ_c is the reciprocal value of the critical volume v_c , as mentioned in the third column of the table).

It is wise to avoid situations with $0.95 * T_c < T < 1.1 * T_c$ (T in K) for $0.5 * \rho_c < \rho < 2 * \rho_c$.

MBWR-model

Temperatures from triple point up to $1.2 * T_c$ (T in K) for pressures up to $2.2 * p_c$. Situations near the critical point should best be avoided.

ECS-model



$0.35 * T_c < T < 1.2 * T_c$ (T in K) for pressures up to $2.2 * p_c$. Situations near the critical point should best be avoided.

Input parameters

For medium type REFPROP the following input parameters can be specified:

1. Reference state for enthalpy and entropy.

There are 3 possibilities:

- Liquid at normal boiling point (1 atm) (default value)
- Liquid at -40°C (ASHRAE-convention)
- $h = 200 \text{ kJ/kg}$ and $s = 1 \text{ kJ/kgK}$ for saturated liquid at 0°C (IIR-convention)

2. Thermodynamic model to be used to calculate thermodynamic and transport properties.

There are 3 possibilities:

- CSD-equation of state
- If possible MBWR-equation of state, otherwise ECS-model
- Special equation of state for ammonia



E Annexes related to money/economics

E.1 Inflation and exchange rates

Several of the economic data that has been used in this study has been taken from old sources. Then, inflation has been taken into account with the BCE data [Ref. 74] (shown in Table E.1).

EU inflation (HICP)	
2010	1,61 %
2009	0,30 %
2008	2,95 %
2007	2,13 %
2006	2,18 %
2005	2,17 %
2004	2,15 %
2003	2,10 %
2002	2,24 %
2001	2,33 %
2000	2,09 %
1999	1,15 %
1998	1,11 %
1997	1,57 %
1996	2,18 %

Table E.1 – Historical inflation in EU

Also, some of the data was expressed in dollars. In this case, we converted from dollars to euros according to the exchange rate of the corresponding year. Table E.2 below shows the historical exchange rates: dollar to euro [Ref. 75]

Exchange rates (\$ to €)	
2010	0,755
2009	0,719
2008	0,683
2007	0,731
2006	0,797
2005	0,804
2004	0,805
2003	0,885
2002	1,061
2001	1,118
2000	1,087
1999	0,939

Table E.2 - Historical exchange rates



E.2 Updating costs through inflation and conversion

Finally, table E.3 shows the process (step by step) that was followed to convert and update the cost figures. Numbers have been rounded up to the tens.

	Source	Year	Original data	Euro conversion	Euro 2010	
O&M Chapter 3.3.2	Lovekin	2005	2,5 c\$/kWh	2,01 c€/kWh	2,2 c€/kWh	
	ETSAP	2010	140.000 \$/yr	113.000 €/yr	113.000 €/yr	
	Leslie	2009	200.000 \$/yr	144.000 €/yr	150.000 €/yr	
ORC Chapter 4.5	U.S. Dep. of Energy	2008	2.500 \$/kW	1.708 €/kW	1.750 €/kW	
	Pernecker	1995	1.580 €/kW	1.580 €/kW	2.090 €/kW	
	Leslie	2009	2.500 \$/kW	1.800 €/kW	1.830 €/kW	
	Schuster	2009	3.755 €/kW	3.755 €/kW	3.820 €/kW	
	Theдки	2007	3.500 \$/kW	2.560 €/kW	2.700 €/kW	
	ACEP: P&W	2009	1,4 M\$	1,13 M€	1,15 M€	
	ACEP: Pacific	2009	2,25 M\$	1,81 M€	1,85 M€	
	Sherman	current		50 c\$/lb	37,75 c€/lb	82,22 c€/kg
		current		90 c\$/lb	67,95 c€/lb	149,8 c€/kg
Kalina Chapter 5.4	Hawaii	2003	1.200 \$/kW	1.070 €/kW	1.230 €/kW	
	Húsavík	1999	973 \$/kW	920 €/kW	1.150 €/kW	
	Unterhaching	2009	2.170 €/kW	2.170 €/kW	2.210 €/kW	
	Bruchsal	2009	9.600 €/kW	9.600 €/kW	9.780 €/kW	
	Theдки	2007	3.000 \$/kW	2.200 €/kW	2.310 €/kW	
	ICIS.com	current		380 \$/ton	287 €/ton	28,7 c€/kg
		current		780 \$/ton	589 €/ton	58,9 c€/kg

Table E.3 – Detail of costs updates for ORC and Kalina

E.3 Electricity prices in EU countries

We already established that the average electricity price for industrial consumers was 8,5 c€/kWh and now we want to see how it compares to the rest of the EU countries, as shown in Figure E.1 from Eurostat [Ref. 39]:

The Netherlands value is just below the average of the EU-27 and the Euro Area (EA). However, should we carry out this project in any other country, we would obtain very different revenues:

- In Bulgaria, Estonia, France and Finland, the project would probably not be profitable due to the low price of electricity for industrial consumers.
- On the other hand, this project would be more profitable and (it would make even more sense) in countries where electricity is expensive, like Malta, Cyprus, Ireland, Spain or Slovakia



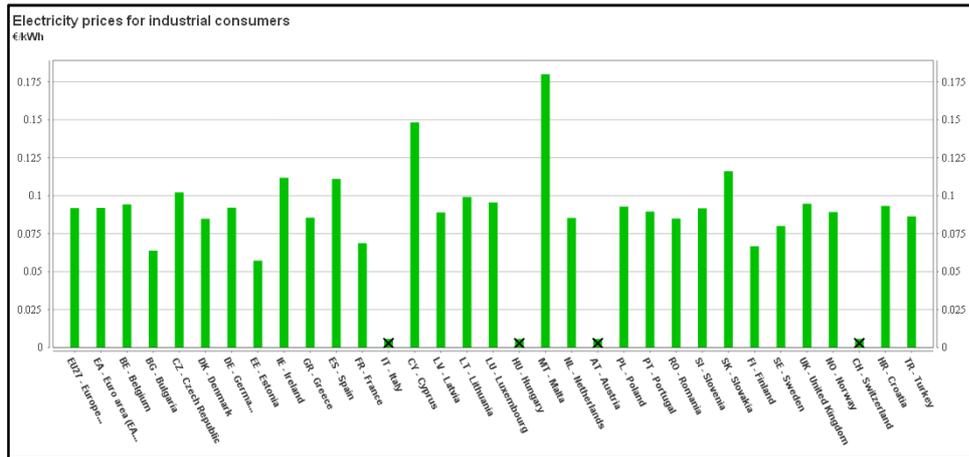


Figure E.1 – Electricity prices for industrial consumers in 2010 in the EU

E.4 Euribor 1-year

Our timespan for the investment is 15 years. It would be wrong to choose the current Euribor 1-year rate (1,3533% for year 2010) because it will not stay like this for the next 15 years. Therefore, we will use an average of the last 15 years of the Euribor in order to calculate an interest rate for our investment. Table E.5 and Figure E.2 show these values, extracted from the ECB Statistical Data Warehouse [Ref. 41].

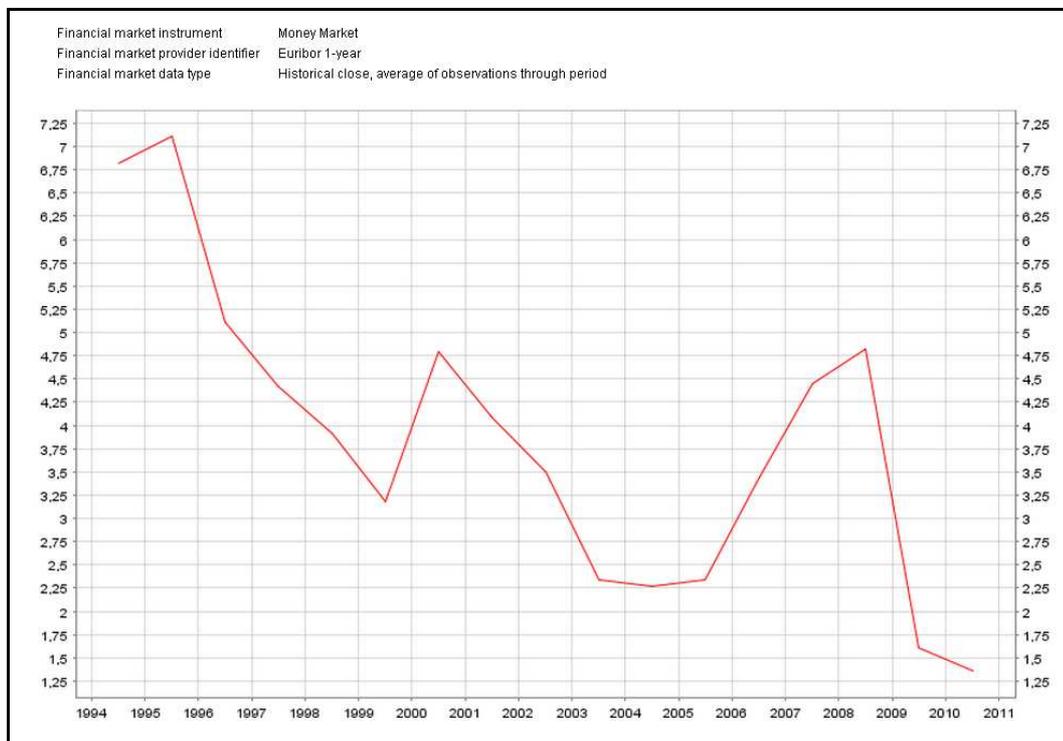


Figure E.2 – Chart of the Euribor 1-year values



Year	Euribor 1-year
2009	1,6103 %
2008	4,8260 %
2007	4,4500 %
2006	3,4360 %
2005	2,3328 %
2004	2,2746 %
2003	2,3339 %
2002	3,4926 %
2001	4,0862 %
2000	4,7890 %
1999	3,1833 %
1998	3,9058 %
1997	4,4192 %
1996	5,1067 %
1995	7,1067 %
Average	3,82 %

Table E.4 - Euribor 1-year values and average

We could also have chosen as a reference the 10-year interest on the Dutch government bonds, but these are one of the most conservative interest rates of the market, as shown in Figure E.3 [Ref. 76]:

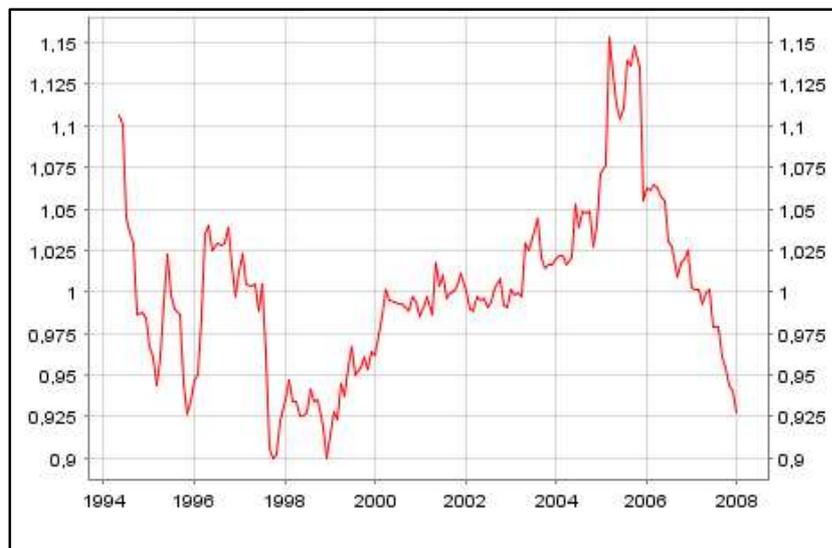


Figure E.3 – Interest on the 10-year government bonds in the Netherlands

As we can see, the interest rate has been kept between 0,90% and 1,15% for more than 10 years. This shows that Netherlands is a very financially stable country.



E.5 Tax discounts

The government of the Netherlands has several support schemes in order to promote renewable energy sources (RES) (for electricity, gas, heat and others) with the hope to achieve its targets (see Chapter 1.1).

The Renewable Energy Incentives (SDE, Stimuleringsregeling Duurzame Energieproductie) is a fund that pays for the difference between the “grey energy” price and renewable energy [Ref. 77, 78]. This way, it compensates for the fact that RES are more expensive than “grey energy” and it ensures that RES producers can make a profit. This case, however, is not applicable to our project because we don't intend to sell electricity in the wholesale market.

Another rewarding scheme is called Energy Investment Deduction Scheme (EIA, Energie Investeringsaftrek): it allows for a 41,5% deduction of an investment in renewable energy.

Year	0
Profit	0 €
Investment	1.500.000 €
41,5 % of the investment	622.500 €
Tax applicable profit	-622.500 €
Tax rate	20 %
Tax amount	-124.500 €

Table E.5 – Calculations for Energy Investment Scheme

If a company makes no profit during the year of the investment, it can be “passed” on to the next 6 years. Therefore, we will discount the 124.500 € from the tax amount due of the next six years after the investment (years 1 to 6).

The economic variables (IRR, NPV and payback) would slightly improve, as shown in Table E.6 (for Kalina cycle) and Table E.7 (for ORC): the IRR and the NPV increase and the payback decreases. We can conclude (as expected) that the tax discounts would slightly increase the profitability of the investment.



KALINA	Without tax deduction	With tax deduction
IRR	6,39 %	6,86 %
NPV	177 k€	236 k€
Payback	8,85 years	8,48 years
Amount deducted	0 k€	76,6 k€

Table E.6 – Kalina economic variables with and without tax deduction

ORC	Without tax deduction	With tax deduction
IRR	6,18 %	6,63 %
NPV	195 k€	267 k€
Payback	9,9 years	9,56 years
Amount deducted	0 k€	94,9 k€

Table E.7 – ORC economic variables with and without tax deduction

As we can see, we would not be able to discount the full 124,5 k€; the best case would be for ORC because we could discount 94,9 k€ while with Kalina system only 76,6 k€.

Chart E.1 shows the revised Kalina incomes with the tax deductions, and Chart E.2 shows the same for ORC. We can see that for the first six years there are no tax payments:

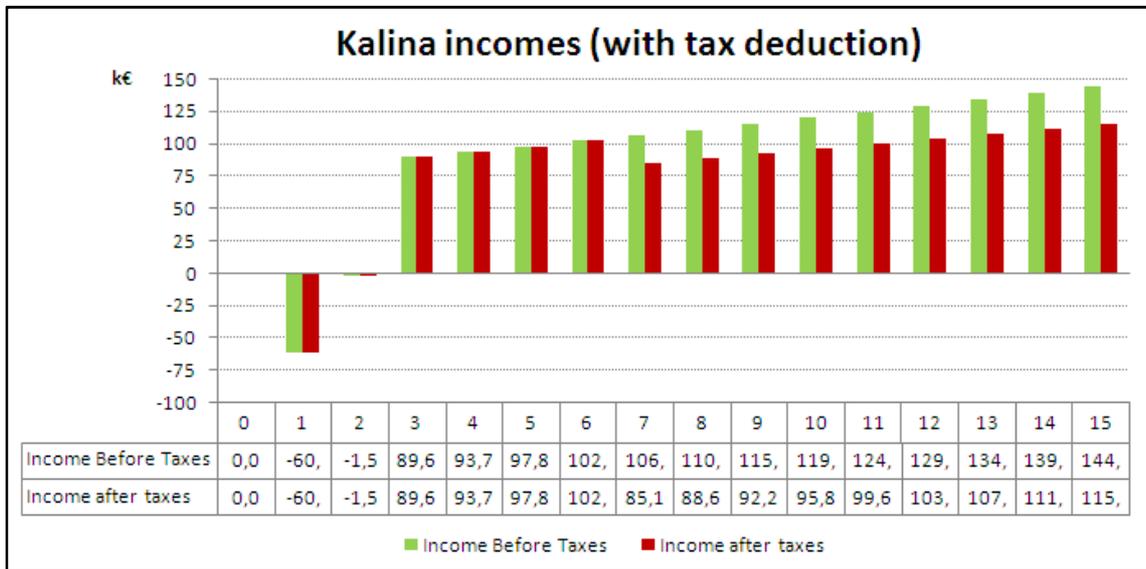


Chart E.1 – Kalina incomes with tax deductions



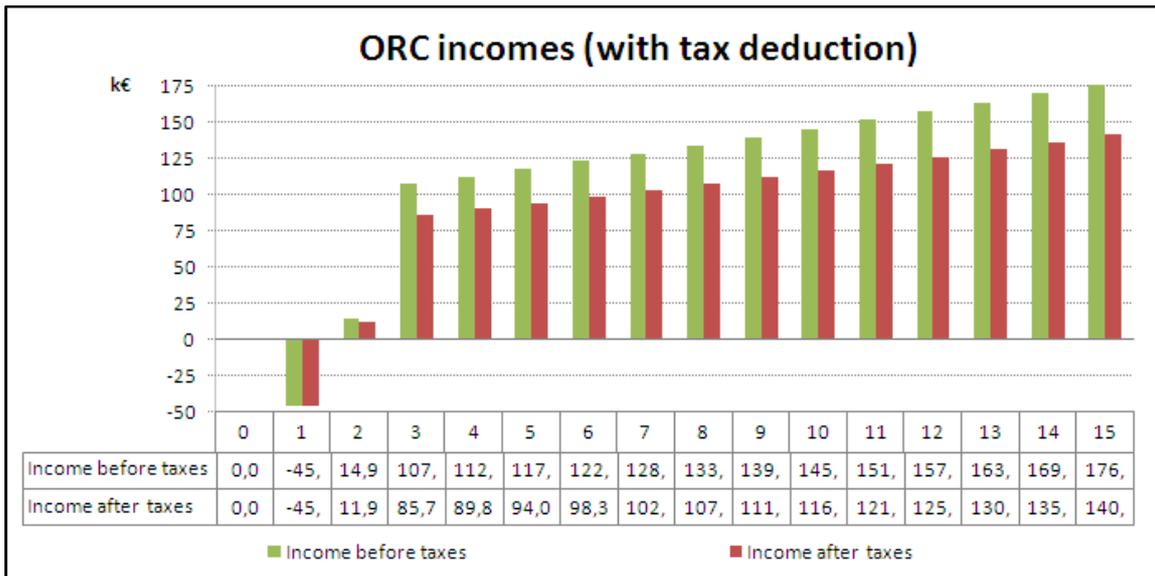


Chart E.2 - ORC incomes with tax deductions



F Cycle-Tempo results

F.1 ORC (isopentane) results with summer conditions

This is the Cycle-Tempo diagram with the results of the simulation for OC with isopentane as working fluid and summer conditions.

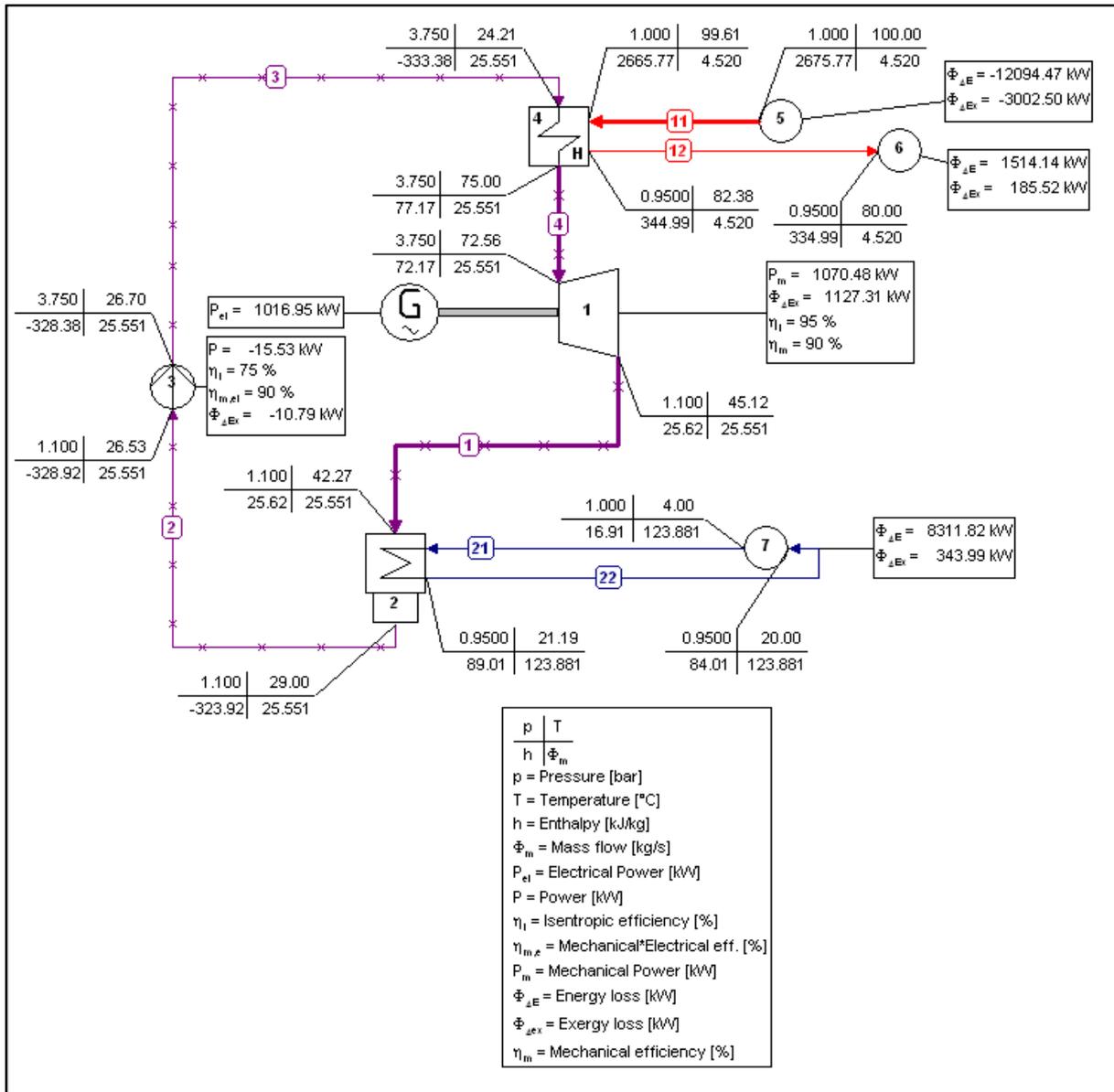


Figure F.1 – Schematic of Cycle-Tempo simulation for ORC (isopentane) in summer



No.	Name	Type	Energy loss (enthalpy)	Energy loss (HHV)	Energy loss (LHV)
			[kW]	[kW]	[kW]
1	Turbine	3	1189.42	1189.42	1189.42
2	Condenser	4	0.00	0.00	0.00
3	Pump	8	-13.97	-13.97	-13.97
5	Sink/Source	10	-12094.47	-11714.73	-624.69
6	Sink/Source	10	1514.14	1134.40	-9955.64
7	Sink/Source	10	7207.82	7207.82	7207.82
4	Heat Exchgr.	12	0.00	0.00	0.00
1	Pipe		0.00	0.00	0.00
2	Pipe		-127.75	-127.75	-127.75
3	Pipe		-127.75	-127.75	-127.75
4	Pipe		-127.75	-127.75	-127.75
11	Pipe		-45.20	-45.20	-45.20
12	Pipe		-45.20	-45.20	-45.20
22	Pipe		-1723.40	-1723.40	-1723.40
	Total:		-8788.00	-8788.00	-8788.00

Figure F.2 – Energy balance for ORC isopentane with summer conditions

No.	Name	Type	Exergy transmitted from system [kW]			Rel. Ex. Loss [%]	Func. Exergy eff. [%]	Univ. Exergy eff. [%]
			Total	Power/Heat	Losses			
1	Turbine	3	1122.79	1070.48	52.31	2.22	95.34	96.31
2	Condenser	4	195.84	0.00	195.84	8.32	31.81	33.39
3	Pump	8	-10.56	-15.53	4.97	0.21	68.00	74.56
7	Sink/Source	10	59.06	0.00	59.06	2.51		-0.78
4	Heat Exchgr.	12	809.33	0.00	809.33	34.38	63.77	65.66
1	Pipe		0.00		0.00	0.00		
2	Pipe		3.30		3.30	0.14		
3	Pipe		2.33		2.33	0.10		
4	Pipe		19.78		19.78	0.84		
11	Pipe		9.63		9.63	0.41		
12	Pipe		7.81		7.81	0.33		
22	Pipe		32.29		32.29	1.37		
	Medium to/from env.							
5	Sink/Source	10	-2353.96	0.00	-2353.96	-100.00		
6	Sink/Source	10	102.36	0.00	102.36	4.35		
	Total:		0.00	1054.95	-1054.95	-44.82		

Figure F.3 – Exergy balance for ORC isopentane with summer conditions

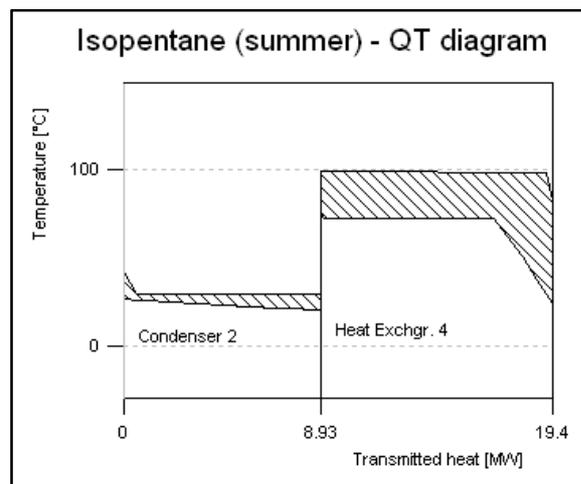


Figure F.4 – QT diagram for ORC isopentane in summer



F.2 ORC (isopentane) results with winter conditions

This is the Cycle-Tempo diagram with the results of the simulation for ORC with isopentane as working fluid and winter conditions.

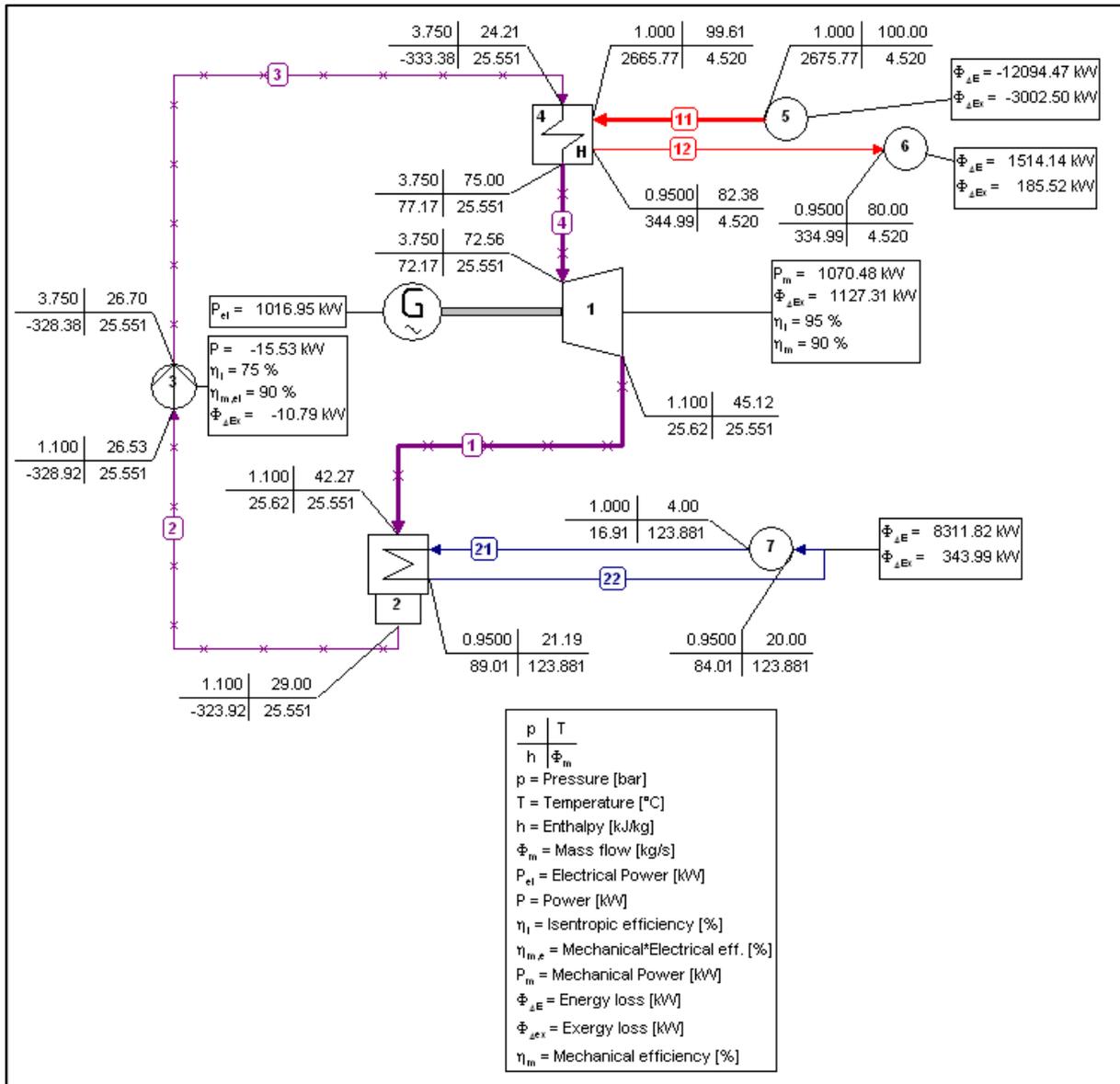


Figure F.5 – Schematic of Cycle-Tempo simulation for ORC (isopentane) in winter



No.	Name	Type	Energy loss (enthalpy)	Energy loss (HHV)	Energy loss (LHV)
			[kW]	[kW]	[kW]
1	Turbine	3	1189.42	1189.42	1189.42
2	Condenser	4	0.00	0.00	0.00
3	Pump	8	-13.97	-13.97	-13.97
5	Sink/Source	10	-12094.47	-11714.73	-624.69
6	Sink/Source	10	1514.14	1134.40	-9955.64
7	Sink/Source	10	8311.82	8311.82	8311.82
4	Heat Exchgr.	12	0.00	0.00	0.00
1	Pipe		0.00	0.00	0.00
2	Pipe		-127.75	-127.75	-127.75
3	Pipe		-127.75	-127.75	-127.75
4	Pipe		-127.75	-127.75	-127.75
11	Pipe		-45.20	-45.20	-45.20
12	Pipe		-45.20	-45.20	-45.20
22	Pipe		-617.93	-617.93	-617.93
	Total:		-4367.00	-4367.00	-4367.00

Figure F.6 – Energy balance for ORC isopentane with winter conditions

No.	Name	Type	Exergy transmitted from system [kW]			Rel. Ex. Loss [%]	Func. Exergy eff. [%]	Univ. Exergy eff. [%]
			Total	Power/Heat	Losses			
1	Turbine	3	1127.31	1070.48	56.83	1.89	94.96	97.26
2	Condenser	4	486.76	0.00	486.76	16.21	44.30	49.31
3	Pump	8	-10.79	-15.53	4.74	0.16	69.49	93.76
7	Sink/Source	10	343.99	0.00	343.99	11.46		3.97
4	Heat Exchgr.	12	754.39	0.00	754.39	25.13	73.01	75.27
1	Pipe		0.00		0.00	0.00		
2	Pipe		11.75		11.75	0.39		
3	Pipe		10.85		10.85	0.36		
4	Pipe		27.11		27.11	0.90		
11	Pipe		12.05		12.05	0.40		
12	Pipe		10.34		10.34	0.34		
22	Pipe		43.22		43.22	1.44		
	Medium to/from env.							
5	Sink/Source	10	-3002.50	0.00	-3002.50	-100.00		
6	Sink/Source	10	185.52	0.00	185.52	6.18		
	Total:		0.00	1054.95	-1054.95	-35.14		

Figure F.7 – Exergy balance for ORC isopentane with winter conditions

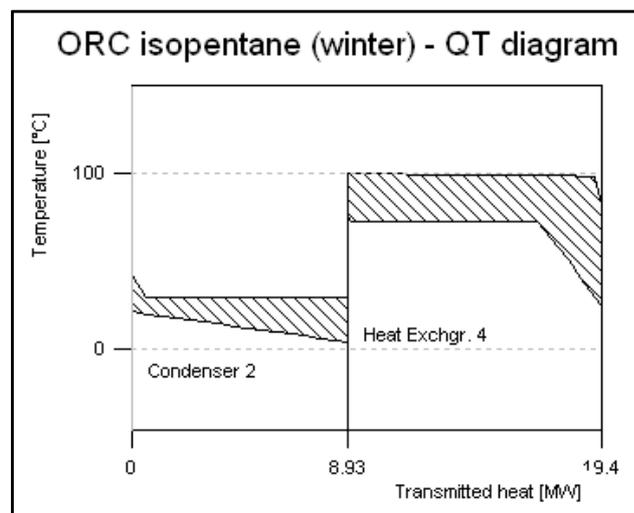


Figure F.8 – QT diagram for ORC isopentane in winter



F.3 Kalina cycle results with summer conditions

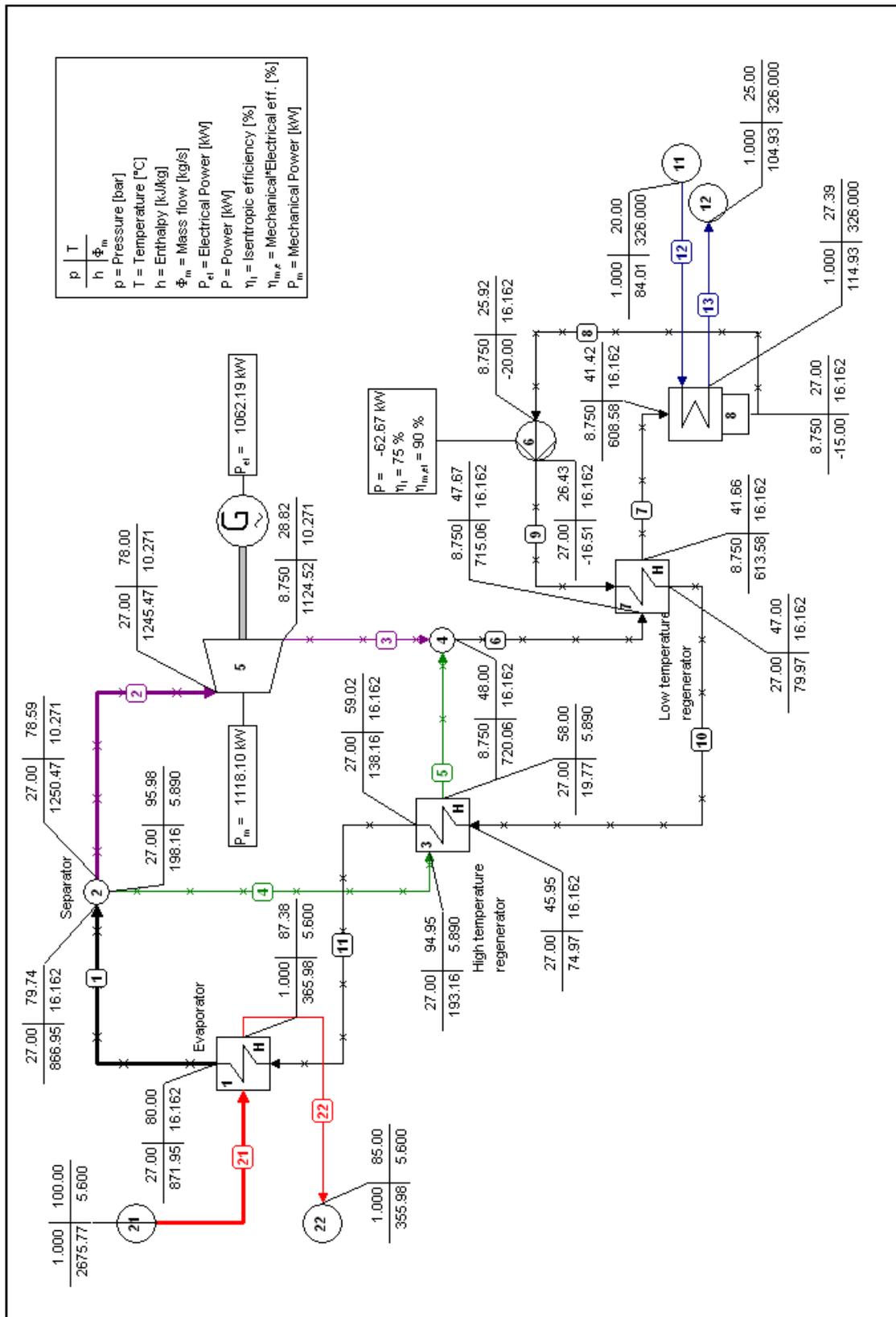


Figure F.9 – Schematic of Cycle-Tempo simulation for Kalina cycle in summer



No.	Name	Type	Energy loss (enthalpy)	Energy loss (HHV)	Energy loss (LHV)
			[kW]	[kW]	[kW]
5	Turbine	3	1242.15	1242.15	1242.15
8	Condenser	4	-0.52	-0.52	-0.52
3	Heat Exchgr.	6	0.00	0.00	0.00
1	Heat Exchgr.	6	996.48	3657.81	3657.81
7	Heat Exchgr.	6	0.00	0.00	0.00
6	Pump	8	-56.40	-56.40	-56.40
4	Node	9	0.00	0.00	0.00
11	Sink/Source	10	-27387.85	0.41	799857.56
12	Sink/Source	10	34205.04	6816.78	-793040.38
21	Sink/Source	10	-14984.30	-14513.82	-773.95
22	Sink/Source	10	1993.46	1522.99	-12216.89
2	Node	11	0.12	-2661.22	-2661.22
1	Pipe		80.80	80.80	80.80
2	Pipe		51.35	51.35	51.35
3	Pipe		0.00	0.00	0.00
4	Pipe		29.45	29.45	29.45
5	Pipe		29.45	29.45	29.45
6	Pipe		80.80	80.80	80.80
7	Pipe		80.80	80.80	80.80
8	Pipe		80.80	80.80	80.80
9	Pipe		80.80	80.80	80.80
10	Pipe		80.80	80.80	80.80
11	Pipe		80.80	80.80	80.80
13	Pipe		-3260.00	-3260.00	-3260.00
21	Pipe		0.00	0.00	0.00
22	Pipe		-56.00	-56.00	-56.00
	Total:		-11912.00	-11912.00	-11912.00

Figure F.10– Energy balance for Kalina with summer conditions

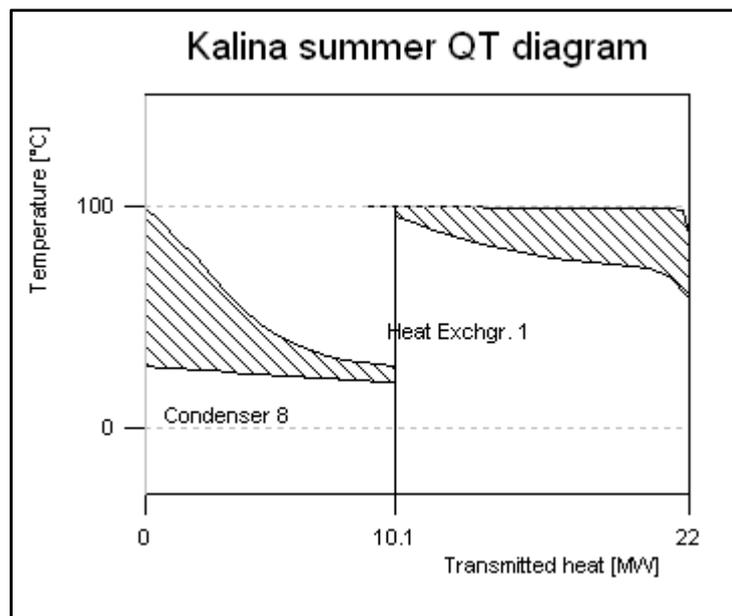


Figure F.11 – QT diagram for Kalina cycle in summer



No.	Name	Type	Exergy transmitted from system [kW]			Rel. Ex. Loss [%]	Func. Exergy eff. [%]	Univ. Exergy eff. [%]
			Total	Power/Heat	Losses			
5	Turbine	3	1396.86	1117.93	278.93	9.56	80.03	93.40
8	Condenser	4	284.87	0.00	284.87	9.77	30.21	89.78
3	Heat Exchgr.	6	62.68	0.00	62.68	2.15	61.91	97.80
1	Heat Exchgr.	6	382.05	0.00	382.05	13.10	86.15	93.06
7	Heat Exchgr.	6	38.14	0.00	38.14	1.31	69.20	99.29
6	Pump	8	-42.39	-62.66	20.28	0.70	67.64	99.17
4	Node	9	72.37	0.00	72.37	2.48		97.59
2	Node	11	361.35	0.00	361.35	12.39		92.70
1	Pipe		14.76		14.76	0.51		
2	Pipe		8.62		8.62	0.30		
3	Pipe		0.00		0.00	0.00		
4	Pipe		6.03		6.03	0.21		
5	Pipe		15.29		15.29	0.52		
6	Pipe		7.94		7.94	0.27		
7	Pipe		7.17		7.17	0.25		
8	Pipe		1.87		1.87	0.06		
9	Pipe		1.61		1.61	0.06		
10	Pipe		6.70		6.70	0.23		
11	Pipe		9.38		9.38	0.32		
13	Pipe		67.46		67.46	2.31		
21	Pipe		0.00		0.00	0.00		
22	Pipe		10.31		10.31	0.35		
	Medium to/from env.							
11	Sink/Source	10	0.43	0.00	0.43	0.01		
12	Sink/Source	10	55.43	0.00	55.43	1.90		
21	Sink/Source	10	-2916.41	0.00	-2916.41	-100.00		
22	Sink/Source	10	147.47	0.00	147.47	5.06		
	Total:		0.00	1055.27	-1055.27	-36.18		

Figure F.12 – Exergy balance for Kalina with summer conditions



F.4 Kalina cycle results with winter conditions

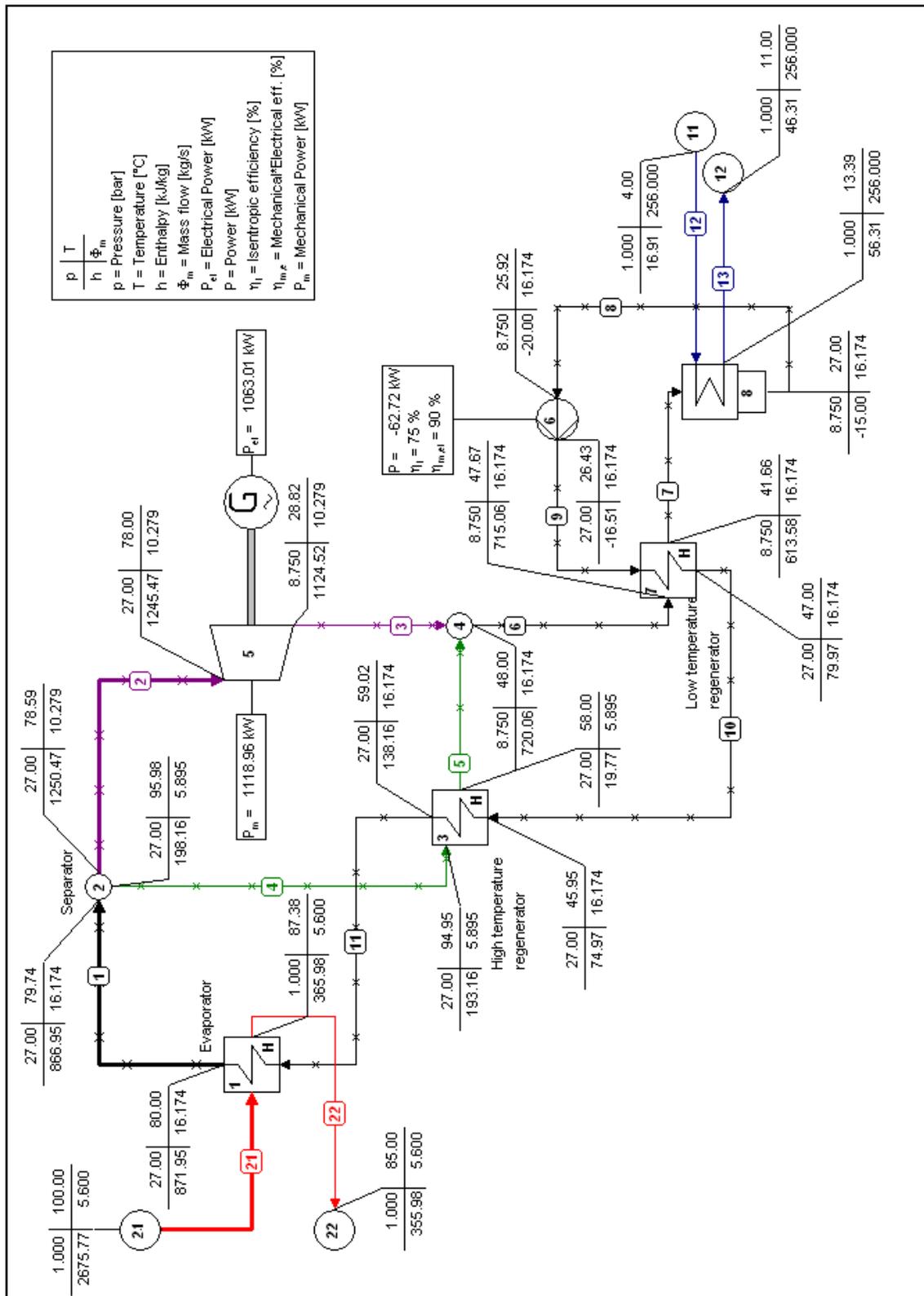


Figure F.13 – Schematic of Cycle-Tempo simulation for Kalina cycle in winter



No.	Name	Type	Energy loss (enthalpy)	Energy loss (HHV)	Energy loss (LHV)
			[kW]	[kW]	[kW]
5	Turbine	3	1243.14	1243.14	1243.14
8	Condenser	4	-0.52	-0.52	-0.52
3	Heat Exchgr.	6	0.00	0.00	0.00
1	Heat Exchgr.	6	986.97	4344.12	4344.12
7	Heat Exchgr.	6	0.00	0.00	0.00
6	Pump	8	-56.44	-56.44	-56.44
4	Node	9	0.00	0.00	0.00
11	Sink/Source	10	-4329.45	-4205.81	635972.38
12	Sink/Source	10	11854.66	11731.03	-628447.12
21	Sink/Source	10	-14984.30	-14981.59	-977.70
22	Sink/Source	10	1993.46	1990.76	-12013.14
2	Node	11	0.12	-3357.03	-3357.03
1	Pipe		80.86	80.86	80.86
2	Pipe		-51.39	-51.39	-51.39
3	Pipe		0.00	0.00	0.00
4	Pipe		-29.47	-29.47	-29.47
5	Pipe		-29.47	-29.47	-29.47
6	Pipe		-80.86	-80.86	-80.86
7	Pipe		80.86	80.86	80.86
8	Pipe		80.86	80.86	80.86
9	Pipe		80.86	80.86	80.86
10	Pipe		80.86	80.86	80.86
11	Pipe		80.86	80.86	80.86
13	Pipe		-2560.00	-2560.00	-2560.00
21	Pipe		0.00	0.00	0.00
22	Pipe		-56.00	-56.00	-56.00
Total:			-10258.00	-10258.00	-10258.00

Figure F.14 – Energy balance for Kalina with winter conditions

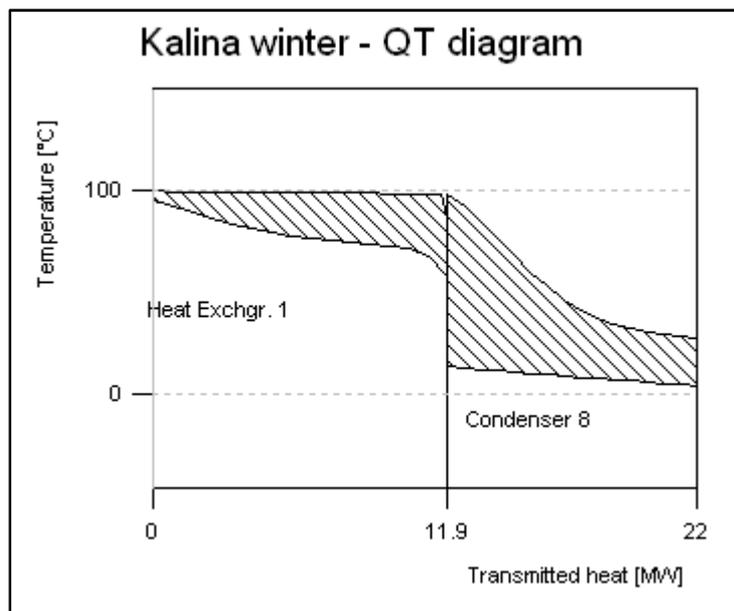


Figure F.15 –QT diagram for Kalina cycle in winter



No.	Name	Type	Exergy transmitted from system [kW]			Rel. Ex. Loss [%]	Func. Exergy eff. [%]	Univ. Exergy eff. [%]
			Total	Power/Heat	Losses			
5	Turbine	3	1387.46	1118.82	268.64	7.17	80.64	93.17
8	Condenser	4	760.14	0.00	760.14	20.27	28.65	68.44
3	Heat Exchgr.	6	58.47	0.00	58.47	1.56	73.77	96.94
1	Heat Exchgr.	6	623.75	0.00	623.75	16.64	81.92	88.43
7	Heat Exchgr.	6	35.58	0.00	35.58	0.95	84.32	99.10
6	Pump	8	-43.37	-62.71	19.34	0.52	69.16	98.59
4	Node	9	67.51	0.00	67.51	1.80		97.50
2	Node	11	134.69	0.00	134.69	3.59		96.99
1	Pipe		19.26		19.26	0.51		
2	Pipe		11.53		11.53	0.31		
3	Pipe		0.00		0.00	0.00		
4	Pipe		7.62		7.62	0.20		
5	Pipe		16.27		16.27	0.43		
6	Pipe		12.90		12.90	0.34		
7	Pipe		12.18		12.18	0.32		
8	Pipe		7.24		7.24	0.19		
9	Pipe		6.99		6.99	0.19		
10	Pipe		11.74		11.74	0.31		
11	Pipe		14.24		14.24	0.38		
13	Pipe		108.48		108.48	2.89		
21	Pipe		0.00		0.00	0.00		
22	Pipe		13.42		13.42	0.36		
	Medium to/from env.							
11	Sink/Source	10	-29.38	0.00	-29.38	-0.78		
12	Sink/Source	10	226.13	0.00	226.13	6.03		
21	Sink/Source	10	-3719.91	0.00	-3719.91	-99.22		
22	Sink/Source	10	257.07	0.00	257.07	6.86		
	Total:		0.00	1056.11	-1056.11	-28.17		

Figure F.16 – Exergy balance for Kalina with winter conditions



G Sensitivity analysis for CO₂ savings

When calculation the CO₂ savings, the most sensible piece of data is the average kg of CO₂ emitted per MWh of electricity generation. We have found several values from different sources and each of them would lead to a different result of CO₂ amount saved per year. The summary of these values can be found in Table H.1. Only the first value (from International Energy Agency) was used in Chapter 5.1 because it is direct (not obtained by calculation) and it comes from a very reliable source.

Data source	[kg CO ₂ per MWh]	[tons CO ₂ saved per year]
International Energy Agency	392	2575
Calculated from table H.2	450	2956
Calculated from table H.3	513	3370
From [Ref. 79], CARMA	549	3607
From [Ref. 80], Kerseens	570	3745

Table H.1 – Sensitivity analysis for CO₂ savings

In conclusion, we can see that the estimated savings would be in a range of **[2575 – 3745] tons of CO₂ per year.**

Source	Electricity generation [TWh] [Ref. 81]	share [%]	emission rate [kg CO ₂ per MWh] [Ref. 66]	CO ₂ emissions [Mtons]
coal	24,92	24,14%	870	21,7
oil	2,22	2,15%	750	1,7
gas	62,58	60,62%	370	23,2
nuclear	4,2	4,07%	0	0,0
renewables	9,15	8,86%	0	0,0
other	0,18	0,17%	0	0,0
TOTAL	103,24	100,00%	450	46,5

Table H.2 – Calculation of CO₂ emission rate through electricity generation sources

Electricity generation	103,2	TWh
CO ₂ emissions from electricity production	53,0	Mtons CO ₂
Emission rate for Netherlands	513,4	kg CO ₂ /MWh

Table H.3 – Calculation of CO₂ emission rate through 2007 aggregated figures [Ref 81]



H Safety sheets

H.1 Description of safety measurements

The following definitions have been taken from the Safety Glossary of The Physical and Theoretical Chemistry Laboratory, Oxford University [Ref. 82]

The **Flash Point** of a chemical is the lowest temperature at which a flame will propagate through the vapour of a combustible material to the liquid surface. Put more simply, it is the minimum temperature at which the liquid produces a sufficient concentration of vapour above it that it forms an ignitable mixture with air. Note that the source of ignition need not be an open flame, but could equally be, for example, the surface of a hot plate, or a steam pipe.

The **Auto-ignition Temperature** of a chemical is the lowest temperature at which a material will ignite without an external source of ignition.

The **Flammable Limits** refer to the conditions under which a mixture of a flammable material and air may catch fire or explode. If the percentage of flammable material in the air is between the minimum and maximum limits, the presence of a flame or a source of ignition is likely to lead to rapid combustion or explosion. **Flammable limits** for many materials are in the range 2 - 10%, but for some materials the limits are much wider. Ether (diethyl ether) for example, has flammable limits of 1.7 - 48%, which is an unusually wide range. This, coupled with the low boiling point of ether (34.6 C) and high vapour pressure at room temperature (400 mm Hg at 18C) means that it is easy to create a potentially explosive mixture of ether in air, and renders this compound an extreme fire hazard. The material for which flammable limits are quoted may be a flammable liquid, such as ether or methanol, or a powder or dust such as flour or grain dust. Flammable limits are also sometimes referred to as **explosion limits**.

A **Corrosive** material is one which causes damage to skin, eyes or other parts on the body on contact. The technical definition is written in terms of "... destruction, or irreversible damage to living tissue at the site of contact". Often this damage is caused directly by the chemical, but the action of some corrosive materials is a consequence of inflammation which they may cause. Concentrated acids are obvious examples of corrosive materials, but even dilute solutions of bases such as sodium or ammonium hydroxide may also be very corrosive, particularly in contact with the eyes.

A **Toxic** substance is one that is capable of causing injury or damage to a living organism. A wide variety of materials are considered as toxic; examples are sulfuric acid whose action is notably corrosive; compounds of heavy metals like tetraethyllead, which may act as systemic poisons; selenium compounds, such as selenium dioxide and natural products such as the aflatoxins.

IDLH is an acronym for Immediately Dangerous to Life or Health. This refers to a concentration, formally specified by a regulatory value, and defined as the maximum exposure concentration of a given chemical in the workplace from which one could escape within 30 minutes without any escape-impairing symptoms or any irreversible health effects. This value is normally referred to in respirator selection.

The **NFPA**, the National Fire Protection Association, is responsible in the USA for classifying substances according to their fire and explosion hazard.



 NFPA Rating Explanation Guide					
RATING NUMBER	HEALTH HAZARD	FLAMMABILITY HAZARD	INSTABILITY HAZARD	RATING SYMBOL	SPECIAL HAZARD
4	Can be lethal	Will vaporize and readily burn at normal temperatures	May explode at normal temperatures and pressures	ALK	Alkaline
3	Can cause serious or permanent injury	Can be ignited under almost all ambient temperatures	May explode at high temperature or shock	ACID	Acidic
2	Can cause temporary incapacitation or residual injury	Must be heated or high ambient temperature to burn	Violent chemical change at high temperatures or pressures	COR	Corrosive
1	Can cause significant irritation	Must be preheated before ignition can occur	Normally stable. High temperatures make unstable	OX	Oxidizing
0	No hazard	Will not burn	Stable		Radioactive
					Reacts violently or explosively with water
					Reacts violently or explosively with water and oxidizing

This chart for reference only - For complete specifications consult the NFPA 704 Standard
NFPA-Chart_1 www.ComplianceSigns.com

Figure H.1 – NFPA Rating Explanation Guide

NIOSH National Institute for Occupational Safety and Health. This sets OELs and provides services in occupational health and safety investigations in the USA.

OEL (Occupational Exposure Limit) A (generally legally-enforcable) limit on the amount or concentration of a chemical to which workers may be exposed

OSHA is the (USA) Occupational Safety and Health Administration, which adopts and enforces health and safety standards.

PEL - Permissible Exposure Limit is a time-weighted average (TWA) or absolute value (usually prescribed by regulation) setting out the maximum permitted exposure to a hazardous chemical.

The **TLV-STEL** or Threshold Limit Value, Short Term Exposure Limit, is the maximum concentration permitted for a continuous 15-minute exposure period. There may be a maximum of four such periods per day, with at least 60 minutes between exposure periods, and provided the daily TLV-TWA is not exceeded.

TWA (Time Weighted Average) This term is used in the specification of Occupational Exposure Limits (OELs) to define the average concentration of a chemical to which it is permissible to expose a worker over a period of time, typically 8 hours.



UN Hazard codes

Class 1 Explosive

- 1.1 Substances with a mass explosion hazard
- 1.2 Substances which present a projection hazard but no mass explosion hazard
- 1.3 Substances which present both a fire hazard and a minor blast or projection hazard (or both) but not a mass explosion hazard
- 1.4 No significant hazard
- 1.5 Very insensitive substances with a mass explosion hazard
- 1.6 Very insensitive articles with no mass explosion hazard

Class 2 Gases

- 2.1 Flammable gases
- 2.2 Non-flammable, non-toxic gases
- 2.3 Toxic gases

Class 3 Flammable liquids

Class 4 Flammable solids

- 4.1 Flammable solids, self-reactive substances and solid desensitized explosives
- 4.2 Materials liable to spontaneous combustion
- 4.3 Substances which, in contact with water, release flammable gases

Class 5. Oxidizing substances and organic peroxides

- 5.1 Oxidizing agents
- 5.2 Organic peroxides

Class 6 Toxic and infectious substances

- 6.1 Toxic substances
- 6.2 Infectious substances

Class 7 Radioactive substances and articles

Class 8 Corrosive substances

Class 9 Miscellaneous dangerous substances

H.2 Ammonia safety information

This is the NIOSH card for ammonia [Ref. 83]:



Ammonia		Formula: NH ₃	CAS#: 7664-41-7	RTECS#: BO0875000	IDLH: 300 ppm
Conversion: 1 ppm = 0.70 mg/m ³		DOT: 1005 125 (anhydrous); 2672 154 (10-35% solution); 2073 125 (>35-50% solution); 1005 125 (>50% solution)			
Synonyms/Trade Names: Anhydrous ammonia, Aqua ammonia, Aqueous ammonia [Note: Often used in an aqueous solution.]					
Exposure Limits: NIOSH REL: TWA 25 ppm (18 mg/m ³) ST 35 ppm (27 mg/m ³)				Measurement Methods (see Table 1): NIOSH 3800, 6015, 6016 OSHA ID188	
Physical Description: Colorless gas with a pungent, suffocating odor. [Note: Shipped as a liquefied compressed gas. Easily liquefied under pressure.]					
Chemical & Physical Properties: MW: 17.0 BP: -28°F Sol: 34% Fl.P: NA (Gas) IP: 10.18 eV RGasD: 0.60 VP: 8.5 atm FRZ: -108°F UEL: 28% LEL: 15%		Personal Protection/Sanitation (see Table 2): Skin: Prevent skin contact Eyes: Prevent eye contact Wash skin: When contam (solution) Remove: When wet or contam (solution) Change: N.R. Provide: Eyewash (>10%) Quick drench (>10%)		Respirator Recommendations (see Tables 3 and 4): NIOSH 250 ppm: CcrS*/Sa* 300 ppm: Sa:Cf*/PapR*/CcrFS/ GmFS/ScbaF/SaF §: ScbaF:Pd,Pp/SaF:Pd,Pp:AScba Escape: GmFS/ScbaE	
[Note: Although NH ₃ does not meet the DOT definition of a Flammable Gas (for labeling purposes), it should be treated as one.]					
Incompatibilities and Reactivities: Strong oxidizers, acids, halogens, salts of silver & zinc [Note: Corrosive to copper & galvanized surfaces.]					
Exposure Routes, Symptoms, Target Organs (see Table 5): ER: Inh, Ing (solution), Con (solution/liquid) SY: Irrit eyes, nose, throat; dysp, wheez, chest pain; pulm edema; pink frothy sputum; skin burns, vesic; liquid: frostbite TO: Eyes, skin, resp sys			First Aid (see Table 6): Eye: Irr immed (solution/liquid) Skin: Water flush immed (solution/liquid) Breath: Resp support Swallow: Medical attention immed (solution)		

Figure H.2 – Ammonia information, extracted from NIOSH



And this is the ICSC for ammonia, number 0414 (ICSC are numbered with 4 digits) [Ref. 84]:

AMMONIA (ANHYDROUS)		0414	
		March 1998	
CAS No: 7664-41-7 RTECS No: BO0875000 UN No: 1005 EC No: 007-001-00-5		(cylinder) NH ₃ Molecular mass: 17.03	
TYPES OF HAZARD/ EXPOSURE	ACUTE HAZARDS/SYMPTOMS	PREVENTION	FIRST AID/FIRE FIGHTING
FIRE	Flammable.	NO open flames, NO sparks, and NO smoking.	In case of fire in the surroundings: use appropriate extinguishing media.
EXPLOSION	Gas/air mixtures are explosive.	Closed system, ventilation, explosion-proof electrical equipment and lighting.	In case of fire: keep cylinder cool by spraying with water.
EXPOSURE		AVOID ALL CONTACT!	
Inhalation	Burning sensation. Cough. Laboured breathing. Shortness of breath. Sore throat. Symptoms may be delayed (see Notes).	Ventilation, local exhaust, or breathing protection.	Fresh air, rest. Half-upright position. Artificial respiration may be needed. Refer for medical attention.
Skin	Redness. Skin burns. Pain. Blisters. ON CONTACT WITH LIQUID: FROSTBITE.	Cold-insulating gloves. Protective clothing.	ON FROSTBITE: rinse with plenty of water, do NOT remove clothes. Refer for medical attention.
Eyes	Redness. Pain. Severe deep burns.	Face shield or eye protection in combination with breathing protection.	First rinse with plenty of water for several minutes (remove contact lenses if easily possible), then take to a doctor.
Ingestion			
SPILLAGE DISPOSAL		PACKAGING & LABELLING	
Evacuate danger area! Consult an expert! Ventilation. NEVER direct water jet on liquid. Remove gas with fine water spray. Personal protection: gas-tight chemical protection suit including self-contained breathing apparatus.		T Symbol N Symbol R: 10-23-34-50 S: (1/2)-9-16-26-36/37/39-45-61 UN Hazard Class: 2.3 UN Subsidiary Risks: 8	
EMERGENCY RESPONSE		SAFE STORAGE	
Transport Emergency Card: TEC (R)-20S1005 or 20G2TC NFPA Code: H3; F1; R0		Fireproof. Separated from oxidants, acids, halogens. Cool. Keep in a well-ventilated room.	
			
<p>Prepared in the context of cooperation between the International Programme on Chemical Safety and the European Commission © IPCS 2006</p> <p>SEE IMPORTANT INFORMATION ON THE BACK.</p>			



0414		AMMONIA (ANHYDROUS)	
IMPORTANT DATA			
<p>Physical State; Appearance COLOURLESS COMPRESSED LIQUEFIED GAS, WITH PUNGENT ODOUR.</p> <p>Physical dangers The gas is lighter than air.</p> <p>Chemical dangers Shock-sensitive compounds are formed with mercury, silver and gold oxides. The substance is a strong base, it reacts violently with acid and is corrosive. Reacts violently with strong oxidants and halogens. Attacks copper, aluminum, zinc and their alloys. Dissolves in water evolving heat.</p> <p>Occupational exposure limits TLV: 25 ppm as TWA; 35 ppm as STEL; (ACGIH 2004). MAK: 20 ppm, 14 mg/m³; Peak limitation category: I(2); Pregnancy risk group: C; (DFG 2004).</p>		<p>Routes of exposure The substance can be absorbed into the body by inhalation.</p> <p>Inhalation risk A harmful concentration of this gas in the air will be reached very quickly on loss of containment.</p> <p>Effects of short-term exposure The substance is corrosive to the eyes, the skin and the respiratory tract. Inhalation of high concentrations may cause lung oedema (see Notes). Rapid evaporation of the liquid may cause frostbite.</p>	
PHYSICAL PROPERTIES			
<p>Boiling point: -33°C Melting point: -78°C Relative density (water = 1): 0.7 at -33°C Solubility in water, g/100 ml at 20°C: 54</p>		<p>Vapour pressure, kPa at 25°C: 1013 Relative vapour density (air = 1): 0.59 Auto-ignition temperature: 651°C Explosive limits, vol% in air: 15-25</p>	
ENVIRONMENTAL DATA			
The substance is very toxic to aquatic organisms.			
NOTES			
<p>The symptoms of lung oedema often do not become manifest until a few hours have passed and they are aggravated by physical effort. Rest and medical observation is therefore essential.</p> <p>Immediate administration of an appropriate inhalation therapy by a doctor or a person authorized by him/her, should be considered.</p> <p>Turn leaking cylinder with the leak up to prevent escape of gas in liquid state.</p> <p>Card has been partly updated in October 2005. See sections Occupational Exposure Limits, Emergency Response.</p>			
ADDITIONAL INFORMATION			
LEGAL NOTICE		Neither the EC nor the IPCS nor any person acting on behalf of the EC or the IPCS is responsible for the use which might be made of this information.	
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Figure H.3 – ICSC 0414, ammonia (anhydrous)



H.3 Isopentane safety information

This is the ICSC for isopentane, number 1153 [Ref. 85].

ISOPENTANE		1153 April 1994	
CAS No: 78-78-4 RTECS No: EK4430000 UN No: 1265 EC No: 601-006-00-1		Ethyl dimethyl methane 2-Methylbutane Isoamyl hydride C_5H_{12} / $(CH_3)_2-CH-CH_2-CH_3$ Molecular mass: 72.2	
TYPES OF HAZARD/ EXPOSURE	ACUTE HAZARDS/SYMPTOMS	PREVENTION	FIRST AID/FIRE FIGHTING
FIRE	Extremely flammable.	NO open flames, NO sparks, and NO smoking.	Powder, AFFF, foam, carbon dioxide.
EXPLOSION	Vapour/air mixtures are explosive.	Closed system, ventilation, explosion-proof electrical equipment and lighting. Prevent build-up of electrostatic charges (e.g., by grounding). Do NOT use compressed air for filling, discharging, or handling.	In case of fire: keep drums, etc., cool by spraying with water.
EXPOSURE			
Inhalation	Cough. Dizziness. Drowsiness. Headache. Shortness of breath. Sore throat. Irregular heartbeat.	Ventilation, local exhaust, or breathing protection.	Fresh air, rest. Half-upright position. Refer for medical attention.
Skin	Dry skin. Redness.	Protective gloves.	Remove contaminated clothes. Rinse skin with plenty of water or shower.
Eyes	Redness. Pain.	Safety spectacles or eye protection in combination with breathing protection.	First rinse with plenty of water for several minutes (remove contact lenses if easily possible), then take to a doctor.
Ingestion	Abdominal pain. Nausea. Vomiting. (Further see Inhalation).	Do not eat, drink, or smoke during work.	Rinse mouth. Refer for medical attention.
SPILLAGE DISPOSAL		PACKAGING & LABELLING	
Evacuate danger area! Consult an expert! Collect leaking and spilled liquid in sealable containers as far as possible. Absorb remaining liquid in sand or inert absorbent and remove to safe place. Do NOT wash away into sewer. Personal protection: filter respirator for organic gases and vapours.		F Symbol Xn Symbol N Symbol R: 12-51/53-65-66-67 S: (2-)9-18-29-33-61-62 UN Hazard Class: 3 UN Pack Group: I	
EMERGENCY RESPONSE		SAFE STORAGE	
Transport Emergency Card: TEC (R)-30S1265 or 30GF1-I+II NFPA Code: H 1; F 4; R 0		Fireproof. Well closed.	
    			
Prepared in the context of cooperation between the International Programme on Chemical Safety and the European Commission © IPCS 2005 SEE IMPORTANT INFORMATION ON THE BACK.			



1153		ISOPENTANE	
IMPORTANT DATA			
Physical State; Appearance COLOURLESS LIQUID, WITH CHARACTERISTIC ODOUR.		Routes of exposure The substance can be absorbed into the body by inhalation and by ingestion.	
Physical dangers The vapour is heavier than air and may travel along the ground; distant ignition possible. As a result of flow, agitation, etc., electrostatic charges can be generated.		Inhalation risk No indication can be given about the rate in which a harmful concentration in the air is reached on evaporation of this substance at 20°C.	
Chemical dangers May explode on heating.		Effects of short-term exposure The substance is irritating to the eyes, the skin and the respiratory tract. Swallowing the liquid may cause aspiration into the lungs with the risk of chemical pneumonitis. The substance may cause effects on the central nervous system and heart, resulting in impaired functions.	
Occupational exposure limits TLV: 600 ppm as TWA; (ACGIH 2004). MAK: 1000 ppm, 3000 mg/m ³ ; Peak limitation category: II(2); Pregnancy risk group: D; (DFG 2004).		Effects of long-term or repeated exposure The liquid defats the skin.	
PHYSICAL PROPERTIES			
Boiling point: 28°C Melting point: -160°C Relative density (water = 1): 0.6 Solubility in water: none Vapour pressure, kPa at 20°C: 79 Relative vapour density (air = 1): 2.5		Relative density of the vapour/air-mixture at 20°C (air = 1): 2.2 Flash point: <-51°C c.c. Auto-ignition temperature: 420°C Explosive limits, vol% in air: 1.4-7.6 Octanol/water partition coefficient as log Pow: 2.3	
ENVIRONMENTAL DATA			
The substance is harmful to aquatic organisms.			
NOTES			
Use of alcoholic beverages enhances the harmful effect. High concentrations in the air cause a deficiency of oxygen with the risk of unconsciousness or death. Check oxygen content before entering area. The relation between odour and the occupational exposure limit cannot be indicated. Card has been partly updated in April 2005. See sections Occupational Exposure Limits, EU classification, Emergency Response.			
ADDITIONAL INFORMATION			
LEGAL NOTICE		Neither the EC nor the IPCS nor any person acting on behalf of the EC or the IPCS is responsible	
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Figure H.4 – ICSC 1153, isopentane



Another Chemical Fact Sheet can be found in Figure H.5 below [Ref. 86]:

CHEMICAL FACT SHEET for emergency responders									
CHEMICAL:		Isopentane							
(CH ₃) ₂ CHCH ₂ C H ₂	1965	77-78-4	128	--	--	--	1	4	0
Chemical Formula	UN #	C.A.S. #	ERG #	Hazardous Substance	Extremely Hazardous Substance	RQ	Health	Fire	Reactivity
Characteristics				Exposure Limits			Common Uses		
Appearance: Clear liquid with Hydrocarbon odor				LEL:	1.4 %	<ul style="list-style-type: none"> Chemical intermediate. 			
Specific Gravity: 0.62				UEL:	7.6 %				
Flash Point: -70°F				IDLH:					
Auto Ignit.: 788°F				STEL:	750 ppm				
Vapor Density: 700 (mmHG@20°C)				PEL:					
B. P.:				ERPG2:	NA				
				ERPG3:	NA				
Emergency Response PPE (Fire Fighters)									
Respiratory: Use with adequate ventilation. SCBA or supplied air respirator with escape Pack needed for concentrations above the exposure limits.					Hazards <ul style="list-style-type: none"> Overexposure can cause headaches, drowsiness and decreased coordination Exposure to high concentrations can cause increase the sensitivity of the heart to certain drugs Respiratory tract irritant – inhalation hazard if swallowed-can enter lungs and cause damage Mild-moderate irritant to nose, throat, eyes, skin, respiratory and digestive tracts 				
Eye/Face/Body: If not wearing full-face respirator, wear goggles, face shield, protective gloves and Chemical Protective Clothing.									
Emergency Medical Actions									
<ul style="list-style-type: none"> Remove from contaminated area to fresh air. Give artificial respiration/CPR if needed. Remove contaminated clothing/articles. Wash with soap and water until no odor is present. Wash eyes with copious amounts of water for 15 minutes. Do not induce vomiting. Do not give liquids. 									
Notes									
<ul style="list-style-type: none"> Synonyms - 2-methylbutane Extremely flammable liquid DOT Hazard Class 3 - Flammable Liquid 									
Initial and Protective Action Distances									
Small Spills <>					Large Spills <>				
<ul style="list-style-type: none"> Remove ignition sources. Disperse vapors with water spray Consider initial isolation of 160'-300' in all directions. 					<ul style="list-style-type: none"> Remove ignition sources. Disperse vapors with water spray Consider initial isolation of 160'-300' in all directions. 				
Emergency Response Actions									
<ul style="list-style-type: none"> Cool tanks/containers. Extinguish fire with CO₂, dry chemical, water spray, or regular foam. Use water spray to disperse vapors. 					1/99				

Figure H.5 – Chemical fact sheet for isopentane

