

# Lesson learned from a Wet Steam Turbine (WST) demonstration

– a report on efficiency, performance, and security



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# 1 Foreword

This report includes the technical experience and lessons learned from installing and running a pilot plants within the Life+ *project Small Scale CHP from biomass – a demonstration in Southeast Sweden* (2014-2020), which has been financed within the EU Life+ programme and partly by the Swedish Energy Agency and Swedenergy. The purpose of the study is to summaries the lessons learned and experience for others to learn from. The data in this report are gathered throughout the whole project and is based on a pilot plant of a Wet Steam Turbine in Ronneby.

The goal for the demonstration project Small Scale CHP from biomass has been to disseminate experience and knowledge to pave the way for others to invest in small scale CHP technologies.

The authors of the study will give a large thanks to all involved in the work with the demonstration project and especially to the members of the steering group from Svebio, Energiföretagen Sverige, LNU and VEAB.

The study has been possible due to financial support from the EU Life+ programme, the Swedish Energy Agency and Swedenergy.

## 2 Summary

This study has been conducted by Energikontor Sydost (Energy Agency for southeast Sweden) as a result from a demonstration project running from June 2014 until December 2020. In this report the aim has been to summarize the experience and the lessons learned from installing a pilot plants for small scale cogeneration, based on the wet steam turbine technology:

- A 500kW<sub>e</sub> Wet Steam Turbine (WST) at a district heating plant in Ronneby, Sweden

Europe and Sweden are in the middle of the transition from fossil and nuclear-based electricity to renewable energy resources such as wind, solar and bioenergy. The increasing share of weather dependent electricity (solar, wind power) increases the need for planned electricity production that can guarantee production all year round, such as hydropower and cogeneration from biomass, in combination with energy storage for solar and wind in the future.

Cogeneration, also called combined heat and power, is resource efficient and independent of weather conditions and can supply electricity when needed most – during the winter when it is dark and cold.

For combined heat and power (CHP) plants, to operate in a way that is economically and ecologically beneficial, both the electricity and the heat produced must be utilized. Therefore, all cogeneration is based on the existence of a district heating network or an industry that can receive the heat generated in the process. The district heating industry is an important target group for small scale CHP because the heating base already exists. The sawmill industry is also pointed out as an important industry where small-scale co-generation has great potential.

This report summarizes the experiences and lessons learned from installing and running a wet steam turbine. The pilot plant had initial problems, but after the problems were solved, the turbine was up running at high availability for one district heating season. The pilot plant produced 1.9 GWh of electricity during that time. However, an installation of a new wet steam turbine was found more complicated to install in an existing heating plant than expected. For that reason, a small-scale wet steam turbine is probably better to install as part of a new district heating plant.

### 2.1 Aim and Scope of the study

The aim of this report is to summarize the technical experience from demonstrating a wet steam turbine between spring 2016 until December 2020. The experience and lessons learned is disseminated to pave the way for others. By this report, others can learn and take inspiration in their decision for installing this technology or to get inspired for further evaluations.

### 2.2 Delimitation

Small Scale CHP = CHP generation with less than 10 MW heat generation.

The results in this report is based on experience and data from the pilot plant at the district heating plant, Sörbyverket, owned by Ronneby Miljö & Teknik AB. The structure of that plant is the base of the results. Different results can appear in other systems.

## 2.3 Abbreviation

WST	Wet steam turbine	CHP -	Combined heat and power
Alfa value -	The relationship between electricity and heat production in a cogeneration plant, calculated as (electricity generation heat divided by heat generation)	RFP -	request for procurement

## 3 Background

### **Small Scale CHP and the EU Life project: Small scale Combined Heat and Power based on biomass in the region of southeast Sweden**

Combined Heat and Power (CHP) technologies based on biomass combustion have great potential to reduce CO<sub>2</sub> emissions since they use renewable energy sources, such as wood fuels or sawdust. Typical fields of application for biomass CHP plants are wood processing industries, sawmills, district heating systems and industries with a high process heating and cooling demand. For CHP plants to operate in a way that is economically and ecologically beneficial, both the electricity and the heat produced must be utilized.

CHP technology is already available on both Swedish and European markets. Due to the high installation costs, and a lack of information about its efficiency, the technology is currently not widely used in small-scale implementations (less than 10 MW<sub>thermal</sub>). Extensive research has been undertaken to illustrate the vast environmental potential of CHP technology but a larger initiative that looks at increasing market application is still needed.

Therefore, to meet the gap between commercialization and research, three different techniques for small-scale electricity production of biomass-based cogeneration have been built and demonstrated between 2014 and 2020 in southeast Sweden as part of the project LIFE + *Small scale Combined Heat and Power based on biomass in the region of southeast Sweden (short: Small scale CHP)*. Partners of the project, where the demonstration plants are built, are Emå Dairy in Hultsfred and Ronneby Miljö & Teknik AB and Ronneby Miljöteknik Energi AB in Ronneby. The project is also partly financed by the Swedish Energy Agency.

The aim of this project was to pave the way for a broader application of biomass-based CHP and thereby increase the production of local, renewable electricity. Three different techniques have been demonstrated at three different sites, namely a micro-scale gasifier (50kW<sub>e</sub>) at a dairy, and two turbine solutions in district heating facilities using wet steam (500kW<sub>e</sub>) and an Organic Rankine Cycle, so called ORC, (50kW<sub>e</sub>).

The technical experience and lessons learned from these demonstration plants have been disseminated along the project and is now gathered in one report for each technology in which reports on performance, efficiency and security are summarized. This report concerns the experience from installation and one district heating season of operation for wet steam turbine at the district heating company Ronneby Miljö & Teknik AB.

### **3.1 Theory – Steam turbine**

The traditional steam turbine is the most common way to produce electricity. The technology is used in coal condensing power plants, in CHP plants and in nuclear power plants.

The traditional steam turbine is available in various designs and with large variations in electrical power, from below 0.1 MW to over 1000 MW and with steam pressure of a few bar to several hundred bars.

- 1-2, Electricity is supplied to the pump
- 2 – 3: The working medium is heated at constant pressure, in i.e. a steam boiler, and evaporated to saturated steam (and possibly also overheated (2-3')).
- 3- 4: The saturated steam is expanded through a turbine and generates electricity. Both temperature and pressure are lowered in the steam. Some condensation occurs. If the steam is overheated, the steam instead expands to saturated (dry) steam and condensation of the steam is thereby avoided (step 3' – 4').
- 4-1: The wet steam condenses at constant pressure to saturated liquid. Instead, in step 4' – 1, the dry steam is condensed to saturated liquid at constant pressure.

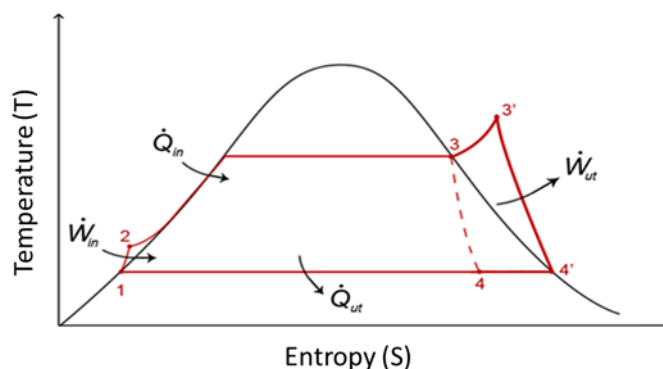


Figure 1 shows the Rankin cycle, so-called T-S diagram. The curve shows the saturation line of a working medium. On the left side of the line the working medium is in liquid state and on the right side of the line the working medium is in vapor phase. Between the lines, the medium evaporates or condenses. (i.e. a mix of steam and liquid). Source: Wikipedia, 2019

The steam turbine is limited by the formation of water droplets through the expansion of the turbine (steps 3-4 in Figure 1). Water droplets formed during steam condensation damages the turbine blades and lead to corrosion which reduces the efficiency of the turbine. Most easily, these problems are avoided by overheating the steam (steps 3' and 4' in Figure 1).

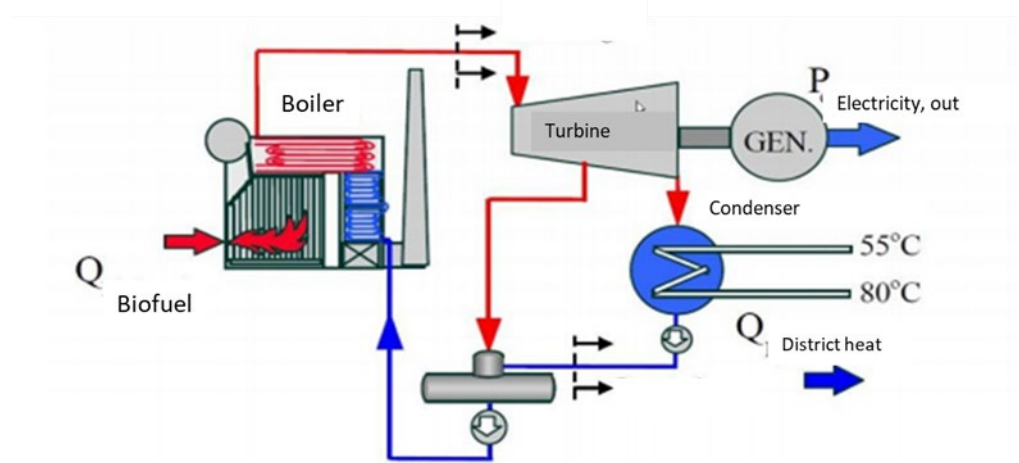


Figure 2 A schematic picture of a steam turbine cycle at a district heating plant. Source: Energikontor Sydost 2002.

The traditional steam turbine is still the best technology in sizes over 2MW<sub>el</sub>. For small-scale cogeneration can also other technologies, depending on the plant-specific condition, be



interesting and profitable. In this report the experience from demonstration a wet steam turbine is described.

## 3.2 A Wet steam turbine demonstration plant

At Ronneby Miljö & Teknik AB, a municipality owned Energy Company, a wet steam turbine with the size of 500 kWe has been demonstrated since the year of 2016. The wet steam turbine is placed in an existing district heating plant, Sörbyverket, in connection to a boiler of 9 MW heat. The feedstock to the district heating plant is wood chips.

The demonstration plant is in line with the strategic plan at AB Ronneby: *"to combine environmental responsibilities with economic effectivity"*

The wet steam at Sörbyverket is the first wet steam turbine installed in a district heating plant with a boiler size less than 10 MW of heat and with a power capacity of 500 kWe.



### 3.2.1 The wet steam technology and prerequisites

A wet steam turbine is a steam turbine powered by saturated steam instead of superheated steam. See Figure 3 for a schematic view of the wet steam connected to a steam boiler. To be able to resist possible water drops during condensation, the design is more robust compared to conventional steam turbines.

There exists, although unusual, hot water boilers at heating plants built with steam domes. In these cases, it is possible to adjust the boiler for steam production in prior to an installation of a wet steam turbine. However, at most district heating plants a steam dome must be added to the boiler in prior to an installation of a wet steam turbine.

Since the steam turbine is based on the same principle as the conventional steam turbine, it needs to be cooled to condense the water and release the heat. In a district heating plant, the turbine process is cooled with the district heating return water. The most economic system would be a wet steam turbine installed at an existing boiler already prepared for steam production with a steam dome.

The main utilities in the total CHP system are: feedstock storage, the existing boiler and the steam cycle containing: wet steam turbine, condenser, feed water tank, valves and pumps, see also Figure 3.

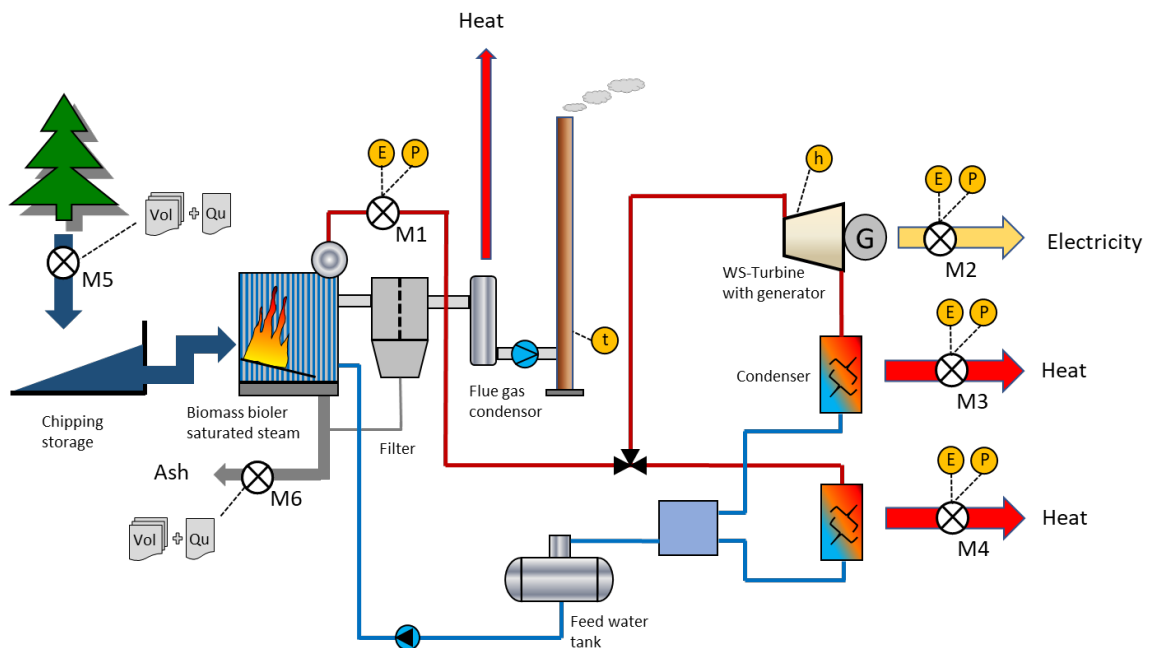


Figure 3. Schematic picture of the wet steam CHP process.

#### Prerequisites needed:

- Steam at approx. 200°C and 14 bar – need a steam dome on the boiler
- A cold source to cool the turbine cycle (return district heating water)
- Space for the turbine and auxiliary system (i.e. Feed water tank and pumps, pipes, condenser, and heat exchangers).

### 3.2.2 Technical data

The wet steam turbine installed in Ronneby at the district heating plant, Sörbyverket, is a steam turbine which operates on saturated steam instead of overheated steam, which is the most common. The technical data such as pressure, temperature and power are listed in Table 1.

Table 1. Technical data for the wet steam turbine in Ronneby

Power Capacity	500 kW <sub>e</sub>
Rotation speed	21 500 rpm
Turbine wheels	3 stages
Steam Pressure	14,3 bar (a)
Steam flow	8,8 t/h
T <sub>steam, in</sub> (from boiler)	180°C
T <sub>cold, in</sub> (return district heating)	45 – 53°C
Weight	11 tonne

### 3.2.3 Modification of existing system

The district heating plant in Ronneby was built in 1998 with one oil boiler and one 6 MW biomass boiler. In 2001 the boiler capacity was increased with a 9 MW biomass boiler. In the construction phase the company also planned for power generation with a small turbine. But after the economic calculations the company decided to build a boiler with heat water production but to include a steam dome for the possibility to add electricity generation later, when the economics became more profitably. Therefore, the boiler was built to stand 204°C and 16 bar and equipped with pipes to be able to generate steam for power generation in the future.

The district heating network (before the WST installation) was heated through three heat exchangers by the hot water from the boilers, as illustrated in Figure 4.

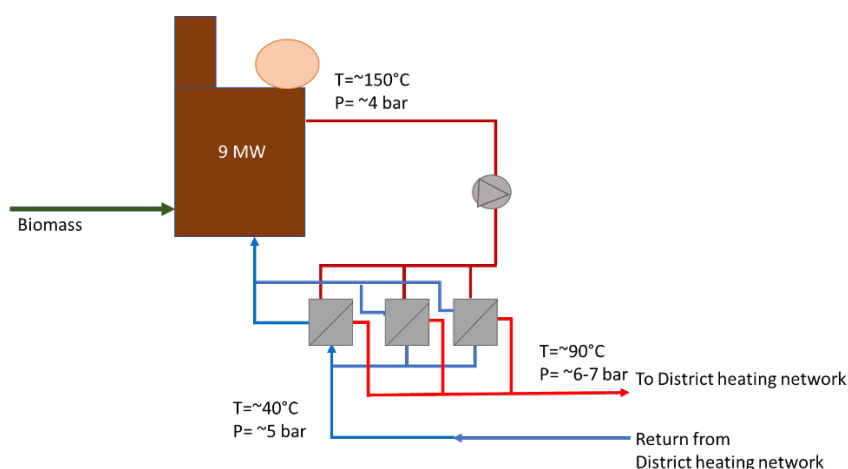


Figure 4. Schematic visual of the district heating plant, Sörbyverket, before the installation of the turbine.

In 2015 and in prior to the installation of the wet steam turbine, the boiler had to be adjusted to be able to run in steam mode. Pipes and valves in the boiler and in the dome were replaced and additional pipes and valves were installed. The old system for hot water generation was saved and gave the possibility to by-pass the turbine and run only on hot water – if necessary.

The new system installed included: new pipes for the steam cycle, the turbine, feedwater tank, condenser, pumps and water treatment and several new control and measurement points. Figure 5 illustrates the district heating system after modification and installation of new equipment.

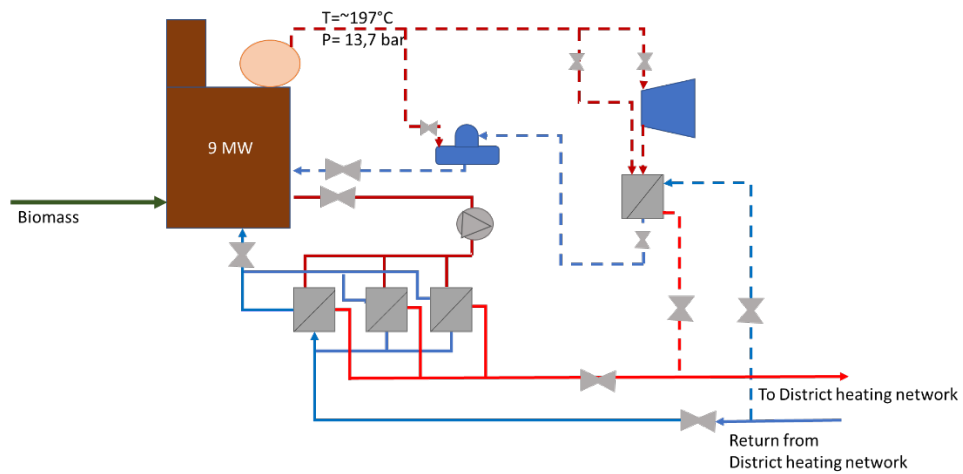


Figure 5. Schematic visual of the district heating plant, Sörbyverket, after the installation of the turbine. The dashed lines indicate the new connections and equipment.

## 4 Report on Performance

The performance report contains a summary of performance indicators which has been measured during the demonstration of the wet steam turbine in Ronneby.

After the start of the project and as start of the procurement of the CHP (wet steam turbine) a screening of possible supplier of wet steam turbines was performed by a consultancy firm. The result showed that no turbines were available at the size of 500 kW. The procurement process confirmed the result of the screening. No offers were received that fully complied with the request for procurement (RFP) sent out by Ronneby Miljö och Teknik AB. In the RFP Ronneby Miljö och Teknik AB asked for solutions between 500 and 900 kW. During the procurement of this demonstration plant, two tenders were received. Both tenders deviated from the RFP. Only one tender was within the asked capacity (500 to 900 kW). Both tenders were deemed by Ronneby Miljö och Teknik AB as the total costs would be far above the limit for the available budget. Ronneby Miljö och Teknik AB thereafter asked for solutions with reduced scopes and significantly lower costs from both tenderers to be able to continue the procurement. Later, one of the tenders was accepted as the capacity was still in the originally requested span from the RFP, the scope was still acceptable, and the total costs were acceptable in relation to the available project budget. During the negotiations Ronneby Teknik och Miljö AB and the supplier agreed on a design of the CHP system (turbine, condenser etc), which was especially created for the implementation of this demonstration project (a pilot plant for a wet steam turbine). This solution had never been done and was not a commercial solution. The solution is unique for the technology and for its small size (500kW) in connection to an existing district heating system. The turbine is a 3-stage turbine and the supplier has had “free hands” in the design to fit the budget and the existing system.

### 4.1 *Experiences from rebuilding and installation*

The connection between the new technology (wet steam turbine cycle) and the existing technology (20-year old boiler) has been more challenging than expected. The two systems must “talk” and exchange signals to perform well and work safely both for heating and electricity generation. Costs for equipment and for external expertise have increased more than foreseen in the start due to the complexity in installation but also due to that the new and old software have had problems to interconnect. This has, now, partly been solved with new software. It is essential that all signals work correctly – to be able to firstly guarantee the security for personnel and secondly the operation.

Before the installation of the turbine, the boiler needed to be adjusted to steam mode, which was made by installing new pipes, both inside the boiler and to and from the turbine cycle as well as adjusting the boiler properties. Several new pipes were needed for the turbine cycle, as can be seen in Figure 5 and in Figure 6.

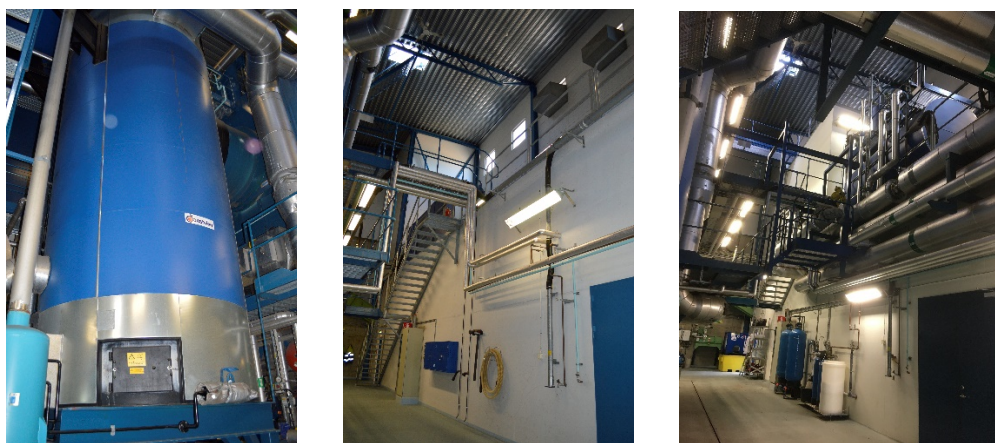


Figure 6. The district heating plant before and after modification of existing boiler. The first picture shows the boiler which has been modified. The second picture shows the space in the district heating plant before installation of steam pipes and the third picture shows the same space but after the modification of the boiler and the piping from and to the boiler (the turbine cycle).

One challenge with modifications in already existing buildings is to find free space for the additional equipment. In Ronneby, the need of free space led to that the existing conference room was rebuilt into a pump room to the condenser. No space was available to host a new conference room and instead, the conference room had to be placed in a barrack outside the district heating plant. The barrack did not exist but needed to be built just for this purpose. The turbine was placed on the second floor (above the stairs that can be seen in Figure 6) which required improvements for the building floor/ roof. The wet steam turbine also needs additional equipment such as pump, condenser, water, feed water tank and water treatment. The feedwater tank and water treatment were placed on the second floor (above the steam pipes in picture three in Figure 6) floor besides the turbine. The condenser was placed vertically from the second floor down, through the floor, to the first floor. Holes were needed in the concrete floor to be able to fit the condenser and the steam and water pipes, as seen in Figure 7. The pumps were placed in the room on the first floor, see picture three in Figure 8.

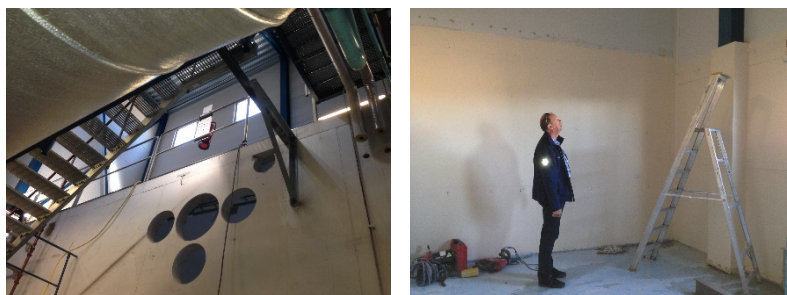


Figure 7. The pictures show the district heating plant under construction.

It was understood quite quickly that the turbine had to be installed in an isolated turbine house to reach the approved levels of noise in the working environment requirements. However, when the turbine house was isolated from noise – the room became too warm – which needed installation of a chiller to protect the turbine from becoming overheated. Pictures of the turbine and turbine room as well as the pump room on the first floor with part of the condenser hanging through the roof is found in Figure 8.





Figure 8. The two first pictures shows the turbine inside the turbine room. The third picture shows the former conference room, which gave space for the pump and condenser connected to the turbine.

To be able to receive study visitors to the turbine, Ronneby Miljöteknik decided to build a balcony on the outside – which made it very easy to reach the turbine for study visitors. Pictures in Figure 9 illustrates the building of the balcony and the final view of the turbine from inside the balcony.



Figure 9. The pictures illustrate the building of the balcony. The last picture shows how it looks from the inside of the balcony.

Several cables were needed for the power connection to the power grid, as can be seen in Figure 10.



Figure 10. Connection to the electricity grid.

#### 4.1.1 Summary of lessons learned from rebuilding and procurement

- Make sure that the contract cover insurance for loss of operation/operational failure
- Due lack of turbines in the size and price that was asked for in the procurement, technical compromises and down scaling of existing technologies was needed and removing of surrounding equipment. This was shown to result in compromises in the quality and led to problems and additional equipment that has been very costly for both the company and the supplier.

- The company had to rely on external expertise concerning contract and technical design of the turbine.
- In retrospect, a larger responsibility for the overall process from the supplier would be defined in the procurement or in the contract. As the procurement was designed in this case, the supplier was only responsible for the turbine, which created conflict of interests when problem arose.
- Make a more detailed prestudy, many of the changes build in this project was not planned for from the beginning.
- Be careful in the contract writing and include guarantees in addition to fines for possible delays. Include also guarantee for how the turbine affects the district heating system, i.e. pressure and district heating flow rate.

## 4.2 Experience from start of operation

The final installation of the wet steam turbine was delayed due to delays in delivery of the turbine. However, the installation was finished in December 2016. During the performance test it was noted and confirmed that vibrations started at a power of 250 kW. After that, a one-year problem solving period and discussion began around the debt issue and on which side the problem lay. A contribution reason why it took so long was that the supplier did not see to the whole system, they were focusing on the turbine only as stated in the agreement. After several meetings, installations on various equipment and many hours of problem solving, it was finally found that the problem was due to a failure in the design.

The supplier solved the problem and in April 2018 the turbine was ready to start again. However, at that time the low need for district heating due to weather conditions did not allow the turbine to run at full load, 500 kW, for more than a few hours. However, the time was enough to prove that the problem with vibrations was solved but the performance test for a longer period had to wait until next district heating period, in October 2018.

In October, when running the performance test for a longer time it was found that the two systems (district heating pumps and feedwater pumps) did not harmonize with each other as foreseen. The fluctuations in the boiler capacity could be as high as between 4 MW and 9 MW, which had enormous effect on the system. Extensive work with external expertise started to evaluate the reasons to the variations. The problem solving and changes in the steering system lowered the fluctuations in the boiler down to between 0.5 to 1 MW. Additional work is still needed before optimum operation.

During the test period a water leakage from the turbine was detected but later solved by the supplier.

From January 2019 until April 2019, the wet steam turbine ran at high availability and at full capacity.

Due to very low electricity prices, the turbine has not been up running during district heating season 2019/2020. This document will therefore, henceforth, focus on the performance of the wet steam turbine from October 2018 until May 2019.



## 4.3 Data collection methods and necessary calculation

At the district heating plant in Ronneby several systems are used to log and calculate different parameters for the boilers, the biomass and from the district heating and steam cycle.

The performance of the wet steam cycle is documented during a daily check by the personal at Ronneby Miljö & Teknik AB, to track the performance and to find deviations. The documentation is written by hand and saved at the company.

At the district heating plant in Ronneby a data system called FIX is used for logging values concerning the biomass boiler. Parameters such as temperature of the flue gases, oxygen content in the flue gases, load in the boiler and temperature of the district heating system are logged in INDUS.

Another data system continuously logs measured values from the boilers. In this system instantaneous values are logged and saved as mean values each hour. These daily reports use a network of equations and parameters for calculating different efficiencies. For example, the data system shows the power content of the input fuel, the hot water and steam production in the boiler as well as the power output from the turbine.

In an additional system, values for the turbine and condenser are logged. These values are available from January 2019 and contains for example, steam flow rate, pressure and temperatures through the steam cycle.

### Possible sources of errors:

The summary of the monitoring of the turbine in this document consists only of data collected for a limited time, which affects how realistic and accurate the results will be. The logged value is also a mix of signal inputs and calculated values, which also affects the results.

## 4.4 Output indicators

### Operating hours

The wet steam turbine (WST) in Ronneby is connected to a 9 MW biomass boiler at the district heating plant. The biomass-boiler produce hot water to the district heating network during the district heating season, normally from September until May each year. During the summer period, the heat is produced by another biomass-boiler.

Since the wet steam turbine is connected to the biomass-boiler which only runs during the district heating season, the operating hours are limited to the district heating season.

The total operating hours for the wet steam turbine from the installation has been 7463 hours. The operating hours per day is documented from mid-January 2019. The operating hours for each month between February and October 2019 are<sup>1</sup>:

- February: 658 hours
- March: 727 hours
- April: 658 hours
- May: 139 hours

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<sup>1</sup> The hours can differ with a few hours since the hours are documented only once a day and this has been corrected for, however the exact time for the documentation is not noted.

To be able to measure the availability of the wet steam unit, the operating hours per months is divided by real hours per months. As can be seen in Figure 11, the availability has been high during the winter months, February and March (approx. 98%).

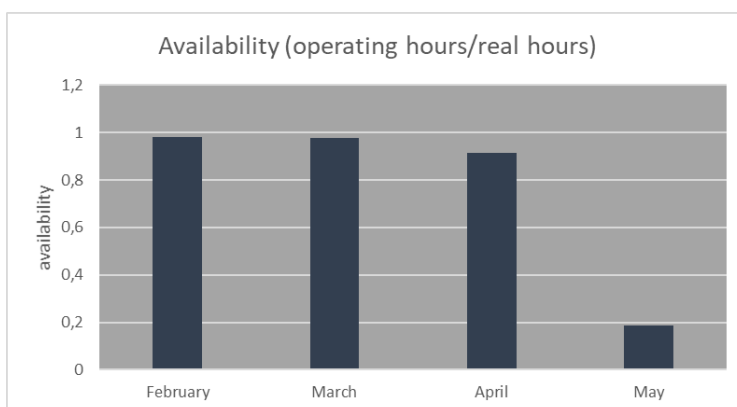


Figure 11. Availability for the WST between February and May 2019.

The boiler tubes are cleaned once a week for approx. 4 hours. During that time, the system is off and hence also the turbine.

The lower availability of the turbine, i.e. lower operating hours compared to real hours, in April and May is due to warm weather conditions that makes it impossible to run the turbine.

#### Operating pressure

The pressure varies between 13.7 barg to approx 1.3 barg within the steam cycle. Steam is generated in the boiler at 13.7 barg and enter the wet steam turbine at approx. 13.3 barg. The pressure is lowered over the turbine to approx. 1.3 barg.

#### Power capacity and electricity generation

The installed power for of the wet steam turbine is 500 kW. The average and maximum electricity generation per months is summaries in Table 2.

Table 2. Average and maximum electricity per months during 2018/2019 district heating season

Months 2018/2019	Average Power [kW]	Maximum power [kW]
October	19	451
November	324	480
December	419	485
January	467	485
February	422	484
March	479	493
April	376	491

The average capacity is also shown in Figure 12.

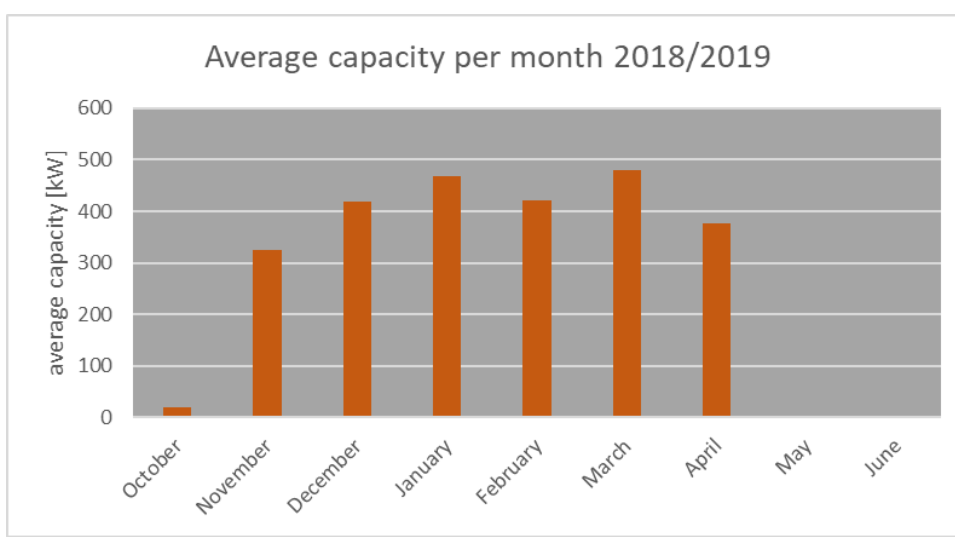


Figure 12. Average power capacity during district heating season 2018/2019.

The wet steam turbine has since the installation in 2016 generated 2 GWh of electricity. The electricity generation during the district heating season 2018/2019 was 1.89 GWh. The electricity generation for each month is illustrated in Figure 13.

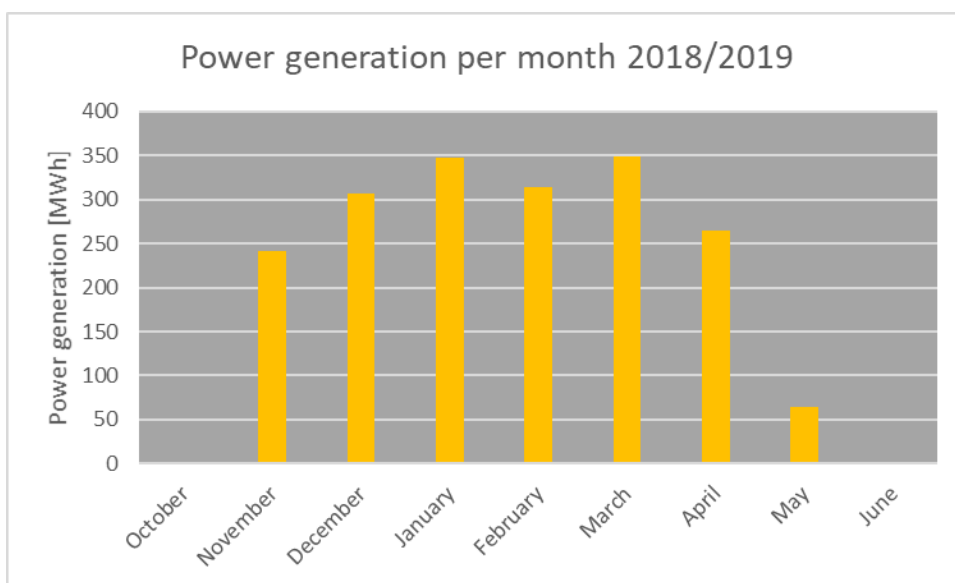


Figure 13. Power generation per months during October 2018 until May 2019.

From the figure above it can be seen that the electricity generation is highest in January and March 2019. The availability and power capacity were similar also for February, but the total generation that month is less due to less hours and days in February (28 compared to 31). The lower generation in November and December 2018 can be explained by that where still problems with the turbine both due to steering and due to a water leakage, which lowered the operation hours and hence the electricity generation. The lower electricity generation in April and May is due to weather conditions that makes it impossible to run at full load and some days impossible to run the turbine at all, due to little need for district heating in the system.

### Biomass handling

The wet steam turbine is part of the existing district heating system, which already runs on biomass. The installation of the wet steam turbine and increase of biomass use did not affect the performance or procedure for the handling of the biomass.

The biomass burned in the boiler is a mix of bark, roundwood, branches and tops, and dried wood chips. The moisture content of the fuel varies between 48 to 52% moisture. Since 2020, the moisture content is decreased and varies between 40 and 50% moisture.

## *4.5 Availability, maintenance, and control system*

After solving the initial problems with the wet steam turbine, the availability has been high during the first winter months in 2019, 98 % in February and March 2019.

The parameters affecting the operating hours are:

- Weather conditions – the system is designed for a minimum flow and temperature – below a certain flow and above a certain T the turbine will not run.
- Service duties on the turbine – which appears one day, once a year
- Service duties in the boiler – one a week the boiler is shut off for cleaning the tubes.
- Unforeseen/unexpected stops

### Unforeseen/unexpected stops

- The wet steam turbine stops when the boiler stops, due to e.g. fuel failure, which happens time to time.
- Replacement of sensor in the condenser

### Security in running the plant for longer periods

- The WST have been running on a high and stable availability from January 2019. Maximum running hours were between January and March.
- After solving the initial issues both concerning the turbine and its design but also concerning the steering of the system.
- There is still potential to improve the steering of the total plant to optimally run the district heating plan in steam mode.

### **4.5.1 Maintenance**

The daily maintenance of the turbine is a daily inspection and documentation of the system, which takes around 20 minutes.

The weekly maintenance when not running is a rotation of the turbine axes.

The yearly maintenance is a yearly service done by the supplier.

The min maintenance is a yearly service, with a yearly fee included in the contract from the supplier.

To guarantee no droplets of water from ventilations during times when the turbine is not running a drying system would be referable. However, such an installation is not made in Ronneby.

### 4.5.2 Control systems

There is an operation journal for monitoring. The steam system, turbine, and the auxiliaries, have several alarming points.

## 4.6 *Lessons learned from operation*

- The wet steam turbine installed is a new technology which has gained knowledge both for the supplier and for the employees at Ronneby Miljöteknik.
- It is necessary to have good help from consultants and experts when installing new technologies in a small company without large resources for development.
- The project has led to new contacts with both experts and consultants and suppliers. However, it has also been challenging to communicate on English, both due to language barriers and due to inexperience from the new system.
- It took a lot more work and many more hours to install a turbine than was expected
- It is much challenging to regulate the district heating plant in steam mode. The margins are smaller, and it is harder to adjust the process.
- It is more difficult to adjust and regulate the whole process after installing the turbine. The safety margins are smaller.
- After installing the system there are parameters that indicates that the existing steam dome does not have the capacity needed.
- It is more difficult to install new systems into old systems with a lack of system perspective compared to designing a new plant with electricity generation included in the system perspective.
- The project has included both learning periods and very hard periods.
- During the harder periods, the work has resulted in a too high working load – which has affected some of the staff badly.
- The project has included a lot of bureaucracy. Had it been bought in as a whole concept would probably have been easier, and the supplier would have had to take a greater responsibility.

## 5 Report on Efficiency

The analysis in this section is based on numbers from January 2019 until December 2019. The reason to not include the whole district heating season 2018/2019, is due to lack of documentation of the process until January 2019.

### 5.1 Calculation methods and delimitations

To calculate the efficiency of the district heating system with the WST the following parameters has been considered:

- Alfa-value for the system
- Electricity-efficiency for the system
- Decreased need of power
- Total energy efficiency for the system
- Increase of biomass use in the system

#### Total energy efficiency for the district heating system

The total efficiency for the studied system is the relationship between useful energy (heat and power out from the system) and energy supplied to the system. The total efficiency defines the energy losses in the system. In the studies system the energy loss is related to the need of energy for the pump work and the energy loss in the generator (Eq.2).

$$n_{tot} = \frac{\text{Useful energy}}{\text{Supplied energy}} = \frac{Q_{out}}{Q_{in}} = \frac{Q_{heat,ut} + Q_{power}}{Q_{biomass\ in}} \quad (\text{Eq.1})$$

#### Alfa value

The alfa value is the relationship between electricity and heat production in a cogeneration plant, calculated as electricity generation heat divided by heat generation (Eq.2).

$$\alpha = \frac{P_{electricity}}{P_{heat,ut}} \quad (\text{Eq.2})$$

#### Electricity efficiency for the studied system

The electricity efficiency is defined as electricity generated divided by the energy supplied to the system.

$$n_{power} = \frac{\text{Power energy}}{\text{Supplied energy}} = \frac{Q_{power}}{Q_{Biomass,in}} \quad (\text{Eq.3})$$

## 5.2 System boundary

The installation of the WST affects the total system with increased electricity generation. The steam mode and electricity generation also affect the heat generation, boiler efficiency, total efficiency, alpha value and increase of biomass and decrease of electricity demand. Figure 14 shows the energy streams in and out from the district heating plant, which is affected by the WST installation.

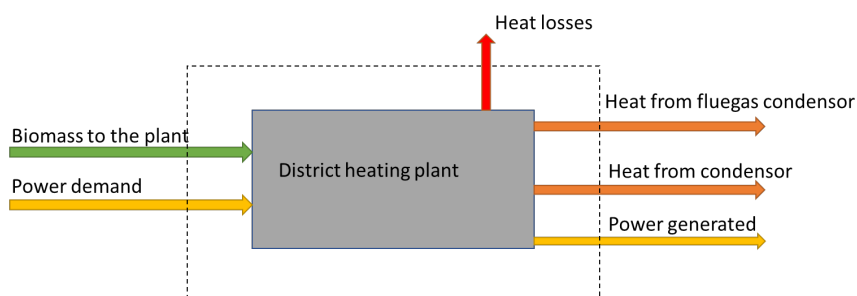


Figure 14. Schematic picture of the energy flows in and out from the district heating plant.

## 5.3 Impact on the district heating system

### Total energy efficiency, alpha value and the electricity efficiency in the system

The impact of the WST installation in the total district heating system is analysed in this chapter. The impact is evaluated by calculating the efficiency, alpha value and the electricity efficiency. All numbers are summarised in Table 3.

When the WST is running, the boiler operates in steam mode and the heat for the district heating is produced both from the condenser after the turbine and by condensing the flue gases from the boiler. When the WST is turned off, the boiler operates in hot water mode and district heat is produced from heat exchanges between the hot water and the district heating system and by condensing the flue gases from the boiler, see also Figure 4 and Figure 5. In Table 3 the energy need and the energy generated, as well as the total efficiency for the district heating plant is showed for 5 months during 2019. During the four first months (January until April) the WST was up running. The energy balance for these four months is compared to November and December the same year when the turbine was not operational (due to low energy prices). The produced heat ( $Q_{\text{heat}}$ ) in Table 3 shows the total heat generated in the district heating plant, i.e. both from the flue gases and from the condenser/heat exchanges. From the table it can be seen that the share of heat generated from flue gas condensing is higher during steam operation (January, February, March) compared to the months when the boiler is running in hot water mode (November and December). The share of heat generated in the flue gas condenser is between 22 and 23% when the boiler is running in steam mode compared to 16 and 19% when the boiler is running in hot water mode. The explanation is that the temperature in the boiler is higher in steam mode, which results in higher temperature of the flue gases. The higher flue gas temperature results in a higher heat generation from the flue gas condenser.

From Table 3 it can also be seen that the boiler efficiency is lower for January, February, March and April compared to the boiler efficiency for November and December. The conclusion is that the boiler efficiency is lower in steam mode compared to hot water mode, which can be explained by that the boiler is not built for steam mode from the beginning.

The electricity efficiency for the WST is around 5% and the alpha value is 0.07.

The total efficiency of the district heating plant i.e. heat and power generated divided by the energy input (biomass) is lower for the district heating plant when the boiler operates in steam mode even though electricity is generated. As can be seen in Table 3, the total efficiency varies between 94 and 96% for January to March 2019 when the turbine is running on full load. This can be compared to November and December 2019 when the district heating plant only produces hot water and the total efficiency of the plant is between 101 and 107%.

The conclusion is that the installation of the WST results in lower energy efficiency, and hence a loss in energy. The reasons for the energy loss are several:

- The energy losses occur in several stages: in the steam cycle, in the boiler and in the flue gas system.
- The flue gas temperature is higher in steam mode, 250°C. Most of the energy is recovered in the flue gas exchangers – but not all.
- The boiler is not built for steam generation – and therefore not fully adjusted for steam generation.
- The steam dome is not fully optimised due to the modification.
- Some of the difference could be due to calculations, i.e. the numbers

A future study would be to further investigate the reasons and thoroughly evaluate the energy losses to increase the efficiency.

Table 3 The total efficiency, alpha value, and electricity efficiency in the district heating system.

2019										
	$Q_{\text{biomass, in}}$	$Q_{\text{heat, CHP mode}}$	$Q_{\text{heat, heat only mode}}$	$Q_{\text{heat, flue gas condensor}}$	Share of heat from flue gas condensing	$Q_{\text{power}}$	$\eta_{\text{boiler}}$	$\eta_{\text{power}}$	$\alpha$	$\eta_{\text{tot}}$
	MWh	MWh		MWh	%	MWh	%			
<b>2019</b>										
<b>January</b>	6 905	4 837		6 290	23	347	82	0,05	0,07	96,1
<b>February</b>	6 314	4 399		5 613	22	314	81	0,05	0,07	93,9
<b>March</b>	6 916	4 765		6 149	23	348	81	0,05	0,07	93,9
<b>April</b>	5 107	3 530		4 200	15	264	85	0,05	0,07	86,7
<b>November</b>	6 332	0	5 364	6 383	16	0	85	-	-	100,8
<b>December</b>	6 766	0	5 852	7 241	19	0	86	-	-	107,0

### Increase of biomass

The total system has the same need of district heating delivery before and after the installation of the WST unit. That means that the difference in use of biomass is the energy needed for the electricity generation and increased need of biomass for heat generation due to lower efficiency in the system. The need of biomass that is required for the electricity generation is calculated using Eq.4. The equation is used for environmental evaluation of combined heat



and power and recommended to use by Swedenergy. The equation is based on EU directives and recommendations<sup>2</sup>:

The increased need of energy (biomass) is calculated following Eq.4:

$$\alpha_{h,i} = \frac{\frac{E_{h,tot}}{\eta_{h,i}}}{\frac{E_{h,tot}}{\eta_{h,i}} + \frac{E_{p,tot}}{\eta_{p,i}}} \quad \alpha_{p,i} = \frac{\frac{E_{p,tot}}{\eta_{p,i}}}{\frac{E_{h,tot}}{\eta_{h,i}} + \frac{E_{p,tot}}{\eta_{p,i}}}$$

$\alpha_{h,i}$  = allocation factor for the fuel in the part of the fuel

and also the environmental value that should be allocated for the produced heat

$\alpha_{p,i}$  = allocation factor for the fuel in the part of the fuel

and also the environmental value that should be allocated for the generated power

$E_{h,tot}$  = Total produced heat, exclusive heat from flue gas condensing

$E_{p,tot}$  = Total generated power, exclusive auxiliary power

$\eta_{h,i}$  = Reference efficiency for separate heat production with fuel=0,86

$\eta_{p,i}$  = Reference efficiency for separate power generation with fuel=0,33

By using Eq.4, the proportion of biomass used for electricity generation is 16%. Table 4 shows the amount of biomass used for the district heating plant when the WST was up running in 2019. It also shows the share and amount of biomass used for the electricity generation.

Table 4 Total amount of biomass used in the district heating plant and the share and amount of biomass use for electricity generation.

	Biomass to boiler	Share of biomass for power generation	Biomass for electricity generation
	MWh	%	MWh
January	6 905	16	1088
February	6 314	16	990
Mars	6 916	16	1106
April	5 107	16	833

### Electricity generation as share of total electricity demand

The electricity generation from the WST is on average 150% of the power demand for the district heating plant, see Table 5.

Table 5 Power generation from the WST compared to the power demand at the district heating plant.

	Power from the WST	Power demand for the district heating plant	% of total demand
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<sup>2</sup> <https://www.energiforetagen.se/globalassets/energiforetagen/statistik/fjarrvarme/miljovardering-av-fjarrvarme/hjalp-vid-berakning/guide-for-allokering-i-kraftvarmeverk-och-fjarrvarmens-elanvandning-2019.pdf>

	MWh	MWh	
January	347	242	143%
February	314	209	150%
Mars	348	223	156%
April	264	168	157%

## 5.4 Side effects of the WST installation

The WST installation at Sörbyverket had the following side effects:

- Resulted in new knowledge and challenge for the employees at Sörbyverket. Some of the staff have found it challenging and fun while others have found it difficult and hard.
- To run the boiler on steam mode is more time consuming than having it running on hot water mode. Every alarm from the boiler and each action takes more time. In hot water mode the boiler starts again after approx. 30 minutes, but in steam mode it takes up to one hour before the boiler runs after stopping. It takes therefore more time for the employees to control every alarm and to start the boiler and the turbine after every action. It is perceived extra hard if an alarm occurs outside normal working hours, i.e. on weekends or during night.

## 6 Report on Security

### 6.1 *Environmental parameters*

The installation of the WST does not affect the environmental parameters at the district heating plant significantly. The installation increases the use of biomass, however, the ash and the flue gases from the boiler are handled in the existing cleaning system of the district heating plant.

There is no clear impact on the emissions if the plant is operated in steam mode. Factors as fuel quality, moisture content and heat capacity also affect the emissions.

### 6.2 *Connection to the power grid*

It was necessary to modify the transformer station to sell electricity to the grid. Several power cables have also been connected between the transformer station and the turbine. Before the installation and connection, it is also needed to inform and having a dialog with the power grid owners.

### 6.3 *Safety measures*

Operating in steam mode involves greater risks in the district heating plant. The pressure in the system is around 4 bar when producing hot water. In steam mode the pressure is increased to 14 bar. It means that the boiler runs harder, and all parts wear out faster. The safety level is already high in a district heating plant, but it is even more important when running in steam mode.

Before the installation and modification, a risk assessment was made by a third party.

As the boiler was modified to steam mode a new warning system was installed. The WST installation was completed with warning system. All safety circuits have been reviewed by an independent third party.

All employees have undergone education for steam and high pressure to manage the new system.

### 6.4 *Risks*

The risk is larger after the installation of the WST and when running in steam mode. The risks are connected to the steam generation with higher temperature and higher pressure. The turbine also contains moving parts that spin at very high speeds and which can cause major damage if broken during operation.

The system with a steam turbine is also more sensitive and the risk for operational failure is therefore greater.

The energy balance of the system with and without electricity generation also shows that risk for energy losses is greater in steam mode at the plant in Ronneby.

For the employees, the largest risk is the increased noise level that is created when the turbine is up running.

## *6.5 Security of supply and Island operation*

The installation of the WST increases the possibility for island operation. However, the district heating plant needs electricity to start the process and the turbine will not produce electricity until the boiler is up running. Therefore, it is hard to cut of the power grid.

## 7 Discussion

This report reflects the experience and the lesson learned from installation of a WST at a district heating plant. The largest challenge has been to connect the new equipment to an existing boiler and district heating plant not fully build for the conditions of steam mode.

The results from the energy balances in the plant indicates that the system is less efficient in steam mode compared to original mode. Several aspects described before, could explain the result. Some part of the explanation could also lie in possible errors in the data collected or in the calculations for the energy balances in the plant. Therefore, a recommendation would be to further investigate and thoroughly analyse the energy losses during next district heating season, for example as a research project.

During this project, there has been several initial problems that has been solved along the way. However, the WST run at high availability during January to March in 2019. It would therefore be very interesting to install a WST in a new district heating plant from scratch. In that case the whole system could be designed with a full system perspective to optimise the operation of the district heating plant for best conditions both for heat and power generation from the beginning. In that way the supplier would have more responsibility to fit the turbine for the best system parameters.

The more the power demand increases and the more flexible power generation that is put into the net, the more important it becomes to use all sources for renewable stable power generation.

The wet steam turbine is still an alternative but some more evaluations are still needed, and it would be interested to evaluate an installation of a WST in connection to a new boiler, designed for steam generation.

Most important - next district heating plant owner that are interested to install a WST will, by reading this report, have learned a lot and by that lower the costs for the installation.

## 8 References

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Wikipedia 2019, Rankinecykel with overheating, picture from 2019-06-01