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Natural working fluids for low temperature power cycles

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Abstract

This work investigated utilizing a thermal energy storage (TES) to aid production of electricity from a periodic waste heat pulse. A thermal energy storage has several effects on the electricity production, chief among them is to enable continuous power production throughout the entire period, instead of one hour of production and five hours of idle time.

Supervisor's comment to the student work:

This report summarizes Simons work during a 6-week summer internship at SINTEF Energy Research. The internship was funded by FME HighEFF. This work describes a first effort to explore both effect and implications of recovering intermittent (or highly variable) heat sources with aid of a thermal storage. The studied case is relatively abstract in nature in order to isolate the desired mechanisms. As such, the absolute values of the results on the presented form are not likely transferable to real industry scenarios.

Simon is currently working on his 5th year project thesis at NTNU within the same topic, linked to activities in HighEFF.

Memo

Power production from industrial waste heat

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1 Introduction

In 2017, the industry consumed more than half of all energy consumed on Norwegian territory [1]. As such, the emissions from the industry is considerable. 25.9% of total energy consumed in the European Union is consumed for industrial purposes, and said industry is responsible for 47.7% of CO2 emissions [2]. Thus, increasing energy efficiency and reducing emissions from the industry should be a priority to combat the ever increasing emissions and global temperatures.

A byproduct of a lot of industrial processes is waste heat. If there are no cost effective options for handling this heat, it is often released into the ambient. Options for dealing with the waste heat could be to meet a local need of heating, supplying the waste heat to a district heating network, or to use the waste heat to produce power.

Research Area 3 (RA3) of the FME HighEFF has been investigating the possibility of converting waste heat to electricity using a(n) (Organic) Rankine Cycle. This could increase the utilization of the process heat, reduce heat released to the ambient, and produce electricity to be used internally or possibly be sold onto the electrical grid.

Industrial waste heat sources are not necessarily constant. Depending on the industrial process, the waste heat might fluctuate. The process might periodically release bursts of high temperature, or the process might only produce waste heat in certain intervals. This fluctuation could prove challenging for the Rankine cycle. To implement a power cycle utilizing the waste heat, one would need to decide on the design parameters of the cycle. This includes heat exchanger and expander geometries and sizes, as well as working fluids. A fluctuating heat source would cause the components to not operate at design point most of the time, which would lead to a Rankine cycle less efficient than expected. Off-design operation could also lead to a shorter than expected lifespan for the components in the power cycle. A fluctuating heat supply would also lead to a fluctuating electricity generation, which is not ideal.

To reduce the impact of a varying heat source, a thermal energy storage (TES) could be introduced between the waste heat and the Rankine cycle. The energy storage could act as a buffer, flattening out peak heat loads and supplying the excess heat to the Rankine cycle once the waste heat supplied is less than design heat load. If the waste heat is periodic, only releasing heat at certain intervals, a TES might be the only option for power generation, as constantly switching on and shutting off the process could be a real strain on the lifetime of the system.

1.1 Topic of summer project

The main focus of this summer project was to investigate the impact a thermal energy storage has on a the production of energy from waste heat using a Rankine cycle. To amplify the impact of the TES, a heat pulse was chosen as heat source. The heat source is periodic, and delivers heat for one hour every six hours. This kind of heat source would necessitate a thermal storage to ensure continuous operation. Figure 1 and Table 1 describes the parameters of the heat source.

The summer project consisted of me looking into several aspects of this system

- Model the thermal energy storage using Excel

Table 1: Heat source parameters

	Value	Unit
Heat source temperature, T_1	600	°C
Ambient temperature, T_{amb}	10	°C
Heat source energy content, mc_p	1.667	$\frac{kW}{K}$
Heat source time period	6	hours
Heat source delivering heat	1	hours
Heat source not delivering heat	5	hours

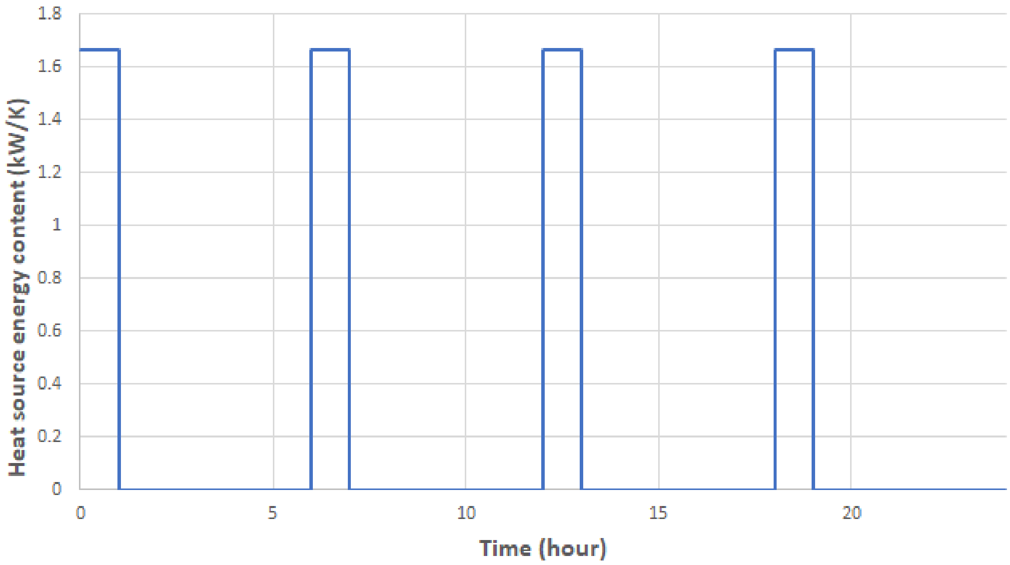

Figure 1: Heat source

- Use the TES model results to investigate the power generation of the system, using a in-house Rankine cycle simulation tool.
- Investigate the effect of off-design operation
  - Losses related to off-design operation
  - At what conditions to design the system
- Consider options to ensure a more stable power generation
- Practical considerations
  - Effect of storage capacity
  - TES material
  - Heat losses and insulation

2 Method

The system consisted of a waste heat source transferring heat to a TES through a heat exchanger. The TES was connected to the evaporator of a power cycle. The power cycle consisted of three heat exchangers: the aforementioned evaporator, a recuperator, and a condenser. The working fluid was chosen as CO2, and as such the Rankine cycle was transcritical. The recuperator is not a necessity, but the inclusion of a recuperator in transcritical CO2 cycles has been shown to increase net power by 10% [4]. The system is shown in Figure 2.

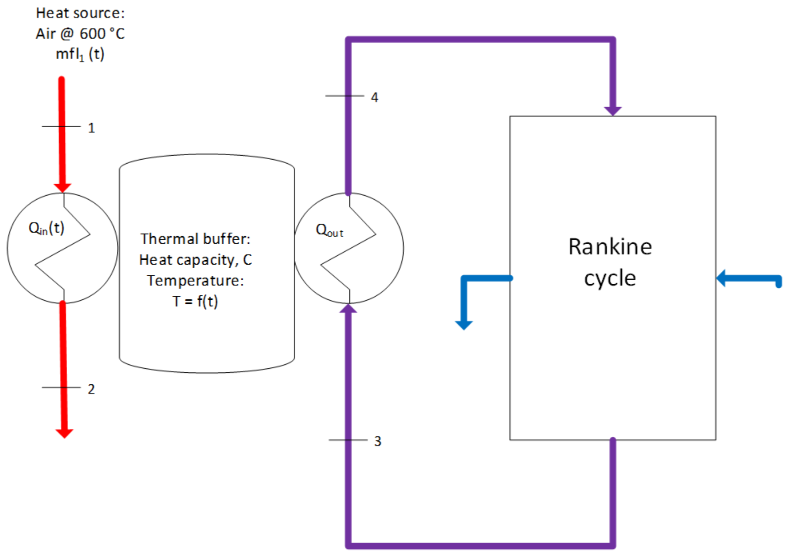

Figure 2: Overview of the system

2.1 Thermal Energy Storage

2.1.1 Theory

Thermal Energy Storage technologies is a wide range of technologies designed to store excess thermal energy to be used at a later time. The thermal energy could be stored for hours, weeks or months depending on the storage technology used and application intended for the heat stored. There are three types of thermal energy storage. Sensible, latent and thermo-chemical heat storage [3].

Latent heat is the heat absorbed or released by a material during phase change. This heat will be released and absorb at a constant temperature (single component systems or azeotropic mixtures), either the temperature of evaporation/condensation or melting/freezing, depending on whether the material changes phases between solid and liquid or liquid and gas.

Sensible heat storage is heat stored in a material by heating said material without phase change. As there are no phase change present, the heat will absorb and release at gliding temperatures. Sensible heat storage is usually a liquid or a solid, and the amount of heat stored is dependent on the amount of material used and the specific heat of the material. Assuming c_p is constant, the sensible heat stored is governed by Equation 1.

$$Q = m_s \int_{T_L}^{T_H} c_{p,s} dT = C \left(T_H - T_L\right) \tag{1}$$

where m_s is the mass of the storage material, T_L and T_H is the temperature range of the storage, and $c_{p,s}$ is the specific heat of the material. Throughout this summer project, $C = m_s C_{p,s}$ has been used to describe the thermal storage capacity of the TES.

Thermo-chemical storage is heat stored using reversible chemical reactions involving adsorption and release of heat.

Sensible heat storage was chosen for this project. Sensible heat was chosen due to a need for simultaneous waste heat absorption and release. The waste heat source is periodical, and with parameters as outlined in Figure 1, there is up to 983.53 kWh of heat released during the first hour of each period, if transferred between 600 °C and the ambient. The TES needs to store (some of) this energy, and release it to the power cycle during the entire 6 hour period. This entail that the TES need to absorb heat and release a portion of it during the first hour of each period, and release the rest of the heat absorbed during the next 5 hours.

The amount of heat absorbed by the storage is highly dependent on the change in temperature of the waste heat source. Heat transferred from the waste heat source is described by by Equation 2,

$$\dot{Q}{=}mc_p\left(T_1-T_2\right) \tag{2}$$

where mc_p is the heat source energy content, T_1 and T_2 is the temperature at point 1 and 2 in Figure 2, namely the temperature of the heat source before and after heat has been transferred to the TES. As seen in the equation, a low temperature in the TES will increase the possible heat the heat source can release to the storage, while maintaining a high storage temperature limits the amount of heat the TES can recieve.

An important aspect of the storage is to ensure that each period is identical. To make certain of this, the temperature of the storage must be the same at the beginning of each period. This entails that the temperature at the beginning must be equal to the temperature at the end of each period. To achieve this, one can study the control volume around the TES (Equation 3),

$$\varDelta Q_s{=}C\left(T_H-T_L\right)=\sum Q_{in}-\sum Q_{out} \tag{3}$$

where $\varDelta Q_s$ is the change in heat during the period, as described by Eq. 1. If all heat absorbed by the TES during one period is released during the same period, there will be no net accumulation of heat, and the initial temperatures of each period will remain the same.

2.1.2 TES model

To simplify the dynamics of the storage, the TES was modelled using the lumped capacitance assumption. Lumped capacitance neglects the temperature gradient in the solid medium by assuming that the resistance to thermal conductivity in the storage medium is small compared to the resistance to heat transfer between the storage medium and its surroundings. By using this assumption, the storage temperature will remain spatially uniform, while still varying with regards to time. The lumped capacitance model can be expressed as following:

$$C\frac{dT_s}{dt}{=}\sum\dot{Q}_{in}-\sum\dot{Q}_{out}{=}\dot{Q}_{in}-\dot{Q}_{out}-\dot{Q}_{loss} \tag{4}$$

where T_s is the storage temperature, $\dot{Q}_{in}$ is the heat transferred from the heat source to the TES, $\dot{Q}_{out}$ is the heat transferred from the TES to the power cycle, and $\dot{Q}_{loss}$ is the heat loss between the storage and the ambient. The heat loss was initially neglected, but is revisited in section 3.4.3.

The model was modelled in Excel using a forward, explicit Euler method to solve Equation 4. This model was created with the assumption that $\dot{Q}_{out}$ can be varied independent of the storage temperature. Using Eq. 2 and the equation governing heat transfer in a counter flow heat exchanger, Equation 6 was derived to find an expression for T_2. Equation 7 was constructed using Euler to find the temperature profile of the storage.

$$mc_p\left(T_1-T_2\right){=}UA\times LMTD{=}UA\frac{\left(T_1-T_s\right)-\left(T_2-T_s\right)}{\ln\left(\frac{T_1-T_s}{T_2-T_s}\right)} \tag{5}$$

$$\Rightarrow T_2{=}T_2+\ \left(T_1-T_s\right)e^{-\frac{UA}{mc_p}} \tag{6}$$

$$\begin{aligned} T_{s,n+1} &= T_{s,n}{+}\frac{dT_{s,n}}{dt}\varDelta t \\ &= T_{s,n}+\frac{1}{C}\left(Q_{in,n}-Q_{out,n}\right)\varDelta t \\ &= T_{s,n}+\frac{mc_p\left(T_{1,n}-T_{2,n}\right)-Q_{out,n}}{C}\varDelta t \end{aligned} \tag{7}$$

Here Δt is the iteration time step, UA is the UA value of the heat exchanger transferring the heat to the TES from the heat source. This parameter was set to 4 kW/K for the entirety of this project. The n and n+1 subscript represents the iterations of the Euler method. Also notice that $\frac{dT_{s,n}}{dt}$ can be found from Eq. 4 (while neglecting Q_{loss}), while $Q_{in,n}$ can be found from Eq. 2. Losses were later introduced by modeling heat loss from the storage as a heat exchanger between the storage and the ambient

$\dot{Q}_{out}$ was decided through user input, while $\dot{Q}_{in}$ is a direct consequence of the temperature in the TES. Thus, the model could not ensure a periodic heat balance around the thermal storage. Therefore, the Excel optimization tool Solver was used. Solver was tasked with optimizing either the initial storage temperature or $\dot{Q}_{out}$ to ensure that the initial and final temperatures match, ensuring periodic heat balance.

2.2 Exergy

The amount of thermal energy in a heat stream that can be converted to electricity is heavily dependent on the temperature of the heat stream and the temperature of the heat sink. Together, they place an upper bound to the fraction of heat that can be converted into electric power. A measure of this energy is exergy, which is the maximum amount of usable work a system can theoretically produce. The carnot efficiency is a measure of the fraction of useful work in a heat source at a given temperature. While it is not possible to reach cycle efficiencies similar to those of carnot cycles, they can be used to represent the potential work output from a heat source. Using the carnot efficiency as a basis, the exergy of a heat stream is given in Equation 8.

$$\dot{E}_x = \dot{Q} \times \frac{T_H - T_L}{T_H} \tag{8}$$

2.3 Power Cycle

The power cycle was a transcritical recuperated Rankine CO2 cycle. Being a transcritical cycle, it operated both in the sub critical and super critical region. As such, the condenser pressure was below the CO2 critical pressure of 73.8 bar, while the condenser pressure was considerably higher. As a a recuperated cycle, it contained a recuperator, meant to utilize the heat in the expander outlet. By integrating the hot exhaust gas from the expander with the colder high pressure CO2 at the pump discharge, it is possible to preheat the CO2 to increase cycle efficiencies.

A numerical tool was utilized to model the behavior of the cycle. The tool is a power cycle optimizer developed by SINTEF Energy Research. It is designed to find the optimal working conditions to maximize the net power output from the cycle. The power cycle parameters can be constrained, defined as a set value, or be decided by the optimizer tool. The model can not model transient cycle behaviour, only the steady state performance of the system. An in depth description of the optimizer tool was written by Hagen [4].

In this project, the tool was utilized for two different purposes: To find the optimal power cycle design given a certain heat source temperature and heat content, and to find the power output when the power cycle design was fixed and the power cycle operated at conditions other than its design point. As such, the parameters decided by the optimizer would vary depending on the purpose of the simulation. When finding the optimal design, the model would design the system to achieve a pinch point of 10°C/5°C/5 °C in the evaporator, condenser and recuperator, while varying heat exchanger area, working fluid mass flow and pressure levels. When considering off-design operation, the model was not to design the system anew, therefore heat exchanger area was not to be changed. With the system already designed for different heat loads and temperatures, heat exchanger pinch would not be fixed to its design specification. A complete list of optimizer parameters is shown in Table 2.

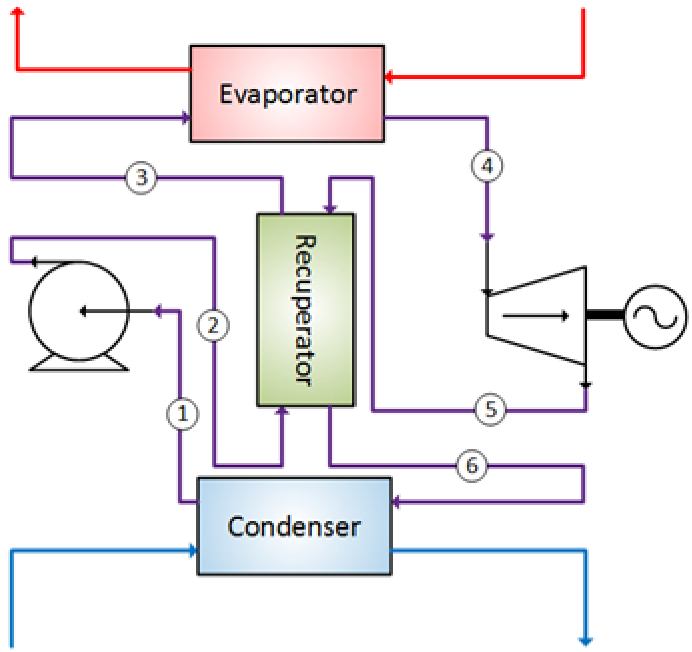

Figure 3: Model of the recuperated Rankine cycle

The heat load and temperature onto the Rankine cycle were variable, but the model could not model transient behaviour. To simulate power generation from a thermal storage with varying temperature, there was a need to discretize the the temperature and heat delivered to the power cycle from the TES. Then, one could simulate the power cycle once for each discrete point. At each point, one could log the net power produced, power cycle parameters, calculate the amount of exergy in $\dot{Q}_{out}$ and find efficiencies. An approximation to total electrical energy produced during one period was found as the time integral of power produced in each discrete point, calculated using the trapezoid method.

3 Results

In this section, the results attained throughout the duration of the project work will be listed and relevant figures will be shown. Unless otherwise specified, all results listed will have used a thermal storage with storage capacity of C=10000 kJ/K.

3.1 TES temperature profile

With a fixed thermal storage capacity, it was shown that the heat load onto the power cycle had a large effect on the temperature profile of the storage. As shown in Figure 4, increasing the heat output from the TES would decrease both initial and max temperatures, as well as increase the temperature rise of the storage. It also showed that for a given storage capacity, the initial storage temperature is directly linked with its $\dot{Q}_{out}$. Figure 5 shows a selection of temperature profiles and and the power produced from said storages throughout a single six hour period.

3.2 Power cycle

3.2.1 Constant $\dot{Q}_{out}$

As noticed in section 3.1, the temperature profile of the storage was heavily dependent on the fixed $\dot{Q}_{out}$. The performance of a Rankine cycle will vary with temperature, with higher expander inlet

Table 2: List of model parameters

	Optimal design	Off -design
High pressure	Variable	Variable
Low pressure	Variable	Variable
Expander inlet temperature	Set	Variable
Working fluid mass flow	Variable	Variable
Recuperator capacity	Variable	Variable
Evaporator pinch	$10\ °C$	Variable
Condenser pinch	$5\ °C$	Variable
Recuperator pinch	$5\ °C$	Variable
Total UA value	Variable	Set
Evaporator UA value	Variable	Set
Condenser UA value	Variable	Set
Recuperator UA value	Variable	Set
Off-design expander model	No	Yes
Heat sink mass flow	$2\ \frac{kg}{s}$	$2\ \frac{kg}{s}$

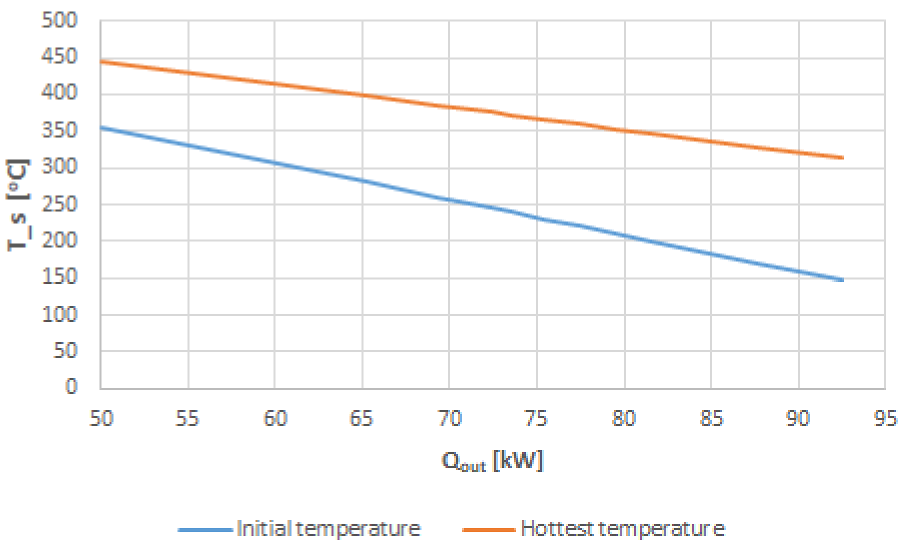

Figure 4: Periodic cold and hot storage temperature with varying $\dot{Q}_{out}$

temperatures associated with higher cycle efficiencies. As such, it would be beneficial to increase storage temperatures. On the other hand, an increase in storage temperatures would lead to a decrease in the heat load, which would not be beneficial to the power cycle. Figure 6 shows total electricity production during one heat source period at different heat loads, and it visualizes the trade off between cycle temperature and heat load. An increase in the heat load will cause an increase in total electricity produced, until temperatures have decreased to such a degree they hinder cycle efficiencies and decrease power production. At a storage capacity of 10000 kJ/K, the optimal fixed $\dot{Q}_{out}$ was found to be 73.5 kW, where total periodic electricity production reached 99.78 kWh.

As seen in Figures 5 and 7, the power produced throughout the period is not constant. It will vary with the changing storage temperature. Thus, to help reduce the change in power produced one could reduce the heat load, at the cost of some loss of produced electricity.

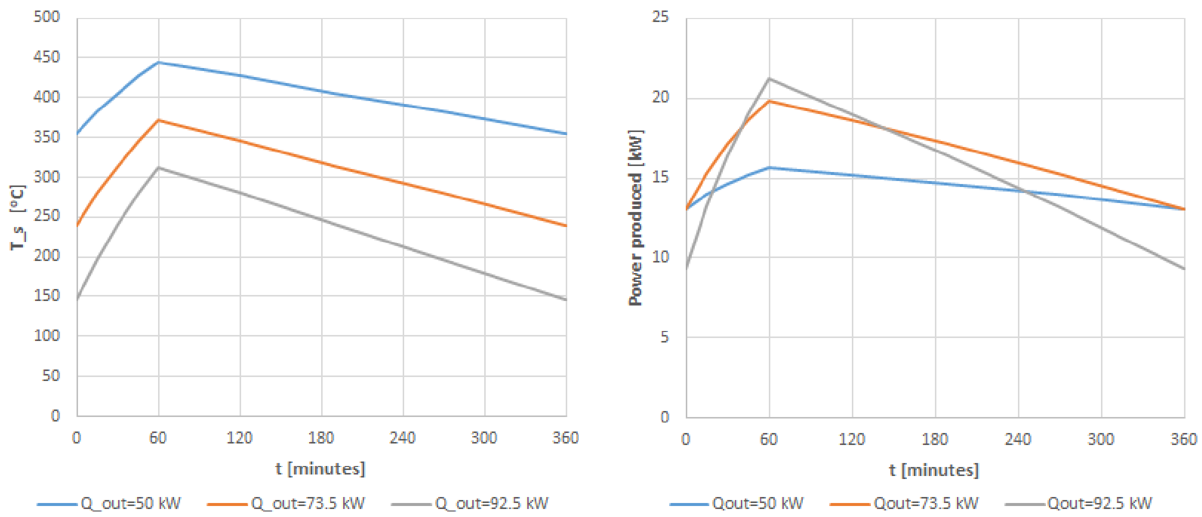

Figure 5: TES temperature profiles and power produced

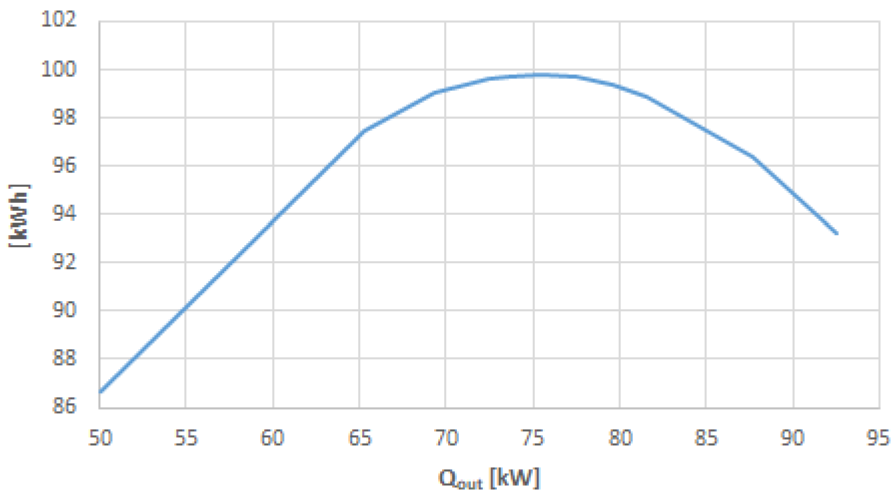

Figure 6: Total electricity produced during a 6 hour period with a fixed $\dot{Q}_{out}$

3.2.2 Variable heat load

To help reduce the periodic variations in power produced, a variable $\dot{Q}_{out}$ was introduced. The variable heat load was meant to counteract the changing power consumption due to a changing storage temperature. $\dot{Q}_{out}$ was increased at low storage temperatures and decreased at hotter storage temperatures. In section 3.2.1, a heat load of 73.5 kW was found to be associated with peak electricity production, given a storage capacity of 10000 kJ/K. A $\dot{Q}_{out}$ of 73.5 kW means a total of 441 kWh of heat was stored and released by the TES in each period. Therefore, it was decided to design the variable heat load in a way kept total heat at 441 kWh.

During the project work, there were a focus on two variations of variable heat load. The initial variable heat load was a simple linear variation. It would decrease in a linear fashion during the first hour of each period and then revert to its initial condition during the next five hours. The other variable heat load was modelled as a second degree polynomial, reaching is minima after one hour, then increasing at a rate five times slower during the rest of the period. The four most interesting cases are shown in Figure 8 and Table 3, where case 1 and 2 have linear heat profiles, while case

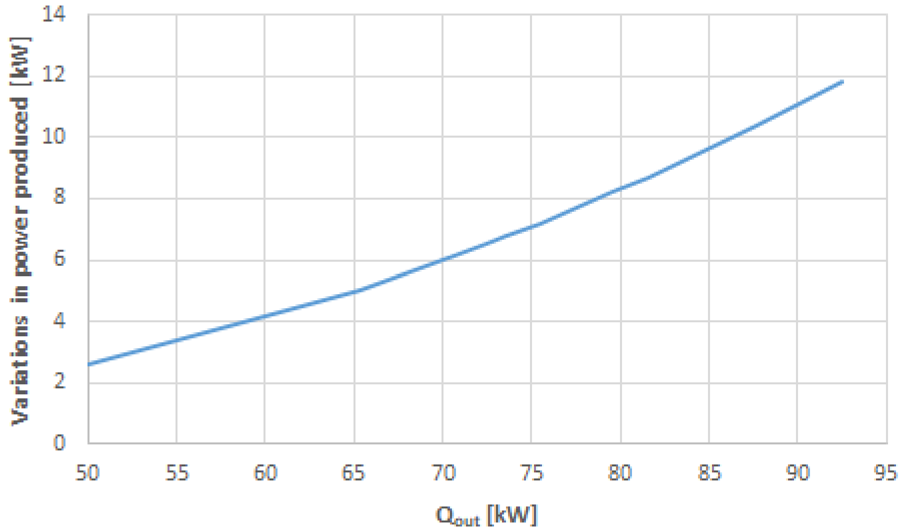

Figure 7: Maximum difference in power produced throughout a period.

3 and 4 have polynomial profiles. In all four cases, a variable heat load is shown to reduce the the periodic power production variations, while at the same time somewhat reduce total energy produced during the period. There were no instances found of a variable heat load managing to produce more electricity than that of a constant $\dot{Q}_{out}$.

As long as total heat output and input was kept at 441 kWh, the temperature profile of the TES changed little compared with instances with a constant heat load. Initial temperatures and the temperature rise of the TES changed less than 1 $°C$ compared to simulations with a heat load of 73.5 kW. The variations in temperatures during the period was at most 11 °C.

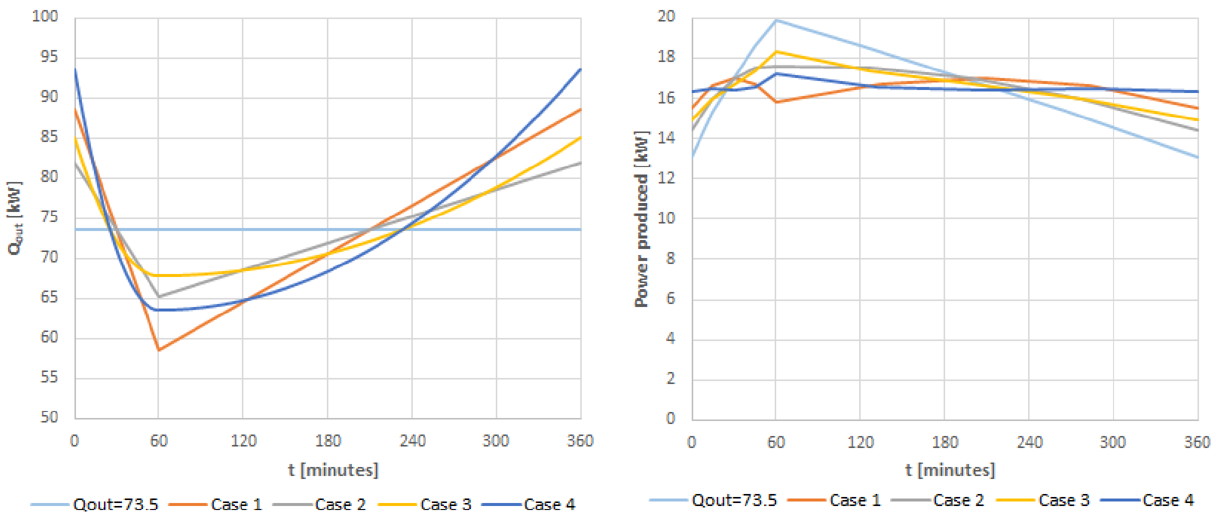

Figure 8: Four cases of variable $\dot{Q}_{out}$ and power produced

3.2.3 Off-design simulation

Until now, the effects of off-design operation has been neglected. Introducing these effects had a negative effect on the performance of the power cycle. Once the system operated away from its design point, expander isentropic efficiencies was reduced and the system had to deal with heat

Table 3: Key values from simulations with variable $\dot{Q}_{out}$

	Shape	$\Delta\dot{Q}_{out}$ $[kW]$	$\Delta\dot{W}$ $[kW]$	W $[kWh]$
$\dot{Q}_{out}$=73.5 kW	Flat	0	6.77	99.73
Case 1	Linear	15	1.45	98.93
Case 2	Linear	16.32	3.17	99.41
Case 3	Polynomial	17.27	3.36	99.62
Case 4	Polynomial	30	0.84	99.37

exchangers designed for other heat loads and temperatures than those present. In Figure 9, off-design simulations was conducted with a fixed $\dot{Q}_{out}$=73.5 kW. Key values are shown in Table 4 The three cases are designed for the coldest possible temperature (t=0 min) of the TES, the warmest storage temperature (t=60 min) and halfway through the heat accumulation period (30 minutes into the period).

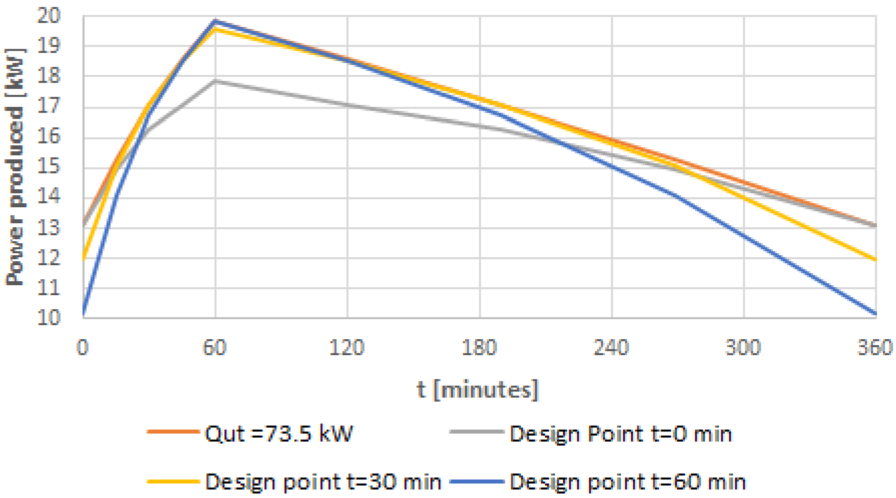

Figure 9: Off design simulations with constant $\dot{Q}_{out}$=73.5 kW

Table 4: Key values for a off-design simulation with a fixed heat load

	$\Delta\dot{W}$ $[kW]$	W $[kWh]$	UA $[kW/K]$
Design point at 0 min	4.7432	94.64	10.21642
Design point at 30 min	7.6347	98.03	9.578497
Design point at 60 min	9.667	94.5569	9.22331

In each case the cycle efficiencies declined once operating conditions moved away from the design point. The tendencies shown in Figure 9 was present for all off-design simulations using constant heat loads. The reduction in power produced was more prominent in cases with a higher heat load (and thus higher change in storage temperatures). With a heat load of 92.5 kW, the power produced declined with up towards 9.34 kW at certain test conditions. With a heat load of just 50 kW, the worst declination in produced power was merely 2.9 kW. However, net electricity produced was far lower in the 50 kW case, still making a heat load of 73.5 kW the best alternative

To maintain the highest power production throughout the period, having the design point half way through the heating of the TES proved most beneficial. However, to reduce variations in produced power, another alternative could be to to place the design point at the conditions present at the beginning of each period. The reduced difference in power produced comes from losses far from design point, which in this instance is where the storage is at its hottest and the power cycle produces the most amount of power. While this choice of design point will reduce variations in power produced, it will at the same time reduce total electricity produced. Also shown in Table 4 is the varying UA values. With a non-variable heat load, the heat exchanger at design point changed little, but decreased a bit with an increase to temperature. Higher UA values is related to greater heat exchanger area, increasing cost.

Similar off-design simulations were conducted with variable heat loads. The results proved similar to the results with constant heat loads, albeit with some differences. As with the constant heat load scenarios, the performance of the cycle tended to drop once operating conditions moved away from design point and power production was most stable when designed for the colder temperature conditions of the TES. However, UA values were found to differ more than in earlier simulations. This was a consequence of the heat load increasing during colder conditions, requiring greater heat exchanger area, and decreasing at hot conditions, requiring less heat exchanger area. Designing this cycle for the warmer part of the temperature profile proved to not be viable, as the decline in power produced during the colder parts of the temperature profile proved to be substantially larger than other design points. Figure 10 and Table 5 shows an example off variable off-design simulations on case 4 from Table 3.

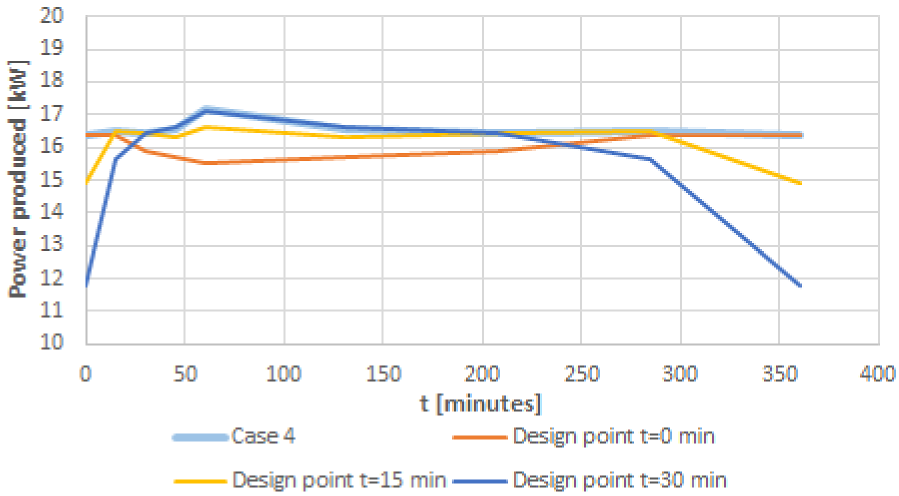

Figure 10: Off design simulations of case 4

Table 5: Key values for off-design simulation of case 4

	$\Delta\dot{W}$ $[kW]$	W $[kWh]$	UA $[kW/K]$
Design point at 0 min	0.87	95.97	12.64475
Design point at 15 min	1.73	97.55	10.68851
Design point at 30 min	5.29	94.69	9.316254

For case 4, designing the system for its coldest temperature resulted in only 0.87 kW variation in power produced during a period, which was the best attained result for a off-design power cycle found in this project. In addition, simulations on case 3 showed that a design point at 15 minutes into the period resulted in 98.29 kWh produced, with a variation of 3.67 kW. During this project work, no other off-design case managed to produce more electricity in a period.

3.3 Power production without TES

While heat to power production from this waste heat source without a TES would prove challenging, power produced from such a scenario was still of interest. By changing the heat source to represent a scenario without a TES, but using the same optimizer constraints as employed in the simulations with heat storage, the optimizer tool would find design that were not comparable with the designs found when employing a TES. There were two reasons for this. The UA values found were 7-8 times higher than the values used in simulations with a TES. In addition the temperature rise in the sink would be in the rage of 50-60°C. The mass flow in the sink was increased from 2 to 10 kg/s to limit heat sink temperature rise, while the total amount of heat exchanger area were constrained with an upper bound. Figure 11 shows how power production without a TES will vary with available total UA value. The highest UA value was 73.9 kW/K, the unconstrained UA value found by the optimizer tool. The increased UA value and working fluid mass flow has to be seen in relation to the increase in the amount of heat delivered from the heat source. Where scenarios with a TES had heat loads mostly ranging from 50 to 100 kW, scenarios without a TES ranged from 480 to 620 kW.

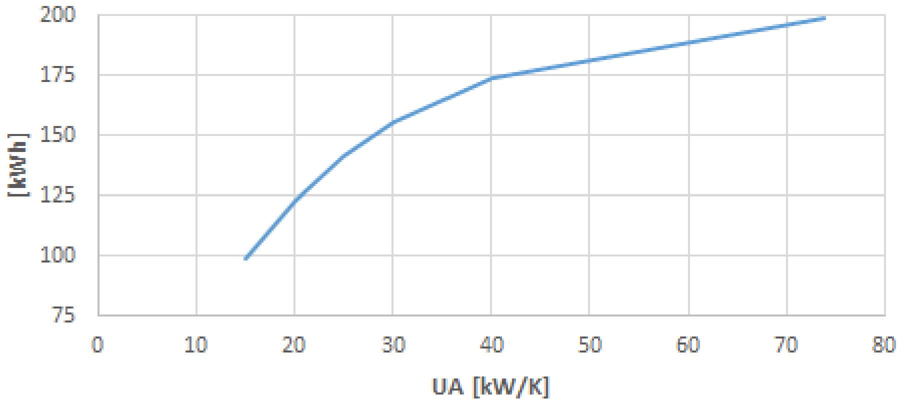

Figure 11: Total electricity produced without TES in a single period, as a function of total UA value used by the power cycle tool

3.4 TES practical considerations

3.4.1 Storage capacity

Another important aspect of this system is the capacity of the thermal storage. A larger capacity will be able to store more energy, or store the same amount of energy with less change in temperature. A larger storage capacity will also result in higher investment costs. To understand this dynamic, Figure 6 was expanded upon by including storage capacities ranging from 2500 kJ/K to 50000 kJ/K in Figure 12, which shows how in increase in storage capacity will not lead to an increase in electricity produced after a certain point. However, an increase in storage capacity did make it possible to release the same amount of heat at a higher temperature with a lower periodic change in storage temperatures.

3.4.2 Storage material

A simple analysis of possible storage materials were conducted. Once the storage material is decided, the cost and size of the storage unit is easier to quantify. Using thermal properties found online [5] and using a storage capacity of 10000 kJ/K, Table 6 was made. The storage unit was assumed spherical (least surface area per unit volume). Some of the storage materials listed are fiscally irresponsible to use. Some cubic metres of cast iron or aluminum would prove too expensive, making the project not feasible. Other materials, such as concrete, is relatively inexpensive and readily available.

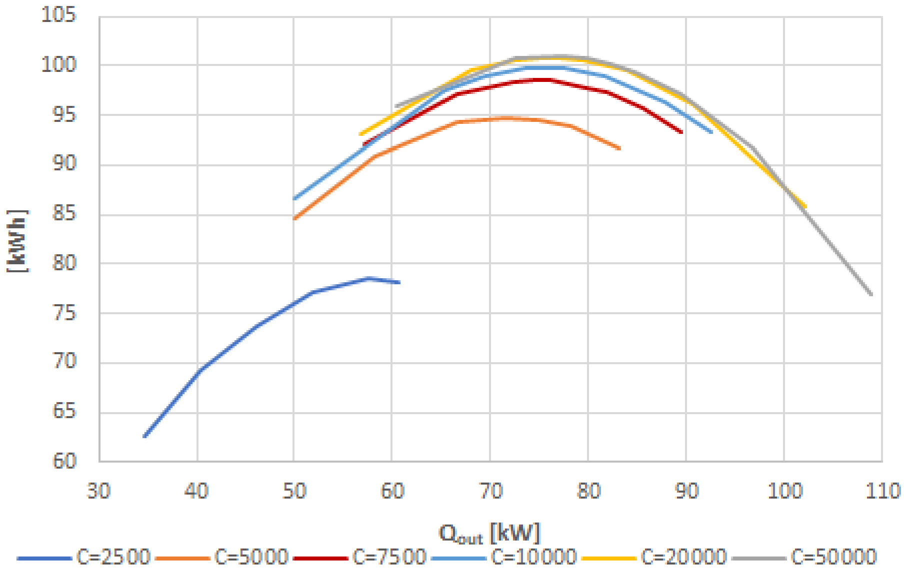

Figure 12: Electricity produced during a 6-hour period at fixed $\dot{Q}_{out}$

Table 6: Possible storage materials for the TES

Storage material	Temperature limitations [°C]	Density $[\frac{kg}{m^3}]$	$c_{p,s}$ $[\frac{kJ}{kgK}]$	$m_s[kg]$	V_s $[m^3]$	A_s $[m^2]$
Aluminum	max 600	2700	0.92	10870	4.03	15.3
Cast iron	max 1150	7200	0.54	18519	2.57	11.3
Concrete		2305	0.92	10870	4.72	16.9
Draw salt	220-540	1733	1.55	6452	3.72	14.4
Granite		2400	0.79	12658	5.27	18.2
Liquid sodium	100-760	750	1.26	7937	10.58	28.9
Molten salt	142-540	1680	1.56	6410	3.82	14.7

3.4.3 Thermal losses

Another practical consideration would be to reduce the heat losses from the storage to the ambient. This heat loss have been neglected in the simulations, but will always be present. Without neglecting the losses, heat losses will result in either a decrease in storage temperatures, a decrease in heat load onto the power cycle, or a combination of both. This effect is not wanted, as it will negatively affect the performance of the power cycle. To reduce heat losses, the thermal storage would have to be insulated. The insulation could be represented as U_{loss}, representing the overall heat transfer coefficient between the storage and ambient conditions (10 °C). Figure 13 was made by keeping the heat load constant at 73.5 kW, while varying the U value between 0-20 W/m^2K and letting the initial storage temperature change to assure heat balance. The storage material was chosen as concrete, with a surface area of 16.9 m^2. In addition, Figure 14 shows how total production will decrease when U_{loss} increases.

The figures shows how losses will become the dominating factor if the system is not properly insulated. EnergyNest, a Norwegian company specializing in thermal storage in concrete, claim their units will only lose 2% of heat stored during a 24 hour period [6]. Assuming this holds true for the TES model employed in this project, total heat transfer coefficient between the storage and the ambient would be 0.381 W/m^2K.

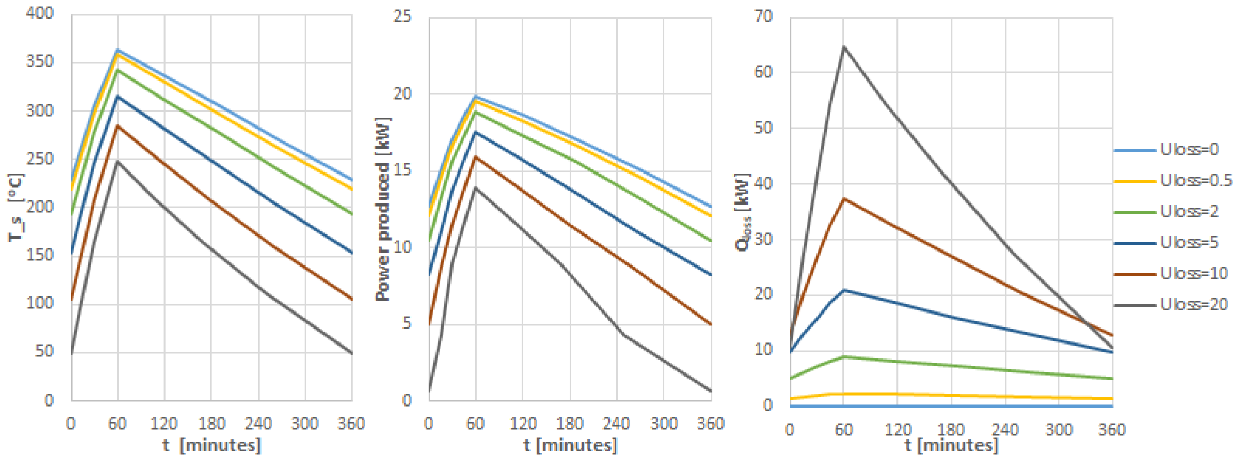

Figure 13: Temperature profile, power produced and heat losses with $\dot{Q}_{out}$=73.5 kW

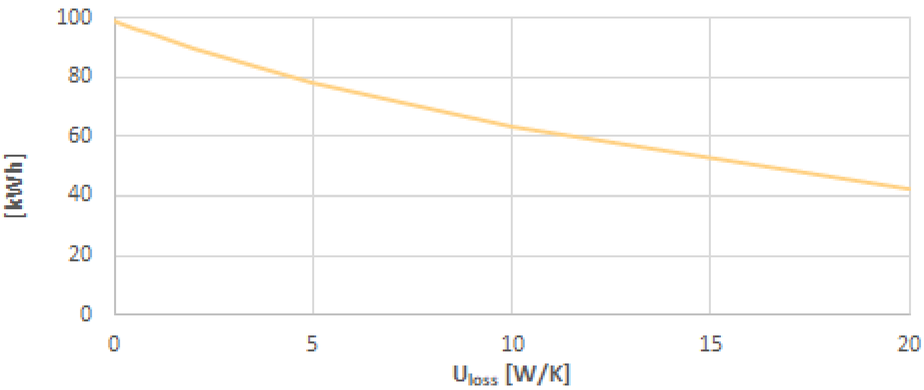

Figure 14: Electricity produced at different values of U_{loss}

3.5 Exergy as an indicator for power production

When selecting thermal storage temperature and heat loads, there was an attempt to use the amount of exergy in the heat load as a indicator of cycle performance. While the power cycle would never produce the same amount as a carnot cycle, it could be used as a indicator of how to choose storage heat load. Using the TES model to calculate the net amount of exergy transferred onto the power cycle at a given heat load, it was shown that the amount of net power produced does not follow the amount of exergy in the heat load, as shown in Figure 15. Exergy production is at its max at a heat load of 92.5 kW, and does not match up with the maximum electricity production at a heat load of 73.5 kW. Similar tendencies appear with other storage capacities as well.

Another attempt at using exergy was to try to maximize the fraction of exergy to heat in the heat delivered to the power cycle. A high fraction of exergy is related to high storage temperatures and low heat loads, a high quality heat source. However, lower heat loads meant higher temperatures and higher exergy fractions. This attempt would always prefer to reduce the heat load further and further, which was of no use in this project.

As neither maximizing for heat load exergy content or heat load quality (exergy fraction) proved successful, an attempt to somewhat maximize both was made. The cost function of the Solver tool used for the TES model was changed to maximizing the product of total amount of exergy in the heat load and the quality of the heat: $Cost = E_x \times \frac{E_x}{Q_{out}}$. This attempt was more successful. The Solver tool recommended heat loads in close vicinity to the optimal heat loads, with only small differences in electricity produced. It proved to be a good choice of initial heat load before further testing. Table 7 shows how the heat loads found by the Solver tool differ from optimal heat loads,

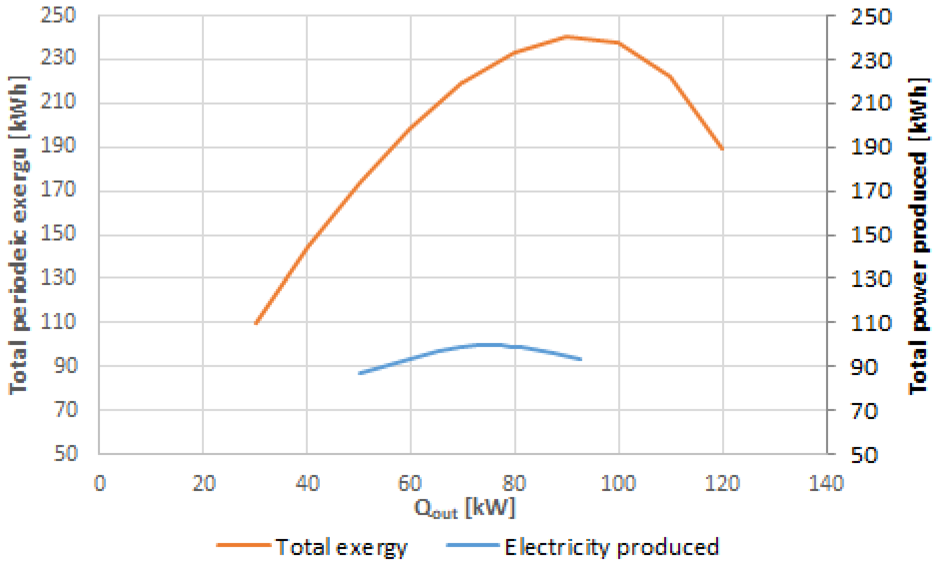

Figure 15: Exergy content of heat output from storage and power produced

Table 7: Solver recommended heat loads and optimal heat loads, along power produced from each

	Solver recommended		Simulated optimum	
Storage capacity	$\dot{Q}_{out}$ $[kW]$	W $[kWh]$	$\dot{Q}_{out}$ $[kW]$	W $[kWh]$
2500	53.8	77.6	57.7	78.5
5000	68.2	94.4	71.5	94.6
7500	72.1	98.4	74.2	98.5
10000	73.5	99.7	75.5	99.8
20000	74.9	100.8	77.1	100.8
50000	75.2	100.7	77.4	101.0

as well as the power produced from both.

Exergy was also used in an attempt to flatten out the power produced throughout a period, when using a variable heat load onto the power cycle. Case 3 in Figure 8 was designed to minimize the change in exergy during a period. The exergy varied only 0.725 kW. However, this did not lead to the flattest power production, with variations of 3.35 kW. Case 4 however, had a much more variable exergy content in the heat load, but far less variation in power produced. This is illustraded in Figures 16 and 17.

4 Discussion

4.1 The effect of a TES

The results have shown that there are several factors influencing the amount of electric energy to be produced from a thermal energy storage buffering heat from a periodic waste heat source. The electric energy produced vary with the thermal capacity of the storage, the temperature of the storage, the heat output onto the power cycle and the design conditions of the power cycle.

When producing power from heat, there is a need for a lot of heat at high temperatures. As such, the thermal storage should store as much heat as possible and deliver said heat at high temperatures to ensure high power cycle efficiencies. However, the results showed that this is not possible. High temperatures is in direct opposition to high amounts of heat. To ensure a high amount of heat transferred to the storage, there needs to be a high temperature difference between the waste heat source and the TES. High temperature differences leads to low storage temperatures. In addition,

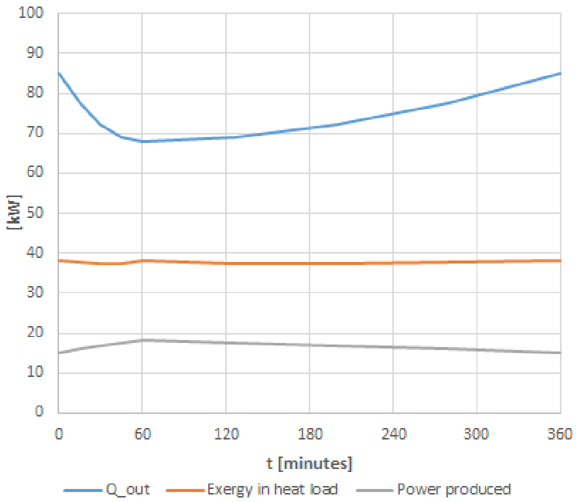

Figure 16: Heat load, exergy content and power produced from case 3

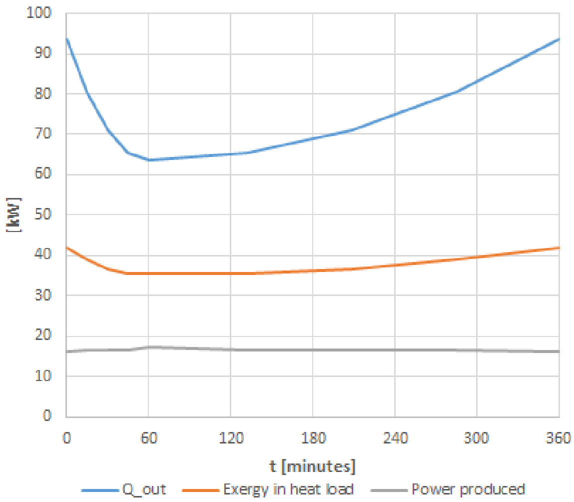

Figure 17: Heat load, exergy content and power produced from case 4

large amounts of heat stored will lead to a large change in storage temperature, which will cause a large variation in cycle efficiencies throughout the period. As discussed in section 3.2.1, a balance between these effects is necessary to ensure optimal power production. As shown in Figures 6 and 12, there is an optimal heat output for a given storage capacity. But even when utilizing the optimal power output, the amount of heat and the temperature of the heat delivered to the power cycle has decreased compared to not using a TES.

As seen in section 3.3, the inclusion of a thermal energy storage will cause a decrease in power produced from the heat source. While a system utilizing a TES produced close to 100 kWh of electric energy every six hour period, a scenario without a TES produced upward of 200 kWh in the same period. However, to produce nearly 200 kWh of electricity necessitated a UA value of 73.9 kW/K, while UA values of scenarios utilizing a TES ranged from 9 to 12 kW/K. This disparity in UA values is a sign of the non-TES scenario being a bigger investment that the scenario utilizing a TES. Bigger UA values is a sign of bigger heat exchanger area, of which there is a greater investment cost tied to. In addition, a system not utilizing a TES will have higher heat loads onto the power cycle, and higher working fluid and heat sink flow rates, which will lead to a larger expander and pump, increasing investment cost. The expander inlet temperature will be higher, potentially leading to higher cost due to a need to ensure the materials exposed to said temperature is able to withstand it.

To compare scenarios with and without TES, there is a need to compare systems with approximately the same economic cost. In a scenario without a TES, one would avoid the cost of investing in a thermal storage unit, which would open up the possibility of investing in larger heat exchangers, pump and expander. However, too large heat exchangers in the non-TES system could cause the system to be far to costly. The systems are assumed to be comparable in cost when the non-TES system has a UA value about double that of the system with a TES. Within this assumption, the electricity produced from the two scenarios are not too far apart. The system without TES produces more electricity, while suffering from only producing power for a few hours every day, shutting off and starting up again four times a day. The system with a TES will on the other hand be operating continuously, with only slight variations in power throughout each period. Figure 18 compares power production from systems with and without a thermal storage. The system utilizing a TES is case 4, described in Figure 3. The system without a TES has a total UA value of 20 kW/K. Total electricity production through a six hour period was around 99 kWh for the TES system and 123 kWh for the non-TES system.

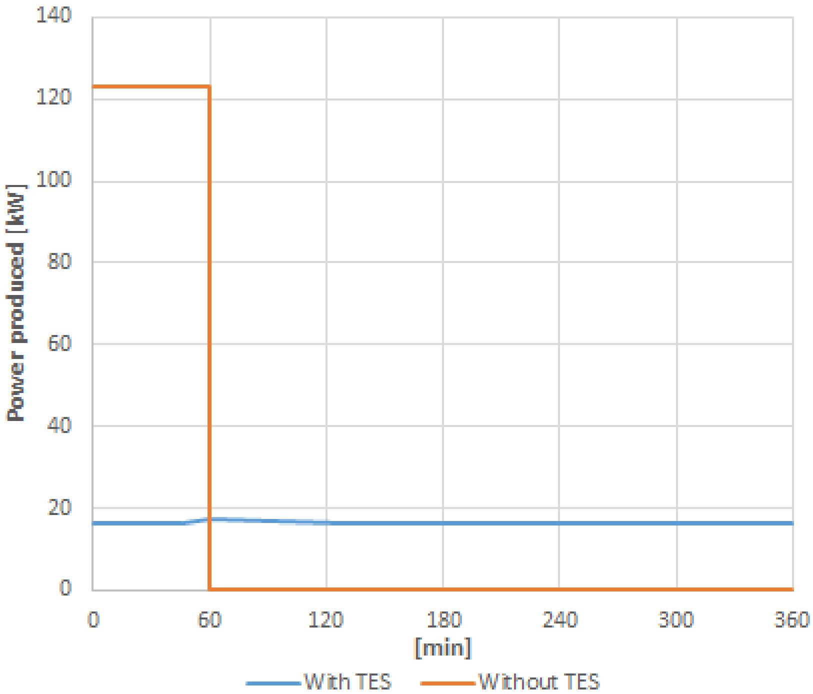

Figure 18: Power produced during a period with and without a TES

With the waste heat source used in this project, producing electricity without a TES results in one hour of electricity production and 5 hours of idle time. During the hour of production the heat source and operating conditions will be constant and well suited for power production. As a consequence of the heat source, the power will produce power for only four hours a day, meaning the system will not in operation 83.3% of the time. At the same time, the system will be shutting off and started up again four times a day. This system will be larger than the TES-system, but not in operation most of the time. The strain of producing power for only one hour every six hours will potentially decrease the lifespan of the system quite substantially. If there is a desire to sell the produced power onto the electrical grid, a power profile such as this is not desirable, as the grid operator most likely would like a constant input of electricity, instead of sudden pulses of electricity provided to the grid.

4.2 The effect of a variable heat load

As seen in section 3.2.2, time was spent during the project work investigating the effects off a variable heat output from the thermal storage. There was a hope that a variable heat profile could reduce variations in power produced and possible produce more power than a constant heat output. In this project work, the former was found to be true, while no examples of the later was found.

From the TES-model, it was found that initial storage temperatures and the the temperature rise in the storage remained unaffected by a variable heat output as long as the total amount of heat into and out of the TES remained constant during a period. This can be seen from equations 1, 3, and 2. The temperature profile throughout the period remained nearly the same as well. If total heat energy stayed put, one could change the heat profile with close to no change in the temperature profile. Then the heat profile could be shaped in a way to counteract the variations on power production caused by the changing temperatures. Heat output was increased while the storage temperatures were low, and decreased while the storage temperatures were high.

These changes proved successful in reducing the variations in power production. But all power production with a variable heat load did lead to some reduction in power produced compared to a scenario using a constant heat output. Once off-design consideration were made, scenarios utilizing a variable heat output showed the least variations in power produced and the highest total electricity produced. However, no scenarios achieved both of these results at the same time. In addition, when applying a variable heat load and simulating at off-design conditions, it proved most desirable to design the power cycle for conditions encountered at the colder end of the storage temperature range, where temperatures are close to initial storage temperatures and heat outputs are high. Designing for these conditions lead to low variations in power produced and high overall power production, but it also leads to the largest heat exchangers, as the UA value at design point would be largest in this region.

If the priority is to ensure most power produced from a TES-system, while keeping costs low, maintaining a constant heat output might be the best option. Even when including off-design simulation, designing for a constant heat output meant close to maximal power produced while ensuring a low UA value. Variations in power produced did increase without a variable heat output.

4.3 The storage

In section 3.4.1 the effect of storage capacity on power production was studied. While an increase in storage capacity lead to an increase in power production, said increase did not go on forever, but capped out at around 101 kWh. To invest in an increasing storage capacity after about 5000-7500 kJ/K proved to be a poor return on investment. However, an increase in storage capacity will lead to a smaller periodic variation in storage temperature, as the TES can store more energy with less change to temperature. The initial storage temperature will also increase, but is limited by the amount of heat delivered to the TES. These changes will cause the electricity production to experience less variations at higher storage capacities. Therefore, an increase to storage capacity will reduce variations in power production.

An increase to storage capacity will also make the TES more capable of storing heat if some unforeseen event were to happen. If there was a spike in the heat source or a maintenance break pauses power production, a bigger thermal storage will be preferable. Either because a heat spike will cause less of a temperature spike in the TES, or because the storage will retain more heat, and thus withstand heat losses more efficiently.

While losses have not been considered in any power cycle simulations, section 3.4.3 proved they can become a dominating factor if not properly dealt with. Properly insulating the storage must be a priority to justify the usage of a TES. However, the model used might exaggerate the effect of losses compared to a more realistic model. With an assumption of lumped capacitance, the storage temperature along the outer part of the storage might be higher than they should, magnifying the effect of heat transfer between the storage and the ambient.

5 Conclusion

This work has investigated the effect of utilizing a thermal energy storage (TES) to produce electricity from a periodic waste heat pulse. A thermal energy storage has several effects on the electricity production, chief among them is to enable continuous power production throughout the entire period, instead of one hour of production and five hours of idle time. This will allow the power production to be less variable and the strain on the system due to starting and shutting off the system four times a day.

There are disadvantages tied to a thermal energy storage. With a TES the temperatures into the power cycle will be reduced compared to not using a TES. This is due to the need for temperature driving forces between the waste heat source and the storage. In addition, the heat output from the TES will be reduced, mostly due to the heat from the heat pulse being delivered over a period of six hours instead of the one hour duration of the pulse, but the utilization of a TES reduced the heat delivered to the power cycle even further, reducing the rate of waste heat utilization. The reduced temperatures and heat output resulted in the TES system producing less electric energy. The TES system produced about 99 kWh during a heat pulse period, while a somewhat comparable non-TES system produced 123 kWh.

While power production are lower in a TES-system, the system will be continuously producing power, reducing maintenance and increasing cycle life time. The power system will be smaller, as it is dimensioned for lower heat loads and temperatures, reducing investment cost. The storage unit will be another investment, but assuming concrete is a viable choice of heat storage material, said investment might not be the greatest.

The utilization of a TES resulted in a continuous power production, decreasing the variations in power produced from 123 kW to a couple kilowatts. During the project work, some strategies for reducing fluctuations in power production was investigated. If the heat output from the storage is varied in a way that counteracts the effects of changing storage temperature, it proved possible to reduce the variations in power production further. This reduction often came at the expense of some loss of net power produced and a increase to the UA values of the heaters. A reduction of the heat output will increase storage temperatures and reduce temperature variations, reducing variations in power, but also reducing power production. An increase in storage capacity will initially increase power production and/or decrease variations, but at the cost of a higher investment cost for the thermal storage unit.

To conclude, a TES has been shown to enable continuous power production from a periodic, pulsing heat source. It removed the need for periodic starting and shutting off the system. It also resulted in less net power produced compared to a system without the utilization of a TES. As it stands, producing power from this heat source without a heat storage would probably not be feasible, making power production with a thermal energy storage a viable option.

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