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Implementation and evaluation of Low Temperature Waste Heat Recovery Power Cycle using NH3 in an Organic Rankine Cycle.

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ABSTRACT

With increasing cost for power generation the opportunities for small scale power generation from waste heat have increased. The awareness of untapped resources such as local waste heat streams as well as the available range of technology and products to harvest such streams is increasing steadily. For ORC power plant applications the number of open parameters is large though the reported field data is limited, particularly for low temperature waste heat recovery.

This paper presents field data and a performance analysis of an ORC power generation plant operating with NH3 as media. The ORC unit operates on waste heat from a Swedish pulp mill at an available temperature level of 75 to 85degC. Performance at low waste heat temperatures and during capacity variation is reported as well as an analysis of the particular investment case.

The field data was generated by remote logging of control system information during a 15 day period.

The results show a thermal efficiency of 8 to 9% during a capacity range of 50 to 100% power generation. The results indicate a flat thermal efficiency curve from 20 to 100% power generation.

The investment case is a supplier own-and-operate type of arrangement supplying the pulp mill with electric power at a predefined cost during a long period of time.

Nomenclature

WHR	Waste Heat Recovery
LTPC	Low Temperature Driven Power Cycle
NPO	Net Power Output (Electric work minus parasitic losses inside the defined system)
η_{therm}	Thermal efficiency (NPO/Heat rejected from heat source)
η_{cl}	Local Carnot Efficiency in an infinitesimal heat exchange between heat source and heat sink
$\eta_{c,II} = \frac{1}{n} \sum_{i=1}^n \eta_{cli}$	Integrated Local Carnot Efficiency
$FoC = \frac{\eta_{therm}}{\eta_{cl}}$	Fraction of Carnot
$\alpha_1 = \frac{1}{\left(\dot{m}_1 * C_{p1} \right)}$	Heat source inverse of thermal capacity [K/kW]

$$\alpha_2 = \frac{1}{\left(\dot{m}_2 * C_{p_2} \right)} \quad \text{Heat sink inverse of thermal capacity [K/kW]}$$

Introduction

Small scale local power generation using waste heat have become increasingly economical due to technology maturity, increased electric prices and increased competition among suppliers. In applications using waste heat below 100°C few commercial installations have been reported. Several geothermal ORC-plants using the now banned fluid R114 as well as more modern synthetic ones have been reported, such as [1. Brasz, J.J., Holdmann, Gwen. 2005] have been published.

One of the trade-offs regarding Organic Rankine Cycles, ORC, is the issue of operating fluids. The synthetic fluids, such as silicone oil, R245fa and R134a suffer from being excessively priced as well as having some environmental drawbacks. To make things worse ORC's often require large filling amounts as the heat exchangers need to be large.

Several of the ORC suppliers are therefore investigating the use of naturally occurring substances such as hydrocarbons, NH3 and CO2.

This paper show typical performance of an ORC-plant using NH3 in an industrial waste heat recovery application.

MUNKSJÖ pulp mill WHR situation

Plant facts



Fig 2. The MUNKSJÖ paper mill at Aspa.

The mill produces bleached and unbleached pulp at a capacity of 200.000tons/annum. It is located by the lake Vättern with yearly water temperatures according to Table 1

Table 1. Cooling water temperature at plant

Jan	Feb	Mar	Apr	may	Jun	Jul	Aug	Sept	Oct	Nov	Dec
3	2	6	8	13	16	21	21	14	8	5	4

Waste heat source characteristics

The heat source is a waste water stream originating from several parts of the manufacturing processes.

The waste water temperature is stable though the flow rate varies significantly. The water has to be cooled in order for the bio treatment systems to operate which is required by regulations.

The waste water contains contaminants such as lignin, fibres and other waste compounds with a PH of roughly 5,7. The relative content of waste compounds varies with fluctuations in the paper production process.

Heat sink characteristics

The chosen heat sink is a duct of lake-water already installed at the plant. A maximum rate of 720m³/h is available for cooling of the WHR-unit.

ORC power plant

The ORC power plant was supplied by Opcon under the brand name Opcon Powerbox.

Opcon Powerbox is a modularized range of ORC power plants utilizing waste heat as prime energy source, producing up to 750kWel NPO, se below.

The power plant is a self sustained “container”-type structure, fully automated and remote controlled.



Fig 1. Opcon Powerbox.

The ORC consists of a closed loop of circulating NH₃. Heat is drawn from the source by first preheating pressurized liquid followed by boiling without any superheat. The NH₃ gas is expanded to a lower pressure in a Lysholm type turbine which transfers shaft work to a synchronous electric generator. The mixture of liquid and gaseous leaving the turbine is condensed by emitting heat to the cooling water heat sink. After condensation the liquid is pumped to the higher pressure to be preheated thus completing the cycle. [2. Öhman, H. Hedeback, P. 2008]

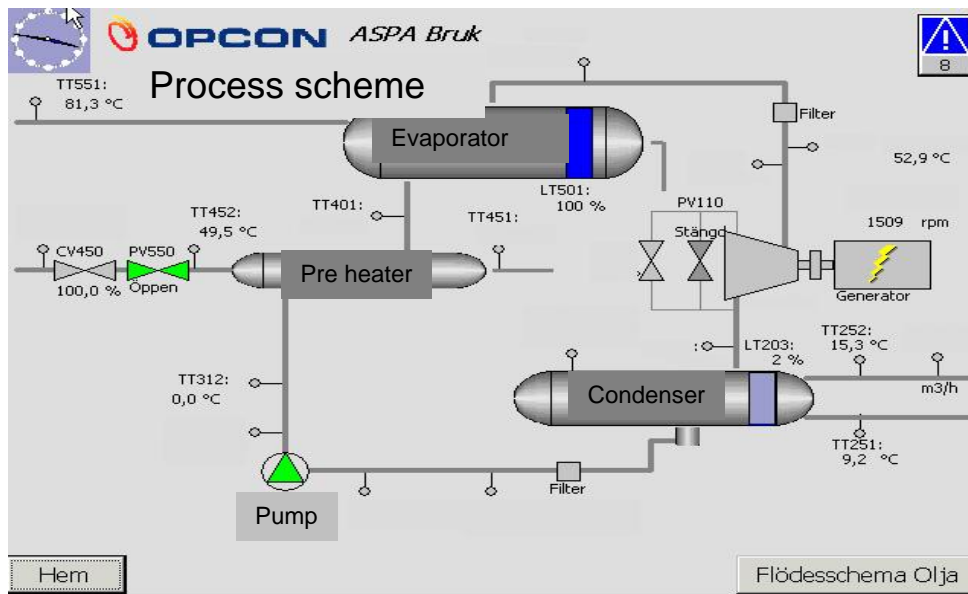


Fig 3. The ORC-system in an Opcon Powerbox.

Technical data for Opcon Powerbox ORC power plant

Power	950 kVA/50Hz	Length	11m
Voltage	500V	Height	4m
Generation	Synchronous	Width	3,5m
Media	NH3	Heat source	Waste water
Weight	27.000 kg	Heat sink	Lake water

Table 2. Technical data for the Opcon Powerbox in Aspa

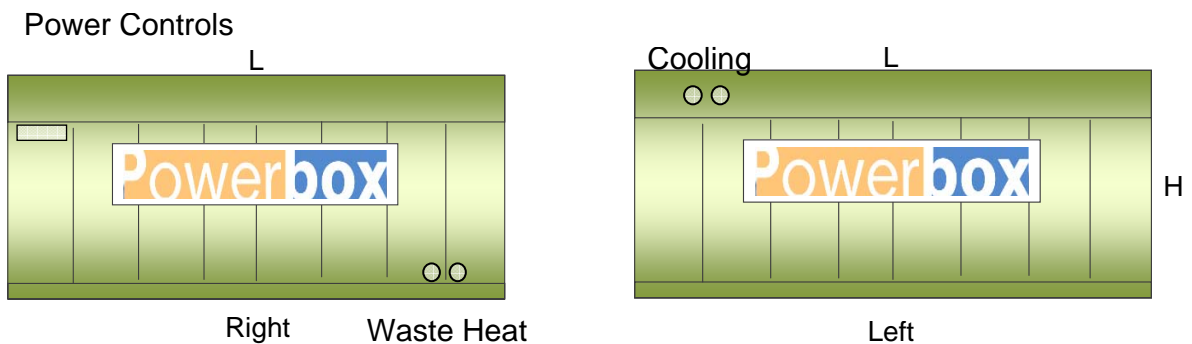


Fig 4. Schematic view of an Opcon Powerbox

Ammonia

The choice of NH₃ as the preferable operating fluid required some minor changes to the product, previously only supplied with synthetic fluids. The main changes were material compatibility of heat exchangers, pipes and polymer seals, higher class of corrosion resistance, enhanced worker safety protection and significantly more comprehensive operating, safety and service documentation.

The legal workload was mainly limited to a municipality registration of NH₃-storage, a renewed plant safety assessment and a registration at the National Energy Board for power supply to the grid net.

As the unit is remotely operated with all access points locked the safety assessment of the application became surprisingly straight forward.

Lysholm Turbine

The expansion device used in the ORC plant is a positive displacement type, twin rotary, helical body machine invented by the late Professor Alf Lysholm in the 1920's. The technology bears some generic similarities to screw compressors though the design differs significantly between a similar capacity turbine and compressor. The particular Lysholm Turbine used is designed and built by the leading industrial technology centre for screw machines and technology licensor Svenska Rotor Maskiner AB in Stockholm, Sweden. [3. SRM. 2008]

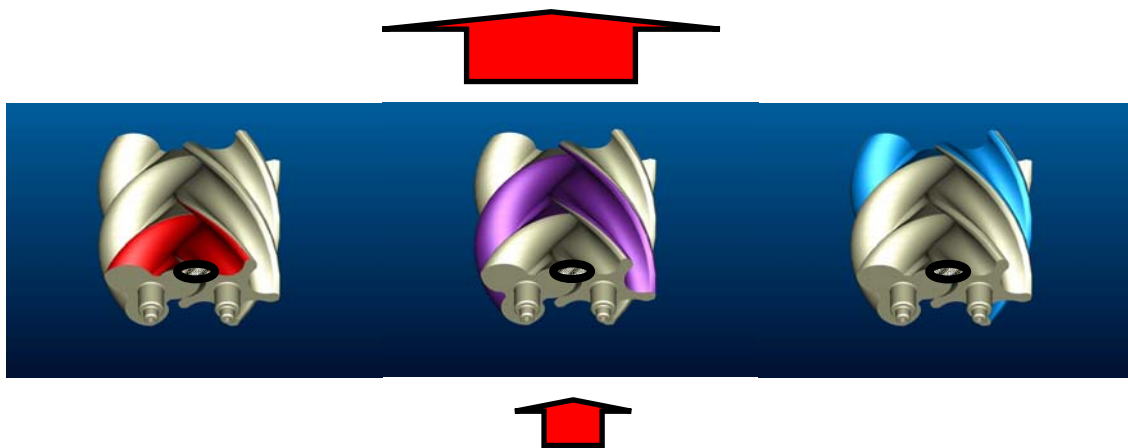


Fig 5. Visual operational mode of a Lysholm turbine. From left to right: Filling of pressurized 2-phase fluid through drilled hole in casing (oval), fluid expansion and simultaneous boiling in expansion chamber, discharge of 1- or 2 phase fluid through drilled hole in casing (backside).

The advantage with Lysholm turbine characteristics in LTPC is that the preferred operating condition is a mixture of liquid and gas. (The use of Lysholm Turbines has traditionally been limited to two-phase or three-phase humid air expansion and wet steam expansion.) This allows the ORC to operate without superheating the NH₃-gas, in turn allowing a higher boiling temperature with consequently higher system efficiency. Note particularly the insensitivity to “liquid slugging” in the case of transient operating conditions.

Another reason for the choice of a Lysholm Turbine is the relatively flat efficiency characteristics when exposed to a wide variety of operating conditions. [4. Öhman, H 2004]

In the same reference a Lysholm turbine with 100% liquid inlet fluid is reported. The turbine used in this article however was limited to max 85%, by mass, liquid inlet fluid.

The Lysholm Turbine is one of very few available multi-phase turbines in its size. Dynamic turbines suffer poor efficiency and blade wear using large contents of liquid inlet fluid. Piston motors generally suffer from “slugging” when liquid is injected. Some alternatives for multi-phase flow expansion exist for powers below 20 kW though the author was unable to find other industrially available 2-phase turbines in the same range as reported in this article.

WHR performance

After commissioning and extended performance tests the unit has been in remote, self-automated operation from the autumn of 2010.

Practical aspects

Several practical issues have been overcome during the test period, a significant such was the notoriously difficult task of measuring the waste water flow correctly. (As the variation is significant an accurate flow measurement is required in order to evaluate power plant efficiency. Unfortunately that task failed several times delaying the collection of proper data.)

The ORC power plant is installed according to the Swedish Refrigeration Industry Code rigorously addressing the validation of safety [5. KYS 2007]. As the MUNKSJÖ plant at Aspa already had experience from handling ammonia this did not cause any delays to the project.

Fouling and similar issues in heat exchangers was expected but has not been experienced up to the time of writing this paper.

Functional aspects

The power plant is fully automatic except for restart after fault alarm. In this situation the plant is started remotely by the plant central operations.

Synchronisation between the generator and the grid net is fully automatic. Starting time is 0.5 to 2 minutes to synchronisation and further 1 to 2 minutes to full load.

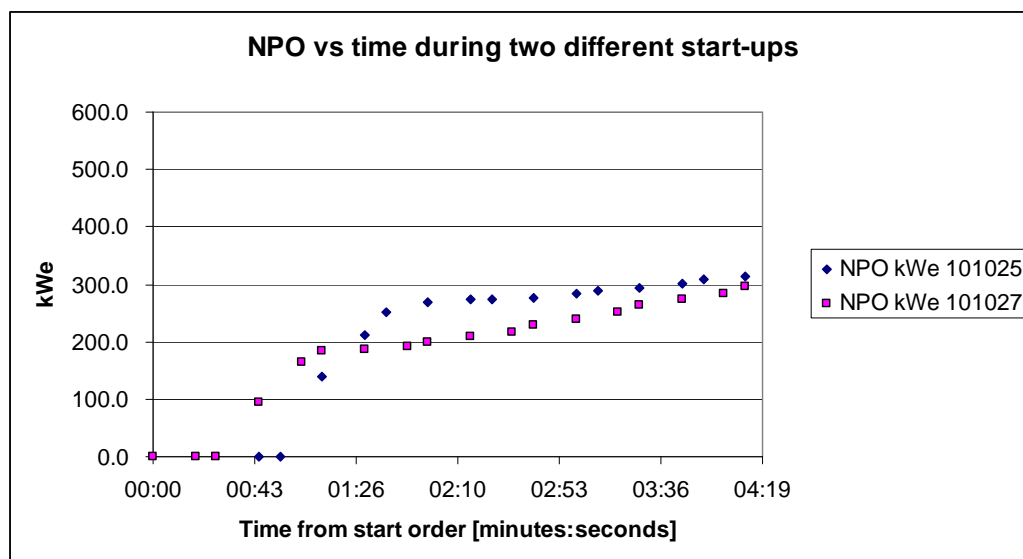


Fig 6. Start-up characteristics during two randomly chosen starts

NPO (Net Power Output) defined as measured at the walls of the ORC-unit, has exceeded predictions mainly due to the lack of heat exchanger fouling.

During the commercial operation availability has been good although the measured period was short. An analysis of the availability will be made after 12 months commercial operation.

WHR efficiencies

Electric output ratio, or thermal efficiency, is of little value in determining LTFC-efficiency with finite heat source and heat sink. *The size of the ORC has a larger impact on thermal efficiency than the quality of the process or its components, as indicated in [3].*

Therefore the Fraction of Carnot and Integrated Local Carnot Efficiency are calculated according to [6. Öhman, H. Lundqvist, P.G.].

As seen in Fig 7 the Integrated Local Carnot Efficiency varies significantly with heat source characteristics α_1 and heat sink characteristics α_2 .

Note that the Integrated Local Carnot Efficiency is a thermodynamic quality of the combination of heat source and heat sink at each particular operating condition. It is irrelevant of type of process, or efficiency of the process, used for WHR as long as it absorbs an equivalent amount of heat from the heat source.

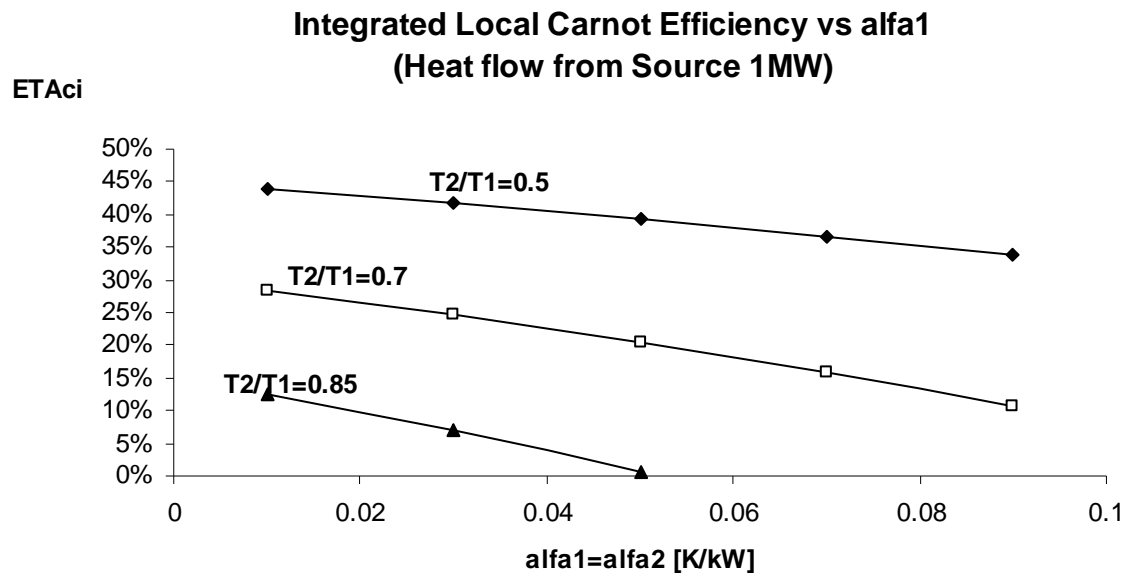


Fig 7. General visualisation of Integrated Local Carnot Efficiency vs α_1 and α_2 . T_1 and T_2 are entry temperatures [K] of a heat source and a heat sink respectively.

Fraction of Carnot is calculated at measured operating conditions by comparing the thermal efficiency with the Integrated Local Carnot Efficiency. FoC shows the true efficiency of the WHR as compared to the theoretical potential with regards only to the heat source and heat sink.

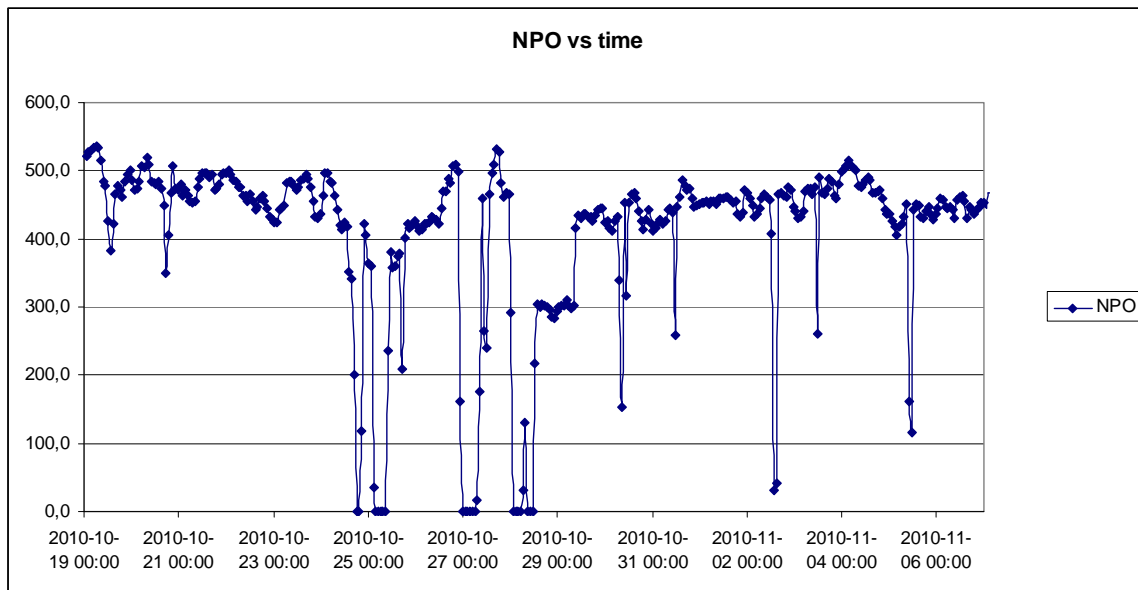


Fig 8. NPO (kW) vs time during the time studied

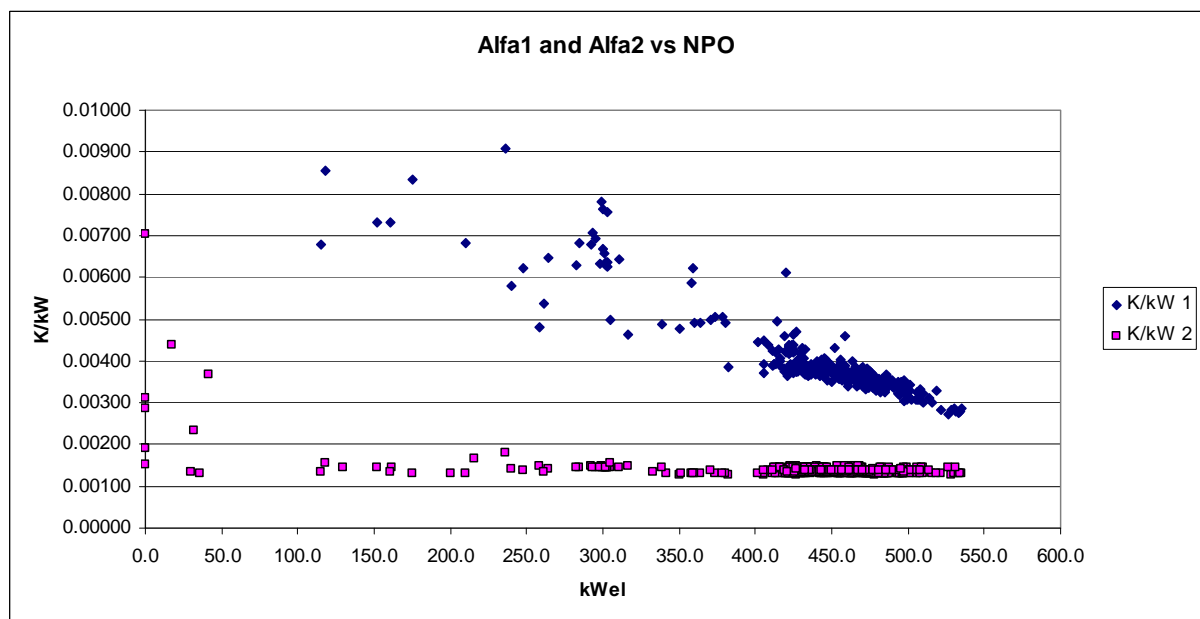


Fig 9. α_1 and α_2 vs NPO during the time period

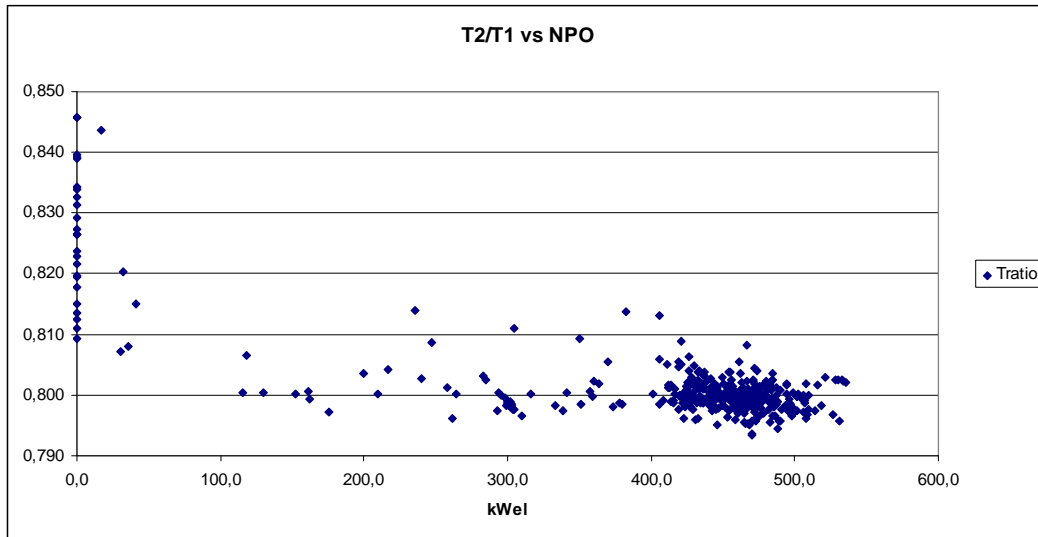


Fig 10. T_2/T_1 vs NPO during the time studied

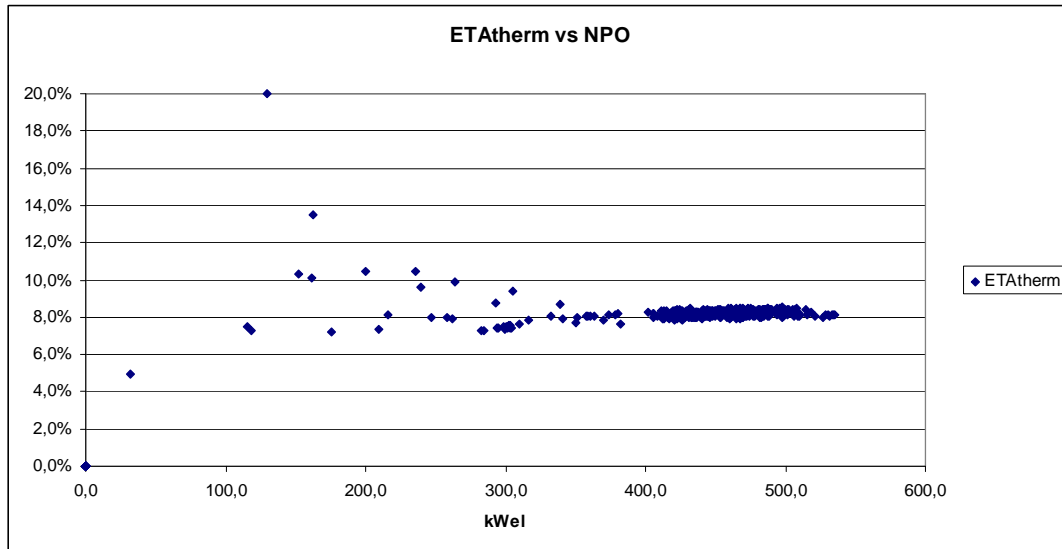


Fig 11. η_{therm} vs NPO during the time studied

From Figures 9 to 11 the following data was extracted for further analysis of the FoC.

NPO	α_1	α_2	T2/T1	η_{therm}	η_{cl}	FoC
525 kWel	0,0028	0,0013	0,795	8,2%	16,6%	49,4%
500 kWel	0,0033	0,0013	0,795	8,4%	16,5%	51,0%
475 kWel	0,0035	0,0013	0,80	8,4%	16,8%	50,0%
450 kWel	0,0038	0,0013	0,80	8,3%	16,8%	49,4%
425 kWel	0,0039	0,0013	0,80	8,2%	16,6%	49,3%

Table 3. Aggregation of the measured performance data and corresponding FoC

Evaluation of WHR efficiency

The obtained FoC can be compared to the general performance prediction of an Organic Rankine Cycle with Saturated expansion inlet ORCS.

A general simulation of FoC is performed at $\alpha_1=0,0035$, $\alpha_2=0,0013$, $T_1=82^\circ\text{C}$, $T_2=11^\circ\text{C}$ and internal process efficiencies chosen as reversible, high, average and low internal process efficiencies, se Table 4.

	Reversible	High	Average	Low	Comment
<i>External pumping efficiency</i>	100%	95%	90%	85%	<i>Ex, motor air cooling</i>
<i>Internal pumping efficiency</i>	100%	95%	75%	50%	<i>dh(isentropic)/dh(real)</i>
<i>External expansion efficiency</i>	100%	95%	90%	85%	<i>Ex, alternator air cooling</i>
<i>Internal expansion efficiency</i>	100%	95%	75%	50%	<i>dh(real)/dh(isentropic)</i>
<i>dT boiler</i>	0°C	1°C	3°C	5°C	<i>dT at critical pinch</i>
<i>dT condenser</i>	0°C	1°C	3°C	5°C	<i>dT at critical pinch</i>

Table 4. Assumed internal process efficiencies for an ORCS for reference purposes, see [6]. Efficiency is divided in to kinds: External efficiency means that heat from losses is emitted externally to the atmosphere. Internal efficiency means that heat from losses is internally absorbed by the operating fluid.

Fig12 shows the simulated results side by side with the real results from the ORC power plant in Aspa. As can be seen the result indicates that the Opcon Powerbox in MUNKSJÖ paper mill performs very similarly to a high internal process efficiency ORCS with regards to waste heat recovery efficiency.

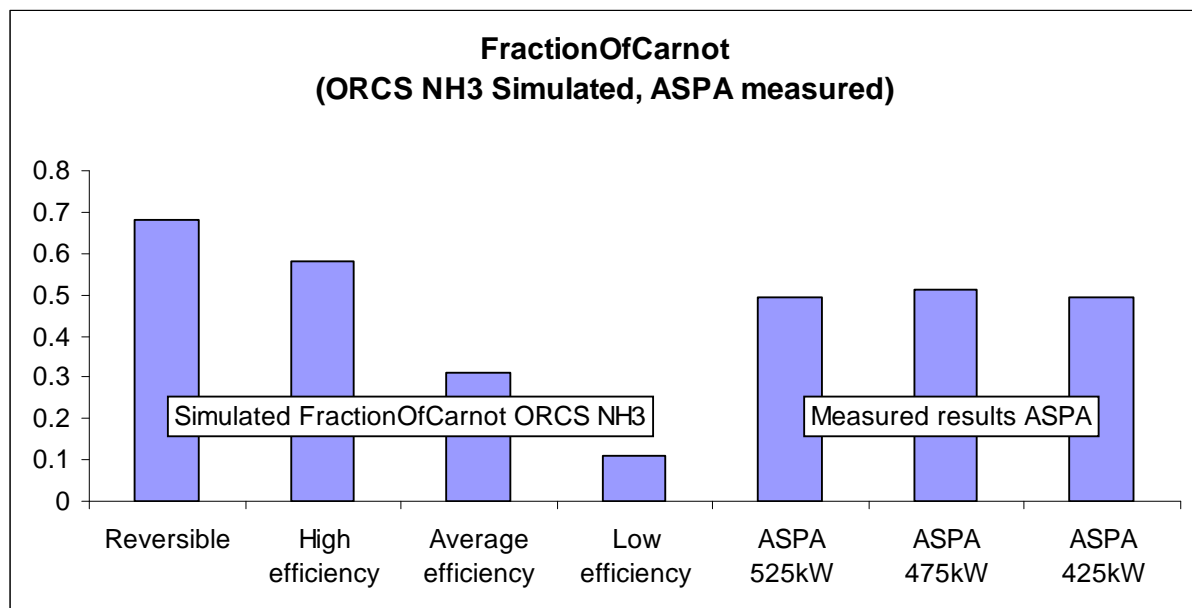


Fig 12. FoC at real operating conditions. (Reversible, High, Average, Low and Measured)

Evaluation of part load performance

The thermal efficiency vs NPO is a significant indicator on part load efficiency. Fig 11 indicates an efficiency variation of 3% in the NPO range from 100% to 65%. Though the results are less concentrated below 65% Fig 11 indicates roughly constant thermal efficiency down to 20% power generation.

Table 3 shows that in the range of 425-525kWe the Fraction of Carnot is fairly constant. As α_1 is very stable, Fig 9, this means that the system is insensitive to the variations in α_2 as shown in the same figure. α_2 represents the variations in waste water conditions.

Economy

The WHR-unit was supplied by Opcon and is owned and operated by the utility company Boxpower AB. Boxpower sells a minimum of 3133MWh/year, to MUNKSJÖ at a fixed price/kWh while MUNKSJÖ supplies a guaranteed minimum amount of warm and cold water.

This arrangement means that MUNKSJÖ is able to hedge its power costs without the necessity to invest in equipment. Furthermore it gives an incentive to Boxpower AB to operate the unit as productively as possible.

A more conventional sale/purchase arrangement was originally offered from the supplier. Though such an arrangement was fully satisfactory, enabling a Pay-off time of 3 years, MUNKSJÖ valued the opportunity to hedge the cost for electric power instead of purchasing and operating the equipment themselves.

Quotation data:

Technical life: 30 years

Costs of materials and installation: 12 MSEK

Depreciation: 10 years

Interest rate: 5%

Cost for yearly maintenance was in the same order as the savings in plant process maintenance due to the WHR-installation, therefore it could be ignored in the investment analysis. SEK/EURO exchange rate was 10,3 SEK/EURO at the time of quotation.

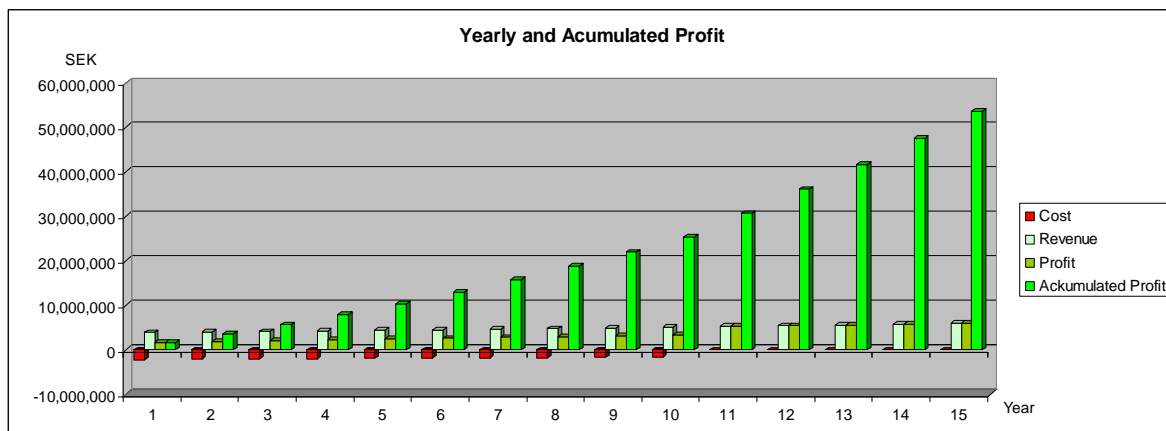


Fig 13. Investment case using quotational data calculated at electric price of 1SEK/kWh. The investment case shown is profitable from the first year of operation.

Using the above quotational information a yearly average NPO of 460kWe would give a straight Pay-back time of 3 years. Fig 8 indicates the possibility of achieving that though longer time of operation is required for that conclusion.

Conclusions

The WHR-system at the MUNKSJÖ pulp mill in Aspa, Sweden shows high efficiency, insensitivity to variations in waste water conditions and allow for a profitable arrangement between the utility company and the pulp mill.

The complexity of the waste water conditions has, until finalizing this article, not caused any trouble.

The results are encouraging with regards to the utilization of other process industry waste heat streams.

Further investigations are required after about 1 year of operation in order to evaluate availability.

References

1. Brasz, J.J., Holdmann, Gwen, Power Production from a Moderate -Temperature Geothermal Resource, paper presented at the GRC annual meeting, Reno, Nevada, September 25-28, 2005.
2. Öhman, H. Hedeback, P 2008 "Electricity from waste heat already at a low 55°C" Conference proceedings p. 228-230, World Bioenergy 2008, ISBN 978-91-927624-0-3
3. Timuska, K. 2008 "100 years of energy efficiency"
http://www.opcon.se/web/History_4.aspx
4. Öhman, H. "Test results of a screw type expander/compressor and the implication of phase separators on the refrigeration process" International Refrigeration and Air Conditioning Conference at Purdue, R025, July 12-15, 2004
5. KYS "Aggregat med Ammoniak" Säkerhetsanvisningar för kyl- och värmepumpaggregat. Svensk Kylvnorm, 2007, utgåva 1
6. Öhman, H. Lundqvist, P.G "Theory and method for analysis of low temperature driven power cycles" Journal of Applied Thermal Engineering (*In peer review at time of submitting this paper*)