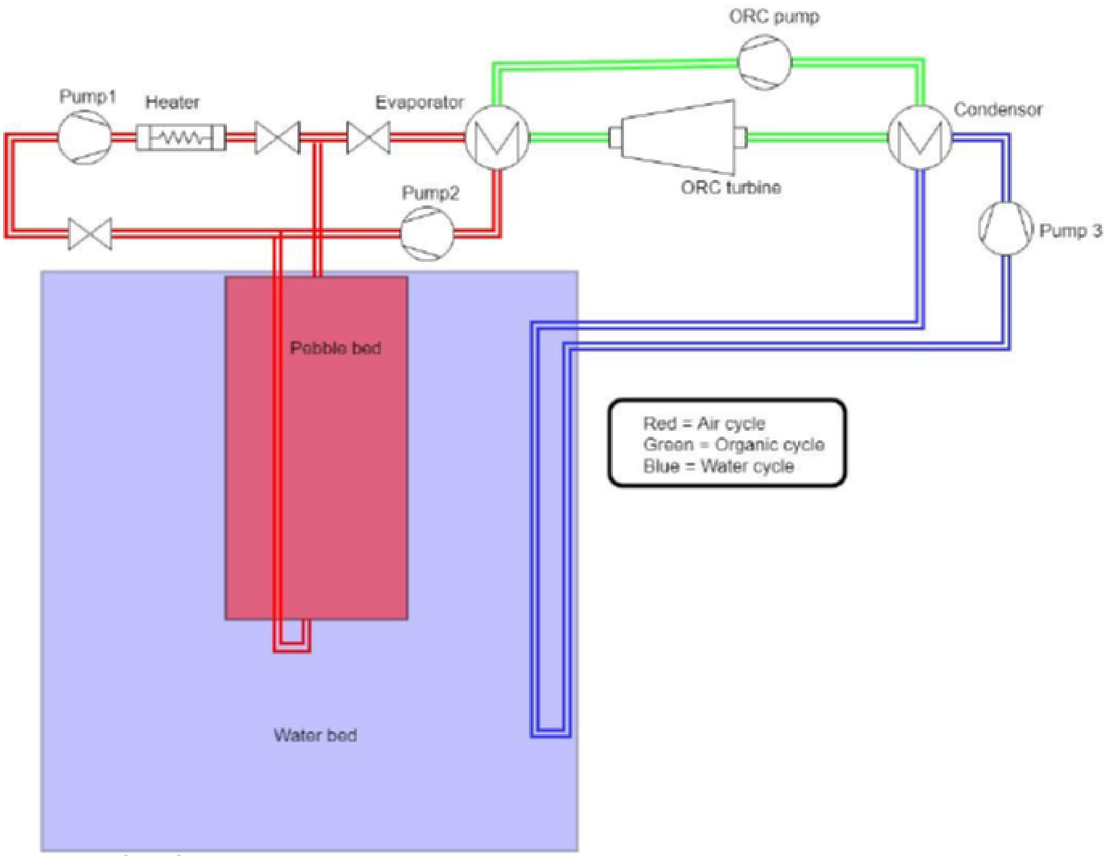


Hoge Temperatuur Ecovat

Economic feasibility of an HT Ecovat

In opdracht van:

ecovat®

Information

Titel	Hoge Temperatuur Ecovat
Ondertitel	Economische haalbaarheid van een HT Ecovat
Projectnaam	Ecovat High Temperature
Projectnummer	E161102
Date	13-12-2018
Datum	21 September 2018
Auteur	Hette de Vlieger
Supervisor from University	Camilo Rindt
Supervisor from Ecovat	Arne Kaas
Telefoon	0640416454
ID NR	20174610
Research group	Energy technology, mechanical engineering
Master program	Sustainable Energy Technology
E-mail	hettedevlieger@gmail.com

Abstract

Promising renewable energy technologies are almost all intermittent by nature. Because of the intermittency, the need for storage to enable a reliable energy supply will become more pressing in the near future. Price, efficiency and durability are the most limiting factors of current storage technologies. The Ecovat provides a large buffer for thermal energy that is able to enhance the efficiency of existing technologies. Excess electricity is converted into heat and stored in a high temperature storage, the storage medium consists of low cost pebbles. In case of an electricity deficit, the heat is converted back into electricity by means of an ORC. The Ecovat provides the cooling water and absorbs the waste stream of the ORC. The waste stream of the ORC, which contains up to 79% of the input energy, is due to the Ecovat converted in useful exergy and stored for later usage. Moreover, the Ecovat can store this energy as high quality heat. A simulation shows that close to a 1000 full load hours can be achieved by the ORC in a future energy system. However, considering expected policies and price fluctuation, the presented storage setup does not provide a profitable business case. Progressive policies and markets are needed to capitalise the advantages an HT Ecovat can provide to turn the business model profitable.

Inhoudsopgave

1 Introduction

In the near future, production of electricity will be less structured to human needs as the sources are nature driven. Large electricity peaks during summer by means of solar power cannot be consumed directly, moreover, during winter there will be an energy deficit due to the large heating demand which will not be provided by natural gas. Converting electricity to heat and storing it in an Ecovat will make the grid more resilient to the uncontrollable nature of renewables.

By creating a surplus of electricity, the electricity can be stored in terms of heat to provide heating during winter. However, even in case of a surplus of electricity, there are regular intervals with little to no electricity production, hence storing electricity is critical. Current storage techniques are often very expensive, too inefficient, technological not realistic, or even polluting. However, the large storage capacity of the Ecovat enables existing technologies to radically enhance their efficiency and therefore profitability.

This report presents an evaluation of a high temperature storage in combination with a heat to power technology in order to deliver electricity. This system is working alongside and in cooperation with the existing design of an Ecovat. Within this report, HT Ecovat refers to the high temperature Ecovat, where electricity gets converted into heat and back into electricity, possibly including a waste stream. LT Ecovat refers to the Ecovat as it is currently designed.

The energetic simulation shows the performance of an HT Ecovat in a future energy scenario. This future scenario is solely based on energy flows and does not consider market predictions, hence it is a fully energetic simulation.

The economic simulation on the other hand does not consider the energetic behaviour of the Ecovat. Instead, the outcome of the energetic simulation can be used as an input for the economic model. Together with a careful prediction of the economic variables, the value of the system can be determined. Or the other way around, one can determine the economic variables at which the system is profitable.

The report will be concluded with an overall judgement of the proposed techniques, energetic performance and economic feasibility.

2 Technical

2.1 Introduction

In this chapter the optimal performance of a technical design is investigated. The technical setup is defined up till the detail that is necessary in order to define the optimal performance, Therefore, the exact structure of the heat storage is not fixed as it does not majorly influence the optimal performance of the pebble bed. However for the investment cost the most promising design is chosen. The performance of the ORC is mainly based on literature and the input of producers since this is more accurate than a simulation could perform in the scope of this project. The quantities of powers and capacities that are used within this chapter are a result of an iterative process of scaling the system. These quantities will be substantiated within the chapter 'Energy flow'.

2.2 Storage medium

Storing energy as heat is an increasing popular topic among scholars. One can store heat in several ways, in this case, it is chosen to store sensible heat since it has low investment costs, can resist many cycles and can easily be installed in bulk. Moreover, latent heat is often chosen since it has a higher specific energy, however in case of an Ecovat, space is not the main limitation considering the size already needed for an LT Ecovat. A hybrid solution of sensible and latent heat has been suggested, by introducing a top layer of molten salt the output temperature of the storage can be stabilised (Geissbühler, Kolman, Zanganeh, Haselbacher, & Steinfeld, 2016). By stabilising the output temperature, the discharge time can be increased, hence the exergy of the storage increases. Moreover, by increasing the exergy, the size of the storage can be reduced, which will reduce the installation costs. However, the benefit of stabilising the temperature will only have a considerable influence if the output temperature is not allowed to drop more than 15 degrees. However, the maximal allowed temperature within a pebble bed is limited just above 600 degrees by material properties. Moreover, the maximal temperature at the inlet of the evaporator of an ORC is much lower as will be discussed later. Concluding, a purely sensible heat storage seems most relevant for the presented situation.

Converting heat back to electricity is usually done with a Rankine cycle, the theoretical maximum efficiency is given by the Carnot efficiency:

$$eta = 1 - \frac{T_2}{T_1}$$

It can easily be seen that the higher the temperature difference the higher the efficiency. Since the condenser temperature T_2 is limited by the temperature of the LT Ecovat, the evaporator temperature T_1, delivered by the storage, should be as high as possible. Moreover, a higher temperature means a higher energy density. If needed, the stored temperature can always be lowered by mixing the outgoing air of the evaporator with the incoming air.

Various mediums are usable for high temperature storage. Natural stone is a material that can withstand high temperatures, is largely available, perfectly save and relatively cheap. Another advantage of stones is that if in the form of small pebbles, their heat is easily extracted as compared to other materials such as concrete. The choice for pebbles as a cost effective large scale storage medium is broadly uphold by literature(Zanganeh, Pedretti, Haselbacher, & Steinfeld, 2015). Ceramics such as magnesia bricks form an alternative to stones, their heat capacity is up to three times as high. However, as size of the storage is not the problem, the cost is more so. Magnesia bricks have to be specifically produced for the purpose of heat storage, therefore the associated costs are 10 times higher than that for stones per kg. (Tian & Zhao, 2013) An alternative problem, not found in literature, could be the high thermal conductivity. Although this high conductivity will ensure a uniform temperature in the horizontal direction of the bed, it has also the possibility of destroying the stratification within the bed. Moreover, an advantage of magnesia are the channels that one can create, ensuring low pressure drops, however this increases the contact area of the bricks with each other, forming long thermal vertical bridges, hence decreasing the stratification.

In order to choose the right stone for the storage it is advisable to look at the behaviour of different stones during thermal cycling. Becattini et al. (2017) have done tests on various types of stones and found that stones with a low porosity are least likely to fracture during cycling, making them more suitable for high temperature cycling. Limestones are not suitable for temperatures above 600 degrees Celsius whereas mafic rocks are. Different results are retrieved during the thermal cycling of sandstone, this is caused by the different chemical composition among different sites. Concluding, during site exploration, the local stones have to be identified and the most promising stones should be tested specifically on their behaviour during thermal cycling as the chemical composition of the stone is site specific. For the calculations of the pebble bed further on, characteristics of granite have been used as these are most widely used for pebble beds and their characteristics are fairly similar to other stones used in pebble beds.

2.2.1 *Simulation model*

In order to design the pebble bed using realistic parameters, a simulation model is made in Python. The main code in appended in appendix A. Since separate studies have shown that radial gradients of temperature are negligible, a quasi-one-dimensional two-phase heat transfer model is used as is described by Allen, von Backström, & Kröger (2015). This model neglects conduction and radiative heat transfer which have a minor influence in the bed (Hänchen, Brückner, & Steinfeld, 2011). The pressure drop is estimated using the Ergun equation:

$$\Delta p = \frac{L * A * \rho_A * u^2 * (1-\varepsilon)}{d_{pebble} * \varepsilon^3} + \frac{B * \mu * u * (1-\varepsilon)^2}{{d_{pebble}}^2 * \varepsilon^3}$$

The Ergun equation uses the voidage and the pebble diameter to estimate the pressure drop. It is acknowledged that the Ergun equation is but a rough estimation however, it is used as a first guidance to design the pebble bed. The case-dependent factors in the equation are set as A=217 and B =1.83 as has been empirically established for randomly shaped gravel(Macdonald, El-Sayed, Mow, & Dullien, 1979).

Since a computational expensive CFD code is required which is not available for complex configurations, the temperature of the individual pebbles is assumed to be uniform. The validity of assuming uniformity depends on the external heat transfer (h), internal heat transfer (k) and size of the pebble. To represent this in one value, the Biot number is used.

$$Biot = \frac{h * d_{pebble}}{2 * k}$$

With d = 6*V/A for pebbles, with V the total volume and A the total surface of the storage medium, for perfect spheres d is simply the diameter.

For low Biot numbers the entire pebble follows the temperature of the air, whereas for high Biot numbers the core of the pebble experiences a significant delay. Generally it is assumed that for Bi<0.1 the temperature gradient in the pebble can be ignored, so $h_{vol,eff} = h_{vol}$, and therefore the above assumption of a uniform temperature holds. It should be noted that the boundary value of the Biot number for a uniform temperature of the pebble is under debate, therefore the most conservative value is chosen(Allen, Von Backström, & Kröger, 2013). In the case of higher Biot numbers, the Hawley and Löf formula can be used to estimate the effective volumetric heat transfer:

$$h_{vol,eff} = 650 * (\frac{\Delta m}{A * d_{pebble}})^{0.7}$$

With Δm being the mass flow through the bed, A the diameter of the bed and d the diameter of the pebble. So if 0.1<Bi<1, this alternative value for the volumetric heat transfer can be used and the assumption of a uniform temperature during discharge can be used again(Barton, 2013). Therefore, the temperature of the bed can be a function of t and x and we can dismiss d.

When heat is pumped through the bed the density of the air and hence the velocity will differ along the height and the temperature. One can adopt this in the model but that is not necessarily required since the heat exchange coefficient between the air and rock particles depends on the mass flow of the air, which remains constant through the bed(Barton,2013). Cumulative effects of radiation and conduction in the bed are very small considering the cycle time, therefore, these can be neglected(Hänchen et al., 2011).

The air temperature has an exponential profile:

$$T_{A,t+1} = T_{A,t} - (T_{A,t} - T_{R,t})(1 - e^{-NTU(\Delta x/L)})$$

With L, the length of the bed, and number of transfer units(NTU):

$$NTU = \frac{h_{vol,eff} * L}{G * c_A}$$

With mass flux:

$$G = \frac{\Delta m}{A}$$

The temperature of the rock at the next time interval:

$$T_{R,t+1} = \frac{T_{R,t}\left(1 - \frac{\Delta t}{2\tau}\frac{L}{\Delta x}\eta\right) + T_{A,t}\left(\frac{\Delta t}{\tau}\frac{L}{\Delta x}\eta\right)}{1 + \frac{\Delta t}{2\tau}\frac{L}{\Delta x}\eta}$$

With: $$\eta = 1 - e^{-NTU(\Delta x/L)}$$

Where the time constant τ consists of the mass of the phases and their heat capacity. The heat capacity is temperature dependent and a fit function was used to approximate its exact value.

$$\tau = \frac{m_R c_R}{m_A c_A}$$

In order to keep the output temperature of the pebble bed at a constant high temperature, charging and discharging is done in opposite direction. Charging happens from the top to the bottom, whereas discharging happens from the bottom to the top. This way, the bed cools down faster at the bottom but retains its maximal temperature at the top for a long time. (Barton, 2013) Moreover, during standby of the pebble bed, a stratified unit is present since the hot end of the bed is situated at the top because of the charge direction. Therefore, the convection of air will be halted.

When sizing the HT system with a discharge period of six hours, in order to provide energy during evening and morning peaks, the pumping losses due to the pressure drop of the total system can be quite high. Moreover, to be able to charge the bed at attractive prices the charging period should be more flexible and be able to happen in a faster time than the discharge. In order to allow for high air velocities, associated with fast charging, the pressure drop should be minimised in order to prevent even higher pumping losses. The two main variables to lower the pressure drop are the bed length and the pebble diameter. The pebble diameter is limited to ensure a homogeneous temperature distribution, otherwise the pebble stays warmer at the inside than the outside at discharge which means an exergy loss.

Secondly, the pebble bed length can be altered to lower the pressure drop. This is done by introducing several layers or segments in the pebble bed that are able to charge and discharge separately from each other. A critical note on lowering the pressure is placed by Torab & Beasley (1987). They recommend to limit the minimal pressure drop to 0.5-1 N/m2/m for an equal flow distribution through the bed. Otherwise one would have an increased flow near the wall since there will a lower resistance due to the higher void fraction which is imposed by the wall.

During charging and discharging the pebbles will shrink and expand. During shrinking the pebbles get more packed, however during expansion they cannot move upwards and the pebbles expand towards the wall creating a destructive force(Zanganeh, Pedretti, Zavattoni, Barbato, & Steinfeld, 2012). To prevent damage of the bed, current large scale storages have a cone shaped bed through which the stones can expand and move upwards instead of damaging the wall. Another solution is to divide the bed in several smaller sections in order to minimise this force, however, this will increase the costs of instalment.

2.2.2 *Simulation results*

Preliminary simulations have been carried out on the pebble bed to guide the design process and keep an eye on the scales we are working with.

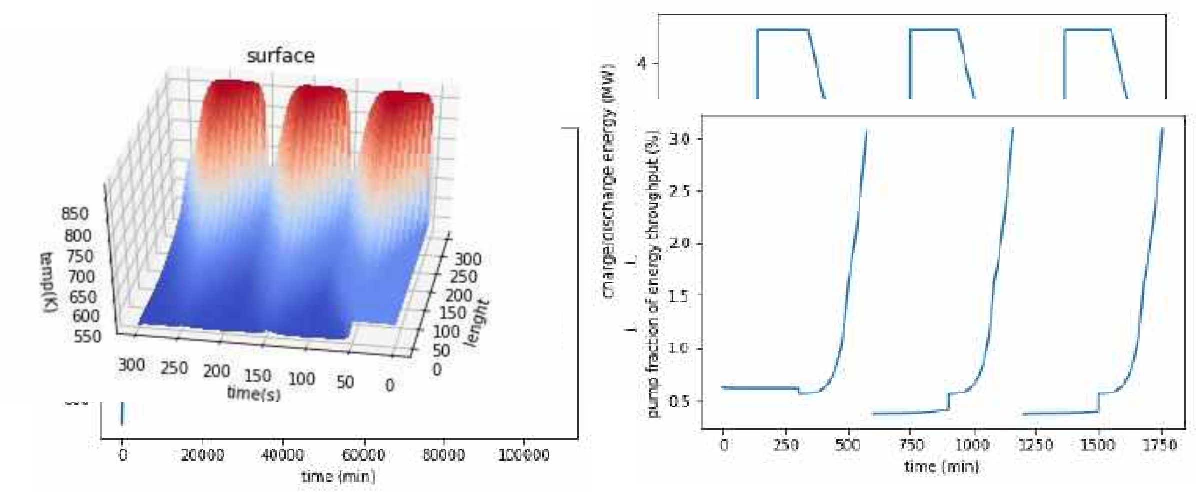
The first thing to be tested was the maximum thermal power the bed could deliver over a period of six hours. Meanwhile, the outgoing air should have a minimum temperature of 380 degrees. The mass flow of the air is variable in order to ensure a discharge power of 5 MWth and a charging power of 4MWth. The following key-parameters where used in the simulation:

```
# key parameters
kWth_ORC = 5000 # amounts of thermal MWs going into the ORC
kWth_heater = 4000
T_ORC_out = 250+273     # C temperature of the air coming into the bed
T_ORC_min = 380+273 # minimum temperature at which the ORC is able to operate
T_heater = 600+273  # C temperature of the air coming from the heater
Dbed = 8 # diameter of bed
L = 7 # m The L of the bed
A = Dbed**2/4*mt.pi # m2 cross sectional area of the bed
dp = 0.04; # The equivalent spherical diameter of the packing
eps = 0.35; # The void fraction of the bed (bed porosity)
h = 15 # W/m^2/K Taken from reference case
k = 3 # W/m/K for granite
```

Figure 1. Key parameters

This resulted in a total capacity of the bed of 50 MWhth with an effective capacity of 46.5 MWhth, the total and effective capacity can be improved by increasing the maximal allowable temperature of the bed. The total capacity is based on the minimal ORC temperature and the maximal temperature of the bed delivered by the heater. The energy of the bed below the minimal ORC temperature cannot be used to retrieve electricity from, therefore the minimal ORC temperature will also be the minimal temperature of the bed. This minimal energy has to be charged during commissioning and will only be lost once in its life time. The total loss during one continuous cycle through the insulation will be around 0.2 MWhth. Moreover, it should be noted that during the first 10-20 cycles(dependent on bed dimensions), the bed will not have reached steady state cyclic behaviour yet if it is not charged during commissioning(Zavattoni, Barbato, Pedretti, Zanganeh, & Steinfeld, 2014). These first cycles during commissioning will have a much poorer performance than the designed optimum. Overall thermal efficiencies are expected to be at least 95%(Zanganeh et al., 2012).

Graph 1 shows three consecutive partial cycles with length being the height of the bed. The power during discharge is set at 5MWth in order to enable a production of 1MWe by the ORC. However, the air flow has a maximum of 17kg/s to limit the pumping power, it can be seen that power is declining towards the end of the discharge. When the temperature has reached the minimum ORC temperature(graph3) the discharge is entirely halted. Graph 4 shows the needed pumping power as a fraction of the energy throughput. Charging only occurs when electricity is relatively cheap, hence the pumping power is not as important. During discharge, electricity is relatively expensive as will be explained later. Moreover, the ORC has a maximal efficiency of around 20 percent, therefore, the pump power as a fraction of electricity during discharge will be about 5 times higher. Especially towards the end of the discharge, the pumping power increases exponentially. This is because a larger mass flow is needed to deliver the 5MWth to the ORC when a smaller temperature gradient is present in the vessel. A consideration could be to limit the power output towards the end of the discharge.



(a) (b)

(c) (d)

Figure 2 Pebble bed behaviour

For the fan, an efficiency of 0.75 and a motor efficiency of 0.9 are assumed. During discharge, with a temperature difference between top and bottom of the pebble bed of 600-250 Celsius, the pumping power is 0.45% of the output power, hence, around 2 percent of the ORC output power. This is reasonable considering reference cases that take a maximum of 2 percent of the thermal output and based on an own appreciation of the consequences. However, as already shown before, the pumping power increases exponentially when discharging the bed entirely. Increasing the stone diameter to 4 centimetres would decrease the needed pumping power to 1.6 percent of the total power output. With the increase of the diameter, the resulting Biot number nears 0.1, as aforementioned an allowable number. Moreover, this design largely corresponds with the proposed design features by Allen, (2013).

In order to allow for faster charging while minimising pumping losses, either requires a further increase of the pebble size or a segmented charge. Increasing the diameter of the pebble further could in itself limit the charge because of the growing Biot number, segmented charge would lead to a more expensive setup. However, notice that the stones are currently treated as perfect spheres, whereas in practice they will have varying shapes. So in reality the stones can have a slightly higher equivalent spherical diameter while their 'real' Biot number will stay allowable. For an accurate determination of their heat transfer capacity, on site stones should be tested.

2.3 Rankine cycle

For returning the energy of the pebble bed storage as electricity, there are a wide variety of options. The most promising for a pebble bed storage is either an organic Rankine cycle (ORC) or a Rankine cycle (RC) with water as the working fluid, in other words, a steam cycle. ORC's are generally more common for solutions up till 1MWe and low temperatures, RC's are generally more common for solutions larger than 2MWe and high temperatures. This division is present since it is generally assumed that the extra maintenance of a steam cycle and the added safety regulations are cost effective when a large capacity is installed because of the higher efficiency of a steam cycle compared to an ORC at these powers. The maximal allowable temperature as present in the pebble bed, is both applicable for a steam cycle as well as an state of the art ORCs. (Quoilin, Broek, Declaye, Dewallef, & Lemort, 2013)(Colonna et al., 2015) Moreover, their optimal efficiency would also be very similar within the power range(Li & Wang, 2016). Therefore, the design parameters as in the case of an HT Ecovat is just at the interplay of these technologies.

A model that compares the entire functioning of an ORC vs an RC within this case is not essential since current research gives a comprehensive picture of both technologies. Moreover it is likely that other factors such as safety, applicability and ease of instalment together with already available knowledge of scholars and businesses are more important than the added insight an in-depth comparative study can provide. In order to give insights in the discussion a brief introduction in the fundamental differences between an ORC and steam cycle will follow.

The most important differences between these two cycles are the lower boiling point associated with organic fluids and that they are often dry fluids. Although a boiling point is quite intuitive, the term 'dry fluid' less so. The classification dry comes from the slope of the saturation curve in the vapour regime. This is best illustrated in the temperature-entropy diagram below.

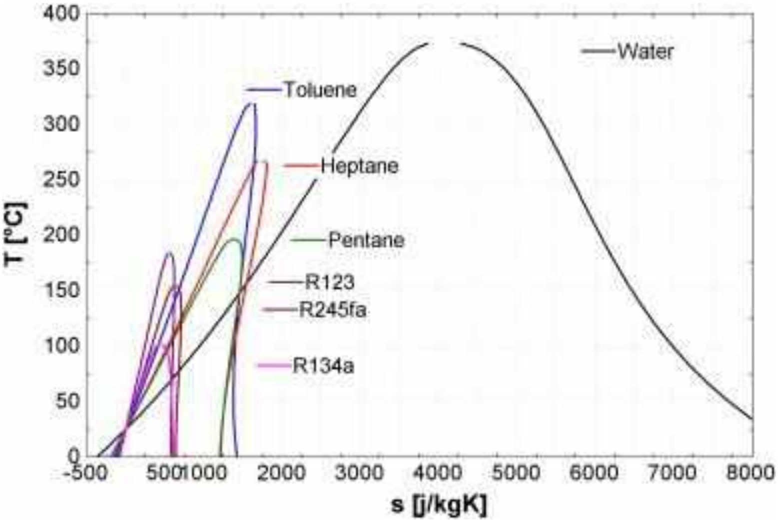


Figure 3. Saturation curve (Quoilin et al., 2013)

All other fluids rather than the water have a positive saturation curve in the vapour regime. The vapour regime is on the right side of the saturation curve. So when a fluid is expanded with a constant entropy(ideal case in a turbine) it can be seen that water is likely to end up in the wet steam regime, the region below the curve. However, for the organic fluids, i.e. the rest of the curves, expansion will not end up below the curve. The main reason to prevent the formation of wet steam in the turbine is the major wear of the turbine through droplets in the steam. In order to prevent this from happening, a steam cycle is usually superheated which prevents the steam from entering the wet steam regime on expansion. In order to superheat the steam, much higher temperatures and consequently pressures, are required compared to organic fluids presented in the graph.

If the boiling point of a fluid increases, the condensation pressure at ambient temperature is likely to be lower. So for water, which has a higher boiling point than most organic fluids, a large condenser is needed to condense the expanded water at the end of the turbine. Organic fluids on the other side have a high density and therefore require a smaller turbine. However, the heat to evaporate organic fluids is generally 10 times lower per mol as can be seen by the 'compressed' curve of the organic fluids. Therefore a higher mass flow is required in the ORC to acquire the same power output and the pumps driving the cycle need more power.

Concluding on these fundamental differences between an ORC and a steam cycle there are several implications for the final design and the effects on the applicability of the technology for a HT Ecovat.

First of all, the high pressures of a steam turbine requires more safety regulations combined with an on-site operator. These safety regulations and on-site operator are a considerable cost item in a small scale set-up. Moreover, it is questionable if these safety regulations are achievable within the built environment. On the contrary, an ORC works with relative low pressures, however, more safety regulations have to be taken regarding the less forgiving working fluid. The overall installation of an ORC is less complex and therefore easier to operate and needs less maintenance.

A relatively big advantage of a steam turbine is the usage of extraction points along the turbine in order to make the power variable. This is more difficult for an ORC because of the significant smaller dimensions, this also results in relatively poor performance during partial load. (Vankeirsbilck, Vanslambrouck, Gusev, & De Paepe, 2011). However, recent ORCs tend to perform quite well with partial load based on input from industry.

An other advantage of an ORC in combination with a sensible heat storage is that the storage can be depleted further without decreasing the efficiency of the cycle. This is a result of the lower operating temperature of an ORC.

Lastly, because of the milder operating conditions of an ORC, the turbines have a much longer lifetime. This is especially important since the turbine is the most expensive part of a complete Rankine cycle as is shown in the pie chart in figure 4.

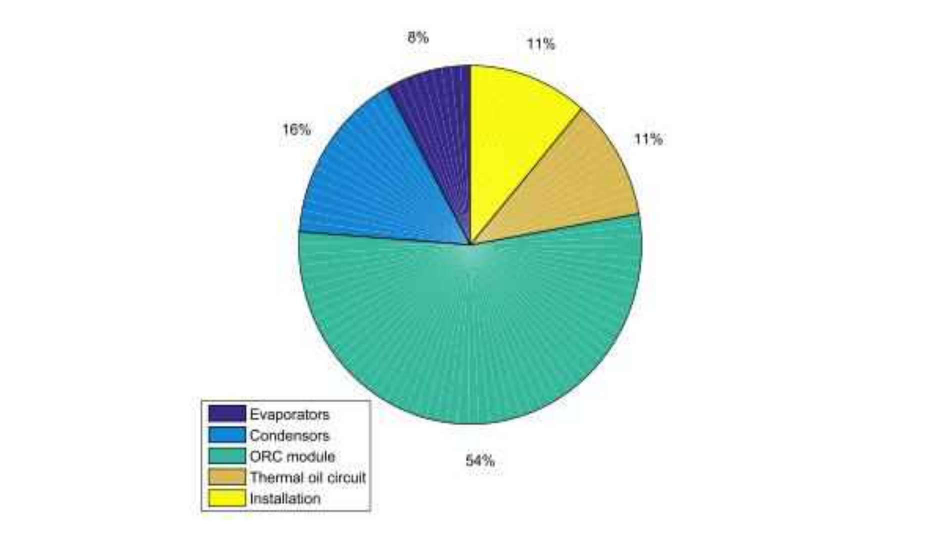


Figure 4. breakdown of the costs of an ORC system (Sanne Lemmens, 2016)

Concluding from the discussion between steam cycle and the ORC, especially the safety concerns of an RC within the built environment are cumbersome. Moreover the ease of operation and reduction of a licensed operator are decisive.

2.3.1 *The ORC performance*

Off-design performance of ORC systems are not described in detail in recent literature, moreover, the off-design performance differs significantly per system. In order to estimate the performance of an ORC in relation to the HT Ecovat system, either a detailed simulation or an enquiry among several producers of ORCs can be made. An enquiry among ORC producers is likely to end up with more reliable data on the state of the art performance than a detailed simulation, especially within the scope of this study.

Several ORCs by different producers have been analysed. The systems should adhere to several constraints. The condenser should be able to deliver heat of at least 80 degrees Celsius as will be explained later. Moreover the maximal power should be in a range of 0.6-1.2 MWe.

Using these constraints, a maximal net electrical efficiency of 21% is identified. It has a thermal oil inlet/outlet temperature of 313/253 and an cooling water inlet/outlet temperature of 60/80. The efficiency of heat in over heat out is 78%. Lowering the in/outlet temperature of the economiser with 1 degrees, results in a 0.1% increase of efficiency. The ORC is able to run at 20% load without major implications on the efficiency as claimed by the producer.

During idle time, the ORC cools down. Especially the large thermal inertia imposed by the evaporator is an important limitation for the ramp up rate. Moreover thermal stresses in the heat exchangers should be avoided. Preheating an ORC from a cold start before ramp up takes at least two hours.

However, having shorter idle times, a properly insulated ORC can stay hot for at least 2 hours. From stand still, it takes about 20 minutes to parallel with the frequency of the grid and another 5 minutes for the remaining ramp up. When keeping the turbine rotating during idle time, paralleling can be shortened to 5 minutes. When having an idle time of about 12 to 20 hours, an extra 20 minutes is needed for preheating. Due to the ramp-up/down of the ORC, it is not desirable to turn it on for periods shorter than at least one hour.

The significance of the ramp up and ramp down time is dependent on the energy markets one wants to be active on. However, if very accurate forecasts can be made one hour(or duration of the ramp up) up front, the long ramp up is not as important.

Lemmens(2016) states that most ORC's are in the price range of 2000-4000 euro/kWe, and specifically waste heat recovering modules near the 2000 euro. Waste heat applications are generally of larger capacity combined with a high temperature so more applicable for our application. However, after enquiry among several producers of ORC systems, systems of 1MWe are identified at a price of 1.3 million, hence, much less expensive than previously stated by Lemmens. This price includes installation, commissioning and start-up.

Relevant suppliers are identified and a document with an overview of these suppliers and the correspondence is made available to Ecovat

2.4 Insulation properties

The physical setup of the pebble bed is largely based on the most optimal layout as defined by Zanganeh (2013). The wall of the pebble bed consists of 1.5 centimetres of ultra-high performance concrete to withstand the force of the pebbles during cycling. Behind this concrete a 25 centimetre low density layer concrete will act as insulation together with 40 centimetres of foam glass. At the bottom, a 2.5 meter thick concrete plate is used as foundation. The top, 20 centimetres of concrete, is insulated with 40 centimetres of foam glass.

Simulating this setup results in an average loss of 48 kW. Part of this has gone to the LT Ecovat if the pebble bed is place in its centre. Hence, charging the LT Ecovat and not losing its exergy. A diameter of 8 meters is used and a height of 7 meters. Moreover, A pause of 24 hours when the storage is fully charged would result in a loss of 1.4 MWh, hence a loss of 3% of its total charge.

Around 54 percent of the losses are lost through the wall, 40 percent through the bottom and 6 percent through the top. The losses through the wall will flow directly in the LT Ecovat, the losses through the bottom will flow indirectly to the Ecovat and the losses through the top are lost.

Microtherm® and FoamGlas® are two insulation materials recommended to insulate the core of the TES system from the external environment as they can withstand high temperatures. (Zavattoni et al., 2014)

2.5 Heater

The heater can either be integrated in the pebble bed, or be placed in a duct just above the pebble bed. Placing the heaters within the pebble bed would not have corresponding heat losses through transportation of the heat. However, the placement of the heating cables would be much more expensive. Moreover, the heat losses of a heater just above the bed would also be minimal and in case of damage the heater is accessible. Lastly, a heater outside the bed is able to charge the bed from top to bottom, hence charging the bed such that it is stratified. An integrated heater would charge the bed equally, hence there is no large output temperature after a short period of charging.

The heater should be able to heat up the bed to a maximal temperature of 600 degrees Celsius. This should be done in a timespan when cheap energy is available and the pressure drop across the bed is still allowable.

IHP provided an invoice with a modular air heater within a range of 1-5MW. The price would be 47€/kWe.

2.6 Pebble bed fan

A leading design choice for the fan would be to install two fans. Pumping air with a 'cold' temperature requires much less energy than hot air. Therefore, it is advisable to place one pump in front of the heater(pump 1 in figure 3), where the air will be around 180 degrees Celsius during most of the charge. During discharge, the flow will cool down in the evaporator, therefore the ideal location of the pump would be between the evaporator and the bottom of the storage(pump 2 in figure 3). For 180 degrees air with a mass flow of 17kg/s a 31 kW pump is needed, whereas for 530 degrees with a similar mass flow a 55 kW pump is needed.

2.7 Condensing pump

The pumping power needed to recuperate the 'waste' heat has to be able to handle 80% of the energy input of the ORC. The expected temperature difference across the condenser is 20 Kelvin. The needed pumping power is P = Q*dP. Currently, a pumping power of 2 kW is estimated based on the current design of the LT Ecovat and its corresponding pressure drop across the heat exchangers. As future Ecovats might be equipped with direct inlets, the pumping power might go down in the future.

2.8 Explain technical setup

As by product of the HT Ecovat, between 75-80% of the energy is delivered as waste heat.

Currently most heat of the LT Ecovat is delivered by heat pumps. These heat pumps can reach a COP of up till 4. Hence much higher than the theoretical COP of 0.8 the HT Ecovat delivers as by-product. Nonetheless, these heat pumps are designed to deliver a maximum temperature of up till 70 degrees, whereas the desired maximum temperature of the Ecovat is up till 90 degrees. In case of an LT Ecovat the last 20 degrees is bridged by an electric boiler.

State of the art ORCs can deliver waste heat streams up till 85 degrees while keeping a 20% efficiency using an evaporator input temperature of 530 degrees Celsius. So energetically it would be a waste to replace the heat pumps with the waste stream of the ORC. However, replacing only the fraction delivered by heat boilers with the waste stream does make sense energetically. Figure 5 is a schematic representation of the integration of the HT and LT Ecovat.

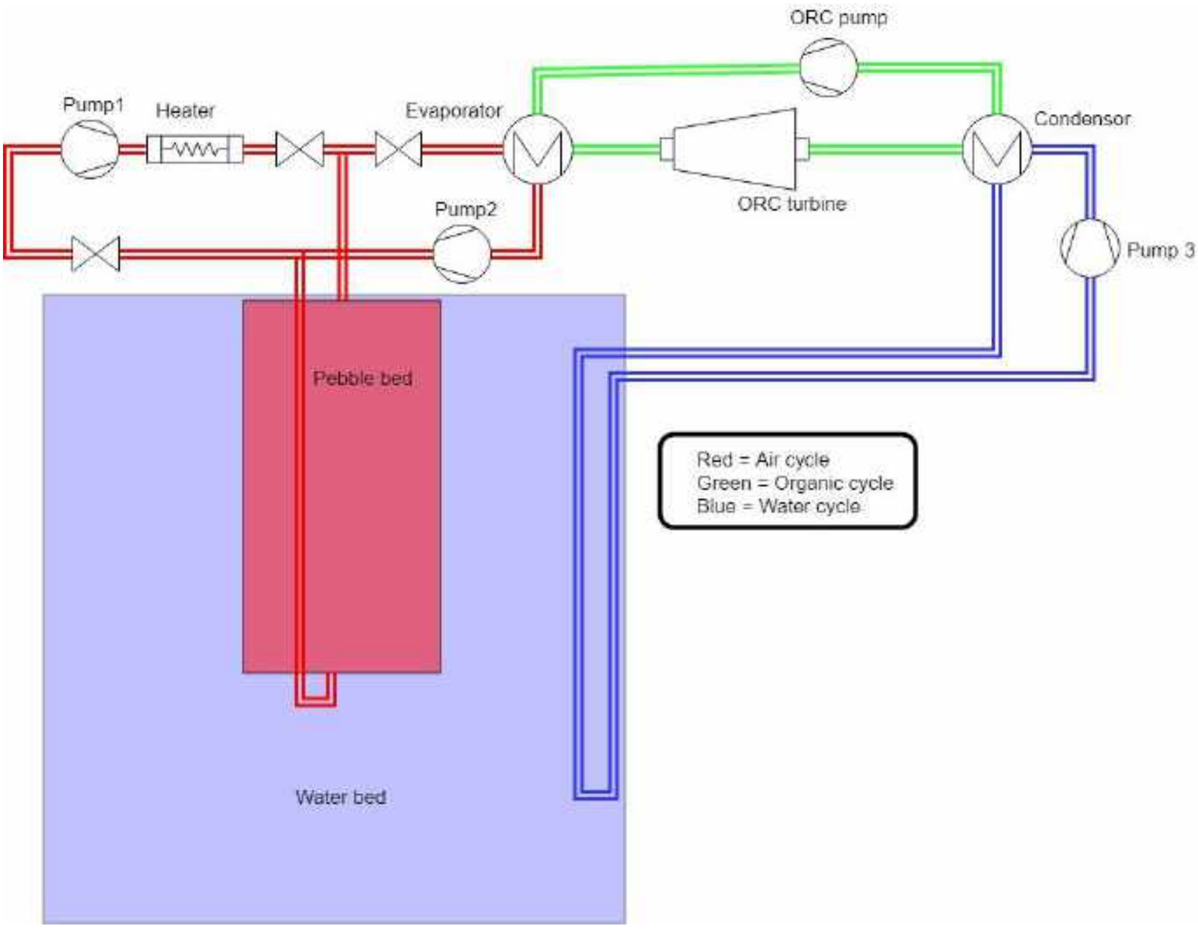


Figure 5. technical setup

2.9 Sizing

Sizing the HT system of the Ecovat is an iterative process, it is dependent on many factors. If the pebble bed is placed within the LT Ecovat, the size of the pebble bed is constrained by the maximum size of the Ecovat minus the space needed for hot water storage. The other constrained is set by the thermal output of the ORC. It is likely that the ORC is only economically viable if the cold waste stream can be recuperated to heat the LT Ecovat and be used for tap water. Therefore, the Ecovat should always have enough cooling water to cool the ORC and the energy delivered should not exceed the demand of tap water.

For example, using these initial constraints for an Ecovat with a diameter of 40 meters and a depth of 48 meters, the pebble bed is constrained at a diameter of approximately 9 meters and a height of approximately 10 meters. The diameter and height are nearly set equal to acquire a minimal area/volume ratio.

Taking these two constraints into account the dimensioning of the HT system becomes an iterative process. This process depends among others on the capacity of the net it is connected to, the demand and production of the surrounding neighbourhood and interaction between the ORC and pebble bed. Within the chapter 'Energy Flow', these consideration are put to practice.

2.10 Hardware and pricing

Table 1 shows the costs per item associated with an HT Ecovat inside an LT Ecovat. Placing the HT Ecovat outside of the LT Ecovat would mean a cost reduction of € 447.573. A detailed description of the realisation of the table can be found in the 'business case' document as delivered to Ecovat. The overall price of the pebble bed including the infrastructure is fairly similar to prices seen in literature (Jacob, Saman, & Bruno, 2017).

Cost Item	Capex
HT Diepwand	€333.352
HT Airtight RVS vessel	€50.000
HT air heater and piping	€25.000
Piping from ORC to LT ERC	€138.820
ORC per kWe	€1.300
Upgrade cost HT Epic	€25.000
HT storage material	€31.758
HT insulation	€119.381
HT air fans	€50.000
Labour and construction	€250.000
LT Element increase	€99.120
Savings on heaters and heatpumps	€258.495
Savings on centre pillar	€54.000
LT increased spouw	€19.101
Instrumentation and control	€7.034
Trafo increase	€11.200
Price per m cable	€73
Increased grid connection	€129.546
HT Heater	€150.400
Total	€2.127.289

Table 1. Cost per item

3 Energy flow

3.1 Energetic simulation

In order to investigate the energetic performance of an HT Ecovat, an energy flow model is made that considers the energy flows(heat and electricity) of a specific case, The model comprises the energy production, consumption and storage.

The parameters of the model can be altered in excel, hence allowing a simple user interface. The simulation itself is executed in python, which allows an easier adaption of the code later on. The main code that calls all functions in included in appendix B. The output is again displayed in excel. A detailed description on the usage of the model is included in the main excel document and the python script.

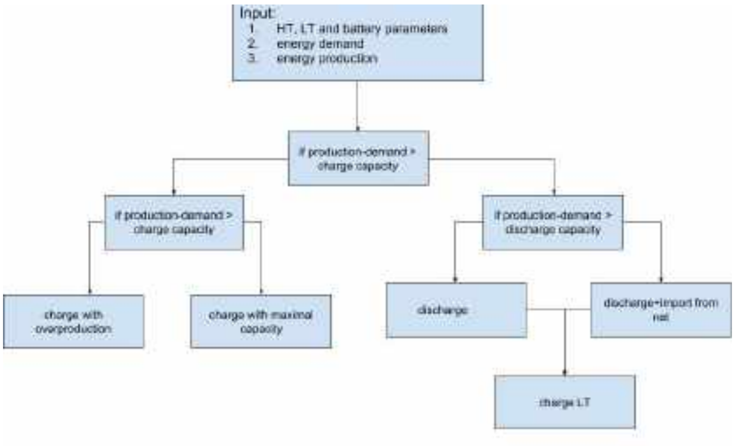


Figure 6. Simplified schematic overview of the python algorithm

3.2 Scenario

Allowing an evaluation of the performance, the parameters of the system itself should first be optimised. Optimising the parameters of a pebble bed, ORC, heater and LT Ecovat should always been done case specific. Figures used in the following explanation are derived using the case of a number of households and the production of electricity with 100% sustainable sources, namely, solar and wind power. The household electricity profiles are based on a future scenario of 2022 which are made available by 'de Vereniging Nederlandse EnergieDataUitwisseling' (NEDU). A distinction is made between heat demand for tap water and space heating. This distinction is made since space heating can be done with a minimal temperature of 40 degrees, whereas tap water needs a minimum temperature of 75 degrees. The total space heating demand is set as maximally allowed by the new BENG policy to which newly built dwellings have to adhere. The total tap water demand is kept constant. The wind and solar production are based on radiation and wind profiles of the Netherlands. The ratio of the production between sun and wind is an input parameter of the model and can be tweaked, just as the total production.

The analysis is based on the heat demand of 2000 households as this is close to the maximum amount of households that can supplied by an LT Ecovat. The electricity profile is also based on these two thousand households in order to show the self-sufficiency that can be reached using an LT Ecovat in cooperation with an HT Ecovat. Moreover, it is a system that is most likely to be implemented in the future.

Due to the ramp up an ramp down of an ORC, the minimum operational time is approximately 1 hour. Therefore, alongside the HT Ecovat, a Li-Ion battery is included in the simulation to bridge these shortages and design a scenario that fits the future. The Li-Ion battery will be reasonably sized considering the demand and production profile, however, its specific performance is of little interest.

3.3 Optimisation process

An HT Ecovat will always be operating together with an LT Ecovat as the LT Ecovat increases the value of the waste stream of the ORC. Therefore it is chosen to set the production such that the heat demand can be fulfilled by normal functioning of the LT Ecovat and the added 'waste' stream of the ORC. The model works in such a way that excess electricity, i.e. production minus the demand, will first be stored in the pebble bed. Any leftover electricity will, if its capacity allows, be absorbed by the LT Ecovat, before being fed back into the grid.

Fixing the production allows to scale the HT Ecovat while minimising imported electricity. However, reducing the imported electricity to zero would result in a very large storage and a peak power capacity that will only be used once a year. Therefore, minimising imported electricity while optimising the pebble bed and ORC parameters is an iterative process,

Important parameters that are related to the HT Ecovat are

- Maximum charging power, mainly dependent on the heater unit.
- Maximum discharging power, mainly dependent on the ORC unit.
- Storage capacity, mainly dependent on the size of the pebble bed.

The other input parameters of the HT Ecovat are a result of performance limitations of the ORC, pebble bed and heater. The input parameters of the LT Ecovat are based on the existing design. The most important system variables are displayed in the table below:

Adjustable Parameters							
demand/ production	Sun percentage	Total heat demand per household	Total Electricity demand per household	Total production per household	Ratio tap vs heating	Number of households	
	17%	6.4	4	6.7	1	2000	
					1		
High temperature	pebble bed capacity (MWh)	HT charging eff	Thermal eff	HT Electrical eff	HT charge capacity	HT discharge capacity	Minimum partial load
	10	96%	78%	20%	6	1.2	20%

Table 2. Adjustable parameters

The average power output as function of the maximum capacity of the ORC has to be maximised, i.e. the utilisation factor, in order to rightly dimension the ORC. Moreover, the operational ORC hours should be maximised as well as the full operational cycles of the pebble bed, since increasing the pebble bed storage will also significantly increase the instalment costs. Lastly, the HT usage, i.e. the percentage of the total electricity demand provided by the HT storage, should be maximised.

3.4 Analysis

The following table shows the most important resulting parameters of the simulation concerning the HT Ecovat.

Results HT	
Total direct energy use	89%
Total HT use	3.9%
Total net use	6.7%
Delivered energy by HT in MWh	313.23
Total stored energy in pebble bed in MWh	-1566
Operational ORC hours	737
Full load hours	261
Average energy output MW	0.43
Average power output as percentage of maximum power	35%
Full cycles of the pebble bed	156.6
Size of battery as a fraction of average energy demand per day	0.5
Percentage of tap water covered by HT discharge	19%

Table 3. Results HT

A first simulation is done while having the adjustable parameters as displayed on the previous page. The outcome of the simulation is displayed above. When increasing the pebble bed capacity to 30 MWh, the total HT use increases substantially to 5.9%. Moreover, also the average power output, .i.e. full load hours increase up to 396 hours. On the contrary, the effective usage of the pebble bed capacity decreases from 156 full cycles to 80 full cycles.

Decreasing the maximum discharge capacity of the ORC to 1 MW, decreases the total HT usage to 6%. It slightly decreases the average power output, but since the size of the ORC is smaller, it increases the full load hours. An increase of total power output when decreasing the ORC seems contra intuitive. However as a consequence of the smaller size, the ORC is also able to supply smaller powers at partial load. Apparently, an ORC of 1.2 MW was oversized for the current demand.

Decreasing the size of the ORC further, up till 0.6 MW, only has a small effect on the total delivered energy. However, as can be seen in the histograms underneath, the ORC of 0.6 MW is producing much more often at its maximal capacity, whereas the ORC of 1 MW is more often producing at a partial load. The ORC of 0.6 MW would be more desirable if one looks at the efficiency of the system and the full load hours. On the other side, the ORC of 1 MW is more suitable to effectively reduce the peak load which, as will be elaborated upon in the next chapter, is important from a financial point of view.

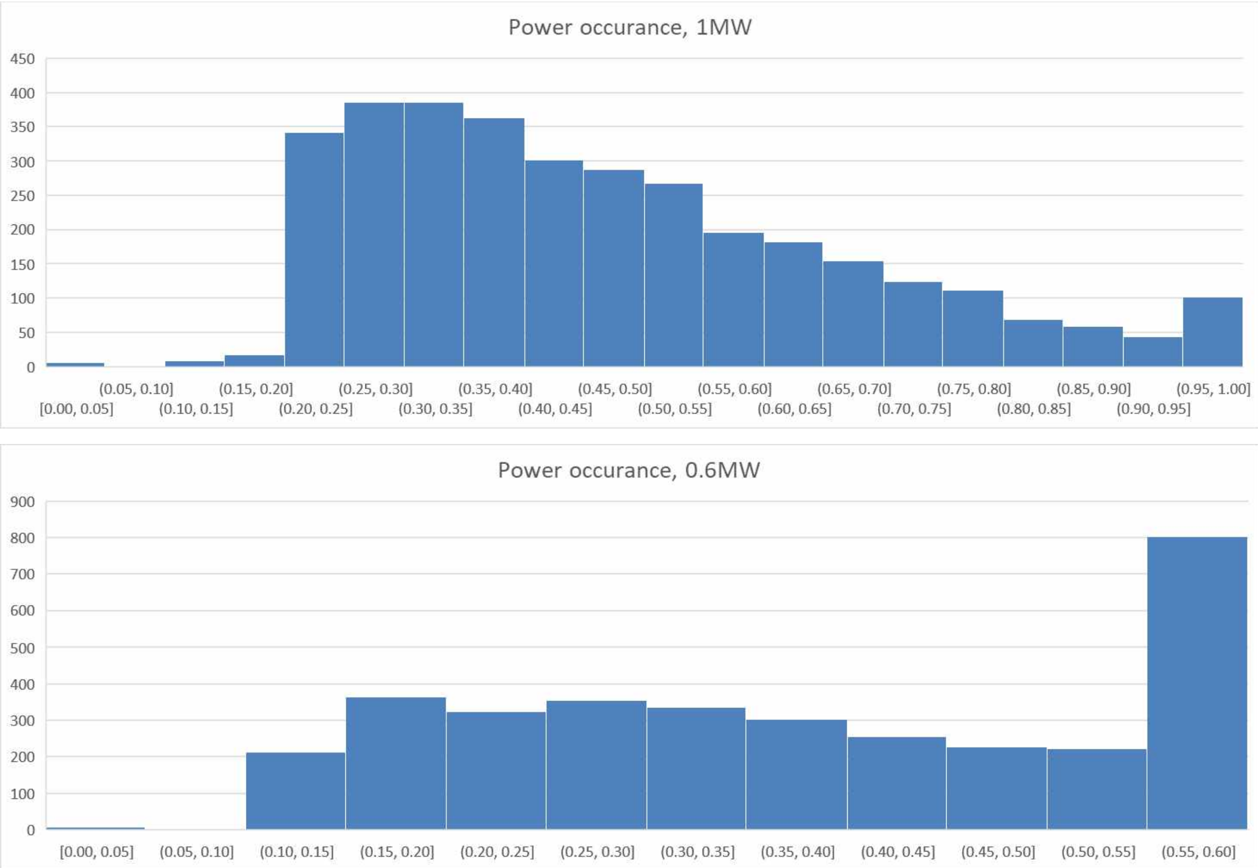


Figure 7. Power occurrence

Results HT	0.6MW	1MW
Total direct energy use	89%	89%
Total HT use	6.1%	5.9%
Deliverd energy by HT in MWh	485.08	471.36
Operational ORC hours	1244	977
Full load hours	808	471
Average energy output MW	0.39	0.48
Average power output as percentage of maximum power	65%	48%
Full cycles of the pebble bed	80.8	78.6

Table 4. Results HT

Increasing the production per household to 7.2 MWh decreases the direct energy usage only by 1%. Moreover the total HT usage as percentage of the total demand is decreased by 0.5% and a rather substantial part of the produced electricity is forced onto the net as the total heat demand is easily met by the LT.

Increasing the solar factor to 35 % with a production of 6.7MWh and an ORC of 1MW, yields an HT usage of 7.4% and a net usage of 7.6%. So apparently the storage is utilised more, however, there is also less direct sustainable energy usage which decreases from 89% to 85%. So apparently, with the current data, the demand is better matched by a solar fraction of 17% than a solar fraction of 35%. The other performance indicators are quite resilient to a change of the solar/wind ratio, e.g. the average power output of the ORC changes from 0.48 to 0.5. What must be noted is that production of high quality heat does increase substantially with the increase of the HT usage, namely, from 86% to 100%. The production of high quality heat means the increase of LT Ecovat water from 70 to 90 degrees Celsius. As can be seen in the following two histograms, the spread of excess or deficit power is higher with an increased solar fraction, needing larger power ranges of the hardware. In the cumulative power figure, the total overproduction is plotted as a percentage of the instantaneous power output. One can see that about 95% of the total power is delivered below 4 MW, hence, installing a heater at 4 MW reduces the investment costs and has a limited effect on the power the pebble bed is able to absorb.

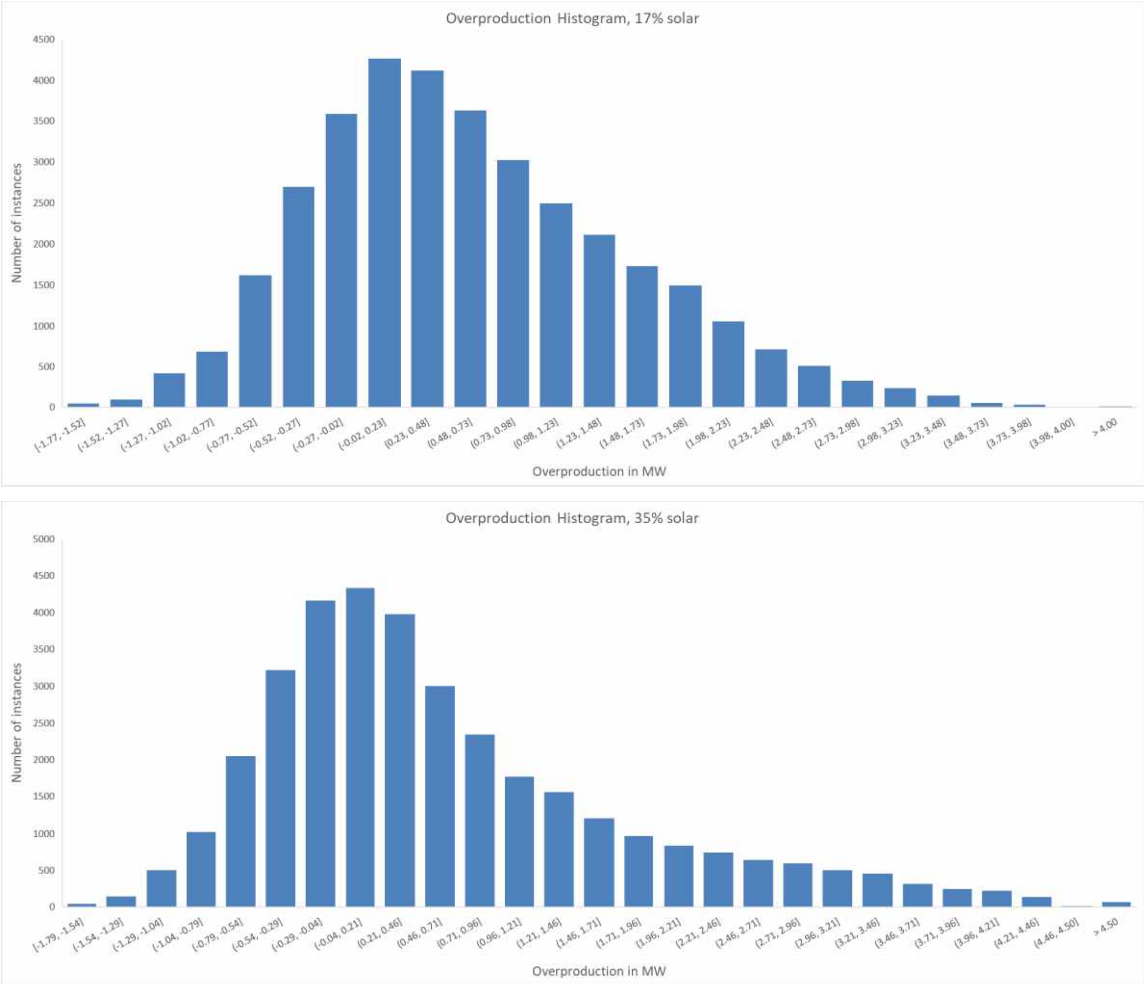


Figure 8. Overproduction histogram

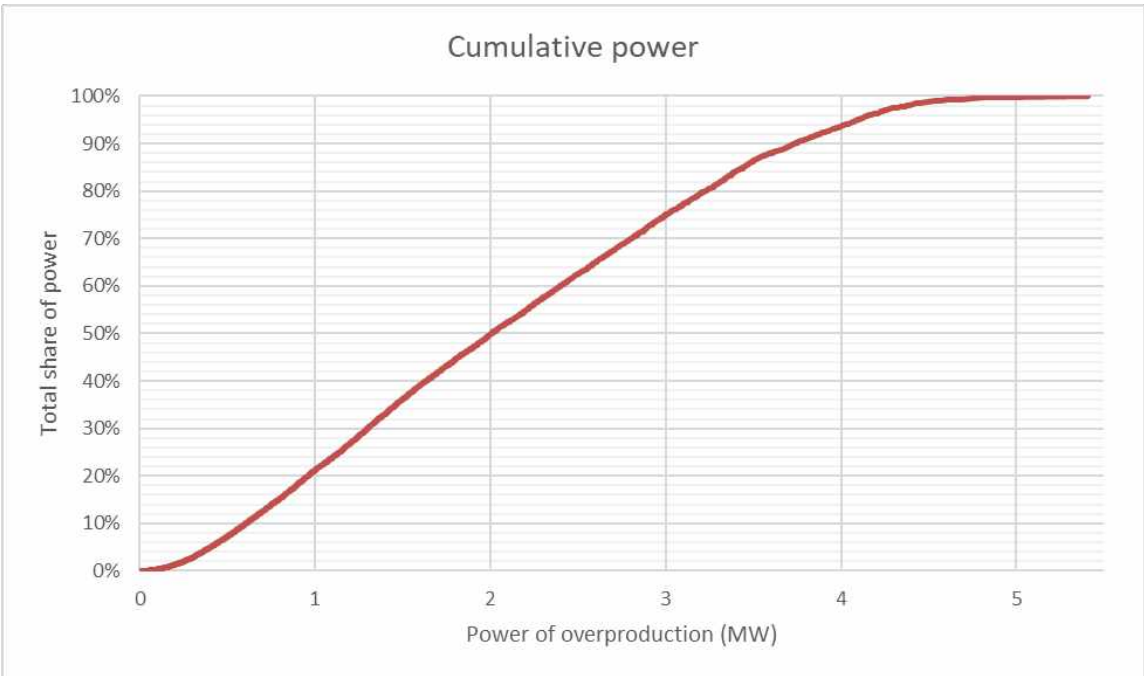


Figure 9. Cumulative power

The li-ion battery also included in the model provides 1% to 2% of the demand in the different simulations.. The battery is scaled at 1 MWh. Considering the size, the battery provides a relative large part of the energy need. Moreover, its efficiency is much larger than that of a HT Ecovat from an electricity point of view. Especially for short fluctuations, it is advisable to install a battery alongside an HT and LT Ecovat.

When inspecting the heat demand, decreasing solar as part of the total electricity production up to 17% results in a better match between electricity surplus and heat demand. This means that a smaller LT Ecovat is necessary in order to provide heat year round. An LT storage with a size of 1/3 of the total demand can potentially be reached, or, in other words, 3 full cycles can be made. The current design of an LT Ecovat considers 3 full cycles to be optimum. Decreasing the number of full cycles, means that one needs a larger storage, hence decreasing the economic performance of an LT Ecovat.

As the simulation shows, the 1 MW ORC seems to be most suitable in case there is an interest in supplying the peak loads. It must be noted that this is for a case with 2000 households, meaning the maximal heat demand an LT Ecovat can provide. In the simulation, a maximum of 100 percent of the high quality heat was provided by the HT to the LT Ecovat. Hence the HT Ecovat is rightly dimensioned considering the most optimal delivery of high quality heat to the LT Ecovat for tap water usage. Increasing the HT usage would mean that this high quality heat cannot be capitalised anymore and has to be drained.

4 Financial

A quick preliminary analysis of the HT Ecovat already shows that that the system, as of yet, is not economically viable. However, as electricity consumption will increase with 19% to 45% by 2050, all coal powerplants are closed by 2030 and the adoption of wind and solar power will increase drastically(DNV-GL ETO 2018), the HT Ecovat proposition has a chance to become profitable. In order to analyse the economic viability in the future, the current electricity market is shortly described, thereafter, likely changes to the current system are elaborated upon. Lastly, the HT Ecovat proposition is described and evaluated on its potential.

4.1 Current system

Market

Currently, there are three markets one can trade on, these are the day-ahead market, the intraday market and the imbalance market.

Day ahead is used to fill the demand of the next day with the cheapest electricity providers. In order to do this, marginal cost and merit order are used. Marginal cost are the actual costs that are made to produce one unit of electricity. So for a coal plant, the marginal cost are among other things, the coal that has to be burned, the efficiency of the plant and the pay check of the operators. To determine the merit order, all marginal costs and their available capacity are ranked from cheap to expensive. The best price for which the demand can be covered determines the price of the merit order. Since renewable sources like windmills and solar PV panels have a marginal cost close to zero, the merit order is used to pay back the CAPEX.

On the other side of the spectrum is the imbalance market. The imbalance market is taking care of temporary shortages. Parties that trade on the imbalance market should be able to deliver their bid within the minute. Moreover, they should be able to provide the power for at least 15 minutes. If the shortage lasts for longer than 15 minutes the intraday market opens up. The opportunity to participate in this market closes an hour before the moment of supply, moreover, the supplier should be able to deliver within 15 minutes. The delivered MWhs are payed along with a standard capacity compensation.

Transport costs

Other than trading, one also has to account for transportation costs. These transportation costs are based on both the contracted power and the real maximum power peak. The contracted power is static, i.e. even if the contracted power is not used it is still being paid for. The real maximum power peak is paid for regardless of the place or time the power peak is demanded. Contracted power is not applicable for large consumers.

Taxes

The main proportion of the price of electricity consists of taxes. These taxes have to be paid for consumed electricity. However, the law does not differentiate between electricity that is directly consumed or electricity that is consumed by a storage and later on, fed back into the grid. Therefore, electricity taxes are paid for at the storage and at the final consumption.

4.2 Future system

A forecast of the energy market in 30 years is difficult to make, however, taking into account current developments, large patterns can be identified.

In order to realize the energy transition, large capacities of solar PV power and wind power have to be installed. More so because they have far less running hours conventional power plants. A 100% renewable scenario made by Siemens (Hoffmann, 2012) includes 35% production of energy by solar panels and 65% by wind turbines. In order to suffice the load, a capacity of 462% and 264% of the average load should be installed of respectively solar and wind power.

As solar PV and wind power are likely to be the most dominant renewable energy technologies, they are also going to have the largest impact on the system and the related imbalance. The effect of solar PV is clearly visible during summer, the storage charges during solar PV generation and discharges from the evening till the next morning. During winter, the imbalance is caused by the difference between wind supply and demand since the production by solar PV is very low. Since wind has a relative flat production during the day, the imbalance is mainly influenced by the peaks of demand in the morning and afternoon.

Market

The current government(Rutte III) is introducing a minimal price for CO2 for electricity companies, this will stop the current decline in electricity prices, moreover, the coal powered plants are planned to shut down by 2030. When the coal plants are shut down, the merit order during peak power supply will be largely influenced by gas power plants, which have a higher associated marginal cost.

The introduction of renewable energy sources with a marginal cost of zero will enter the merit orders on the left, pushing the higher marginal cost to the right. Hence, when the majority of the electricity is produced by renewable sources, the price of electricity will become cheaper on the day-ahead market. This can even drop to zero with a very high penetration of renewables. When subsidies are in place, it might still be profitable to produce energy with negative prices on the day ahead market as has been seen in Germany. However, as subsidies tend to reduce for renewables, this is not expected to be part of a scenario by 2030. Unfortunately, the reduced energy price, will also negatively influence the adaption of renewables as their share becomes larger and profitability will drop.

During periods of low production by renewables, a high price will arise from which the renewables cannot profit themselves. However the conventional plants might not be able to fill this gap because of environmental regulations or their high operational costs accompanied by their high investment costs. Storage on the other hand has the possibility of converting low value electricity to high value electricity, by introducing a delay on the day-ahead market. So essentially, they can prevent sustainable sources from shutting down by taking up their produced electricity and selling it when prices are high.

A study by DNV-GL on the future of the energy system expects that the frequency of the fluctuation of price will not increase substantially, however, a price of zero will happen more often. Moreover, although the frequency will not necessarily differ, the amplitude will increase. DNV-GL states that the heights and lows of the fluctuations can be increased with 25% to have an estimation for 2030. Moreover, the most significant price differences will not be within a day but be in a time span of 2 to 3 days. The average price fluctuation within a period of 6 hours will be between the 10 and 20 euros for all considered scenarios by DNV-Gl.

A key observation of DNV-GL is that the lack of flexibility is one of the largest bottlenecks for the energy transition.

Transport costs

Paying for the peak power is essentially a penalty on either producing or consuming high amounts of power. However, these cost do not take into account the place or the time the peak power is demanded. A storage however, has the ability to enhance grid capacity in certain use cases while using its peak power. By letting the transportation cost follow the wholesale market price, flexibility will be encouraged further as advocated by the 'Markt en Flexibiliteits' report published by CE Delft (2016).

Taxes

The current Dutch government has acknowledged the major drawbacks of taxing stored electricity, therefore they plan is to quit double taxing, however, this has not been implemented yet.

4.3 Proposition Ecovat

An HT Ecovat has a multi-component proposition within the changing energy system and market.

In order to handle the increase in peak power and the imbalance as discussed, the grid has to be expanded and reactive components like storage have to be added. TenneT is responsible for the high voltage grid and to ensure a stable grid in the Netherlands. As for now the relatively low penetration of renewables in the grid does not cause major instability issues, however, this is changing. It may be too costly to maintain conventional powerplants as these peak power plants tend to have very few running hours and high maintenance costs. Instead, the HT Ecovat can be added to the net as a reactive component. It can absorb energy in cases of a surplus(price is zero) and deliver when there is an energy deficit(prices are high). This means that in a combination with renewables it can enable a reliable energy supply for the future. Moreover, it prevents renewable sources to be shut down in case of a temporary surplus as is already shown in the German market. Hence it enables the utilisation of the entire potential of renewables in the future.

However, the increase in amplitude of day-ahead prices alone will not enable a profitable business case for storage. If policies will not be changed, Tennet has the responsibility to ensure this stability, hence it will be their responsibility to invest in storage systems. In order to maintain a healthy market for renewables and utilise their potential, there should be an equivalent of the 'stimuling duurzame energie' subsidy (SDE) for storage. This would enable to continuous production of renewable energy even in times when there will be a high renewable energy penetration as the storage can convert low value energy to high value energy.

Next to energy balancing, the HT Ecovat has the possibility to prevent multiple cases of net congestion at a local level. In case of semi-centralised sustainable electricity production an Ecovat would be beneficial close to the production. The HT Ecovat is than able to absorb electricity at moments of peak production by the local source. Moreover, a grid connection is most often scaled for peak demand. However, when demand is high and production is low, the HT Ecovat can lower the peak power flowing through the net connection and hence lower the installed capacity.

Next to the function the HT Ecovat can fulfil in the electricity grid, it also has the potential to enhance the performance of the LT Ecovat. Nowadays, both tap water and space heating are heated using gas. In the future this heat will have to be generated using alternative sources. Using electricity, a COP of 4 can be reached for low quality heat, reaching a maximum temperature of around 65. This low quality heat can be used for space heating, however, it is not sufficient for tap water. The waste stream of the ORC can be up till 85 degrees and does adhere to the requirements of tap water. As of now, there is no distinction between high quality and low quality heat since they can both be made with a similar efficiency using gas. However, without gas, the production of high quality heat will require much more energy relative to the production of low quality heat.

Although as explained above, the HT Ecovat can deliver vital functions in a new configuration of the energy market, current policies do not suffice. However, policies are subject to continuous change and with the current developments even more so. The benefits an HT Ecovat will provide should be capitalised in order to be profitable. Summarised, these benefits are: 1) the reduction of grid capacity, 2) utilising the full capacity of renewables, 3) securing electricity supply without the need of expensive back-up powerplants and 4) producing high quality heat.

4.4 Economic evaluation

The economic value of the HT Ecovat is evaluated using the internal rate of return(IRR) and the net present value(NPV). The money streams are calculated as if the HT Ecovat would be a stand-alone system trading on the APX day-ahead market. In reality, the cooling cycle of the ORC will be delivered by the LT Ecovat, by which the LT Ecovat will subsequently charge. In order to evaluate the HT Ecovat business case separately from the LT Ecovat, the waste stream is sold to the LT Ecovat for the price a separate LT Ecovat could produce this heat by means of heat pumps or electric boilers. Any avoided cost of the LT Ecovat through the reduction of needed installed capacity of heat pumps or electric boilers will be added to the business case of the HT Ecovat.

Furthermore, the assumption is made that charging the HT Ecovat always happens in case when the electricity price is lowest. So for example, if the electricity is bought at the 648 cheapest hours of the APX day ahead market if the pebble bed is charging for 648 hours. Moreover, the electricity is sold at the most lucrative hours. So if the ORC is turning for 808 hours, the 808 most expensive hours are used. An increase in price amplitude of 25% is implemented to model the market from 2030 onwards and the plan to quit double taxing of stored energy by the current government is implemented. Moreover, an inflation of 1.5% is used in order to calculate the NPV. Also the current SDE on solar panels and wind on sea, namely 53€/MWh is used as SDE prognoses for storage.

The parameters chosen as input for the business case are chosen based on the most promising setups determined in the energetic flow model. An overview of the table that is used as input for the economic evaluation can be found in appendix C.

The analysed setups are with a 35% vs 17% solar fraction and with either a 0.6MWe or 1MWe ORC. The total delivered energy when changing the ORC from 0.6MWe to 1MWe does not change significantly as discussed before. However, the 1 MWe ORC can discharge its total power in a shorter timeframe, this has the consequence that more of the power can be sold in the expensive hours. On the other side an ORC costs 1.300€ per kWe, hence a 400 MWe increase means an added investment of 520.000€. The corresponding CAPEX for both systems are 1.633.480€ and 2.153.480€ hence increasing the size of the ORC has a large influence on the CAPEX. Increasing the solar fraction to 35% has purely positive influences on the business case of storage. The running hours of the ORC are going up and the heat to the LT Ecovat provided by the electric boilers can completely be replaced by the ORC waste stream.

The most positive business case is obtained in case of a 0.6MWe ORC and 35% solar fraction. The resulting IRR is 0.6%, furthermore, the NPV is -322.000€ when inflation of 1.5% is applied. This shows that even with an increase of amplitude in the price and an added SDE for storage, a positive business case is not obtained. The advantages of the storage that are mentioned before should be capitalised in order to make the system financially viable.

5 Conclusion

Through an iterative process during which the techniques, markets, energy flows and policies where considered and discussed, an optimal storage system complementing the LT Ecovat has been designed.

In order to get to an optimal technical design a variety of sources have been consulted. Considering the ORC, the input from the industry on state of the art performance was leading. This was chosen since the performance encompasses all components which are not always included in literature.

As pebble bed storages are most often case specific designed and their usage is much more limited, literature was taken as a starting point. A simulation model was made in order to test a configuration fitting the system needs. Currently the largest pebble bed storage similar to the design proposed in this report is the one in Ait Baha, Morocco. Since it shows an efficiency of at least 95%, the results of the simulation seem achievable in a real case scenario(Geissbühler et al., 2016). Furthermore, the outcomes of the simulation were cross-checked with literature and showed a good resemblance. The outcomes of the technical design have been used as an input for the energy flow simulation.

The energy flow is used to find the best dimensions of the HT system in a future energy scenario. This was done by an iterative process. The simulation is made in such a way that it enables easy usage and can be adapted for other scenarios. The outcomes of the energy flow are used to calculate the profitability of the HT Ecovat. It must be noted that the simulation does not take into account a high penetration of EVs and their possibility to make the grid more flexible.

By implementing future scenarios, the profitability has been estimated for the future. Especially the inclusion of an SDE on storage is still very uncertain. However, other advantages of the HT Ecovat are not capitalised in the scenarios since the added value these advantages will provide are still very uncertain. Moreover, the mechanisms that will enable the capitalisation of these advantages are very speculative. As of now, an HT Ecovat cannot provide a viable business model with current policies and progressive future scenarios. Hence the future profitability of an HT Ecovat as presented in this report will strongly depend on how policies and markets will change regarding 1) the reduction of grid capacity, 2) utilising the full capacity of renewables, 3) securing electricity supply without the need of expensive back-up powerplants and 4) producing high quality heat.

Although an HT Ecovat does not seem profitable in the near future, a reliable cheap alternative has not arose either. A wide spread adoption of the LT Ecovat might even evoke interest of other businesses that see a possible synergy between an electricity storage and the large water reservoir. The advancement of technologies, markets and energy generation are decisive in what kind of energy storage will be most desirable for the future

6 References

Allen, K. G., von Backström, T. W., & Kröger, D. G. (2015). Rock bed pressure drop and heat transfer: Simple design correlations. *Solar Energy*, *115*, 525–536. https://doi.org/10.1016/j.solener.2015.02.029

Allen, K. G., Von Backström, T. W., & Kröger, D. G. (2013). Packed rock bed thermal storage in power plants: Design considerations. In *Energy Procedia* (Vol. 49, pp. 666–675). https://doi.org/10.1016/j.egypro.2014.03.072

Barton, N. G. (2013). Simulations of air-blown thermal storage in a rock bed. *Applied Thermal Engineering*, *55*(1–2), 43–50. https://doi.org/10.1016/j.applthermaleng.2013.03.002

Becattini, V., Motmans, T., Zappone, A., Madonna, C., Haselbacher, A., & Steinfeld, A. (2017). Experimental investigation of the thermal and mechanical stability of rocks for high-temperature thermal-energy storage. *Applied Energy*, *203*, 373–389. https://doi.org/10.1016/j.apenergy.2017.06.025

CE Delft, Hers, S., Rooijers, F., Afman, M., Croezen, H., & Cherif, S. (2016). *Markt en Flexibiliteit. Publicatienummer 16.3E90.35.* Retrieved from https://www.ce.nl/publicaties/1805/markt-en-flexibiliteit

Colonna, P., Casati, E., Trapp, C., Mathijssen, T., Larjola, J., Turunen-Saaresti, T., & Uusitalo, A. (2015). Organic Rankine cycle power systems: A review. In *ICOPE 2015 - International Conference on Power Engineering*.

Geissbühler, L., Kolman, M., Zanganeh, G., Haselbacher, A., & Steinfeld, A. (2016). Analysis of industrial-scale high-temperature combined sensible/latent thermal energy storage. *Applied Thermal Engineering*. https://doi.org/10.1016/j.applthermaleng.2015.12.031

Hänchen, M., Brückner, S., & Steinfeld, A. (2011). High-temperature thermal storage using a packed bed of rocks - Heat transfer analysis and experimental validation. *Applied Thermal Engineering*, *31*(10), 1798–1806. https://doi.org/10.1016/j.applthermaleng.2010.10.034

Jacob, R., Saman, W., & Bruno, F. (2017). Capital cost expenditure of high temperature latent and sensible thermal energy storage systems. In *AIP Conference Proceedings*. https://doi.org/10.1063/1.4984433

Li, C., & Wang, H. (2016). Power cycles for waste heat recovery from medium to high temperature flue gas sources – from a view of thermodynamic optimization. *Applied Energy*. https://doi.org/10.1016/j.apenergy.2016.08.007

Macdonald, I. F., El-Sayed, M. S., Mow, K., & Dullien, F. A. L. (1979). Flow through Porous Media—the Ergun Equation Revisited. *Industrial and Engineering Chemistry Fundamentals*. https://doi.org/10.4103/0366-6999.228249

Quoilin, S., Broek, M. Van Den, Declaye, S., Dewallef, P., & Lemort, V. (2013). Techno-economic survey of organic rankine cycle (ORC) systems. *Renewable and Sustainable Energy Reviews*.

https://doi.org/10.1016/j.rser.2013.01.028

Sanne Lemmens. (2016). A Perspective On Costs And Cost Estimation Techniques For Organic Rankine Cycle Systems. *3rd International Seminar on ORC Power Systems (ASME ORC 2015).* Retrieved from https://www.researchgate.net/publication/301355421_A_PERSPECTIVE_ON_COSTS_AND_COST_ESTIMATION_TECHNIQUES_FOR_ORGANIC_RANKINE_CYCLE_SYSTEMS

Tian, Y., & Zhao, C. Y. (2013). A review of solar collectors and thermal energy storage in solar thermal applications. *Applied Energy*. https://doi.org/10.1016/j.apenergy.2012.11.051

Torab, H., & Beasley, D. E. (1987). Optimization of a packed bed thermal energy storage unit. *Transactions of the ASME. Journal of Solar Energy Engineering*, *109*(3), 170–175. https://doi.org/10.1115/1.3268201

Vankeirsbilck, I., Vanslambrouck, B., Gusev, S., & De Paepe, M. (2011). ORGANIC RANKINE CYCLE AS EFFICIENT ALTERNATIVE TO STEAM CYCLE FOR SMALL SCALE POWER GENERATION. In *8 th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics*. Retrieved from https://repository.up.ac.za/bitstream/handle/2263/41796/Vankeirsbilck_Organic_2014.pdf?sequence=1&isAllowed=y

Zanganeh, G., Pedretti, A., Haselbacher, A., & Steinfeld, A. (2015). Design of packed bed thermal energy storage systems for high-temperature industrial process heat. *Applied Energy*, *137*, 812–822. https://doi.org/10.1016/j.apenergy.2014.07.110

Zanganeh, G., Pedretti, A., Zavattoni, S. A., Barbato, M. C., Haselbacher, A., & Steinfeld, A. (2013). Design of a 100 MWhthpacked-bed thermal energy storage. In *Energy Procedia*. https://doi.org/10.1016/j.egypro.2014.03.116

Zanganeh, G., Pedretti, A., Zavattoni, S., Barbato, M., & Steinfeld, A. (2012). Packed-bed thermal storage for concentrated solar power - Pilot-scale demonstration and industrial-scale design. *Solar Energy*. https://doi.org/10.1016/j.solener.2012.07.019

Zavattoni, S. A., Barbato, M. C., Pedretti, A., Zanganeh, G., & Steinfeld, A. (2014). High temperature rock-bed TES system suitable for industrial-scale CSP plant - CFD analysis under charge/discharge cyclic conditions. In *Energy Procedia*. https://doi.org/10.1016/j.egypro.2014.01.165

7 Appendices

7.1 Appendix A

```
# coding: utf-8

# %% Simulation based on: "Rock bed pressure drop and heat transfer:
Simple design correlations" & Performance characteristics of packed bed
thermal energy storage for solar thermal power plants
#  This model neglects conductive or radiative heat transfer through
the bed
#  as showed by Zanganeh et al. (2012) at mass fluxes less than
0.1kg/m2/s
#  radiation and conduction through the bed have to be investigated
#  experimentally
#  packing direction has a large influence on pressure drop, but little
on
#  heat transfer
#  Change in air temperature as a function of time can usually be
ignored,
#  much smaller than the change in air temp along the flow. For small
#  changes in well conducting particles,



# In[ ]:


import numpy as np
import math as mt
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import axes3d
from matplotlib import cm

from calculate_losses import calculate_losses_to_LT_vessel
from pb_pump import calculate_PePump

# In[physics]:

# In[physics]:

p = 101300 #pascal atmospheric pressure
Rspec = 287.06 #J/(kg*K) specific gas constant for dry air
rhoair1 = 0.78;  # at 180 celsius
rhoair2 = 0.43;  # at 530 celsius
rhoair12 = (rhoair1+rhoair2)/2
rhobed = 2700; #kg/m3 Density of the bed material
mu = 2.81*10**-5; # Dynamic viscosity of the medium
Cpair1 = 1.022*1000 #J/kg.K at 180
Cpair2 = 1.099*1000 #J/kg.K at 530
Cpair12 = (Cpair1+Cpair2)/2
Cpbed = 840 #J/kg/K Dincer et al (1997).
```

```
# In[]:

# key parameters
kWth_ORC = 5000 # amounts of thermal MWs going into the ORC
kWth_heater = 4000
T_ORC_out = 250+273     # C temperature of the air coming into the bed
T_ORC_min = 380+273 # minimum temperature at which the ORC is able to
operate
T_heater = 600+273  # C temperature of the air coming from the heater
Dbed = 8 # diameter of bed
L = 7 # m The L of the bed
A = Dbed**2/4*mt.pi # m2 cross sectional area of the bed
dp = 0.04; # The equivalent spherical diameter of the packing
eps = 0.35; # The void fraction of the bed (bed porosity)
h = 15 # W/m^2/K Taken from reference case
k = 3 # W/m/K for granite




# parameters
Twater = 70+273 #K average temperature of the water on the sides of the
pebble bed
mbed = A*L*rhobed*(1-eps) # mass bed
Qbed = (T_heater-T_ORC_out)*mbed*Cpbed/(3600*1000*1000)
Tbed0 = 500+273    # C temperature of the bed before being charged or
discharged
ncycli = 1
Nseg = 1 #number of segments of the bed
dx = 0.1       # L increment
dt = 1      # time increment
charge = 300   # time in minutes
discharge = 300   # time in minutes
standbytime = 0 # time in minutes
standbytime = standbytime*60     # s total time in seconds
dischargetime = discharge*60
chargetime = charge*60     # s total time in seconds
simtime = (standbytime+chargetime+dischargetime)*ncycli
Lseg = L/Nseg # lenght per segment
wall = mt.pi*Dbed*L # surface area of the pebble bed wall
top = A
bottom = A
# hvol = h*(1-eta)*(6/dp)


# initialising
Tair = int(0)* np.ones([int(simtime/dt),int(L/dx)])
Tbed = int(Tbed0)* np.ones([int(simtime/dt),int(L/dx)])
Qdis = np.zeros([chargetime,1])
dm_log = np.zeros([int(simtime/dt),1])
PePump_log = np.zeros([int(simtime/dt),1])
energy_log = np.zeros([int(simtime/dt),1])
decision_matrix = np.zeros([int(simtime/dt),1])
Qlosstotal = 0  # MWh total loss
Qlosstotalwall = 0  # MWh total loss
Qlosstotaltop = 0  # MWh total loss
Qlosstotalbottom = 0  # MWh total loss
n = 0
```

```
## A valid biot number has yet to be confirmed.
Bi = h*dp/k/6


# In[]: create as input for the pebble bed model

for t in range (0,int(simtime/dt)):
    if n >= int((chargetime+dischargetime+standbytime)/dt):
        n=0
    if n < int(chargetime/dt): #charging
       decision_matrix[t] = 0
    elif int(chargetime/dt) < n <= int((dischargetime+chargetime)/dt):
#discharging
       decision_matrix[t] = 1
    elif int((dischargetime+chargetime)/dt) <= n <=
int((dischargetime+chargetime+standbytime)/dt): #standby
       decision_matrix[t] = 2
    n=n+1

# In[ ]:

for n in range (0,Nseg):
    for t in range (0,int(simtime/dt)):
        if t == simtime/dt-1:
            continue
# First calculate the losses of the vessel as function of x
        for x in range (0,int(L/dx)):
            DT=Tbed[t,x]-Twater # temperature difference between pebble
bed en water
            Qlosswall, Qlossbottom, Qlosstop =
calculate_losses_to_LT_vessel(DT,x,wall,top,L,dx,dt)
            Tbed[t,x] = Tbed[t,x]-
(Qlosswall+Qlossbottom+Qlosstop)/(mbed/(L/dx))/Cpbed
            Qlosstotal = Qlosstotal +
(Qlosswall+Qlosstop+Qlossbottom)/(3600*1000*1000)
            Qlosstotalwall = Qlosstotalwall +
(Qlosswall)/(3600*1000*1000)
            Qlosstotaltop = Qlosstotaltop + (Qlosstop)/(3600*1000*1000)
            Qlosstotalbottom = Qlosstotalbottom +
(Qlossbottom)/(3600*1000*1000)


# Determine the charge and discharge parameters
        if decision_matrix[t] == 0:
            load = 'charge'
            Tair_in = T_heater
            Tair_out = Tbed[t-1,0]
            energy = kWth_heater
            if Tair_out >= T_heater-10:     #if the bottom is has
heated up till T_heater-10, charging can be halted
                load = 'fully_charged'
                Tbed[t+1,:] = Tbed[t,:]
                energy = 0
                continue
            entrance = int(Lseg/dx-1)
        elif decision_matrix[t] == 1:
            load = 'discharge'
```

```
            Tair_in = T_ORC_out
            Tair_out = Tair[t-1,int(L/dx)-1]
            if Tair_out <= T_ORC_min:
                Tbed[t+1,:] = Tbed[t,:]
                continue
            energy = kWth_ORC
            entrance = 0
        elif decision_matrix[t] == 2:
            load = 'standby'
            Tbed[t+1,:] = Tbed[t,:]
            continue

        Cpair_in = Tair_in*0.2+952.1  # Cpair of the air flowing into
the bed
        Cpair_out = Tair_out*0.2+952.1  # Cpair of the air flowing out
of the bed
        dm = abs(energy*1000/(Tair_out*Cpair_out-Tair_in*Cpair_in)) #
difference in energy flowing in and out
        if dm>17:
            dm = 17
        dm_log[t] = dm
        G = dm/A; # kg/m2/s air mass flux
        hvol = 650*(dm/(A*dp))**0.7  # W/m**3K Hawley and Löf formula
for typical values for volumetric heat transfer coefficient

# Calculate pumping power
        PePump_log[t] =
calculate_PePump(Tair_out,Tair_in,load,dm,A,L,eps,mu,dp)
        Pepump =
calculate_PePump(Tair_out,Tair_in,load,dm,A,L,eps,mu,dp)
        energy_eff = dm*(Tair_out*Cpair_out-Tair_in*Cpair_in)/1000
        energy_log[t] = energy_eff
        energy_eff = abs(energy_eff)
        # if Pepump/energy_eff*0.1 >= 5:
        #    break

# Calculate the new state of the pebble bed as function of x and t
        for x in range (0,int(L/dx)):
            if load == 'discharge':        #discharging is from bottom
to top
                x1 = x
            elif load == 'charge':         #charging is from top to
bottom
                x1 = int(L/dx-x-1)
            Cpair = Tair[t,x1]*0.2+952.1   # a fit function that
performs well in the region between 150 and 1500 K, the heat capacity
is quite linear in this range
            NTU = hvol*L/(G*Cpair)
            eta = 1-mt.exp(-NTU*(dx/L));  # is it dx or x, dx, mistake
in the paper
            tau = mbed*Cpbed/(dm*Cpair)   # time constant

            if x1 == entrance:
                Tair[t,x1] = Tair_in
            if load == 'discharge':
                if x != L/dx-1:
                    Tair[t,x1+1] = Tair[t,x1] - (Tair[t,x1] -
Tbed[t,x1])*(1-mt.exp(-NTU*(dx/L)))
```

```
            elif load == 'charge':
                if x != L/dx-1:
                    Tair[t,x1-1] = Tair[t,x1] - (Tair[t,x1] -
Tbed[t,x1])*(1-mt.exp(-NTU*(dx/L)))
            Tbed[t+1,x1] = (Tbed[t,x1]*(1-
(dt/(2*tau)*(L/dx)*eta))+Tair[t,x1]*((dt/tau)*(L/dx)*eta))/(1+(dt/(2*ta
u))*(L/dx)*eta);


# In[]


DTair = Tair[int(chargetime/dt-1):int(simtime/dt),int(L/dx)-1]-
(T_ORC_out);   # K Temp between inlet and outlet
Q = dt*DTair*dm*Cpair12;     # Joule the air extracted from the bed
avPair = sum(Q)/chargetime/1000;        # kW average thermal power
output during time
Pair = Q/dt/1000;                # kW vector with instantenous power
output
totalQ = sum(Q)/3600/1000/1000;           # Total energy output in kWh
DTbed = T_heater-T_ORC_out;
Qbed = A*L*rhobed*(1-eps)*Cpbed*DTbed/3600/1000/1000; #kWh bed
potential
etap = Pepump/avPair # percentage of pump losses as fraction of the
thermal output
unloaded = (sum(Tbed[int(simtime/dt)-1,:])/(L/dx)-T_ORC_out)/(DTbed)  #
percentage of energy left in bed
etaloss = (Qlosstotal/(ncycli))/totalQ

#print(Dp,avPair,totalQ,Qbed,etap,unloaded,etaloss)

# In[ ]:



## number of houses that can be supplied with electricity

etaORC = 0.18   # ORC efficiency
Phouse = 0.4    # kw average household consumption
nhouse = avPair*etaORC/Phouse # number of houses


# for t = 1:time/dt
#         Qdel(t) = sum(Q(1:t)/3600/1000); #kWh delivered by air
# end





# In[ ]:

# getting a 100 grid points in the graph in order to minimise the data
in
# the plot

xlength = 300 # number of grid cell
ylength = 300 # number of grid cells
```

```
Tair1 = np.zeros([xlength,ylength])
Tbed1 = np.zeros([xlength,ylength])


simetimet = simtime/dt/xlength;
distst = L/dx/ylength;
for n1 in range (0,xlength):
    for n2 in range (0,ylength):
        Tair1[n1,n2] = Tair[int(simetimet*n1),int(distst*(n2))];
        Tbed1[n1,n2] = Tbed[int(simetimet*n1),int(distst*(n2))];

tar1 = np.linspace(1,xlength,ylength)
xar1 = np.linspace(1,xlength,ylength)
x = xar1
y = tar1


p = simtime/(simtime*dt/60)
dm_log1 = np.zeros([int(simtime*dt/60)])
PePump_log1 = np.zeros([int(simtime*dt/60)])
energy_log1 = np.zeros([int(simtime*dt/60)])

for n in range (0,int(simtime*dt/60)):
        dm_log1[n] = dm_log[int(p*n)];
        PePump_log1[n] = PePump_log[int(p*n)];
        energy_log1[n] = energy_log[int(p*n)]/1000;

pump_share = abs(PePump_log1/energy_log1*0.1)


# In[ ]:

X, Y = np.meshgrid(x, y)
Z = Tbed1
fig = plt.figure()
ax = fig.gca(projection='3d')
surf = ax.plot_surface(X, Y, Z, cmap=cm.coolwarm,
                       linewidth=0, antialiased=False)
#ax.contour3D(X, Y, Z, 10, cmap='binary')
ax.set_xlabel('lenght')
ax.set_ylabel('time(s)')
ax.set_zlabel('temp(K)');

ax.set_title('surface');


for angle in range(0,360):
    ax.view_init(40,190)

plt.show()


plt.plot(dm_log1)
plt.xlabel('time (min)')
plt.ylabel('mass flow (kg/s)')
plt.show()

plt.plot(PePump_log1)
```

```
plt.xlabel('time (min)')
plt.ylabel('pump power (kw)')
plt.show()

plt.plot(energy_log1)
plt.xlabel('time (min)')
plt.ylabel('charge/discharge energy (MW)')
plt.show()

plt.plot(Tbed[:,int(L/dx)-1])
plt.xlabel('time (min)')
plt.ylabel('Bed temperature top (K)')
plt.show()


plt.plot(Tbed[int(simtime/dt)-1,:])
plt.xlabel('time (min)')
plt.ylabel('Bed temperature top (K)')
plt.show()

plt.plot(pump_share)
plt.xlabel('time (min)')
plt.ylabel('pump fraction of energy throughput (%)')
plt.show()
```

7.2 Appendix B

```
# -*- coding: utf-8 -*-
"""
Created on Mon Oct 15 12:39:31 2018

@author: Lenovo
"""

import pandas as pd
import numpy as np
from pandas import DataFrame
import matplotlib.pyplot as plt
from Calculate_charge_HT import calculate_charge_HT
from calculate_charge_LiIon import calculate_charge_LiIon
from calculate_net import calculate_net
from calculate_charge_LT import calculate_charge_LT
from collections import Counter
from numpy import multiply


from xlutils.copy import copy # http://pypi.python.org/pypi/xlutils
from xlrd import open_workbook # http://pypi.python.org/pypi/xlrd
from xlwt import easyxf # http://pypi.python.org/pypi/xlwt


#%%

# Explanation on the usage of this program
"""
The excel_write_location file gets created by the code, the
excel_location should refer to the location of
the original excel file as this is the input for this program.

The excel_write_location has to be opened when the code has been
executed. The data can be copy pasted to the 'copy output' sheet
in the excel_location file. This will create
"""

# Explanation of the algorithm
"""
First, the electricity demand is subtracted from the produced
electricity. Thereafter, the electricity storage is given first
priority.
In case of electricity deficit, the storage is discharged and if
depleted the energy from the net is used. Excess produced energy and
thermal energy when discharging the HT storage is added to the LT
vessel. This takes into account the maximum allowable power that can
be processesed by the heat pumps.
"""


#%% initialising and loading all values


excel_location = "./storagemodel1.xlsx"
excel_write_location = './output.xlsx'
excel_location_sheet_name = "Python_input"
```

```
csv_write_location = './output.csv'


write = 'excel'           #either define csv or excel in order to
determine output file

prde = pd.read_excel(excel_location,excel_location_sheet_name)

HTcap = prde.loc[0,'pebble bed capacity MWh']
charging_eff = prde.loc[0,'HT charging eff']
thermal_eff = prde.loc[0,'Thermal eff']
electrical_eff = prde.loc[0,'HT Electrical eff']
HT_charge_cap = prde.loc[0,'HT charge capacity MW']/4    # divided by
four since it is quarterly data
HT_discharge_cap = prde.loc[0,'HT discharge capacity MW']/4    #
divided by four since it is quarterly data
LT_charge_cap = prde.loc[0,'LT charge capacity MW']/4
COP = prde.loc[0,'COP LT']
LiIon_cap = prde.loc[0,'Battery capacity MWh']
LiIon_charging_eff = prde.loc[0,'Battery charging eff']
LiIon_electrical_eff = prde.loc[0,'Battery Electrical eff']
LiIon_charge_cap = prde.loc[0,'Battery charge capacity MW']
LiIon_discharge_cap = prde.loc[0,'Battery discharge capacity MW']
Power_decision_parameter = prde.loc[0,'Power decision parameter MW']
Duration_decision_parameter = prde.loc[0,'Duration decision parameter']
Minimum_discharge_power = prde.loc[0,'Minimum discharge power HT MW']/4
# divided by four since it is quarterly data

p0 = HTcap
p1 = charging_eff
p2 = thermal_eff
p3 = electrical_eff
p4 = HT_charge_cap
p5 = HT_discharge_cap
p6 = LT_charge_cap
p7 = COP
p8 = LiIon_cap
p9 = LiIon_charging_eff
p10 = LiIon_electrical_eff
p11 = LiIon_charge_cap
p12 = LiIon_discharge_cap
p13 = Minimum_discharge_power
input_parameters = [p0, p1, p2, p3, p4, p5, p6, p7, p8, p9, p10, p11,
p12, p13]

hours = prde.shape[0]
heatdemand = prde['Heat Demand'].values
overproduction = prde['Production profile'].values-prde['Electricity
demand'].values # over production profile
prde = prde.values
HT_SOC_log = np.zeros([hours])
LiIon_SOC_log = np.zeros([hours])
net1_log = np.zeros([hours])
HTpower = np.zeros([hours])
LiIonpower = np.zeros([hours])
LTcharge = np.zeros([hours])
LT_charge_power_net_log = np.zeros([hours])
LT_charge_power_HT_log = np.zeros([hours])
```

```
LT_SOC = 0 # initial charge
HT_SOC = 0 # initial charge
LiIon_SOC = 0
net2_log = np.zeros([hours])
count_log = np.zeros([hours])
count2_log = np.zeros([hours])
count = 0
j = 0
count2 = 0
i = 0
check = 'false'
running = 'false'
HTflow = 0

#%% Calculating energy flows
print('simulation started')

for n in range(0,hours):

    diff = overproduction[n]
    LiIon_SOC_log[n] = LiIon_SOC
    HT_SOC_log[n] = HT_SOC
    # Calculate HT charge based on the overproduction, efficiencies and
maximal capacity

    # If 'potential' discharging lasts as long as the
duration_decision_parameter, use the HT pebble bed as back up
    if diff >= 0:
        check = 'false'
    elif diff < 0 and check == 'false':
        for t in range (0, int(Duration_decision_parameter)):
            if n >= hours -Duration_decision_parameter:
                check ='check'
            elif overproduction[n+t] < 0 and Minimum_discharge_power <
abs(overproduction[n+t]) and HT_SOC >=
Minimum_discharge_power*Duration_decision_parameter:
                check = 'check'
            else:
                check = 'false'
                break

    # check how long the ORC has been running, total discharge is only
aloud if it happens at the minimal discharge time
    if HTflow < 0:
        running = 'check'
    else:
        running = 'false'


    if check == 'check':
        HT_SOC, HTflow, diff= calculate_charge_HT(HT_SOC, diff,
input_parameters, check, running)
        LiIon_SOC, LiIonflow, diff = calculate_charge_LiIon(LiIon_SOC,
diff, input_parameters)

    # if discharging and the deficit is smaller than the power decision
parameter use the battery as back up
    elif  diff < 0 and abs(diff) < Power_decision_parameter:
```

```
        LiIon_SOC, LiIonflow, diff = calculate_charge_LiIon(LiIon_SOC,
diff, input_parameters)
        HT_SOC, HTflow, diff= calculate_charge_HT(HT_SOC, diff,
input_parameters, check, running)

   # for all other situations give HT pebble bed the priority
    else:
        LiIon_SOC, LiIonflow, diff = calculate_charge_LiIon(LiIon_SOC,
diff, input_parameters)
        HT_SOC, HTflow, diff= calculate_charge_HT(HT_SOC, diff,
input_parameters, check, running)
    # save the flow in an array
    HTpower[n] = HTflow
    LiIonpower[n] = LiIonflow

    # calculate  consecutive discharging hours
    if HTflow < 0:
        count = count + 1
    elif count != 0:
        count_log[j] = count
        count = 0
        j = j+1
    # calculate consecutive charge hours
    if HTflow > 0:
        count2 = count2 + 1
    elif count2 != 0:
        count2_log[i] = count2
        count2 = 0
        i = i+1



    # Calculate net load based on overproduction and state of charge of
the battery
    net = calculate_net(HT_SOC, HTflow, diff)
    net1_log[n] = -net
    # Calculate LT charge based on heat demand, and HT discharge
    heat_demand = heatdemand[n]
    LTcharge[n] = LT_SOC
    LT_SOC, diff, LT_charge_power_HT, LT_charge_power_net =
calculate_charge_LT(diff, heat_demand, LT_SOC, HTflow,
input_parameters)
    net2_log[n] = -diff
    LT_charge_power_HT_log[n] = LT_charge_power_HT
    LT_charge_power_net_log[n] = LT_charge_power_net

#%% Calculating energy flows

HTpower = -HTpower
LiIonpower = -LiIonpower
count_log = sorted(count_log[count_log != 0])
count2_log = sorted(count2_log[count2_log != 0])
HTpower_histo = (HTpower[HTpower != 0])
HTpower_histo = HTpower_histo[HTpower_histo >= 0]
underproduction = sorted(overproduction[overproduction < 0])
underproduction = underproduction[::-1]
overproduction = sorted(overproduction[overproduction > 0])
HTpower_histo = multiply(HTpower_histo,4)
```

```
undersummy = np.zeros([len(underproduction)+1])
undersummy1 = np.zeros([len(underproduction)])
underproduction1 = np.zeros([len(underproduction)])

overproduction = multiply(overproduction,1)
summy = np.zeros([len(overproduction)+1])
summy1 = np.zeros([len(overproduction)])
overproduction1 = np.zeros([len(overproduction)])

for n in range(len(overproduction)):
    summy[n] = summy[n] + overproduction[n]
    summy[n+1] = summy[n]


l = 0
for n in range(len(overproduction)):
    t = t+1
    if t == 10:
        summy1[l] = summy[n]
        overproduction1[l] = overproduction[n]
        t=1
        l = l+1

for n in range(len(underproduction)):
    undersummy[n] = undersummy[n] + underproduction[n]
    undersummy[n+1] = undersummy[n]


l = 0
for n in range(len(underproduction)):
    undersummy1[l] = undersummy[n]
    underproduction1[l] = underproduction[n]
    l = l+1

#%% Write outcome to a new excel file
c1 = pd.DataFrame({'HT SOC':HT_SOC_log})
c2 = pd.DataFrame({'LT SOC':LTcharge})
c3 = pd.DataFrame({'net before LT':net1_log})
c4 = pd.DataFrame({'HTpower':HTpower})
c5 = pd.DataFrame({'LT_charge_power by HT':LT_charge_power_HT_log})
c6 = pd.DataFrame({'LT_charge_power by net':LT_charge_power_net_log})
c7 = pd.DataFrame({'net after LT':net2_log})
c8 = pd.DataFrame({'Battery SOC': LiIon_SOC_log})
c9 = pd.DataFrame({'LiIon Power':LiIonpower})
c10 = pd.DataFrame({'consecutive discharging hours':count_log})
c11 = pd.DataFrame({'consecutive charging hours':count2_log})
c12 = pd.DataFrame({'HTpower hist0gram':HTpower_histo})
c13 = pd.DataFrame({'overproduction': overproduction1})
c14 = pd.DataFrame({'sum of overproduction':summy1})
c15 = pd.DataFrame({'underproduction': underproduction1})
c16 = pd.DataFrame({'sum of underproduction':undersummy1})



# Refresh database
import mysql.connector
```

```
mysqlconf={
'host' : 'arnekaas.nl',
'database' : 'arne_ecovat',
'user' : 'arne_ecovat',
'password' : 'HEtte123'}

cnx =
mysql.connector.connect(user=mysqlconf['user'],password=mysqlconf['pass
word'],host=mysqlconf['host'],database=mysqlconf['database'])
cursor = cnx.cursor()
cursor.execute("TRUNCATE TABLE HT_simulations")
cnx.commit()
cursor.close()
cnx.close()

# Import dataframe into MySQL
import sqlalchemy
database_username = 'arne_ecovat'
database_password = 'HEtte123'
database_ip       = 'www.arnekaas.nl'
database_name     = 'arne_ecovat'
database_connection =
sqlalchemy.create_engine('mysql+mysqlconnector://{0}:{1}@{2}/{3}'.

format(database_username, database_password,
                                                      database_ip,
database_name))

c17 = pd.DataFrame({'HT SOC':HT_SOC_log,'LT SOC':LTcharge,'net before
LT':net1_log,'HT power':HTpower,'LT_charge power by
HT':LT_charge_power_HT_log,'LT_charge power by
net':LT_charge_power_net_log,'net after LT':net2_log,'Battery SOC':
LiIon_SOC_log,'LiIon Power':LiIonpower})
for n in range(0,34):
    c17[n*1000+1:(n+1)*1000].to_sql(con=database_connection,
name='HT_simulations', if_exists='append')

# print(c17)
#%%



writer = pd.ExcelWriter(excel_write_location, engine='openpyxl')
c1.to_excel(writer, startcol=0, index=False)
c2.to_excel(writer, startcol=1, index=False)
c3.to_excel(writer, startcol=2, index=False)
c4.to_excel(writer, startcol=3, index=False)
c5.to_excel(writer, startcol=4, index=False)
c6.to_excel(writer, startcol=5, index=False)
c7.to_excel(writer, startcol=6, index=False)
c8.to_excel(writer, startcol=7, index=False)
c9.to_excel(writer, startcol=8, index=False)
c10.to_excel(writer, startcol=9, index=False)
c11.to_excel(writer, startcol=10, index=False)
c12.to_excel(writer, startcol=11, index=False)
c13.to_excel(writer, startcol=12, index=False)
c14.to_excel(writer, startcol=13, index=False)
c15.to_excel(writer, startcol=14, index=False)
```

```
c16.to_excel(writer, startcol=15, index=False)
writer.save()
print('simulation finished')
#%%

if write == 'csv':
    df =
pd.DataFrame([HT_SOC_log,LTcharge,net1_log,HTpower,LT_charge_power_HT_l
og,LT_charge_power_net_log,net2_log,LiIon_SOC_log,LiIonpower,count_log,
count2_log,HTpower_histo,overproduction1,summy1])
    df = df.transpose()
    df.to_csv(csv_write_location, index=False, header=None)





#

#%% Plot the energy flows

#
=======================================================================
======
# plt.plot(net_log)
# plt.show()
#
# plt.plot(HT_SOC_log)
# plt.show()
#
# plt.plot(LTcharge)
# plt.show()
#
# plt.plot(HTpower)
# plt.show()
#
# plt.plot(LT_charge_power_HT_log)
# plt.show()
#
# plt.plot(LT_charge_power_net_log)
# plt.show()
#
=======================================================================
======
```

7.3 Appendix C

LT case input					
		hours/efficiency	Power	unit	remarks
	LT boiler	288	0,5	MWth=MWe	
	LT heatpump	3500	0,44	MWe	
	COP	3	1,33	MWth	
	required grid connection		0,5	MWe	
	Charge heat		4800	MWh_th	
	Yearly LT cost	**hours**	**Price €/MWh**	**Cost**	**remarks**
	buying LT boiler	288	19,1	€ 2.749	buying price based on 288 cheapest hours
	buying HT heatpump	3500	29,5	€ 45.788	buying price based on 3500 cheapest hours
	Total cost of energy		10,1	€ 48.537	
HT case input					
		hours/efficiency	**Power**		**remarks**
	LT boiler	50	0	MWth=MWe	
	LT heatpump	3500	0,22	MWe	
	COP	3,1	0,67	MWth	assumption that fewer hours lead to high cop?
	ORC	1000			
	HT Electrical efficiecy	16%	0,5	MWe	Based on overall efficiency tab in energy model
	HT thermal efficiency	76%	2,4	MWth	Based on overall efficiency tab in energy model
	thermal losses to LT vessel	2%	0,1	MWth	
	HT HEATER	973	3,2	MWth=MWe	
	required grid connection		3,4	MWe	not used in cost calculations
	required LV transformer		0,5	MWe	not used in cost calculations
	Checks	**MWh**	**percentage**	**check**	**remarks**

	LT transformer size	-	100%	OK	Current trafo is over-dimensioned, to 1MVA.
	LT charged heat by ORC	2441	51%	OK	
	LT charged heat by heatpumps	2359	49%	OK	
	HT Storage vessel cycles	110 days	30%	OK	Is is possible to always run the full HT heater per day and reach the charge hours (throughput)
	Yearly new LT cost	**hours**	**Price €/MWh**	**Cost**	**remarks**
	LT heatpump	3500	29,5	€ 22.452	buying price based on 3500 cheapest hours
	LT boiler	50	10,0	€ 0	buying price based on 50 cheapest hours
	buying HT heater	973	24,0	€ 74.584	buying price base on 973 cheapest hours
	selling electra (ORC)	1000	64,8	-€ 32.385	selling price based on avg price of most expensive 1000hrs
	Total cost of LT energy		13,5	€ 64.650	positive value is losses!!!!
	HT profit			-€ 16.113	negative is losses
	avg LT heatpump + heater price		10,1	-€ 24.052	based on LT businecase (not used, just a check calculation)
HT aditional cases input		start	change/yr	end	
	Scale factor buying	75,00%	-0,50%	50%	Assumption that the lowest prices scale by this %
	Scale factor selling	150%	1%	200%	Assumption that the highest prices scale by this %
	Yearly LT cost	**hours**	**Price €/MWh**	**Cost**	**remarks**
	new LT heatpump	3500	22,1	€ 16.839	buying price based on 3500 cheapest hours
	new LT heater	50	7,5	€ 0	buying price based on 50 cheapest hours
	buying HT heater	973	18,0	€ 55.938	buying price base on 973 cheapest hours
	selling electra (ORC)	1000	97,2	-€ 48.578	selling price based on avg price of most expensive 1000hrs

	Cost of LT energy without HT		10,1	€ 48.537	
	HT energy profit (+) / loss (-)			€ 24.339	
	Imbalance trading income	100	100	€10.000	it's assumed that 100 hours are rewarded with 100€/MWh (for reduced/increased charging)
	Local Grid support fee	486	100	€48.646	it's assumed that 50% of the ORC hours are rewarded with 100€/MWh
	Total Profit (+) / loss (-)			€82.984	
	SDE	**hours**	**Price €/MWh**	**Cost**	**remarks**
	SDE sun		53,0		Figures are based on SDE while delivering energy
	SDE wind on land		40,0		Figures are based on SDE while delivering energy
	SDE wind at see		53,0		Figures are based on SDE while delivering energy