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Energetický ústav
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ZADÁNÍ DIPLOMOVÉ PRÁCE

student(ka): Bc. Lukáš Jančok

který/která studuje v **magisterském navazujícím studijním programu**

obor: **Energetické inženýrství (2301T035)**

Ředitel ústavu Vám v souladu se zákonem č.111/1998 o vysokých školách a se Studijním a zkušebním řádem VUT v Brně určuje následující téma diplomové práce:

Kogenerační zdroj

v anglickém jazyce:

Cogeneration Unit

Stručná charakteristika problematiky úkolu:

Proveďte technicko-ekonmický návrh kogeneračního zdroje tepla, který bude pracovat v podmínkách Ruské federace - na Sibiři. Palivem je dřevní odpad. Teplo bude pokrývat vlastní spotřebu dřevozpracujícího závodu a uvažuje se s prodejem externím zákazníkům. Záložní palivo mazut/těžký topný olej.

Cíle diplomové práce:

Cílem práce je technicko-ekonomické posouzení kogenerační jednotky na dřevní odpad o poměrně malém výkonu cca do 10 MWe.
Jedná se o komplexní vyřešení energetické situace v dané lokalitě včetně technického návrhu případných variant řešení a jejich ekonomické analýzy.

Seznam odborné literatury:

Fiedler,J.: Parní turbiny - návrh a výpočet, CERM- Brno 2004
Kadrnožka, J.: Tepelné turbiny a turbokompresory, CERM- Brno, 2007
Kolektiv: Strojní zařízení tepelných centrál, PC-DIR, 1999
Firemní literatura zadavatele KP - RIA

Vedoucí diplomové práce: doc. Ing. Jan Fiedler, Dr.

Termín odevzdání diplomové práce je stanoven časovým plánem akademického roku 2012/2013.

V Brně, dne 19.10.2012

L.S.

doc. Ing. Zdeněk Skála, CSc. Ředitel ústavu	prof. RNDr. Miroslav Doupovec, CSc., dr. h. c. Děkan fakulty

Master thesis specification from KRALOVOPOLSKA RIA

Title: Technical-economic assessment of a wood-fired cogeneration unit for a Siberian-like climate

Master thesis guidelines:

1. Carry out a review of district heating and power sources with output power in the region of 1MWe.
2. Offer a study - and back it up by calculation - of available cogeneration technology for solving off-grid energy situation at a given destination. Assess its performance, operations and safety factors.
3. Prepare information collection about local energy market. Carry out a project feasibility study at a given destination, and specify conditions for a suitable solution.
4. Draw conclusions. Propose hardware solution for the cases. Offer recommendations for further development, according to the results.

Summary

This thesis deals with providing both electric power and heat for an ordinary Siberian town. On site observation and measurements to determine the local conditions were not an option. Hence information gathering is presented. It covers the energy situation for the public and for the wood processing plant. The technical part of the thesis starts with a review of an existing technology. The options are presented, and the decision is to recommend particular new system based on the Rankine cycle. At such distant location power source depends very strongly on the available combustible resources. This thesis presents also the evaluation of economics. The main objective was to carry out an analysis and design an adequate and economical cogeneration application where the most important criteria are reliability, safety and simplicity.
Design of auxiliary equipment and heat distribution network are not in the scope of this thesis. The conclusion deals also with next recommended steps.

Key words: biomass, cogeneration, back-pressure steam turbine, Siberian-like climate application, off-grid application, off-the-grid

Abstrakt

V diplomové práci je krok po kroce vypracováno řešení zabezpečení energetického zdroje pro typické město v Sibiřské oblasti. Data, která tvoří zadání, byla získána od zákazníka pomocí dotazníku, protože pro nás oblast v čase vypracování nebyla dostupná. Na základě informací o aktuální energetické situaci, obyvatelstvu a dřevospracujícímu průmyslu je vybrána vhodná technologie pro zabezpečení tepla a elektrické energie. Druh zdroje byl vybrán dle dostupného paliva a následně byl proveden výpočet a design energetického zdoje založeného na Rankine Clausiovém cyklu. Řešení obsahuje technický i ekonomický návrh. Technické řešení ukázalo, že nejdůležitější parametry jsou spolehlivost, bezpečnost a jednoduchost řešení.
Design sítí, přídavných zařízení a plánování údržby není obsahem této práce. O dalších projektových krocích pojednává závěr.

Klíčová slova: kogenerace, Sibiř, biomasa, ostrovní zdroj energie, protitlaková turbína, malá teplárna

Declaration

I hereby declare that this thesis is my own work and effort with a factual contribution of know-how by my supervisor Doc. Fiedler and consultant Ing. Pelak. Where other sources of information have been used, they have been acknowledged.

In Brno .... Signature ....

Acknowledgements

I would like to express my thanks to my supervisor, Doc. Ing. Jan Fiedler, for his time and for the guidance he provided at all times.

I have to thank my wife Ivana, who has pushed me toward finish line when needed.

I also thank my friend Robin Healey, who kindly edited this thesis.

Motivation

My major driving force was the vision that my senior thesis deals with a "real world problem", and all the energy and time that I have devoted to it was well used. I hope it will be usefull as a cook book or inspiration for the future biomass cogeneration projects. I was also pulled into the problem by close cooperation with my supervisor and with the company KP Ria. It is always motivational for me when I cooperate with someone skillful. From the beginning, I was focused on maximizing the value of the results for academic and commercial utilisation. This also drove me forward.

Contents

List of Figures

Nomenclature

in alphabetical order:

e - power-heat module
H - turbine enthalpy gradient
h_X - enthalpy of the medium at point X
i_X - enthalpy of the medium at point X
i_{fw} - enthalpy of feeding water
kW_e - unit is a standard kilowatt, subscript e refers to el. power
$\dot{m}_X$ - mass flow rate of steam at point X
$\dot{m}_{cp}$ - mass flow rate of combustion products
$\dot{m}_c$ - mass flow rate of combustible
$\dot{m}_{sl}$ - mass flow rate of boiler slag
$\dot{m}_{air}$ - mass flow rate of boiler air
η_c^t - thermal cogeneration efficiency of the entire cycle
η_e - thermal efficiency with respect to electric power
η_g - electrical efficiency of the generator
η_b - boiler thermal efficiency
η_t - turbine overall efficiency, including sealing loss and mech. losses
P_e - electric power output
P_{shaft} - power on the shaft of the turbine (torque)
Q_h - heat power output
Q_s - heat supplied in combustible

Abbreviations List

OSB Oriented Strength Board

RC Rankine Cycle

ORC Organic Rankine Cycle

CI Compression Ignition

MCA Multi-Criterion Analysis

Part I

Introduction

0.1 Preface

The goal of this thesis is to place a technical proposal for ensuring electric power and heat supply at a distant Siberian location. The proposal has to include the design of the thermal circuit, selection of machinery, and its implementation. The workflow of the thesis is shown in Figure 1

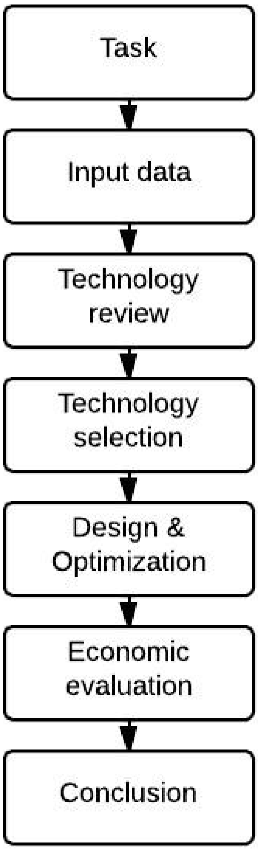

Figure 1: Thesis flow chart

At this point the problem statement for the thesis is not specific enough. Above all, I want to avoid just scratching the surface, and not getting to its technical core. Hence - prior to the beginning of the analysis - I am breaking the problem statement down into the following sections.

- Introduction of the location, the current energy situation of the location, identification of the stakeholders, such as public, investors, and the operator of the power plant.

- The technical section deals with the type of combustible material or the combination, taking into account local availability, waste, ecology and the influence on local production, the demands on the technology and its selection.
- The economic observation deals with impacts on the economy, payback time, energy prices (electricity and heat), production limits, waste burning, savings achieved on the technology and savings on exhaust gases.

Since this is a technical thesis, most importance is on the technical research, the technology proposal, and the technical calculations.

0.2 Technical and economic data collection forms

No technical project can be started just like that, without data. The supervisor of my thesis, Ing. Pelak, who has over 40 years of experience in the energy business, helped to prepare two questionaries for the submitter of the request.
These forms include questions that will provide us with necessary details for the analysis. See the translation of the forms from Russian in the appendixes to this thesis.
Question forms as such are common practice in the pre-project phase. The only problem is that overwhelming majority of customers do not have the necessary data. This partially applies in this case, and since the location of the project is very far away, and it was not possible to arrange a site visit, I have to cope with limited data.

Chapter 1

Analysis of the current situation

1.1 Placement

This application is intended to be implemented in Stepanovka, which is one of 41 small towns in the Tomsk oblast in the Asian part of the Russian Federation. Stepanovka itself is at GPS coordinates 58.63765, 86.771049. It is located in the West Siberian plain. All towns of this nature in the region were built on the river side, as the river is the main transport artery and food source.
The climate is classified as cold. The countryside is characterised as taiga or tundra, with coniferous forests and swamps.

(a) In winter

(b) In summer

Figure 1.1: Photo of the countryside, for illustration only [2]

1.2 Means of Transport

It is worth mentioning at the beginning that there is no railway. All minor to medium-sized shipments are delivered by truck, most of them arriving by road from Tomsk. Stepanovka is about 400 km north of Tomsk, which takes about 10 to 12 hours by car when conditions are favourable. The window of opportunity for road transport is as narrow as 4 months a year.

Some of the towns in the Tomsk oblast are not accessible by road, but there is also a possibility to use air transport for lightweight and personal transport, mainly in summer. For heavy loads, the main means of transport is by water. Cargo ships are able to operate 5 to 6 months a year. Rivers also provide a special winter route so-called ice roads. When the rivers are frozen, see Figure 1.1 there is a possibility to transport high volume loads of fuel or coal.

1.3 Population

Total population of the Tomsk oblast is 1,034,900 people. The population density is 3.27 person/km^2, but over 50 % of the people live in the regional capital city, Tomsk. [2] The rest live in unevenly spread steppe towns such as Stepanovka. Most of these towns were founded by political prisoners, who were sent there during the first half of the 20th century. The towns vary in size according to the opportunities to make a living.

Stepanovka has 2,324 inhabitants as of 2011 [4]. There are almost no services, and people find employment mostly in the mining industry, as the region is rich in mineral resources, and in forestry. Woodlands cover about 60 % of the territory of the Tomsk oblast. A major part is made up of commercial forests. Coniferous species, especially Siberian cedar pine, spruce, silver fir and larch appear to prevail. The most of the forestry work is in the wood processing industry, but a few people make their living by farming. Less than 5 % of the land is dedicated to agriculture, but there are also opportunities to collect large quantities of wild berries or mushrooms for sale. [2]

1.4 Climate

The climate in Stepanovka is typical Siberian inland cold taiga. The average annual temperature is 0.6 °C. In July it is plus 18.1 °C, and in January 19.2 °C below zero. The frost-free period is only 100-105 days a year. The annual precipitation is 435 mm. [2]

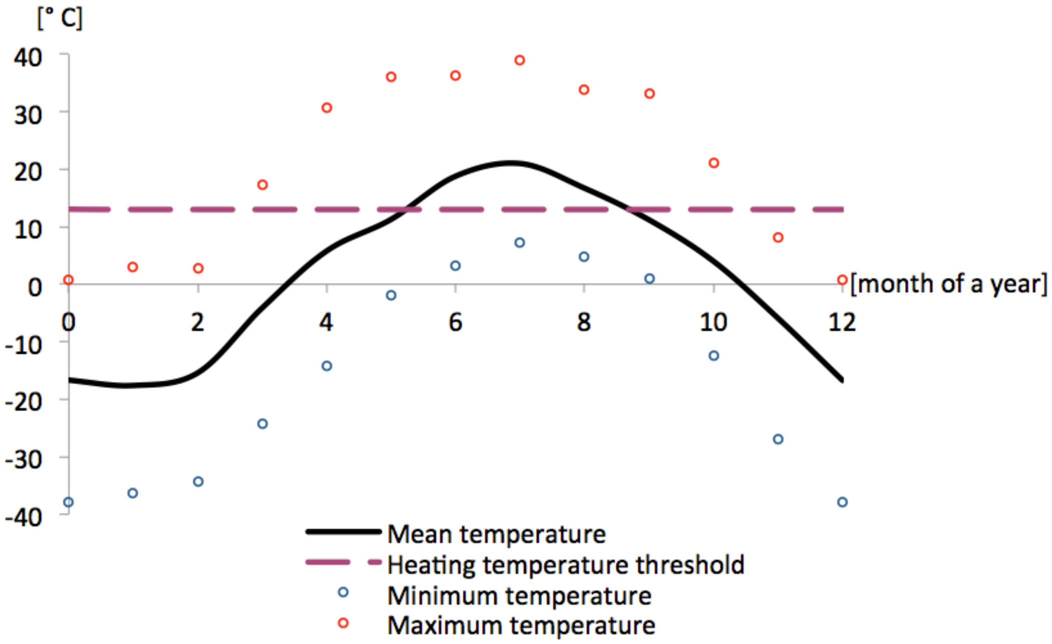

Figure 1.2: Annual temperature profile

1.5 Energy

1.5.1 Current energy consumers

The demand for electrical power is about constant throughout the year, but the demand for the heat strictly reflects the mean temperature curve.
The heating season starts on September 15th and ends on May 15th. This rule usually applies every year within a two-week interval. During the other three months there is a maximum 14-day shutdown for summer maintenance and servicing of the machinery and boilers. A longer shutdown is not allowed due to unavailability of domestic hot water.

In 2011: 3 GWh of electric power and 1582 Gcal of heat was generated. When converted to SI units, this is 6.624 TJ or 1.840 GWh of heat.

The three stakeholders in the energy network are residents, public facilities, and the local wood-processing plant. The first two consume up to 50 % of the overall electrical power and heat. Wood processing plant takes the other 50 %. Additionally, the majority

of households use wood for heating in the domestic furnaces.
Householders in buildings connected to the grid pay their own energy bills according to the consumed amount at intersection divided by the number of connected units. No detailed measurement is in place. Public places heating is paid for by the Tomska oblast, which heavily subsidies all the fuels and combustible materials that are delivered to the town.

At 2011 rates, the price of energy is 14.95 RUB/kWh [1] for electricity and 3867.6 RUB/Gcal which is 924 RUB/GJ[2].

1.5.2 Current installation

Clearly, we are talking about an off-grid application. At this point in time there is one centralised source of electrical power. A diesel generator is installed with nominal power 1.034 MW. This engine is usually runs 12 hours a day, loaded at 50 to 70 %.

Currently, a 90/70 °C central heating system is in place that provides heat for heating and domestic hot water. Public places like the school, the health centre and the town hall are heated by centralised heating. However not all blocks of flats and none self standing houses are yet connected. There are 2 independent heating stations that work on coal or mazout. Each station has a coal fired hot-water boiler with nominal power 1600 kW. Both are back up sources in case of very low temperatures. Most of the energy then goes toward domestic hot water production, because the basic system is inadequately proportioned for the centralised heating requirement of the town.

1.5.3 Combustible

The primary combustibles are coal, mazout and diesel. All are imported by cargo boats on the river during the short navigation season (mid March - mid September).

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[1] 9.7 CZK/kWh according to ČNB on 1.4.2013 the exchange rate 100 RUB/64.762 CZK

[2] 598.4 CZK/GJ according to ČNB on 1.4.2013 the exchange rate 100 RUB/64.762 CZK

1.5.4 Specific requirements and features of the wood-processing plant

Electrical energy is required mainly in the production of semi-finished wood products to drive the electric motors, actuators and drives in the cutting, clamping, crushing and transporting machines. The biggest consumption of heat is at the workshop and management buildings. The heat potential required is standard temperature heating system water at potential 90/70 °C.
The wood processing plant runs in two-shift mode - 16 hr/day - 5840 hr/year. Winter operation is based on exploiting the highest quality wood for construction. In cold winter time, the wood from needled-leaf trees is naturally resin-less. Large quantities of wood are stored over a period of several months every year.

1.5.5 Potential energy sources

The Russian federation is generally well known for its rich raw material deposits. This evokes feeling of wide range of energy applications. The reality at Stepanovka is different, though. It is too expensive to run a gas pipe there, since the distances are too long and the population is low. Diesel and mazout are products refined in Tomsk, but they have to be shipped to Stepanovka. The local wood processing plant produces a large amount of wood waste, which obviously could be used in biomass boilers. Right on the spot, various types of wood chips are available free of charge.

1.6 Future consumption, and an estimate of future developments

The future energy demand of Stepanovka is not to be defined by current consumption. The standard procedure when dealing with future needs should examine all subjects involved in the distribution network. According to our limited information, no further development is planed by the municipality.
There is a development project planned by wood processing plant. They are planning to extend the production line and possibly add some new products. They require a stable electricity source and more technological heat for drying. Any increase of heat would give them manoeuvring space for extending the volume and hence more jobs for local residents. As it is right now, the stored wood is dried by natural processes only, and the drying period takes orders of months. Drying could be applied not only to the preprocessed wood but also to the wood chips that are a semi-product for wood-fiber boards

such as OSB.

1.7 Kralovopolska RIA a.s. experience

Kralovopolska Ria is focused on turnkey applications. The company is well aware of the climatic conditions in the Siberian region and their implications for speed of construction during summer time, the need to place the equipment into insulated buildings, and also questions of high reliability and quality. The company delivers only tested and well tuned systems. It traditionally cooperates with local companies and contractors on these types of constructions. This allows the company to use local materials and construction capacities if available.

Typical Kralovopolska RIA projects across industries include:

- Chemical plants, Refineries and other oil processing plants
- Metallurgy plants
- Heat and power plants
- Paper production plants
- Agricultural plants, Food-processing plants
- Textile plants
- Brick works
- Wood-processing plants

The technical part of the project is elaborated on the basis of this information and these requirements, stated in introduction section. Several options for the cogeneration energy source will be introduced and the economics of these solutions will be shown in this work before the conclusion is drawn.

Part II

Technical

Chapter 2

Deployment of cogeneration

A biomass-fired cogeneration power plant seems to be a good solution to the requirements of Stepanovka, for the following reasons:

- The wood processing plant not only needs energy, but also produces a free combustible, the plant needs to be kept in operation to provide employment for the local people,
- The cold local inland climate requires heating for 260 days a year
- The heat can be used practically all year for the technological processes, and also for domestic hot water
- This is an energy island application
- A hot water grid is partially in place and the existing boiler houses can be refitted

The rest of this section of the thesis is dealing with the technology. It will offer a step-by-step walk through the design of the project. It will begin with investigation allowed by calculations, leading to a proposal for a cogeneration power plant for Stepanovka, and for other similar locations. The proposal is based on technical data that has been made available to us.

Chapter 3

The combustible

The type of fuel determines many parameters of a power plant. For the sustainability of the power source and in order to reduce the cost for delivering the combustible, we should explore whether it is possible to stop using black coal and diesel altogether, and use only locally available fuel.
Wood chips, forestry wastes, and the waste from the wood processing plant are locally available. Wood falls into the biomass category, but it has some specific features that will be dealt with in following sections, and that will form the core of this work.

Biomass is extremely popular topic to present-day in power generation. In recent years, it has attracted the attention of law-makers, ecologists, and technicians all around the world, because of the so-called closed carbon dioxide cycle. This refers to the process in which biomass is burned, producing carbon dioxide, which is then cycled by the photosynthesis of other plants. The point is that carbon dioxide which is buried underground in form of fossil fuels will remain stored there. Biomass is a source of energy that is encouraged in western countries, but engineers are concern about the volume of biomass material that is needed to supply the power now provided by conventional fossil fuels. In spite of this concern, it appears possible that a combination of biomass heat and power generation with other renewable sources in a decentralised electricity supply holds promise for future years.

It is important to keep in mind that Siberian conditions require high reliability. An application like this therefore usually calls for more than one combustible material, in order to provide greater flexibility in the event of a break-down or wood shortage.

Chapter 4

A review of biomass heat and power plants

The first question that we must ask is what ways are there to obtain the energy from biomass? In general, there are three main categories of power extraction: biological, chemical and thermochemical. According to [12, 15]

We have mentioned that wood has certain specific features. These come into play at this point, and narrow down the ways in which this material can be used for power production.
Wood-to-electricity transformation offers only limited options. A chemical method is used for producing biodiesel from any oily biomass. Biological processes use fermentation or anaerobic digestion. Neither of these processes is suitable for use with wood. What remains is the family of thermochemical processes, among which are pyrolysis, carbonisation, and catalytic liquifying that are unsuitable. We are left with just two options: gasification and combustion, see Figure 4.1

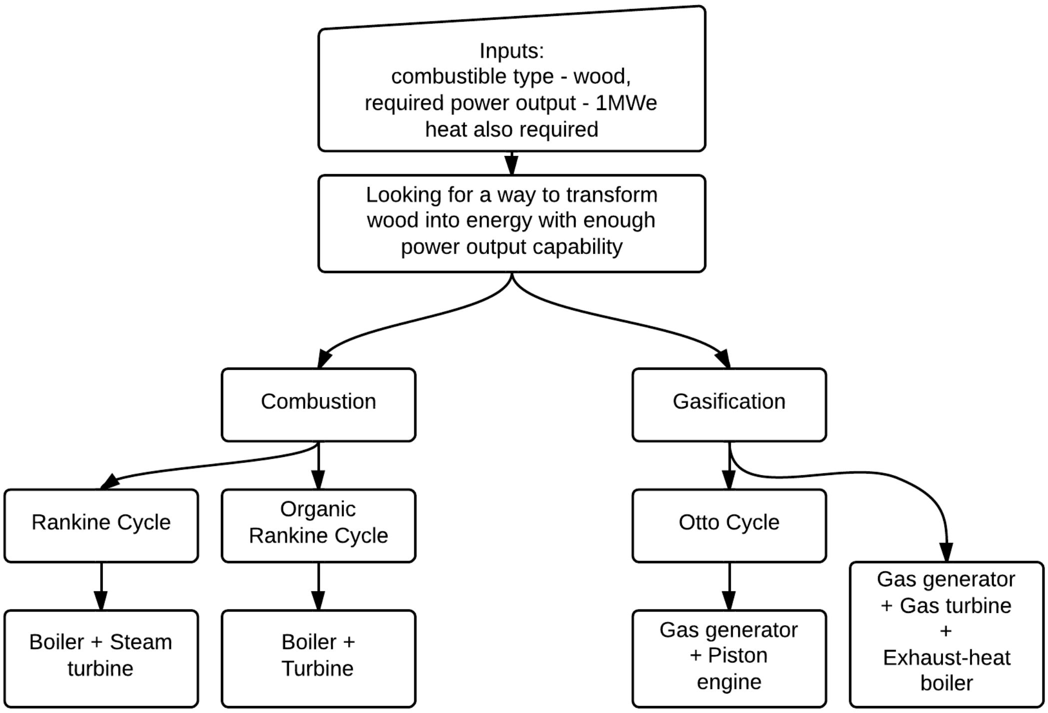

Figure 4.1: Suitable technologies for wood-to-electricity transformation

At this point, I will make two remarks. Firstly, I am not going to take into consideration the Stirling engine. It has 25 % to 33 % efficiency according to [12], but the limiting range of the power output on the shaft is 50kW, which will not cover requirements of the town.
Secondly the gas generators, gas turbines and exhaust heat boilers are not the type of technology we are looking for. They are more expensive than the rest of the spectrum, and for this reason they are disqualified from further consideration.
We will now introduce three available and suitable technologies for our purposes.

4.1 The Rankine cycle

The Rankine cycle is the most frequently used cycle in classical large scale power plants. It is a thermal cycle where the medium is water. The water undergoes a state change in each loop of the cycle. The water enters the feeding pump as a saturated liquid. The pump brings the water to high pressure and feeds it to the boiler, where it evaporates. It exits from the last stage as superheated steam which then drives the turbine. The steam expands in the turbine to a lower temperature and pressure. Its enthalpy loss is transformed into mechanical work. The rest of the energy has to be gotten rid of in the condenser prior to starting the cycle all over again. Some small part of the medium is continuously being lost due to the leakages and in the boiler slag. New water has to be fed into the system according to the level gauge of the boiler tank.

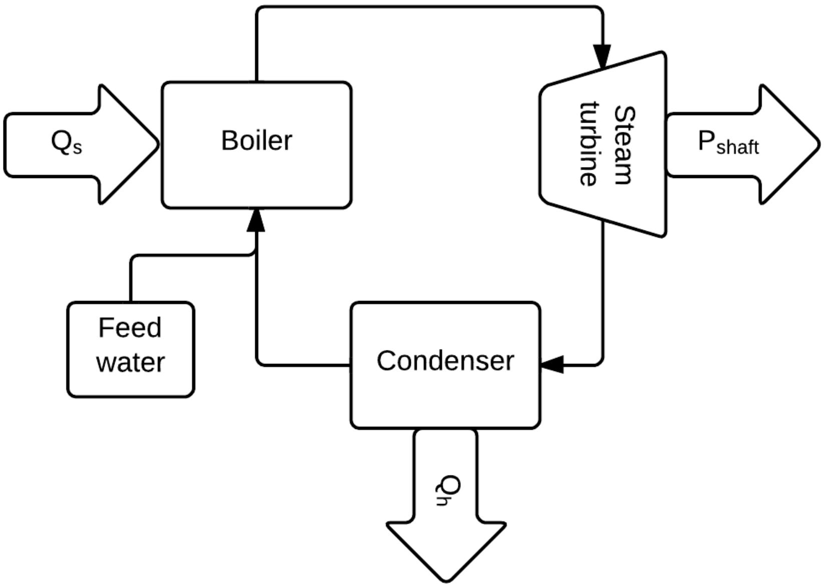

Figure 4.2: Basic scheme of main equipment in the Rankine cycle

On large scale power plants in orders of hundreds of megawatts, this cycle is optimised and works with 35-39 % electrical efficiency. This means that less than four tenths of the energy supplied to the cycle by the fuel is transferred to electrical power and the rest is just discharged to the ambient through the condenser.
Nevertheless, a boiler coupled with a steam turbine is the most wiely-used combination in power generation. This cycle has also found its place also in nuclear power generation, because of its features, where boiler is replaced by steam generators.

For decentralised cogeneration application we certainly have to consider lower values of electrical efficiency. Our scenario requires a steam boiler with steam output somewhere around ten tons of steam per hour. The electrical power could be provided by a single-stage, back-pressure steam turbine or by a multi stage turbine for higher thermodynamic efficiency.

It is also a possible to use a piston machine in the RC, but it seems to be undesirable for our application. According to Doc. Fiedler from VUT, who reports that he made the calculation several times, steam machines should be considered when designing an electric power source up to 100 kW [8]. The Czech company Polycomp has installed a steam machine with power output 300 kWe. A major disadvantage of this solution is that the efficiency of steam machines is strictly dependent on high steam parameters. If this condition is fulfilled, the maximum efficiency is about 10 to 15 %. There is also a transportation issue, because a steam engine would be one order of magnitude heavier than a steam turbine for the same power output. Finally, it would not be economical to install four steam machines instead of one turbine to provide the required output.

Parameter	Quality
η_e with a single-stage turbine	ranges from 5-7 %
η_e with a multi-stage turbine	12 to 16 %
η_c of the circuit	up to 80 %
Boiler manufacturers:	Bresson, a.s., SEA CZ, a.s.; Clauhan, s.r.o.; Tenza, a.s.; PBS, a.s., Alstom; The Babcock & Wilcox Company; POLYTECHNIK Luft-und Feuerungstechnik, GmbH
Turbine manufacturers:	PBS, a.s.; Ekol, spol. s r.o.; Getura, spol. s r.o.; G-Team, a.s.; Polycomp, a.s., Alstom

Table 4.1: Summary of RC parameters

4.2 The Organic Rankine Cycle

The organic Rankine cycle is a standard RC, but the medium is mineral oil rather than water. The medium provides suitable thermal properties for small and medium-sized application up to several MWe. The main point for this tweak is that higher efficiency can be achieved at low temperatures of the medium. [3] This is actually a positive factor for biomass combustion applications because of the relatively low achievable temperatures in the furnace. However it is not so much an issue for a wood-fired boiler, which can easily reach temperatures higher than 400 °C.

4.2.1 How ORC works

A closed system working on the ORC principle is a cogeneration unit that produces electricity and heat from biomass. It can be fed with wood chips, straw or turf. Biomass is burned in the furnace chamber. Hot gases from the furnace exchange heat with the mineral oil. Residual heat from the gases is then exchanged in the economiser, and the exhaust gases pass through a filter directly to the atmosphere, via a chimney.
The mineral oil circuit transfers the energy for electricity generation to the turbine. This circuit is closed, so it does not exchange mass with any other part of the system. The mineral oil fumes then condensate in a heat exchanger, and the released heat is transferred by water to the hot water network. [3]

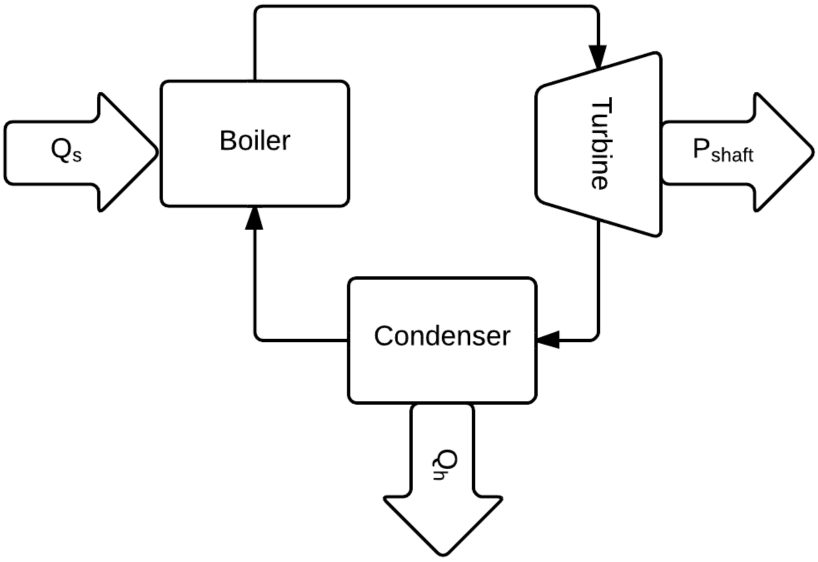

Figure 4.3: Basic scheme of the equipment for the Organic Rankine Cycle

The tightness of the system is a crucial factor for ORC technology, because the medium must not escape from the circuit through the sealing or due to any leakage.
The mineral oil is usually a silicate compound. This substitute for water is used because oil can remain in a fluid state at much lower pressures and at temperatures up to 300 °C. Because of these properties, steam superheating is not needed and after exiting the evaporator it goes directly to the turbine. It should also be noted that since the system is built to be supertight no feed water is needed, and therefore no purification process is required. This also influences the overall efficiency of the process.

There is also an ecological consideration. The organic medium in the primary circuit has to fulfil demanding ecological standards.

ORC systems in general are often standardised into container modules. Achievable electrical outputs range from hundreds of kW to units of MW. Combined efficiency up to 85 % can be achieved in cogeneration modes.

Parameter	Quality
η_e of the circuit	ranges from 14 to 20 %
η_c of the circuit	up to 85 %
Technology providers:	Turboden, srl; TTS, a.s.; Kotlemont, a.s.; Schiestl, spol. s r.o.

Table 4.2: Summary of ORC parameters

4.3 Wood gasification

Biomass, and particularly wood, has a great portion of volatile flammable compound. This can be extracted in the process of gasification. This takes place in an air tight volume where no oxygen is allowed. Gas produced in this way contains many imperfections, and has to be cleaned. In normal operations, the first step in the gas cleanup process is a novel catalytic cracker that reforms tar compounds generated during the gasification process to hydrogen and carbon monoxide. Next, the gas is cooled and passed through bag filters to remove dust. [1] Cleaning is done by mechanical filters because the major gas pollutant consists of particles of mineral compound that are taken by the stream of gas. Clean gas is later stored in pressure vessels, or goes directly to the burning process. Purified gas can be burned quite easily in burners or in hot water boilers. For the electrical power generation the gas is burned in combustion chamber of a gas turbine or piston engine, which has to be manufactured for the particular properties of the gas. In case of utilisation of piston engine, we are talking about the standard Otto cycle.

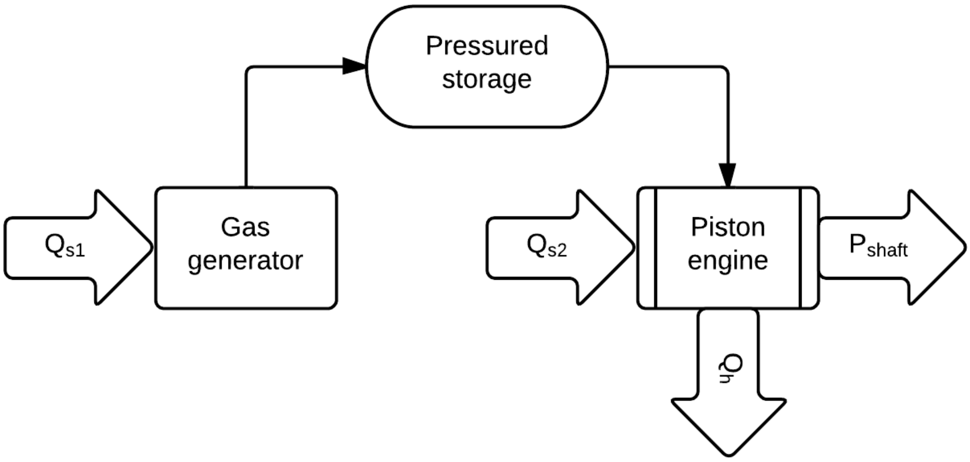

Figure 4.4: Basic scheme of the Otto Cycle

A wood gasification furnace or gas generator is coupled with a piston engine, which is usually a CI engine remade into a gas-fired engine.
A fluid gas generator produces gas with caloric value 4-7 MJ/Nm^3. Gasification takes place in the fluid layer, much like fluid layer combustion, at a high temperature but without the presence of oxygen. Gas produced in this way contains particles and also nitrogen and tar.
Steam gasification is a more complicated process that produces cleaner gas with caloric value 15 MJ/Nm^3.

Carbona, Finland is a company that offers a whole package. A prototype of a biomass power generation cycle with a fluidized bed gasifier was installed in Skive, Denmark. The commissioning of the plant started in late 2007 and, using one gas engine, operations initially began in the early summer of 2008. The second and third gas engines were installed during summer 2008. [1]

Wood gasification of this type and scale is financially demanding and finds implementations in Europe only thanks to subsidised programs for biomass energy.
The machinery is super sensitive to the quality of the gas. Even after elaborate cleaning procedures this technology has caused plenty of trouble in operation. Besides, after the installation it takes a long time to troubleshoot.
A low quality gas in a piston engine causes severe consequences. While the gas is being burned in the piston, mineral compound is deposited on the walls. The compound gradually bonds the moving piston with the stationary cylinder, and finally the engine seises up.

Application with 1 MWe power has one more problem. At this power output, there is a problem with the stability of gas generation. It is necessary to install a gas storage tank to provide a stable supply of gas to the engine, because the output quantity of the gasification process is time variable.

Parameter	Quality
η_e of the circuit with a piston engine	ranges from 18 to 25 %
η_e of the circuit with a gas turbine (only for reader's information)	25 to 30 %
η_c of the circuit	up to 90 %
Gas generator providers:	Boss (Bucovice); Kolinske Strojirny a.s.; Ateko a.s.
Cogeneration set providers:	Jenbacher GmbH, Zeppelin Baumaschinen GmbH, Tedom a.s.

Table 4.3: Summary of parameters of gasification with the OC

Chapter 5

Technology selection

Wood gas generators and the gas turbines are the cleanest and the most technically advanced technologies for a cogeneration source. However there are some decision criteria upon which the technology has to be evaluated before it is implemented in any distant location. These criteria will be considered in a multi-criterion analysis, on the basis of which the most suitable solution will be selected and then custom designed.

5.1 Multi-criterion analysis

MCA consist of two parts. The first is to define each criterion and to evaluate the performance of a technology in this area. The second part is the importance of the criterion that is being considered for the actual application.
It was decided to assign points from 1 to 3 in the evaluation of performance of the technology. There are three technologies, and they will be ranked from first place, which will be awarded 3 points, to the least well performing, which will be awarded 1 point. The weighting of the criteria is set that there are 10 points for crucial criteria, and there is only 1 point for the least important criteria.
Only the most important criteria are evaluated, and the analysis can be extended by adding more criteria according to the actual situation.
Then it is a matter of summing the performance points multiplied by importance points. The higher the resulting value, the more suitable the technology is for the required purpose.

5.1.1 Cost

Importance of the criterion: 8
Driving the cost down is a key factor for the technology. The goal is to balance quality and cost of the initial investment, and operation expenses.
The installation cost is assumed to be about the same for all technological circuits. If we judge only according to the price of the machinery and equipment per megawatt installed, RC comes out best, followed by ORC, with gasification combined with OC in last place.

5.1.2 Simplicity

Importance of the criterion: 10
Simplicity is the most important criterion of all when selecting the power generating technology for an application such as a remote off-grid town, where the operating staff will be people with limited or no professional qualifications.
The simplest type of technology assembly is a container version of the ORC unit. This is followed by a container version of RC equipment. The the least simple option is gasification, which additionally requires gas filtering and storage tanks, besides container with cogeneration unit.

5.1.3 Reliability

Importance of the criterion: 10
Reliability is the ability to serve the required function, when all the required operational criteria must be within given intervals according to technical specifications. [14]
This ability to fulfil continuously the required function at given time and given conditions is crucially important for a distant application.
RC is well tested and mastered technology, and is awarded 3 points. ORC is based on the same principles of operation, and is awarded 2 points.
For a highly demanding application as required in this study, gas generators are a problem. We have no problems using OC with natural gas, but the situation with wood gas is different. The piston engine needs to be fed a stable quantity of fuel. This can be achieved only with a pressured gas accumulator. Pressure tanks would raise the project cost of the project, and in addition all pressure vessels require registration by a federal agency in Russia, which means unpredictable time investment. Finally this is quite a sensitive process with various potential weak points, and it is therefore given 1 point.

Maintainability

Importance of the criterion: 8
Maintainability is the capability to prevent failures by prescribed maintenance [14]
This involves lubrication, boiler checks, filter regeneration, etc. In a remote location, this is again an important issue. Requirement is the longest running time spans without any stop, and maintenance has to be done quickly and quite easily. The requirements for each of these technologies vary, and the conclusions are inconclusive. Hence this criterion is not further used.

Repairability

Importance of the criterion: 6
Repairability refers to the capability to investigate the causes of failures and remove their consequences by repair [14]
Most of the technology is already automatised to such an extend that we can predict failures prior to their occurrence. This can be done thanks to detailed measurements of any process variable. For example a temperature or pressure deviation from the nominal value can predict an occurring failure. Considering that the crucial pieces have to be backed up the importance of this criteria is only 6 points.
The performance of each technology is extremely hard to assess because each of them is on the same high technical level, and none of them can be repaired by non-qualified personnel. Hence this criterion is again inconclusive and not further used.

Longevity

Importance of the criterion: 8
Definition of longevity is the ability of the object or system to fulfil the required function when maintenance and servicing are done properly [14]
Application like Stepanovka is demanding on operation hours. The machinery will be running practically nonstop, which can be as much as 8200 hours per year.
Experience with operating the technology has shown that RC has been in reliable operation for the longest period of time. ORC has the second longest period of operation before some parts have to be refitted, and OC occupies last position. The piston engine, which forms the heart of OC is rated to several thousands of hours of operation, which is much less than the operation life of a turbine. A steam turbine doubles or triples the lifespan of a piston engine.

5.1.4 Efficiency

Importance of the criterion: 7
This criterion is greatly influences the operating costs and the combustible requirements. It is taken very seriously because it is closely related with the transportation extend, and has the direct influence on the environment. Gasification with OC has the highest efficiency. RC and ORC are about equally efficient since they are based on the same thermodynamic principle. It can be argued - that because of the design - ORC is expected to be slightly more efficient.

5.1.5 Other criteria

I have mentioned above the main criteria that we should take into account here. However there are other factors that can also have a big impact e.g. safety, system dynamics, impact on the environment during the lifetime of the plant and even after, etc.
Safety of the system can be assessed from two perspectives. Work safety and safety of the town in case of a failure. If risk assessment is done it is probable that all the three options would come out to be very similar.
Dynamics of the system is clearly in favour of OC. It allows much shorter starting times and greater operation flexibility.
We have no way to make in-depth investigation of the environmental impacts. Each technology has various effects on emissions, transport, ground water, and so on.
Actually any of the criteria are too complex to be assessed in detail in the scope of this thesis.

5.1.6 Analysis

Our decision was reached on the following basis: a number from one to three was assigned for each criterion according to performance of the technology in that area. This number is multiplied by the importance factor for the category (in parentheses below the name of criterion). The sum of the products for each technology provides the total value for the technology. Hence higher the total value the better.

Criteria	Cost	Simplicity	Reliability	Longevity	Efficiency	**Total**
Importance	(8)	(10)	(10)	(8)	(7)	**-**
RC	3	3	3	3	1	**115**
ORC	2	2	2	2	2	**86**
Gas. + OC	1	1	1	2	3	**65**

Table 5.1: Multi-criterion analysis for the technology selection

The MCA shows that according the methodology used here the RC circuit will best fit the tough operating conditions in Siberia.

5.2 Reserve and redundancy

Redundancy refers to a functionally spare object or component that is meant to increase the reliability of the given system.
Reserve is a method to maximise the reliability of an object or a system by utilising back ups. [14]

Some parts of machinery are designed to include redundancy e.g. the feeding armature. Redundant design is anchored in the boiler standards, firstly because the feeding head is critical to the function of the whole system, and secondly for the safety of the boiler, because when water stops being fed to the boiler, it can overheat critically and be destroyed.
To satisfy the requirement for reliability I am proposing biomass-fired boilers with back-up fuel from the already existing diesel infrastructure. It is a matter of putting extra nozzles on the furnace and the diesel tank in the boiler house. This may sound easy, but it is an extra cost for the project scope, and also a possible technical problem.
The diesel generator is already in place, and can be left as a backup. It can be completely overhauled including the generator, as an integral part of the project.

Chapter 6

Calculation and circuit optimisation

The technical calculation is elaborated, on the basis of the data presented in previous sections. The main goal is to propose the simplest design possible, operational reliability, minimal requirements on operation personnel, and minimisation of the cost of the installation as a whole. This chapter quotes the know-how and experience shared with me by Doc. Fiedler in person.

Given:

- Electrical power 1000 kW
- The combustible is wood

Selected parameters:

- The selected technology is the Rankine cycle, because the reliability and simplicity of the solution outerform the other options.
- A single-stage back-pressure steam turbine directly coupled with the generator is selected because of its relatively low investment requirements.
- 13 bar admission pressure is selected to minimise the cost of all the equipment. The lower the pressure, the lower the requirements on the thickness of the pipes, on the power of the pumps, etc.
- 1 bar back pressure, i.e. atmospheric pressure.

- Temperature of the feed water 105 °C, which is the unwritten standard for almost all boilers.

From here we can draw some facts about the circuit. Figure 6.1 shows our assumptions on the simplified t-s diagram of the medium.

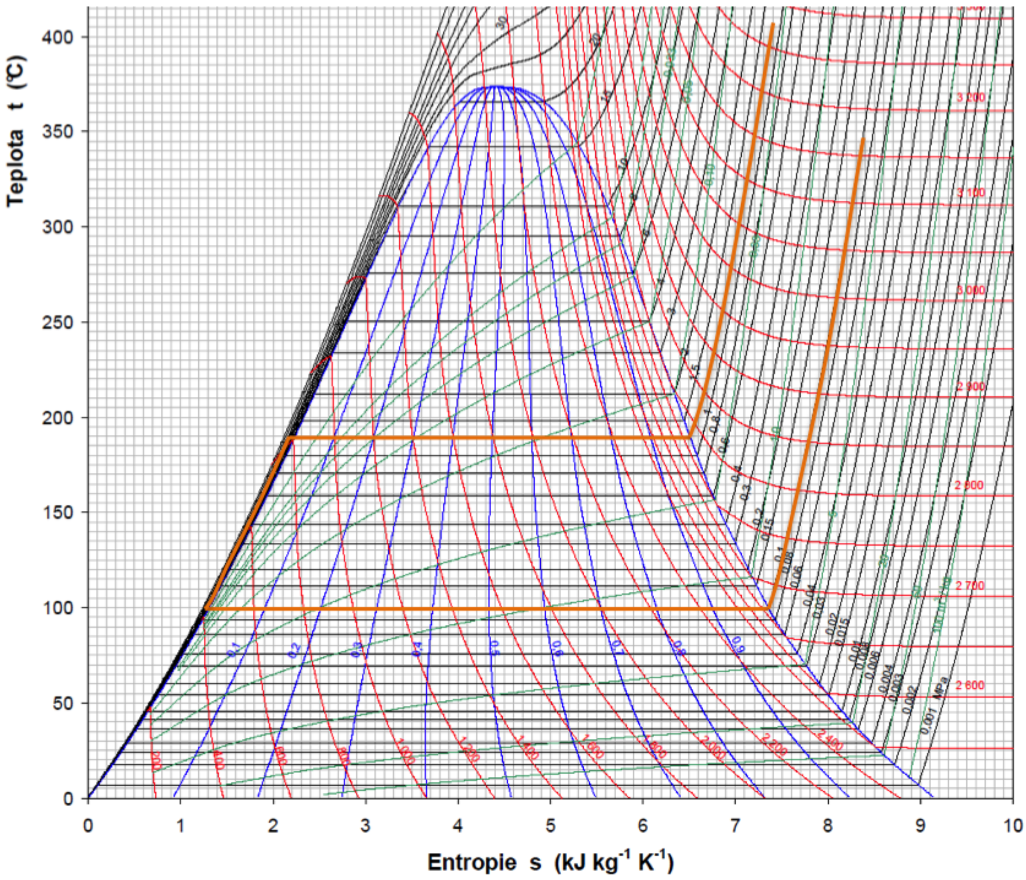

Figure 6.1: ts diagram implying the assumptions that have been made [diagram used by courtesy of Ing. Hugo Šen]

Other parameters are subject to selection. The calculation aims to achieve maximum electrical efficiency of the circuit at given required power and minimal consumption of superheated steam.

6.1 Thermal calculation and optimization of the circuit

The calculation method for optimal parameters based on minimum overall heat efficiency is not applicable in this case. The overall efficiency of the back-pressure cogeneration steam circuit is

$$\eta_c^t = \frac{P_e + Q_h}{Q_s} \tag{6.1}$$

η_c^t is determined mainly by the boiler losses, where 0.9 is achievable.

The partial thermal efficiency with respect to electric power is calculated

$$\eta_e = \frac{P_e}{Q_s} \tag{6.2}$$

The dependent variable entering the optimisation process is the temperature of the superheated steam from the output of boiler t_3. Increasing t_3 generally leads to increasing partial thermal efficiency of the circuit η_e. So far we have considered a steam boiler with its output temperature within the interval from 200 to 250 °C. Hence this change in t_3 is so small that it cannot increase η_e by much.

It is better to set the temperature of superheated steam t_3 on the basis of some other consideration. We could optimise the coupling of the boiler and the turbine by tweaking pressure p_3 and temperature t_3, but the limitation is the enthalpy gradient for a single-stage turbine, which is at most 350 kJ/kg. An increase in t_3 brings an increase of enthalpy gradient H on the turbine. At a given power output this lowers the necessary steam mass flow $\dot{m}_3$, because

$$P_e = \dot{m}_3 * H * \eta_t * \eta_g \tag{6.3}$$

This effect will not become apparent for a small increase in t_3, as there is no apparent increase in thermal efficiency with respect to the production of electric power.

$$\eta_e = \frac{P_e}{Q_s} = \frac{\dot{m}_3 * (i_3 - i_1) * \eta_t * \eta_g}{\dot{m} * (i_3 - i_{fw})} * \eta_b \tag{6.4}$$

In the term $\frac{\dot{m}_3}{\dot{m}}$ the steam mass flow changes in the numerator and the denominator and the enthalpies are the same. Hence the term η_e remains practically constant.

The end point of steam expansion i_4 is significant for the design. This point moves on the isobaric line $p_4 = p_1 = 0.1$ MPa as t_3 increases. Thus point i_4 is moving toward higher steam dryness x. We are looking for the value of t_3 that corresponds to i_4 on the saturation curve, where $x = 1$.

The slope angle of expansion curve i_3 to i_4 is bonded directly to the thermodynamic quality of the turbine. It can be expressed by the value of the internal thermodynamic efficiency.

$$\eta_{tdi} = \frac{H}{H_{is}} = \frac{i_3 - i_4}{i_3 - i_{4is}} \tag{6.5}$$

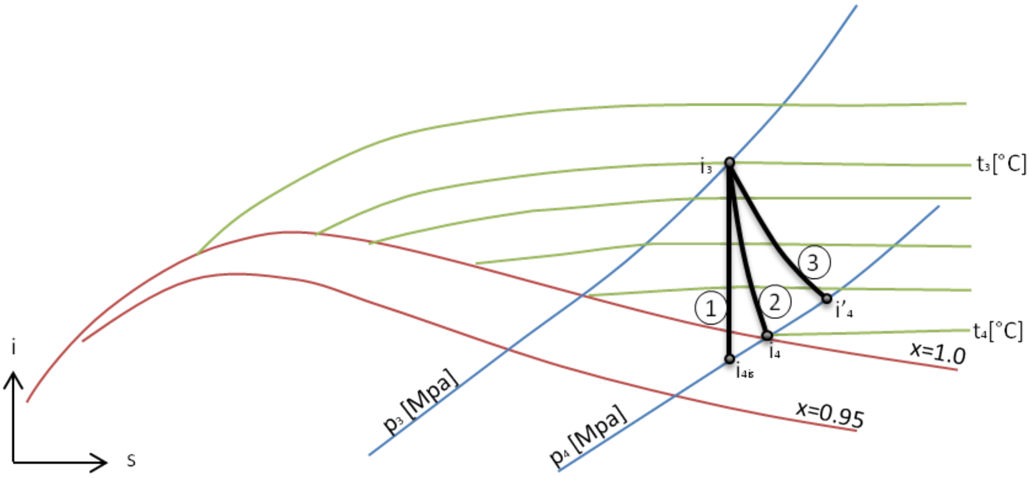

Figure 6.2: t_3 selection as a function of η_{tdi}

An illustrative difference is shown in Figure 6.2, where ideal turbine is plotted as number 1, and two real turbines with different internal efficiencies are plotted 2 and 3, where number 2 is more effective.

The optimal end of expansion in the steam turbine is at steam dryness $x = 1$. Any decrease in dryness below $x = 95$ % brings problems with erosion on the blades of the impeller wheel. This happens even in the axial flow channel.
For two reasons this is not economical to end expansion anywhere above the saturation curve in the area of superheated steam.

1. Enthalpy gradient H is wasted.
2. The heat energy in the heat exchanger behind the turbine is shared in principle by condensation of the steam. It is not suitable and obviously pointless to design the exchanger with a precipitator to utilise the superheated steam.

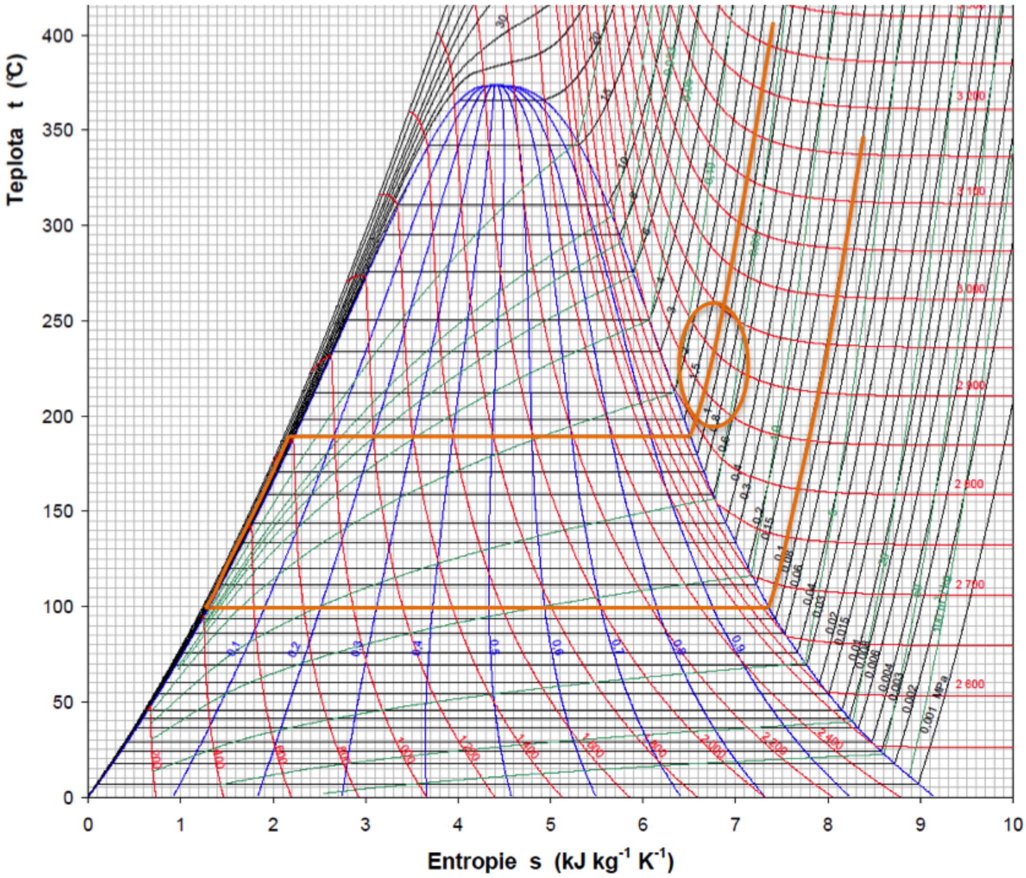

Figure 6.3: ts diagram showing the area for the search for the optimal temperature [diagram used by courtesy of Ing. Hugo Šen]

Higher temperatures t_3 with respects to i_4 in the area of saturated liquid line $x = 1$ is a function of internal thermodynamic efficiency. The higher the η_{tdi}, the higher the optimal temperature t_3 and the higher the optimal enthalpy gradient i_3 to i_4

If we are to select a real internal efficiency value for a single-stage steam turbine directly coupled with a generator and the pressure ratio

$$\pi = \frac{p_3}{p_4} = \frac{0.1}{1.3} = 0.0769 \cong 0.077 \tag{6.6}$$

and mass flow rate $\dot{m}_3$ we will find that $\eta_{tdi} = 0.5$ is guaranteed for 1MWe power range units.

Optimisation of the t-s diagram will now be shown in the following table 6.1. If shows the optimal temperature on the output of boiler t_3 with respect to the dryness of the steam at the end of the expansion i_4 for a practically negligible change in efficiency η_e

1.3MPa / $t_3[°C]$	210	220	230	240	250
$i_3[kJ/kg]$	2835.676	2860.661	2884.912	2908.598	2931.833
$s_3[kJ/kgK]$	6.597	6.648	6.697	6.743	6.788
$i_{4is}[kJ/kg]$	2391.154	2410.235	2428.383	2445.759	2462.475
$i_4[kJ/kg]$	2613.415	2635.448	2656.648	2677.179	2697.154
$H = i_3 - i_4[kJ/kg]$	222.260	225.213	228.264	231.419	234.678
$x[-]$	0.972	0.982	0.992	1	1
$t_4[°C]$	99.606	99.606	99.606	100.683	110.402
$v_4[m3/kg]$	1.648	1.664	1.680	1.699	1.746
$\dot{m}_3[kg/s]$	4.786	4.723	4.660	4.597	4.533
$\eta_e[-]$	0.0715	0.0717	0.0720	0.0722	0.0726
$\eta_{tdi}[-]$	0.5	0.5	0.5	0.5	0.5

Table 6.1: Temperature t_3 optimisation

Selected temperature is 240 °C. Production of electrical power is important in this case. The quality of the turbine is therefore important, because the electrical efficiency of the whole thermal circuit is directly dependent on the turbine. An increase in the internal thermodynamic efficiency of the turbine η_{tdi} while keeping the power of the boiler the same would in practice increase the electrical power from the generator and the heat-power ratio at the same rate.

The complete ts diagram for the heat circuit is shown in Fig. 6.4

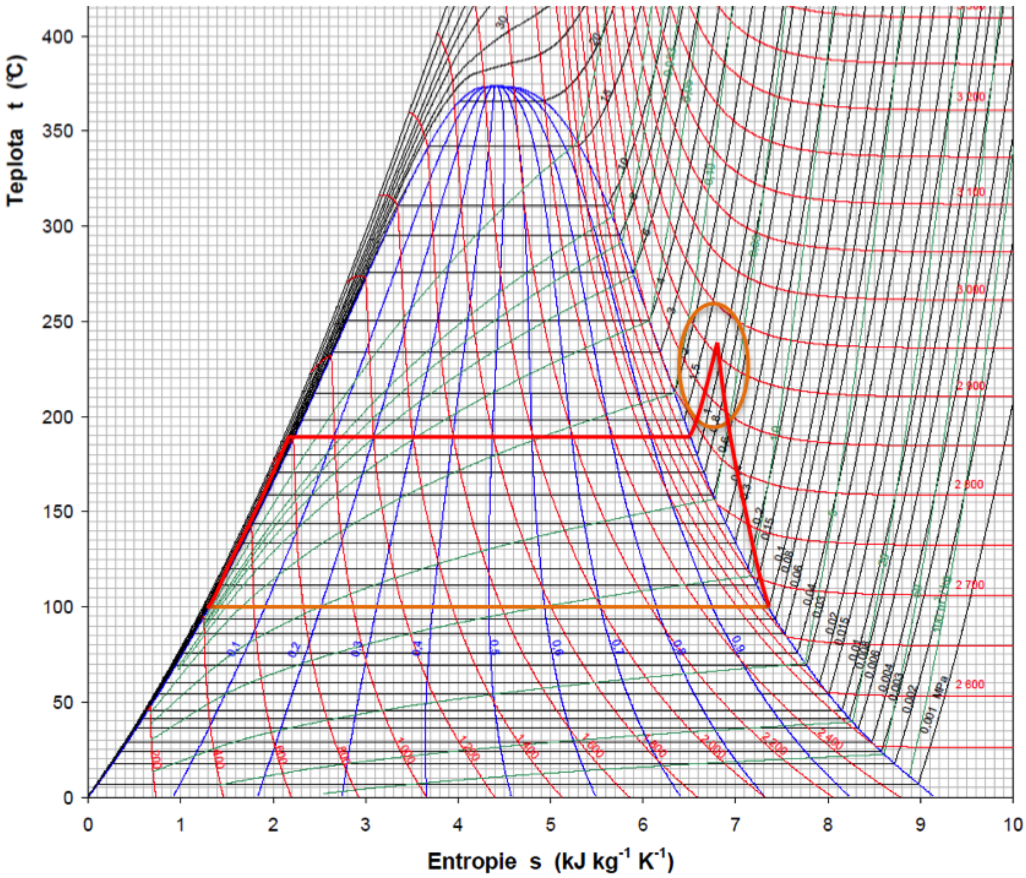

Figure 6.4: ts diagram of the complete cycle [diagram used by courtesy of Ing. Hugo Šen]

6.2 Design of the circuit

Table 6.1 shows that if the output power on the terminal of the generator is to be 1 MWe the effective power on the shaft of the turbine has to be divided by 0.97, which is the expected efficiency of the generator.

$$P_{shaft} = \frac{P_e}{\eta_{gen}} = \frac{1}{0.97} \tag{6.7}$$

which turns out to be 1063 KW.
In order to produce this amount of shaft power, the system needs to be supplied by 14.17 MW in combustible if we consider boiler's thermodynamic efficiency 0.8.

The volume of wood is then dependent on its caloric value. The caloric value is directly dependent on the dryness of the wood material. If we consider standard wood, containing 30 to 40 % water with a caloric value of 10 MJ/kg, the process will require 6.4 tons of wood per hour.
This is indeed an alarming amount, but it can be reduced by drying the combustible wood or by using a turbine with higher internal efficiency.

6.3 Heat circuit synthesis

6.3.1 Steam turbine

A single-stage machine is used. It is directly coupled with the generator, back-pressure with an overhung wheel. The output power is manually regulatted by partial admission. The nominal power output is 1000 kW. This turbine can be controlled on wide interval 300 kW to 1300 kW. An overloading valve controls the steam flow, allowing a 30 % temporary power increase in the nominal power output.

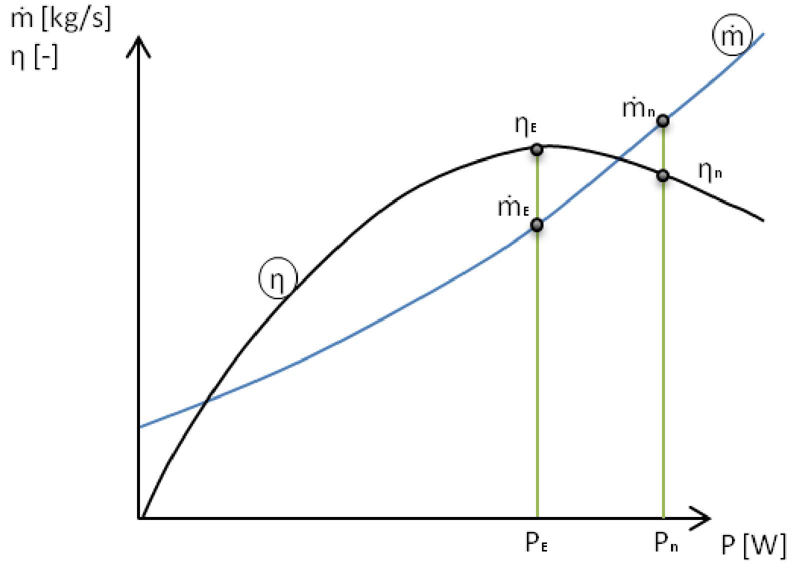

Figure 6.5: Relation between power and steam mass flow in a steam turbine

Index n points to nominal operation mode, and index E is where the operation is the most economical. In this case the point P_E is 1000 kW.

Technical concept description:
Thermodynamic efficiency η_{tdi} is additionally corrected by the mechanical losses of the turbine. It is the loss in two radial bearings and one axial two-way friction bearing $\eta_{mech} = 0.98$.
The efficiency of the bipolar asynchronous air-cooled generator is $\eta_G = 0.97$ The beginning point of the expansion in turbine i_3 was chosen after registering all the pressure losses in the entrance armature and the starting valve. It is about 3 % of pressure p_3.

6.3.2 Minimising the circuit

Reducing the items in the circuit is a priority for simplicity and also for reliability. Minimisation is done consistently item-by-item with respect to contribution of an item. The result is then compared with the installation demand of the particular item.
This analysis is carried out for the heat exchangers, the sealing steam condenser and the slag steam releaser.

6.3.3 Steam turbine connection

The steam shaft sealing is designed and connected for a steam mass flow of 15.12 t/hr. It is designed as classical connection with steam transfer from the area of the shaft sealing and the drive of the start valve leading off to the sealing steam condenser. A small underpressure approximately 0.7 m water column is maintained by a radial fan with an electric drive in this branch. This fan extracts non-condensable fumes and gases from the sealing steam condenser. If the fan breaks down, or during the starting procedure of the turbine the ejector is used. It is connected in the back pressure branch of the turbine with the exhaust to the atmosphere outside of the boiler house. It is recommended to use shaft contact less labyrinth seal. The steam mass flow-through is expected to be 0.4 % of $\dot{m}_3$, i.e. 67 kg/hr. A contact carbon sealing could also be used as an alternative to decrease the amount of escaping sealing steam, but this would also increase the maintenance and inspection requirements before each start. From the experience of the turbine suppliers, a rate of about 45 kg/hr is an allowable escape of shaft sealing steam to the boiler house. This should not cause any problems in the machinery hall.

6.3.4 Water heater on the back-pressure branch of the turbine

The water heater on the back-pressure branch of the turbine was designed according to energy balance of the circuit and the mass balance of the working medium. The medium outside the tubes condenses steam at $p_4 = 1$ bar without reheating. The undercooling of the condenser is selected to be 20 °C. The heat transferred is $\dot{Q}_t = 10898$ kW. The mass flow of the water flowing in the tubes is calculated from the standard temperature gradient of heating water 90/60 °C, which is 143 kg/s, as labeled in Figure 6.6. These values can vary up to the maximum, depending on customer requirements, the ways in which the heat energy is used, the options for excess heat transfer, according to annual heat consumption diagram, the ways of cooling the condensate, etc.

The hot water heat exchanger is situated after the turbine. It isolates the primary circuit and the heating grid. It was chosen to be a simple, piped surface exchanger with a relatively big temperature difference on the water output of 10 °C. This type of exchanger is inexpensive, with a smaller heat exchanging area than a plate exchanger.
Problems are expected with condensate cooling in lower-than-nominal output operation, for example in summer. In this operation regime there is excess heat in the feed tank and in the degasifier. We can fix the problem with this regime by shutting down the exchanger of the sealing steam condenser and optionally the slag extractor from the hot side of the boiler. They can be cooled by an external source.
In general there is a great deal of excess heat in any circuit with a single-stage turbine. Therefore there is always a way to supply enough energy to heat the feed water to the desired temperature without using additional exchangers.
Problems may occur if an installation with high electrical power is set up in a place where there is a lack of water.
The need for chemically treated and heated water may be as high as 1080 kg/hr for 1000 kWe power. This is caused by

1. turbine sealing losses
2. a slag trap
3. circuit leakages.

These losses are the reason why all types of heat exchangers are utilised in a circuit to minimise the demand for water.
Where additional water demand is not a problem, the circuit can be further simplified. However this comes with a cost. While fewer parts means lower investment cost, it conflicts with the operational economics and with the ecological standards for the slag trap drain of the boiler, which has to be cooled to 50 °C and discharges sealing steam to

the atmosphere. In this case, it is necessary to install all these exchangers, even if there is no thermodynamical reason for them. For the primary circuit, their recovered heat contribution is negligible.

6.3.5 Regeneration steam reheater

The heat circuit is designed with only one stage of steam reheating of the feed water. It is also possible to recover the heat from the shaft sealing and from the boiler slag, which would otherwise be lost down the drain. This heat is also transferred by surface exchangers. They heat the make-up water before it enters the feed tank. The two exchangers are connected in parallel because they have practically the same temperature gradient. This design brings advantages for the control of the thermal power of the heat exchangers because one of the exchangers can be closed by a valve, if there is lower demand.

The power regenerated from the sealing condensate and from the boiler slag is irrelevant in smaller installations. In this case of a circuit designed in order to achieve the energy balance. We can accept contributions of condenser of sealing steam heat exchanger and slag cooler to make up water circuit branch. Hence the make-up water is heated to 90 °C, far enough from the saturated state. That transfers enough heat from the steam to the condensate. Therefore we do not have to face the problem of excess energy in the system. In a smaller application, there is a good chance that water escaping from the system will take away more energy that could be transferred back to the system in the make-up water. Even after the transfer, steam from the sealing does not condensate and an additional external selfstanding cooling circuit has to be used.
It is also important to take into the consideration that, from the energy balance point of view, the excess heat can also be transferred to the feed water degasifier. This will lead to savings of back-pressure steam. When investigating specific cases, it is necessary also to take economic consideration into the account. Energy balance is technically achievable, but at the cost of an additional heat exchanger. If the costs are known, it can easily be calculated whether the investment cost will be paid back by the energy savings from the shaft sealing and the boiler slag.

6.3.6 Make-up water

Additional water has to be purified and treated chemically to cover the losses by the boiler slag and the untightness of the thermal circuit. Depending on the design of the circuit, some of the medium is captured and brought back. This is the case for almost all of the shaft sealing steam, and for some part of the boiler slag mass flow rate that is in the form of saturated steam sucked from the slag expander. The amount of water that is lost is therefore equal to the thick leftovers from the slag that goes to the drain, forms plumes, and is lost due to lack of tightness of the system.

Plumes are non-condensed fumes and gases that have zero water solubility. They are continually being removed from the degasifier. They are extracted from above the water surface, along with the saturated steam. The mass flow of these fumes is about 1 % of the heating steam brought to the degasifier. Some calculation methods recommend about 1 kg of extracted gases for each 1000 kg of condensate. In our case this means about half of the amount that is designed.

The total volume of treated water is 1080 kg/hr out of which 2/3 is caused by continuous boiler slag extraction. The condenser of sealing steam from the heat circuit cannot be excluded from the design because steam discharged into the atmosphere at a rate of 67 kg/hr can be against environmental law. In addition the loss of the heat is significant.

6.3.7 Water degasification

Thermal degasification of feed water is proposed by heating the water to saturation temperature in a degasifier. Heat is provided by expanded superheated steam taken after the turbine. From the thermodynamic point of view, it is better to take heating steam at a lower temperature after partial expansion which would lower the irreversibility losses. However steam bleeding is not technically possible on a single-stage turbine, where expansion is not divided into more than one stage.

For maximal simplification of the circuit, we chose in parallel with the turbine a connection of steam from the outlet of the reduction valve. This reduction station also works as safety bypass in the event of total failure of the turbine.

The amount of expanded steam to be heated is about 3.5 to 4 % of the mass flow from the boiler. To minimise the irreversibile losses on the heat exchanger of condenser of sealing steam and slag cooler are used for heating of additional water. They are configured in a way that enables the output temperature of the water to reach 90 to 100 °C - nearly the saturation state.

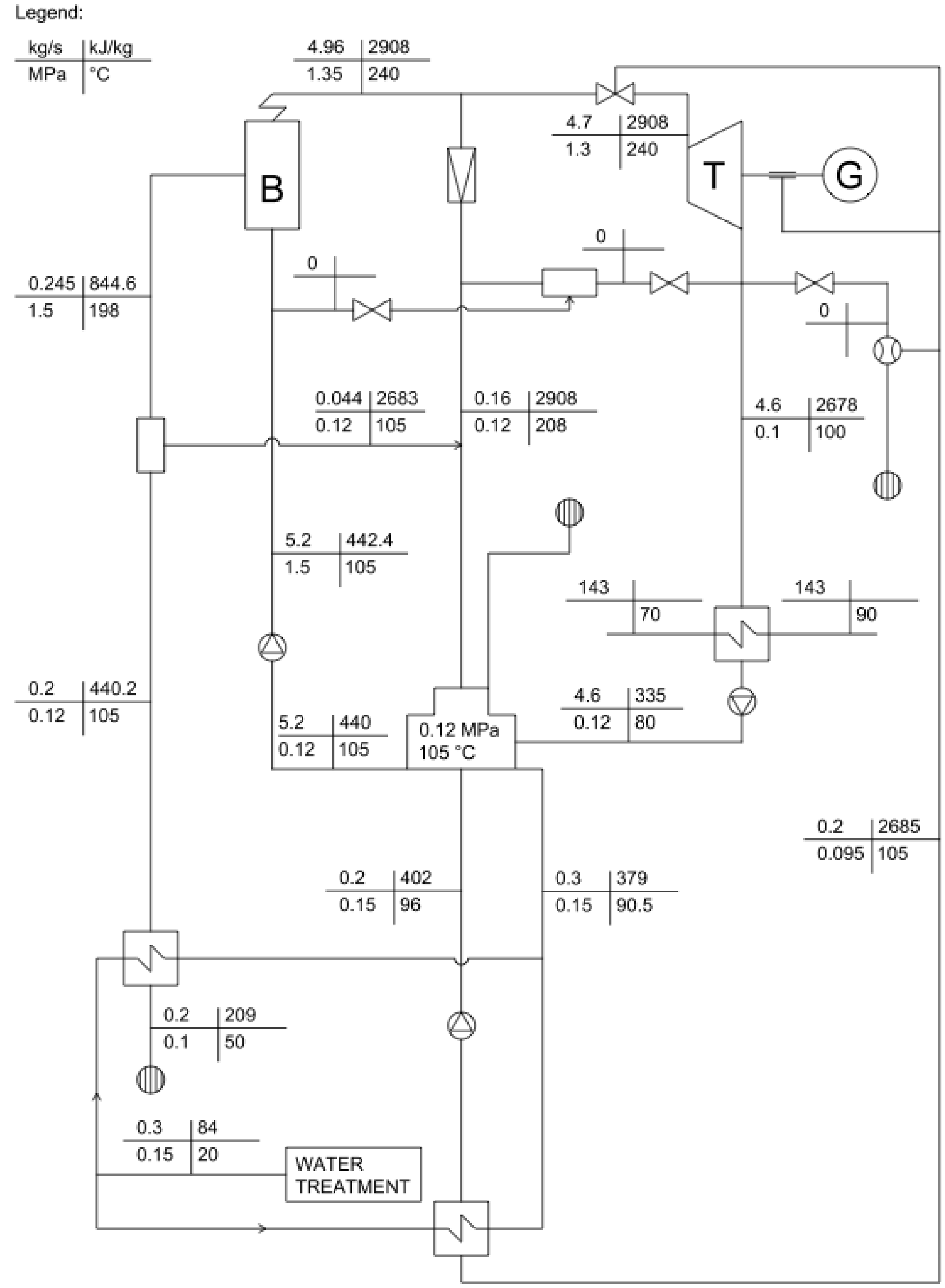

Figure 6.6: Circuit proposal with the single-stage turbine

6.4 Annual performance overview

Annual operation is represented by the graph in Figure 6.7.

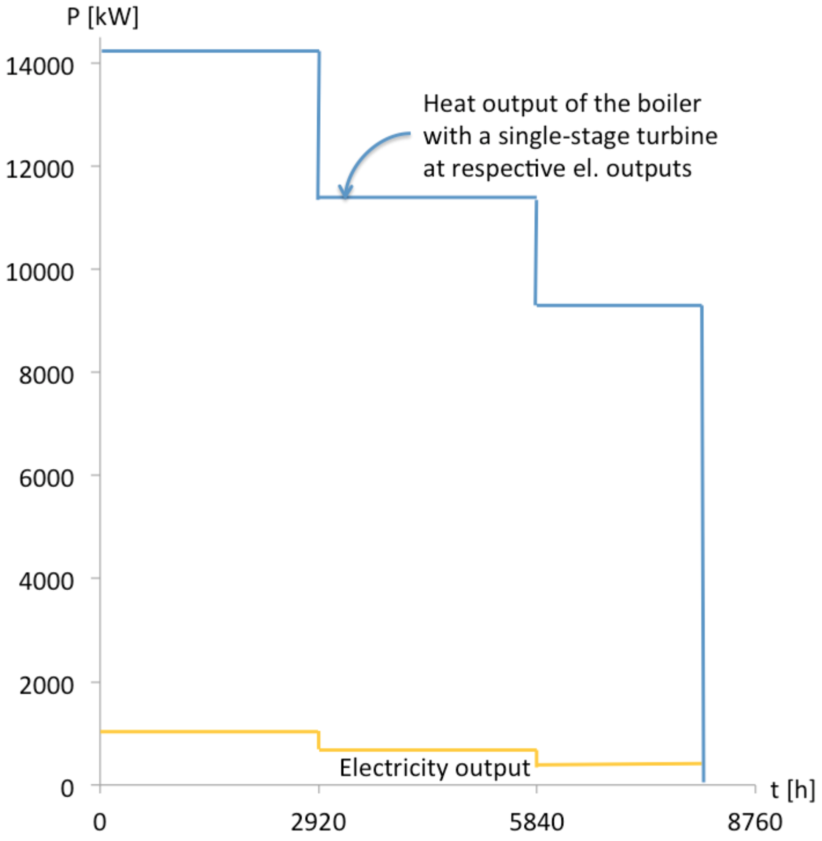

Figure 6.7: Annual heat and power plant utilisation curve

The year is split according to the demand for electric power. The turbine is expected to run for about one-third of the year at nominal 1000 kW power and about two-thirds of the year at a lower power output. These regimes are estimated as 700 kW and 300 kW and both levels are at a lower efficiency. In any case there will be a problem to use all of the heat that is produced. The heat should not be wasted, and this issue is addressed in section 7.1.

6.4.1 Heat-power ratio

Experience shows that there will always be some excess heat in a circuit with a single-stage turbine that has low thermodynamic efficiency. In our case, the electric power output required is the base for the calculation. The heat power output corresponds to it, and the ratio between the two is represented as power-heat module e.

$$e = \frac{P_e}{Q_h} \tag{6.8}$$

The value for this case is $e = 0.092$ The reason for such low e is the low overall thermal efficiency of the circuit related to electric power production. A significant increase in electrical efficiency cannot be achieved by further optimisation of the designed circuit. The options for changing the main parameters - the admission steam temperature, and the pressure - are limited, and cannot influence the efficiency radically, as was shown at the beginning of this chapter. A radical change in the efficiency would require a different technology or a more effective turbine.

6.5 Higher efficiency option synthesis

The selected technology is still the Rankine cycle with a boiler and, in this case, a multi-stage steam turbine with admission pressure 2 MPa. The same optimisation method is used as for the previous option.

2MPa / $t_3[°C]$	360	370	380	390	400
$i_3[kJ/kg]$	3159.894	3182.062	3204.164	3226.215	3248.227
$s_3[kJ/kgK]$	6.994	7.028	7.063	7.096	7.129
$i_{4is}[kJ/kg]$	2538.842	2551.792	2564.503	2576.992	2589.273
$i_4[kJ/kg]$	2663.053	2677.846	2692.435	2706.837	2721.064
$H = i_3 - i_4[kJ/kg]$	496.841	504.216	511.729	519.378	527.163
$x[-]$	0.9947	1	1	1	1
$t_4[°C]$	99.606	101.005	108.092	115.163	122.203
$v_4[m3/kg]$	1.685	1.701	1.736	1.770	1.804
$\dot{m}_3[kg/s]$	2.141	2.110	2.079	2.048	2.018
$\eta_e[-]$	0.137	0.138	0.139	0.140	0.141
$\eta_{tdi}[-]$	0.8	0.8	0.8	0.8	0.8

Table 6.2: Temperature t_3 optimisation for a multi-stage turbine

The optimal admission temperature for pressure 2 MPa is $t_3 = 370$ °C where, after expansion, temperature $t_4 = 101.005$ °C
These steam parameters also fit well because generally when we reach an admission temperature of 400 °C and the feed water is 105 °C there is a threat of undercooling the economiser and understepping the condensation temperature.
Additionally, for boiler output temperatures up to 400 °C the boiler working class is 3. Above 400 °C, for each increment of 25 °C the working class increases, resulting in the selection of higher grade materials for the furnace and for the heat exchanging surfaces, therefore directly influencing the cost of the boiler.

The turboset consists of a single-body high-speed back pressure steam turbine, coupled with the synchronous generator by a one-shift gearbox. The turbine with the gearbox are situated on their own frame. The generator sits on a separate base plate.

Tab 6.2 shows that if the output power on the terminal of the generator is to be 1 MWe, the effective power on the shaft of the turbine has to be divided by 0.93, which is the expected efficiency of the generator and the gearbox.

$$P_{shaft} = \frac{P_e}{\eta_{gen}} = \frac{1}{0.93} \tag{6.9}$$

which turns out to be 1075 KW.
In order to produce this amount of shaft power, the system needs to be supplied with 7.2 MW in combustible.
The volume of wood is then dependent on its caloric value. The caloric value is directly dependent on the dryness of the wood material. If we consider standard wood with a 30 to 40 % water content, with a caloric value of 10 MJ/kg, the process would require 3.25 tons of the wood per hour. This is almost a 50 % reduction in comparison with the single-stage machine.
This is achieved by synergy of two factors. Firstly, the internal efficiency of the turbine is higher, and secondly, the available enthalpy gradient is also higher.

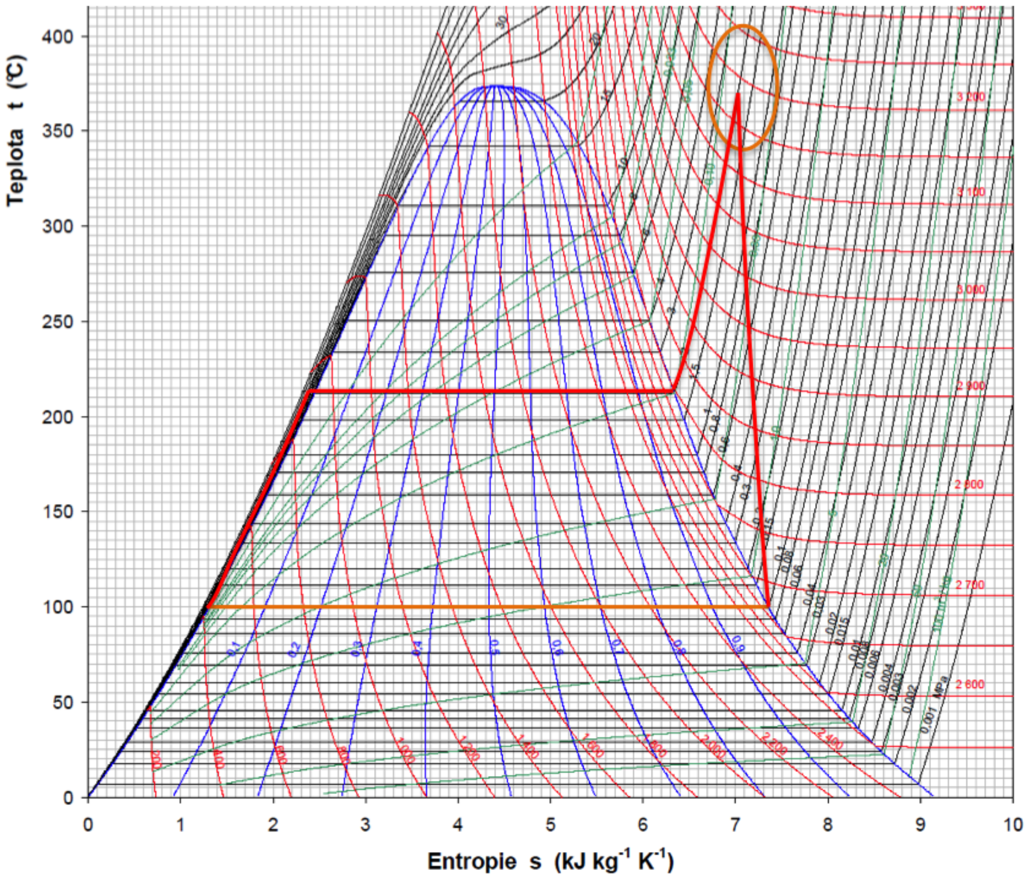

Figure 6.8: ts diagram of the complete cycle with a multistage turbine [diagram used by courtesy of Ing. Hugo Šen]

The boiler size and boiler output are determined by the required electrical power and by the turbine admission parameters of the steam $\dot{m}_3$, p_3 and t_3, see tab 6.2. The characteristics of the boilers further elaborated in the next chapter.

The following Figure 6.9 shows the difference in power input to the turbine. See the yellow line showing the respective electric output that is equal for both turbines but the energy needed to produce this much of electricity is rather different. The heat required by the turbine is directly correlated with the combustible so we can state that savings in heat are equal to the savings in wood.

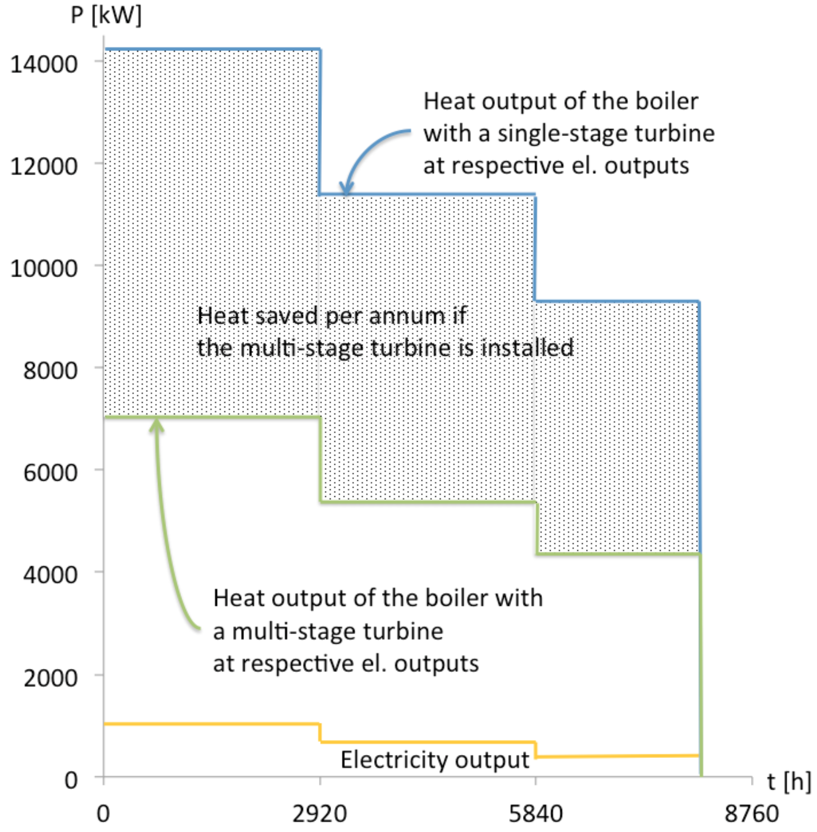

Figure 6.9: Comparison of two annual heat and power plant utilisation curves

The cost of the project will obviously be the main limiting factor for the technology. However the use of a relatively cheaper single-stage turbine with low thermodynamic efficiency will lead to higher consumption of combustible material.

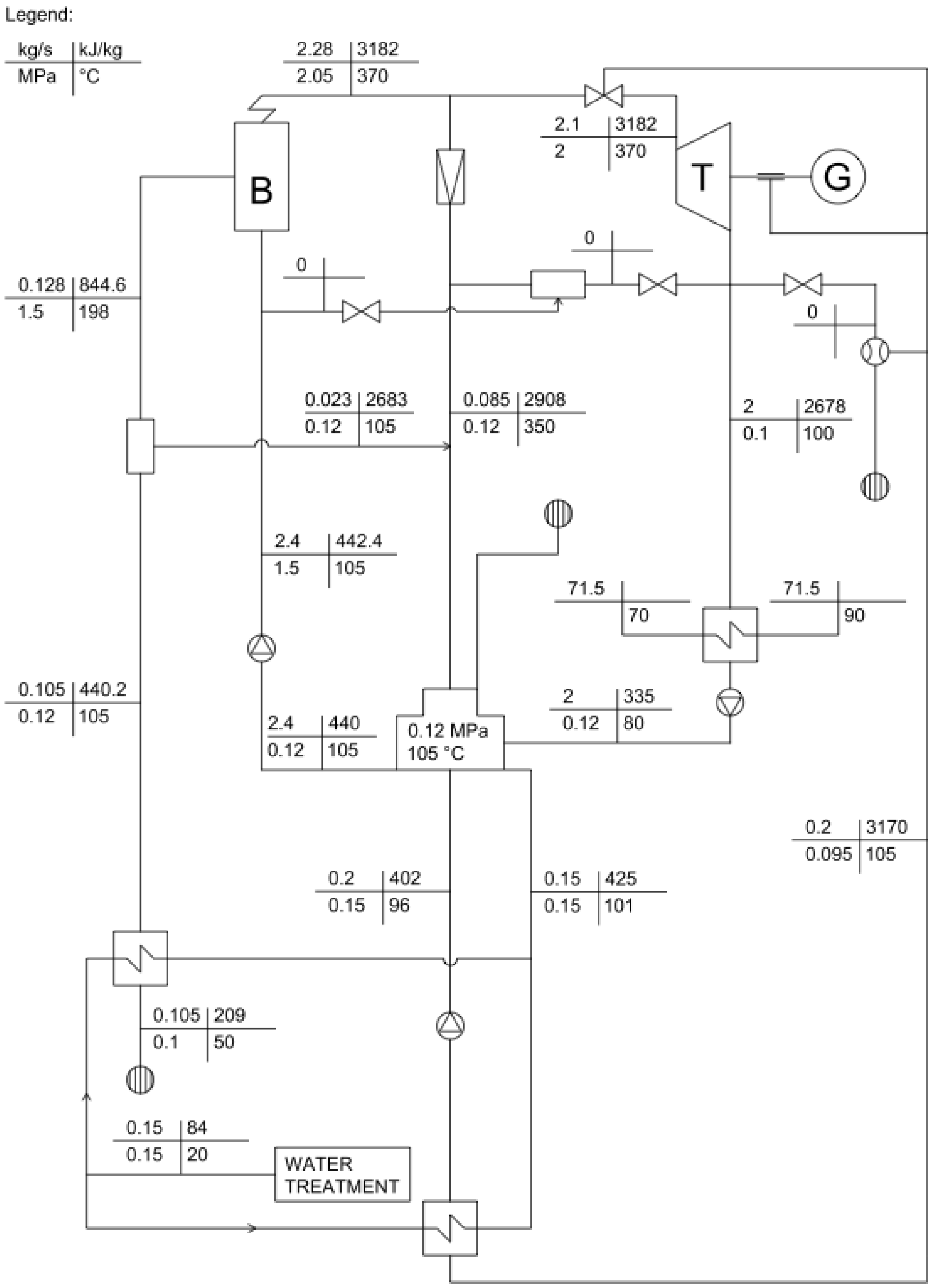

Figure 6.10: Circuit proposal with the multistage turbine

Chapter 7

The project

There are specific features to the project that are worth listening so that they can be taken into account prior to any realisation. Surely, these items lie beyond the scope of this thesis.

- Seminars should be held for local residents who will be plant operators.
- Custom-made burners with nozzles can be ordered for the boilers for the diesel back-up fuel. Biomass boilers for 1 MW are not mass produced, so custom-made equipment will be needed.
- Design electrical storage or a small scale back-up power generator that will serve for internal consumption of the power central during start-up.
- Boilers are usually not offered with a chemical water treatment assembly. Our application will need that.
- The current diesel engine has reached the point where a complete overhaul is recommended. If we keep it as a backup source of electricity, an overhaul should be included as a part of the project.
- The heat grid is too small in the current state, and new branches for higher heat capacities should be installed.
- The electrical output has to be taken care of. Transformation, control of the turboset and primary control of the local network have to be synchronised.
- Sufficient and safe storage of both diesel and wood is needed for sustainable operation during the winter period.

7.1 Wood drying facility

In our application, where the boiler house is close to the wood processing plant, the residual heat after the turbine can be used for drying the fuel and also for drying the products. Complementary to the vacuum condenser for water, there needs to be an extra heat exchanger in the condenser loop to transfer the heat to the secondary circuit, which will then lead to the drying area or the hall. Figure 7.1 shows a possible layout of facility. Two very simple and inexpensive sheds build next to each other in such a manner that the storage will be directly accessible from the wood processing plant.

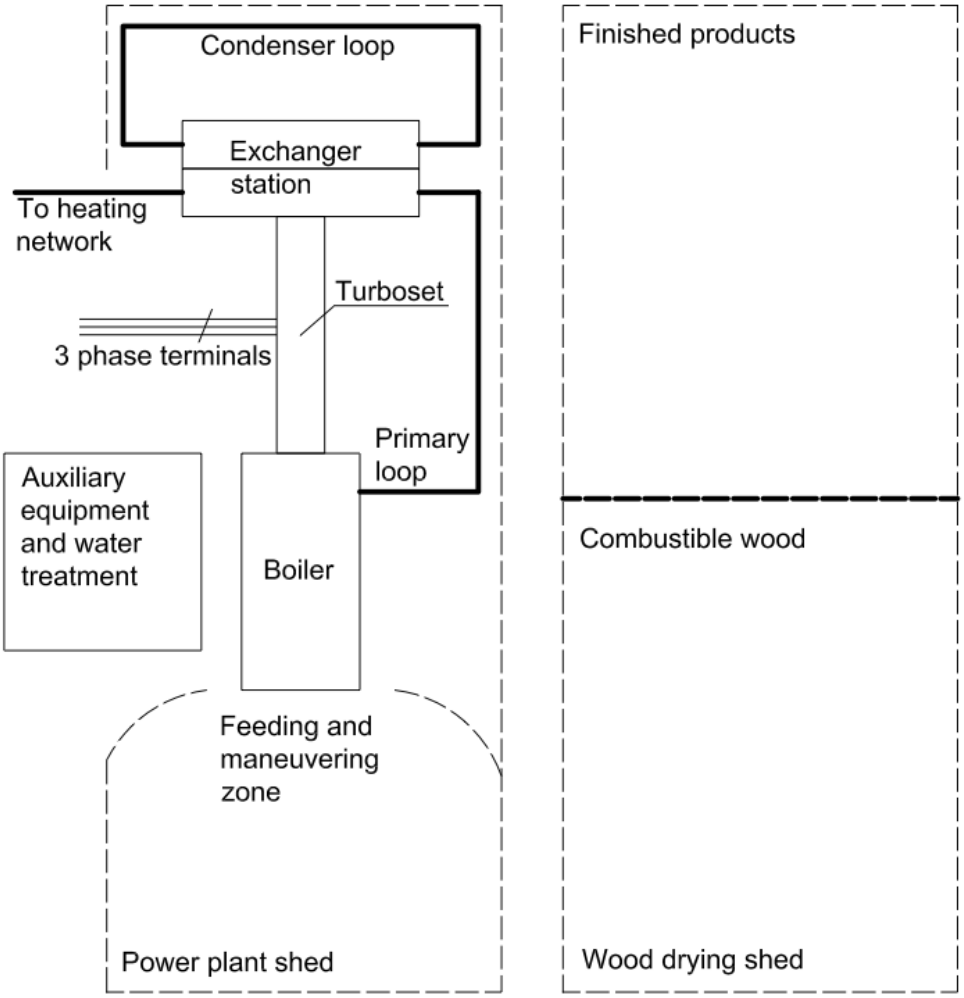

Figure 7.1: Scaled cogeneration plant layout with combustible storage

There are basically two options: hot air drying, or ground heating. When the wood

chips are dried, they are dehumidified. This increases their caloric value and no condenser of hot combustion fumes is needed. The cycle is completed when the waste produces steam and hot water to dry the next generation of wooden chips going to the furnace chamber. This will improve the caloric value, so that less wood will be needed.
For more details, see Cerny, J [5].

7.2 Lead time for construction

With respect to the power output of the heat and power plant, we advice modular construction. It is a standard procedure to fabricated the main equipment section by section. Containers for the turbine and heat exchangers will make it easy to transport, and almost all parts can be pre-made in container units on the factory shop floor. On-site construction then can be completed in as little as 3 months.

The only downside with this type of modular construction is that *special care must be taken when designing the fittings* to make sure that all the modules will fit together after arrival on site.

Approximate process times:

- 9 to 15 months – Preparation of construction works in machine shops, from the day on which the order is placed
- 2 months – Transportation and custom clearance, in parallel with on-site construction works
- 3 months – Mounting and connection, in parallel with training of the operators
- 1 month – Testing, starting up and training of the operators

Part III

Economics

Chapter 8

Costs and capital return

The goal of this chapter is to find which of the options is more economical and to provide clear evidence why it makes sense to be proceeded.

8.1 Investment cost

Now when the design of the cogeneration source is done we can take a look on the financial side of the power generation business. The cost of a plant can be simply divided into three main areas: the boiler, the steam turbine and construction works on site.

8.1.1 Boiler

From the technical part of the thesis we have got two options for Stepanovka. One is a single-stage turbine and the other is multi-stage turbine. Each of them has different input parameters, which will affect the cost of the boiler.

1. A 1 MW single-stage turbine with internal efficiency 0.5 needs boiler with output 17 t of steam per hour, pressure 13 bar and temperature 240 °C.
2. A multi-stage turbine with the same output power and internal efficiency 0.8 needs a boiler with output parameters 7.5 t of team per hour at 20 bar and 370 °C.

We were in touch with several companies, which produce biomass boilers. By the time of thesis deadline three of them were able to send cost estimates.

The first producer is a Czech company PBS who estimated the cost for the first one 94 mil. RUB and for the second boiler 62.5 mil RUB. These prices are excluding electrical installation, dust filtering, combustible and ash handling, chimney and chemical water treatment. [13]

The second producer is also Czech company Invelt who sent more detailed estimation for both. The 17 t/hr boiler:
Project: 5.5 mil. RUB
The boiler: 61 mil. RUB
Installation: 8.2 mil. RUB
Putting into operation and testing: 5 mil. RUB
In total 79.7 mil. RUB excluding control system, electro installation, dust filtering, combustible and ash handling, chimney, chemical water treatment.

The estimate for the 7.5 t/hr boiler:
Project: 5 mil. RUB
The boiler: 37.5 mil. RUB
Installation: 6.1 mil. RUB
Putting into operation and testing: 4.5 mil. RUB
In total 53.1 mil. RUB excluding control system, electro installation, dust filtering, combustible and ash handling, chimney, chemical water treatment. [9]

The third company is Polytechnik from Austria. They sent very detailed offer, see electronic attachment of this thesis. The 17 t/hr boiler ex works costs 202 mil. RUB and the 7.5 t/hr boiler excluding works cost 120.7 mil. RUB. [10]

8.1.2 Turbine

Czech company G-Team makes turbosets called "turbine reduction" with single-stage turbines, cost of which is 13.3 mil. RUB
Such set consists of a single-stage turbine, generator with primary regulation and auxiliary equipment, such as oil management unit and control valve.

Also Czech company EKOL produces small multi-stage turbines, which cost 23.5 mil. RUB Turbosets consist of a multi-stage turbine, gearbox and the generator the generator with primary regulation and auxiliary equipment, such as oil management unit and control valve.

8.1.3 Total investment cost

At this point is totally clear that it makes no sense at all to further consider this instalment with a single-stage turbine. There are two lethal disadvantages of this technology.

- The efficiency is inferior, which almost doubles combustible consumption
- The cost of the single-stage turbine and respective boiler is higher than the cost of superior multi-stage turbine technology

We reviewed three studies by power consulting companies that provided us this data.

Agency	Total investment installed [RUB/kW]	Additional fossil investment [RUB/kW]	Year
IRENA	59,000 - 215,000	4,500 - 26,700	2010
IEA Energy	47,000 - 95,000	-	2007
ENERGINET	146,700 - 199,700	-	2009

Table 8.1: Installation investment cost per kW installed

The total predicted investment cost consist of the boiler plus the turbine. Then has to be added 15 % of this sum for the works and auxiliary units. On the top of it 10 % contingency.
Price for the boiler is chosen 120.7 mil. RUB because it is the most complete offer and the price for the turbine is 23.5 mil. RUB.
The total cost of the project is calculated to be 180 mil. RUB.

At this point prior to the analysis it is important to add that technical life of power plant with a steam turbine is at least 20 years. [6, 7, 11]

8.2 Operating economics

Operating cost, service and wages are unknown therefore we estimate annual costs according [11] to 9 % of the initial investment. This is 16.2 mil. RUB

The combustible is widely available, and it can be considered free of charge.

Operating revenue per year is 51 mil. RUB if considering consumption from section 1.5. However, there will be much more heat available, hence more revenue can be made.

8.3 Simple payback

Feasibility study would have been more appropriate at this point but because of the lack of financial data simple payback is elaborated instead.

If the installation comes through under these conditions it will return the initial investment in 5.19 years.
Return on equity after technical life for this power plant is 286 %.
Note: If additional extension of the heating grid would be installed it can change these numbers dramatically. Not necessarily in negative sense if we manage to sell more heat.

We had anticipated that a private investor might be interested in sharing this overhaul, however the payback time is long.
Tomska oblast is not investing because the margin is unattractive. This investment will make savings on transport and on the cost of combustible supplied every year.

Part IV

Conclusion

Chapter 9

Proposal

9.1 Technical proposal

Throughout the thesis it has been evident that the best way to use the primary biomass combustible for a remote Siberian town is a cogeneration source. Using it with the highest efficiency through combined electricity and heat generation is the most environment-friendly and the most cost-effective solution.

This technical proposal has been elaborated on the basis of the first part of this thesis. It deals with an energy source to replace the current energy source in Siberian town of Stepanovka, and therefore it will not be built independently on a greenfield site. This thesis shows the most important criteria for the site. They are **reliability, safety and simplicity**. Efficiency, cost and technical excellence are less important.

The total electrical power of the designed cogeneration source is 1 MW. The source is suggested to be built module-by-module.

- module 1, the boiler and water treatment facility
- module 2, the turbo-set with a multi-stage back-pressure turbine,
- module 3, the distribution room with heat exchangers and connection to the network
- module 4, the safety condenser

The designed plant will be connected to the existing grid. The heat delivery system - outside the combined plant - lies beyond the topic of this thesis.

The back-pressure turbine can be operated in the interval from 300 to 1300 kW output power, depending on the actual electricity consumption. The waste heat can be dissipated in a wood drying facility or in a condenser.

Due to the harsh Siberian climatic conditions, it is recommended to include in the project

- 100 % generator back up - diesel engine,
- additional burner nozzles in the boiler's furnace for the diesel back-up combustible,
- a turbine bypass.

Additional boilers installed in evenly spread boiler houses can provide a reserve in the event that there is an inefficient amount of heat in the system. The old hot water boilers can undergo a furnace refit for biomass fuel, or a new pair of boilers can be installed if the old boilers are not worth refitting. This design will also minimise the transition losses, if it is connected to the existing hot-water pipe network.

For any practical implementation of the designed circuit or its derivatives, it is necessary to keep in mind that maximal utilisation of the heat power is advised for maximum effectiveness of the combusted energy. When there is less heat demand than designed, mainly in summer, the electrical power will be lowered accordingly. From the point of view of usability, this is a highly unfavourable operation mode.

In a circuit with a back-pressure steam turbine, the relation between electric power and thermal power is given by the first and the second law of thermodynamics. We can therefore consider taking out the excess heat using a circulation chiller connected in parallel to the hot water heater in the back of the turbine. The heat would be discharged into the atmosphere and lost, but in this way it is possible to keep the electrical power constant even in times of lower heat consumption.

9.2 Technical economic proposal

Based on the findings presented in second and third part of this work, the proposed technology for the application is a multi-stage turbine.
This turns out to be two times more effective than a single-stage turbine with the same electrical output.
The initial investment assessment also proves that RC with a multistage turbine is less costly. A 180 mil. RUB budget is estimated for this wood-fired power plant.

9.3 Future work recommendation

Recommendation for the next steps

1. Make sure that there is enough wood waste available to satisfy the needs for this type of cogeneration source.
2. Start a search for residential buildings and ways of connection to the heating grid. Then design the grid and calculate the consumption, so that the full potential of the heat energy can be used in the community.
3. Design auxiliary technology for the cogeneration source.

All the domestic wastes that are being burned in the local furnaces. We have no way to ensure environmentaly-friendly energy use of these a materials. It is desirable to investigate ways of including organic materials and biomaterials produced in the town as safe fuels for the plant.

This document demonstrates the knowhow of Kralovopolska RIA and our ability to design and build a cogeneration energy complex in a remote location in Siberia.

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