MORE EFFICIENT USE OF BIOGAS AT WASTE WATER TREATMENT PLANTS

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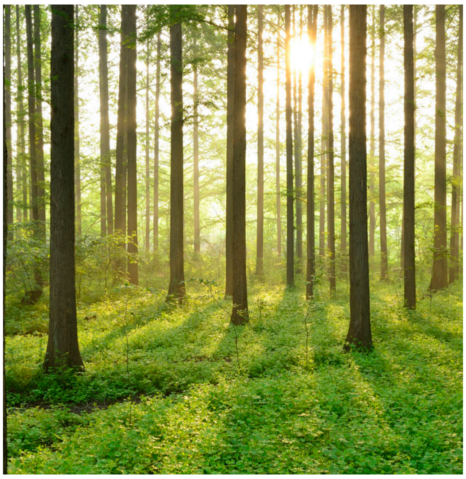

ENERGIGASTEKNIK

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More Efficient Use of Biogas at Waste Water Treatment Plants

Possibilities from integration of heat power

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Foreword

This project evaluated the integration of heat power in waste water treatment plants.

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The study had a reference/working group with the following members: Peter Lundström (Opcon), Jan Bergland (ECT Power), Joachim Karthäuser (Climeon), Jan-Erik Petersson (NSVA), Anders Johnsson (VA SYD), Heidi Lemström (SYVAB) Marie Berg (SYVAB), Robert Holm (Lackeby products), Daniel Ling (Purac) and Anton Fagerström (Energiforsk).

Reported here are the results and conclusions from a project in a research program run by Energiforsk. The author / authors are responsible for the content and publication which does not mean that Energiforsk has taken a position.

Abbreviations and explanations

ORC = Organic Rankine Cycle

WWTP = Waste Water Treatment Plant

CHP = Combined Heat and Power production

Mesophilic digestion = Biogas production at 37 °C

Thermophilic digestion = Biogas production at around 55 °C

H_LT = Low temperature heating system

H_HT = High temperature heating system

E_El = Electricity produced

Q1 = Heat flow to H-LT

Q2 = Heat flow to H_HT

T_H1 = Inflow of high temperature heat to ORC heat circuit

T_H2 = Outflow of high temperature heat from ORC heat circuit

T_C1 = Inflow of low temperature heat to ORC cold circuit

T_C2 = Outflow of low temperature heat from ORC cold circuit

pe = person-equivalents connected to WWTP

Sammanfattning

Idag produceras det årligen ungefär 700 GWh biogas (2016) på avloppsreningsverken (ARV) i Sverige, varav 60 % uppgraderas till fordonsbränsle och resten omvandlas till el och/eller värme via gaspannor, gasmotorer eller gasturbiner. Kylvatten som genereras vid förbränningen ligger vanligtvis runt 90 °C och används i huvudsak till uppvärmning av lokaler samt av slam och rötkammare. Det totala värmebehovet varierar över året och när värmebehovet är lågt facklas betydande mängder av den producerade biogasen. I snitt ligger mängden facklad gas på 10% av den totala biogasproduktionen på ARV.

Detta projekt syftar till att undersöka om detta gasöverskott på ett tekno-ekonomiskt fördelaktigt sätt kunna utnyttjas för elproduktion genom integrering av så kallad värmekraft (~ lågtemperatur ORC Organic Rankine Cycle) i kombination med befintliga gaspannor, gasmotorer eller gasturbiner. Det föreslagna systemkonceptet minskar behovet av extern el samtidigt som gasfacklingen minskar och den totala energiverkningsgraden på ARV ökar.

Denna undersökning bygger på fallstudier på tre ARV: Himmerfjärdsverket (SYVAB), Klagshamn (VA SYD) samt Nyvång (NSVA). På samtliga anläggningar rötas slammet till biogas och mer än hälften av den internt producerade värmen från gaspanna eller gasmotor används för att värma rötkammare (37 °C, mesofil rötning). Övrig värme används till tappvarmvatten, uppvärmning av lokaler och eventuell hygienisering av slam. Genom att istället fördela ARV:ens värmeflöde i två separata system, ett lågtemperatursystem för uppvärmning av rötkammaren och ett högtemperatursystem för det övriga värmebehovet skulle flera fördelar kunna uppnås. Dagens värmesystem på 80-90 °C för uppvärmning av rötkammaren skulle värme från värmekraftens kylkrets användas för uppvärmning av rötkammare och på så vis ökar den totala energieffektiviteten.

Den potentiella elektricitetsproduktionen och dess kostnad per kWh exklusive skatt för värmekraft - (ORC)-teknik, summeras nedan:

Tabell 1. Den potentiella elektricitetsproduktionen och dess kostnad per kWh exklusive skatt.

ARV	SYVAB	VA SYD	NSVA	Enhet
Elektricitetsproduktionspotential	530-710	480	80	MWh
Produktionskostnad, exklusive skatt	0.84-0.63	1,0	5,59	SEK/kWh

Intervallet för SYVAB i Tabell 1 svarar mot mer/mindre detaljerade beräkningar i avsnitt 2.7 och 2.8.

Från Tabell 1 ser vi att integrationen av värmekraft i de studerade fallen inte är ekonomiskt försvarbart, givet det nuvarande elpriset på ca 0.89 SEK/kWh (inklusive elcertifikat) samt skatten på 0.331 SEK/kWh på internt förbrukad el. Det är dock värt att lyfta upp att värmekraftmodulerna inkluderade i studien är grovt överdimensionerade, vilket resulterar i en väldigt hög och missvisande produktionskostnad.

Elproduktionen för värmekraftsystemet beror både på mängden facklad gas och på rötkammarens totala värmebehov; en storlek som varierar betydligt mindre än den facklade gasen för sig själv. Detta resulterar i att värmekraftmodulen används jämnare över året och får viktiga konsekvenser vid dimensionering, jämfört med alternativa kraftvärmeproduktionsslag som t ex gasturbiner och gasmotorer, som endast är beroende av mängden facklad gas.

Förutsatt att värmekraftmodulen inte är grovt överdimensionerad, ser vi att den föreslagna lösningen är konkurrenskraftig jämfört med andra kraftvärmeproduktionsslag och solceller.

Alternativet att använda fjärrvärme för att ersätta det existerande värmesystemet, ger möjligheten att uppgradera mer biogas, men är väldigt beroende av de specifika omständigheterna vid ARV, som t ex hur långt det är till ett närliggande fjärrvärmenät.

Summary

About 700 GWh biogas is today annually produced on the wastewater treatment plants (WWTP) in Sweden. Approximately 60 % of this biogas is upgraded to vehicle fuel. The remaining is converted to power and/or heat by combustion in gas boilers, gas engines and/or gas turbines. The temperature of the water from the gas boilers, engines and turbines is generally at around 90 °C and is mainly used for space heating and for supplying heat to the digestion chamber at the site. The internal heat demand at the WWTPs varies however with season and consequently, there are periods of time when there is significant biogas surplus at the sites. Today, this surplus is flared off and corresponds to about 10% of the total production. This project has been aimed to investigate whether this seasonal biogas surplus instead, in a techno-economic way, could be used for electricity production by integrating heat power technology (i.e. low temperature ORC) with the existing boilers, gas engines and / or gas turbines at the site. By such an installation, the need for external electricity could decrease on the same time as the flaring could be reduced.

The analysis includes techno-economic studies at three different Swedish WWTPs which differ in for example biogas production capacity, heating needs and existing infrastructure, etc. More than half of the produced heat from the boiler/engine is used for heating the sludge and the digester. The remaining heat is used for domestic hot water, space heating and possibly hygienization, for which the temperature requirement is higher. The temperature of the digestion (biogas production) is around 37 °C (mesophilic digestion) and by splitting the heat flow into two networks, one low temperature system for digestion/sludge and one high temperature system for the remaining heat demands, it is possible to use the cold side of the heat power installation for heating the digester and thus increase the overall energy and electrical efficiency.

The potential electricity production and the cost per kWh excluding energy tax, are summarized below:

Table 2. The potential electricity production and the cost per kWh without energy tax.

WWTP	SYVAB	VA SYD	NSVA	Unit
Electricity production potential	530-710	480	80	MWh
Production cost excluding tax	0.84-0.63	1.0	5.59	SEK/kWh

The interval for SYVAB in Table 2, corresponds to the less/more detailed calculations made in Sections 2.7 and 2.8 respectively.

From Table 2 we see that the integration of heat power in the studied cases is not economically feasible given the actual electricity price of about 0.89 SEK/kWh (including green certificate) and the tax of 0.331 SEK/kWh on internally consumed electricity. It is, however, important to emphasize that the heat power modules included in the study are very over-sized, resulting in a misleading very high production cost.

The electricity production of the heat power system depends on both the amount of flared gas and the heat demand of the digestion chamber; a quantity which varies less than the amount of flared gas alone. This results in a more even use of the heat power module over the year and has important consequences on the dimensioning, compared to other cogeneration techniques (e.g. CHP) such as gas engines and turbines, which depend on the flared gas alone. Given that the heat power is not very over-sized, we see that the proposed solution is competitive compared to other CHP solutions and solar cells.

The alternative approach of using district heating to replace the existing heating system gives the possibility of a larger amount of upgraded biogas, but is very dependent on the specific circumstances of the WWTP, such as the distance to a district heating network.

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1 Background

There are a total of 140 Waste Water Treatment Plants (WWTP) producing biogas corresponding to a production of around 700 GWh/yr in Sweden. Today, approximately 60 % of this biogas is upgraded to biomethane and used as vehicle fuel. Most of the remaining part is used for heat and electricity production, where the heat is mainly used for space heating and for heating the digester chamber (source: Energimyndigheten 2016). The heat demand at the WWTPs varies however with season and consequently, there are periods of time when there is a significant biogas surplus at the sites. Today, this surplus is flared off, corresponding approximately to 10% of the total biogas production. One way for minimizing the flaring and also increasing the overall energy efficiency of the WWTPs is to use the biogas surplus for electricity production using heatpower-technology i.e. Organic Rankine Cycle (ORC), integrated or combined with the existing combustion system. Especially, there is one interesting solution which could be applied. A so called low temperature ORC process uses around 90 °C waste heat as input, a temperature which is well in line with the temperature of the cooling water generated by the biogas combustion in the existing gas boilers or CHPs at WWTPs. Larger WWTP often have Combined Heat and Power (CHP) solutions (e.g. UMEVA, VA SYD, SYVAB), but periodically they still produce excess of biogas. The surplus can be used to generate more electricity to be used on site or sold to the electrical power network.

1.1 AIM OF PROJECT AND WORKING APPROACH

This project´s aim has been to investigate whether the seasonal biogas surplus at WWPTs in a techno-economic favorable way could be utilized for electricity production by heat power (i.e. low temperature ORC) with the existing boilers, gas engines and gas turbines at the site. The work is divided into several work packages (WP).

The work packages, besides the reporting, have been:

WP1. Identification of relevant technologies for small-scale electricity production from waste heat
WP2. Technical process analysis of flow data/schemas on WWTP
WP3. Data compilation and evaluation of technologies applicable to WWTP in different sizes
WP4. Case studies on WWTP –economic calculations
WP6. Design and cost analysis of a low temperature heating system
WP6. Comparison of proposed solution to use of district heating
WP7. Alternative low temperature systems

Critical questions in focus:

- Are there economic and technical potentials to install low temperature ORC solutions at WWTPs?

- Under what conditions is the suggested low temperature ORC process advantageous?
- What price levels and available heat flows are required for an installation to become cost-effective?

The project has involved RISE (project leader) and Sweco, which have contributed with the calculations and the report, the waste water treatment plants SYVAB, VA SYD and NSVA, which have contributed with data from the WWTP, the ORC suppliers Climeon, ECT Power and OPCON, which have contributed with information on heat power and finally the WWTP suppliers Purac and Lackeby Products, which have contributed with information on the digestion chamber.

1.2 LITERATURE REVIEW

1.2.1 Power from waste heat

R&D work is on-going world-wide on different technologies for small-scale electricity production from heat sources with low temperature.

Targeted against the district heating sector, a survey study covering technology for small-scale electricity generation was performed in 2010 (thermal power) (1). The study concerned high-temperature ORC modules installed commercially in Germany, but nor a techno-economic analysis was carried out neither an overall feature study in a Swedish context. Germany has installed a number of the ORC devices that operate at high temperatures (around 200^0 C or higher) to generate electricity. Germany has, however, a special situation with high energy prices (feed in-tariffs), compared to other countries, making the solution competitive.

Grontmij carried out a survey in 2008 funded by Värmeforsk (2), where process-integrated ORC modules were mapped out and evaluated. Goldschmidt conducted two case studies with ORC-technology combined with waste heat and bio boilers (3) (4). Both of these studies are based, however, on the process of integrated units or the use of waste heat.

In the Nordic countries, there is a handful of suppliers of ORC solutions for generating electricity from heat (ETC Power, Opcon, Againity, Climeon, etc.). Most operates, however, with higher temperatures and steam to generate electricity.

In Germany, there are also a large number of ORC manufacturers that mainly operate at high temperatures. Some examples are presented below:

- Orcan Energy AG, Munich
- Bosch KWK Systeme GmbH, Lollar
- Conpower Technik GmbH, Kaufungen
- Dürr Cyplan Ltd., Bietigheim-Bissingen
- GE Jenbacher GmbH & Co OG; Jenbach, Austria
- LTi ADATURB GmbH, Dortmund
- ORC energy GmbH, Dortmund
- ORmatiC GbR, Berlin

Bronicki, (2015) investigated the performance and different uses for Ormats ORC technology. The study revealed a number of relevant applications and how much energy and CO_2 emissions could be saved, but at the same time the study was very general and not strictly relevant to this project.

The Energy Agency for Southeast Sweden has been funded by Life+ program to examine and evaluate small-scale solutions to make electricity from hot water, including a low temperature-ORC installation at a power plant in the region.

1.2.2 ORC-Technology at biogas plants

In the majority of the European countries with biogas production, the biogas is used for the production of electricity and heat. The product in focus is normally the electricity and large amount of the waste heat is generally not utilized. The electricity and heat is commonly generated by conventional gas engines or gas turbines, whereas the use of ORC-technology is much scarcer in the field. There exists however a few installations of the latter and one of these installations is located in Aarhus (Denmark) (5). Another example can be found at a WWTP in Helsinki (Finland) (6), where the ORC-process is used for converting fumes at > 400 °C into electricity.

An installation of a 50kW ORC-module delivered by Againity using high temperature waste heat at a WWTP in Norrköping, Sweden was done during the spring 2017 (7).

ElectraTherm, has installed a so called Power+ Generator at a biogas production plant in Bad Köstritz, Germany. The site will generate fuel and emission-free power while using 100% of the heat from several biogas engines to qualify for Germany's EEG technology bonus resulting in additional revenue and a payback of less than three years.

ElectraTherm's Power+ Generator generates power from low temperature heat between 77-122°C. The facility uses biogas to power up to four 540kWe engines. The Power+ Generator utilizes the waste heat from 2 to 3 of the engines at any given time to produce clean electricity that will be sold back to the utility at an incentivized rate.

The ORC-technology is thus, although the relatively few existing installations, still considered as a proven technology at WWTPs when it comes to electricity production from high temperature streams. However, a low temperature ORC working with streams at 70-100 °C has still not yet not been evaluated in this industrial segment, which potentially could open up for big market in both EU and other countries that produce biogas.

2 Results

2.1 OVERVIEW OF TYPICAL MASS AND ENERGY FLOWS OF THE WWPTS

The characteristics and the mass- and energy flows of the WWPTs are presented in short in this section. To facilitate the understanding of the integration in question, a general process scheme, Figure 1, of a typical WWTP is presented below with its critical energy flows appointed and briefly explained.

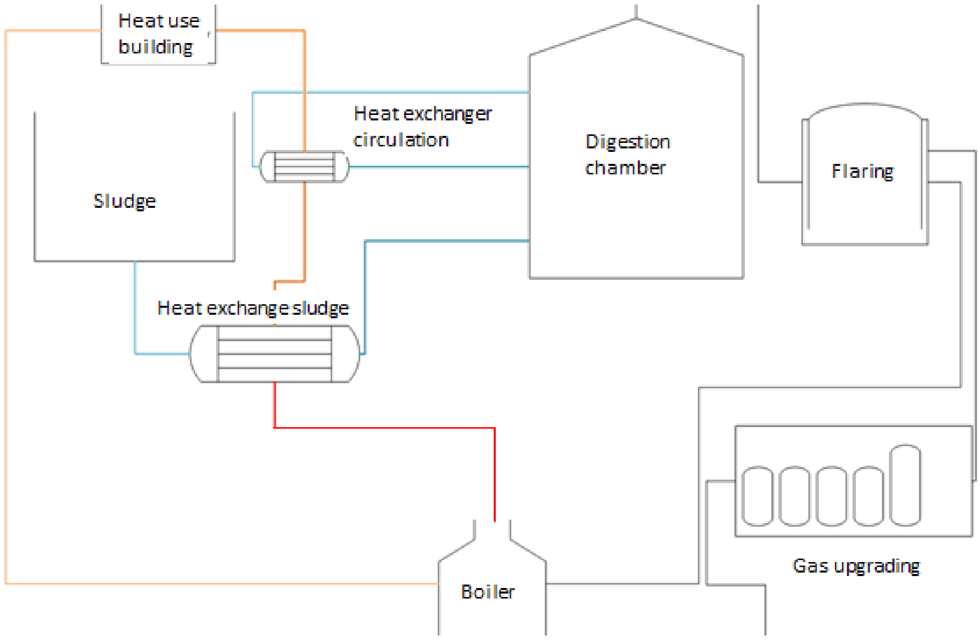

Figure 1. Typical process scheme of a WWTP.

The heat is produced from the biogas combustion, either in the forehead or in the gas engine or gas turbine. For our analysis, it is necessary to map the characteristics of the heat flow in terms of temperature, power profile, energy carrier and different uses of heat, among others in general. The heat required and its fluctuation to the digesters, sanitation, upgrading to vehicle fuel quality, premises, domestic hot water, return flow to the boiler and the electric engine, etc., are parameters that have been analyzed at the selected WWTPs.

2.2 OVERVIEW OF AVAILABLE SMALL-SCALE HEAT POWER TECHNOLOGIES

Heat power is a thermodynamic technique which converts heat energy to electricity by using the temperature difference of two separate flows, Figure 2.

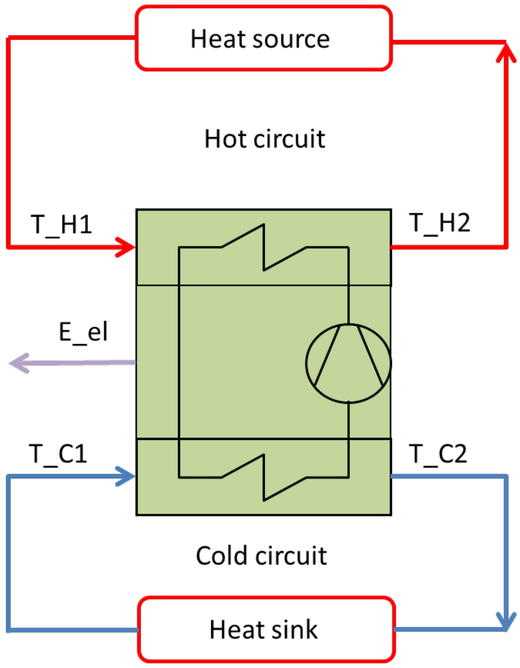

Figure 2. Schematic illustration of heat power process.

The system is composed of a heat power module, hot and cold circuits, a heat source and a heat sink (cold source). A hot flow at temperature T_{H1} goes into the heat power module, together with a cold flow at temperature T_{C1}. In the heat power module, heat is transferred from the hot circuit to the cold circuit and electricity, E_{el}, is generated. The outgoing hot flow has reduced its temperature to T_{H2} and the outgoing cold flow has increased its temperature to T_{C2}. Heat is transferred to the hot circuit by a heat source, increasing the temperature from T_{H2} to T_{H1}. Heat is transferred from the cold circuit to a low temperature heat sink, decreasing the temperature from T_{C2} to T_{C1}.

The heat supply from the heat source is

$$Q_h = \dot{m}C(T_{H1} - T_{H2}), \quad [1]$$

where $\dot{m}$ is the mass flow and C is the specific heat capacity of water. The amount of electricity produced is then given by

$$E_{el} = \mu Q_h, \quad [2]$$

where μ is the efficiency of the heat power. Furthermore, the corresponding cooling demand Q_C is given by

$$Q_C = (1 - \mu)Q_h. \quad [3]$$

The amount of heat Q_C is therefore the amount of heat in the cold circuit. Typically the efficiency of the heat power is in the range 5-14 %, thus 86-95% of the heat from the hot circuit is transferred to the cold circuit, in the form of semi-warm water[1]. In order to make the integration of heat power more efficient it is therefore important to make use of this large amount of heat. When using waste heat, where the cost of heat is zero, the use of the cold circuit makes the economic and environmental case more attractive. In the case where the heat has a value, such as coming from the combustion of a fuel with an associated cost, the valuable use of the cold circuit becomes essential.

One main advantage of heat power is that it is integrable with all kinds of heat sources such as heat from a boiler, waste heat from industries, but also with the cooling circuits of a CHP. The most well-known heat power technique is the Organic Rankine Cycle (ORC) which is a proven process for creating mechanical work and electricity from heat sources at 70-200 ° C. It is a further development of the Rankine cycle, but instead of using an organic fluid as cooling medium, a mixture of water and ammonia is used.

In the ORC-process, the electrical efficiency is a function of ΔT (i.e. the temperature difference between the heat source and the cold circuit) and the system efficiency. As can be seen in Figure 3, an electrical gross efficiency of around 10 % is expected when having a heat source and a cooling temperature of 90 °C and 20 °C, respectively.

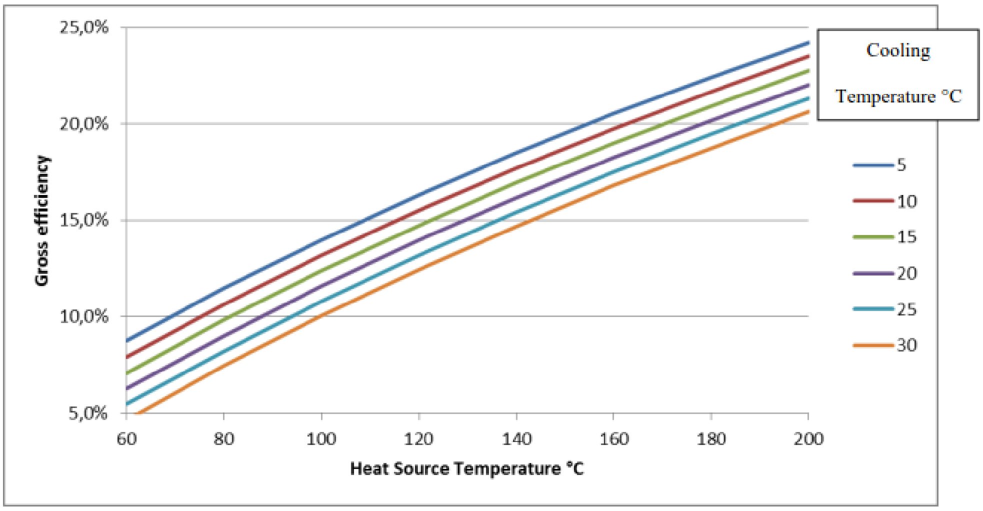

Figure 3. The electrical (gross) efficiency vs. the temperature difference in the ORC, reference Climeon.

[1] The outgoing temperature of the cold circuit T_{C2} depends on the temperature of the heat source and heat sink, the flow of the cold circuit and it varies between different suppliers. It is, however, possible to adjust the T_{C2} to some extent, to achieve a desired temperature level, which gives a slightly varied efficiency.

In addition to the ORC, there exist a technique called C3-process, which is very similar to the ORC-process, but uses other working fluids and operate under lower pressures (for more details, see Section 2.3.1).

2.3 TECHNICAL SUPPLIERS

In this project, three different Swedish suppliers (Climeon, C3-process; Opcon Energy Systems, ORC-process; ECT Power, ORC-process) of heat power modules have contributed with data about costs, maintenance and efficiency for the techno-economic analysis. The supplying companies and their respective heat power technologies are briefly described in the following.

2.3.1 CLIMEON

Climeon is a public company that developed and supplies the C3- heat power technology for electricity production from hot (waste) water. C3 was developed in 2011-2014 and is currently manufactured in Sweden. The product is modular, meaning that it is possible to combine several modules in order to meet the customer´s demand of power output. Climeon´s process is designed for taking use of energy streams at relatively low temperatures and pressures (down to 70⁰ C and 2-4 bars). The technology could therefore be relevant to several industry segments having access to low value waste heat. Typical performance of the C3-process and the module are shown in Figures 4 and 5, respectively.

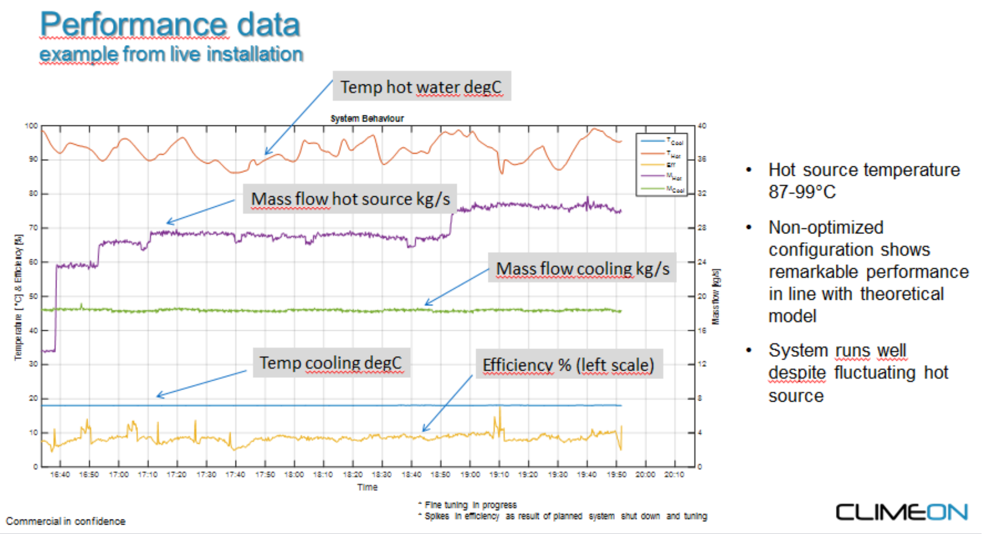

Figure 4. The graph displays the temperatures and the mass flows on the hot and cold flows as well as the efficiency on-line by a Climeon module installed at SSAB in Borlänge (http://climeon.com/heat-power/, published with permission of Climeon).

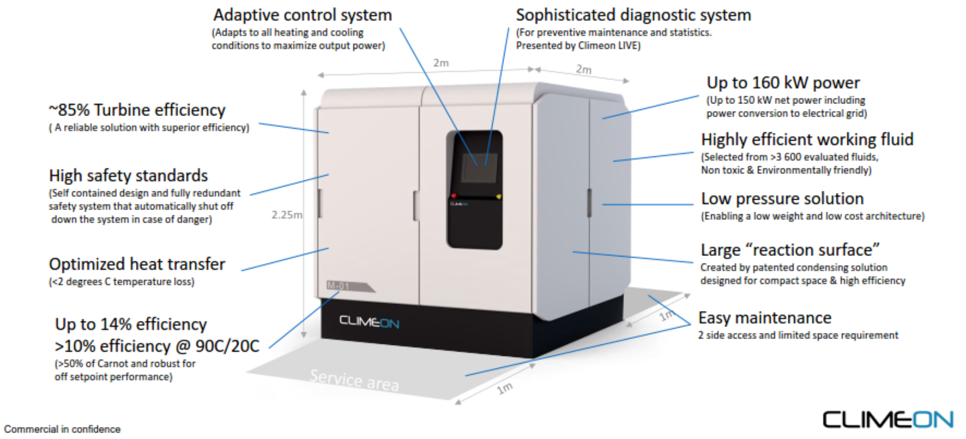

Figure 5. Climeon module with a power output of 150 kWe. (http://climeon.com/heat-power/, published with permission of Climeon).

2.3.2 OPCON

The Opcon Powerbox is a product developed by the private company Opcon for the production of electricity from waste heat at temperatures ≥ 55° C. Opcon Powerbox can be supplied in sizes ranging from 150 to 1600 kWe. An Opcon Powerbox ORC uses hot water to produce electricity while an Opcon Powerbox WST uses wet, saturated steam directly. Examples of Opcon Power applications include large process-industry plants, power stations or onboard larger ships.

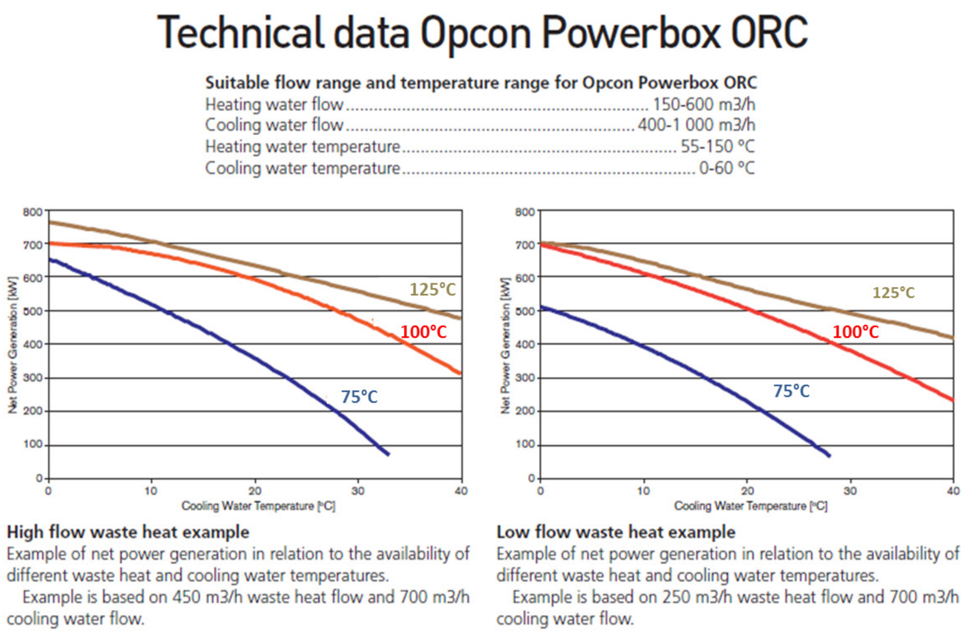

Figure 6. Technical data from Opcon, published with permission of Opcon.

2.3.3 ECT POWER

The private company ECT Power develops heat power systems for the re-use of waste heat of industries such as paper, saw, refinery, cement and incineration. The temperature of the utilized heat source is normally around 80-180°C and their installed heat power systems are within the power range of 500-3000 kWe. Typical performance data of their heat power units as a function of various ΔT are shown in Figure 7 and Table 3, respectively. The system efficiency referred to includes pumps, turbines, evaporators, coolers and generators.

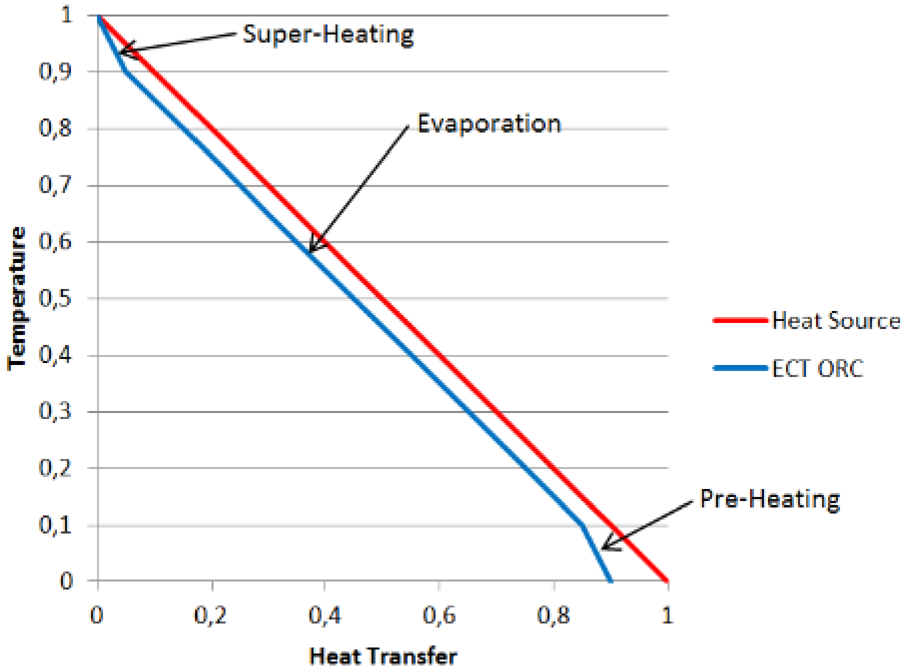

Figure 7. Performance data obtained with the ECT ORC-process. Reference: ECT Power.

Table 3. The net power efficiency (min –max) obtained with the ECT ORC- process as a function of different heat source and coolant temperatures. Reference: ECT Power.

Heat source (°C)	Cooling temperature (°C)	Min net power efficiency %@30 % system efficiency	Max net power efficiency % @ 75 % system efficiency
80	10	3	8
80	20	2	7
100	10	4	10
100	20	3	9
140	10	5	13
140	20	4	12
180	10	7	16
180	20	6	15

To summarize Section 2.3., the electrical efficiency of a heat power unit is normally within the range of 5-14 %, depending on the actual temperatures of the heat source and the cooling medium, respectively. The design operation window and the power output of the different techniques presented in this chapter can all, to some extent be customized but the *off-shelf* modules are typically within the following ranges:

OPCON: 55-160 °C, 0.3-3 MWe

ECT Power: 80-200 °C, 0.3-3 MWe

Climeon: 70-120 °C, 0.15-0.6 MWe

2.4 INTEGRATION OF HEAT POWER ON WWTP – THEORETICAL POTENTIAL

As described in the previous section, heat power is a technology designed for converting waste heat into electricity. In the case of WWTP, there is however rather waste biogas than waste heat to make use of, which put the heat power technology in competition with conventional CHPs and it is therefore also necessary to clarify how these technologies stand in relation to each other. With respect to solely the given electrical efficiency, conventional CHPs would be the expected technology of choice (ca 30-35 % (CHP) vs. ca 5-14 % (heat power)). However, it should in this respect be noted that a fair comparison between the two needs to also take in consideration that the definition of the electricity efficiency in the two cases differ and reflects the intrinsic difference of the two techniques. The efficiency of the heat power system is defined as the *fraction of heat* which is converted into electricity, whereas the efficiency of the CHP is defined as the *fraction of the energy in the fuel* converted into electricity.

The main advantage of the *heat power* is that it can make use of a *much larger part of the total heat produced* compared to the heat produced from the flared gas while a *new CHP only makes use of the flared gas*. This is based upon a *valuable use* of the cold circuit, as will be seen below.

2.4.1 Temperature differentiation

A given heat demand requires a certain amount of energy with a heat carrier (such as hot water) at a given temperature. Some heat demands have a high temperature requirement (such as domestic hot water) while for others it is sufficient with a lower temperature. To make use of this, the heating system therefore needs to be differentiated into a high temperature system, which covers the high temperature demands and a low temperature system, which covers the low temperature demands. It is in the low temperature system that the heat power is integrated.

The differentiated energy system with high and low temperature heat demands, H_{HT} and H_{LT} respectively, is illustrated in Figure 8.

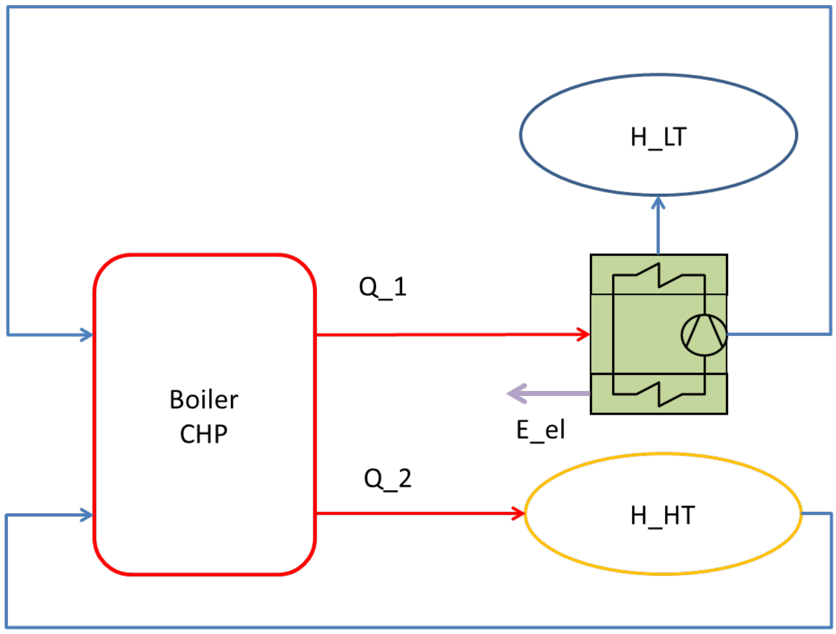

Figure 8. Schematic design of a temperature differentiated system. H_LT and H_HT are low and high temperature heat demands, Q_1 is the heat flow to the heat power, Q_2 is heat flow to the high temperature heat demand and E_{el}.

2.4.2 Integration of heat power through low temperature system for WWTP

At a WWTP, a common low temperature heat demand is the (mesophilic) digestion chamber and the preheating of the incoming sludge[2], which requires a temperature of 37 °C and which stands for a large fraction (in our case studies between 50 – 80%) of the total heat demand of the WWTP.

The main idea is to use the heat from the cold circuit for the digestion chamber, which needs essentially lower temperatures than the output from boilers and CHPs (typically 80-100 C), thus giving the possibility to extract electricity via heat power.

The integration of heat power with a low temperature heating system implies an increased use of biogas, which currently is flared, to provide the same amount of heat to the digestion chamber. For the WWTP included in this study, there is an excess of flared gas beyond this increased use of biogas. The combustion of the remaining gas gives a heat flow on the cold circuit which is not needed in the digestion chamber and which needs to be dumped, e.g. in the outgoing water of the WWTP.

In the following discussion we assume that there is no power capacity limitation in the boilers/CHP or the heat power module. This means that the whole potential of the flared gas, G_F, can be used. This assumption is rather severe as the profile of the flared gas varies substantially over the year, as will be seen in the case studies. An over dimensioning of the heat power installed increases its relative cost. The question of a varying flared gas over the year is however less severe in the case of

[2] For convenience we will hereafter refer to the combined heat demand of the digestion chamber and of the incoming sludge as the heat demand of the digestion chamber.

heat power, compared to solutions, such as CHP, as the heat power is integrated in the ordinary functioning of the digester. This will be clarified below.

We consider the part of the heating system which supplies heat to the digestion chamber[3]. Figure 9 is a schematic design of a heating system of the digestion chamber without heat power. The heat demand of the digestion chamber is H_{LT}, which is supplied by Q (corresponds to Q_2 in Figure 10) from the boiler/CHP.

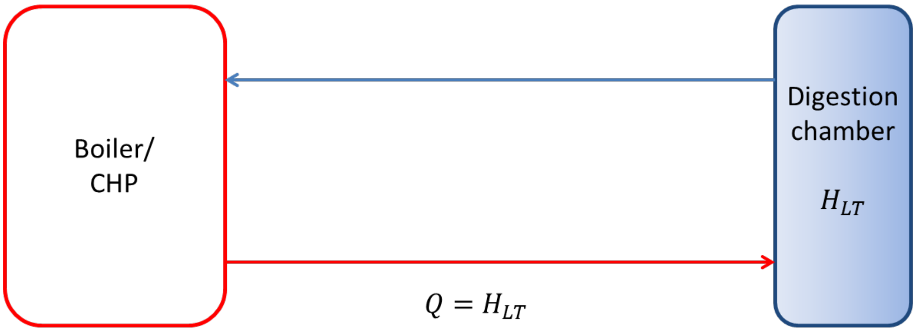

Figure 9. Schematic design of heating system of the digestion chamber without heat power.

The integration of heat power is done by replacing the heating of the digestion chamber by a low temperature system from the cold side of the heat power.

It is worth noting that in the following discussion we assume that the heat to digestion chamber can be taken directly from the cold circuit. In case that the temperature requirement of the digester is higher than the temperature of the cold circuit, or that the efficiency of the heat power module gets too affected, heat can be taken from the hot circuit to increase the temperature and obtain the necessary temperature. This will be further discussed in Section 2.8. The general results, discussed in this section remain, however, the same.

Figure 10 is a schematic design of heat system of digestion chamber with heat power.

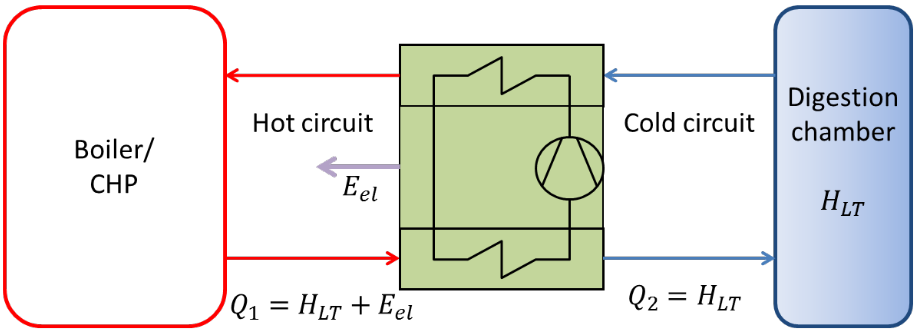

Figure 10. Schematic design of heat system of digestion chamber with heat power. Here the heat demand H_{LT} is supplied by the cold circuit of the heat power.

[3] Observe that the heating system is initially not differentiated, but we only consider the fraction of the total heat flow which goes to the digestion chamber.

The heat demand of the digestion chamber is, as above, H_{LT} and there is $E_{el} = \mu Q_1$ electricity produced, where μ is the efficiency of the heat power and Q_1 is the total heat flow from the boiler/CHP.

The boiler/CHP in Figure 10 needs to produce $Q_1 = H_{LT} + E_{el}$ heat, assuming negligible energy loss. By comparing Figures 9 and 10 we see that the energy value of the increased heat output from the boiler/CHP corresponds to the electricity produced, $\Delta Q = Q_1 - Q = E_{el}$. The increased use of gas thus corresponds to the electricity produced, $\Delta G = \frac{\Delta Q}{\varepsilon} = \frac{E_{el}}{\varepsilon}$, where ε is the heat efficiency of the boiler/CHP[4].

In order to satisfy the low temperature heat demand from the cold circuit of the heat power we have

$$Q_1 = \frac{H_{LT}}{1-\mu} \qquad [5]$$

Therefore, the increase of heat use from the boiler/CHP is given by

$$\Delta Q = \frac{\mu}{1-\mu} H_{LT} \qquad [6]$$

If the currently flared gas potential, G_F, is larger than the increased gas used by the low temperature system, ΔG, then this excess gas can be used in the boiler/CHP and the corresponding heat be used for the heat power module. In this case the additional electricity produced is $E_{dump} = (G_F - \Delta G)\varepsilon\mu$, where the excess heat in the cold circuit is dumped in e.g. the outgoing water of the WWTP.

The total potential electricity production becomes[5]:

$$E_{el}^{tot} = E_{el} + E_{dump} = \Delta Q + (G_F - \Delta G)\varepsilon\mu = \frac{\mu}{1-\mu} H_{LT} - \frac{\mu^2}{1-\mu} H_{LT} + G_F \varepsilon\mu = \mu(H_{LT} + G_F\varepsilon) \quad [7]$$

By examining the equation above we see clearly that the electricity potential is given by the amount of flared gas and the heat demand of the digestion chamber.

In practice this potential is restricted by the installed capacity of system components (boiler/CHP, heat power module and cooling solution).

The intrinsic difference between the heat power and cogeneration technique is clearly manifested in Equation 7. The heat power converts thermal energy into electricity, while the CHP converts the energy in the fuel to electricity. By having a low temperature heating system for the digestion chamber, the heat power can make use of a much larger heat flow than the one originated from the flared gas, while the CHP only make use of the energy of the flared gas. In Equation 7, this results in two terms for the produced electricity: $\mu\varepsilon G_F$ and μH_{LT}. The first one corresponds to the potential of the flared gas, which is very similar to the expression for the potential electricity production of the CHP, θG_F, where θ is the efficiency of the CHP[6]. The second term, μH_{LT}, however, only appears in the expression for the heat power electricity potential. In situations where the heat

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[4] The heat efficiency is the fraction of the energy value in the fuel which is transformed into usable heat in the boiler/CHP. For a boiler it is typically 80%.

[5] Observe that the equation below is restricted to G_F-ΔG≥0.

[6] Observe that θ and $\mu\varepsilon$ are both constants but θ is of the order of 0.35 while $\mu\varepsilon$ is of the order 0.08.

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demand of the digestion chamber is large, this term becomes very important, which can result in a much larger electricity potential for the heat power solution compared to the one of an extra CHP. In fact, the term μH_{LT} is about 4-5 times larger than $\mu\varepsilon G_F$ for the investigated cases in Section 2.6. The heat demand of the digester is therefore generally a more important (larger) quantity than the amount of flared gas.

When dimensioning the size heat power module one should consider the sum of the heat demand of the digestion chamber, H_{LT}, and contribution from the heat flow during periods of flared excess gas εG_F over time. This is in contrast to the dimensioning of an additional CHP, to make use of the flared gas, where only the flared gas enters. In that respect the heat power is more advantageous, as the heat demand of the digestion chamber decreases in the summer, while the flared gas increases; the opposite being true for winter. The fact that the heat power is integrated in the ordinary heating system of the digestion chamber means that it is used through a large part of the year, while a CHP is only used in the summer time.

The fact that the relevant quantity when dimensioning the heat power is $\varepsilon G_F + H_{LT}$ instead of εG_F as in the case of a CHP has also consequences on the tax on internally used electricity, see appendix 4.1. The flared gas profile is much more pronounced in summer, which results in that the CHP will be charged with tax for a lower amount of electricity produced than the case of a heat power module (given that an individual heat power module has a power < 50 kWe).

In addition to the energy of the flared gas, the low temperature system can be used to optimize the consumption of natural gas or oil during the periods of the year where the locally produced gas is not sufficient to satisfy the heat demand. In that situation, the use of natural gas or oil is increased in a similar way as described above for the biogas. This, however, implies an additional cost.

It is worth mentioning that the WWTP involved in the project brought up that the existing CHP often had maintenance problems. The heat power solution is expected to be more robust, as it is based upon heat from a boiler[7], which is very robust against, for example, the composition of the biogas.

2.4.3 Numerical example

To clarify the potential of the proposed heat power concept at a WWTP, a simple numerical example (data given in dimensionless units of energy (UE)) is given in the following[8]:

Total gas produced G_{tot} = 1200 UE

Flared gas, G_F= 120 UE

[7] The heat to the heat power module can come both from a boiler and a CHP, but in practice it can be considered to come from a boiler as the installed capacity of the boiler is sufficient to use all biogas produced and supply all heat, thus a failure of the CHP does not affect the heat power module.

[8] The numbers in the example are given by the typical proportions of the flared gas and heat demand of the digesters from the WWTP included in the project.

Heat need of digestion chamber, H_{LT}=450 UE

Efficiency of boiler, ε=0.8

Efficiency of heat power, μ=0.1

The electricity production is given by

$$E_{el}^{tot} = \mu(H_{LT} + G_F\varepsilon)$$

The first term, μH_{LT}, results in 0.1*450 = 45 UE, while the second term, $\mu\varepsilon G_F$, results in 0.1*120*0.8 = 9,6 UE. Thus in total, E_{el}^{tot} = 54,6 UE.

Therefore 120 UE flared gas give for a WWTP with a heat demand of digestion chamber of 450 UE a total of 54,6 UE electricity, which corresponds to 45,5% of the energy of the flared gas.

2.4.4 Integration of heat power in WWTP with other heating systems

The discussion above refers to WWTP which have heating systems based upon combustion of biogas produced in excess at the plant. It is worth noting that the integration of heat power is not necessary in competition with upgrading of biogas, if there is gas which is flared. This will be seen in the case of SYVAB (where the biogas upgrading capacity is limited) in the following chapters. The integration of heat power could also be applied in WWTP which upgrade all their excess gas. In that case the techno-economic analysis would involve the price and cost of upgrading, and is not included in this study.

It would also be possible to integrate heat power in WWTP whose heating system is based upon district heating. In that case the heat to the heat power module would come from the district heating instead, and a secondary, low temperature circuit would be built for the digestion chamber as described above. The difference would be that the high temperature from the district heating would have a cost. The techno-economic consideration of this case is not included in this study.

2.5 DESCRIPTION OF CASE STUDIES

As described in section 1, the suggested installation of heat power at a WWTP is in this project evaluated at three different existing Swedish WWTPs.

2.5.1 Himmelsfjärdsverket (SYVAB)

Himmerfjärdsverket (SYVAB) is a WWTP collecting waste water from Botkyrka, Salem, Nykvarn, the major part of Södertälje, parts of Huddinge and southwestern Stockholm. At the site, biogas production is a part of the sludge management. The produced biogas is used for heating; around 50 % of the heat produced is supplied to the mesophilic digester, and electricity production. Since 2009, there is also a biogas upgrade facility at the site for the production of vehicle fuel (~around 2,7 MNm^3/yr vehicle gas, 2014).

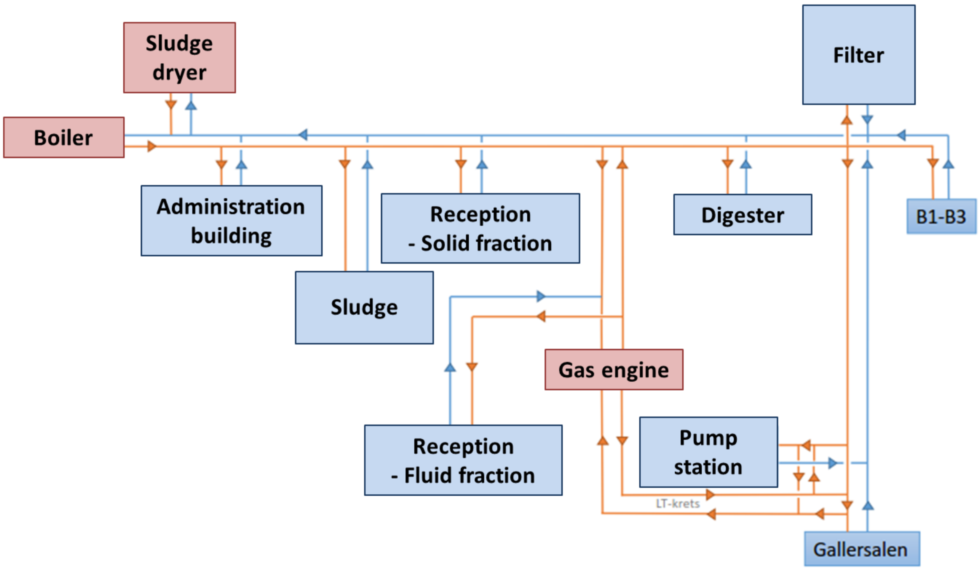

Figure 11. The use of heat at Himmerfjärdsverket from the combustion of biogas.

As seen in Figure 11, gas boilers are used for the 80 - 90 °C heat circuit, which is mixed with the return water from the WWTP-plant, resulting in a temperature of about 60-65 °C. Part of the latter is then used as cooling water for the gas engine. The return water therefrom (about 80 °C) is used to heat the pasteurization tanks with ABP (Animal Bioproducts Regulation) materials (70 °C for 1 h) 2-3 times per day.

During the warmer season of the year, the heat demand of the site decreases and the resulting biogas excess produced at the site is flared off, see Figure 12. In average, around 10 % of the biogas produced is flared off per year corresponding to around 1,7 GWh wasted biogas production.

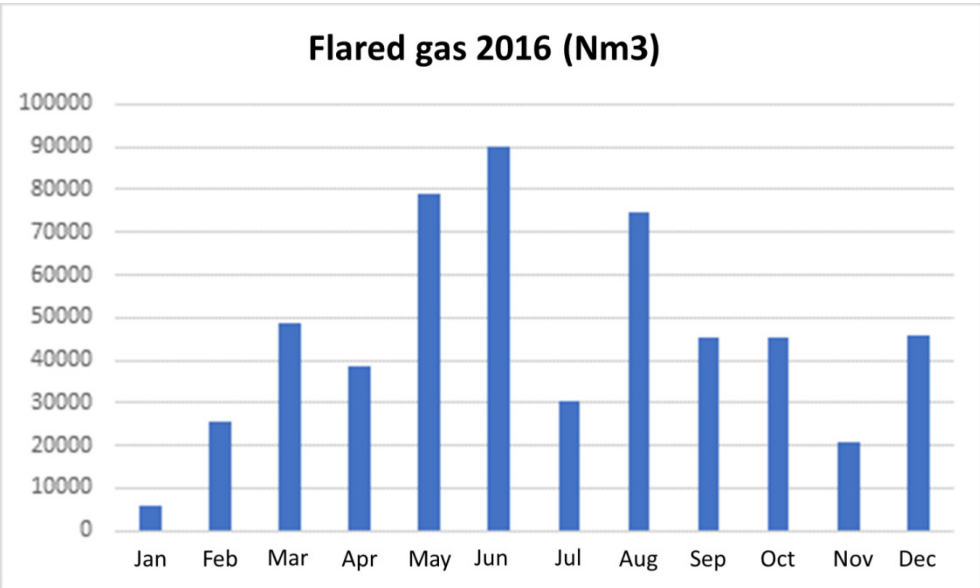

Figure 12. The amount of biogas flared off at Syvab – Himmerfjärdsverket in 2016.

2.5.2 Klagshamn (VA SYD)

VA-SYD Klagshamns WWTP is located south of Malmö and receives water equivalent to 73 full baths per minute (230 liters/second) from the southern city of Malmö and the entire Vellinge municipality. Similar to Himmerfjärdsverket, biogas production is a part of the sludge treatment. At this site, upgraded biogas is also fed into to the nearby natural gas transmission net, mainly during winter time. Instead, the majority of the biogas is combusted in a micro-turbine (100 kWe capacity) producing electricity and heat for internal usage. The micro-turbine capacity is to some extent limited and some of the produced biogas is therefore combusted in two gas boilers (total capacity 1600 kW, outlet temperature is ~95°C), in which the biogas fuel is mixed with and replaces some of the otherwise used natural gas. Around 80 % of the heat produced by the boilers is typically supplied to the biogas process (drying of sludge, heating of the digester chamber). Likewise at Himmelfjärdsverket, the actual heat demand at the site is varying with season and around 10 % of the produced biogas is in average per year flared off (concentrated to April-October).

Figure 13. Photo of VA-Syd WWTP in Klagshamn near Malmö.

2.5.3 Nyvång (NSVA)

Nyvång WWTP (NSVA), located outside Åstorp in Skåne, treats municipal and industrial waste water from Åstorp, Björnås, Hyllinge, Nyvång and Grytevad; corresponding to a catchment area of around 12 000 inhabitants. Biogas production is likewise the other WWTPs included in this analysis at this site a part of the sludge treatment, but in contrast to the WWTP in Himmerfjärdsverket and

Klagshamn, no electricity production occurs in Nyvång and the produced biogas is only used for internal heating purposes. To fully cover the heat demand at the site, the biogas combustion is complemented by an oil burner during certain periods of the year.

2.5.4 Summary from the wwtp survey

Table 4 summarizes the heat and electricity flow characteristics at the three different WWTP included in the case analysis. In addition to given parameters, estimations of the amount of heat that can be used power production has been done.

Table 4. Electricity, heat and gas flow characteristics at Himmerfjärdsverket (SYVAB), Klagshamn (VA SYD) and Nyvång (NSVA), respectively.

Parameters	Himmerfjärdsverket (SYVAB)	Klagshamn (VA SYD)	Nyvång (NSVA)
Total biogas produced, kWh	17 846 000 [1]	6 245 000	1 547 189
Biogas use in boiler, kWh	6 922 470	N/A	1 403 975
Biogas use in CHP, kWh	9 272 299	N/A	0
Natural gas/oil use, kWh	0	962 000	303 240
Flared gas, kWh	1 651 231	730 000	143 314
Total heat used, kWh	11564970	5181600	1365692
Fraction of the total heat demand of digester	0.5	0.8	0.5

[1] Does not include the biogas upgraded for vehicle fuel.

During the cold season, the WWTPs Klagshamn (VA SYD) and Nyvång (NSVA) need natural gas and oil to satisfy overall internal heat demand. Himmerfjärdsverket (SYVAB) needs no external supply of gas or oil.

Common to the different WWTPs is that when there are both boilers and CHPs, then the CHP is run preferably to the boiler for economic reasons.

- To summarize this section, it can be concluded that:
- The sludge digesters account for a significant portion of the total heat demand of the WWTPs.
- The WWTPs are heat compensated but have an excess of biogas which is flared, in average 10 % per year of the total biogas production.
- Over the year there is large variation in the amount of sludge to digest. This, together with a variation of the outside temperature leads to a varying heat demand.
- CHP is run preferably to boilers.

2.6 THE ELECTRICITY POTENTIAL AT THE SELECTED WWTPS

The three WWTP were analyzed for electricity production potential according to section 2.4.

In the analysis, we have assumed:

1. That a low temperature heating system has been realized in connection to the sludge and digestion chamber.
2. No capacity bottlenecks – heat power installation can use all the heat and the boilers can use all biogas supplied.
3. Fixed efficiency for partial load for boilers, CHP:s and heat power.
4. Efficiency range of heat power modules available on the market according to Section 2.3 at relevant temperature levels: 6-10 %. This results in the presented ranges in Table 5 and 6.
5. At the WWTP, the CHP is run preferably to gas boilers.

The results of the analysis of the potential electricity production from the flared gas for the different WWTPs are summarized in Table 5.

Table 5. The estimated annual electricity production potential of the studied WWTP from the flared gas.

WWTP	SYVAB	VA SYD	NSVA
Electricity potential MWh	420-710	250-410	40-70
Percentage of energy of flared gas turned into electricity	25-43	34-56	28-47

In addition to biogas, VA SYD and NSVA utilize an additional amount of natural gas. The implementation of a low temperature system implies an increased use of this external fuel, resulting into an increased electricity output, summarized in Table 6.

Table 6. The estimated annual electricity production potential of the studied WWTP from the flared gas and the increased use of natural gas or oil.

WWTP	SYVAB	VA SYD	NSVA
Electricity potential MWh, including increased use of natural gas or oil	420-710	280-480	50-80
Percentage of electricity production increased gas use, including natural gas	25-43	37-59	32-50
Percentage of use of heat power module			

It is worth noting that total electricity efficiencies presented in Table 5 and 6 should be compared to the typical efficiency of a CHP of around 35%. The main reason for the substantially higher total electricity efficiencies of the heat power compared to the cogeneration efficiencies is the fact that one makes use of a larger heat flow than the one coming from the increased gas use, as discussed above.

In the cases studied, the fraction of the flared gas used to compensate the increase used heat for the low temperature system is about 50%, while the rest of the increased heat production is dumped in the outgoing WWTP. Using $\Delta G = \frac{G_F}{2}$ in Equation 7 gives: $E_{el}^{tot} = \frac{\varepsilon}{2} G_F (1 + \mu)$. The total efficiency then becomes:

$\frac{E_{el}^{tot}}{G_F} = \frac{\varepsilon}{2}(1 + \mu) \approx 0.44$, which is in line with the results given in Table 5 and 6 and larger than the typical efficiency of a CHP of typically 0.3-0.35[9].

2.7 CASE STUDIES WWTP – ECONOMIC CALCULATIONS OF HEAT POWER

The selected WWTPs have been analyzed with respect to heating systems, heat, gas and electricity needs, electrical efficiency, cost and by compiling and evaluating the process scheme of the site relating to the operation and flow profile over a year. In addition, information on operating experience at the WWTPs with regard to function, efficiency and maintenance requirements (a situation analysis) have been compiled and taken into consideration. The electricity prices used are the actual electricity prices of the different WWTP.

The input and the assumptions made for the economic analysis in this work are summarized in Table 7. Efficiency and cost data (including installation and maintenance) used correspond to the most favorable case given by the ORC-suppliers in Section TECHNICAL SUPPLIERS 2.3.

The potential electricity production in Table 5 and 6 is small[10] compared to the production capacity of the existing modules of the suppliers involved in the project. Therefore the analysis is performed using the smallest module of 150 kWe.

Table 7. Input data and assumptions made in the economic analysis of the project

Parameter	Input
Heat power electrical efficiency	10 %
Investment cost heat power	2800 SEK/kWe
Maintenance cost heat power	2 % of total investment/year
Cost external electricity	SYVAB 0.8 SEK/kWh, VA SYD 1 SEK/kWh, NSVA 0.8 SEK/ kWh
Cost green electricity certificate[11]	0.09 SEK/kWh
Cost of natural gas[12]	0.345 SEK/kWh
Electricity tax	0.331 SEK/kWh if installed power > 50 kW
Installation cost of a low temperature circuit[13]	0.6 MSEK
Discount rate	5 %
Depreciation time	20 years
Rest value	0 SEK

[9] It is important that this comparison is made assuming that the efficiency of the heat power is 10%. In Section 2.8 we see that it is actually decreased to 7.5% due to high temperature levels on the cold circuit. To make a more accurate comparison of heat power and conventional CHP solutions, one has to make a more detailed study of the WWTP.

[10] The percentage use of 150 kWe module is 54% for SYVAB, 36% VASYD, 6% NSVA, respectively for the upper limit of electricity production potential in Table 5.

[11] (11)

[12] (12)

[13] This estimation is based upon results in Section 2.8.

The corresponding results from the economic analysis are summarized in Table 8.

Table 8. Economic assessment of the studied WWTPs with installation of HeatPower modules (150 kW).

Parameter	**Himmerfjärdsverket (Syvab)**	**Klagshamn (VA-syd)**	**Nyvång (NSVA)**
Maintenance and operation, 2 %, kSEK/yr	64	64	64
Cost of increased use of natural gas, KSEK	0	30	6
Production of electricity, ORC, MWh/yr	710	480	81
Percentage use of heat power module, %	54	36	6
Production cost excl. tax, SEK/kWh	0.63	1.0	5.59
Production cost incl. tax , SEK/kWh	0.96	1.33	5.82
Price external electricity, including certificate	0.89	1.09	0.89

From Table 8 we see that the installation is not economically for any of the WWPT, and only defendable to some extent for the case of SYVAB if there were no taxes on internally consumed electricity.

The results in Table 8 clearly show that the module sizes of the involved suppliers are very large for the studied WWTP, which has a decisive effect on the electricity production cost. The impact of the energy tax of 0.331 SEK/kWh is also of great importance.

To illustrate the effect of an over dimensioned module we have performed calculations of a fictional WWPT, where a 150 kWe heat power module is used 100%. Without taxes, the production cost would be 0,37 SEK/kWh, while with taxes it would be 0,66 SEK/kWh.

To give an indicative size of a fictional WWTP for which a 150 kWe module would run full time we assume to have a 10% flaring of biogas of the total production, the heat demand of the digestion chamber is set to be 50 % of the total heat demand and $\Delta G = \frac{G_F}{2}$, as discussed in Section 2.6 above. Using Equation 7 we have that the flared gas should be $G_F = \frac{2E_{tot}}{\varepsilon(1+\mu)}$. This results in a corresponding WWTP with 300000 PE, where we have used that 1 PE generates 100 kWh/year biogas (8), excluding the part of the produced biogas which is upgraded.

Furthermore, we exemplify the effect of the tax by calculating the size of the WWTP for which the cost of production equals the cost of the electricity including electricity certificate, set to 0.89 SEK/kWh. In the case without tax the minimum size of a WWTP for which the cost of production is lower than the cost of electricity is about 180000 PE compared to about 120000 PE when no tax is applied.

To summarize this section we see that the heat power technique could be economically relevant for WWTP but has two major limitations, namely the size of the heat power modules of the suppliers participating in the project and the tax on internally consumed electricity for installations with power larger than 50 kW, see Appendix 4.1. This results in that the proposed system becomes more relevant for larger WWTP. A heat power module of less than 50 kW would be more suitable, as it circumvents both major limitations.

2.8 CASE STUDY: SEPARATED LOW TEMPERATURE NETWORK (HIMMELSFJÄRDSVERKET, SYVAB)

The overview studies made of the three different WWTP:s in the previous sections, Himmerfjärdsverket, owned by SYVAB showed the highest economical potential. Therefore a more in-detail study of the different technical designs and cost estimations were made of integration of an ORC module (Oraganic Rankine Cycle) into an existing waste water treatment plant where the low temperature side of the ORC is connected to a digester to supply the necessary heat.

2.8.1 Design basis of heat power integration

From the available heat power modules, the smallest 150 kWe module is chosen, due to the potential electricity production in Table 6.

The ORC-module requires cooling and the low temperature heat should be used to heat a digester at the WWTP to 38°C. It is assumed that this requires a water temperature of 55°C. This temperature is based upon the heat exchanger proposed by Lackeby Products to handle the temperature levels and sludge composition in the digestion chamber.

The schematic design of the integration of the heat power module is presented in Figure 14, and is in essence the same as the one presented in Figure 8.

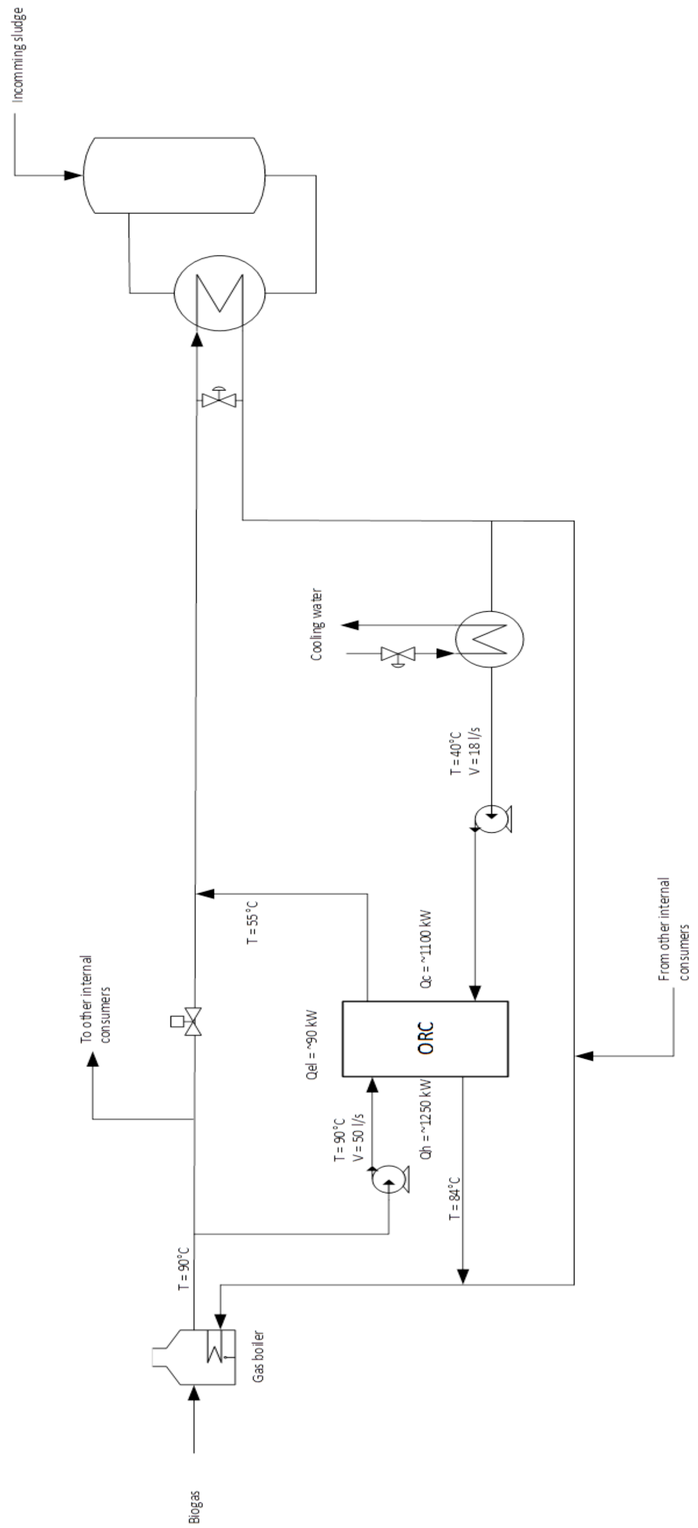

Figure 14. Schematic design heating system with integrated heat power module, where the water from the heat power module on the cold circuit has a temperature of 55°C and goes directly to the digestion chamber. Here the incoming heat is set to 1250 kW, which corresponds to about 83% of the heat power capacity.

The hot water at 90°C is pumped from downstream the gas boiler to the hot side of the ORC-module. The water evaporates the working media of the ORC-module and the water is cooled to 84°C. On the low temperature side of the ORC-module, water at 40°C is used to condense the working media of the ORC-module. The outgoing water temperature on the low temperature side is 55°C and is fed to a circulation heat exchanger over the digester.

Since the heat demand of the digester is not perfectly balanced with the heat production on the low temperature side of the ORC-module, a bypass valve needs to be installed over the circulation heat exchanger. Downstream the circulation heat exchanger the water is fed back to the gas boiler and a circulation pump supplies the required flow for the ORC-module cooling. A heat exchanger is installed upstream the circulation pump to be able to control the incoming cooling water temperature to the ORC-module.

The external cooling presented in Figure 14 comes from the water flow in the WWTP[14].

2.8.2 Electricity potential and economic calculations

Closer study of the temperature levels, based upon the temperature requirement of 55 °C, show that the actual efficiency of the heat power module is rather 7.5% than 10% as assumed in Sections 2.6 and 2.7. In the more detailed design, presented in Figure 14, we include a new heat exchanger for the digestion chamber and for external cooling with additional cost of 380 kSEK and 200 kSEK respectively.

This results in a lower electricity output and higher production cost, as seen in Table 9.

Table 9. Comparison of electricity production and cost at SYVAB with different efficiencies.

	10% efficiency	**7.5% efficiency**
Electricity production, MWh/year	710	530
Percentage of energy of flared gas turned into electricity	32	43
Production cost electricity without taxes, SEK/kWh	0.63	0.84
Cost external electricity, including certificate	0.89	0.89

By comparing the results in Table 9 we see that a more accurate calculation gives a considerably lower electrical output and thus the production cost becomes essentially the same as the cost of external electricity, even without taxes.

The results above should be interpreted in a similar way as is Section 2.7, namely that the main reasons for which the proposed system is not economically interesting for the studied case studies with the involved ORC suppliers, is that the modules used are much to large, which result in high production costs and tax on internal energy consumption. In other words, the proposed solution is believed to be economically feasible for proportionally smaller ORC modules.

[14] The temperature of the outgoing water from the WWTP is increased less than a fraction of a degree.

2.8.3 Alternative design of integration of heat power

One may argue that one could integrate the heat power in a different way to increase the electrical efficiency. One example would be to set the incoming cooling water to the cold side of the ORC to 20°C by external cooling. The outgoing cooling water flow from the cold side is heat exchanged with the outgoing water from the hot side to reach a temperature of 55°C, see Figure 15. This solution gives a higher temperature difference between the hot and cold side of the ORC-module gives a higher electric efficiency.

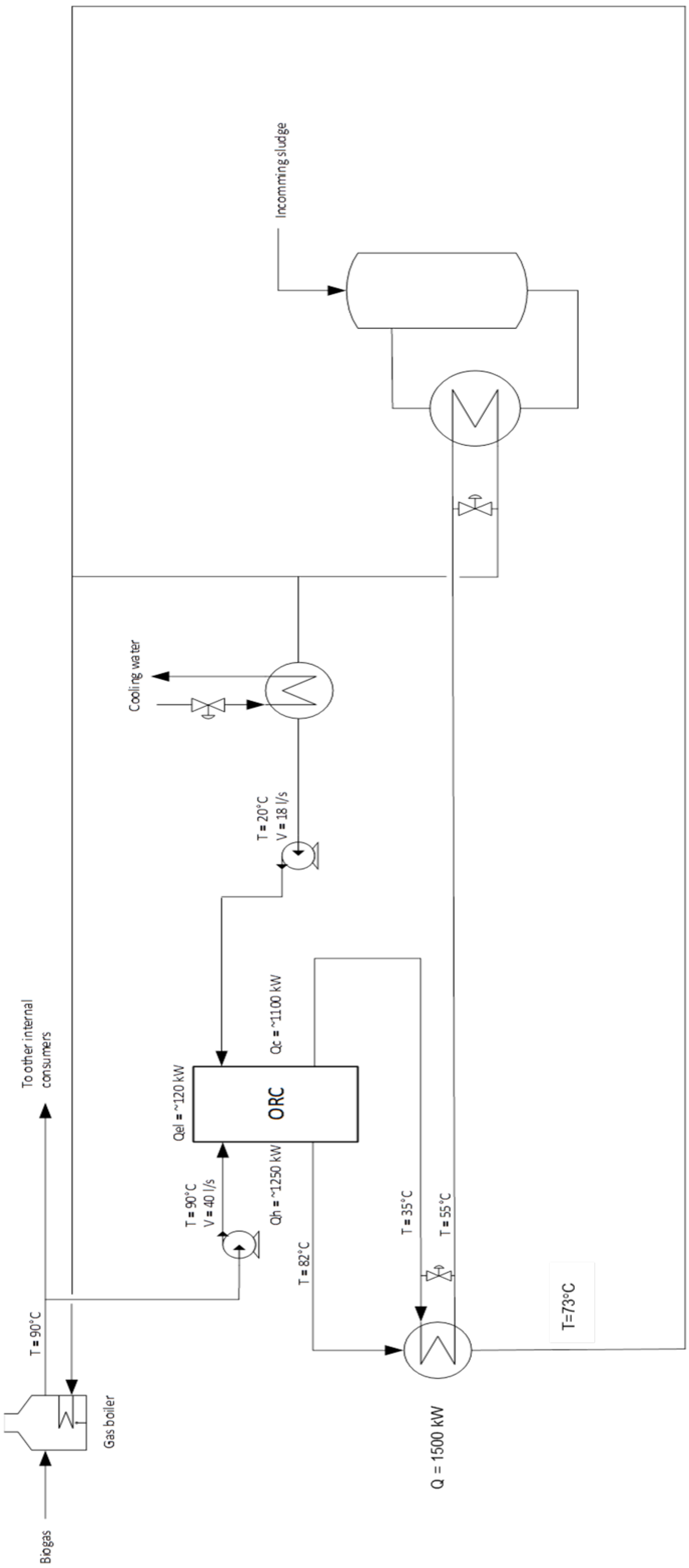

Figure 15. Schematic design of a solution, where the temperature of the water from the heat module on the cold circuit is raised to 55°C, by heating from the hot circuit, before the digestion chamber. The water on the cold circuit is then cooled against the water in the WWTP before going back to the heat power module.

In Figure 15 the outgoing water from the high temperature side of the ORC-module is heat exchanged with the outgoing water from the low temperature side. After the heat exchanger the water is fed to the digester. Downstream the digester, the water is cooled to 20°C before it's fed to the ORC-module once again.

The system design in Figure 15 has the desired efficiency of 10%, but *the total electricity output is much decreased*[15] *compared to the system design proposed above.* The main reason for this decrease can be understood by examining the heat exchanger which increases the temperature from 35C to 55C of the water to the digester, a step involves actually a larger amount of heat, about 1500 kW, than the one used by the heat power, about 1250 kW. In other words, the increased efficiency of the heat power is achieved by a decreased total amount of heat passing the module, resulting in a total decreased electricity production.

This system design is included to enlighten the importance of having a valuable use of the cold circuit.

2.9 COMPARATIVE TECHNO-ECONOMIC EVALUATION WITH OTHER ELECTRICITY SOURCES

In this section we compare the proposed system, based upon heat power, with other solutions for internal electricity production, namely conventional CHP-solutions (gas turbine and gas engine) and solar cells. The comparison is made for the case of SYVAB, for which the heat power solution is most advantageous. The other electricity production units are less sensitive to over dimensioning.

2.9.1 Conventional CHP-solutions

When dimensioning the size of the installed CHP one makes use of the highest power of flared gas. This is contrast to the dimensioning of the heat power, for which one uses the sum of the flared gas and the heat demand of the digestion chamber; a quantity that varies much less than the flared gas alone.

From Figure 12 in Section 2.5.1, we see that in June 2016, 90 000 Nm^3 was flared on the WWTP of SYVAB, which corresponds to approximately[16] 585 MWh or 810 kW gas in average. In November 20 000 Nm^3 was flared, which corresponds to 130 MWh or 180 kW gas in average. In total, about 1.7 GWh biogas is flared per year on SYVAB.

The data for the gas turbine and gas engine used in this project are budget prices obtained from Biogas Systems[17], see Table 10. This data is consistent with other prices found in literature[18].

[15] In this case the electricity output is decreased almost by half.
[16] The energy in 1 Nm3 of non-upgraded biogas is about 6.5 kWh. (13)
[17] The prices given in this report are only gross budget prices. For more correct prices, one needs to look at the specific circumstances on the specific WWTP (14).
[18] See for example (15), (16).

Table 10. Costs and efficiencies of gas turbine and gas engine, source Biogas Systems.

	Gas Turbine, 100 kWe	Gas engine, 500 kWe	Gas engine, 500 kWe	Gas engine, 500 kWe
Investment, MSEK	2.5	3.2	2.6	1.6
Maintenance and cleaning, SEK/kWh	0	0.05	0.05	0.05
Electrical efficiency	0.34	0.4	0.4	0.4
Depreciation rate, years	20	10	10	10

Gas turbine

The data for the gas turbine is summarized in Table 11, where we have included three 100 kWe gas turbines.

Table 11. Operation and installation cost of five 100 kWe gas turbines at Himmerfjärdsverket, SYVAB and the corresponding estimated electricity production cost.

WWTP (Syvab)	Gas turbine
Investment, SEK	7 500 000
Flared gas, total, kWh/yr	1 700 000
Power gas, Kw	810
Installed power, kWe	300
Interest rate	5%
Depreciation time	20
Electrical efficiency, %	34
Produced electricity (total), MWh/yr	560
Maintenance	0
Electricity production cost excluding tax, SEK/KWhe	1.07

Gas engine

The data for the gas turbine is summarized in Table 12, where we have included one 250 kWe and one 100 kWe gas engines. In the case of the gas engine, the biogas needs to be cleaned before used[19] and regular maintenance is also needed.

[19] The biogas needs to be cleaned from siloxanes and sulfuric acid, see for example (17).

Table 12. Installation and operation cost of 350 kWe gas engine at Himmerjärdsverket, SYVAB and the corresponding electricity production cost.

WWTP (Syvab)	Gas engine
Investment, SEK	4 200 000
Flared gas, total, kWh/yr	1700000
Interest rate	5%
Depreciation time	10
Installed power, kWe	350
Electrical efficiency, %	40
Produced electricity (total), MWh	660
Maintenance and cleaning, SEK/kWh	0.05
Electricity production cost excluding tax, SEK/kWhe	0.87

2.9.2 Solar cells

The cost of solar cells for electricity production has declined significantly during the last few years. Today, the investment of solar cells amounts approximately 15000 SEK/kWe and the electricity output is about 950 kWh/kW (9). The resulting production cost is 1.27 SEK/kWh excluding tax, where we have used a depreciation time of 20 years and an interest rate of 5% and no maintenance cost. It is worth noting, that when installing the solar cells, one does not make use of the wasted flared gas.

2.9.3 Summary heat power vs. Other electricity production

The Table 13 summarizes the production costs of heat power, gas engine, gas turbine and solar cells for the WWTP of SYVAB.

Table 13. Comparison of production cost of heat power with other electricity production on the WWTP of SYVAB.

	Heat power	Gas engine	Gas turbine	Solar cells
Production cost, excluding tax, SEK/kWh	0.84	0.87	1.07	1.27

In Table 13 we see that the production cost of heat power and of the gas engine are very similar and much lower than for a gas turbine and solar cells. All these production types will be subject to tax[20] and therefore none of the solutions will be commercially viable.

We emphasize, as in Section 2.7, that the main reason for which the proposed heat power solution is not commercially viable is the over dimensioning of the heat power modules by the suppliers included in the study, both in terms of production cost and taxes.

[20] The solar cell installation can be dimensioned to any desirable size. However, if it is supposed to produce the same amount of electricity as the other production types, it needs to have an installed power of about 600 kW, thus being subject to tax, see appendix 4.1.

It is worth mentioning that the calculations for the gas engine, gas turbine and solar cells are based upon bulk figures.

2.10 LOW TEMPERATURE SYSTEM BASED UPON GAS TURBINE?

In this project we have studied how a heat power module can make use of low temperature heating system for the digestion chamber and we assume that the temperature of the cooling circuit of the gas turbine is around 90°C. It could, however, be possible to decrease the cooling temperature of the gas turbine to about 55°C and use that for the digestion chamber. By considering the temperature of the steam of the turbine and its pressure, one can make estimations on how the electrical efficiency may increase if one decreases the cooling temperature. In the case of a pressure of 40 bar, the electrical efficiency may be increased from 34% to about 35% and in the case of 16 bar it would increase to about 36%, where we have assumed a steam temperature of 400°C. The more detailed study of how this would modify the total electrical efficiency and production cost is not included in this study.

It is important to realize, however, that a low temperature system, based upon a gas turbine, would still only depend on the total amount of flared gas and thus not have the same benefits as heat power regarding e.g. dimensioning and use in normal operation.

2.11 HANDLING EXCESS BIOGAS BY USING DISTRICT HEATING

An alternative way of handling the excess biogas is to replace the existing heating system, based upon internal combustion of biogas, by district heating (10). In that way not only the gas which is flared, but also the gas used for heating of the WWTP could be upgraded to natural gas standard and used for transport.

To make a comparative study to the low temperature system, based upon heat power we assume that there is an existing district heating network close to the WWTP, so that the additional cost of connecting the WWTP to the district heating network is reduced to a heat exchanger[21]. We also assume that there is an existing distribution system for the natural gas[22].

For simplicity we assume that the existing heating system is based upon a gas boiler.

The economic assumptions of the district heating solution are summarized in Table 14.

[21] This assumption is, obviously, a very severe assumption, as the connection cost can vary a lot depending on the physical distance of the WWTP to the district heating network.
[22] This will most likely be the case of WWTP, where there is already upgrading of biogas.

Table 14. Economic assumptions for district heating and upgrading of biogas.

Investment heat exchanger, SEK	500 000
Interest rate	5%
Depreciation time, year	20
Price district heating, SEK/kWh[23]	0.35
Cost upgrading biogas, SEK/kWh[24]	0.167
Price upgraded biogas, SEK/kWh[25]	0.56

We calculate the marginal revenue of replacing the heat from internal combustion of biogas by heat from the district heating, by taking the marginal revenue of the upgraded biogas divided by the efficiency of the boiler, yielding 0.49 SEK/kWh. Given that the price of the district heating is 0.35 SEK/kWh, we have a net profit of about 0.14 SEK/kWh. Considering the investment costs, we see that this solution is economically viable for WWTP with heating demands higher that about 300 MWh/year, which is quite small in terms of WWTP.

It is worth mentioning that replacing the existing heating system actually includes its rest value. This is, however, not included in this study.

It is important to realize the assumptions made above are quite rough and that a more detailed study would have to take into consideration the actual cost of upgrading, as well as the seasonal variation of the price of district heating.

[23] The price is based upon district heating prices for companies in spring/autumn with highest installed power/energy consumption. The price of district heating varies from around 200 SEK/kWh in summer to around 500 SEK/kWh in winter.

[24] (18)

[25] (19)

3 Discussion and conclusions

The project has aimed to investigate the possible integration of heat power on WWTP to make use of the excess produced biogas, which is currently wasted by flaring. The project has involved a description of how the heat power could be integrated in the heating system of the WWTP, by introducing a low temperature heating system for the digestion chamber, as well as a techno-economical evaluation of the proposed solution on three case studies at Himmerfjärdsverket (SYVAB), Klagshamn (VA-SYD) and Nyvång (NSVA) WWTPs. A more detailed investigation on actual investment costs and electricity production has been done for the case of SYVAB.

The heat power solution has been compared with other electricity production units and a different approach of how to make use of the flared gas, by substituting the actual heating system with district heating, has been discussed.

The potential electricity production and the cost per kWh excluding energy tax, are summarized below:

Table 15. The potential electricity production and the cost per kWh without energy tax

WWTP	SYVAB	VA SYD	NSVA	Unit
Electricity potential	530-710	480	80	MWh
Production cost excluding tax	0.84-0.63	1.0	5.59	SEK/kWh

The intervals for SYVAB in Table 15, corresponds to the less/more detailed calculations made in Sections 2.7 and 2.8 respectively.

From Tabell 1 - Table 15 we see that the integration of heat power in the studied cases is not economically feasible given the actual electricity price of about 0.89 SEK/kWh (including green certificate) and the tax of 0.331 SEK/kWh on internally consumed electricity. It is, however, important to emphasize that the heat power modules included in the study were very oversized, resulting in a very high production cost. Considering the production cost, when a heat power module is used to 100%, it is very likely that the proposed system becomes economically feasible, especially if the installed power < 50 kW, for which no taxes would be imposed.

4 Appendix

4.1 TAXES ON RENEWABLE ELECTRICITY IN SWDEDEN

In Sweden, the overall statement is that electricity production is taxable. The same applies for energy companies as for e.g. individuals. However, if the total installed power capacity is < **50 kWe,** exemption from tax is made. If the electricity is produced from wind, waves, solar or other energy sources, see below.

Electricity is not taxable if it:
• is produced
a) in a plant with a total installed generator capacity of less than **50 kW**,
b) by someone who possesses a total installed generator capacity of less than 50 kW, and
c) the electrical power has not been transferred to a pipeline subject to a concession granted pursuant to Chapter 2. Electricity Act (1997: 857)
• is produced and consumed on a ship or other means of transport,
• is **consumed for producing electric power,**
• is produced in an auxiliary power unit and has been transferred to a pipeline subject to a concession granted pursuant to Chapter 2. Electricity Act, or
• is produced
a) in a plant with a total installed capacity of less than **100 kW,**
b) from fuel referred to in Chapter 2. 1 § 1-6 first paragraph (not biogas),
c) by someone who possesses a total installed generator capacity of less than 100 kilowatts, and
d) the electrical power has not been transferred to a pipeline subject to a concession granted pursuant to Chapter 2. Electricity Act.

As mentioned in the first paragraph under a and b of installed generator capacity should for electricity produced from
• Wind or waves: corresponds to **125 kW** of installed generator power,
• Solar: corresponds to **255 kW** of installed peak power, and
• Another source of energy without generator: corresponds to 50 kilowatts of installed power.

If electricity is produced from various sources, the different installed power shall be added.

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MORE EFFICIENT USE OF BIOGAS AT WASTE WATER TREATMENT PLANTS

The project has aimed to investigate the possible integration of heat power on WWTP to make use of the excess produced biogas, which is currently wasted by flaring. The project has involved a description of how the heat power could be integrated in the heating system of the WWTP, by introducing a low temperature heating system for the digestion chamber, as well as a techno-economical evaluation of the proposed solution on three case studies at Himmerfjärdsverket (SYVAB), Klagshamn (VA-SYD) and Nyvång (NSVA) WWTPs. A more detailed investigation on actual investment costs and electricity production has been done for the case of SYVAB.

The techno-economical analysis for the three studied cases show that the integration of heat power modules from the suppliers included in the study is not economically feasible. It is, however, expected to be economically interesting for other suppliers with smaller heat power modules, especially for units < 50 kW which are exempt of energy tax.

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