Datum
2021.03.25

Dnr
2019-002439

Projektnr
48190-1

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|---|---|
| Energimyndighetens titel på projektet – svenska<br>Integration av el och värme via högtempererade värmelager | |
| Energimyndighetens titel på projektet – engelska<br>Integration of Electricity and Heat using High Temperature Thermal Storage | |
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| Nyckelord: 5-7 st<br>Högtempererade värmelager, kraftvärmeverk, förnybar energi | |

## Preface

This study has been financed by The Swedish Energy Agency through the 2018 call of the TERMO research program.

We would like to acknowledge the support from Kraftringen, with special thanks to Peter Ottosson, which provided technical information about their biomass combined heat and power plant at the Örtofta site outside Lund. Hereby, we could use that plant as reference plant for the scientific analysis in this study.

This project was performed at Halmstad University between August 1, 2019 and March 31, 2021. We presented the results at Research conference on Smart Cities and Communities in November 25, 2020. We had a seminar/workshop in March 11, 2021 for invited representatives from the target group, for example relevant industry. We also intend to write a scientific article in an international energy journal about this research issue, expected to be submitted within a couple months.

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## Sammanfattning

I detta projekt analyseras möjligheterna att skapa en flexibel balansresurs för elnätet via högtempererade värmelager (t ex smält salt) i anslutning till kraftvärme, i det följande benämnt som det integrerade systemet

Överskottsel används för att värma upp lagret, och den lagrade värmen kan senare ersätta bränsle i kraftvärmeverket. Eftersom man drar nytta av den infrastruktur som redan finns, ångkraftanläggning och fjärrvärmenät, bedöms konstruktionen kunna bli kostnadseffektiv jämfört med andra sätt att lagra el. Potentialen och nyttan för elnätet vid storskalig introduktion studeras. Det ursprungliga systemet och det integrerade har jämförts med hjälp av energi- och exergianalys, och resultatet visar på obetydlig skillnad mellan systemen i detta hänseende.

Enskilda kraftvärmeföretag kan dra nytta av lägre bränsleåtgång och samtidigt bli mer flexibla att möta efterfrågan. I ett läge med större variation på elpriset, likt det som för närvarande finns i Danmark, kan det integrerade systemet bli lönsamt för kraftvärmeverket. Det integrerade systemet kan bidra till ny lagringskapacitet i elnätet med en ökande andel intermittent förnybar elgenerering, så som vind- och solkraft. I ett rimligt framtida scenario med en bred implementering av det integrerade systemet kan 53% av den el som annars skulle ha spillts nyttiggöras. Samtidigt ersätts 21% av bränslet i kraftvärmeverken. Detta kan bidra till att nå det svenska målet om ”100% förnybar elproduktion till 2040”.

## Summary

The purpose of this project was to create a flexible balancing resource for the electric grid with the help of high-temperature thermal storage (e.g., molten-salt storage) in combined-heat-and-power (CHP) plants, here called the integrated system.

Excess electricity is used to heat up the storage, and the stored heat can later replace fuel in the CHP plant. Since the infrastructure is already in place (steam turbine and district heating distribution), the proposed construction has a potential to be cost efficient in comparison to other electricity storage options. The potential and benefit for the electric grid at large scale implementation is also studied. The original and integrated systems have been compared by energy and exergy analysis, the results show no substantial difference.

Individual CHP companies can benefit from saving fuel and become more flexible towards customer demands. Assuming a more volatile electricity price, as currently found in Denmark, the integrated system can be profitable for the CHP plant. The integrated system can contribute to new storage capacity in the national electric grid with increased share of variable renewable electricity, such as wind and solar power. In a reasonable future scenario with a broad implementation of the integrated system, 53% of electricity that would otherwise be curtailed, could be absorbed and used. At same time it will be able to replace about 21% of the fuel in the CHP plants. This can help to phase out nuclear power towards the Swedish goal of “100% renewable energy production by 2040”.

# 1 Background

Hydro and nuclear power are the main electricity sources in Sweden. Each covered about 40% of total electricity production in 2017 (Swedish Energy Agency, 2020). Sweden has set an ambitious goal of "100% renewable energy production by 2040" to mitigate environment impact (Swedish Parliament, 2018). Thus, nuclear power will eventually have to be replaced by renewable energy sources, such as solar and wind power. The challenge of a large-scale transition to renewable energy sources is, however, the ability of handling the variation in electricity generation to meet electrical demands. Therefore, energy storage will play an important role in this transformation.

Several studies have highlighted wind power as the probably most important source of energy in a future sustainable energy system (Connolly, Lund, & Mathiesen, 2016; Jacobson & Delucchi, 2011). Wind power production varies widely across different time scales in most places. Energy storage is one solution to ensure reliable power supply with a large share of wind power. Therefore, obtaining cost-effective and sustainable methods for energy storage will become one of the most important tasks for energy research in the future.

Electric energy storage technologies were reviewed by (Chen et al., 2009). Pumped hydroelectric storage is, and will remain, the dominant large-scale electric energy storage at least in the very near future. High temperature storage (HTS) offers another option for electric energy storage; it is technically developed and commercially available. HTS allows for electricity generation via a standard Rankine cycle.

Currently, biomass and waste account for most of the fuel in Swedish combined-heat-and-power (CHP) plants (Swedish Energy Agency & Statistics Sweden, 2019). In the future, it is not "a given" that biomass is available for energy services at a large scale as the competition for biomass is likely going to increase (Hoogwijk et al., 2003); in addition, the amounts of waste that go to incineration is expected to decrease in a longer perspective. In principle, the CHP plants constitute a balancing resource; this potential has not been utilized in Sweden so far, but could be implemented to balance a large proportion of renewable power in the electricity system. A future reduction of distribution temperature levels in district heating networks will increase the power-to-heat ratio in the CHP plants, further increasing the balancing potential. The integrated system with HTS addresses these issues by reducing fuel demand in the CHP plants, and enhancing the balancing capability by absorbing surplus renewable electricity, making the system more flexible.

## 1.1 Renewable electricity situation

In the Nordic countries, wind and solar power will play a major role in the future energy systems. Wind and solar power are variable and are expected to cover a share of around 30% of electricity production on average in the Nordic countries (Karlsson et al., 2016). A large share of variable production, as wind and solar, poses challenges to the electricity system to meet electricity demand at any time.

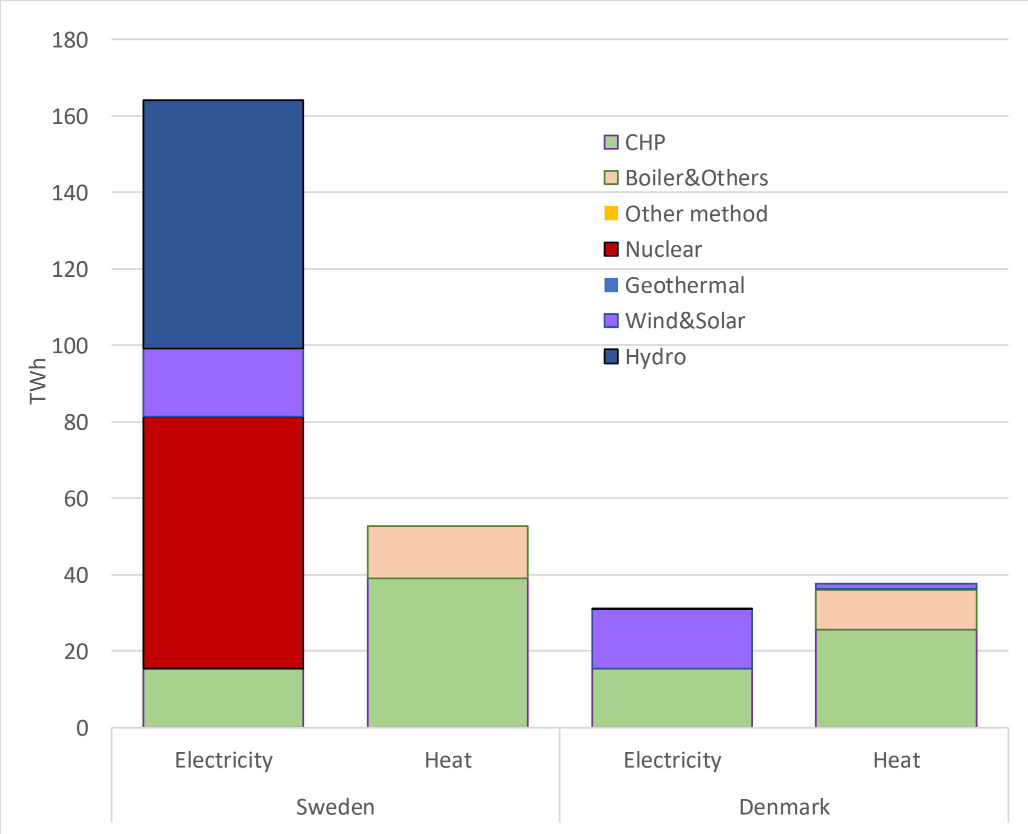


**Figure 1 Electricity and heat production by technology in Sweden and Denmark in 2017. Data source: (IEA, 2019)**

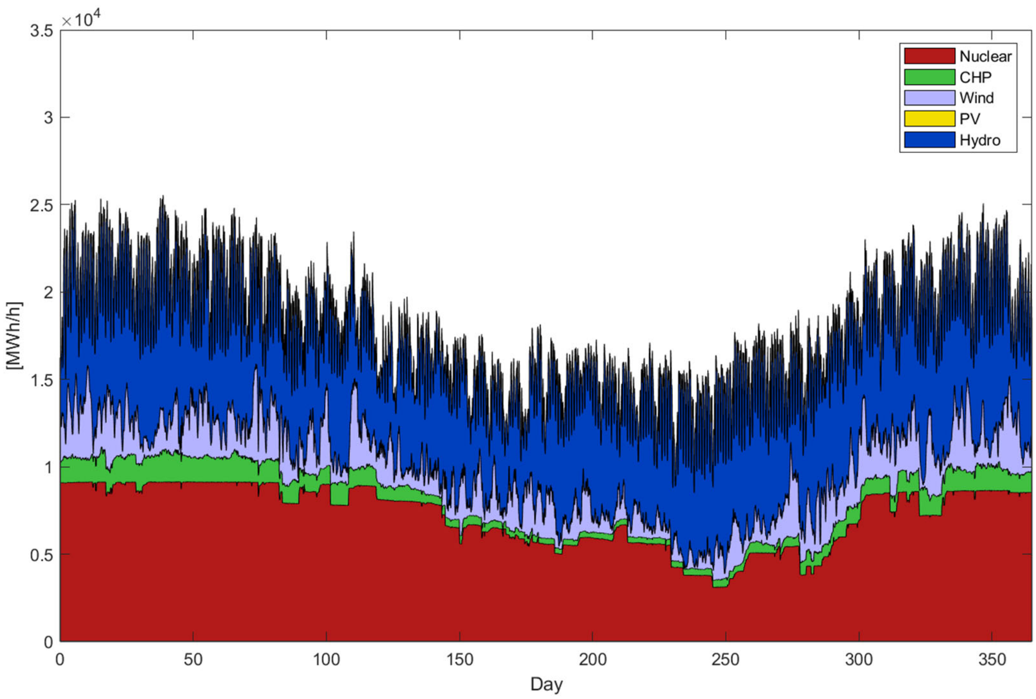


**Figure 2 The hourly values of the power production in Sweden, year 2017. Data source: Svenska kraftnät (Swedish national grid).**

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As shown in Figure 1, currently hydropower and nuclear electricity amount to 80% of total electricity production in Sweden, while wind power and CHP share almost 50% of the total electricity production each in Denmark. CHP produces the majority of the heat products in both Sweden and Denmark.

Figure 2 displays the variation of the power production in Sweden. Hydropower accounts for most of the load following in the Swedish electricity system. The amount of wind power is on a level clearly manageable by hydropower. However, in a future system with less nuclear power and more wind and solar power, hydro power might not always be able to balance the variations, and additional measures are needed.

The Nordic electricity market price level is expected to rise and become more volatile in the long term. A possible synergy of CHP and variable renewable energy is therefore interesting to study.

### 1.2 High temperature thermal energy storage (HTS)

The common types of energy storages are chemical storage, such as batteries; mechanical storage, such as pumped-hydro storage; and thermal storage, such as low-temperature thermal storage and high-temperature thermal storage. The thermal storage has the lowest investment cost per stored energy. Lower temperature thermal storages, typically the hot water storages, are widely used in district heating systems. On the other hand, HTS may be considered as electricity storage, due to the higher temperature that allows for a Rankine cycle to generate electricity from the heat. It has several advantages: minimal environmental effects, long cycle life and low investment cost per stored energy. However, HTS has also the disadvantage of large losses when converting from electricity to the storage heat and back again.

Today molten salt storages are commonly used in the concentrated solar power (CSP) plants, where they represent a relatively small part of the total cost of the plant (IRENA, 2016). The molten salt is used in eutectic mixtures as a storage medium since these are liquid and stable in the operational range, have good heat capacity, and are non-toxic. The solar power plant Gemasolar in Spain is the world’s first commercial-scale solar power plant that combines a central tower receiver system and molten salt storage technology. It have been operative since 2011 and can generate power continuously 24 hours a day (Solar thermal energy news, 2018). The maximum temperature of the hot molten salt tanks can reach 650 °C, and the temperature of the cold molten salt tanks is about 300 °C. In the CSP plant, a Rankine-cycle steam-turbine process is used to converting high-temperature heat (steam) to electric power. Some CSP plants also distribute district heat.

Recently a research project “High temperature thermal energy storage” launched a demonstration plant using stones as thermal storage in Denmark in 2019 (Berggreen, 2019). The high temperature stone storage consists of a pile of insulated stones which are heated to 600 °C by surplus wind power. The heat generates electricity by a steam turbine and the residual heat is used in district heating. The rock bed with a storage capacity of 450 $kWh_{th}$ was built and tested. In the experiment a thermal efficiency of rock bed high temperature energy storage was estimated around 68%. However, in industrial high temperature thermal energy storage applications, the thermal efficiency of rock bed plant could reach around 90–95% depending on the charge/discharge cycles history and duration (Soprani et al., 2019).

Other HTS technologies are room temperature ionic liquids, phase change materials, air receivers using solid material, saturated water/steam, high-purity graphite, etc. (Chen et al., 2009).

### 1.3 Aim

An efficient technology for converting high-temperature heat to electric power and district heating is already in place in a CHP plant, with a back-pressure steam turbine connected to a power generator. Therefore, it is interesting to consider the possibility of coupling a high-temperature thermal storage to a CHP plant. This concept should be a simple and cost-effective alternative for balancing the electricity requirements.

The aim of this project is to investigate the economic and technical possibilities of utilizing an established HTS technology to handle surplus electricity in the grid, given that this HTS technology is integrated into a CHP plant. This integration has not been extensively studied before.

## 2 The Örtofta CHP plant

In this study one typical Swedish biomass CHP plant in Örtofta outside Lund in southern Sweden was used in the analyses, see aerial photo in Figure 3. In order to gather necessary data and gain understanding of this particular plant, the Örtofta CHP plant was visited.

The plant has installed capacities of 38 MW electricity and 90 MW heat, including 16 MW from the flue gas condensation unit, with a fuel input of 123 MW based on Lower Heating Value (LHV). The steam process can be characterized by live steam conditions of 11.1 MPa, 540 °C and 44 kg/s. Two turbine condensers are used to increase the electrical efficiency by using two different condenser pressures. Annual fuel input is about 310 000 tons of biomass for generating the outputs of 220 GWh electricity and 500 GWh heat. More information in English about the CHP plant is available from (CASI, 2019).

Kraftringen AB owns the plant that was initially commissioned in March 2014. Kraftringen’s district heating system consists of 1050 km pipes and is responsible for space heating and domestic hot water in Lund, Lomma, Dalby, Genarp, Eslöv, Bjärred, Klippan, Ljungbyhed and Östra Ljungby. The main grid connects Lomma with Eslöv, via Lund, see map in Figure 4. Örtofta CHP plant has also a network connecting district heating networks in Landskrona and Helsingborg.

**Figure 3 Overview of the Örtofta CHP plant including the biomass fuel yard.**


**Figure 4 Kraftringen district heating grid. (Kraftingen, 2020)**

# 3 Methods

## 3.1 Principle

Figure 5 shows the structure of integrating HTS into a CHP plant. The CHP plant includes five basic parts: boiler, turbine, generator, condenser, and pump. The black color is main cycle in a simple CHP plant, and the violet color indicates the district heat circuit including flue gas condensation. Red color is the additional HTS parts. When the price of electricity drops below the equivalent fuel price, electricity can be purchased and stored as heat in the high temperature storage. The high temperature storage is connected to the steam pipe to the turbine and will deliver heat to it according to the operational strategy. The typically strategy is to draw heat from the storage whenever possible, since the storage is then ready, as frequently as possible, to be filled when the electricity price becomes low.

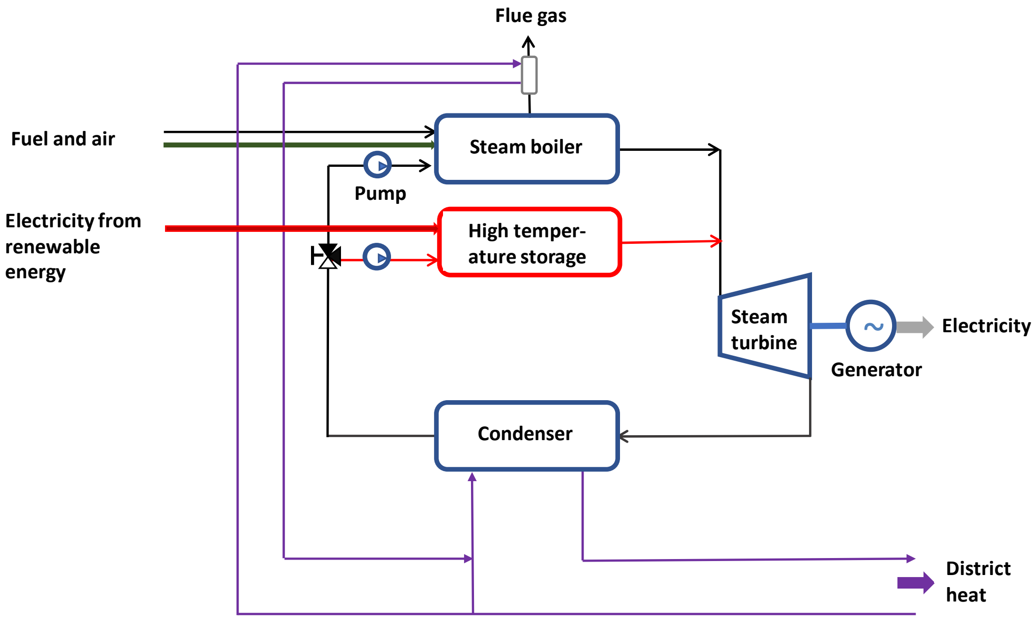


**Figure 5 Basic ideal of integrating the high temperature thermal storage (red color) into CHP plant.**

### 3.2 Data collection

The data is collected in the Örtofta CHP plant, but also from official statistical data on electricity price, electricity production, and scientific papers.

### 3.3 Modelling

A simulation model has been built for the analysis. More detail information can be found in the following chapter.

## 4 Integrating HTS into a typical CHP plant

### 4.1 Simulation model

A simulation model has been developed in MATLAB for exploring various operational schemes made possible by integrating a HTS into a CHP plant and for estimation of the payback time. Fixed variables are the efficiency of the boiler and turbine, the heat loss of the HTS, the heat transfer loss from the HTS to the steam pipe to turbine, and, for some of the simulations, the charge and discharge rates of the HTS.

The biomass fuel prices are based on wood fuel- and peat prices in Sweden (Swedish Energy Agency & Statistics Sweden, 2018). This price has been varied from 100 SEK/MWh to 250 SEK/MWh in order to display the relation between the biomass-fuel price and pay-back time. The investment cost of the molten salt storage, as an example of a HTS, is according to (IRENA, 2016). This specific cost given in (IRENA, 2016) relates to storage size within a typical CSP solar-tower plant, around 1400 MWh, which is roughly twice the size found suitable for the Örtofta CHP plant. The cost figures are therefore roughly applicable. However, for a much smaller storage (which is also considered in the simulations), the specific cost is likely to be higher in reality.

The steam productions from the boiler was collected hourly from the Örtofta CHP plant for the year 2017. The hourly electricity spot price was gathered from Nord Pool for the same year 2017 (Nord Pool, 2020). The electricity spot prices in both Sweden and Denmark are analyzed. Sweden aims at 100% renewable electricity by 2040 (Swedish Parliament, 2018), which will require a substantial increase in wind power capacity, see for example (Swedish Energy Agency & Swedish Environmental Protection Agency, 2019) where 100 TWh of wind power is considered. In Denmark, wind power already stands for half of the electricity production; this is a five times larger share of wind power than Sweden currently has, and on par with the scenario presented in (Swedish Energy Agency & Swedish Environmental Protection Agency, 2019). The current electricity price in Denmark may then provide an approximate baseline for the volatility of the electricity price that can be expected in a future Sweden; it should however be said that there are many other influencing factors and the future price situation is highly uncertain.

**Table 1 Some parameters that were used in simulations.**

| **Parameter** | **Value** |
|---|---|
| **CHP plant** | |
| Boiler, efficiency with LHV | 91.8% |
| Turbine, isentropic efficiency | 86.5% |
| Generator, electricity capacity | 38 MW |
| **High temperature storage (HTS) – Molten salt** | |
| Charge rate to HTS | 190 MW when fixed analysis<br>90 – 250 MW |
| Discharge rate from HTS | 90 MW |
| HTS capacity | 800 MWh when fixed analysis<br>100 - 1500 MWh |
| Thermal heat loss due to insulation | 1% of stored energy per day (Stoddard, Andrew, Adams, & Galluzzo, 2016) |
| Energy loss due to transfer salt to steam | 3% |
| **Economic analysis** | |
| Biomass fuel price | 150 kr/$MWh_{th}$ when fixed analysis<br>100 - 250 kr/$MWh_{th}$ |
| Electricity spot prices | Sweden (SE3) and Denmark (DK1) 2017 (Nord Pool, 2020) |
| Investment of molten salt storage | 200 kr/$kWh_{th}$ (IRENA, 2016) |

The simple pay-back time and the wood-chips reduction are used to evaluate the investments of HTS. The pay-back time is calculated by considering an annual income from the difference between the expenses for the purchased electricity and the saved cost for replaced fuel, and relating this to the capital cost of the storage. Interest is not considered in this model. The wood-chips reduction is calculated as the ratio of the saved fuel energy to the original fuel energy. Some parameters are presented in Table 1.

Some simplifications have been made in the simulation modelling. An upgrade of power line, which could possibly be needed, is excluded in the economic analysis. The additional energy needed to keep the salt liquid during longer periods when the storage is not used, is not implemented into the model. However, the profitability is not necessarily affected, since the main period of low usage is the summer period, when the plant is dispatched due to low heat demand. During this period the electricity prices are seen to be negative on a regular basis (considering Danish electricity prices), and the salt can then be kept in liquid state for free.

### 4.2 The HTS charge and discharge strategy

The HTS charge and discharge strategy is presented in Figure 6. The strategy can be outlined as follows. Electricity is purchased to charge the storage if the equivalent steam price, which is based on the electricity price and corresponding losses, is lower than fuel equivalent steam price. The profit comes from replacing fuel in the normal operation of the plant with the cheaper electricity. Once there is energy in the storage, the discharge starts immediately since this enables the storage to as quickly as possible become ready to charge whenever the electricity price becomes low.

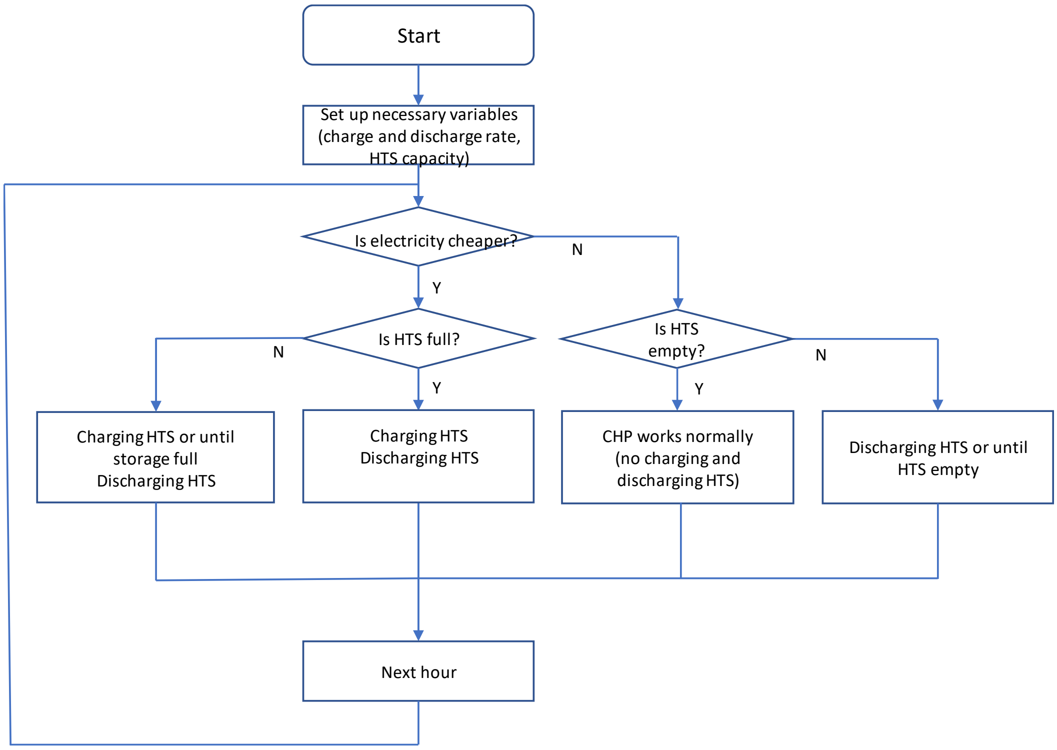


**Figure 6 Flowchart of HTS charge and discharge strategy.**

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The implemented strategy for charging the storage is the simplest possible, i.e., to charge as soon as the equivalent steam price from electricity falls below the equivalent price from the fuel. Knowing the prices beforehand, this is not the optimal strategy; sometimes the storage is charged at a moderately low electricity price and ends up being filled upon entering a period of very low electricity prices. However, prices are typically hard to forecast, and the strategy implemented in the simulation is at least possible to implement in reality as well.

### 4.3 Performed simulations

The value of an added molten-salt HTS to the Örtofta CHP plant was analyzed in an initial simulation. The profit, from the plant's point of view, comes from the savings by using electricity to replace fuel in the normal operation of the plant, the molten-salt charge and discharge strategy according to section 4.2. Additionally, the fuel price is considered fixed, and the timing of using the fuel is not critical (a couple of days to buffer the fuel stream is unproblematic).

Figure 7 shows a simulation with a HTS with the capacity of 800 MWh, the Danish electricity prices for year 2017, and operational data from the Örtofta CHP plant for the same year. The heat and electricity output of the CHP plant is unchanged, but a fraction of the fuel is replaced by heat from the storage, the fraction in this particular case is about 14%, see Figure 8. The Örtofta CHP plant is dispatched during the summer period, and this year it was dispatched a few other days, which explains the fact that the storage is not always charged when the electricity price is low. After day 250 the storage was charged, but then the plant was dispatched and the storage is left unused for 20 days; however, the heat losses occur so the storage level declines slowly.

Different storage sizes were examined, particularly with respect to pay-back time, but also fuel reduction. The result, again for Danish electricity prices, is presented in Figure 8. It is seen that pay-back time increases linearly with the storage size; however, for very small sizes, the capital cost is uncertain and probably distinctly higher than the figure used here, as previously noted.

The amount of replaced fuel, on the other hand, increases rapidly for the small sizes of storage capacity, and more slowly for larger sizes of storage capacity. One objective of adding the storage is to save fuel, since increased competition for biomass is expected in the future. Therefore, a reasonable size of a storage for this plant is proposed to be 800 MWh (the dotted line in Figure 8). The payback time is then reasonable (about 20 years), and the gain in saved fuel would be only moderate by increasing the storage further. This means 9 hours of storage, relating to the set maximum discharge rate at 90 MW. This storage capacity is typical in the context of molten-salt storages in CSP plants. For example, the recent Noor III CSP plant in Morocco has 7.5 hours of storage (Relloso & Gutiérrez, 2017). The amount of salt needed for an 800 MWh storage, using standard solar salt according to Table 1, can be contained in a cylindrical tank with diameter 18 m and height 12 meter. Typically, two tanks are needed, one for the cold salt and one for the hot salt.

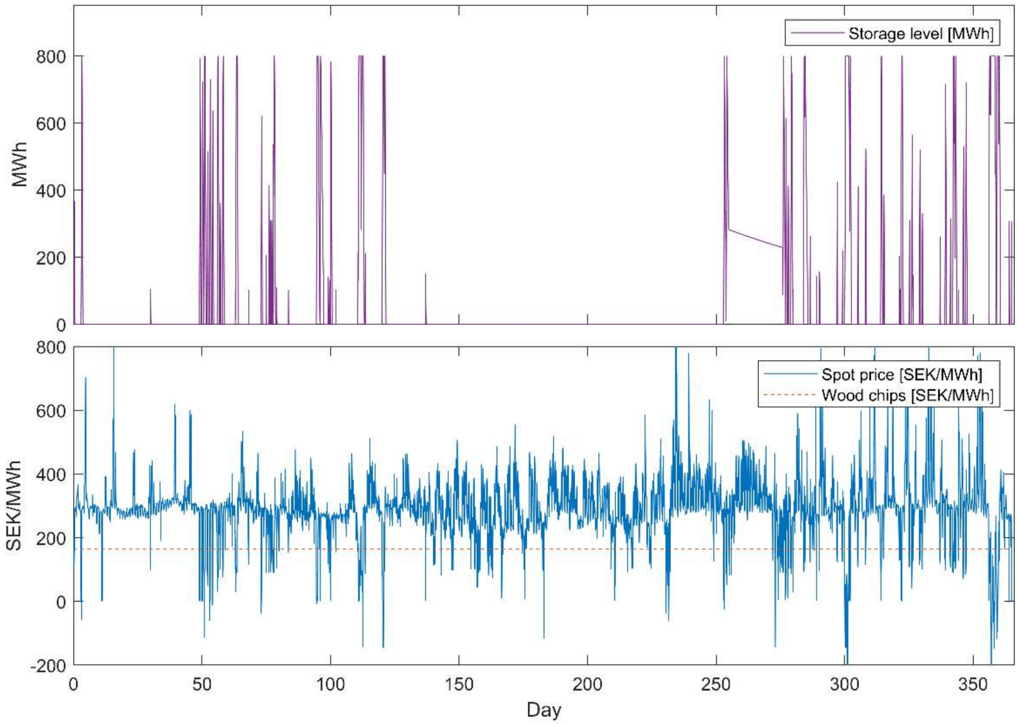



**Figure 7 Hourly storage level and electricity prices (DK1) and operational data of Örtofta CHP plant for the same year 2017. Maximum storage level is 800 MWh.**

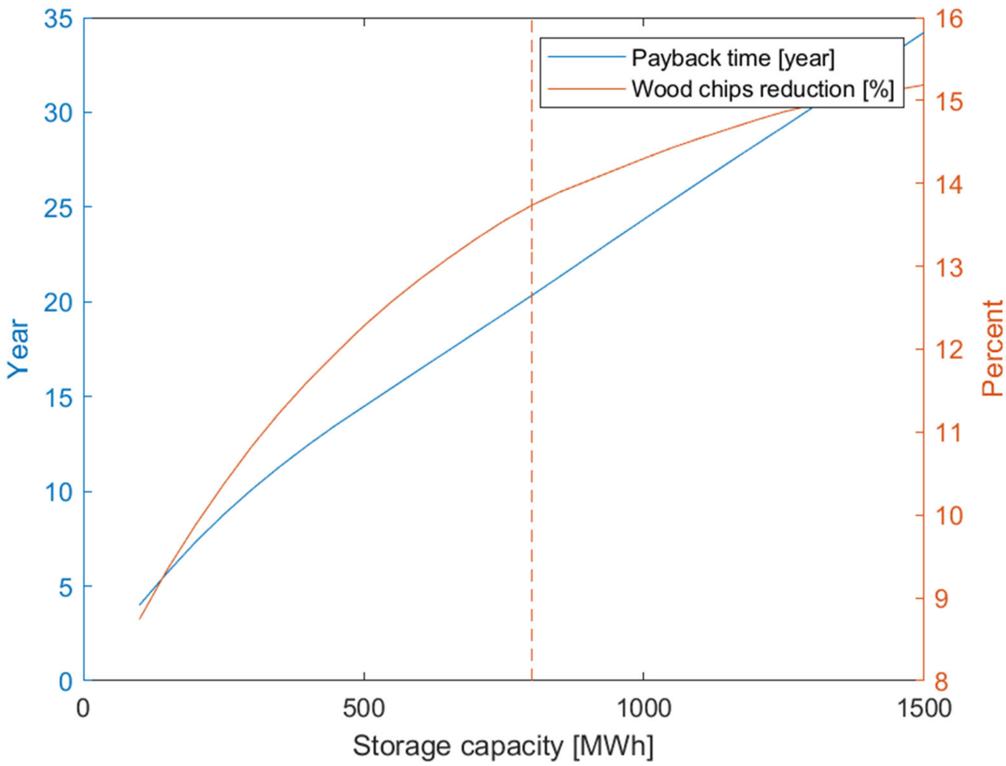



**Figure 8 The payback time and wood chips reduction for various storage capacity from 100 MWh to 1500 MWh.**

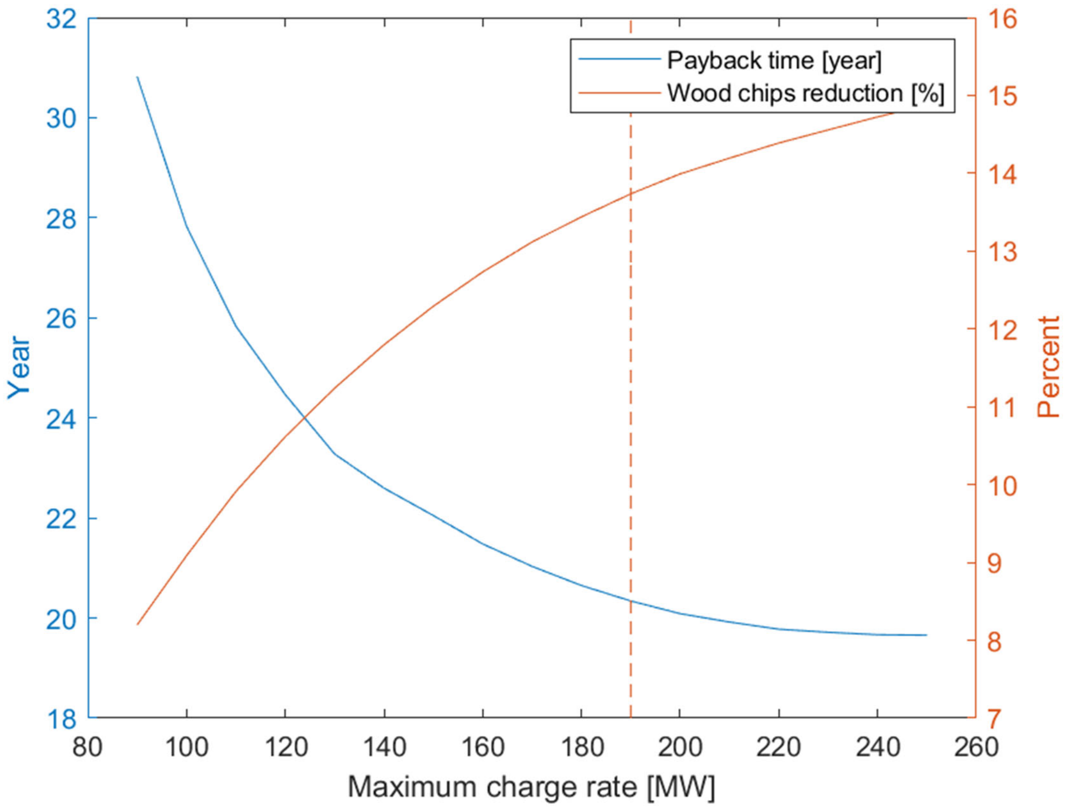



**Figure 9 Payback time and fuel reduction as a function of maximum charging rate to the storage with the storage capacity of 800 MWh.**

The effect of payback time and wood chips reduction with the maximum charging rate to the storage is displayed in Figure 9, where the dotted line marks the chosen maximum charge rate, representing a good tradeoff between fuel reduction and payback time.

It should be said that when the maximum charging rate equals the maximum discharge rate (the leftmost part of the plot) the storage no longer becomes meaningful, as the electricity that is charged into the storage is immediately discharged at the same rate to the steam. While this is a possible, fairly simple, and cheap construction for surplus-electricity handling (in which case the storage need not be introduced), this is not the focus of this study. Here we want to be able replace more biomass fuel and generally maximize the grid-balancing contribution, while keeping reasonable profitability. Therefore, to get a meaningful storage usage that leads to replacement of a reasonable amount of fuel, a maximum charging rate is proposed approximately twice the discharge rate, which is also five times larger than the maximum power the turbine. This might require an upgrade of the power line to the plant, as the power line could potentially be narrowly dimensioned with respect to the 38 MW of electric power of the turbine. The potential need for an upgraded power line is excluded in the economic analysis.

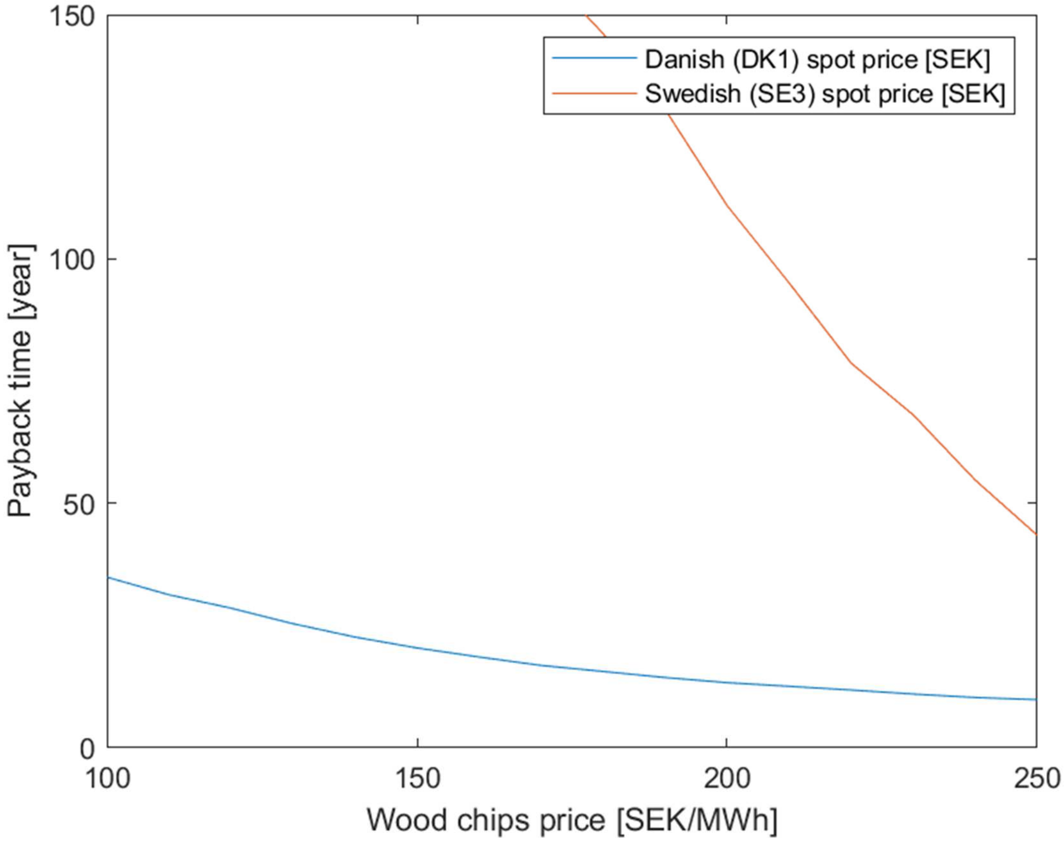



**Figure 10 Payback time for different fuel prices, using both Danish and Swedish spot prices for electricity from 2017, and a storage capacity of 800 MWh.**

The influence of the fuel price on the payback time is shown in Figure 10, for the selected storage size at 800 MWh. For the current fuel price in Örtofta 150 SEK/MWh and Danish electricity spot prices, the payback time is, as previously stated, about 20 years, but decrease to about 10 years for a hypothetical fuel price of 250 SEK/MWh. Biomass will probably be more costly in the future due to increased competition, as the fossil oil is phased out as raw material for plastics and various chemicals, for example. However, a realistic future wood-chips price is difficult to forecast.

Considering the current Swedish electricity spot prices, there is no profitability of this concept with revenue only from replaced fuel costs, since very low spot prices are rarely seen. Consequently, the storage is not used very often and the amount of replaced fuel, at 150 SEK/MWh fuel price, is below 2%.

As can be seen in Figure 7, the storage is not used during the summer since the CHP plant is not in operation due to low heat demand. The Danish spot price is, however, often low during the summer, also evident from Figure 7, and it is natural to ask if the storage could be used during this period as well. Adding a cooling tower to the CHP plant, it is a technical possibility to run the plant in condenser mode during the summer. The storage could then be charged at a low spot price and discharged at a high spot price. However, since no heat is sold in the condenser caser, the poor round-trip efficiency (electricity to electricity) becomes an issue, which has been compensated for by a large difference in spot price between buying and selling; as a consequence, it is difficult to get a substantial net income from this extended use. Additionally, it would mean frequent starting and stopping of the turbine, which will shorten its lifetime. It should be said, however, that the heat demand could be increased during the summer, using for example absorptions chillers, which could motivate running the facility in back-pressure mode. This would increase the summer profitability.

### 4.4 Energy and exergy analysis

Exergy is the quality of energy in short word. It is "fuel" for dissipative systems which is the systems that are sustained by converting energy and materials (Gong & Wall, 2016). In the studied biomass CHP plant, biomass is used as fuel. In the integrated system, parts of the biomass are replaced by renewable electricity, such as wind, solar. The amount of replaced fuel by HTS is according to hourly electricity and biomass price.

Molten salts have been proposed as heat transfer fluids for high temperatures from 250 °C to 1000 °C. The liquid range for an individual molten salt could be from 150 °C to 600 °C (Reddy, 2011). The heat capacity varies with chemical composition. In this exergy analysis, the specific molten salt configuration used in the previous simulation of the HTS is considered, and the heat capacity is assumed constant within the temperature range.

In order to analyze the efficiency of the resources, simple energy and exergy flow diagrams are created for the original and integrated system, as shown in Figure 11. Flows are from left (sources) to right (products). The unnecessary parts, such as preheater and water tank, are excluded from the diagram for simplification. The reference temperature 25 °C is used for the exergy analysis. The base load is 100% for the original system. The low limitation for the boiler is 20% of full load during the operating period, so the largest capacity of HTS is 80% of electricity at full load. The integrated system is analyzed when the ratio of produced steam to turbine and the molten salt steam generator is 1:4. Both systems produce same amount of electricity.

Figure 11 a) and c) show the energy content. The use of biofuel and renewable electricity are very efficient with flue gas condensation. The largest loss occurs when converting electricity to heat in the molten salt storage. Overall, the energy efficiency of the original CHP plant is slightly higher than the integrated system.

Figure 11 b) and d) show the exergy content. The biofuel and electricity have a high exergy factor (i.e. the ratio of energy to exergy). The exergy factor of heat depends on temperature and pressure. The total use of biofuel and renewable electricity are less efficient, the exergy efficiency is about one third of energy efficiency due to low exergy factor of district heat. Most exergy is destroyed in the boiler and in the molten salt storage. The exergy efficiency of the original CHP plant is very close to the exergy efficiency of the integrated system. However, the energy and exergy efficiencies of only electricity production are almost identical in both systems. In molten salt storage the heat leakage and conversion loss has almost no exergy. The largest exergy destruction occurs when converting from biofuel or electricity to steam, the corresponding exergy destruction with respect to the total exergy destruction of the system is about 90%.

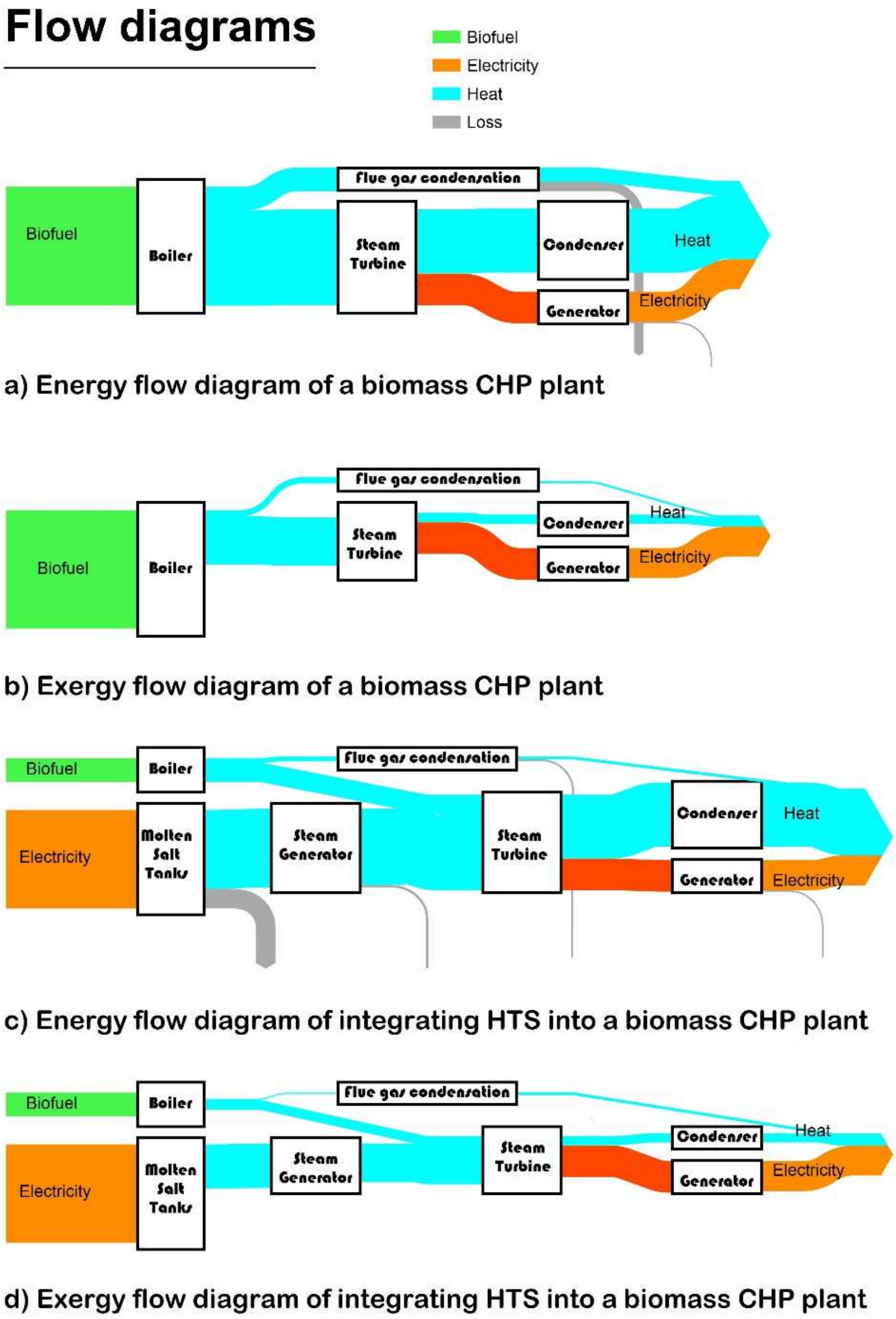



**Figure 11 Simple flow diagrams. a) Energy flow diagram of a CHP plant, b) Exergy flow diagram of a CHP plant, c) Energy flow diagram of integrated system with 20% steam from boiler and 80% steam from Molten salt storage, d) Energy flow diagram of integrated system with 20% steam from boiler and 80% steam from Molten salt storage. The reference temperature is 25 °C.**

There is no substantive difference between the two systems in total energy and exergy efficiency. In this analysis, the transportation of biomass to the plant and the conversion of renewable energy to electricity are excluded in the analyses. Biomass is easy to store, but the wind speed and solar radiation are variable and unpredictable. In this regard, the integrated system is more flexible and possible economic benefit.

# 5 National potential of the integrated system

It is interesting to explore the potential of this concept with respect to balancing services to the national electric grid, when implemented broadly on all CHP plants in Sweden. Compared to the previous one-plant analysis, the straightforward profitability for the individual plants will be different in this analysis and generally lower, as the electricity spot price will be influenced by the large amount of extra load that is then added at the low-price periods. Additionally, while the previous one-plant analysis assumed a constant charging rate whenever the electricity price was favorable, here it is more reasonable to consider a dynamic charging rate that balances the surplus generation in a scenario with exclusively renewable electricity generation within the system. Therefore, the economic analysis here is kept simple; it is focused on the cost for this balancing resource, viewed as an addition to the overall electricity price, to get a feeling for the magnitude of the cost. The amount of replaced biomass fuel is, however, an interesting measure that is still straightforward to calculate. A broader implementation is likely to require a financing structure (policy measures) that supports the specific balancing services that an added storage can give.

In this scenario a Swedish electricity production system with decommissioned nuclear power has been considered, compensated for by a greatly increased amount wind and solar power. Compared to the Figure 2, wind and solar capacity are assumed to be roughly 5 and 100 times larger, respectively (see motivation below).

Hydro power will be able to balance some, but not all, of the added wind and solar power. There are minimum and maximum discharge rates of the hydro stations and maximum ramp rates. Figure 2 shows that the maximum and minimum hydro power production is about 2100 MW and 12800 MW respectively, and that the maximum ramp rates are 3300 MW/h up and 2400 MW/h down. To be somewhat conservative in the simulation, the minimum and maximum hydro production were set to be 2500 MW and 12500 MW, and the max ramp rate to 3000 MW/h. With no further changes in the production and demand, there will be numerous hours where it is not possible to follow the load. One way to mitigate this is to add storage to the electric grid, and here the potential of extending all CHP plants with HTS is considered. The HTSs are sized according to the findings of the one-plant analysis performed above. This is only a handling of surplus generation, and will not mitigate low-generation situations, where other means are needed.

The total installed CHP capacity in Sweden is 3528 MW of electrical power (excluding industrial CHPs, but including both biomass and waste incineration) (Swedish national grid, 2018a). It is questionable if the previously studied discharging strategy (section4.2) is possible in a waste incineration plant, since the waste stream cannot typically be put on hold for too long. A couple of days might be conceivable, but the longer periods are likely to be possible only for biomass plants. Another crucial difference is that the waste-incineration plants get paid to treat the waste (i.e., negative fuel cost), so the financial support structures would need to be more far-reaching for these types of plants, in order for HTS to be added on commercial grounds. For simplicity however, these complications are not incorporated into the current analysis.

The total amount of storage (based on the size relative to installed capacity of the Örtofta plant) becomes 74. 3 GWh. The total cost of this addition amounts to about 15 000 MSEK, which, assuming a 30-year lifetime, would add below 0.5 öre/kWh to the electricity spot price if the consumers were to (indirectly) finance this addition.

Simulation results from one possible scenario are shown in Figure 12. The simulation is based on electricity generation data from 2017 (Swedish national grid, 2018b). The original amount of wind and solar power generation in the data was 17 TWh and 79 GWh respectively. These resources have been scaled up to 88 TWh for wind and 7.5 TWh for solar in order to compensate for the decommissioned nuclear power. The amount of wind power is then somewhat less than the number studied in (Swedish Energy Agency & Swedish Environmental Protection Agency, 2019), where 100 MWh was considered. It is, however, substantially more than 63 TWh, which was the production of the nuclear power in the original data. It is reasonable to assume that the wind and solar power will need to be over-dimensioned, since various losses due to the intermittency (curtailment, round-trip efficiencies for storage) are likely to be inevitable. The hydro power production is actually lower in the simulation (57 TWh, compared to 65 TWh in the original data) due to the added wind and solar power, combined with hydro being the primary balancing resource. This opens up for extended export of electricity, at times when the hydro installed capacity allows for it.

Also shown in Figure 12 is the charging of the HTS in the CHP plant. The charging power is displayed as negative values, and the corresponding power is, for clarity, subtracted from the production from wind and solar. This means that the production of wind and solar electricity is the sum of the light blue and yellow areas above and below the $x$ axis, and the production above the $x$ axis corresponds to electricity available on the grid for other purposes than charging the HTS.

Every time the storage capacity is being charged, hydro power was not able to balance the production from wind and solar power, and the production would have to be curtailed if no other balancing mechanism are implemented. From Figure 12, it is clear that implementing the studied amount of HTS will be able to handle most of these situations, avoiding curtailment and at the same time replacing fuel in the CHP plants. For this particular year, 53% of the wind power that would otherwise have to be curtailed, comes to use to replace fuel in the CHP plants.

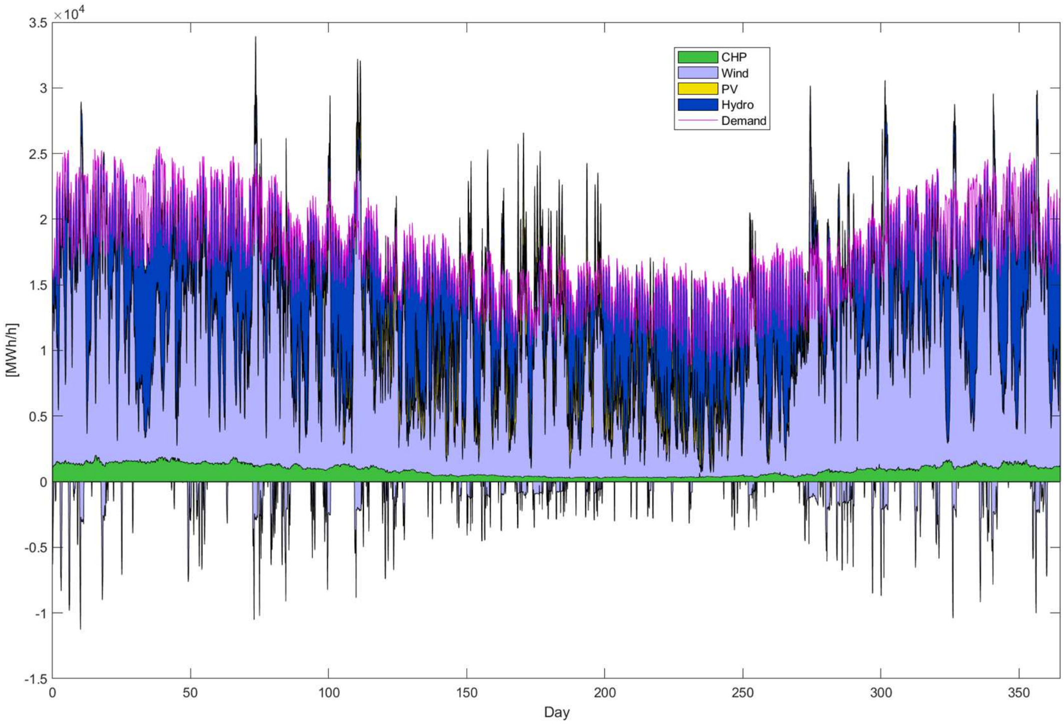
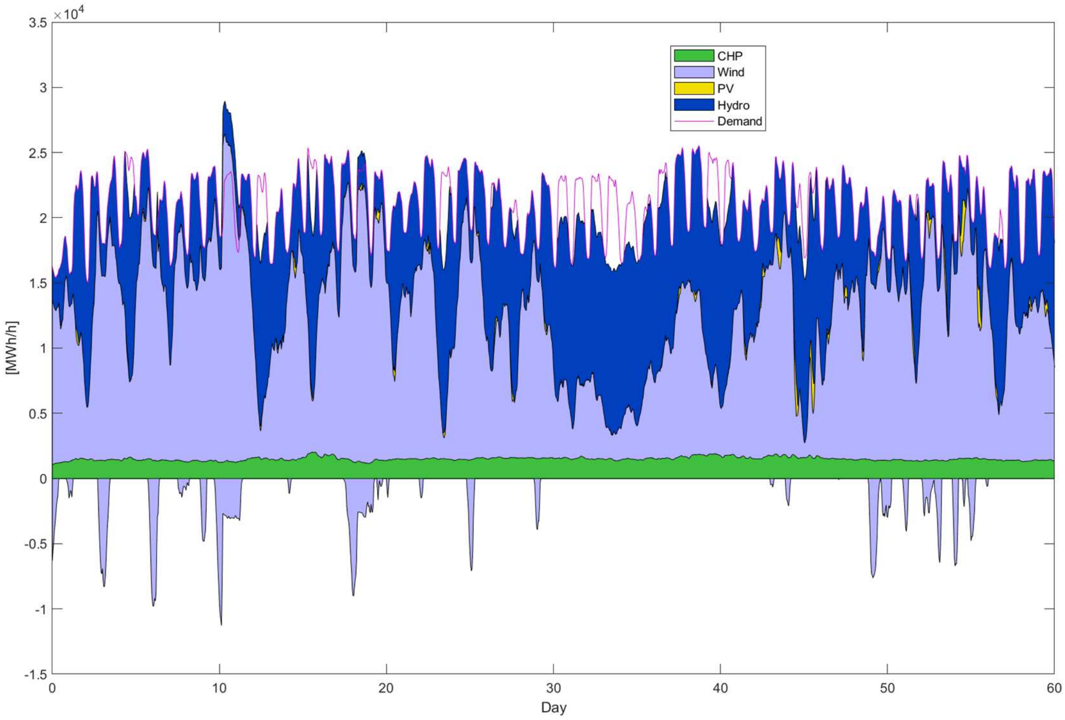


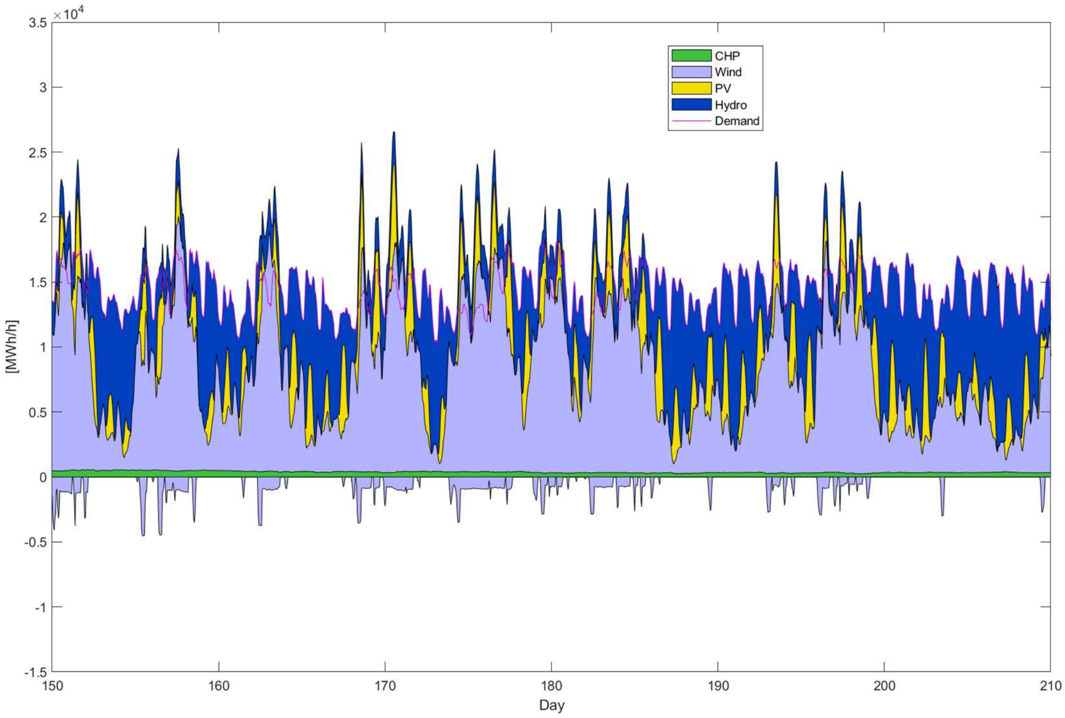

**Figure 12 Hourly electricity products from CHP and renewables with HTS to meet electricity demand when phasing out nuclear electricity in future for one year. The data for electricity demand from 2017. Demand data source: (Swedish national grid, 2018b)**

The simulation results of 60 days during winter and summer, respectively, are enlarged and presented in Figure 13. During wintertime, winds are generally stronger and the wind power production larger on average as compared to the summer. However, periods of low winds and low production are found even during the winter. Moreover, the production from solar PV is low while the electricity demand is high. The production is therefore not able to meet the electricity demands at all times, as seen in Figure 13 (a). As previously mentioned, the studied implementation does not mitigate these situations, and other solutions are necessary. In the context of CHP plants, it should be said, however, that one possibility would be to run the CHP plants more dynamically, for example switching to condenser mode at times of high demand (which would typically need larger turbines to be installed in the CHP plants).

During summertime, shown in Figure 13 (b), more electricity is produced from solar PV while the electricity demand is generally low. While it is clear that HTS greatly improves the load following, the electricity production from solar and wind is sometimes even larger than the hydro power and the HTS together can balance. In the future, an increased number of electric vehicles with a smart charging scheme could help absorb the excess wind power and solar power.




(a) Winter




(b) Summer

**Figure 13 Hourly electricity products from CHP and renewables with HTS to meet electricity demand when phasing out nuclear electricity in future. The data for electricity demand from 2017. (a) Winter (Day 0 to day 60), (b) Summer (Day 150 to day 210).**

The amount of fuel saved in the CHP plants in this scenario is about 21%. This means that substantial amounts of biomass are available to the other industry processes, such as plastics. Ideally, if segregation of waste and reuse of materials in the society can increase further, the amount of waste that goes to incineration will decrease as well. By the studied construction, there is still usage for the steam turbines and the plant capacity, which at the same time contributes to grid stability.

# 6 Results

The simulation analyses and exergy analyses provide the following main results:

- The wood chips reduction with the integrated system increased with the increment of HTS capacity. A reduction of 14% can be achieved with reasonable HTS size in the studied plant.
- The payback time of investing high temperature storage is about 20 years with a reasonable charging rate and storage capacity. The payback time becomes very long when applying Swedish electricity spot prices rather than Danish spot prices at present.
- In the future nuclear power will phase out. When the hydroelectric power plants are not able to balance the extensive production from wind and solar power, implementing HTS in the CHP plants will be able to handle these situations, to avoid about 53% of otherwise needed curtailment of wind and solar power produces, and to replace about 21% of the fuel in the CHP plants at the same time.
- With a 30-year lifetime, investing in high temperature storage at a national level will add below 0.5 öre/kWh to the electricity spot price.
- There is no substantive difference between two systems in total energy and exergy efficiency. The boiler and molten salt storage including steam generator need to be improved first due to the largest relative exergy destruction.

These results provide the following main conclusions from this study:

- Individual CHP companies can benefit from saving fuel and become more flexible towards customer demands.
- The integrated system can balance variable renewable electricity with electricity demands to a large extent; however, other means are also necessary, especially during low production periods from wind and solar.
- The integrated system at national level can help to phase out nuclear power towards the Swedish goal of “100% renewable energy production by 2040”.

# 7 Discussion

## 7.1 Profitability

The integrated system gives opportunity to balance the future overabundance of renewable electricity with electricity demands, at the same time replacing fuel used in CHP plants.

Örtofta CHP plant generated about 171 GWh of electricity and 500 GWh of heat during 2017 according to KRAFTRINGEN (Kraftringen, 2019). 14% of the fuel is replaced with high temperature steam from the storage, and the hourly electricity and heat products are kept same in the simulation model. During summertime this CHP plant is dispatched, due to the heat demand of domestic hot water being low. At the same time, it can be noted that the electricity spot price is often low during the summer period. For this reason, it could be beneficial to keep the plant in operation if absorption chillers are introduced for space cooling during summer period. Thereby the low spot prices during the summer can be accessed, which may increase profitability.

The payback time of investing in a two-tank molten salt HTS storage is about 20 years with reasonable choices regarding size and fill/drain capacity. The one-tank concept is under development and can be able to decrease the overall costs of up to 40% compared to a two-tank molten (Mathur, Kasetty, Oxley, Mendez, & Nithyanandam, 2014). Other HTS technologies, such as stone storage, are promising.

In order to reach the Swedish goal of 100% renewable electricity by 2040, increasing renewable power capacity is required in the future. Intermittency is one of the drawbacks of renewable electricity. The integrated national system studied here, with increased amount of wind and solar, and decommissioned nuclear power, can handle parts of the variation in electricity generation. With no further changes in the production and demand, there will still be hours when it is not possible to follow the load. There are many possible ways to help mitigate this: increased export/import, demand-side participation, added parallel turbines to existing hydro stations, smart charging of electric vehicles, vehicle-to-grid integration, batteries and other storage, and a reserve of gas turbines fuelled by biogas. Overall, however, the HTS provides a significant balance contribution upon large-scale introduction in CHP plants.

The investment in HTS storage on a broad scale, assuming a 30-year lifetime, is estimated to amount to less than 0.5 öre/kWh in addition fee to the electricity spot price. This appears as a fairly small price to pay for the extensive services that are obtained. It should be pointed out that there will be no profitability for the individual CHP plant based solely on current Swedish spot prices, and running the storage according to the large-scale scenario studied above will not be profitable for the individual CHP plant even with Danish spot prices. New policy measures are needed to make sure that this integration becomes profitable for the individual CHP plant if maximum support of the grid is aimed for.

### 7.2 Further study

A comparison of different kinds of HTS can be made to view the effect of different HTS technology, carbon dioxide emission and economic benefits. Several scenarios of future renewable electricity development would be interesting to analyze in the integrated system.

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