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Master of Science Thesis

Techno-economic analysis of the performance of a HT-TES unit based on the rock-bed technology

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2. Preface

The present Master thesis is performed in DTU Energy Conversion department. It was submitted a partial help thanks to the Polytechnic di Torino in DENERG department.
This work has been done from 08-10-2017 to 08-04-2017 under the supervision of Stefano Soprani (PostDoc at DTU Energy), Kurt Engelbrecht (Senior Researcher at DTU Energy), Allan Schrøder Pedersen (senior researcher at DTU Energy), Leone Pierluigi (Associate professor DENERG-Energy Department in Polytechnic di Torino) and Marco Cavana (PhD student DENERG-Energy Department in Polytechnic di Torino). Also Dominik Dominkovick (PhD student at DTU Energy) helped me to perform my work.
This project is credited 16 ECTS points.

Ilaria Sorrenti

3. Abstract

Nowadays there is a mismatch between the electricity produced and the electricity consumed, due to the fact that this type of energy it is not possible to store. One of the best solutions, up to now, would be a storage that has the possibility to store it and to reuse the energy in a better moment. This present thesis is a techno-economic analysis of the performance of a HT-TES unit based on the rock-bed technology it is performed an analysis with this because the compromise between the cost and the performance is very high. The main idea is to integrate it in three types of power-to-power plant connected in a Danish electrical and district heating grid based in Copenhagen. The aim is to verify, knowing the electricity and district prices, like in a perfect prediction scenario, the performance and the feasibility of the plants that store sensible heat for a long time, in order to understand if could be advantageous to build a plant with this new type of technology. In the end, for these three different types of plant the best size of all components is determined from an economical point of view, considering the Payback time as criterion for the evaluation.

The structure of the thesis is subdivided into five main parts. The first one is a techno-economic analysis. This is part has the aim to size all components of the plant knowing that the plant could be divided into three main physical parts, charge, storage and discharge phase, characterized by different components, different sizes and several degrees of freedom for optimization

The second part of this work is to perform an energy analysis of the power-to-power storage plant in order to know all energy fluxes when the plant is on.

After that an investment cost analysis is performed, through the NETL methodology considering that the plant is built in the year 2014 starting from the components prices to the whole investment cost of the entire plant.

Subsequently, it is built an algorithm to carry a perfect prediction analysis during the whole year 2017 and the whole year 2035, future scenario considering the development of renewable sector. This algorithm has the aim to maximize the yearly profit knowing the three power-to-power plants characteristics.

The final work is to evaluate the payback time of the plant and to make a parametrical analysis varying the three base parameters of the charge, storage and discharge parts. Therefore, for three types of the plant and for the two past and future scenarios, the best size of the storage plant is determined in order to have an acceptable payback time.

The main results about these simulations are that a plant that has the possibility to produce heat for district heating has a higher profit and the plant is more active and the district heating market is fundamental to have a good yearly profit and a low payback time.

The main result extrapolated by the tool developed for this analysis is that considering the year 2017, there is no plant feasible up to now. The yearly profit is

too low and the payback time is high. The only possibility up to now is to make a repowering of a conventional plant with this type of HT-TES.
Considering the renewable development in the future scenario of 2035, the results confirm that this technology is very promising because the plant is feasible having a very low payback time and an high yearly profit and, even for the future, the district heating market is necessary and fundamental for this type of storage technology.

4. Introduction

In this first chapter is developed a general introduction to the energy production change thanks to the development of the renewables due to the depletion of conventional energy resources. In this chapter, it is shown how energy storage could help society to use energy more effectively and to control the energy peaks. Here, it is briefly explained in which form it is possible to store energy and shown the various types of storages that are used for different works and for different uses.

There is a short section in which there is a summary of HT-TES, the storage that is studied in this present work.

4.1 Depletion of the energy resources

The development of the society is inevitably linked to energy consumption. The way to reach a good quality of life is related to an economic development that necessarily carries with it a huge use of energy resources. The energy consumption, thanks to resources, means a development of a country that is why it is very important to have a lot of resources to use in different ways such as: electricity for all devices, to transportations to domestic uses, to the offices etc. In the last 25 years the use of non-renewable energy sources have increased because there were a discovery a new oil fights, so, up to now the energy prices and oil and gas prices in this period are quite constant. Nevertheless, it is true anyway; the possibility that all of non-renewable energy sources could be depleted it is very close to reality. A prevision affirms that if people use the same quantity of energy in the future as it is used now, the coal will finish in 113 years, the natural gas in 59 years NG and the petroleum in 52 years. The consequence of that is that if people use constantly only non-renewable energy resources probably they will finish in a few years. That is why there is renewable energy exploitation such as wind turbines, solar panels, fuel cells etc. Another problem is that nowadays but moreover in the past a lot of energy is lost without possibility to recover it. This issue in the past, like in industrial revolution period for example was negligible, a huge percentage of available energy was lost into transformation and in a not efficient energy conversion.[1]

[1] ("Utilizzo sostenibile delle risorse Risorse e sostenibilità," n.d.)

4.1.1 World energy overview

Now, people are more sensible to the problem of energy savings, in fact in a lot of institutes and companies, researchers and engineers are involved to solve this issues increasing and improving the efficiency of energy conversion in general. The goal is to reuse that heat in another way and to store the energy in a lot of ways.

Another aspect about the development of the society and the consequently the exploitation of energy sources is to decrease emissions on the environment. More energy is used, more greenhouse gases are released in the atmosphere deriving from non-renewable energy resources. As it is known, the greenhouse gases alter the clime and create environmental change concerning the quality or the air and temperature but it creates some issues concerning quality of life nowadays and, in the most important way, in the future. It is important to assure to the future generations a welfare, so it is important to find the good compromise between the welfare of our society and, in the most important way, the welfare of the future generations. From 1972 to now, there were many conferences concerning the environment and the depletion of energy sources to have a sustainable development related to our society.

Concerning the future, especially in 2040, energetic mix will change a lot.[2] In principle, there will be a development of renewables and the nuclear. The diversification of energy sources means a reflection of different aspect of economy and technology development and the energy polity interested to the important topic of 'clean' energy.

Nowadays, the oil remains the main energetic sources. This type of energy demand will be maintained by transportation and energy production power but with the development of the electric cars and a different energy mix, the petroleum demand will be reduced.

The natural gas has a great increase because is a non-renewable energy with a low greenhouse gases emissions but considering the use of it even this, thanks to renewables improvements it will be reduced.

There will be a great improvement and advancement of renewables in order to reduce the oil and natural gas usage and in order to reduce the CO2 emissions and a lot of systems like CCS (carbon Capture and sequestration) in order to sequestrate or re-use (CCU-carbon capture and utilization) the dioxide carbon to clean the air in the environment.

The situation in the future will be the following: the economic expansion linked to the demographic increase of 25%. Moreover, there will be an economic increase so a lot of people will belong to the middle class. Another prevision is that the nuclear and renewables will increase at least of 50%.

Concerning the electricity demand, will increase of 60% due to the technology development and to the growth of the population. (U.S. Energy Information Administration, 2017)

[2] https://www.iea.org/weo2017/

The efficiency improvement will determine a significantly improvement and an emission containment, and the storage is one of most critical point to reduce the losses in energetic conversion and to increase the efficiency.

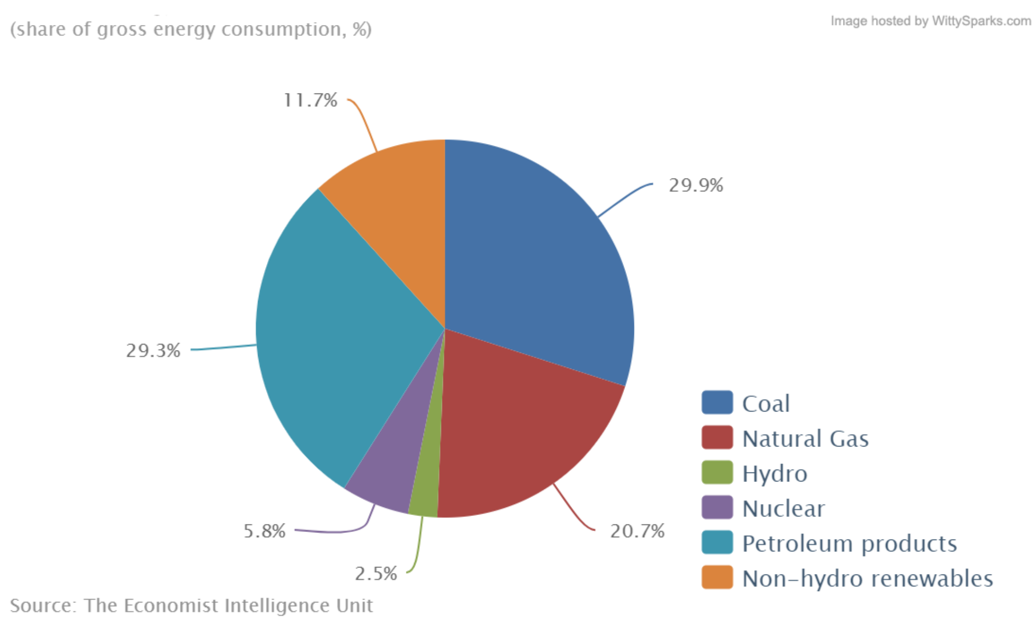

FIGURE 1 WORLD ENERGY MIX-2015[3]

As it is possible to see in the pie chart, the main worldly energy mix is composed by non-renewable energies like coal (29.9%), natural gas (20.7%) and petroleum products (29.3%). The summation of these corresponds to almost the 80% of the total energy used.

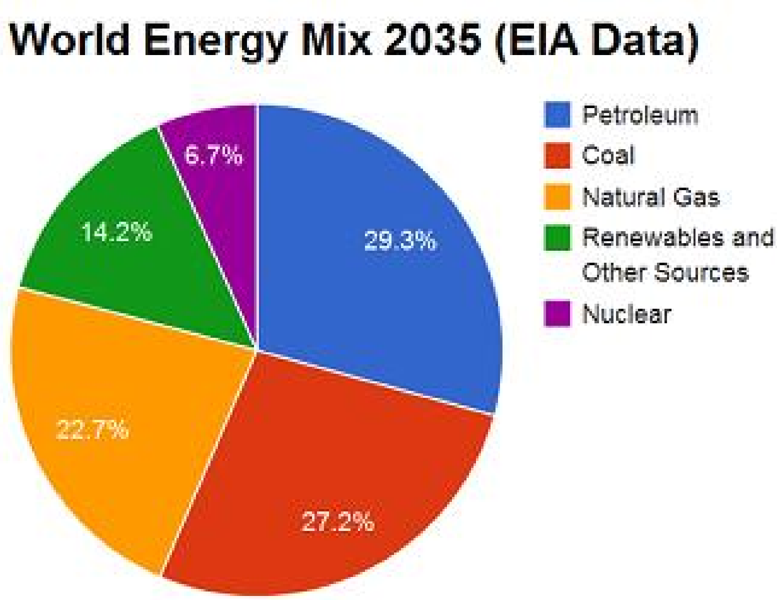

FIGURE 2 WORLD ENERGY MIX 2035 (EIA DATA)[4]

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[3] (U.S. Energy Information Administration, 2017)

[4] Benjamin J. Sovacool writing for the journal Energy Policy.

In the future, the main energy resources remain non-renewable but there will be an increasing of renewables and other sources. The final aim is to use rationally the energy derived from conventional energy and increasing the renewables percentage.

4.1.2 Denmark energy overview

The energy mix in Denmark, the country where I conducted my investigation more environmentally friendly than the world energy mix.
In 2014 57.4% of the net electricity generation came from renewable resources. Denmark is the main leader in the world concerning wind turbine and wind energy production. One of the main leading Danish companies is Vestas Wind systems A/S as expanded a lot having in the 2015 a revenue equal to €8.423 billion. In the year 2014, the 42.7% of the electricity production was produced by Danish wind turbines in Denmark. The idea is to extend this percentage up to 80% in the 2024.
The main aim of Denmark is to produce almost the 30% of energy produced from renewable resources by 2020. A great increase of renewables production came from 2005. Denmark has an ambitious project: from 2050, the country wants to use only renewable energy in all sectors, even in transport one.
Even the heating sectors had an important and large improvement and development in this past years concerning piping insulation, network systems optimization in high population areas. In 2013, the heating demand was satisfied thanks to district heating over 60% of households. Denmark is leader concerning industrial pumps and thermostat designs.
Concerning the electricity sector, it moves to be produced from the large central power station to the smaller ones, based on energy savings CHP systems plants like wood and pellets.

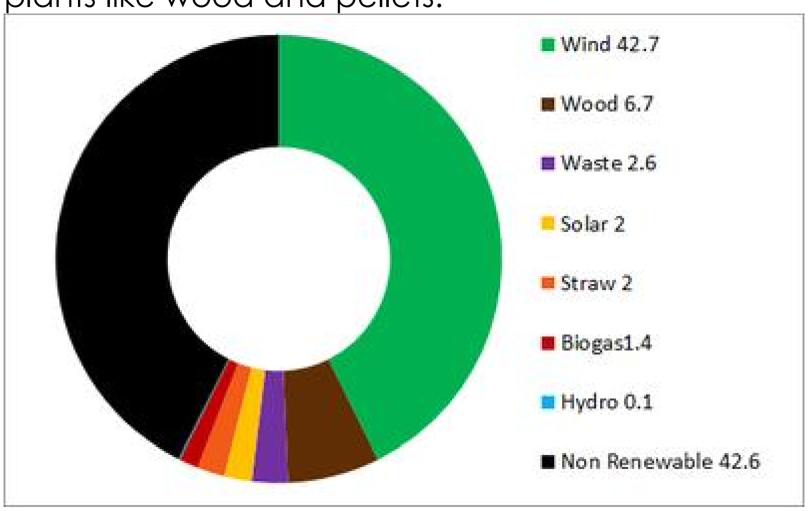

FIGURE 3 DENMARK ENERGY MIX 2014[5]

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5 https://www.google.it/url?sa=i&source=images&cd=&cad=rja&uact=8&ved=2ahUKEwi-

As it is possible to see in the pie chart, Denmark is very environmental friendly. Only the 42.6% of energy is produced by conventional plant. This is a real good goal cached from Denmark.[6]

Denmark, the country where I performed my thesis, has various goals for the future in order to improve the energy production efficiency and the energy production too. They impose to their self to conduct to realize the following goals:

2020 goal: 50% of electricity production by wind:

2030 goal: to eliminate coal from power production;

2035 goal: CO2 neutrality concerning electricity and heat;

2050 goal: CO2 neutrality of the whole energy system.

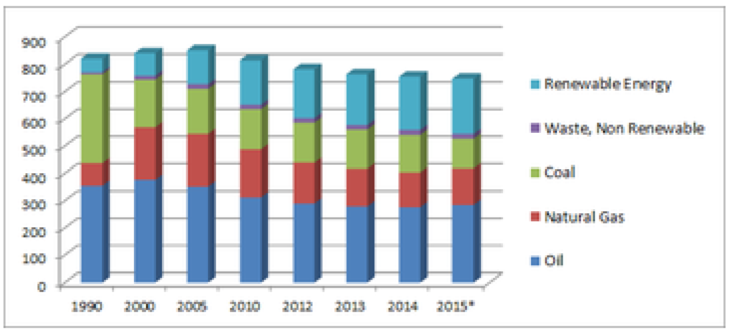

FIGURE 4 GROSS ENERGY CONSUMPTION IN DENMARK (PJ) 1990-2015. PRELIMINARY DATA. DANISH ENERGY AGENCY[7]

There are many types of solution that it is possible to adopt to stem all of these issues like:

- Reducing emissions as soon as possible
- Improving combustion processes
- Introducing some renewable energy systems like wind hydro solar energy etc.
- Introducing energy storage in order to remove the delay between the demand and offer of energy, especially concerning the electrical one.

Nowadays a mature society has to be able to use energy in a rational way in order to increase the energy efficiency of all type of energy conversion and to

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3lL745ncAhXLZlAKHWQ5C_8QjRx6BAgBEAU&url=https%3A%2F%2Fen.wikipedia.org%2Fwiki%2FRenewable_energy_in_Denmark&psig=AOvVaw0WSg8NmtTAGMgk_jAmJi7E&ust=1531492381060099

[6] from Energinet.dk, 2014

[7] https://upload.wikimedia.org/wikipedia/commons/thumb/a/a1/Gross_Energy_Consumption_in_Denmark_by_Type.png/360px-Gross_Energy_Consumption_in_Denmark_by_Type.png

introduce storages and renewable energy sources to delay the problem of the depletion of the oil, gas and coal.

For this motivation, all people are interested on the research to this issue and it is very interesting to create new technologies that could reduce or decrease the not renewable energy use. Nowadays the main energy demand is satisfied by non-renewable energy resources like natural gas, gas oil and coal. Even if there were a great increase of renewable energy on the world market, they are already a small part of the wordy energy mix. This is the motivation for what, knowing that the most energy vector is not renewable the most important thing, up to this moment, is to avoid the energy losses and to use them rationally. A way to do that is to store the energy and to use it when it is convenient and when there is a demand of them. An energy storage is a thermodynamic space in which it is avoided the exchange of mass and energy with the surroundings. The aim is to store energy in order to convert it in another form of useful energy when there will be a necessity.

All forms of energy could be reconducted to four types of energy:

Potential energy: the energy that a body has for the fact that is in a certain position relative to a reference state, stresses within itself, electric charge, and other factors.

Kinetic energy: it is the energy that a body has for the fact that it is in motion.

Mechanical energy: it is a form of energy that a body has due to this motion.

Thermal energy: it is an energy that a body has for the fact that it has a certain temperature with respect to a reference temperature.

Usually when a type of these energies is produced not always, this whole energy produced is used thus creating a waste of resources depleting the energy of the environment. To reduce the waste of resources it is a common way to create new way to store the energy not used and to use that in another moment.

All type of these forms of energy can be stocked in a proper way. A lot of technology researches are introduced to understand how to store the energy produced and how to convert it in a useful energy reducing as soon as possible the losses of energy conversion and energy storing.

5. Storage

5.1 Storage overview

The possibility to store energy is an important issue if there is an intermittent source like renewables for example wind and solar in a particular way.

Concerning the wind and solar energy linked to the grid, there are some periods, and especially for wind unpredictable too, in which there is a large production of electricity production unused because the request it is not in line with the energy demand. So the storage facilities could collect some of the excess energy from renewables that otherwise would be lost and make it available when the demands becomes higher, reducing the energy production by non-renewables resources.

As it is discussed before, the importance of the storage is fundamental for our society. Especially for the future considering the depletion of the energy resources, this technology has to be studied in order to improve the storage efficiencies, charge and discharge behaviours in relation to the motivation that we adopt to use it. The diffusion of this type of devices are connected to the increasing of renewables on the electricity and district heating market. Renewables technologies like solar panels, windmills , hydro pumps etc. are intermittent sources. A storage is a set of devices and equipment that have the capability to absorb energy (in general all types of energy), to store it for a certain lapse of time and in a following moment it has the function to release the energy. Therefore, this type of device has the ability take the energy and to release it in a different moment and this is very useful if the demand of energy is different with respect to the production side.

There are different types of storage and the difference come from the time that the device is able to store it considering the storage time it is possible this following typology:

- ✓ Daily;
- ✓ Monthly;
- ✓ Seasonal;
- ✓ Yearly.

In the first part the different types of energy that is possible to store is thermal, chemical, potential and mechanical. There are two main macro-groups in which is possible to store energy; they are electric and thermal storage.[8]

ELECTRICAL TYPOLOGY OF STORAGES

Considering this type of macro-group of energy storage, the typology of electric energy stored is chemical (Hydrogen), electrochemical (batteries), mechanical (flywheel, compressed air, hydroelectric basins) and electrical (supercapacitors)

- *Hydrogen:* it is used as a storage medium and positioned underground or in the vehicles. it is usually compressed at almost 20.7 [MPa] in gas cylinders or stored at pressure gauge for quantity higher that 15e3 Nm3. Usually this type of storage is limited to a quantity lower than 15000 [Nm^3], because there are a huge use of land and high costs with respect to the underground storage. There are many ways to store the hydrogen like absorption, absorption throw porous materials. The hydrogen is a fuel environmental friendly: higher low heating value (in mass) that the natural gas but lower low heating value in volume, because their density is very low.
- *Batteries:* use like a storage system. In a battery of a stack, there is a current flowing thanks to a spontaneous red-ox reaction. The pile is divided in anode, cathode and electrolytic layer. The work that it

[8] http://www.nextville.it/Sistemi_di_accumulo/2147/Accumulo_elettrico

produces is due to the voltage difference at the opposite anode-cathode side. Obviously, this device is rechargeable. The charging and discharging irreversibility is different but is very low. The major disadvantage is represented by an high elevated cost even if the market diffusion has carried to an high diminishing of the prices of them. The MIT (Massachusetts of Technology) affirms that the cost will decrease rapidly up to 100 dollars per [KWh], now the cost is 600 dollars per KWh. Batteries are fundamental to the isolated plant by electricity and they are very mostly used for electric energy auxiliaries. There are a lot of typology of batteries, they are different concerning the materials that we have to oxidize like (nickel-cadmium; lithium-ions, lithium-air etc.). The most promising batteries are lithium ions, most used for pc and electronic devices. It has an higher energy density (150 kWh/kg), higher longevity and, and it is very fast to charge it (even if the period of charge will diminishing using the same device to irreversible reactions).

- *Flywheels:* they are robust containers in which there is a certain vacuum degrees in order to reduce sounds and friction. In order to eliminate definitely the friction, the bearings are magnetically levitated. These systems are suitable for power up to 500 [kW], sometimes they are used in parallel to higher power. Their costs are competitive considering the batteries because they are a long lifetime and the maintenance is almost null. They are the possibility to recharge very quickly.
- *Compressed air:* this devices use electric energy to activate the air electric pump at low energy cost to compress air and charge the storage . When the this price is high and when there is necessity to produce electric energy. It is a type of storage advantageous concerning costs and concerning the electricity production mismatching. The air is stored at 70-100 [bar]. Usually the storage device is an underground cavern in which there is a good capacity almost 2-3 [kWh/m^3]. The net efficiency is very good and usually is higher than 80%. There are a lot of this type of storage in German.
- *Supercapacitors:* two polarised electrodes and an electrolytic separator compose them. The energy that is stored inside is an electric field in which more the electrode interfaces are near between them ore the energy is densified. The electric field is generated by the positive and negative charge separation due to the electrons motions. The disadvantage is linked to the electrodes surfaces because this energy is directly proportional of them, so means more cost and more space to put them. Now the most promising technology among the capacitors are the supercapacitors. They are supercapacitors made on carbon nanotubes with an high energy density like (76 [Wh/kg]) and an high power density like 506 [kW/kg], 20 times higher with respect to the conventional ones.

Thermal Typology Of Storages

Considering the other macro group, thermal energy, is exergetically inferior with respect to the electric type because it has the Carnot factor efficiency. If the electric energy is considered, its exergy is exactly equal to the energy produced because it correspond at pure work. The thermal energy storage techniques can be grouped in three big categories: sensible heat storage, phase change materials, and thermochemical heat storage. So it means that the thermal energy is a degrading one. It could be stored in different ways like:

- *Solar pond:* this storage device is composed of a mass of water, inserted in a basins, that has the aim to receives the solar rays in order to accumulate the energy inside it. The technique used to well store heat is to insert salt in the lake. the gradient has the aim to stratify the temperature and to maintain the heat down the first layer. Concerning the solar pond construction, if pond area is larger than thousands square meters, the cost per unit area is very low if the stratification is well done, the energy could be maintained there for a long time, for seasons for example, with very low energy losses. The solar lake cost is referred to a surface unit, from 150 to 70 [€/m^2] for a surface of 2e5 [m^2].

Molten salts devices: molten salts devices are used for parabolic mirrors, to concentrate the heat's sunlight received from the solar rays into a tube where it is put molten salts. Some plants use molten salts nitrate in order to store heat and to produce steam. The molten salts are used because it has better efficiencies and a great flexibility in electric energy production. Its cost nowadays is very interesting, it is 35 [€/kWt]; but in the future, the perspective would be 10 [€/kWt].

For example the heat recovery through a storage could increase the performances of a plant stabilizing the load (reducing the requiring peaks of energy to satisfy the demand), having more efficiency carrying the plant to have a lower energy cost. There are a lot of available technologies with different efficiencies, response mode to demand changes. The choice between various solutions depends on economic and technical parameters that it has to take into account. For example it is very important the storage period (daily, seasonal, annual, hourly etc.), economical availability, operatively conditions. The storage systems that now are diffuse could store energy for different periods of time and in different forms: chemical, mechanical (potential kinetical), magnetically and thermal energy. Every system is developed in order to answer to specific requests like efficiency, storage period, temperature etc. Therefore, it is possible to make a classification regarding the storage method and it is important to understand, when a storage device is built, which storage type could be the optimal one.

4.2 HT-TES rock bed storage

We focus on the sensible heat energy storage. As we said before, a storage, is a device able to maintain the energy and exergy for a certain period (of course with some losses, so a certain efficiency according to the second principle of the thermodynamic). Considering that this is a good technology to improve the energy production performance and to the development of the society and its knowledge.

It is a very interesting technology because, moreover concerning electric energy, there is a certain period of big and low demand, forcing the conventional plant to change their power production. Conventional plants are thought to work at maximum power, the power that permit to have the minimum losses. Therefore, if the electric demand changes and if would have only conventional plant, the change of the power production would create a lot of losses. That is why the introduction of the storage, that permit to produce energy in a different moment with respect to the moment that you have to use it reduce the losses.

Considering the energy that it stores, it is a heat at high temperature, and the heat at high temperature means high efficiency the heat is releasing of all energy conversion so it is important to understand how to use it even if it is the most degrading part of energy. Considering the thermal heat storage exists two main branch of this technology: latent and sensible, and it depends on which material stores energy and at which temperature. The latent heat is released and stored by changing phase materials (PCM) that storing heat with a high energy density. However, these materials are very expensive and usually they could store heat at low temperature. [9]

Considering the sensible heat storage material, we have many ways to store heat even if the efficiency of charge, discharge and storage are lower with respect to the latent ones, the energy density usually is lower and it depends on which material we consider. The temperature of the storage, so the exergy inside of them depends on which material we use to store the heat. In this analysis we focus on a heat sensible heat storage. The sensible storage has a low energy density, It is necessary to have a large space to insert it a plant. The material that in this thesis is used to make a storage is a type of rock vey common in Denmark; Swedish diabase. The diabase belongs to the magmatic igneous rocks cathegory and the 'filonian subcathegory. The main material that composes this rock is 'pirosseni' and 'plagioclasio' with a certain quantity of quarzo, oliviana, magnetite, and zirconia. The texturing of this type of rocks is olocristallina ofitica, rarely porfiric. Its colour is a dark colour like grey, black and green.

The main idea is inserted in a plant a container plenty of this typology of rocks. The heat specific sensible capacity is equal to 300 KWh/m3. Considering that in general it is a low value but the cost is very low, that is a good compromise considering cost and performance. As following there are the main advantages of this rock inserted in a plant to produce electricity thanks to the heat released to the rocks.

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[9] (Rubin & Davide, 2012)

FIGURE 5 A SAMPLE OF DIABASE WITH A POLISHED SURFACE ON ONE SIDE; THE WHITE MINERALS ARE PLAGIOCLASE FELDSPAR AND THE BLACK ARE CLINOPYROXENE.[10]

This type of rock changes their shape after and before the heat cycle. As it is possible to see in the figure, the colour and the thermophysical characteristics[11].

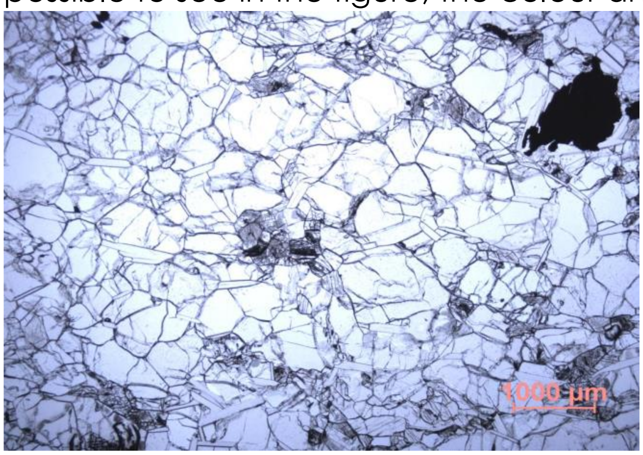

FIGURE 6 SWEDISH DIABASE BEFORE THERMOCHEMICAL CYCLE

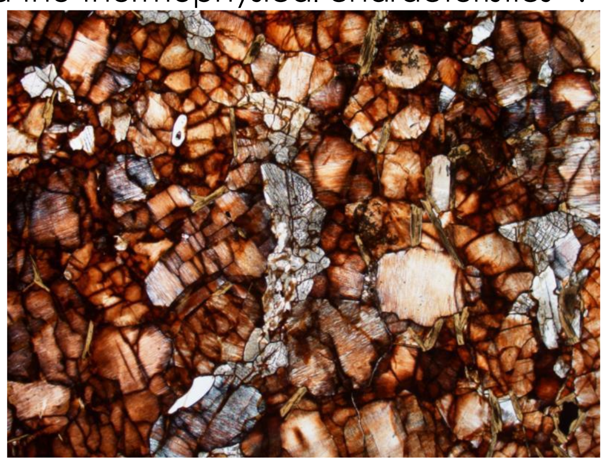

FIGURE 7 SWEDISH DIABASE AFTER THE THERMOCHEMICAL CYCLE[12]

FIGURE 8 SWEDISH DIABASE BEFORE AND AFTER THE THERMAL CYCLE

The main advantages of a high temperature sensible heat storage are:

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[10] https://it.wikipedia.org/wiki/Diabase#/media/File:Polished_Diabase.jpg

[11] https://commons.wikimedia.org/w/index.php?curid=10722179

[12] (Engelbrecht et al., n.d.)

- Due to the reduced efficiency associated with thermal conversion to electricity, the technology relies on relatively high electricity price fluctuations;
- The great advantage is the low cost compared to the others storage costs and easy scalability of the storage, useful for many applications;
- Storage period is from some hours up to weeks or months, it is strictly depending on which type of insulations around the storage it is put. It determines the heat losses and so the efficiency of the energy converting process.
- Low cost electricity is stored in form of sensible heat in the rocks bed and then it is used for producing electricity or district heating when the electricity prices are high through a bottoming steam cycle or an heat exchanger to the district heating networks.

Concerning the type of material that we are talking about it is a Swedish diabase thanks to that we could store heat at high temperature like 600 °C so being the temperature very high it is possible to re-use this heat to produce electric energy in a steam cycle plant.
The main advantages to use these rocks to industrial application are the following

i. We chose Swedish diabase as the first rock material;
ii. Available in different sizes;
iii. Able to withstand cycling to 600 [°C];
iv. First rocks tested were sieved between 20 [mm] and 40 [mm];
v. We are looking at different rock types and sizes for future experiments.

Usually to refill and to use the heat in the right way it is convenient to insert it a power-to-power plant.
The power-to-power plant is a typical plant that has as an input energy (usually electrical) useful to charge the storage and an output to produce energy (it could be electrical again or thermal or mechanical or potential etc.) as we said before, this type of plant is very useful to save energy, so especially for the future it is important to understand if a type of plant like this could be advantageous or not.
This is the motivation for what it is carried a feasibility analysis on this type of plant.

6. Power to power plant

The feasibility analysis that we are going to perform is about a HT-TES unit used for power-to-power applications. The aim of the power-to-power plant is to produce electrical and thermal energy having electric energy as an initial input. This new storage technology that is being investigated in Risø DTU, is inserted in this type of plant. It is a high temperature sensible heat storage, made of rocks, whose name is 'Swedish diabase'. Their price is very cheap and the specific heat of them is quite high, that are the main motivations for what it is very interesting to study them and carry a feasibility analysis about this new technology. (rocks price: 35€/ton and specific heat is equal to 3000[kJ/kg/K]).

This power-to-power plant (i) receives electric energy as input and converts it in high temperature heat in a first moment; (ii) in a second moment this thermal energy is stored; (iii) and finally the heat is recovered through a HRSG in order to produce electricity or district heating. The aim of this work is to understand in which moments it is convenient to operate these three phases in order to reach the maximum profit.

The aim of this chapter is to analyse in detail all parts of the plant and, making some assumptions, to size it.

To perform this analysis it is built a tool able to simulate the power-to-power plant behaviour in a whole year. It is possible to do that making an algorithm in order to understand if it is a winner idea or not. Following the electricity and district heating Danish prices, the algorithm has to be able to understand when it is best to charge the storage and when it is most convenient to discharge and store the energy in order to obtain the maximum profit. In principle when the electricity price is low it is convenient to charge the system and when the price becomes high it is convenient to discharge it. A feasibility thermo- economic analysis on the HT-TES made of rocks, inserted in an electric and district heating producing plant, can optimize the charge-discharge activities to maximize profit. The final idea is to carry a yearly 'perfect prediction' on this plant,using an algorithm that optimizes the power-to-power plant behaviour using the yearly electricity and district heating prices as an input it creates a perfect behaviour of the every phase considering the charge storage and discharge of the plant in order to reach the maximum profit. The plant works in three different phases in three different moments, so the aim of the algorithm is to understand when it is convenient to charge, to store heat and when to discharge in order to reach the maximum profit. Assuming a "perfect prediction " perspective means to consider known the trend of the electric and district heating prices over the year prior to operations. That significantly differs from the actual operations, in which forecast operators are hired to define a trend scenario for the upcoming days, but can give a good estimate of the profit margin that such a technology could have on the market. The analysed plant is assumed to opearate in the Copenhagen district heating and electric networks. Energinet, a Danish electrical company is also involved in this project in order to understand if this type of non-conventional technology is feasible and could give a reasonable profit or not, now and in the future.

Knowing that the plant is physically divided into three parts and knowing that they work in three different moments, it is considered that the plant is made of three separate parts. For each phase of the power-to-power plant there is a size parameter that characterizes it, thanks to which it is possible to size all the components. A way to size the whole plant it is therefore to set the three parameters concerning the size.

To do that it was built an algorithm that receives as an input three parameters: heater power [MW] for charge, storage capacity [MWh] for storage phase and turbine power [MW] for discharge. Giving some values to these parameters, the Matlab algorithm allows to do the following things:

To dimension the single components for each phase and consequently define the technical operating parameters

To know the heat fluxes inside the plant at maximum regime;

To know the costs of each component inside the plant;

To know the entire cost of the plant using the NETL methodology;

To know which revenues in 2017 and in 2035 you can reach with this parameters;

To know the economical parameters like return of investment, Pay Back Time, Net Present Values ;

To make a parametrical analysis varying the three input values in order to find the optimal size of the plant from the economical of view;

The final aim is to carry a parametrical analysis to understand which are the best size of this type of plant from the economical point of view.

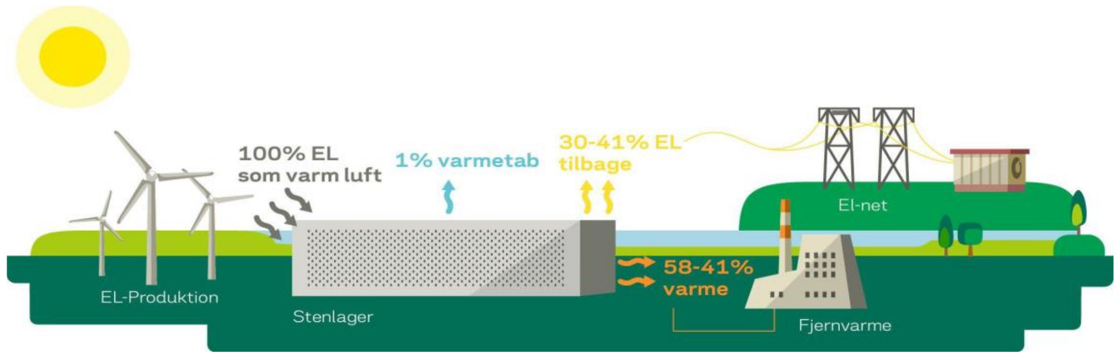

FIGURE 9 POWER-TO-POWER PLANT OVERVIEW[13]

It could be divided into three main sections. This plant does not exist on the market, so one of the aim of the thesis is to find the optimal size of each part of the plant. Dividing the plant in these three parts, it is simpler to manage the calculation and to do the final work that concerns creating a script in which the input parameters are the heater power [MW] (charge), storage capacity [MWh] (storage) and turbine power [MW] (discharge). These three parameters are independent among them and if someone sets a value for them it is possible to size the whole plant and to conduct a feasibility analysis thanks to the MatlabR2017b script.

When this thesis was performed it was imagined that this plant would be a power to power plant, so it means that it receives electrical energy as a input and it produces electric energy and in some case district heating as output. This plant is based in Copenhagen so it is inserted in a Danish electrical grid and in a district heating networks. The main scheme could be generalized like the following scheme shows:

[13] (Engelbrecht et al., n.d.)

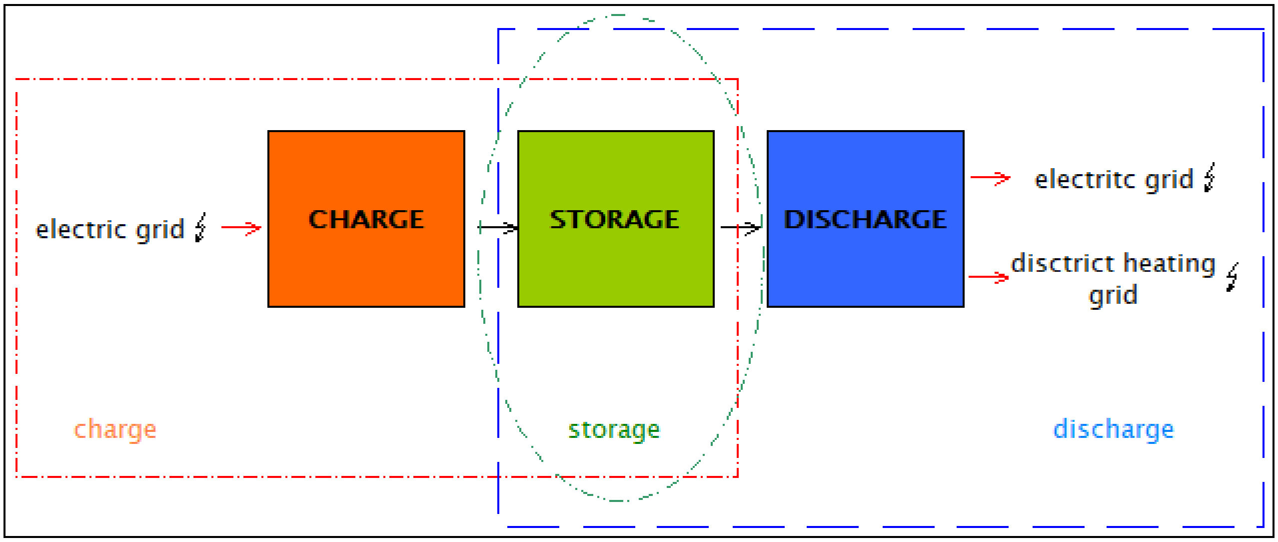

FIGURE 10 MAIN PHASES OF THE POWER-TO-POWER PLANT.

6.1 Introduction to power to power plant

The plant works in the following way:

When it is convenient to charge the system, ambient air is blown by a fan inside the heater, where it is heated up to high temperature and then carried inside the storage. The hot air progressively exchanges heat with the rocks. When the plant is in the storage phase, the valves are closed and the heat remains stored inside the rocks. When it is convenient to discharge the valves are opened and a fan carries cold air inside the storage to recover the heat from the rocks and to carry this heat inside an HRSG that exchange this thermal energy with a steam cycle that produces electricity and heat for district heating.

Therefore, for simplicity it is possible to subdivide the plant into three phases: charge, storage and discharge.

These three parts work sinergically in order to maximize the profit following the electricity and district heating prices.

After having a general overview now, we focus the attention on each part and component of the plant.

In this work it is analysed three typologies of power to power plant to understand which is the most feasible and how this high temperature sensible storage could be the best promised technology in the Danish market.

This three different typologies concern only the discharge part, the charging and storage phase remain the same. The differences among these three power-to-power plant concern the various energy that this plant could produce. They depend on the various factors that, in the following chapters will be explained.

1. POWER-TO-POWER PLANT – simple steam turbine- electric power only

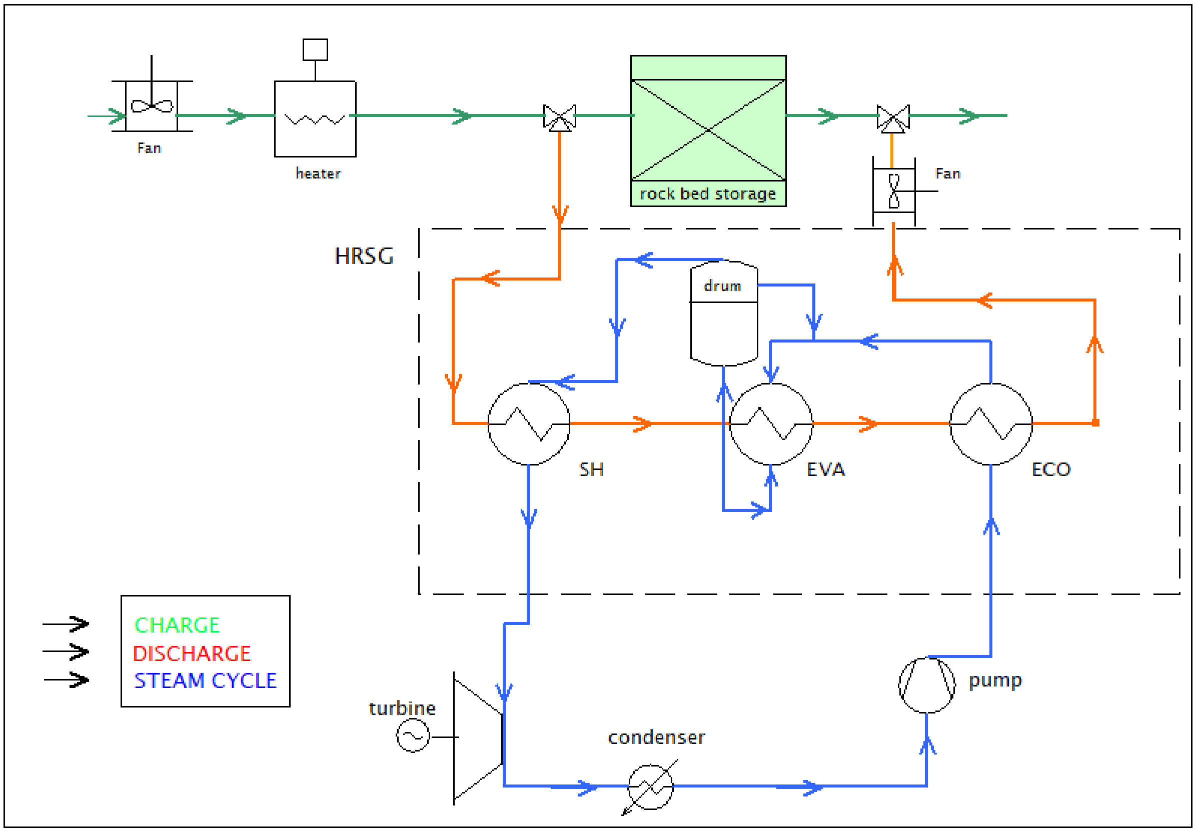

FIGURE 11 TYPE ONE - SIMPLE STEAM TURBINE IN DISCHARGE PHASE.

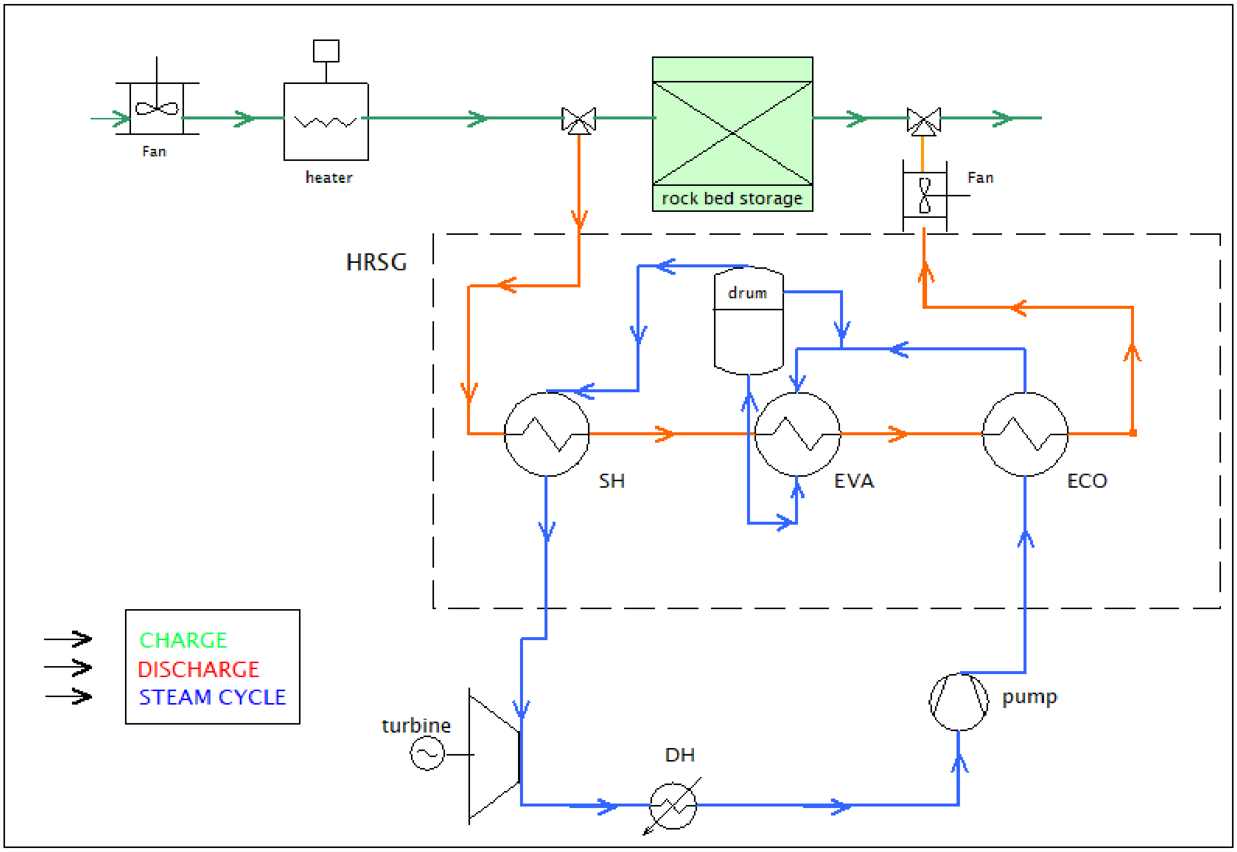

FIGURE 12 TYPE TWO - SIMPLE STEAM TURBINE AND STEAM TURBINE WITH DISTRICT HEATING IN DISCHARGE PHASE.

1. POWER TO POWER PLANT – simple steam turbine - electric power only; a steam turbine - heat and electric power and heat exchanger – heat (DH)

for district heating

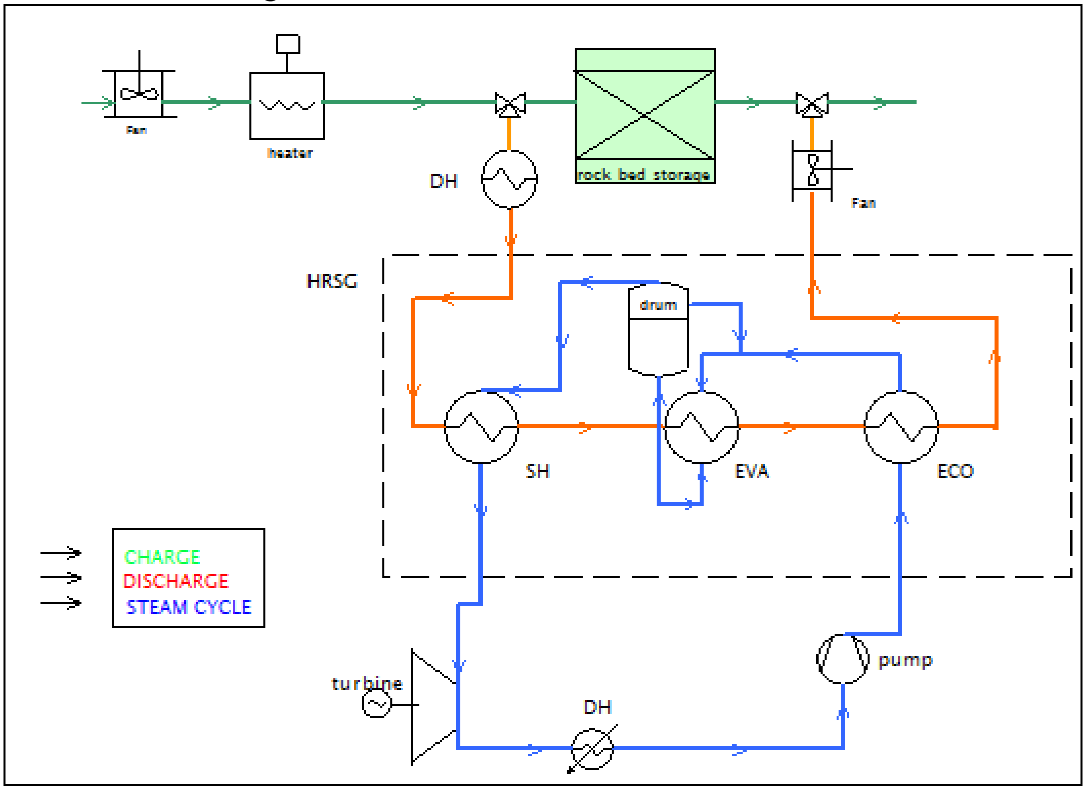

FIGURE 13TYPE THREE - SIMPLE STEAM TURBINE AND STEAM TURBINE WITH DISTRICT HEATING AND HEAT EXCHANGER FOR DISTRICT HEATING IN DISCHARGE PHASE.

CHARGE

This part of the plant works when the HT-TES has to or it is convenient to heat up. Basically the charging part works when the prices are low in order to use in an intelligent way this plant. It is possible to do that inserting hot air at the inlet of the storage at 600°C. It was decided to use this temperature because operating at higher temperatures would mean to use more heat-resistant and expensive components and materials, which would significantly increase the cost of the whole plant. To satisfy this work in the charging part a fan is used to push the air though the insulated pipe towards the electric heater. Here, the air will warm up and it go towards the storage passing through a throttling valve. The piping is made of stainless steel insulated with rockwool or superwool materials.
The main components of charging phase are:

1. Axial fan;
2. Electric Heater;
3. Pipes;
4. Pipes insulations.

5.1 HT-TES STORAGE

The main important part of the plant is a high temperature sensible energy storage made of rocks. This component has the aim to store heat at T=600°C as long as it is possible and then to discharge the heat stored before throw the bottom cycle. We consider a cubic shape of the storage made by Swedish diabase rocks whose equivalent diameter is 3 [cm] and a porosity of the bed of around 0.4[-]. The storage is linked with the other parts of the plant thanks to two throttling valves inserted in tubes. As we said, the shape of the storage is cubic; the idea is to put it underground with the top side in contact with the air. In principle, rocks, in charging phase, are invested of hot air through a pipe put on the higher part of the left side of the cube. The air heats up the rocks with conduction, convection and radiation. The cold air that exits from the storage is on the higher part of the left side of the cubic storage. Considering the discharging phase, we use cold air in which the aim is to heat up the air using a mass flowrate that use the same tube but in the opposite direction with the aim is to not alter the thermocline if the bed. The sensible high temperature storage is made of rocks with a heat capacity equal to 300 [KWh/m3] that release heat during time.

The main components of storage phase are:

1. Swedish diabase - Rocks;
2. Hard insulation - Scamol;
3. Soft insulation high temperature - Superwool;
4. Soft insulation low temperature - Rockwool;
5. Concrete;
6. Valves.

DISCHARGE

The third and last part of the power-to-power plant is the discharge phase. When it is economically convenient (basically when the electricity prices are high) and when the storage is sufficiently full, the heat stored is used to produce energy. A cold air flux will passes through the rocks as it is said, in the opposite direction with respect to the charging part in order not to modify the thermocline and the exergy stored inside the rocks. The cold air pressed by a fan is to heat up from the heat stored in the rocks. The air goes out from the storage at 600 ºCheating up the steam cycle in the heat recovery steam generator, the device where there is the exchange of heat between air and steam. The final aim is to use the heat recovered in the rocks to produce available energy. Considering the energy production it was considered two types of energy, thermal for district heating and electrical for the grid. Here, to produce that it was considered three options:

- To transform the heat into electrical power using a steam turbine in order to produce only electricity. Considering the steam cycle, it is studied a one pressure level simple Rankine cycle in which the maximum temperature at 570°C with a high pressure of p=70 [bar] and a low saturation pressure of temperature equal to 30 [°C] with a thermodynamic efficiency equal to 34%.
- To produce either electricity either heat for district heating thanks to the heat that is stored in the rocks. In this option, it is considered a steam cycle

with the same characteristics of the previous case but in this case there is the possibility to discharge in district heating too. So in this case it needs to raise up the steam cycle low pressure level in order to use higher heat of condensation of the water that went out from the turbine to reach more heat useful for the district heating at the saturation pressure of temperature equal to 100°C with a thermodynamic efficiency equal to 28% and an overall efficiency equal to 60%. So in this case we more option to produce energy.

- In this third option there are the same steam cycle of the second option(with two types of low pressure level) but is added another heat exchanger to release heat for district heating before HRSG, bypassing the steam cycle.

The main components of the discharge phase are:

1. Axial fan;
2. Heat recovery steam generator (HRSG);
3. Pipes;
4. Pipes Insulations;
5. Turbine;
6. Condenser (for the 1st option) or heat exchanger (for the 2nd and the 3rd option);
7. Heat exchanger for the 3rd option;
8. Economizer;
9. Evaporator;
10. Super heater;
11. Drum;
12. Pump.

5.2 Technical parameters

The design parameter that allows to find the correct size of components is done considering three free parameters. As it is said before, this plant does not exist on the market so to carry an optimal feasibility analysis of this type of new technology it is important to find, as the final work the right size of each part of the plant. Studying it, it is possible to discover that there are three free parameters, one for each part of the plant. If it is set a value for these components, it is possible to size all plant. These three parts work sinergically but considering the charge and discharge phase they are completely independent. The only link is the storage that is involved in the three phases, even if the size of the storage phase is independent on the charge and discharge part parameters, that is why we have to set three parameters to size each part of the plant and to find the optimal one for now and the for the future scenario.

1. Heater power [MW]
2. Storage capacity [MWh]

3. Turbine power [MW]

The developed tool that is performed receives as an input these parameters and through these defines all technical components size of the plant.

5.2.1 Charge phase

Input parameters: HEATER POWER [MW], STORAGE CAPACITY [MWh]

In the charging phase, the input parameters are the heater power and the storage capacity. The main components of the charging phase are the heater, fan, piping and pipe insulation. Knowing the sizing power of the heater it is simple to know the mass flowrate making an assumption of the heater efficiency (95%) and supposing the air as an ideal gas with 21% of oxygen and 79% of nitrogen. The formula that we use for this device determines its effective heat energy that the air flux receives imposing the final and initial temperature. The final temperature is imposed and it must be 875.15 [Kelvin] in order to be sure that an heat flux of 873.15 [Kelvin] arrives at the storage knowing that 2 [Kelvin] temperature drop is lost in pipes. Even the initial temperature is imposed. An initial outside temperature is imposed equal to 273.15 [Kelvin]. This initial temperature it is not a casual value. Considering that the plant is located in Copenhagen and it is imposed that the air that enters in the plant comes from outside. Basically, this plant or this part of the plant could work in every moment of the year so to be cautelative it is decided to impose the lowest mean monthly temperature.[14] This value, like the figure shows is equal to zero degrees in January.

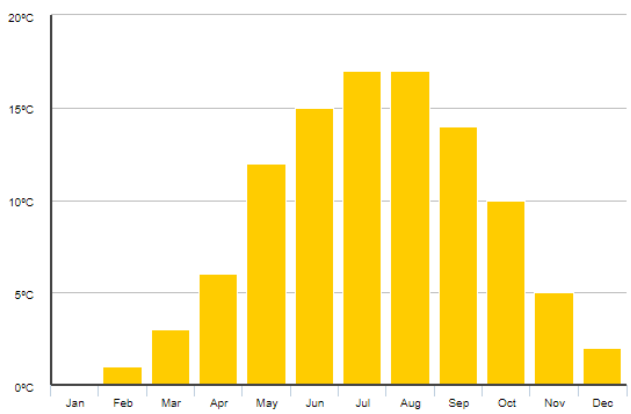

FIGURE 14 MEAN MONTHLY TEMPERATURE IN COPENHAGEN[15]

Considering the specific heat at constant pressure to calculate the mass flowrate a mean value between the initial and final temperature is imposed. Considering the air like an ideal gas the specific heat (c_p [kJ/Kg/K]) is only temperature dependent[16]. A mean value is calculated. Like the figure shows the specific heat at constant pressure increases if the temperature rises up. The mean value is

[14] https://www.holiday-weather.com/copenhagen/averages/

[15] https://www.holiday-weather.com/copenhagen/averages/

[16] https://www.ohio.edu/mechanical/thermo/property_tables/air/air_cp_cv.html

calculated using the corresponding c_p values of initial and final temperature imposed.

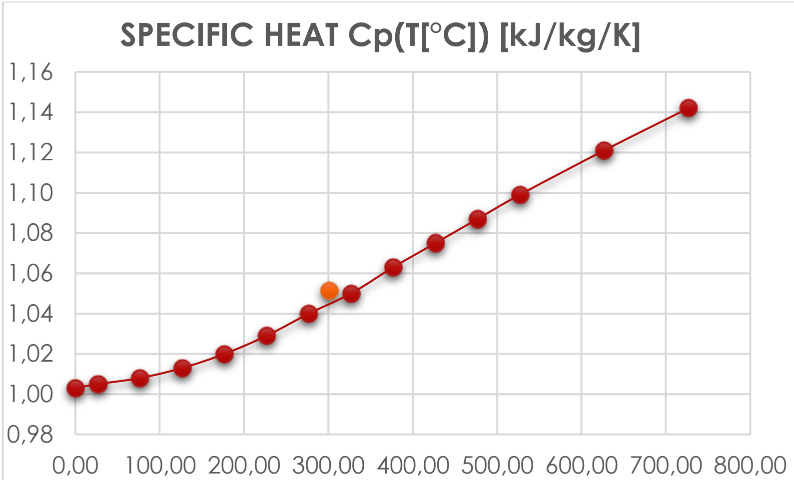

FIGURE 15 SPECIFIC HEAT AT CONSTANT PRESSURE FOR THE AIR VARYING WITH TEMPERATURE. THE MEAN VALUE USED FOR THE MASS FLOWRATE CALCULATION IS SHOWN IN THE GRAPH.

Therefore, using this data it is possible to find the right value of the mass flowrate with the following formula:

$$\dot{m}\left[\frac{kg}{s}\right] = \frac{heater_{power} * \eta_{heater}}{c_p * (T_{heater} - T_{ref})}$$

Onece the mass flowrate is found, it is necessary to size the fan. It is assumed the isothermicity of this device, therefore it is used the following formula:

$$Fan_{power}[KW] = \dot{m}RTln(\frac{P_{out}}{P_{in}})$$

Where T [K] is the outside air temperature and R [kJ/kg/K] is the gas air constant calculated considering 21% of oxygen and 79% of nitrogen.

The aim if this device is to take the air from outside and to push the air inside the storage. It is not possible to know a priori the pressure drop that the air inside the pipe because they are not already sized. A way to proceed is to fix the pressure drop that there will be inside the pipe.

We consider as assumption that the pressure drop inside the pipe as to be below 10% with respect to the storage pressure drop, useful to know the power of the Fan assuming that the fan efficiency has to be 60%. To know the storage pressure drop there is a correlation about concerning the pressure drop inside rocks. The Ergun equation is used to evaluate the pressure drop inside the storage: correlation is used having as an input the using the following assumption.

$$\frac{\Delta p}{L}\left(\frac{\varepsilon^3}{1-\varepsilon}\right)\left(\frac{\phi_s d_p}{\rho_f V_o^2}\right) = \frac{150 * (1-\epsilon) * \mu_f}{\phi_s d_p V_o \rho_f} + 1.75$$[17]

[17] http://www.doiserbia.nb.rs/img/doi/1451-9372/2015/1451-93721400044P.pdf

Where:
$\Delta p\ [Pa]\ is\ the\ pressure\ drop\ inside\ the\ packed\ bed\ rocks$;
$L\ [m]\ is\ the\ length\ of\ the\ storage$;
$\varepsilon\ [-]\ is\ the\ porosity\ of\ the\ media$;
$d_p[m]\ is\ the\ equivalent\ diameter, which\ is\ set\ equal\ to\ 3e-2\ \ [m]$;
$\rho_f\ [m^3]\ is\ the\ density\ pf\ the\ fluid\ that\ passes\ throught\ the\ rocks$;
$V_o[m^3]\ is\ the\ total\ volume\ of\ the\ porous\ media$;
$\phi_s\ is\ the\ sphericity\ of\ the\ particles\ in\ the\ packed\ bed$;

$\mu_f\ is\ the\ dynamic\ viscosity\ of\ the\ fluid$;

Considering the sphericity ϕ_s we assume that the rocks are completely spherical, so we use the following formula knowing that the average equivalent diameter s equal to 3e-2 [m]

$$\phi_S \frac{\pi^{\frac{1}{5}}(6V_p)^{\frac{2}{3}}}{A_p{}^{18}}{}_{19}$$

Where:

$V_P\ [m^3]\ is\ the\ volume\ of\ one\ rock\ that\ composes\ the\ porous\ media$

$A_p[m^2]\ is\ the\ surface\ of\ one\ rock\ that\ composes\ the\ porous\ media$

To know the total volume of the rocks another information is added about the rocks packed bed total volume. To this plant we carry a feasibility analysis about a specific typology of rocks; Swedish diabase. The Swedish diabase are a density equal to $\rho_{rocks} = 3000\ [\frac{kg}{m^3}]$; so to know the total volume, set like a input parameter the storage capacity [MWh], the following formula is used:

$$c_{storage}\left[\frac{KWh}{m^3}\right] = \frac{c_{p_{air}} * \left(\mathrm{T}_{600[°\mathrm{C}]} - T_{0[°C]}\right) * \rho_{rocks}}{3600 * (1-\varepsilon)}$$

$$V_o[m^3] = \frac{storagecapacity\ [MWh]}{c_{storage}[\frac{KWh}{m^3}]}$$

Where $c_{storage}[\frac{KWh}{m^3}]$, is the specific heat that the storage could store in one cubic meter (~300 kWh/m^3). This quantity is calculated in the following way, knowing that in the rocks there are air at 600 [°C].

Another assumption, that the storage has a cubic shape, through the Ergun's equation is possible to calculate the pressure drop inside the storage. In the

[18] https://en.wikipedia.org/wiki/Sphericity

project phase of the charging phase we assume that the pressure drop inside the pipe has to be equal to the 10% with respect to the storage pressure drop. In this way the fan power is known.

Once it is known the total pressure drop, it is simple to calculate the correct size of the fan that has to carry the air inside the storage through the tubes. The fan is considered isothermal and an efficiency of 60% is supposed. An axial fan is used because the mass flowrate is very big so we need an axial one that pushes the air inside the storage and it has to be able to carry the air up to the storage.

The final thing that has to be done is to size the pipes diameter.

It is possible to consider in the charging phase two pieces of pipe; the piece that links the fan and the heater and the piece between heater and the storage. We assume a fixed pipe length: 20 [m] in total; for the first part (fan-heater)it is used 7 [m] and for the second one(heater storage) is 13 [m]. In principle it is not possible to know the pipes diameter a priori, but imposing the pressure drop and imposing the length it is simple to know using the Coolebrook correlation to know the Darcy friction factor thanks to Moody diagram. The main assumption that it is made are the following:

- The pressure drop has to be less of 10% w.r.t. the rock bed pressure drop
- The length of the pipe is fixed
- If a pipe diameter equal to 2 [m] it is not sufficient to respect the obligation of the pressure drop it is assumed that there is the possibility to add more pipes in parallel to satisfy this constraint.

To know it firstly you have to calculate the mass flowrate and then the Reynolds number imposing a maximum velocity equal to 25 [m/s] in order to avoid that the pipe could whistle.[20]

$$Re = \frac{\rho * w * D}{\mu}$$

If the Reynolds number is Re<2300 you can use 64/Re to find the value of the Dacy's friction factor otherwise it was mandatory to use the Moody diagram. In fluid dynamics, the Darcy friction factor formulae are equations that allow the calculation of the Darcy friction factor, a dimensionless quantity used in the Darcy–Weisbach equation, for the description of friction losses in pipe flow as well as open-channel flow.

So in Matlab script is it iteratively increase the diameter value and the number of the pipe in order to find the minimum size of diameter and the minimum number of tubes that could satisfy all this conditions. The final formula to verify if the pressure drop is minor than the set value is the distributed pressure drop correlation:

$$\frac{\Delta p}{L} = f \frac{w^2}{D*2} \left[\frac{Pa}{m}\right]$$

Then, with Colebrook correlation, the diameter is known. We assume that the maximum diameter has to be 2 [m], if the pressure drop will be higher than the 10% with respect to the pressure drop of the rocks bed iteratively we add a pipe

[20] tesi.cab.unipd.it/28283/1/PaggiaroFabioTesi.pdf

in order to reach a pressure drop minor with respect to the pressure drop established before it is possible to stop the iteration.

Once we reach the correct number of tubes and their diameter calculated with Colebrook correlation, it was found the commercial diameter using the Renard series.[21]

The 'Renard series' is proposed by Colonel Charles Renard, a French Mathematician graduated in army engineer in 19^{th} century. It is a system of preferred numbers divided into 1 to 5 or 10 or 20 or 40 steps. The system was adopted from 1949 by ISO and then this series is used by international ISO to determine the commercial diameter of the pipe. The difference between series' number are approximately the same, so the relative error is minimized if a number is replaced by the nearest number multiplied by a power of ten. This is a geometric sequence like the following:

$$R(i,k) = 10^{\frac{i}{k}}$$

It is a geometric succession. Any series with any reason start from 1. Concerning commercial diameter, the series' reason is ten. The previews series could be showed in a recursive like:

$$\begin{cases} R(0,k) = 1; \\ R(i+1,k) = R(i,k) * \sqrt[k]{10} \end{cases}$$

Then to know the maximum strength of the stainless steel and knowing the pipe maximum pressure we could achieve to the thickness of the stainless steel. We considered the pipes thermally insulated with an inner layer of high-temperature insulation (superwool) and an outer cheaper layer of low-temperature insulation (rockwool).

Now, to preserve the heat losses it is important to choose the right thicknesses of the insulations.

The insulations layers that are considered are superwool and rockwool. Rockwool is an insulation material that has the possibility to overcome the heat losses throw the pipe. It is a cheap material but it could support a maximum temperature of 400°C. In order to obtain a cheap but consistent insulation we use after stainless steel superwool. When the maximum temperature of the rockwool is reached we use rockwool in principle. It is known that the maximum temperature of the fan is equal to 300°C. In the piece of the pipe that links the fan and the heater a temperature higher than 300°C will never be reached that is why only rockwool is applied. Considering the second piece of the pipe in charging phase, so that one that links the heater and the storage a temperature higher than 400°C surely it will be reached, so that is the motivation for what the superwool is also used.

Considering the first piece of the pipe a temperature drop equal to 2 °C it is assumed. Imposing this value it is possible to know the thickness of the insulation (only rockwool in this case) knowing the heat transfer coefficient of the inside and outside of the air, the thickness of the stainless steel and imposing an heat fluxes it

[21] www.cadem.com/single-post/cnc-preferred-sizes

is possible to calculate the thickness throw the Fourier formula throw the radial direction. We assume a radial system to know the insulation thickness. To size the insulation the inside and the outside temperatures are set: Tin=600 [°C] (cautelative assumption) and the outside air temperature is set equal to 15°C.
The same procedure is applied for the second part of the pipe. We use the same system and the same assumption like a temperature drop equal to 2°C, and the same Fourier's formula. We could find the right thicknesses of the insulations knowing that the maximum temperature that the rockwoool could support is 400°C the either thicknesses are found. The motivation for what we do not use only superwool is that rockwool is cheaper with respect to superwool, that is why we use two insulation layers.
As it is written, knowing the heater power and the storage capacity it is possible to size every components of the charging part.

5.2.2 Storage phase

Base parameter: STORAGE CAPACITY [MWh]
The second phase to size is the storage phase. The main components are: rocks, insulations, valves. Let us imagine that the storage is underground for 5 sides and only the top side are in contact with the air. When the plant has the necessity to store the heat the two valves are closed in order to avoid heat losses. When the storage has the possibility to be charged the valves are opened in order to let the flow passing inside the storage and the same thing happens for discharging phase. A cubic shape of the storage is assumed. The rocks that it is used to stock the heat is the Swedish diabase, a type of rocks[22]. The motivation for what these rocks is studied is firstly because they are the same types of rocks in which in Risø National Laboratory (DTU) are been found all thermophysical parameters, useful to make calculation. The second motivation is that it is a type of rocks very cheap, very common in Denmark and in Scandinavian too.
The main motivations for using these rocks is the cost compared to the capability of to store heat. Thanks to the informations reported in the table are used to calculate the pressure drop thanks to the Ergun's[23] correlation using these assumptions:

TABLE 1 THERMOSHYSICAL CHARACTERICTICS OF ROCKS

Equivalent diameter : 3e-2 [m]
Porosity: 0.4 [-]
Shape of the rocks: spherical
Specific heat per unit volume at temperature equal to 873.15 [K]: 300 [kWh/m³]
Rocks density: 3e3 [kg/m³]

The Ergun equation formula is the showed in the charging phase.

[22] (http://www.microbas.se/diabase/)

As it is possible to see in the graph showed above, the heat that it is possible to store is quite high. That is the motivation for what it is a good compromise between cost and performance.

To connect the storage to the other part of the plant we the storage has two tubes at the higher part of the lateral sides. The motivation for what it is better to put the tubes in the higher part is to not alter the thermocline and to preserve the exergy inside the storage. The storage phase is always in work.

When the charging part works, from the right part of the storage air at T=600°C enters in the storage through a throttling valve and the cold air exits from the storage to the opposite side. Considering the efficiency of the process, we use experimental data from the storage at Risø Campus National Laboratory. The efficiency of this process is targeted to 0.95; the 1% of losses is towards the walls and 4% is due if we do not consider the recirculation of the hot air that leaves the rock bed.

Vice versa, in the discharging phase, a cold mass flowrate passes in the opposite direction exiting from the storage at T=600°C to go towards the HRSG. The efficiency of this process is also assumed 0.95 because in the storage phase we do not consider the possibility of recirculation. Considering the percentage of losses, 1% wall losses and the rest is due to the air that exits from the storage. The same tube is used to charge and to discharge in order to reach the maximum quantity of exergy.

When are absent the charging or discharging phase, all valves are close to limit the losses throw the tubes. The efficiency of this phase is targeted to 0.008%/hour with respect to the size capacity.

To contain and to avoid the losses it is convenient to add insulations and some materials to contain and to sustain the total amount of rocks. The idea is to put the rocks underground, so the Storage is in contact with the ground for five sides and only the top layer is in contact with the air. The materials that it is used to make the insulation layers are the same of the plant that DTU Risø campus so in this way, having as an input the storage capacity we could scale the problem knowing, as we said, that in one hour we have a loss equal to 0.008% with respect to the capacity when the two valves are closed, so in the rest phase.

The insulation layer that we are talking into are:

- HARD INSULATION: the insulation that we consider is supplied by Skamol A/S. It is an insulating material that has an high strength and a low thermal conductivity, that is why this material is involved in the plant.; The thermophysical properties of this material is k=0.1[W/m/K]; ultimate strength in compressionin cold condition at 800°C= 2.7[MPa][24] the temperature that this. The maximum T that this material could support is

[24] https://www.researchgate.net/profile/Alexey_Belyakov/publication/227313194_Advantage_of_heat_insulation_made_of_materials_with_natural_porosity/links/56a76a2308ae860e02555ca3.pdf

1500°C, so very high with respect to the maximum temperature that the storage could reach, i.e. 600°C.[25]

- SOFT INSULATION HIGH TEMPERATURE: "Superwool® 607® HT™ products are a range of versatile high temperature insulation products which are safe to use and retain their outstanding properties even at elevated temperatures. Historically fibre based insulation products have often been accompanied by health issues associated with their use. However, Superwool® 607® HT™ has been developed as a safe-to-use alternative material with low bio persistence, meaning that any fibres which may be breathed in are rapidly removed by natural processes within the body. In addition to very low thermal conductivity Superwool® 607® HT™ products also have a classification temperature of 1300°C, good strength, low shrinkage and offer thermal stability." [26]The thermophysical characteristics are k=0.040[W/m/K], rho=128 [kg/m^3] and the tensile strength (EN-1094-1) is equal to 75 [KPa]. This material it is very environmental friendly but the cost is very high, so, another cheaper material with a very low value of thermal coefficient but the maximum temperature of only 400 [°C] was used.
- SOFT INSULATION LOW TEMPERATURE: the main thermophysical characteristics are[27] the specific heat at constant pressure c_p=1030 [J/kg/K](UNI EN ISO 10456); thermal conductivity k=0.033 [W/K/m] (UNI EN 12667) density d=70[kg/m^3], linear thermal dilatation coefficient l=$2x10^{-6}$ [1/°C]. This panel has optimal characteristic with high efficiency. The only problem of this material is the temperature limit. The cost of this is very cheap but there is a limit of temperature equal to 400 [°C]. if this limit is overcome the thermophisical characteristics could be modified. So it is not possible to use only rockwool, even if it is the best compromise between cost and performance but we have to add other materials that are able to support higher temperature.
- CONCRETE: the thermophysical characteristics, so the thermal conductivity could vary from 0.3 to 1.8 [W/m/K] and it depends on the porosity and which type of material composition the concrete is made. It is chosen to use a constant thermal conductivity equal to 1.2 [W/m/K]. The aim to use this material is to contain and to protect the rocks from atmospheric agents and to protectans sustain the insulation layers. The thickness is fixed because we have some blocks is concrete. The maximum

[25] https://www.skamol.com/products

[26] http://www.morganthermalceramics.com/media/1814/sw_blanket_data_sheet_english_1.pdf ; http://www.goodfellow.com/corporate/news/2011/Superwool-607-HT-Goodfellow-UK-Sept-2011.pdf

[27] http://www.rockwool.it/prodotti/acoustic-225-plus/

T that this material could support is T=200°C. Therefore it is important to well manage this information in order to avoid some structural problem.

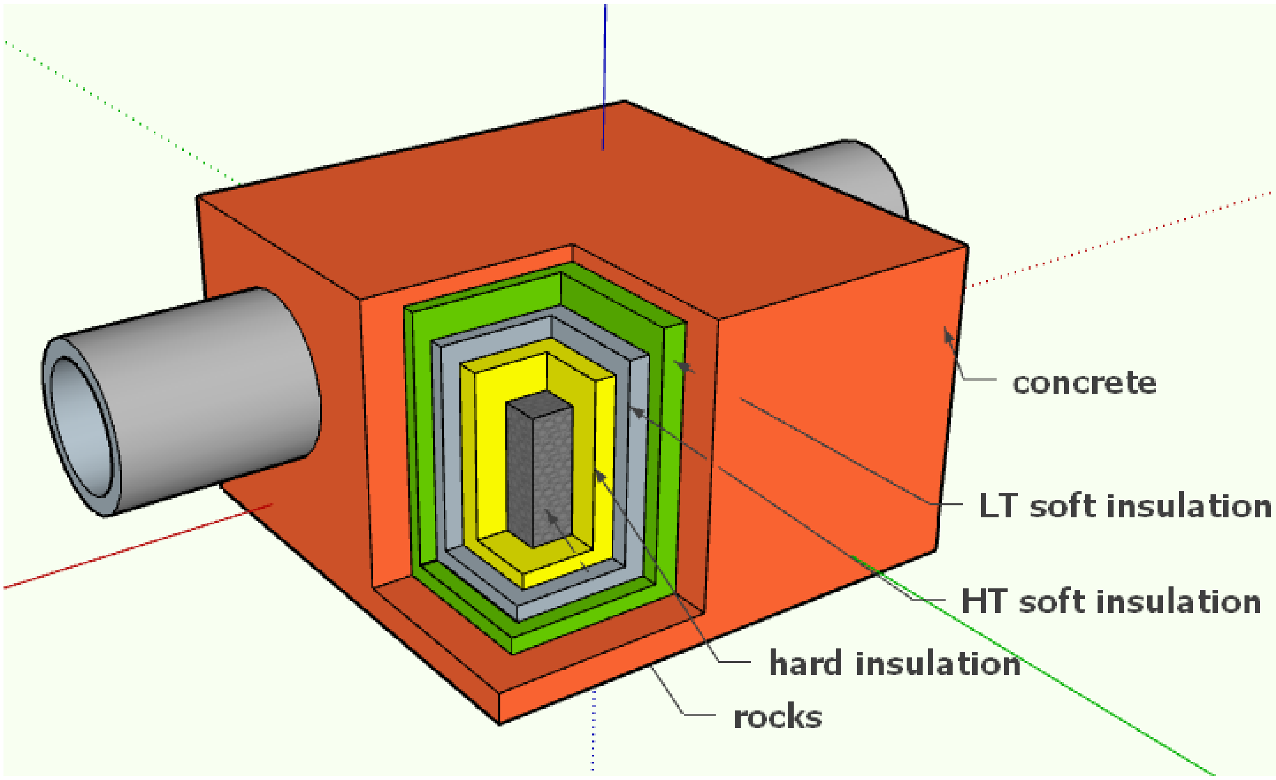

FIGURE 16 STORAGE COMPONENTS.

The aim of the dimensioning of the storage phase is to find the right size of the storage and the thickness of the insulations and the concrete layers having as a input only the storage capacity. The program developed in MatlabR2017b takes as a input only the size only the storage capacity [MWh] and takes, as output the value of the thicknesses of each layer.

Using the storage capacity and knowing the volumetric heat that the rocks could store it is possible to find the volume useful to store the maximum heat. Then knowing that the shape of the store as to the cubic it is possible to find le length of each side and the area of one side.

The main assumptions that is used to size the storage phase are the following:

1. The storage is thermically isotropic, so when fully charged the heat leaks in every direction in the same amount.
2. The storage is considered like a 0D device, so in this work it is not considered the possibility of a thermocline or a temperature drop. This assumption is used even for the following works of the thesis, especially for the optimization section.

Using the assumption that a portion of heat goes outside the storage during the stock of energy phase (equal to 0.008%) it is possible to find the specific heat per surface that goes outside. We set some assumption to know everything about this thermos dynamic problem:

To sustain the structure and to avoid thermic tension it is better to use a large hard insulation layer. We fixed this thickness at 20 [cm]; considering the soft

insulations we use superwool and rockwool. To be cheap we use rockwool when the lowest T of the superwool will be 400 [°C]. In this way we use this two material in a correct way. Then, we use concrete in blocks. One blocks of concrete has a thickness equal to 30 cm. If the maximum temperature of the concrete is below or equal to 200 [°C] everything is ok, otherwise we have to add other block layers to avoid structural problems. It is supposed that the highest temperature of the hard insulation is 600 [°C] (We neglect the conduction of the rocks) we consider that the storage has five sides into ground and we suppose that the temeprature at 15 [cm] of distance has to be 15 [°C]. Concerning the top layer, we consider only conduction with the air (the radiation is neglected) and the mean temperature in Copenhagen in the worst case (January) is 0 [°C], so the dimensioning is done in the worst conditions[28]. To solve the problem we consider the flux perpendicular to the layers, considering that the heat is mono dimensional flowing to the radial direction. Assuming that, it is possible to apply the Fourier's law in order to find the correct thickness for each layers.
As we said, we impose two thicknesses: hard insulation and concrete in blocks. Considering the constraints that we developing in the Matlab tool, in order to reach the optimum insulations and optimum price, if the lowest temperature of hard insulation is below 400 [°C] it is possible to neglect the Superwoool. The same procedure is applied for the soft insulation LT; if its highest temperature is below 200 [°C] (maximum temperature that the concrete could support) we could neglect the soft insulation of the either soft insulation layers.

5.2.3 Discharge phase

The third and the last phase is the discharging phase. This is the part where it is possible to use the energy stored in order to produce electricity or electricity and heat for district heating or only heat for district heating.
The aim of this part is to produce energy using the heat stored in the rocks, when the storage is sufficiently full. In principle, this part works when the electricity or district heating price is high in order to reach the maximum revenues at the right moment.
This last part of the plant is composed of two different flowrates: the air that firstlyis heated up in the storage in order to heat up the second flowrate, the water. Then, there will be an heat exchange between the hot air and the water. This heat has the final aim of to transform the water into steam, in order to produce electricity through a steam turbine.
Considering the 'air side', when the storage is available and when it is convenient to produce energy the fan on the discharge side is activated. The fan push the air from outside into the storage from the cold end to the hot end whose the aim to increase its temperature up to 600°C. The motivation for what it is important to carry the discharge air flux in the opposite direction with respect to the charge

[28] https://www.holiday-weather.com/copenhagen/averages/

flux is not to alter the thermocline inside the storage and in order to give to the air flux the best amount of the energy. The discharge air flux passes through the same tube but in opposite direction. The hot air passes through a tube in order to carry the air into the HRSG (heat recovery steam generator). There, the hot air cools in order to warm up the water that will become steam inside the HRSGand expand in a steam turbine to produce energy.
In this work we analyzed three different ways to produce energy in order to understand what is, for this new technology and for this new type of power-to-power plant the best manner to use the energy stored in the rocks.

1. Considering only electricity production through a steam turbine;
2. We consider the option to increase the low pressure level of the Rankine cycle considered in the first case. The final aim is to use heat of condensation to produce district heating for the network where this plant is inserted. This option considers the possibility to produce either only electricity like in the first case and either to produce district heating too.
3. The last option is to consider the previews options plus another one. There is the possibility to insert an heat exchanger downstream the storage and upstream the HRSG. The aim is to use the energy taken from the storage to warm up the water useful for district heating. So in this last option there is the to use this energy as it is, without converting and uses efficiency, in fact using HRSG and steam cycle efficiencies as in the previews options a large amount of energy is lost.

The motivation for what it is necessary to analyse this part is to find all of technical parameters useful for size the plant as in the previews two phases. The input parameters of discharge part are the turbine power [MW] and the storage capacity [MWh]. Even for this phase a Matlab tool is developed. Inserting the two input, the script gives us all technical parameters relative to discharge phase. Starting from the bottom cycle, this scheme it is followed in order to find all technical parameters:
The first step is to set up some parameters about the steam cycle order to calculate the thermodynamic efficiency. These parameters are low and high pressure and temperatures. The scheme of the bottom cycle is independent on the turbine power that it is inserted as an input discharge phase, so the efficiencies and the specific heat that this steam released is always the same.
Firstly we have to set up the temperature and the pressure of the steam cycle for every thermodynamic state of the one pressure level steam cycle. It is important to set up vales like:

TABLE 2 HRSG (HEAT RECOVERY STEAM GENERATOR)CHARACTERISTICS

	Value	*Unit if measurements*
Inlet air temperature	589	[°C]
Delta pinch point	10	[°C]
Delta approach point	7	[°C]
Low pressure level(turb)	1.014	[bar]
Low pressure level (DH)		[bar]

High pressure level	70	[bar]
η_{mech}	0.95	[-]
$\eta_{turbine}$ (isentropic efficiency)	0.85	[-]
η_{pump} (isentropic efficiency)	0.85	[-]

Thanks to this value is possible to evaluate every point of the steam cycle. Here, it is possible to find the final thermodynamic efficiency and every specific work [kJ/kg]

ho	419	[kJ/Kg]
h1	427	[kJ/Kg]
h2	1,27E+03	[kJ/Kg]
h3	2,77E+03	[kJ/Kg]
h4	3,62E+03	[kJ/Kg]
h5	2,68E+03	[kJ/Kg]
h6	2,57E+03	[kJ/Kg]
h7	4,26E+02	[kJ/Kg]

FIGURE 17 SPECIFIC ENTHALPY OF THE SIMPLE STEAM CYCLE.

And then the final efficiencies:

Eta_td_turb_only	34%
Eta_td_dh	28%

FIGURE 18 FINAL EFFICIENCIES CONSIDERING THE TWO TYPES OF TURBINE

FIGURE 19 FINAL EFFICIENCIES CONSIDERING THE TWO TYPES OF TURBINE

Finding all these values, it is possible to find the mass flowrate of the water using the founded efficiencies, the enthalpy and the input turbine power parameter [MW].

Considering the steam cycle, as it is said, two cases are managed. Considering the simple steam cycle and the steam cycle with district heating two different values of thermodynamic efficiency and overall efficiency are calculated. The TD efficiency is independent on the turbine power, so it has always that type of value. An assumption about the district heating is that the heat exchange efficiency is equal to 90%.

Making a simple pinch point analysis it is possible to find even the mass flowrate of the air, knowing the shape of the steam Rankine cycle and the approach and pinch point.

To find all technical parameters about discharge phase is necessary to know two parameters:

- Turbine power [MW]
- Storage capacity [MWh]

Knowing the turbine power it is possible to know the water mass flowrate [kg/s] and the real quantity of thermal energy that the bottom cycle could discharge in district heating and the energy necessary to heat up the water from liquid to steam.

Another important thing is to evaluate the surfaces inside the HRSG and to know the air mass flowrate that we have to insert in the storage to keep the energy and to know the value of the HRSG efficiency.

Heat exchanger and it is a thermodynamic link between the air that exits from the storage and the production of electric energy throw the cycle plant converting the heat in to useful power. It is subdivided in three parts: economizer, evaporator and the superheater part. Usually in a HRSG, we could find a pre-heater but it is not considered in this analysis. The HRSG is a big counter-current heat exchanger in which it is possible to exchange heat on the surfaces of the water tubes. To be clear, when we are talking about the HRSG, it is simple to use the Pinch point approach. Setting the pinch point subcooling temperature and the approach point with a pinch point analysis heat fluxes, outside HRSG temperature and heat recovery steam generator efficiency are founded.

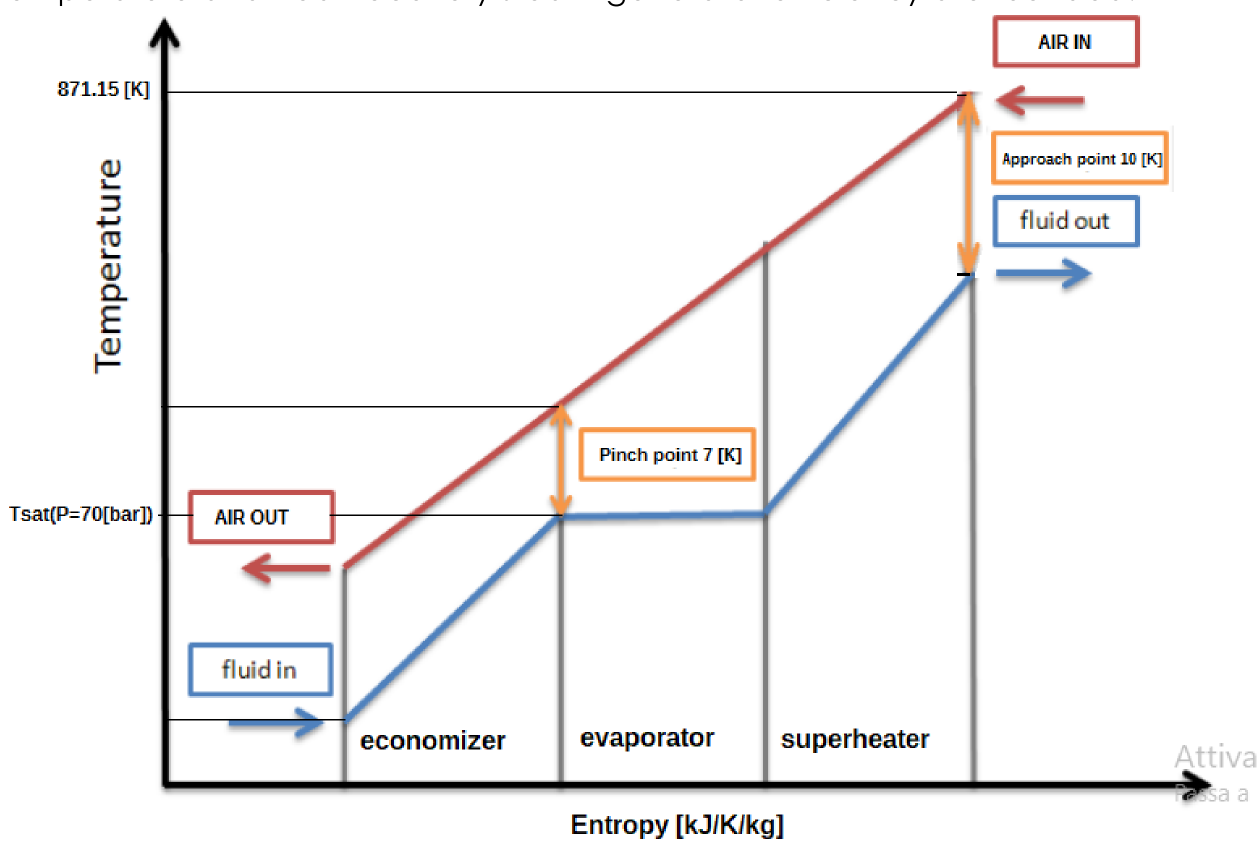

FIGURE 20 PINCH POINT SCHEME.

In the pinch point analysis, it is important to set some parameters like $\Delta_{pinchpoint}$ and $\Delta_{approachpoint}$.

Another important parameter that it has to be found is the surfaces of the HRSG in order to understand what is the land used by the HRSG and the HRSG purchasing cost.

It is possible to do that using the e-NTU method. The data necessary for this calculation are the following:

Firstly, the heat transfer coefficient is set for each part of the heat recovery steam generator sides. There are the air that exchange heat for conduction and convection through the steam tubes. For simplicity only one average value of heat transfer coefficient, it is assumed for the air. Considering the bottom cycle, there are three different phases that this flux has to stand up. The first one is the liquid one in the economizer, than there are the phase in which the temperature is constant and it has to be able to sustain a phase change in the evaporator and finally when all the liquid will become vapour there are the last phase of the water: it will became steam finally in the super heater. All this three phases are three different value of heat transfer coefficient and they are very different among each others.

TABLE 3 HEAT TRANSFER COEFFICIENT VALUES IN HRSG.

Heat trannfer coefficient	Value	Unit of measure
Air α_{air}	5e2	[W/m²/K]
Economizer (water side) α_{eco}	1e2	[W/m²/K]
Evaporator (water side) α_{eva}	1e4	[W/m²/K][29]
Super heater (water side) α_{sh}	1e3	[W/m²/K][30]

We use this type of approach because in the HRSG the maximum temperature, so the inlet temperature of the air equal to 598 [°C], is quite low; therefore the e-NTU method is allowed.

Considering the heat exchange, that there are in the heat recovery steam generator the temperature inside is very low and considering that we have not flue gases (and in that case we should have considered the slagging, the dust and others particles) but only air that comes from the storage so it permits to use the ε-NTU method. This method is useful to discover the available surfaces involved into the heat exchange. Setting NTU value for each part of the steam cycle where the exchange happens it is possible to use this method. [31]

TABLE 4 NTU VALUES FOR HRSG DIMENSIONING.

NTU	Value	Unit of measure
Economizer NTU_{eco}	3.5	[-]
Evaporator NTU_{eva}	2	[-]
Super heater NTU_{sh}	0.4	[-]

29 (Yan & Lin, 1999)

30 Condensation heat transfer in the presence of noncondensables, interfacial resistance, superheating, variable properties, and diffusion
Author links open overlay panel (W.J.Minkowycz†E.M.Sparrow)

31 https://books.google.dk/books?id=meA1WqL-aHUC&pg=PA283&lpg=PA283&dq=ntu+superheater&source=bl&ots=oTPUr_sCwU&sig=CAP51dGATRtgRx5t2N7IbToO7JE&hl=da&sa=X&ved=0ahUKEwiuveDB_rTaAhXB1ywKHRsGCIAQ6AEIJjAA#v=onepage&q=ntu%20superheater&f=false

Than having set these values from each side of the HRSG, it is important to find the value of ‘ε’ for each parts of the exchange. In the previews section, setting the turbine value, as an input is was very simple to find the mass flowrate for the two flows. There, considering their value for the following calculation it is important to find two quantity C_{min} and C_{max}. They are the product between the mass flowrate and the specific heat at constant pressure. C_{min} is the minimum value between the two flows and C_{max} is the maximum between the same flowrate.
Setting this is simple to calculate the surfaces for the three sides of the heat recovery steam generator:
Firstly, it is mandatory to calculate the overall value of the heat exchange between the air and the liquid water or steam or water change phase as follow

$$K_i[\frac{KJ}{m^2K}] = (\frac{1}{\alpha_i} + \frac{1}{\alpha_{air}})^{-1}$$

Then it is possible to calculate the surfaces of the three parts using the NTU method:

$$S_i[m^2] = \frac{C_{water} * NTU_I}{Ki}$$

Finally with the LMTD method is possible to calculate the final temperature of the air. That is means that the final temperature of the air dependent on the size of the steam turbine. After making various simulation it is possible to affirm that the final temperature could vary from 210 to 150 [°C] range, and from this work it is an optimal value to not loose a lot of energy. Therefore, a lot of energy is transferred from the air to the bottom cycle. Founded the final temperature it is possible to stabilize the value of the HRSG efficiency as the heat that the water receive over the energy that the air loose. This value is more or less in this range: [0.7-0.95].
Knowing the storage capacity exactly like in the two others phases, it is possible to find the pressure drop of the storage rock bed with the same assumptions

Knowing the air mass flowrate and the total pressure drop considering the pressure drop of the storage, Ergun’s equation, the pipe pressure drop, set equal to 1% with respect to the storage bed. In the discharging part there is a pressure drop that comes from the HRSG. From a reference it is possible to set a value of this pressure drop that usually is equal of 0.2 [bar] like an average value. Finally, it is possible to calculate the fan power [MW] and, as in the charge part, we could find all technical parameters about piping.
As in the charge phase, we consider a fixed length to calculate the diameter of the tube knowing that the total pressure drop has to be equal to 1% is the pressure drop into the storage rocks bed. Considering the Darcy factor and the Colebrook correlation, the same assumptions are supposed:

- maximum velocity equal to 25 [m/s], to avoid that the pipe could whistle;
- ideal gas air,
- c_p [kJ/K/kg] temperature depending.
- Viscosity temperature depending.

Firstly, setting the length of the pipe and the maximum pressure drop it is important to find the right diameter of the pipe that permits to respect the previews conditions.
Imposing iteratively a certain value of diameter, knowing the length and the mass flowrate a certain velocity is found. If the velocity is higher than 25 [m/s], limit for this pipe otherwise they could whistle, a larger diameter is iteratively imposed.
When the value of velocity is lower than that limit a Reynolds number is found for that describe if the regime of the fluid is laminar or turbulent.
If the Reynolds number is lower than 2300 the Darcy's friction factor is found knowing that the regime is laminar so

$$f_{darcy} = \frac{64}{Re}$$

If the Reynolds number is higher than the 2300 we are in the turbulent regime, so on Matlab we build a Colebrook function in order to calculate the friction factor. To be precise, the real turbulent range is from 4000 but to be cautelative and knowing that the Re [2300-4000] range is an uncertain zone, it was decide to overestimate the Reynolds value in order to be cautelative in the calculations.
The following formula is the Colebrook one:

$$\frac{1}{\sqrt{f}} = -2\log(\frac{\varepsilon}{3.7D_h} + \frac{2.51}{Re\sqrt{f}})$$

Where:

1. $\epsilon\ is\ rougthness\ of\ the\ stainless\ steel, the\ pipe\ material$;
2. $Dh\ is\ the\ idraulic\ diamater\ that\ in\ this\ case\ coincide\ to\ the\ diamater\ supposed\ iteratively$;
3. $Re\ is\ the\ reynolds\ number$

So throw the Colebrook function or the laminar simple correlation the minimum right diameter is found.
The Renard series, well explained in the charge section, is used to find the commercial one and knowing the maximum strength of the stainless steel, it is possible to find the thickness of the pipe using the UNI-ISO formula. We do not consider, as in charge phase, the option to add pipe if the resulting diameter will be higher than a maximum value, we use only one pipe. The motivation is the heat exchanger that we have at the outlet of the storage in discharging phase, so it is mandatory to ensure that all flux goes to the HRSG in an unique way, so that is why only one it is considered.
Considering the total fixed length we assume 40 [m] in total, equally divided in the piece of pipe HRSG-storage and in the part storage- HRSG. We consider for each piece a temperature drop equal to 2 [°C] and this is useful to size the insulation. As in the charging part we consider in the piece of tube that llinks the storage with HRSG where the T has to be from 600 to 598 the insulation layers are superwool and rockwoll, on the other side, that part of the pipe can never reach a temperature higher than

300°C because the fan couldn't support an higher temperature so the only insulation layer will be rockwool using the Fourier law throw the radial direction of the pipe. Considering the pressure drop, to evaluate the value of the fan power, we have to sum the pressure drop inside the HRSG[32] piping and storage. Considering the heat exchanger for the district heating before the HRSG air to water we could size the HRSG making this two assumptions:

1. heat exchanger with an efficiency of 90%
2. Outside air temperature equal to 0 [°C].
3. U[W/m2/K]=100[33];

Considering that like a counter current heat exchanger, it is very simple to know the available surface of the H-EX for district heating.

Three cases are considered:

1st option

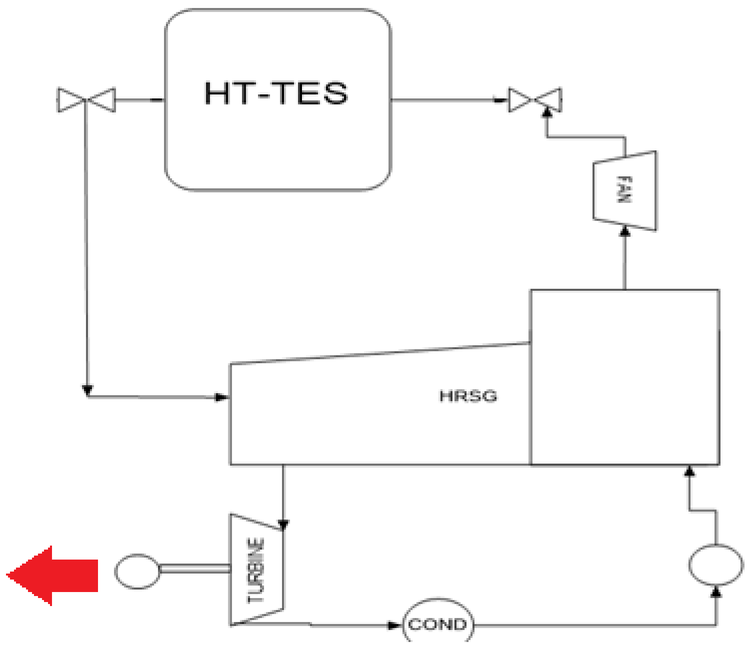

FIGURE 21 1ST OPTION DISCHARGE PHASE SCHEME

In this case it is considered the option to use the discharge phase only to produce electricity. All energy that passes through the heat recovery steam generator and there is the possibility to exchange heat with the economizer, evaporator and the super heater. The air that exits from the storage has a temperature equal to 600 [°C] and considering that it is imposed a temperature drop equal to 2 [°C] the temperature at the inlet of the HRSG is equal to 598 [°C]. Obviously lower is the Temperature difference, higher is the heat exchanged in the heat recovery steam generator but higher these will be the surfaces used for these exchanges so higher it is the total cost. Considering the isentropic

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32 (Ong'iro, Ugursal, Al Taweel, & Walker, 1997)

33 'Heat transfer coefficients of shell and coiled tube heat exchangers'- M.R.Salimpour et al.

efficiencies of turbine and for the pump, we consider an isentropic efficiency of the turbine equal to 0.85 and an isentropic efficiency of the water pump equal to 0.85 and a mechanical efficiency of the alternator equal to 0.98. In the steam cycle we supposed to have a simple Rankine cycle that has only one pressure level. The evaporation pressure is set to P=70 [bar] and condensation pressure is equal to P(T=30°C), so in this way the thermodynamic is equal to 34%. We consider too an alternator efficiency equal to 0.98, to the losses that we lost converting ,mechanical energy into electrical.[34]

TABLE 5 TEMPERATURE AND SPECIFIC ENTROPY OF THE STEAM CYCLE.

T0	30	[°C]	**s0**	1,307	[kJ/kg/K]
T1	30,53	[°C]	**s1**	1,307	[kJ/kg/K]
T2	285,83	[°C]	**s2**	3,122	[kJ/kg/K]
T3	285,83	[°C]	**s3**	5,8146	[kJ/kg/K]
T4	588	[°C]	**s4**	7,058	[kJ/kg/K]
T5	30	[°C]	**s5**	7,058	[kJ/kg/K]
T6	30	[°C]	**s6**	7,058	[kJ/kg/K]
T7	30,47	[°C]	**s7**	1,307	[kJ/kg/K]

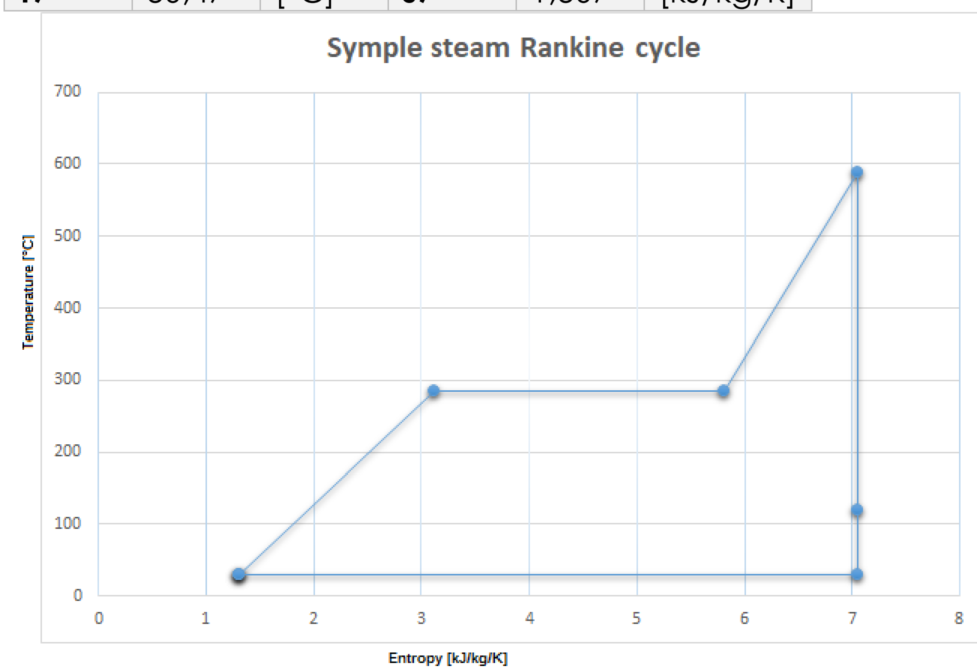


FIGURE 22 SIMPLE STEAM CYCLE.

34 https://elearning8.unibg.it/moodle25/pluginfile.php/9679/mod_resource/content/0/Cicli%20combinati.pdf

2nd option

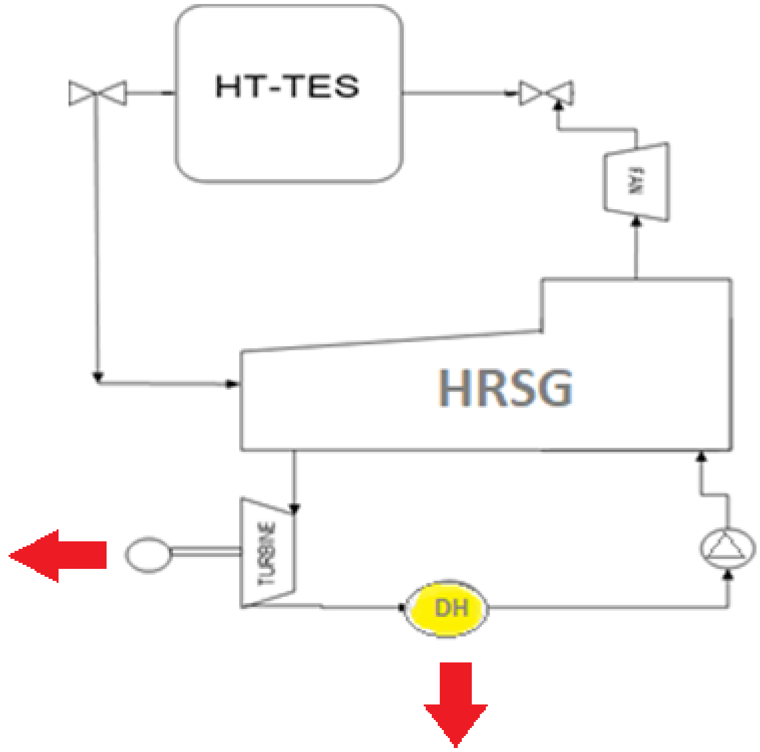


FIGURE 23 2ND OPTION DISCHARGE PHASE SCHEME.

This 2nd option is very similar to the previews one. Here, we consider two options for the steam Rankine cycle. The first is the same of the previews case, in order to produce only electricity. There is another possibility:

The algorithm could choose to discharge only in electricity or to use the discharge phase in order to produce electricity and district heating. Obviously, the algorithm could decide what it is more convenient to do considering the electricity and district heating prices in order to reach the maximum profit. Therefore, the second possibility that we consider is to produce electric energy discharging in turbine and produce heat for district heating using the heat of condensation. In this second option we consider to increase the lower pressure at P(T=100°C), pressure useful to exchange ideal heat for DH. So two options is considered. Rising up the low pressure level the thermodynamic efficiency is lower and equal to 0.28 and considering DH efficiency we set this value equal to 0.9. It is important to say that the electrical efficiency is lower but the total efficiency is equal to 60%.

TABLE 6 TEMPERATURE AND SPECIFIC ENTROPY CHARACTERISTICS.

T0	30	[°C]	**s0**	1,307	[kJ/kg/K]
T1	100	[°C]	**s1**	1,307	[kJ/kg/K]
T2	100.53	[°C]	**s2**	3,122	[kJ/kg/K]
T3	285,83	[°C]	**s3**	5,8146	[kJ/kg/K]
T4	588	[°C]	**s4**	7,058	[kJ/kg/K]

T5	120	[°C]	**s5**	7,058	[kJ/kg/K]
T6	100	[°C]	**s6**	7,058	[kJ/kg/K]
T7	100.47	[°C]	**s7**	1,307	[kJ/kg/K]

FIGURE 24 TEMPERATURE AND SPECIFIC ENTROPY OF THE STEAM RANKINE CYCLE.

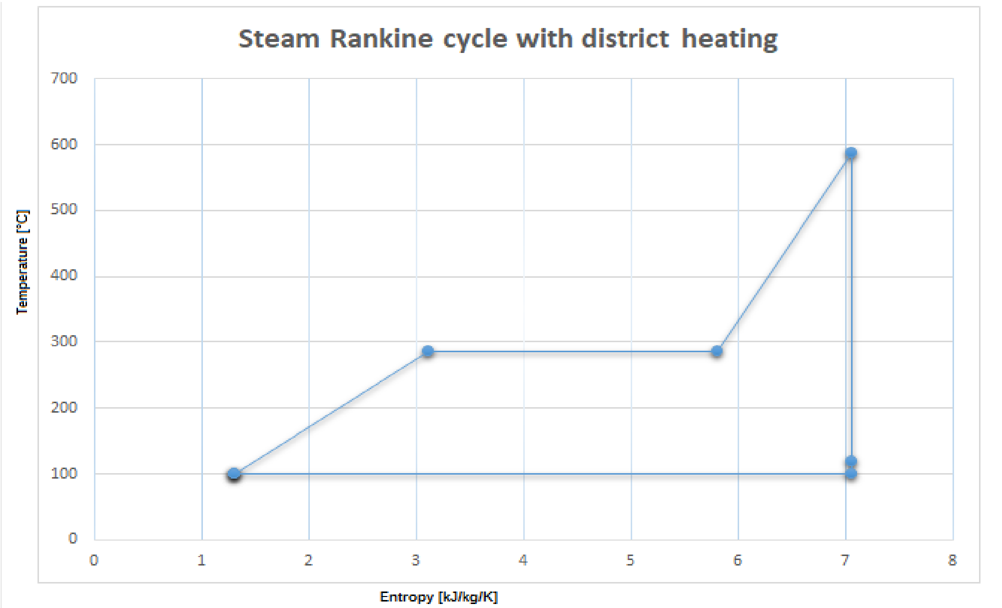


FIGURE 25 RANKINE CYCLE SCHEME.

3rd option

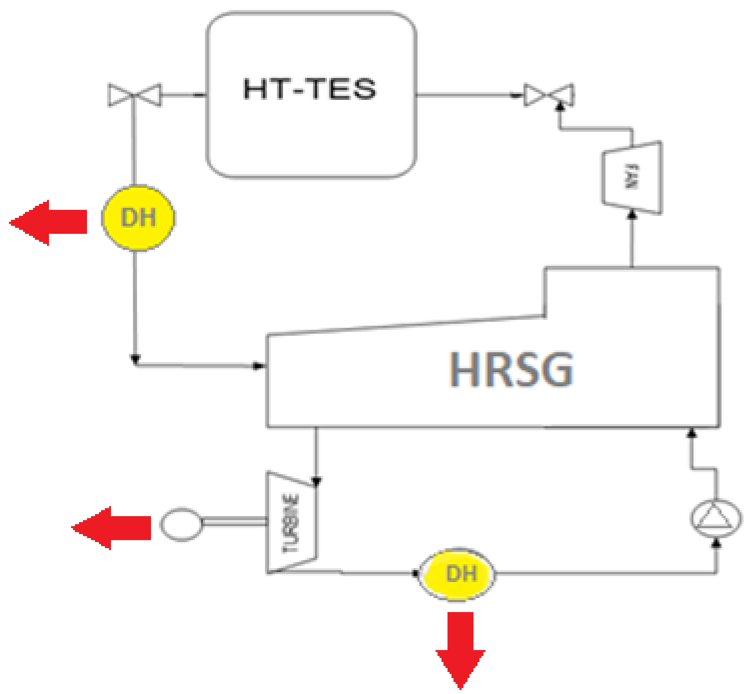


FIGURE 26 3RD OPTION DISCHARGE PHASE SCHEME.

This is a case in which we have three options to use the energy inside the storage: we could produce firstly electric energy through a steam turbine like in the 1st case, the 2nd option is to produce electricity and heat for disseat for district heating rising up the low pressure level in order to have two ways to reach money and finally to produce only heat for district heating bypassing the heat recovery steam generator.

The first two cases are the same of the second option discussed before; the news is the third one.

In this case the idea is to use the energy stored in the rocks by passing the HRSG and using it completely, without another energy conversion like the steam cycle.

The idea is to discharge all heat only in district heating by passing the HRSG. So, between storage and the HRSG an heat exchanger is inserted. So the mass flowrate that comes from the storage with a temperature equal to 600 [°C] has a temperature drop equal to 200 [°C] with an efficiency equal to 90%. The air that exits from the heat exchanger goes into HRSG at a temperature equal to 200[°C], so this heat has the aim to keep the steam cycle warm. It is clear that this last option carry with him a huge amount of energy. if this case it is analysed, the energy that it is used is a very high amount but the exergy is very low. The motivation is that we store energy at high exergetic level to sell it at a low exergetic level in district heating like at 90 [°C].

Every calculation done in this part is made thanks to a Matlab function 'XSteam.m' that calculates the water and steam properties given certain thermodynamic conditions. Considering the air as an ideal gas every air properties are calculated considering the ideal gas formula. This things are well explained in the following section.

5.3 Simulation results

To have an idea how the program works, in this paragraph it is shown some output parameters. The input parameters in the table below there are shown the technical output parameters:

Heater power: 55 [MW]

Storage capacity: 1 [GWh]

Turbine power: 55 [MW]

The output came up from three different functions, so the results are summarized in three following different tables.

TABLE 7 CHARGE PHASE TECHNICAL OUTPUT PARAMETER

CHARGE	VALUE	UNIT OF MEASUREMENT
Fan power	0.5	[MW]
Heater power	50	[MW]
Tubes	3	[-]
Inner pipe diameter	2	[m]
Rockwool thickness	4.2	[cm]
Superwool thickness	1.3	[cm]

Volume flowrate	61.52	[m3/s]
Bed pressure drop	2.6399e3	[Pa]

The program calculated the fan power in charging and as it is possible to see the fan, power is one order of magnitude lower with respect to the heater power. So it means that the maximum power and cost expenditure is about the heater one in the charging phase.

TABLE 8 STORAGE PHASE TECHNICAL OUTPUT PARAMETERS

STORAGE	VALUE	UNIT OF MEASUREMENT
Scamol thickness	20.0	[cm]
Superwool thickness	0.0	[cm]
Rockwool thickness	0.0	[cm]
Concrete thickness	18.8	[cm]
Total volume occupied	2890.3	[m3]

Here are summarized the storage sizing parameters. As it is possible to see in the table above, the superwool and rockwool thicknesses are equal to zero. As it is said before, the tool evaluates the temperature between each layer, if the temperature is so lower there is no the necessity to add that layer. As it is possible to see, the total volume occupied is very large, so considering this technology it is possible to say that there is a large land occupation and it is means that the energy density inside the storage is not so high.

TABLE 9 DISCHARGE TECHNICAL OUTPUT PARAMETERS

DISCHARGE	VALUE	UNIT OF MEASUREMENT
Fan power	0.92	[MW]
Turbine power	3	[MW]
DH power from steam cycle	5.23	[MW]
Inner pipe diameter	3.2	[m]
Rockwool thickness	1.5	[cm]
Superwool thickness	1.1	[cm]
Economizer surface	780	[m2]
Evaporator surface	962	[m2]
Super heater surface	184	[m2]

In the table showed above there are the discharge output parameters. Like in the charge phase, the fan power is two orders of magnitude lower with respect to the turbine power, so the energy consumed is lower. The district heating heat in the turbine has a high value, so it means that economically speaking to sell district heating with the same input of energy from the heat recovery steam generator (HRSG), and intuitively it will be more convenient to sell district heating energy rather than electric one.

5.4 Round trip efficiency

Now, knowing all parameters it is possible to evaluate the round trip efficiency of the plant. To calculate the round trip efficiency it is a way to see how this plant is performant and how many energy could exits from the control volume is it is insert a certain energy quantity inside. It is very important to say that the round trip efficiency is not constant and it change in the discharge part, because the η_{HRSG} changes its value varying the turbine power. Even if this value is not constant, the value goes from 0.7 to 0.9; therefore, the round trip efficiency is usually the same. Below it is shown the round trip efficiency of the three options that it is discussed before. Considering these, it is possible to take some conclusions concerning performances having as an input the following base parameters:

Heater power: 55 [MW]

Storage capacity: 1 [GWh]

Turbine power: 55 [MW]

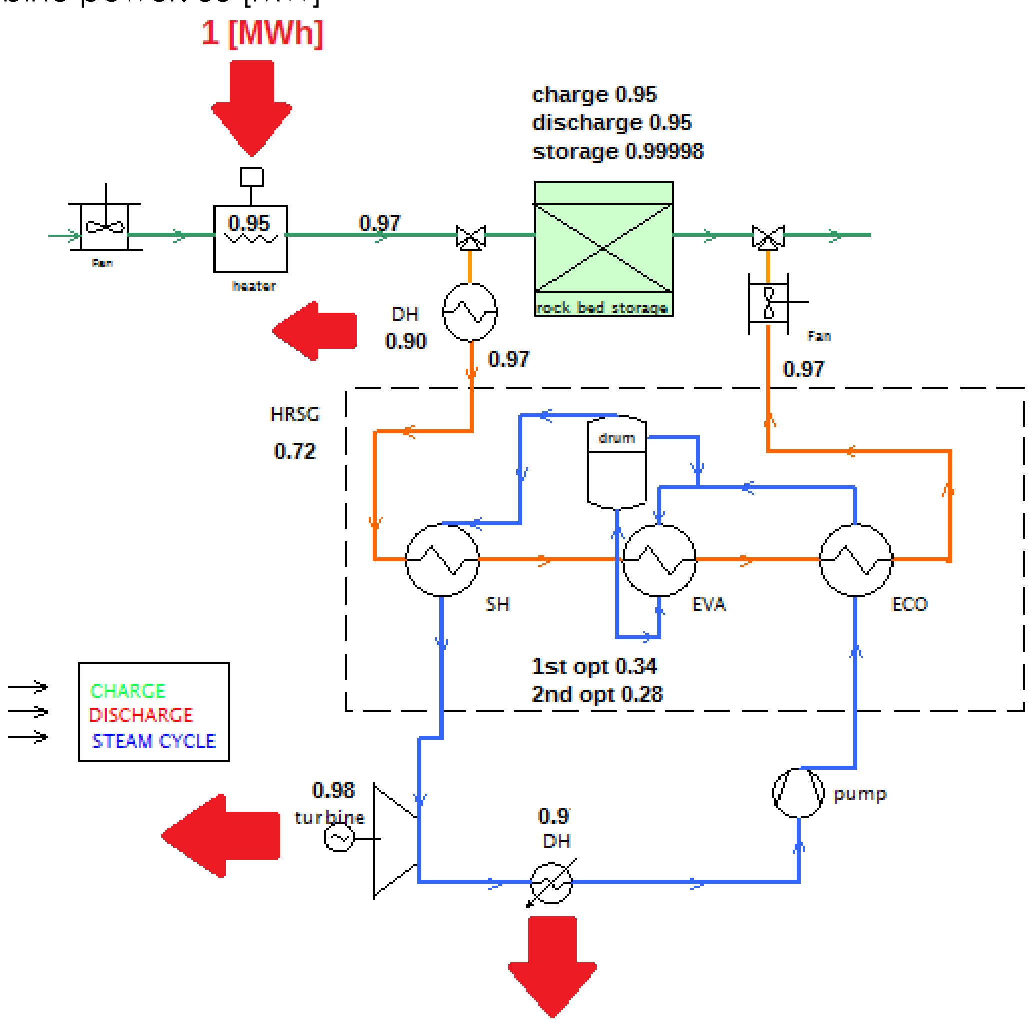


FIGURE 27 PLANT SCHEME

Running the program it is possible to find the mass flowrates, energy, using the reference temperature equal to 0 [°C] useful to calculate the round trip efficiency:

MASS FLOWRATE	VALUE	
CHARGE	85.57	[kg/s]
DISCHARGE	454.59	[kg/s]
STEAM	59.21	[KG/S]

TEMPERATURE [°C]		ENERGY [MW]	
T1	15	E1	1,3019
T2	15	E2	1,7701
T3	13	E3	1,5965
T heater	/	E heater	55
T4	602	E4	53,84651
T5	600	E5	52,07641
T8	600	E8	286,7206
T9	598	E9	285,7649
T HRSG	598	E HRSG	266,3526
STEAM CYCLE TEMPERATURE DIFFERENCE	419,484	E steam cycle	191,6475
MAXIUM STEAM CYCLE TEMPERATURE	588	E turbine	55

FIGURE 28 THERMODYNAMIC OUTPUTS.

1st option: in this case have to consider that the plant has the only option to produce electric energy through a simple cycle steam turbine. Knowing the all parts plant efficiencies and the connected heat losses that go out from the plant to the external environment, it is possible to calculate the round trip efficiency. Its value is equal to **19.8%**, so it means that if it is inserted in the heater a 1 [MWh], the recovered energy is equal to almost 200 [KWh].

1st option - simple steam turbine	
η_{heater}	0.95
η_{tube}	0.97
η_{charge}	0.95
$\eta_{discharge}$	0.95
$\eta_{storage}$	0.999
η_{tube}	0.997
η_{HRSG}	0.72
$\eta_{steamcycle}$	0.34
$\eta_{mechanical}$	0.98

FIGURE 29 TOTAL PLANT EFFICIENCIES – FIRST OPTION.

2nd option: in this case have to consider that the plant has the option to produce either electric energy through a simple cycle steam turbine and to produce heat for district heating using the heat of condensation. Knowing the all parts plant efficiencies and the connected heat losses that go out from the plant to the external environment, it is possible to calculate the round trip efficiency. Its value is equal to **51.2%**, so it means that if it is inserted in the heater a 1 [MWh], the useful energy is equal to more than 500 [KWh].

2nd option - steam turbine and DH

η_{heater}	0.95
η_{tube}	0.97
η_{charge}	0.95
$\eta_{discharge}$	0.95
$\eta_{storage}$	0.999
η_{tube}	0.997
η_{HRSG}	0.72
$\eta_{turbine\&DH}$	0.97
η_{DH}	0.90
$\eta_{mechanical}$	0.98

FIGURE 30 TOTAL PLANT EFFICIENCIES – SECOND OPTION.

3rd option: in this case have to consider that the plant has the option to only produce either thermal energy through an heat exchanger putting between the storage and the HRSG. Knowing the all parts plant efficiencies and the connected heat losses that go out from the plant to the external environment, it is possible to calculate the round trip efficiency. Its value is equal to **74.6%**, so it means that if it is inserted in the heater a 1 [MWh], the useful energy is equal to more than 746 [KWh].

3rd option – district heating

η_{heater}	0.95
η_{tube}	0.97
η_{charge}	0.95
$\eta_{discharge}$	0.95
$\eta_{storage}$	0.999
η_{tube}	0.997
η_{DH}	0.9

FIGURE 31 TOTAL PLANT EFFICIENCIES – THIRD OPTION.

The round trip efficiency of the plant increases three times if the DH is added. Even if the exergetic level decreases because the temperature is always lower, it is possible to take more and more useful energy. It has an impact on the annual profit, well explained in the following paragraphs.

6. Energy Analysis

Once all technical parameters are found thanks to three Matlab functions (i.e. charge, storage and discharge phase), it is possible to make the energy calculation in every part of the plant. The aim of finding the energy will be useful to make the optimization algorithm. The energy fluxes that it is calculated has the unit of measurements of Megawatt hour [MWh], useful unit for the optimization following part of each main parts of the plant.

The value that is possible to calculate is a size value. Therefore, the energy connected to the flux that passes through a certain part of the plant goes from

zero (no mass flowrate inside) to the maximum value (size value; maximum mass flowrate). Considering one year operation, the energy in each part of the plant could vary its value from zero to its size value, calculated in that specific part of the plant. The heat fluxes are the input variables of the optimization program to calculate, as it is said before, the plant behaviour during a whole year.
The energy calculation that is made is calculated in 0D, considering that the section of the tube has an uniform temperature value.
It is imposed that the temperatures are always the same in order to guarantee the same shape of the steam Rankine cycle and in order to have the same thermodynamic efficiencies. The only thing that could change is the mass flowrate, from zero to the size value.
It is mandatory to ensure always at the storage an inlet temperature equal to 600 [°C] and to ensure at the steam cycle and to the district heating the required temperatures to make a good work. One of the assumptions that is done is that if the heat flux is different from zero the temperature that it is set remains the same. The only thing that could change will be the mass flowrate, either of the air or of the steam cycle. Considering the steam cycle, the air could vary from 100% to 30%. If the heat fluxes is equal to zero, that part of the plant that has that type of value is off, otherwise it is on.

6.1 Air energy fluxes

Considering the air flow, if that part of the plant is on, the plant could modulate their energy inside itself. Considering the water in the steam cycle we suppose that the specific enthalpy and the steam cycle is always the same, the only thing that could change is the water mass flowrate.
Considering the air, we suppose that is an ideal gas, so a generic heat flux could be described as follow:

$$E_i[kJ] = \dot{m_{air}} * \overline{c_p(T)} * (T_i - T_{ref})$$

Where:
$\dot{m}$ is the massflowrate calculated before in charging and in discharging matlab functions
c_p is the specific heat that change with the teperature (reference)
T_i is temperature of the fluxes when that part of the plant is on
T_o is the reference Temperature and it is equal to 273,15K
Once received the technical parameters from the three Matlab functions of charging, discharging and storing phase, it is possible to make an energy calculation of each part of the plant [MW] and in [MWh]. Both in the charge and both in discharge there is the air. It is considered like an ideal gas in which the volume percentage are:

Chemical element	*Composition*
Oxygen (O_2)	21 %
Nitrogen (N_2)	79%

FIGURE 32 AIR COMPOSITION.

For the air energy calculation the following formula it is used:

it is considered a specific heat at the constant pressure[KJ/kg/K] depending on the temperature. The specific heat calculated is the mean value of the To and Ti, where 'i' is a generic thermodynamic state of the air in the plant.

As it is said, in each part of the plant, if that part is on, there, it will be always the same temperature value.

6.2 Water energy fluxes

Considering the water inside the steam cycle every part of the bottom is calculated with the "XSteam.m" in the tool. XSteam is a function that calculates all properties of the water so the specific enthalpy too. We imagine to do not change the steam cycle, but when it is on we changes only the mass flowrate from the size value to the 30% of the value's size. So a general heat flux could be described as follow:

$$E_i \ [MW] = \dot{m} \ * \ \Delta h$$

TABLE 10

ho	419	[kJ/Kg]
h1	427	[kJ/Kg]
h2	1,27E+03	[kJ/Kg]
h3	2,77E+03	[kJ/Kg]
h4	3,62E+03	[kJ/Kg]
h5	2,68E+03	[kJ/Kg]
h6	2,57E+03	[kJ/Kg]
h7	4,26E+02	[kJ/Kg]

FIGURE 33 SPECIFIC ENTHALPY.

6.3 Plant overview energy fluxes

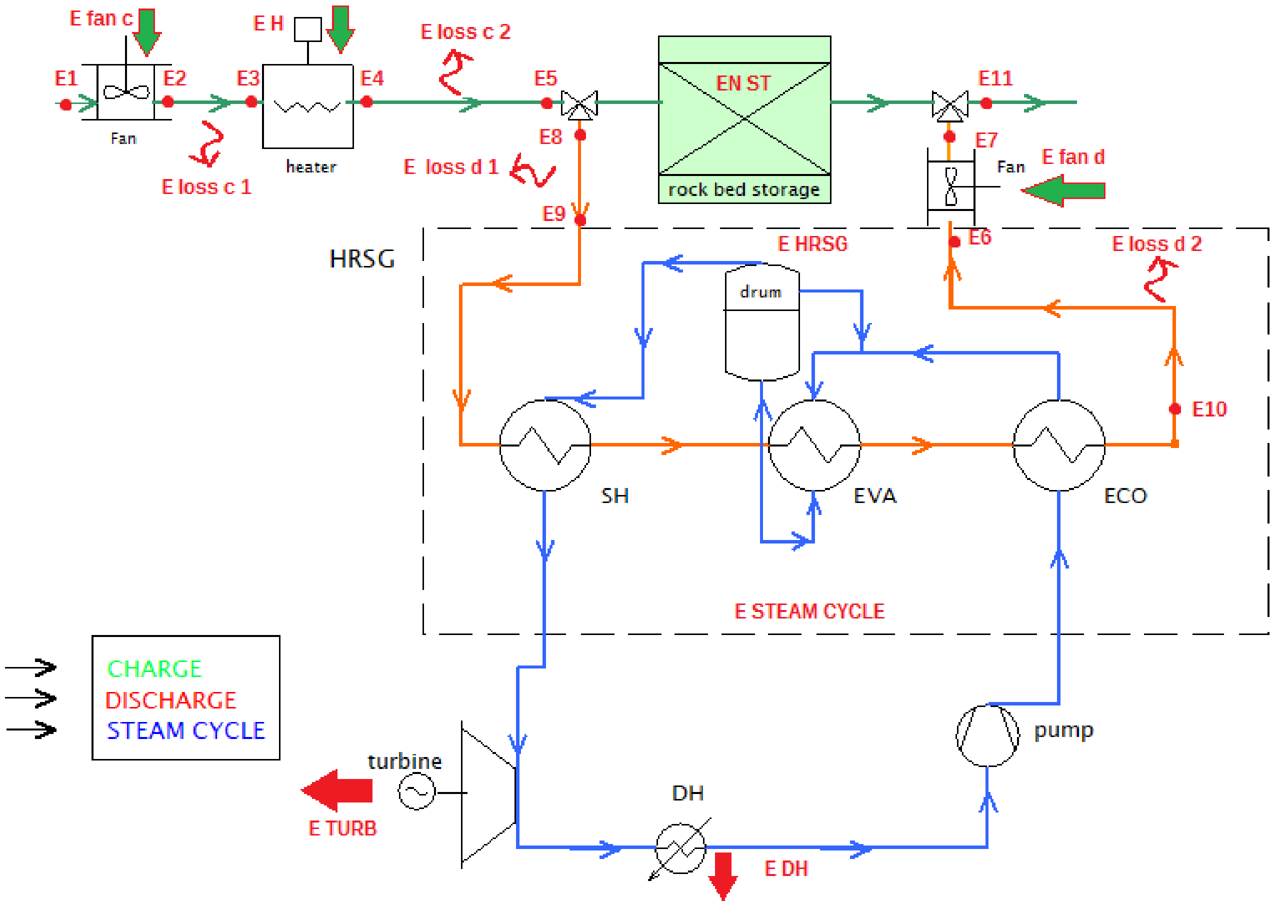


FIGURE 34 PLANT OVERVIEW ENERGY FLUXES.

E_1 inlet fan charge

E_2 outlet fan charge

E_3 inlet of the heater (charge phase)

E_4 outlet of the heater (charge phase)

E_5 inlet of storage (charge phase)

E_6 inlet storage (discharge phase)

E_7 outlet storage (discharge phase)

E_8 outlet storage (discharge phase)

E_9 inlet HRSG (discharge phase)

E_{10} outlet HRSG (discharge phase)

E_{11} inlet fan discharge (discharge phase)

E_{HRSG} energy inside the storage (storage phase)

E TURB= energy produced by turbine

E steam cycle energy received by the water

E DH energy useful for the district heating

E loss c 1 energy losses between E3 and E2

E loss c 2 energy losses between E5 and E4

E loss d 1 energy losses between E9 and E8

E loss c 1 energy losses between E10 and E6

E fan c energy given from the fan in charge phase

E H energy given from the heater

E fan d energy given from the fan in discharge phase

Once the energy fluxes are calculated, it is necessary to link the plant at the external environment:

6.4 Simulation results

The simulation for the energy fluxes has the following input parameters:

Heater power: 50 [MW];

Storage power: 700 [MWh];

Turbine power: 3 [MW].

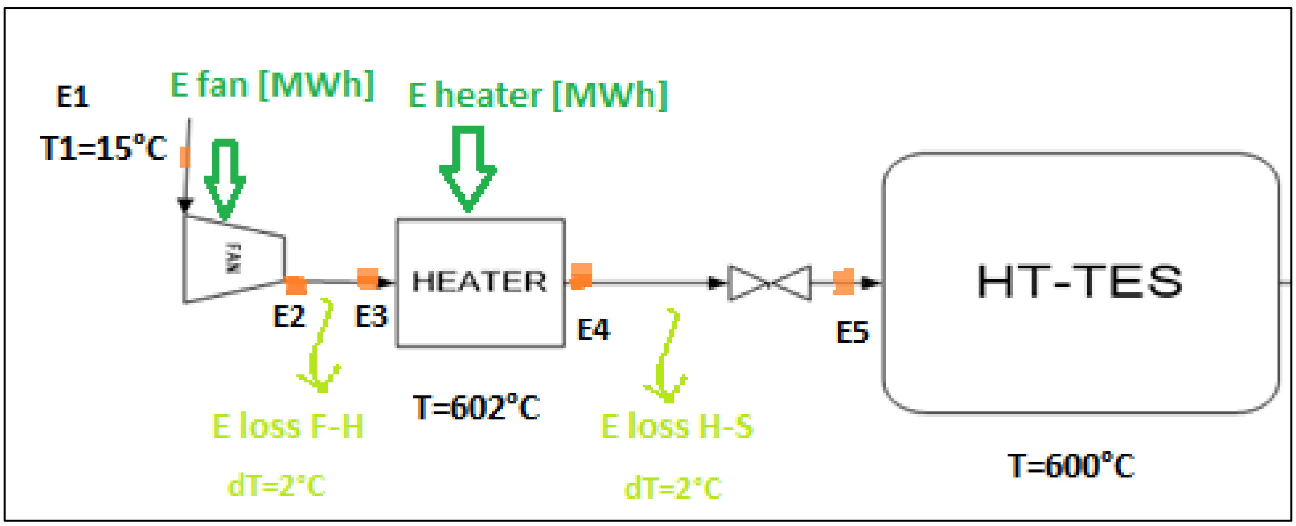


FIGURE 35 CHARGE HEAT FLUXES.

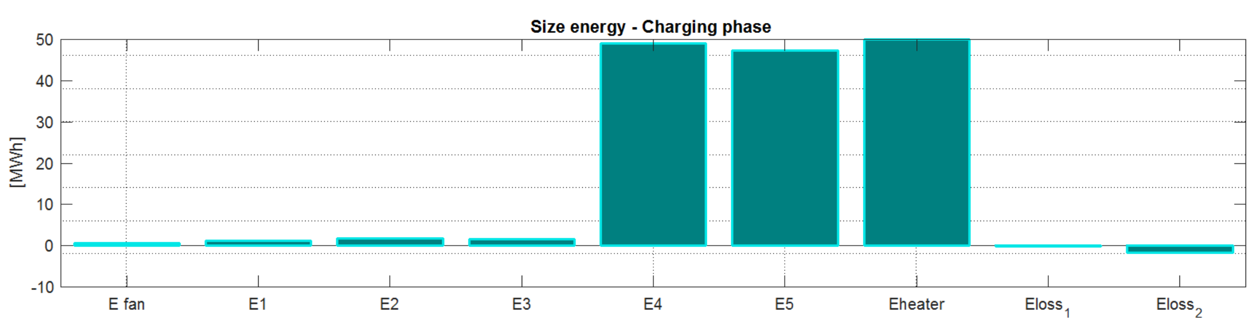


FIGURE 36 CHARGE HEAT FLUXES.

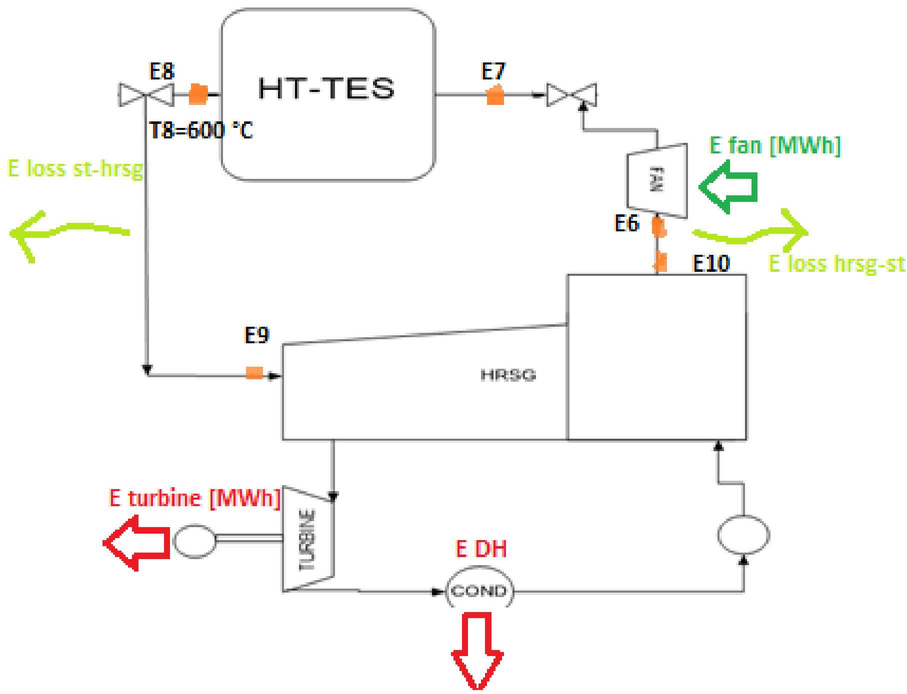


FIGURE 37 DISCHARGE HEAT FLUXES.

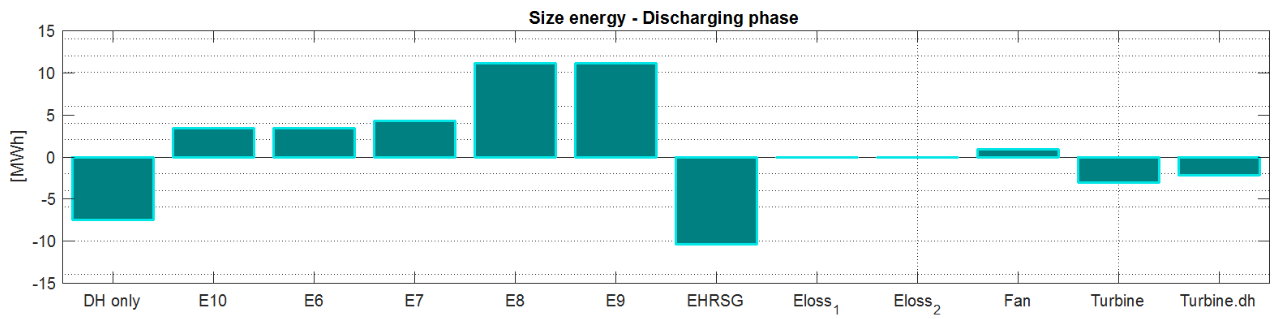


FIGURE 38 DISCHARGE HEAT FLUXES.

7. Insulation pipe sensitivity analysis

In the previews chapters it was explained how to size the insulation pipe in each part of the storage. Carrying a feasibility analysis of the power-to-power storage plant from the economical point of view, it is very important to understand the expenditure in each part of the plant in order to optimize the investment cost and to avoid some unnecessary cost. In the previews analysis cost investment it was made a component analysis in order to, following the NETL procedure, to estimate the final investment imaging that the plant it is built in 2014. Making this investment analysis, it is clear that the cost of the insulation pipe is not negligible, and the main question is if it is necessary to insert it on the investment cost account.
Sizing the plant, the main assumption is in each part of the temperature in each part of the plant is known, so the temperature drop through the pipe is fixed

before to size the insulation pipe, it is an input for the insulation size. As it is well explained in the previous chapter, knowing the temperature drop and consequently the heat lost when the mass flowrate flows in the pipe, knowing the maximum temperature between the inlet and the outlet of the pipe, knowing the length and the thermophysical characteristics of the pipe, the insulation layer is found through the Fourier law. The pieces of pipe that we have to take into account are four. Two of that need only an insulation layer, rockwool because the maximum temperature inside the pipe is 300 [°C], lower than the maximum temperature that the rockwool could support (400 [°C]). The other two pieces of pipe have a maximum higher than the rockwool temperature limit, almost 200 [°C] higher. Therefore, it is necessary to add another insulation layer, the superwool one, between the stainless steel and the rockwool knowing that the superwool end when the maximum temperature rockwool limit it will be reached.
Here the approach will be completely different. Basically, the aim of this part is to understand how much money, considering capital and operational costs in 20 years, and energy losses could be saved if the thickness variation is applied. Then for a specific tube, varying the thickness of the insulation an optimal value between capital and operational cost is found. This thesis is a thermo-economic analysis on a power-to-power plant, so the best result will be the most advantageous from the economical point of view.

7.1 Introduction

In this part of the thesis all tubes that link the main component of the plant are analysed. Knowing that the tubes are four and these characteristics could be divided in two types considering the insulation layer a thermo-economic analysis is made as follows. Firstly for each insulation thickness layer is to evaluated the capital cost of the entire pipe, secondly, it is evaluated the cost of the energy (that has a cost that depends on the electricity prices that vary) that could be lost varying the insulation layer for 20 years. The summation of this two curve gives us a curve with a minimum. The minimum of that curve it is the best compromise with capital and operational cost. The optimal value will change if the electricity price change, so it is made some consideration for different part of the plant considering prices and insulation layer. Another part of this analysis is to understand how many energy could be lost, how many money, in terms of marginal price, could be saved and how many degrees is the outside temperature varying the insulation thickness.
In the following paragraph, for each piece of tube a thermo-economic sensitivity analysis is performed.

7.2 Charge

Considering the charge part it is possible to consider two parts of tube. The tube between the fan and the heater and the one between the heater and the storage. The length is fixed, the first one is 7 [m] and the second one is 13 [m]. In principle the storage should be charged when the price of electricity is low. After to have made some simulations on the tool developed, a range of operational conditions for the charge phase are found. With that range the analysis is built. As follow, it is possible to see the sensitivity analysis for each tube.

7.2.1 Fan heater pipe sensitivity analysis

This piece of pipe has the aim to link the fan to the electric heater is insulated with rockwool only. The motivation is that the fan that is inserted in the plant is an axial made of stainless steel one, so the maximum temperature that it could achieve is equal to 300 [°C]. The flow goes from the fan to the heater, so the maximum temperature is the fan temperature. The previews calculations are made considering an a assumption, that the fan is isothermal, but in reality it is not in this way, so to make a cautelative calculation, knowing that the outside temperature varies with the fan power, this pipe studies are made considering the maximum temperature, 300 [°C].

Knowing that the maximum temperature that we could achieve here is lower than the maximum temperature rockwool limit, another insulation layer it is not necessary, one is sufficient, so considering this piece of pipe we consider rockwool only.

The pipe length is fixed and it is equal to 7 [m].

To understand the following plots it is necessary an explanation of each part calculation:

CAPEX: it is the capital cost of the pipe that includes the pipe and insulation pipe.

OPEX: it is the total money that will be lost in twenty year, considering an interest rate equal to 2%, due to the heat losses that exists from the pipe surface. The calculation are done considering 100 charge cycle in one year for 20 year.

The summation of these curves gives us the total money lost to have this pipe varying the insulation thickness.

The red star in the graphs shows the minimum cost, considering the CAPEX and OPEX expenditures, which it is possible to achieve considering the variation of the thickness layer.

Knowing that the storage is charged and discharged in two different moments depending on the electricity prices it is chosen a certain range on order to understand, in that case what is the best insulation thickness solution. The mean charge price obviously changes if the heater power changes, for example for this analysis the heater power was equal to 50 [MW].

The insulation thickness varies from 0.1 to 1.8 [m].

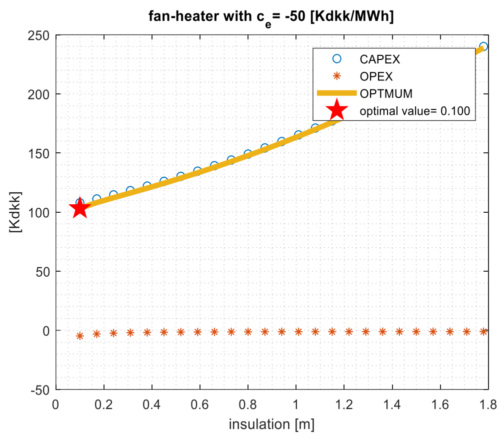


FIGURE 39

__Electricity price c_el=-50 [KDkk/KWh]__

As the graphs shows, the capital cost always increases if the insulation thickness increases, the cost of the heat that it is lost is very close to zero because the energy losses has a low thermal forcing, considering that the maximum temperature is 300 [°C]. CAPEX and OPEX curve are completely monotonic curves, so the summation of that is monotonic and the minimum is the lowest value.

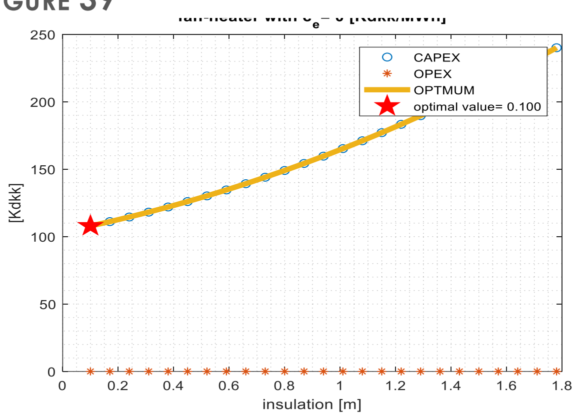


FIGURE 40

__Electricity price c_el=-50 [KDkk/KWh]__

As the graphs shows, the capital cost always increases if the insulation thickness is equal to zero because the electricity price is naught. Therefore, the cost of the heat that it is lost is zero. CAPEX is a completely monotonic curve, while OPEX one is zero constant so the summation of that is completely monotonic and the minimum is the lower value.

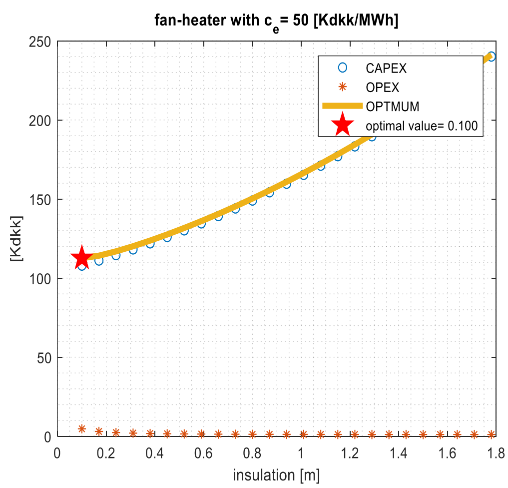


FIGURE 41

__Electricity price c_el=50 [KDkk/KWh]__

As the graphs shows, the capital cost always increases if the insulation thickness increases, the cost of the heat that it is lost is always decreasing a bit because the electricity price is equal to zero, so the expeditures low but decreasing. has a low thermal forcing, considering that the maximum temperature is 300 [°C]. CAPEX curve is completely monotonic curves while the OPEX one is decreasing but less rapidly, as it is possible to see in the graph the OPEX curve is quite constant. So the summation of that is monotonic and the minimum is the lower value.

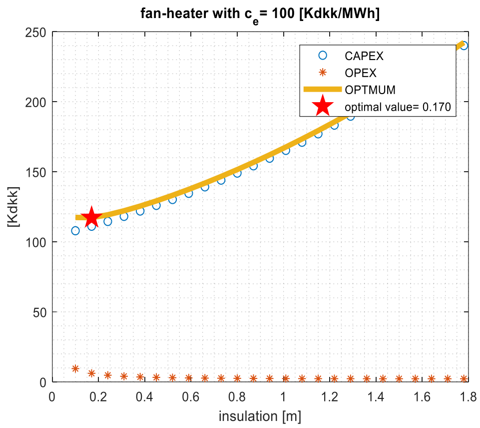


FIGURE 42

Electricity price c_el=100 [KDkk/KWh]

As the graphs shows, the capital cost always increases if the insulation thickness increases, the cost of the heat, so the OPEX curve that it is lost is very close to zero because the energy losses has a low thermal forcing, considering that the maximum temperature is 300 [°C]. The OPEX curve is a decreasing behaviour because if the thickness layer increases the heat lost is lower. Therefore, considering the summation curve, the yellow one, is a curve with the upwards concavity where the lowest, is in the range of 0.1 and 1.8 [m]. As it is possible to see in the graph, the OPEX curve is more descending with the respect to the previews graph because the price of electric energy is higher.

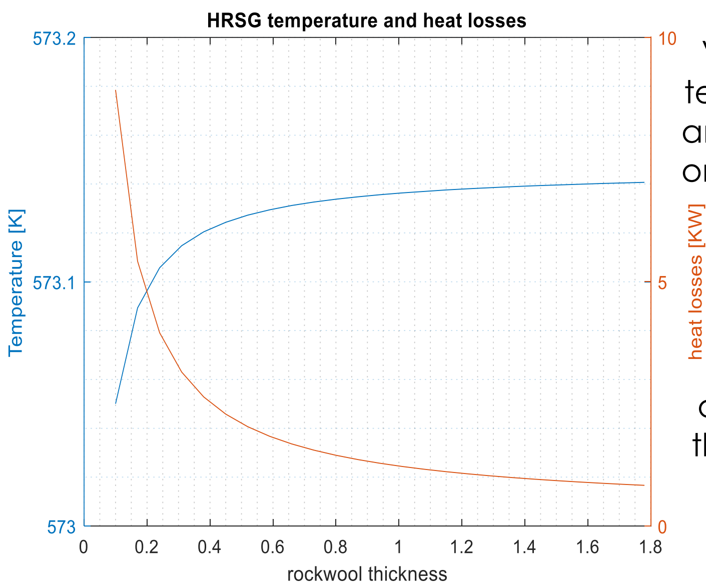


FIGURE 43

Varying the insulation thickness temperature variation is very low and the heat losses decrease a lot, one order of magnitude. Even it is true, if we compare the Heater cost with its marginal cost calculated it is very low, so it is negligible. Results that the temperature drop is negligible due to a large massflowrate inside the pipe.

7.2.2 Heater storage pipe sensitivity analysis

This piece of pipe has the aim to link the electric heater to the storage is insulated with rockwool and superwool. The motivation is that the fan that the storage has to be heat up to 600 [°C] and this value is higher than the rockwool temperature limit. The flow goes from the heater to the storage, so the maximum temperature is the heater temperature. So the temperature of the heater is set to a higher value with respect to the 600[°C], to make an assumption we set as a maximum temperature is 620 [°C]. That is why we use two types of insulation layers, superwool between the pipe and the rockwool layers. The rockwool cost is lower than the superwool one so in order to save money the better choice is to insert it when the temperature is sufficient to not alter the rockwool properties, so 400 [°C]. The pipe length is fixed and it is equal to 13 [m].

To understand the following plots it is necessary an explanations of each part calculation:

CAPEX: it is the capital cost of the pipe that includes the pipe and insulation pipe, the marginal cost of the heater.

OPEX: it is the total money that will be lost in twenty year, considering an interest rate equal to 2%, due to the heat losses that exists from the pipe surface. The electricity prices are set to [-50, 0, 50, 100] [Dkk/kWh]. The calculation are done considering 100 charge cycles in one year for 20 years.

The summation of this curve gives us the total money lost to have this pipe varying the insulation thickness.

The red star showed in the graphs shows the minimum cost, considering the CAPEX and OPEX expenditures, which it is possible to achieve considering the variation of the thickness layer.

Knowing that the storage is charged and discharged in two different moments depending on the electricity prices it is chosen a certain range on order to understand, in that case what is the best insulation thickness solution. The mean charge price obviously changes if the heater power changes, for example for this analysis the heater power was equal to 50 [MW].

The insulation thickness varies from 0.1 to 1.8 [m].

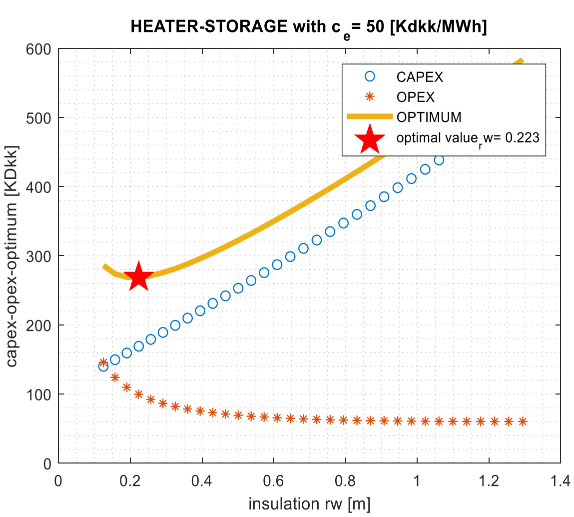


FIGURE 45

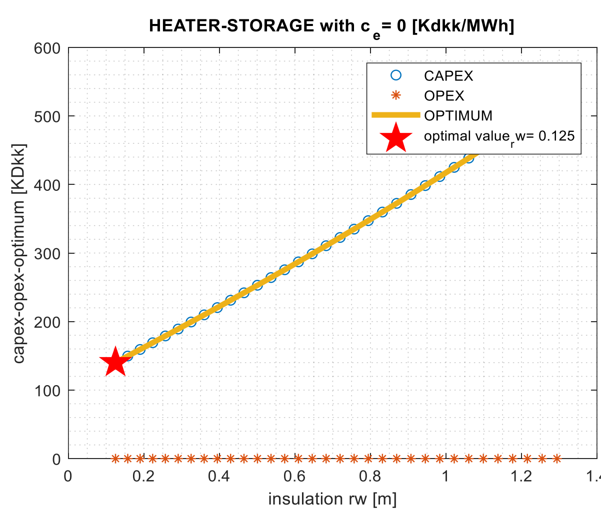


FIGURE 44

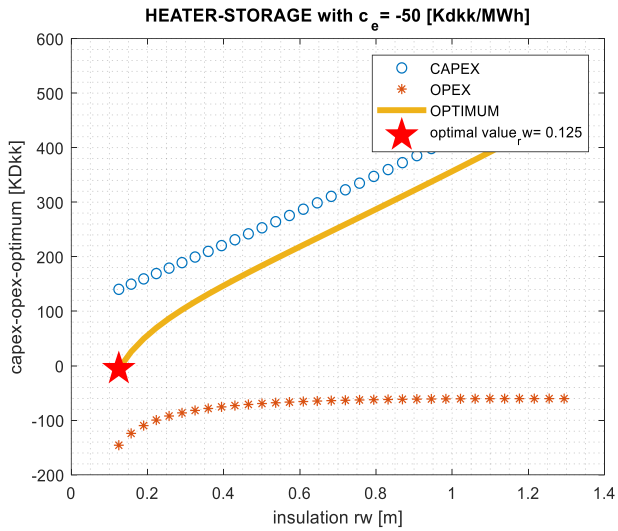


FIGURE 46

This

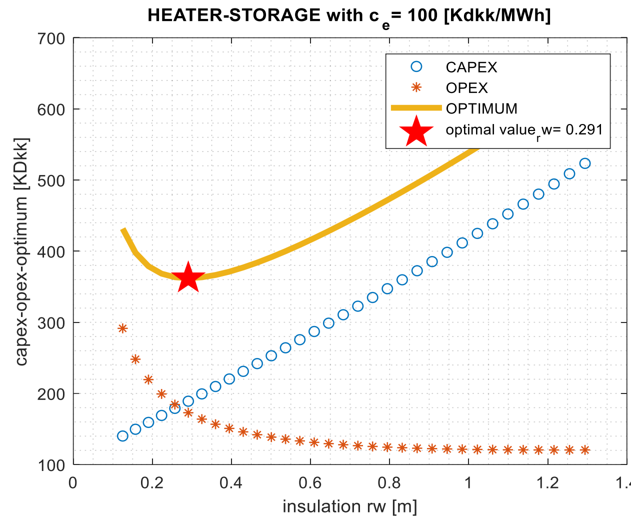
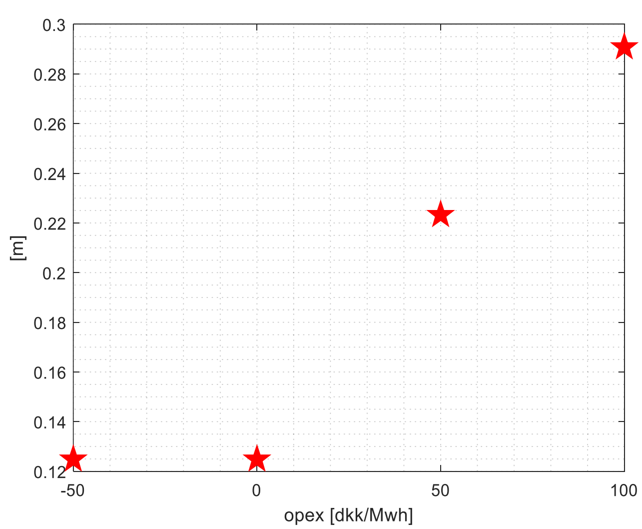


FIGURE 47

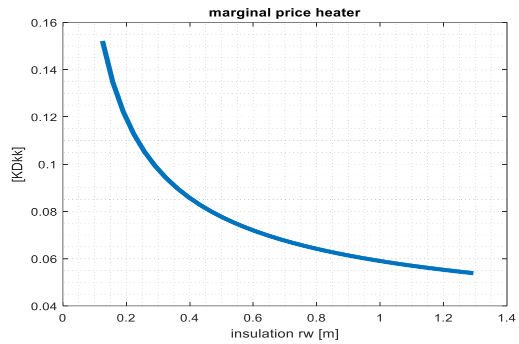
analysis explores the optimal point, so the minimum cost that has to be applied considering the variation of rockwool thickness. In the CAPEX is added the marginal cost of the heater, considering that to maintain the same energy at the storage the heater has to be bigger, the rockwool and superwool insulation price and the pipe price, and that curve is equal in this four graphs. The operational cost changes if the electricity price changes.

As it is possible to see in the graph, if the electricity price increases, the optimal value goes toward right and the total cost increase. Ideally, if it would be possible to have always low or negative prices it would be very advantageous.



In the graph showed it is put in relation the rockwool thickness and the price of the energy. as it is possible to see in the curve, the fitting curve is always monotonic. So, it means that if the electricity price increase, it is a good choice to add more insulation layer to have the lowest possible total price.

FIGURE 48



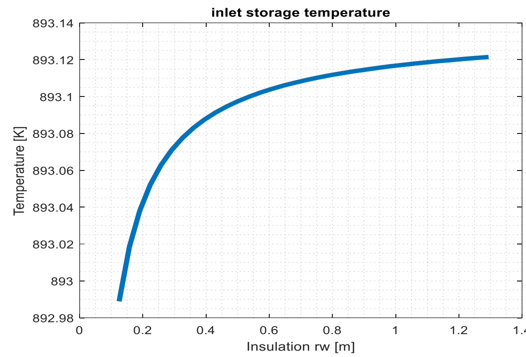
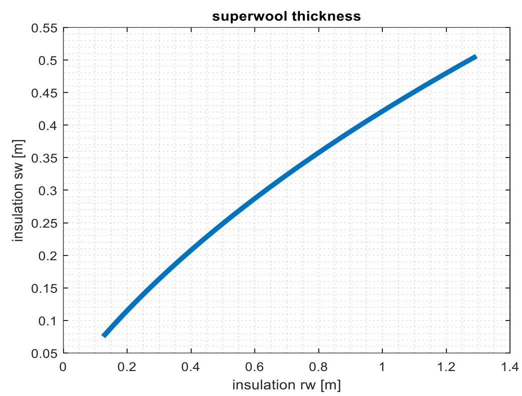


FIGURE 49

FIGURE 50



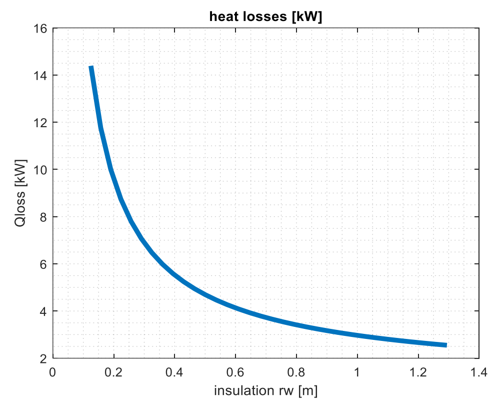


FIGURE 51

FIGURE 52

7.3 Discharge

Considering the discharge part it is possible to consider two parts of tube. The tube between the storage and HRSG and the second one is between the storage and HRSG. The length is fixed, the first one is 20 [m] and the second one is 20 [m] as well. In principle the storage should be discharged when the price of electricity is high. After to have made some simulation on the tool developed a range of discharge is found. With that range is built the analysis. As follow it is possible to see the sensitivity analysis for each tube.

7.3.1 Storage HRSG pipe sensitivity analysis

This piece of pipe has the aim to link the storage to the heat recovery steam generator (HRSG) and is insulated with rockwool and superwool. The motivation is that the storage has to be heated up to 600 [°C] and this value is higher than the rockwool temperature limit. The flow goes from the storage to the HRSG, so the maximum temperature is the storage temperature, equal to 600 [°C]. That is why we use two types of insulation layers, superwool between the pipe and the rockwool layers. The rockwool cost is lower than the superwool one so in order to save money the better choice is to insert it when the temperature is sufficient to not alter the rockwool properties, so 400 [°C]. The pipe length is fixed and it is equal to 20 [m].

To understand the following plots it is necessary an explanations of each part of the calculation:
CAPEX: it is the capital cost of the pipe that includes the pipe and insulation pipe, the marginal cost of the storage including the rocks, excavation costs and insulation layers.
OPEX: it is the total money that will be lost in twenty year, considering an interest rate equal to 2%, due to the heat losses that exists from the pipe surface. The money are lost because the energy that we pay is lost through the insulation surfaces without possibility to recover it. The electricity prices are set to [-50, 0, 50, 100] [Dkk/kWh]. The calculations are performed considering 100 discharge cycle in one year for 20 year.
The summation of this curve gives us the total money lost to have this pipe varying the insulation thickness.
The red star showed in the graphs shows the minimum cost, considering the CAPEX and OPEX expenditures, which it is possible to achieve considering the variation of the thickness layer.
Knowing that the storage is charged and discharged in two different moments depending on the electricity prices it is chosen a certain range on order to understand, in that case what is the best insulation thickness solution. The mean discharge price obviously changes if the turbine power changes, for example for this analysis the heater power was equal to 3 [MW].

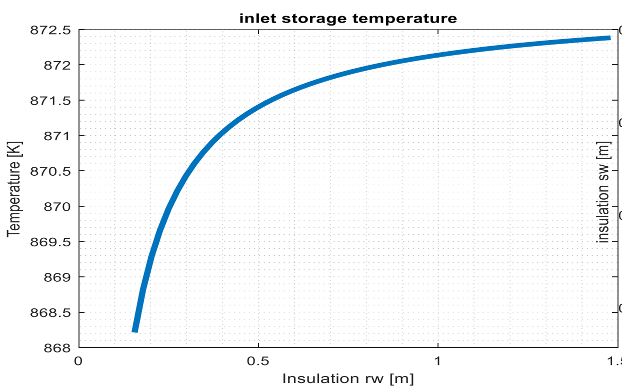
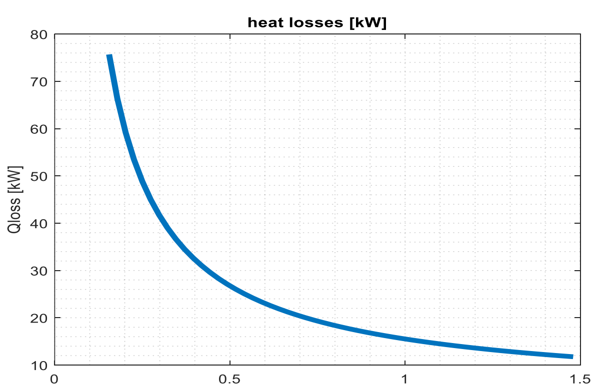


Figure 55 Inlet storage temperature. The graph show tat the temperature drop very low due to great rockwool and superwool insulation characteristics.

Figure 54 It is the superwool thickness. More the rockwool thickness is higher and more the superwoll is hogher. That is means that there is an high heat fux that it is lost throught the insulation surfaces.



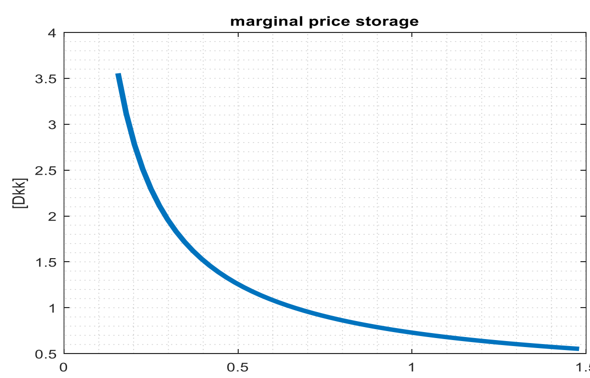


Figure 53 Marginal storage price considering all insuation layers, excavation cost and rocks.

FIGURE 56 THIS IS THE HEAT LOSSES THAT GOES THOUGHT THE INSULATION SURFACES. CLEARLY, IF THE INSULATION LAYERS ARE THIN, THE LOSSES ARE HIGHER, THAT IS WHY THE CURVE HAS THAT SHAPE.

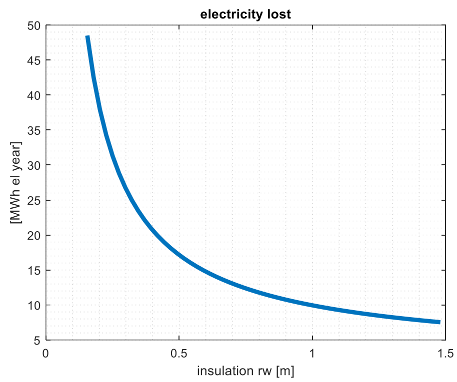


FIGURE 57

Considering the round trip discharge efficiency equal to 26% (considering the TD, electrical mechanical, HRSG efficiency and others), it is possible to obtain the energy that has to be produced at the storage to have a good lost through the surface layers knowing the amount of energy lost.

After make a thermos dynamical analysis now we focus on economic aspects.

Knowing that the discharge phase is active in the moments where there are high electricity prices, after making some simulation it is established a range of validity to carry this thermos economic analysis in discharge phase. The range is the following

Energy price: [200 400 600 800] [KDkk/MWh]

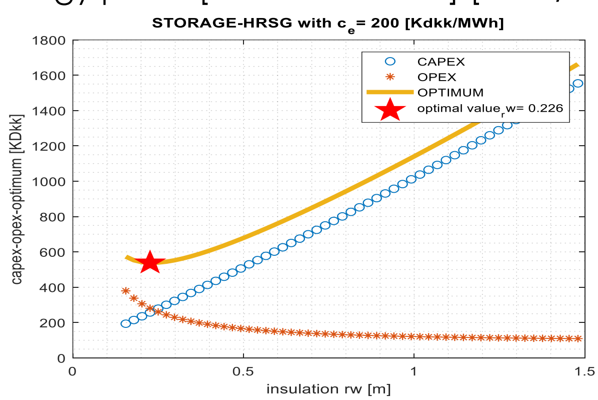


FIGURE 59

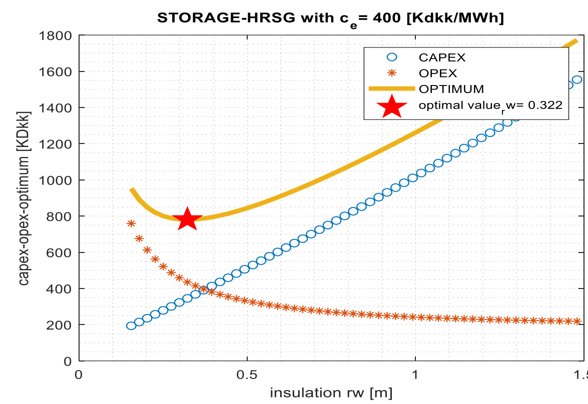


FIGURE 58

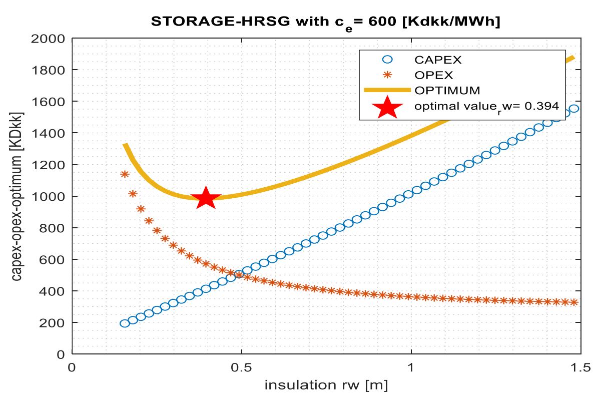


FIGURE 61

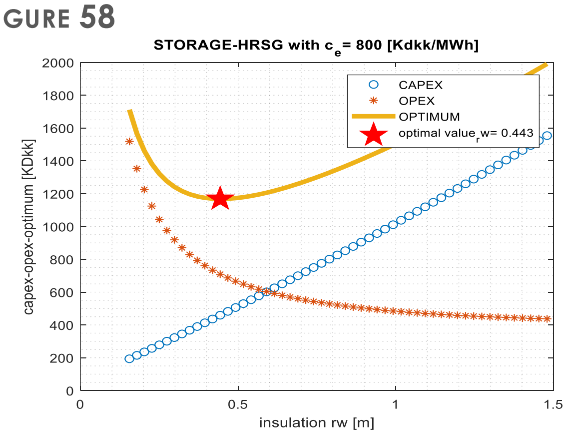
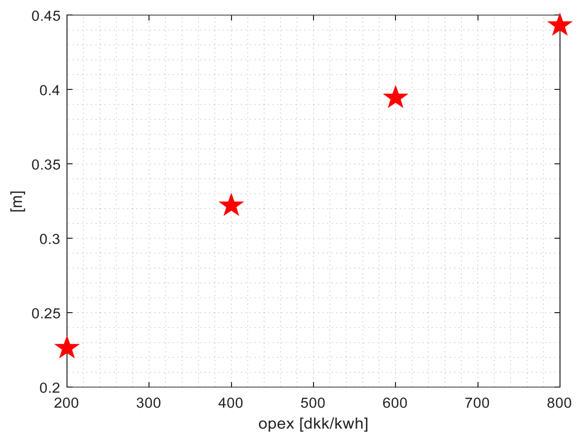


FIGURE 60

As it is possible to see in the graphs, if the energy price is higher, the optimal value goes throught right and the total price is higher. If we make a comparison between heater-storage pipe energy cost and storage-HRSG pipe energy cost the money that we lost in this discharge phase are higher because the price is higher. That is why in this phase is very important tofound the right insulation value because the losses here are very high and that means that the cost is high too.



This is the relation between the energy price and the optimal thickness. The fitting curve has a linear completely monotonic behaiours. That could be a relation useful to size the insulation pipe with that characteristics.

FIGURE 62

7.3.2 HRSG storage pipe sensitivity analysis

This piece of pipe has the aim to link the HRSG to the storage is insulated with rockwool only. The air that exchanges heat with the steam cycle goes to the storage back in order to reuse that heat instead of air flow. After making simulation the maximum outside temperature of the HRSG is equal to 300 [°C]. That is why in this sensitivity analysis it is used this maximum value. Using a maximum value this calculation are cautelative.

Knowing that the maximum temperature that we could achieve here is lower than the maximum temperature rockwool limit, another insulation layer it is not necessary, one is sufficient, so considering this piece of pipe we consider rockwool only. 3

The pipe length is fixed and it is equal to 20 [m].

To understand the following plots it is necessary an explanation of each part calculation:

CAPEX: it is the capital cost of the pipe that includes the pipe and insulation pipe.

OPEX: it is the total money that will be lost in twenty year, considering an interest rate equal to 2%, due to the heat losses that exists from the pipe surface. The calculation are done considering 100 discharge cycle in one year for 20 year.

The summation of this curve gives us the total money lost to have this pipe varying the insulation thickness.

The red star showed in the graphs shows the minimum cost, considering the CAPEX and OPEX expenditures, which it is possible to achieve considering the variation of the thickness layer.

Knowing that the storage is charged and discharged in two different moments depending on the electricity prices it is chosen a certain range on order to understand, in that case what is the best insulation thickness solution. /The mean charge price obviously changes if the heater power changes, for example for this analysis the heater power was equal to 3 [MW].

The insulation thickness varies from 0.1 to 3 [m].

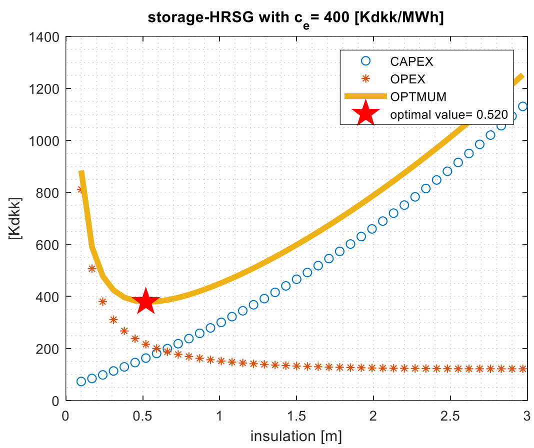


FIGURE 63

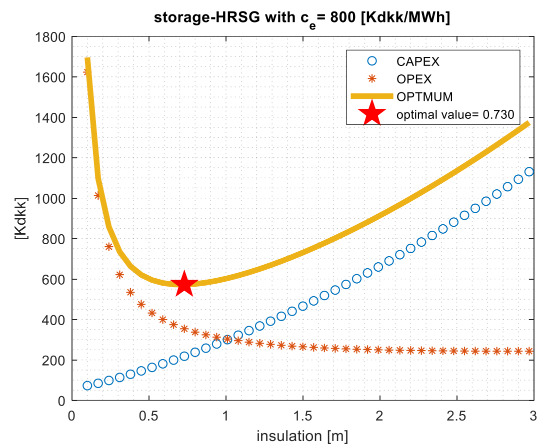


FIGURE 64

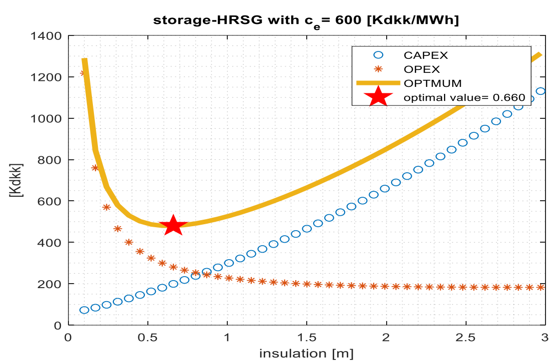


FIGURE 66

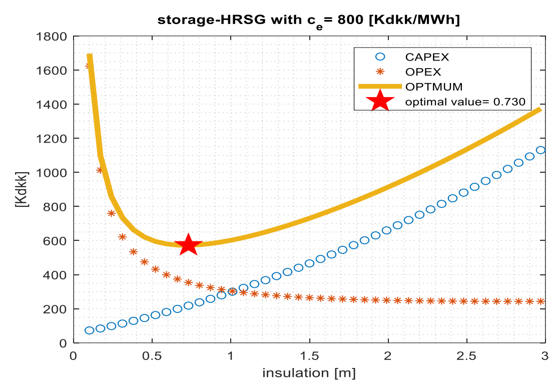


FIGURE 65

As it is possible to see in the graphs even in this pipe analysis the star, so the minimum optimal value, goes towards right but the final optimal value, in terms of money is very low with respect to the previews case, the motivation is that the energy has a lower value. It is important to remember that this pieces of pipe links the HRSG to the storage, at a Temperature equal to 300 [°C]. This energy it is not so 'important', because this energy goes into the storage at a temperature not more useful to produce energy. It is important to see that the optimal value goes around 0.5 [m], so it is the optimal value from the economical point of view for this piece of pipe.

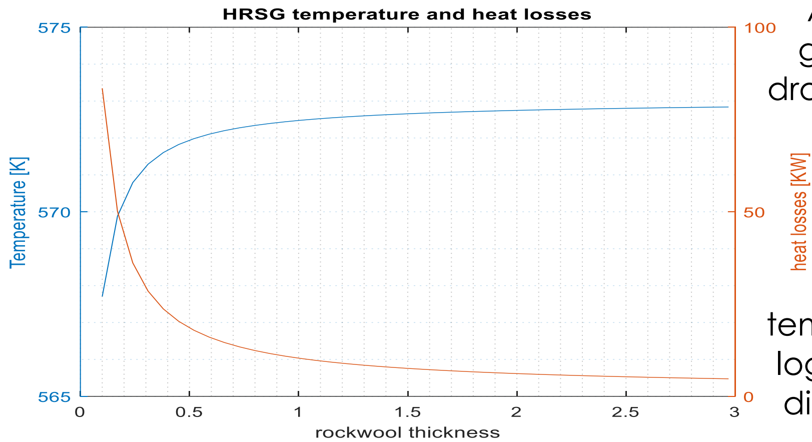


FIGURE 67 TEMPERATURE AND HEAT LOSSES.

As it is possible to see in graph, the temperature drop through the pipe is very low and it means a good thing. Obviously, the heat losses is inversely proportional to the temperature. The temperature trend is logarithmic and the difference temperature varying the thickness is very high. if we consider the 0.5 [m] as a separator, on the left the decrease of temperature rise very quickly and consequently the heat losses do the same in the inversional way. On the right of 0.5 [m] there is a plateau. Therefore, this value is the optimum from the economical point of view.

7.3 Conclusions

It is interesting to see that for all the analyzed cases, an optimal value from the economical point of view is optimal even from the thermodynamic one. The motivation is that the economic loss is strictly related to the heat losses, as it can be seen by the similar shape of the curves. This is very important and advantageous result because the cost minimization is a heat losses minimization too.

Another conclusion could be that it is very important to well insulated the piece of pipe that links the HRSG and the storage, because it is active when there are an high electricity price. On the contrary, in the charge part the price are low, so it is important to well insulated only from a thermodynamic point of view.

8. Investment cost analysis

8.1 Introduction

In this section, an economic analysis is performed in order to understand how economically feasible this new technology is compared to the others. The others non-conventional technologies could be for example batteries, fuel cells, CAES etc.

The aim of this part is to estimate the cost of the total plant and the cost of the three phases to understand what is the main cost of all phases. The final aim is to verify if this new technology and if this plant is feasible and it is possible to put it on the market.

To carry a feasibility analysis of the plant is necessary to know what is the initial cost and how is all components and added costs to verify the feasibility of the power to power plant. Therefore, an economic analysis is necessary in order to know the cost of the whole plant. The aim of this part is to carry an economic analysis for

each component and for each phase (charge, discharge and storage) and finally the whole plant cost. It was performed a research on the prices of each component of the power-to-power plant in order to do that. This investment cost analysis is the initial point of the economic analysis and it is a way to understand how much this technology can be competitive on the market.
Then it is possible to perform a comparison among the others technologies to understand how much the HT-TES rock bed will have a good result now and in the future scenario.

8.2 NETL procedure

To carry this analysis is necessary follow a guideline. When a cost analysis is performed, it is important to consider all costs relative to all components and costs that participate to permit to have this plant.
The methodology used to carry this cost analysis of the plant is performed using the NETL (National Energy Technology Laboratory) methodology. It is a guideline to perform an investment cost developed in United States of America in order to find the cost of chemical and energy plants. The NETL[35] wrote a document where it is possible to find step by step the procedure to perform this analysis. This document will serve as a guideline for performing power generation studies on a consistent, comparable basis. Each year, the National Energy Technology Laboratory (NETL), technology developers supported by NETL, and other organizations conduct techno-economic analyses (TEA) to assess the viability of state-of-the-art and advanced technologies. These analyses help to exploit economic assessments to verify potential risks and benefits of new technologies of a power plant applications. This is a way to evaluate economic feasibility and to identify technology development challenges and risks. This NETL procedure is a way to provide a common basis to facilitate comparison between technology choice. It is important to outline that if we make some different economic assumptions can drastically change the final results of a TEA. Hence, these assumptions are not intended to be used as a complete assessment for a specific power plant, which would require far greater detail and site-specific information. So, this is a way to estimate and to simply verify of it could be (knowing those assumptions) if it is a feasible plant, compared to the other new storage power-to-power storage technologies.
This methodology is a procedure to calculate the cost of the total plant using some multiplicating coefficients starting from the investment cost of components. The analysis is done considering the following assumption:

- Constant currency so it is considered a constant escalation rate during the construction period.
- The construction year is 2014.
- To carry all costs found to this period I use the CEPCI Index.[36]

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[35] (NETL April, 2011)
[36] http://www.chemengonline.com/pci-home

Concerning This methodology defines capital cost at five levels; starting from the costs of components to the whole plant cost:
o BEC – Bare Erected Cost
o EPCC - Engineering, Procurement and Construction Cost
o TPC - Total Plant Cost
o TOC - Total Overnight Capital
o TASC - Total As-Spent Capital

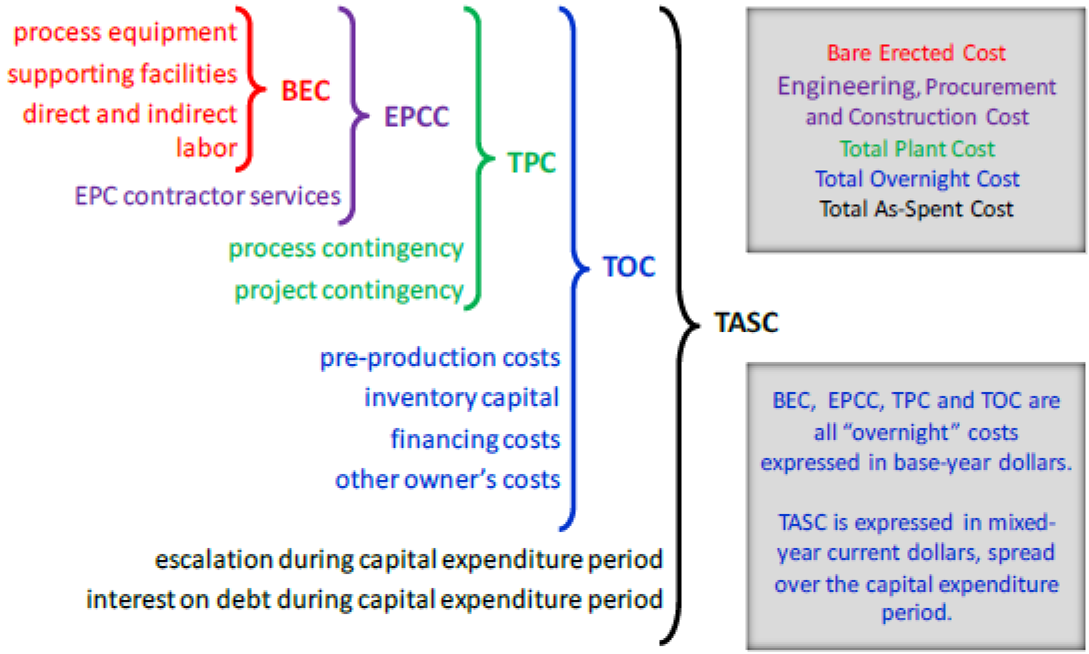


FIGURE 68 NETL INVESTMENT COST OVERVIEW[37]

Below, there is a briefly explanation of the whole procedure, step by step.
BEC 'bare erected cost' is the summation of the costs of the components of the plant. Concerning the Matlab function it is more simple to divide the costs into phases: charge, discharge, storage function. This cost comprises the cost of process equipment, on-site facilities and infrastructure that support the plant (e.g. shops, offices, labs, road), and the direct and indirect labour required for its construction and/or installation. BEC is an overnight cost expressed in constant currency.
EPCC 'Engineering, Procurement and Construction Cost' (EPCC) comprises the BEC plus the cost of services provided by the engineering, procurement and construction (EPC) contractor. EPC includes: detailed design, contractor permitting and project/construction management costs. EPCC is an overnight cost expressed in constant currency.

TPC 'Total Plant Cost' (TPC) comprises the EPCC plus project and process contingencies.
TPC is an overnight cost expressed in constant currency.

[37] (U.S. Energy Information Administration, 2017)

TOC ‘Total Overnight Capital’ (TOC) comprises the TPC plus all other overnight costs, including owner’s costs. TOC is an “overnight” cost, expressed in constant currency and as such does not include escalation during construction or interest during construction.

TASC ‘Total As-Spent Capital’ (TASC) is the summation of all capital expenditures as they are incurred during the capital expenditure period including their escalation. TASC also includes interest during construction. Accordingly, TASC is expressed in mixed, current-year dollars over the capital expenditure period.
Every costs of components is referred to a specific year, 2014. Obviously the components prices found they are not all referred to this is year, so, fortunately there is the possibility to refer all prices to this year thanks to CEPCI indexes.
The cost estimates are based on an engineering, construction and procurement management (EPCM) contracting strategy utilizing multiple subcontracts
This is the approach used to perform this work. The owner has the control of the project, while minimizing, if not eliminating most of the risk premiums typically included in an EPC contract price

• the traditional lump sum EPC contract, the Contractor assumes all risk for performance, schedule, and cost.
• Where Contractors are willing to accept the risk in EPC type lump-sum arrangements, it is reflected in the project cost.
• In today’s market, Contractor premiums for accepting these risks, particularly performance risk, can be substantial and increase the overall project costs dramatically.

The EPCM approach used as the basis for the estimates is anticipated to be the most cost effective approach for the Owner. While the Owner retains the risks, the risks become reduced with time, as there is better scope definition at the time of contract award(s). EPCM contractor services are estimated at 8 to 10 percent of BEC. These costs consist of all home office engineering and procurement services as well field construction management costs
Process and project contingencies are included in estimates to account for unknown costs that are omitted or unforeseen due to a lack of complete project definition and engineering. Contingencies are added because experience has shown that such costs are likely, and expected, to be incurred even though they cannot be explicitly determined at the time the estimate is prepared
Capital cost contingencies do not cover uncertainties or risks associated with

1. scope changes
2. changes in labour availability or productivity
3. delays in equipment deliveries
4. changes in regulatory requirements
5. unexpected cost escalation

Process contingency has the aim to adjust uncertainties concerning the cost estimated determined by performance uncertainties associated with a new technology where some costs could be not sure. Process contingencies cost are inserted in each phase of the plant based on its current technology status.

"AACE International Recommended Practice No. 116R-90, Conducting Technical and Economic Evaluations as applied for the Process and Utility Industries (AACE 16R-90) states that process contingency can range from zero to 70 percent of BEC based on the technology status level at the time of the estimate. QGESS provides guidance on implementing a process contingency, which does require some interpretation and judgment. Depending on the status of the technology being developed, different process contingencies should be applied. Discussing the current status (i.e. laboratory scale, bench scale, demonstration scale) of the technology helps justify the contingencies utilized. As an example, the amine capture system employed for PC plant cases has a process contingency of 20 percent; this is considered appropriate based on the current deployment of the technology in other fields and the application of the technology, as guided by the QGESS. It is suggested that when selecting a process contingency to apply to the technology being evaluated, the percentage be identified and the reason for selection be discussed in the TEA. An overall capital cost sensitivity analysis can also help provide insight into the uncertainty of the process and equipment or R&D goals, as viewed by the developer. Project contingencies are applied to each plant section. AACE 16R-90 states that project contingency for a "budget-type" estimate (AACE Class 4 or 5) should be 15 to 30 percent of the sum of BEC; engineering, procurement, and construction fees; and process contingencies and other performance of the plant after start-up (e.g., availability, efficiency)."[38]

Considering this, it is important to underline that the final cost that it is possible to calculate in Matlab tool developed could have some uncertainty that derives by these more uncertain contributions to the final cost. The final price could vary from -30% to 70%. As it is possible to see this variation is really high.

Concerning the financial structure it is possible to imagine to have two possibilities concerning the person that has money to finance and to develop the project of the plant. He is the person that assume the risk profile of the plant and it could be in low or high risk.

The 1st case is called 'IOU' where the owner/developer was assumed to be an investor-owned utility; the 2nd case is called (IPP) where the independent power producer developer/owner were assumed.

Considering this work, it is chosen to have a low risk and the owner developer of the plant is assumed the investor and the owner (IOU).

In the Matlab tool developed, either options are inserted as an input data but in the design the first option is contemplated.

The final step is to estimate the total as spent capital from the total overnight cost.

For scenarios that adhere to the global economic assumptions specified by NETL, specific multipliers can be used to translate TOC to TASC to account for the impact of both escalation and interest during construction

- TOC is expressed in base-year dollars and the resulting TASC is expressed in mixed-year, current-year dollars over the entire capital expenditure period

38 (AACE International, 2010)

- TASC (Total As-Spent Capital) is the sum of all capital expenditures as they are incurred during the capital expenditure period including their escalation. TASC also includes interest during construction. Accordingly, TASC is expressed in mixed, current-year dollars over the capital expenditure period. For scenarios that adhere to the global economic assumptions specified by NETL, specific multipliers can be used to translate TOC to TASC to account for the impact of both

The first four types of costs are in constant current and are overnight costs while the last one, the TASC, is a cost expressed in current currency and includes the expenses extended to the entire period

When the calculations are made. It is supposed to have a constant currency; I do not consider the effect of inflation during the years, so the discount rate is the weighted average of the cost of capital.

Therefore, introducing this methodology, it is stimulated the cost of the whole plant introducing the three base parameters.

8.3 Costs analysis

It is important to underline that since the plant is composed of three phases, every component is grouped in a specific phase in order to understand what is the phase that has the higher impact on the final cost.

8.3.1 Analysis of components

The first step of the investment analysis is to find the cost of all components and then to refers them to the year 2014.

To derive the cost of the components regardless of the size from the technical characteristics of work and year of marketing, the rules of Turton(Richard Turton, Richard C. Bailie, Wallace B. Whiting, 2013) are used to obtain the actual cost related to that size with those specific characteristics and referred to the year 2014. The tool developed gives us the costs of components and the entire cost of the plant inserting the three base parameters:

- Turbine power [MW]
- Heater power [MW]
- Storage capacity [MWh]

Developing this analysis it is important to evaluate the specific cost of the components, which means to refer them to the unit of size of the phase they belong to. In this way it will be simple for the Matlab tool to calculate, for every value of the base parameters, every cost related to them.

Below there is an analysis of the cost of each components and is expressed in Dkk (Danish Crowns), where 1 eur ~ 7.46 Dkk:

HEATER:
the cost value refers to the size [Dkk / MW_el]. The cost was requested from a Danish company that sold the component to the DTU for the test facility in 2017. The item in question has a cost equal to .. and its size is 30 [KW_el] . Using the rule 'sixth tens rule' with a coefficient equal to 0.6 and [39]using the CEPCI indexes to discount the cost per year of effective construction of the plant, that is to 2014 it is an electric heater, this value is taken from the Risø National Laboratory. This value is proportional to the power and this value is referred to a power equal to 30 [KW] in 2017. To carry this value from 2014 to 2017 it is possible to use the CEPCI index and to scale the power with respect to the input variable (heater power) it was used the sixth tens rule.

$$C_{Heater} = \left(c_{Heater} * \left(10^3 * \frac{Heater_{power}[MW]}{15[KW]} \right) \right)^{0.6} [Dkk]$$

FAN:
The Turton formula is used for the fan. It is supposed an axial fan made of stainless steel. The technical parameters that determine the price are the gauge pressure and the flow rate. The price is always updated thanks to CEPCI indices. This value is taken from the Turton. It is dependent on the mass flowrate and the pressure. The cost is scaled with respect to the date thanks to CEPCI index. The assumption is that this fan is axial made of stainless steel.

$$C_{fan} = F_m * F_p * C_{p_o} * (\frac{I_{CEPCI_{2014}}}{I_{CEPCI_{2001}}})$$

Where:
C_{p_o} is a function of the mass flowrate;;
F_m it is a material factor, it is a function of the material and the typology of the fan; it is chosen to use an axial fan with stainless steel;
F_p it is called pressure factor, it is a function of the pressure that the fan has to overcome.

PIPING:
the cost of piping varies according to length, fixed diameter. An analysis was made on the cost per unit length (just by varying the diameter) and then a third degreepolynomial was used to vary the cost per unit length as the diameter varies. Found at the formula it 'adjusted' the cost with the CEPCI indexes. Concerning piping it is possible to find in a datasheet the values of the prices per length for each diameters. Thanks these all values it is possible to build a function, a cost function per length depending on the diameter. It is built a function that varies with the diameters. Taking data from technical parameters

39 (Richard Turton, Richard C. Bailie, Wallace B. Whiting, 2013)

calculated before it is possible to find the price per unit length of the pipe that has to use. [40]

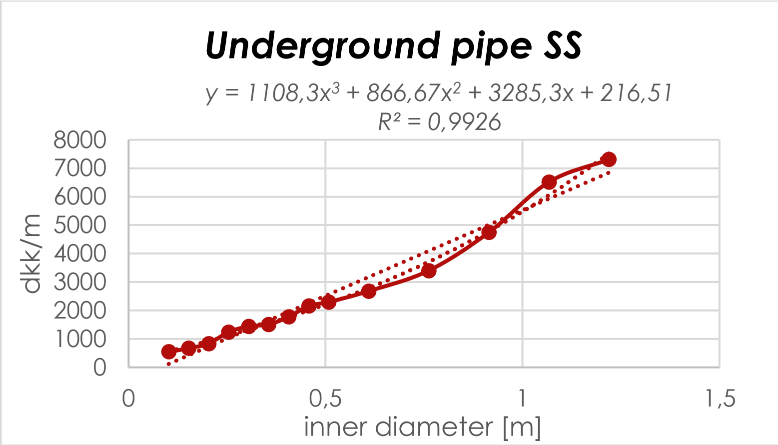


FIGURE 69

ROCKWOOL:

Rockwool is an insulating material used to avoid heat losses throw the tubes. The reference value is taken from the Risø National Laboratory and it is a cost per unit of volume. The cost is referred at 2017 and the CEPCI indexes are used to have the cost referred to 2014.

SUPERWOOL:

Superwool is another insulation material that we use to avoid losses throw the pipe and in the storage. The reference value is taken from the Riso National Laboratory and it is a cost per unit of volume. The cost is referred at 2017 and the CEPCI indexes are used to have the cost referred to 2014.

When these calculations and evaluations done, defines the charge bare erected cost of the power to power plant, $C_{BEC\ charge}$.

STORAGE

SWEDISH DIABASE:

Danish diabase is the material that we use to store heat inside the HT-TES. They are very cheap and it is very common in Denmark and in all Scandinavian zones. The price is known form the supplier in Dkk per unit of volume. The cost found of the reference, obviously is proportional to the weight of the rocks.

VALVES:

They are two three-way valves with the task of conveying the flow in one direction or the other in order to load or unload the storage. They have to ensure the maximum temperature equal to 600 [°C], so the cost in question depends on the temperature they have to endure. Using the sixth tens rule and the CEPCI

[40] (State of Michigan, 2003)

indices we get the real cost. The cost was taken from a website of industrial items; (State of Michigan, 2003)

CONCRETE:

The cost is based on the volume of it. The cost is adjusted thanks to the CEPCI indexes

When these calculations and evaluations done, defines the storage bare erected cost of the power to power plant, $C_{BEC\ storage}$.

ROCKWOOL:

Rockwool is an insulating material used to avoid heat losses throw the tubes. The reference value is taken from the Risø National Laboratory and it is a cost per unit of volume. The cost is referred to 2017 and the CEPCI indexes are used to have the cost referred to 2014.

$$C_{rockwool} = c_{rockwool} * V_{rockwool} * (\frac{I_{CEPCI_{2014}}}{I_{CEPCI_{2016}}})$$

SUPERWOOL:

Superwool is another insulation material that we use to avoid losses through the pipe and in the storage. The reference value is taken from the Riso National Laboratory and it is a cost per unit of volume. The cost is referred at 2017 and the CEPCI indexes are used to have the cost referred to 2014.

$$C_{supewool} = c_{superwool} * V_{superwool} * (\frac{I_{CEPCI_{2014}}}{I_{CEPCI_{2016}}})$$

SKAMOL

Skamol is another insulation material that has the aim to insulate and to support the entire structure. This cost is found from Risø National Laboratory thanks to the pilot plant built there. The cost is proportional to the volume. This found price is referred to 2017, so to transpose this value to the 2014 it is used the CEPCI indexes. This is the highest specific cost concerning the insulating material that cover the storage.

$$C_{skamol} = c_{skamol} * V_{skamol} * (\frac{I_{CEPCI_{2014}}}{I_{CEPCI_{2017}}})$$

When these calculations and evaluations done, defines the storage bare erected cost of the power to power plant, $C_{BEC\ storage}$.

DISCHARGE

HEAT EXCHANGER:

This cost is added only when the 3rd option is considered. It is an air-water heat exchanger that let to pass heat from air to district heating water. The cost of this heat exchanger was taken from the Turton[41] and is proportional to the exchange surface. The heat exchanger is a counter current one. The cost it is adjusted with the CEPCI indexes.

$$\log_{10} C_p^0 = K_! + K_2 \log_{10}(A) + K_3[\log_{10}(A)]^2$$

Where:
Ki is a coeffient and A is a surface of the heat exchanger [m2]
STEAM BOTTOM CYCLE:
From the reference (hermoeconomic optimization of the pinch point and gas-side velocity in heat recovery steam generators A Behbahani-nia1∗, S Sayadi1, andMSoleymani2) the whole cost of the steam cycle plant it is found. That plant that we are talking about is a simple Rankine steam cycle. The cost is relative to the year 2006. Thanks to the CEPCI index it is possible to have the price referred to year 2014. The cost is specific to the size of the turbine, so to have the right cost it is necessary only to multiplication to the specific cost times the turbine power [MW].

$$C_{turbine}[MDkk] = 1.76 * power_{turbine} * (I_{CEPCI_{2014}}/I_{CEPCI_{2016}})$$

HRSG:
This cost was found on a website reference(Behbahani-Nia, Sayadi, & Soleymani, 2010) : the following formula states that the cost comes from the amount of the surfaces of the exchanger in the economizer section, evaporator and super heater. In that cost it is included the cost of the pre heater too but in the steam Rankine cycle of the power-to-power plant it is not present. So to be coherent the value of pre heater surface is equal to zero. The cost was then discounted with the CEPCI indices.

$$C_{HRSG} = \alpha(k_{PRE} * A_{PRE} + k_{ECO} * A_{ECO} + k_{EVA} * A_{EVA} + k_{SH} * A_{SH}) * CRF$$

Where: CRF = i(1 + i)^(Lf)/ (1 + i)^(Lf) - 1

keco(pre-heater)	**659,7036**	**dkk/m2**
keco(economizer)	**659,7036**	**dkk/m2**
Keva(evaporator)	**551,9682**	**dkk/m2**
ksh(superheater)	**1399,1544**	**dkk/m2**

alpha_components	value
Heat transfer area	1
Casing and structure	0,205
Processing equipments	0,216
Piping and insulation	0,078

[41] Richard Turton, Richard C. Bailie, Wallace B. Whiting, 2013)

Control and instrumentation	0,098
Electrical panels and wiring	0,093
Engineering and supervision	0,031
Tax	0,075
Insurance	0,115
Profit of the project	0,095
Other costs	0,125
Total	**2,31**

FIGURE 70 HRSG PARAMETERS[42]

ROCKWOOL:
Rockwool is an insulating material used to avoid heat losses throw the tubes. The reference value is taken from the Risø National Laboratory and it is a cost per unit of volume. The cost is referred at 2017 and the CEPCI indexes are used to have the cost referred to 2014.
SUPERWOOL:
Superwool is another insulation material that we use to avoid losses throw the pipe and in the storage. The reference value is taken from the Riso National Laboratory and it is a cost per unit of volume. The cost is referred at 2017 and the CEPCI indexes are used to have the cost referred to 2014.
When these calculations and evaluations done, defines the discharge bare erected cost of the power to power plant, $C_{BEC\ discharge}$.
Adding all the costs of the components, according to the NETL formulas we obtain the Bare Erected Cost,that is the only cost of the components

To conduct a thermo-economic analysis is necessary to find all cost of components
The investment analysis made considers the whole plant in all its components and in all its sections. The year 2014 is considered as construction year and for the calculation of the total investment cost the NETL procedure is considered, a procedure that allows to have the total cost of the plant starting from its components. The analysis is made in constant currency or a constant rate of escalation is considered during the construction period.

As a first step all the costs of the components were found, creating a list divided by parts of the plant:

CHARGE	Unit of measurements	Formula	Source

[42] Thermoeconomic optimization of the pinch point and gas-side velocity in heat recovery steam generators
A Behbahani-nia1∗, S Sayadi1, andMSoleymani2

Heater	$[\frac{Dkk}{MW}]$	$C_H = C_0 * \left(\frac{S_H}{S_0}\right)^{0.6}$ $C_0 = [Dkk]$ $S_0 = [MW]$	Risø National Laboratory experimental plant DTU
Fan	$f(\dot{m}\left[\frac{kg}{s}\right]; p\ [Pa])$	$C_f = C_{p0} * F_p * F_m$ $C_{p0} = [Dkk]$ $F_m = [-]$ $F_p = [-]$	(Richard Turton, Richard C. Bailie, Wallace B. Whiting, 2013)
Piping	$\left[\frac{Dkk}{m}\right]_{diamater}$	$C_{pipe} = 31542 * D^3 - 21842 * D^2 + 10592 * D - 38.0$	(State of Michigan, 2003)
Superwool	$[\frac{Dkk}{m^3}]$	$C_s = c_s * V_s$	Risø National Laboratory experimental plant DTU
Rockwool	$[\frac{Dkk}{m^3}]$	$C_R = c_R * V_R$	Risø National Laboratory experimental plant DTU

FIGURE 71 CHARGE

STORAGE	Unit of measurements	Formula	Source
Danish diabase	$[\frac{Dkk}{m^3}]$	$C_R = c_R * V_R$ $c_R = \left[\frac{Dkk}{m^3}\right]; specific\ cost$ $V_R[m^3]; volume$	Risø National Laboratory experimental plant DTU
Concrete	$[\frac{Dkk}{m^3}]$	$C_C = c_C * V_C$ $c_C = \left[\frac{Dkk}{m^3}\right]; specific\ cost$ $V_C = [m^3]; volume$	Risø National Laboratory experimental plant DTU
HARD INSULATION	$[\frac{Dkk}{m^3}]$	$C_h = c_h * V_h$	Risø National Laborator

Scamol		$c_h = \left[\frac{Dkk}{m^3}\right]; specific\ cost$ $V_h = [m^3]; volume$	y experimental plant DTU
HIGH TEMPERATURE SOFT INSULATION Superwool	$[\frac{Dkk}{m^3}]$	$C_s = c_s * V_s$ $c_s = \left[\frac{Dkk}{m^3}\right]; specific\ cost$ $V_s = [m^3]; volume$	Risø National Laboratory experimental plant DTU
LOW TEMPERATURE SOFT INSULATION Rockwool	$[\frac{Dkk}{m^3}]$	$C_R = c_R * V_R$ $c_R = \left[\frac{Dkk}{m^3}\right]; specific\ cost$ $V_R = [m^3]; volume$	Risø National Laboratory experimental plant DTU
DISCHARGE	**Unit of measurements**	**Formula**	**Source**
Bottom cycle	$[\frac{Dkk}{MW}]$	$C_T = c_t * P_T$ $c_T = \left[\frac{Dkk}{MW}\right]; specific\ cost$ $P_T = [MW]; turbine\ power$	http://www.localpower.org/deb_tech_st.html
Heat recovery steam generator (HRSG)	$[\frac{Dkk}{m^2}]$	$\mathrm{C_{HRSG}} = \alpha(k\mathrm{Pre}A\mathrm{Pre} + k\mathrm{Eco}A\mathrm{Eco} + k\mathrm{Eva}A\mathrm{Eva} + k\mathrm{SH}A\mathrm{SH})\mathrm{CRF}$ $k_i = surface\ specific\ cost\ [\frac{Dkk}{m^2}]$ $A_i = surface[m2]$ $\alpha = interest\ rate\ [-]$	Thermoeconomic optimization of the pinch point and gas-side velocity in heat recovery steam generators A Behbahani-nia1∗, S Sayadi1, andMSoleymani2
Heat exchanger for DH	$f(p[Pa], S[m^2])$		(Richard Turton, Richard C. Bailie, Wallace B. Whiting, 2013)

Piping	$\left[\frac{Dkk}{m}\right]_{diamater}$	$C_{pipe} = 31542 * D^3 - 21842 * D^2 + 10592 * D - 38.0$	(State of Michigan, 2003)
Superwool	$[\frac{Dkk}{m^3}]$	$C_s = c_s * V_s$ $c_S = \left[\frac{Dkk}{m^3}\right]; specific\ cost$ $V_s = [m^3]; volume$	Risø National Laborator y experimen tal plant DTU
Rockwool	$[\frac{Dkk}{m^3}]$	$C_R = c_R * V_R$ $c_R = \left[\frac{Dkk}{m^3}\right]; specific\ cost$ $V_R = [m^3]; volume$	Risø National Laborator y experimen tal plant DTU
Fan	$f(\dot{m}\left[\frac{kg}{s}\right]; p\ [Pa])$	$C_f = C_{p0} * F_p * F_m$ $C_{p0} = [Dkk]$ $F_m = [-]$ $F_p = [-]$	(Richard Turton, Richard C. Bailie, Wallace B. Whiting, 2013)

FIGURE 72 STORAGE AND DISCHARGE

8.4 Simulation results

To have an idea about the costs, we made a simulation to have some output and to understand what is the final cost and the impact of each component on the final cost. Considering only the cost of components, the percentage are the fractions of the Bare Erected Cost.

The input parameters are :

Parameter		
Heater power	50	[MW]
Storage capacity	700	[MWh]
Turbine power	3	[MW]

FIGURE 73

CHARGE:

TABLE 11 CHARGE COMPONENTS

COMPONENT	[MDkk]
Fan	2.0123
Heater	3.6844
Piping	0.2636
Superwool	0.0126
rockwool	0.015

STORAGE:

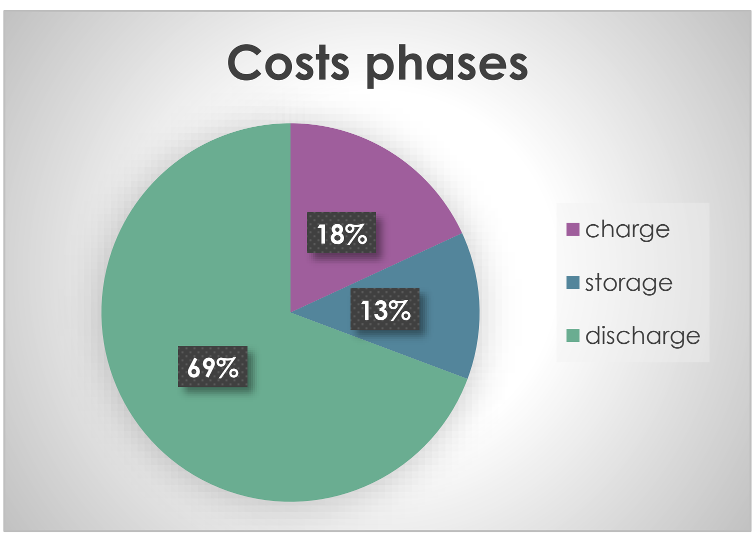
TABLE 12 STORAGE COMPONENTS

COMPONENT	[MDkk]
Swedish diabase	0.97
Hard insulation	0.729
Soft insulation HT	0.0011
Soft insulation LT	0.0
Concrete	0.3375
High temperature valves	0.0065

DISCHARGE:

TABLE 13 DISCHARGE COMPONENTS

COMPONENT	[MDkk]
HRSG	3.606
Fan	0.230
Piping	0.20
Rockwool	3.99e-4
Superwool	4.6e-4
Steam cycle plant	5.6027



charge cost 3.188 [MdKK]

storage cost 1.575 [MdKK]

discharge cost 9.643[MdKK]

As it is possible to see in the graph, more than the half of the total price is due to the discharge phase. In that phase, the main costs are HRSG and the entire steam cycle plant.

FIGURE 74 COST PHASES

Considering the NETL procedure the final total plant cost is found: **57.788[MDKK]**

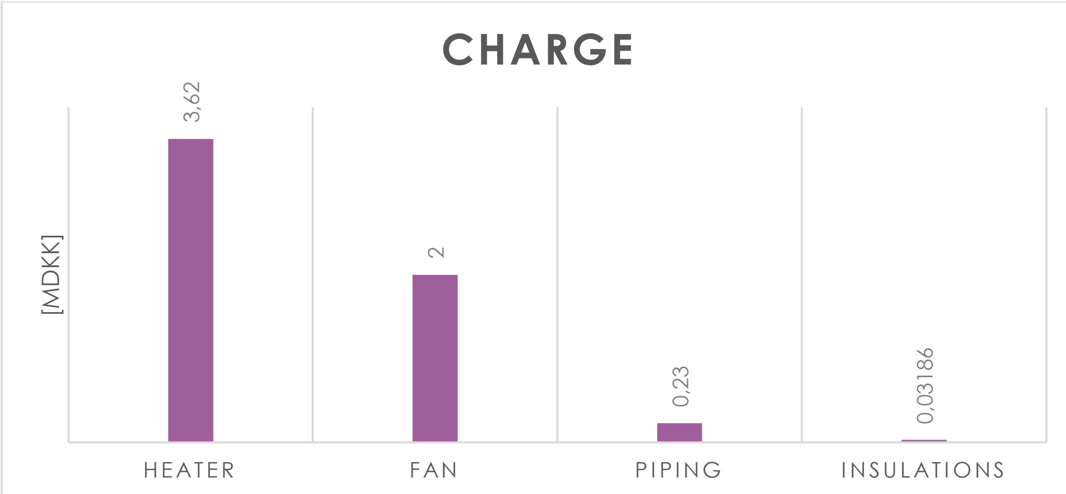


Figure 75 charge cost components.

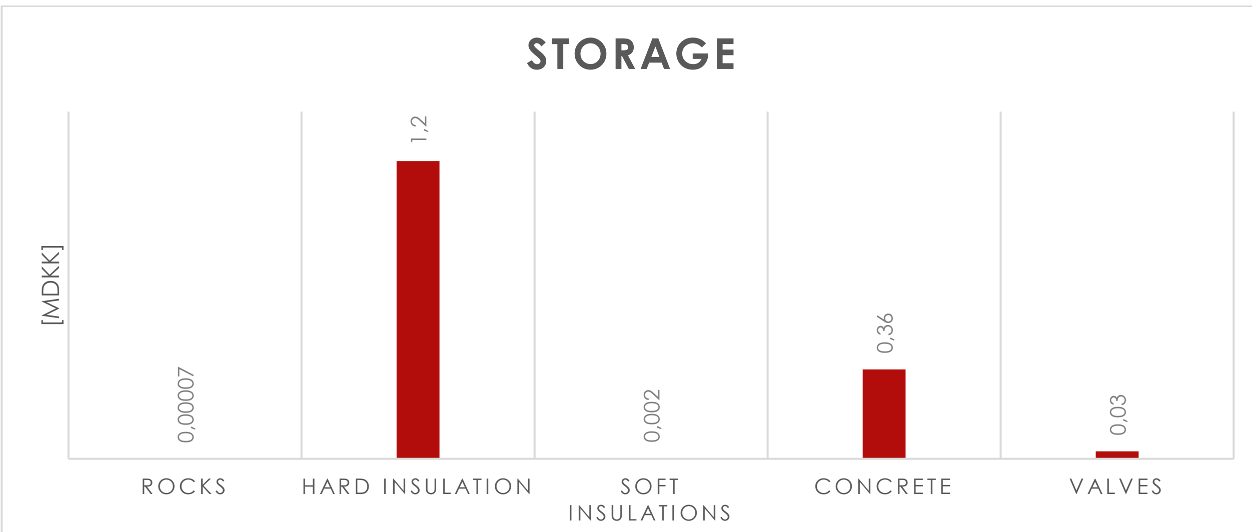


Figure 76 storage cost components.

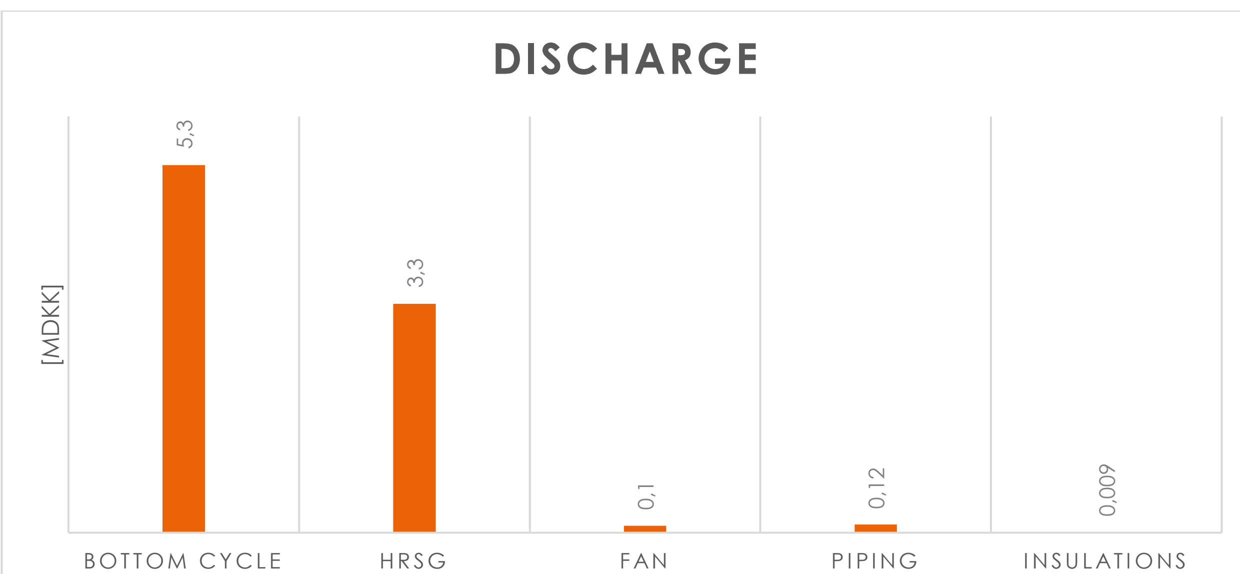


Figure 77 discharge cost components.

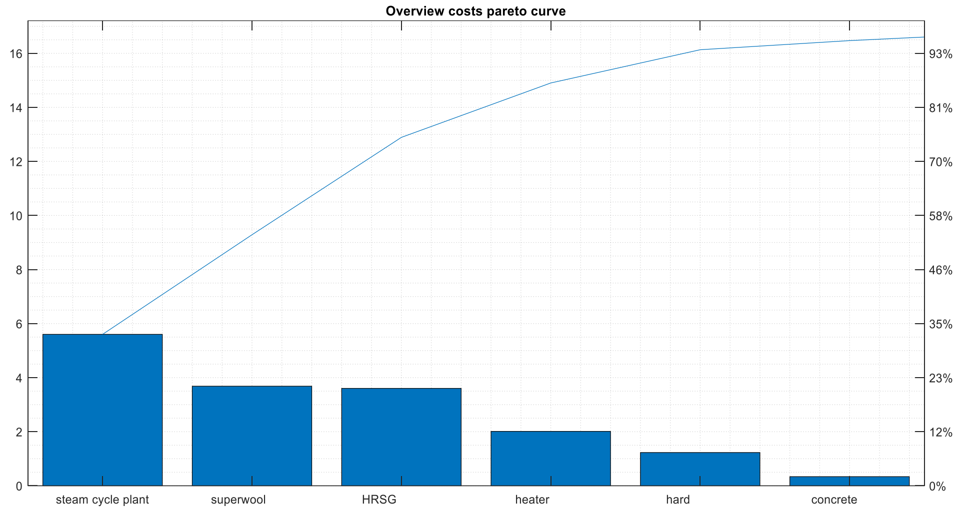


FIGURE 78 TOTAL PLANT COST COMPONENTS.

8.4.1 Overall P2P plant analysis

Running the program several times it is possible to see the following things about the total plant and about each of the phases.

CHARGE: In this part, the preponderant cost is the price of the heater and fan, considering recirculation or non-recirculation the cost changes but only slightly, about 15%. This compared to the other phases is equal to 15%.

STORAGE: the preponderant cost is that of the hard insulation. Obviously, this cost decreases in percentage if the size of the storage is increased more and more. The lowest cost is that of rocks, which is why this technology could be cost-effective and cheaply upscalable from an economic point of view.

DISCHARGE: is the highest cost per unit of power. The preponderant cost is that of the entire bottom and HRSG cycle, even if less incisively. Considering the other phases, this is the highest cost. The major cost is the entire cost of the steam Rankine cycle. The price percentage of discharge phase is around 75%, one order of magnitude with respect to the other phases.

The calculations made and the results show that most of the investment cost depends on the phase of discharge; the most contained cost is that of storage despite being the most cumbersome from the point of view of land occupation.

Considering the input value of the tool, so charge, storage and discharge it will be better to have a lower value of turbine power and an higher value for the heater power. The motivation is that if the have a discharge and storage input value of the same order of magnitude the discharge cost is an order of magnitude higher than the charge phase.

Another problem nowadays is that this type of power-to-power plant do not have incentives because it is not considered a new technology. Moreover, for the same motivation the cost of all components are very high, especially, as it is said, the discharge phase cost.

Considering that, it could be a good idea to make a repowering of an existing power plant with the goal of saving a big part of the cost for the bottom cycle. In fact, considering a conventional plant that uses coal or NG in decommissioning it would be better to improve it.. This could have many advantages:

- We reduce the cost of the whole plant;
- We do not use the natural gas or coal;
- The plant becomes a renewable plant.

Once the Bare erected cost is calculated it is important to find the cost of the total plant. Following the NETL procedure, with the assumptions showed in this chapter it is possible to find the total cost of the plant. Like the following bar graph shows, is it is considered all costs relative to the plant in 2014, every time that it is applied the NETL procedure, the total cost increases of an order of magnitude.

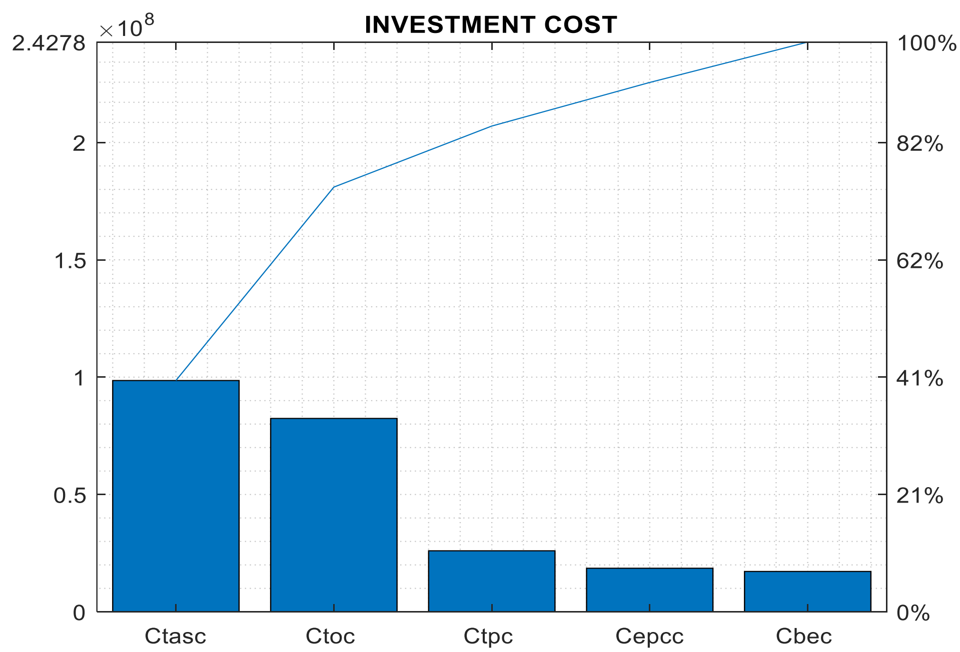


FIGURE 79 OVERVIEW INVESTMENT COST, PARETO CURVE. THESE CALCULATIONS ARE REFERRED TO THE YEAR 2014.

As follow we want to make a comparison within others storage technologies. The comparison concerns the specific cost the efficiencies.

A comparison is necessary to understand from witch point of view this technology is feasible with respect to the others types of storage already put on the market. It is estimated a capital cost of this storage per Kilowatt hour.

TABLE 14 H. CHEN ET AL. / PROGRESS IN NATURAL SCIENCE 19 (2009) 291–312

Storage type	**Value [€/kW]**
PHES	86
Lead acid	349
CAES	43
HT rock bed energy storage total plant	8,94

As it is possible to see in the table the type of storage that it is inserted in this plant has a specific cost very low compared to the others[43]. As it is said before, the cost of this storage is very low but concerning the efficiency[44] the heat sensible energy storage has the lowest value. So, if the cost is very low the efficiency is low.

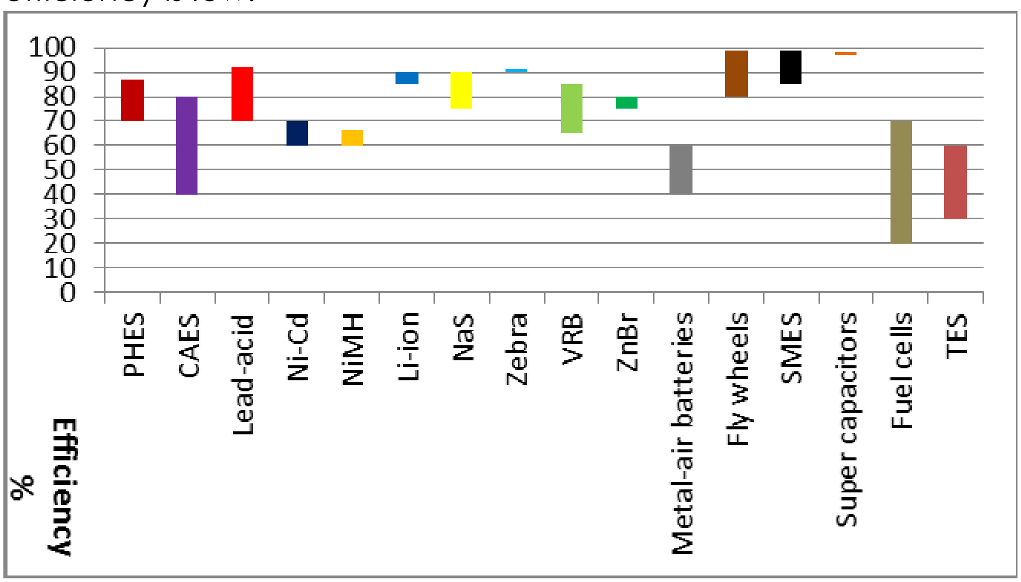


FIGURE 80 ENERGY EFFICIENCY OF STORAGE TECHNOLOGIES.[45]

So, it is important to underline that the HT-TES is very convenient if you buy it because, compared to the others storage technologies it has the lowest value

[43] Chen, Haisheng, et al. "Progress in electrical energy storage system: A critical review." Progress in Natural Science 19.3 (2009): pp. 291-312

[44] (Peng, 2014) "Advanced Materials Research"

[45] (Peng, 2014) "Advanced Materials Research"

but concerning the usage of it is necessary to verify if it has a good performance in time and if it is convenient to put it on the market.

8.5 Operational and maintenance costs

The operational cost for 'charge phase' concerns costs for the heater and fan operation and all components maintenance. This cost is proportional to the power feeds heater and fan. The operational charge cost is proportional to the heater power, the main components of the charging phase.

Concerning the operational cost of the storage phase is a cost concerning only maintenance and it is estimated on an yearly basis. As we can see it a low cost because it concerns only the supervision if it makes a good work.

For the third part the operational and maintenance costs concerns the discharge and steam bottoming cycle operational and maintenance costs. Concerning the discharge costs, they interest the air part, so the HRSG air piping and the fan. Concerning the second one, so the steam cycle is proportional to the power that the turbine spent to produce energy. This is the major cost because it is the more delicate part of the plant. This cost concerns maintenance of turbine, drum, condenser and the change of the water inside the steam cycle.

The aim of this work is to consider all costs relatively to the costs that the plant owner has to do in order to make a perfect prediction feasibility study. As we said, it is inserted in a Danish electrical and district heating grid, so at this moment we consider the Danish electricity market (intraday and day ahead), as well as district heating network and taxation system. The operational and maintenance costs are associated to the amount of money that the administration company has to pay in order to have the plant safe and able to have some product. The operational costs are able to reduce the revenues but it is necessary to make the system work.

They could be a fixed cost, independently by the use of that part of producing plant and the same cost for the whole time. Variable operational costs could change considering time and with respect to the plant utilization, so with respect to the power used or produced. These costs are dependent on the typology of task that is why it is important to understand what are the main function of each part of the plant.

Like in the previous analyses, the research of operational and maintenance costs is divided into the charge, storage, discharge and steam cycle part.

Charge: is related to the function of the heater and the charging phase fan. It is proportional to the fan and heater work, so it depends how much this part of the plant works.

Storage: is a fixed cost and it is independent on the work that the storage part performs. It is a fixed cost very low because there is no electric part, part in motion. So the probability that is could break is very low.

Discharge part: is related to the discharging phase fan

Steam cycle part: it is the most expensive part of the plant concerning operational costs because there are part in motion and part linked of the grid. It is proportional to the works that turbine done.

TABLE 15 OPERATIONAL AND MAINTENANCE COSTS - YEAR 2017 [46]

OPERATIONAL AND MAINTENANCE COSTS			
CHARGE *[Dkk/MWh]*	DISCHARGE *[Dkk/MWh]*	TURBINE *[Dkk/MWh]*	STORAGE *[Dkk/year]*
0.1	8.44	1.01	65

9. Energy market in Denmark

The second part of the thesis is to link the plant to the Danish grid in Denmark to verify if this plant in a certain year could be productive. When we say 'grid', we speak about electric and district heating Danish grid. The final aim, as we said, is to verify if this new type of technology could be feasible and advantageous from the economical point of view. It was imagined that the plant would be in Copenhagen inserted in the Danish electrical and district heating grid. We suppose to insert it into different lapses of time, the past and in the future. So two types of scenarios are created. With this analysis it is really interesting to see if the change of the final profit in relation to the electrical and district heating grid. That is why a tool is developed to simulate the storage behaviour taking as a input the electricity and district heating hourly prices during a whole year. We take two different year: 2017 and 2035.

As it is said, the activity of the storage is related and it is really influenced to the fluctuation of the prices:

- If the price is low it is convenient to charge
- If the price is high it is convenient to discharge

So it would be very interesting if we could know the whole yearly price trend at the beginning and using an algorithm to optimize the profit in order to reach the maximum revenues and to verify if this technology is feasible or not. It was performed a '*perfect prediction*': the perfect prediction is a way to understand if this power to power plant it will be a good idea for the future or not. Therefore, a lot of companies use this type of analysis to understand the potential of a new technology like this.

Usually it is not possible to know a priori the whole price of the one year at the beginning. Usually, for example the day ahead market you know the price only 24h before, and 12h more or less the intraday market prices so the perfect prediction is a way only to understand the goodness of a new technology, so in the best case.

There is another Danish market that it is not considered in the optimization algorithm, the Regulating power market. This market is a trade exchange power, so at each price [Dkk/MW] is associated a certain power [MW]. It has to be fully activated within 15 minutes and the power request could disappear in any

[46] (STATES DEPARTMENT OF ENERGY, 2016)

moment. The power generating plant that could participate at this market are that one that has a base power in the range power [10-50] [MW]. The demand request could disappear in any moment, so the plant has to be able to stop that power production. The motivation for what this market it is not considered are the following:

- We carry a perfect prediction on the power-to-power plant, so knowing the whole price the plant could give its answer in order to decide when to store heat when it is possible to charge or discharge. The lapse of time of 15 minutes is very small and if we consider this type of market the final result could be unrealistic.
- The second motivation is that this power production could be stopped in any moment of the discharge phase. We have not any data concerning the stopping time. This is another motivation for what if we use this market the result will be unrealistic.
- The last one is that they are considered turbines with power out of the range from 10 to 50 [MW], and developing the algorithm and running the program, the most promising turbine for this type of plant are out of the range.
- While for the consumption of energy the plant could be responsive in the order of magnitude of the minutes, the energy production, which involves the use ramp-up up of the HRSG and turbine, would require a longer planning ahead.

For all these motivations the electricity markets considered are the intraday and day-ahead market. [47]

Knowing that the prices fluctuation is advantageous it will be very important to choose two years (one for the past and one for the future scenario) in which there are a lot of prices scattering in a short time. The motivation is that the storage became more active and if the optimization algorithm is well done, there are the possibility to reach more revenues, so the final profit increase. That is why we choose the 2017 and the 2035.

Let us analyse these two years:

Year 2017: it was an year very active and scattered because there were a lot of energy due by wind. As we know, the renewables are an intermittent source, so in certain moments could be an overproduction of electric energy. An over production of renewables electric energy could create a decreasing of the prices of the electricity in a certain moment, creating a great fluctuation with respect to the previous period of time.

Year 2035: This is a scenario. In this prevision, it was supposed that there would be the penetration of renewables. The renewables are a type of intermittent energy sources. Considering the possibility to have about of 50% of renewables penetrations according to the Horizon 2020 energy plan, thanks to statistical calculations and previsions it is possible to build a future scenario.

[47] (Bang, Fock, & Togeby, 2012)

The final idea is to use these external data to see how the plant could behave and answers to the electricity prices. So for the first part of the work it important to know the electricity market like a first part of the external input.

9.1 Electricity market

The objective of the electrical market is to promote the competition concerning the operators, increase the transparency for energy exchange and to guarantee the security and availability of electrical system. In this type of market includes the energy and services ones.There are two types of market models, to centralize and liberalize ones. The first there is only one seller and a lot of producers that buy electricity from him. The seller could use the offers to determine the final price. The second one is made of many consumers and a lot of sellers and every sellers could choose its price independently from another, in a private way. In 1973 there was an oil crisis in Denmark without a regulation about energy sector. After this crisis, the government established a strategy to be independent concerning energy resources. Inn1976 there were a law in which the oil were absorber rapidly by NG and coke so there were a diminishing from 90% to 5% to 1983. The fact that they are independent considering the energy supplying, it has an exploit about the greenhouses emission and the increase the CO_2 in the air. Like in Norway and Sweden, in 1999 an act came in force about an Energy Supply concerning renewable sources. [48] Concerning energy, Denmark is independent thanks to the NG and oil reserves in the northern sea and the great development of renewables. Considering the year 2013 the general energy overview of the electricity consumption is as follows:

[48] http://users.unimi.it/eusers/wp-content/uploads/Electricity-Denmark_L.Bisaschi.pdf

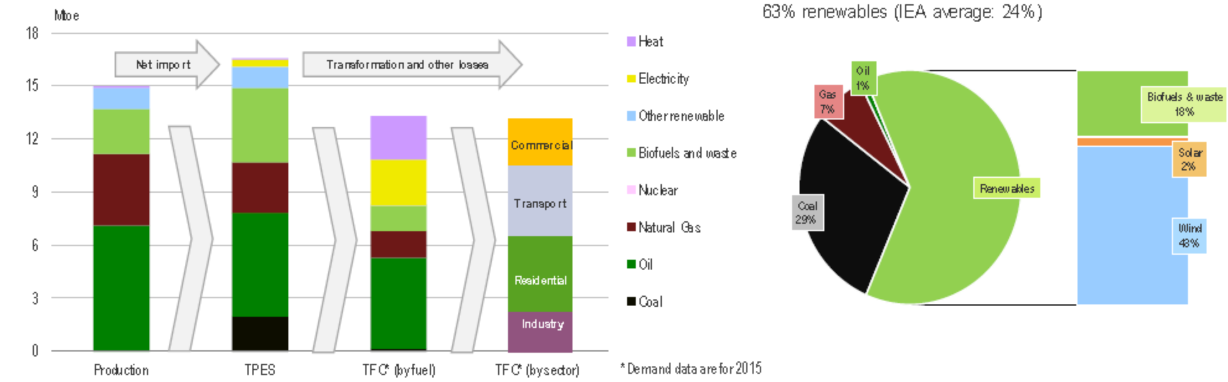
Energy system transformation

SUPPLY AND DEMAND 2016

TPES: 16.5 Mtoe, 32% renewables (IEA average 10%)

ELECTRICITY GENERATION: 30.1 TWh

63% renewables (IEA average: 24%)



Fuel shares compared to IEA average

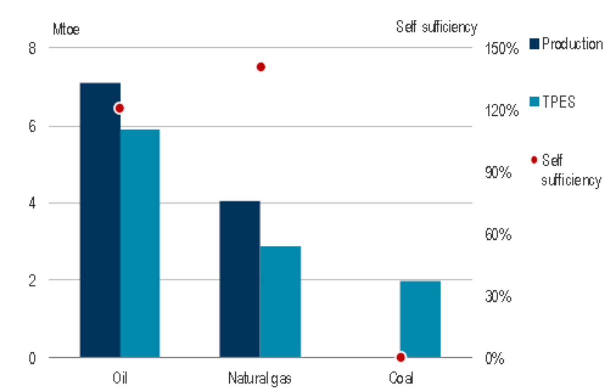
Fuel	TPES (%)	IEA average* (%)	IEA range (%)	Electricity (%)	IEA average (%)	IEA range (%)
Coal	12	17	0-69	29	28	0-84
Oil	36	36	7-58	1	2	0-10
Gas	17	27	2-40	7	27	1-51
Hydro	0	2	0-43	0	13	0-96
Nuclear	0	10	0-44	0	19	0-73
Biofuels	25	6	2-27	18	3	0-26
Wind	7	1	0-7	42	6	0-42
Geothermal	0	1	0-23	0	0	0-18
Solar	1	1	0-3	2	2	0-13

* IEA Average - total supply per fuel / TPES for 29 IEA countries

FIGURE 81 ENERGY MI DENMARK[49]

Energy Security

PRODUCTION AND SELF SUFFICIENCY, 2016



ENERGY IMPORT/EXPORT

FUEL	QUANTITY	IMPORT/EXPORT COUNTRY
Crude Oil		
Imports	3.8 Mt	Norway (69.4%)
Exports	4.3 Mt	Sweden (64.2%)
Oil Products		
Imports	9.3 Mt	Russian Federation (43.6%)
Exports	8.5 Mt	Sweden (30%)
Natural gas		
Imports	0.7 bcm	Norway (71.1%)
Exports	2.1 bcm	Sweden (43.4%)
Coal		
Imports	2.9 Mt	Russia (64.4%)
Exports	0 Mt	Germany (100%)
ELECTRICITY		
Imports	15.6 TWh	Norway (42%)
Exports	9.7 TWh	Germany (54.1%)

Note: 2016 data are estimated — Source: IEA World Energy Balances 2017

FIGURE 82 ENERGY PRODUCTION AND SELF-SUFFICIENCY IN DENMARK[50]

'Thanks to the combination of onshore and offshore wind turbines, wind power share in the electricity supply grew from 12 % in 2000 to 38.6 % in 2014'.

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49 www.iea.org/media/countries/denmark.pdf (u.s. energy information administration, 2017)

50 WWW.IEA.ORG/MEDIA/COUNTRIES/DENMARK.PDF (U.S. Energy Information Administration, 2017)

In 2012 the Danish parliament approved an agreement called 'Energy Agreement' whose the objective is to cover all electricity demand with renewable energy in 2050. [51]the first step is to have the following objectives in 2020:

- More then 35% from renewables
- Approximately 50% from wind
- 7,6 % in gross energy consumption in relation to 2020
- 34% of reduction in gas emission and greenhouse gases with respect to the year 1990

Of course the transition from renewables requires a certain expend of money and a certain capital cost and a consequently electricity prices increasing.

There are two companies that provide for Denmark the 70% with respect to the total capacity: DONG and Vattenfall, the remaining 30% are provided from other local companies.

DONG shares to Denmark the 49% of the total energy that Denmark needs since 2000.

In Denmark, there are two different electrical transmissions: DK1, that is the eastern power system which is synchronised with the Nordic power system and the DK2, in which the power systems is synchronised with the continental Europe. Both the DK1 and either the DK2 is managing from Energinet an independent public enterprise owned by the Danish state under the Ministry of Climate and Energy.

Considering the distribution of energy, Denmark, like in Scandinavian states, is integrated in the Nord Pool Spot, which is the largest electricity market in Europe. The end user, thanks to the liberalisation in Europe about the electricity market it is possible to choose among several suppliers but considering the local area in which people are, every only one distributor it is responsible to the transmission of energy.

The role of energinet.dk is to manage and supervising all market activities. Actually, there are 33 electricity suppliers company.

The DERA is the regulatory authority of Denmark and annually publishes the National Report, which is an account of the development of the markets in Denmark. It declares that the electricity prices, useful for the simulation that it is performed in this thesis, taken by NordPool are influenced by:

- Costumer demand;
- Fuels prices;
- Energetic crisis;
- Precipitation in Nordic countries;
- How many energy comes from renewables.

In this period, from the oil 2006. The prices increase has improved the electricity sector considering the managing and the energy efficiencies. In fact, after the reform there were an increase of the electricity prices with a consequently reduction of electricity consumption. Therefore, the reform save money and

[51] ("Scenari Energetici al 2040 –," 2017)

energy and there were a reduction of greenhouse gases and at the same time becoming a more efficient service.
In fact in 1999, the Energy Suppling Act promoted an environmental and awarding use of energy with the objective was to use only renewables in 2050. The final hope is to use energy consciously in order to respect the environment but to preserve the society development.
Electricity market is controlled by Nordpool, as we said before, there are two types of Danish market that we are considered in the Matlab tool.
The electricity prices change hour by hour and they depend on the energy that you want to buy, so the unit of measurement is [Dkk/MWh]. This two parallel market energies is sold in two different ways. Electricity prices in the NordPool area are calculated every single hour for different price areas depending on bottle necks and available transmission capacities between these areas. Denmark, for instance, is made up of two price areas (DK1/West and DK2/East). The NordPool general price, is an average system price for all the price areas in NordPool (Scandinavia). In hours with no bottleneck problems between price areas, the system price and the price for each price area should be the same. [52]
The analysis that it is performed is located in Copenhagen, in the East side of Denmark, so the data useful to perform this work is taken from DK2.
The objective of the electrical market is to promote the competition about the operators, increase the transparency for energy exchange and to guarantee the security and availability of electrical system. In this type of market includes the energy and services ones.

For example, plants having either an electrical heat pump or an electric boiler has to send bids to NordPool (before 12 noon) for the coming day with amounts and prices for electricity they want to buy for each hour. Besides the electricity price, heat pumps an electric boiler also have to pay taxes and transmission costs.

One of the input data to insert in the optimization profit algorithm is the electricity price. Before to do this it is fundamental to know the Danish market and its rules. One the entity that has the fundamental role to regulate the electricity market in Denmark and has the aim to harmonize and integrate all markets in Europe is the European commission. L'UE has the role to harmonize the electricity price of the day-ahead. The main characteristics of the model is to harmonizer the electricity market and to allow the continuous international trading of electricity energy.in this way it is possible to balance the TSO (transmission system operator) and the transmission rules to have the access to the capacity on the interconnectors.
It has carried a diligent work to the Price Coupling of Regions furniture (PCR) and the northwest western price (NWE) in the February 2014. From that moments a lot of regions has submit to this market.

[52] http://nordpoolspot.com/How-does-it-work/Day-ahead-market-Elspot-/

The multiregional coupling covers now 19 states, so it covers the 85% with respect to European energetic consumption. NordPool is completely involved in the intraday transboundary market (XBID) project, the other parallel market that it is inserted in the simulation to understand how this plant is feasible. Price coupling regions (PCR) is a project of European power exchange for the development of a unique solution negotiating prices to use electricity prices across Europe while respecting the capacity of the relevant network elements on a daily basis.

The aim of that is to harmonize the European electricity market. The motivation for wat it is important to increase efficiency, liquidity, and social well-being.

The common algorithm provides a fair and transparent determination of the electricity prices of the day before and a net position of a supply area across Europe. The algorithm is built using the specific rules of the various energy markets in Europe and the constraints of the electricity grid.

PCR is a process based on not centralized data sharing that provides a robust operation. This project started in 2009 and final it started with a cooperation agreement in co-ownership in June 2012.

PCR matcher and broker service has the aim to exchange, in complete anonymity, power orders between power plants in order to calculate the energy prices in competition zones and other reference prices in all areas. One of the aim of this PCR project is to develop an algorithm to have a unique price coupling. The name adopted is EUPHEMIA (acronym for integration of the pan-European hybrid electricity market). This algorithm is created in order to calculate the energy allocation and the electricity prices across all Europe. There are two important aims related to that. The first is to harmonize the prices and then to increase the wellbeing and transparency concerning the energy and money fluxes.

The energy market stabilized in Denmark has an advanced business model where it is involved are: system operators, producers, distributors, traders, intermediaries, clearing companies, financial analysts, etc.

This project has seven power exchangers: EPEX SPOT, GME, Nord Pool, OMIE, OPCOM, OTE and TGE. The following countries participated to this project: Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.

Electricity system is composed by the following part:

1. TSO TRANSMISSION SYSTEM OPERATOR: One system operators has the responsibility to security to wire transmission.

   The producers: there are 370 companies responsible to the production of energy in nordic states.

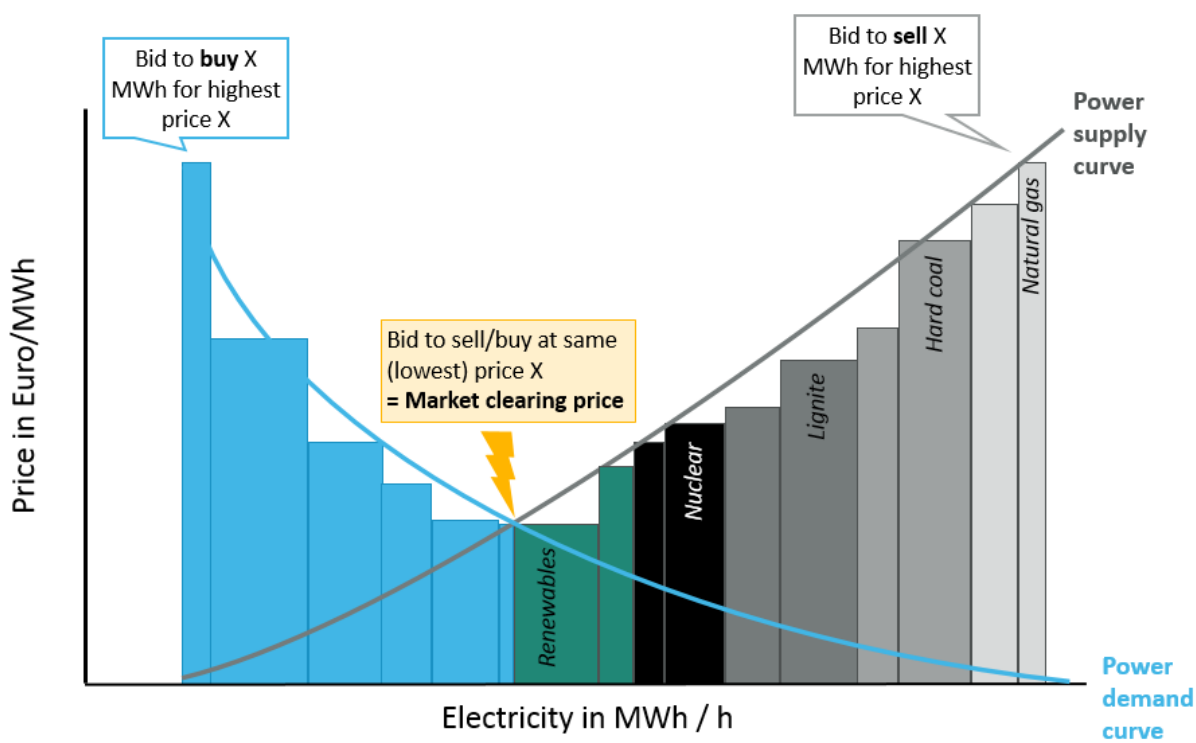
   In one year, here the hydroelectric represents the half of the electrical demand in Nordic zone. In Norway, almost the total power is generates from hydroelectric, Sweden and Finland have a mix among nuclear and thermic (vapour) plant and hydroelectric. In Denmark, it is used mostly thermic energy but in this few years, wind energy has a fundamental role. The production costs could vary. Hydro is the main economic energy source. A low level of hydroelectric fields mean that the producers use not cheaper sources and consequently higher costs of production.

2. DISTRIBUTORS: There are 500 distribution companies in Nordic states. A supplier has to guarantee that the power could arrive to the final users. The power is transmitted from the power plant to the final electric wire.
3. SUPPLIERS: There are 380 companies more or less supply electric energy to final users.There is a great competition among energy suppliers in each nation. Each final users choose their favourite suppliers a makes a choice throw different contracts. Different typology of conctracts could be: fixed price, market price contract ect. Actually final users could choose a supplier from another country.
4. TRADERS/BROKERS: A trader represents the importance that has power during the negotiation process. For example, the merchant can buy energy, but the merchant can choose between a retailer and another retailer. There are many paths from the final producer. Brokers play their role in the real estate market. A broker does not possess the power, but acts instead as an intermediary. For example, a reseller can ask an information broker at a given time.
5. END USERS: An end user of power is a private company or family. The user pays the energy consumed by the supplier, pays the energy transmission to the distributor and pays the taxes. An end user can choose from a wide range of suppliers. Each geographical area is a distributor responsible for the transmission of the network.

9.1.1 Day ahead market

The first electricity market that it is considered in the simulation is the day ahead market. These prices are hourly prices in [Dkk/MWh]. They are the intersection, so the equilibrium point between two curves. The demand and supply ones. The day-ahead market has unique session and it is possible to know the electricity only the day before. This type of market belongs to the Nordic market model. The main part of the electricity exchange takes place in the Nordic power exchange, Nord Pool spot market, the TSO owner in Denmark. The procedure to know the prices is always the same and it happens everything in the same hours every day.
TSO communicates how many capacities the market needs for the day ahead before 10.00;
Before the 12.00 the electricity suppliers and consumers make some proposals about prices

The price for the day ahead are generally announced at 12:42 or a bitter later.Before the 13.00 they are built two cumulative curves: the suppliers and consumers cumulatives. It is take into account the restriction power system to suppliers and producers about the amount of money exchanged for the next 24h.The day ahead market is supervised by Nordpool is an exchange of energy based on auctions to sell electricity at a particular price. Considering the day ahead market, considering the sellers and consumers it is possible to define a demand and an offer : Pd=D(n) and Po=D(n), where 'n' is the price per MWh. Every day consumers publish the price[Dkk/MWh] and the amount of energy that they need [MWh/h],every hour in every day.In auctions of the electricity market, the determination of equilibrium is obtained through researchof the maximum overall well-being, on the basis of known information (offers). The optimization problem is set with the assumptions of not to have losses in the network and no energy transmission constraints in order to find the price for the day after. The market price that is found (it is the Lagrange multiplication) is the variation of benefits with respect to an energy products variation. Therefore, in general the price chosen is the price that producers and offers should pay, that is the equilibrium price[53]. The equilibrium price is the intersection point between the consumers and supply demand.



53 https://www.cleanenergywire.org/sites/default/files/styles/lightbox_image/public/images/factsheet/figure-1-market-clearing-price-diagram.png?itok=5goLAD6C

FIGURE 83 DAY AHEAD MARKET ELECTRICITY PRICES.[54]

In this case, the non-discriminatory rule applies called "uniform price". Therefore, the price corresponds for all to the marginal cost of the system, that is to say the price requested by the least economic plant among those called to produce. This is the price that we have the day ahead. So for this type of market the main objective is to establish an equilibrium point between the supplier and demander curves. This is very important because it is impossible, right now to store electricity, if it is produced, so it is necessary to know, more or less how many energy could be produce in order to not to lose a part of that. There is a final balancing market, the power market, that adjusting the real time the market behaviour. Nord Pool publish the prices in order to balance out the energy consume.

In a competitive market, like Nord Pool, the price is always the lowest at possible for every hour of the day.

This is called like marginal price formation. These prices have this name because it gives the false impression that the cause of this price formation would be very different with respect to the other market. The difference of this market among the others is that this market is more safe and more trustable because the energy produced has to be done in the moment that the consumer wants. It exists an enormous difference between the electricity and the other energies because the costs of installation (i.e. wind and hydropower with respect to CHP plant or gas turbine etc. ...) changes a lot.

In order to give energy even to fluctuating consumers demand at a lower cost it exists a lot of generation energy techniques.

- Hydro, nuclear, coal (high intensity of use);
- CHP (heating and electricity market only in some periods of the year);
- Gas turbine (they are used for short periods and at high prices).

Sometimes, if the energy supply is higher than the energy demand for example, and it is very common in Denmark, if the energy available is a lot due to renewables, the electricity price will became goes down to permit to people to buy it. The motivation for what the price goes down is because the market forced to people to buy it otherwise that type of energy could be lost.

[54] https://www.iea.org/media/countries/Denmark.pdf

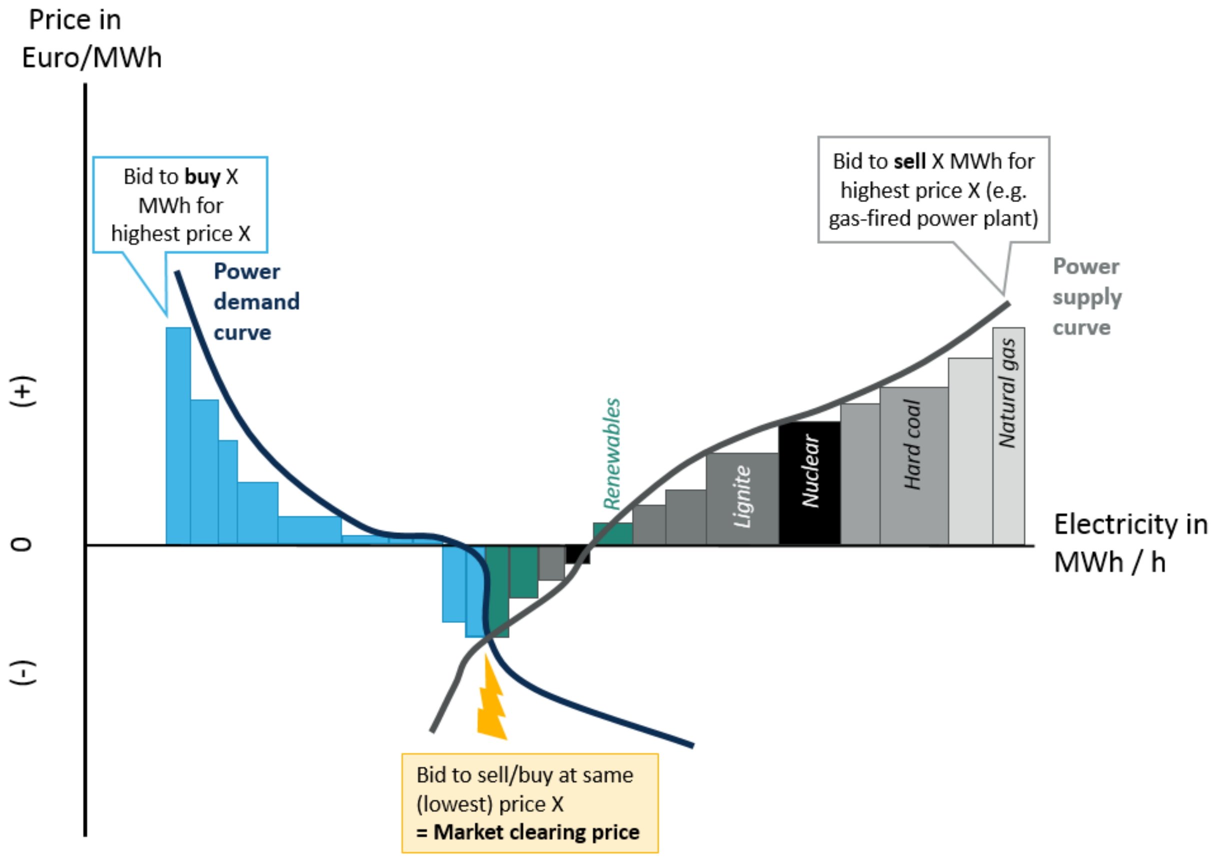


FIGURE 84 DAY AHEAD MARKET ELECTRICITY PRICES - NEGATIVE PRICE.[55]
As the figure shows the price could be negative if the demand is very low.

9.1.2 Intraday market

Another market that it is taken into account in this work is the 'intraday' electricity market. It works in Nordic, UK, Baltic and German thanks to Transmission system operator NordPool. This is a parallel market that joins with the day-ahead Danish market. It has the aim of to supply electric power every day in the northern Europe.
The day-ahead market is safe but the day ahead it could happens various thing like: the nuclear power plant or a gas turbine could suddenly stop its work; a strong wind may reject an high electricity power into the grid. As we know, the main volume of energy is sold thanks to the day-ahead market ensuring the great part of supplying demand there. By the way, some inconvenient, exception or a sudden energy demand could be happened and could be necessary for various motivations the day ahead.
So another parallel market it could be necessary to ensure energy every day, in every moment to the population. As we said before, the problem is that if an amount of energy is necessary the markets should be able to sell that amount of electricity power. So, to ensure that, consumers and suppliers could exchange

[55] https://www.iea.org/media/countries/Denmark.pdf

energy volumes in real time. At 14.00 the capacity available for the daily trading on NordPool is published. This is a continuous market and the market is for that specific amount of energy is closed only one hour before the delivery. So it is a connous market available 24h.
The prices are stabilised thanks to the fist-come principle, first-served in which the best prices comes from before. Therefore, the higher price and the lowest sold price.
The intraday market becomes important when the wind power comes in the grid. Wind power carries with him a great amount of energy but this amount of energy is unpredictable. So like a lot of renewable energy sources they are intermittent and they are included in the day-ahead market. That is why it is very important to have another market to supply energy to consumers. This market plays a key role in Europe to make the electricity market more safe and it grows year by year thanks to the renewables sources. Every

9.1.3 Taxation

Considering taxation, there are a percentage on the overall price that the consumers have to pay to have a certain amount of energy. For example in Denmark, the taxation is a large percentage of the electricity price as the following table shows. Øre corresponds to Danish crown cents. As it is possible to see, in Denmark there are the largest amount of taxation percentage. All this prices vary year by year except the value of the PSO tariffs, it is a trimestral value, and therefore in one year it is possible to have four vales of it. PSO and Distribution tariffs changes area by area. For example DK1 prices are different from DK2 tariffs, and it is depends on the offer and demand in that zone. [56]

TARIFF	[øre/kWh]
PSO	[1.3, 1, 1,0. 9]
Transmission	4.3
System	3.9
Distribution	15

FIGURE 85 TARIFFS

In the algorithm implemented the taxes is inserted. When you buy or sell electricity it is mandatory to buy an amount of money to give or to receive money. Normally the tariffs to buy electricity is based on all consumption, while, when you sell electricity the tariffs is based on the net selling energy. The tariffs are different from consumers and for sellers. The calculation for the taxes are different if we speak about seller of producers of electric energy. Usually tariffs

[56] http://energinet.dk/DA/El/Engrosmarked/Tariffer-og-priser/Sider/Aktuelle-tariffer-og-gebyrer.aspx

are calculated on the total energy consumption while production energy tariffs are calculated considering the net energy.

For net payed producer there are some special rules considering regulation. Client would pay:[57]

PSO tariff-transmission tariffs-system tariffs (considering the consumption for their consumption). Producers and owners that have an installed capacity major than a certain limit, the PSO tariff will be lower. This reduced tariff cost is equivalent to the renewables sources cost.

Consumers: taxes for consumers are:

1. TRANSMISSION WIRE TARIFF: it covers the consumption for the maintenance of electrical grid. (wire 132/150 e 400 kV)it is a constant cost and it changes year by year.
2. SYSTEM TARIFF: it covers the security, capability to store electricity and operation. It is a constant cost and it changes year by year.
3. PSO TARIFF: it is a trimestral constant cost. It covers the cost of renewable energies and administration financial costs
4. VAT TARIFF: this is a cost related to the resources purchasing, that is why it is not involved if the energy it has to produced.

Producer: taxes for producers are:

1. TRANSMISSION WIRE TARIFF: it covers the consumption for the maintenance of electrical grid. (wire 132/150 e 400 kV)it is a constant cost and it changes year by year.
2. SYSTEM TARIFF: it covers the security, capability to store electricity and operation. It is a constant cost and it changes year by year.
3. PSO TARIFF: it is a trimestral constant cost. It covers the cost of renewable energies and administration financial costs

9.2 District heating market

District heating will also play an important role in energy market system with a large share of renewable energy. Today the thermal production of combined heat and power ensures high energy efficiency, for example fuel cells, CHP systems etc. In the production while minimising primary energy consumption. In a future energy scenario, systems with less thermal production and a larger share of renewable energy from fluctuating sources such as wind power, the heating sector is increasingly expected to deliver balance and energy storage services. That is why it is important to consider it to make some evaluation now and for the future scenario. District heating market is a growing market that, year by year will increase its importance in energy purchasing.

In Denmark, this type of market sees an enormous increasing in this years.

[57] https://energinet.dk/El/Tariffer

There, it is anticipated that the district heating's share of total heat consumption will continue to increase The heat production will be based on renewable energy sources in the future, thanks to new storage technologies like rock beds for example. This creates a number of challenges which need to be addressed in the existing heat planning.58

District heating Danish market is in cooperation between the electricity market. In the last century there were an important development in district heating sector.

In 1903 in Denmark was erected the first CHP power plant whose the fuel was waste, it was an incineration plant, which made it possible to handle waste in a more sustainable way. It provided electricity and heat (steam) to a new hospital. In this way, that plant save two types of energies at once.

In 1920's and 1930's, district heating systems was developed based on waste heat from local electricity production. Danish district heating also gave energy to urban areas with heat and accounted for around 4 pct. of the heat supply.

After the oil crisis in 1970 district heating from combined heat and power expanded rapidly in order to save energy. In 1973 and 1974, energy consumption per capita increase to a very high level, so, it the heat and electric demand increased. The main issue in that years was to reduce Denmark's dependency on imported fuels and consumers' expenses for heating considering that the oil crisis there were a need to save energy. As a consequence, Denmark decided to expand the efficiency on energy conversion process combining heat and power system from large cities to medium and small-sized cities. In that years, around 30% of all apartment in Denmark were heated by district heating systems.

In the following years, there was a great expansion of district heating in Denmark up to 2014, in fact in 2014 the production of district heating in Denmark was equal to 121,5 PJ with almost 50%. coming from renewable energy resources.

In this year the district heating technology in Denmark is very important and it will have a great increase in the future because it is a very interesting type of market. From January 7 2008 Varmelast, elaborated a body for the district heating concerning production and distribution e a plan in Greater Copenhagen. In 27 April 2009 it performed a distribution plan in Greater Copenhagen, an area in which Copenhagen is located and our plant too and in other zones. 59 In 2000, before the electricity market liberalization, electricity market was responsable of any decisions of heating market in a plant, the owner could decide how to divide the energy produced into electricity and heating independently if that market is an electricity or district heating one. Considering the fight between Avedøre CHP Plant, HC Ørsted Power Plant e Svanemølle Power Plant, e HOFOR, the owner of Amager Power Plant, producers could't

[58] http://www.ea-energianalyse.dk/themes/district_heating.html

[59] http://varmelast.dk/en/background/background

produce a total optimal distribution concerning elelctricity and heating because the costs related to that it was very heavy in Copenaghen area.
Before the Varmelast company, a report say that a society could guarantee a good offer of heating and to manage in a eco-compatible and I na cheaper way for the future. These analysis, done in 2005 and in 2006 in collaboration with EA Energianalyse A/S affirms that it was not possible to have a district heating market liberalized like in electricity one because they were not enough producers to have a competitive market.
Consumers in Copenhagen could lose a great amount of knowns if the district heating distribution do not would optimized considering the total heating demand in that zone.
If in Denmark would have financially convenient if there are a few big energy producers and a lot of distributors
Therefore, it was stabilized that the district heating company have to guarantee that the daily heating production of CHP and DHPs would be priority w.r.t. an overall optimization where the hourly power is the main input. Heating and energy society have agreed that a society, like Varmelast could carry a heating demand distribution to optimize the distribution and to reduce the energy losses. [60]

One of the most important element of DH networks in Denmark is short-term heat storage. This means that the CHP plants have to optimise their cogeneration processes according to the electricity demand without compromising the heat supply. Both large and smaller DH systems use short term heat storages. Heat storages allows CHP plants to decrease their production when there is full of electricity in the system, for example when it is very windy and they can increase their production when there is a higher electricity demand. When the heat production is higher than the excess heat demand, the heating is simply stored. Denmark has one of the main shares of DH (63%) along with Latvia (65%). Finland, Lithuania, Poland and Sweden also have more than a 50% share of DH. The fuels for heat production to heat only boilers in plants are both fossil fuels and non-fossil fuels (biomass, waste and solar).The heating prices are not the same in all Danish DH areas, but to determine the heating price, it is set by law. The legislation states that the heating price paid by the consumer in principle should cover every costs related to supply heating. The most important thing is that an heating supply company is not permitted to make a profit. Heating cost therefore includes: Fuel costs; Heating production facility; DH network; Buildings; Operation and maintenance (O&M)
The plants that produce heating for DH can't charge more for the heating than the costs of producing and transporting heating to the consumers. It is important to underline that these costs also include depreciation of assets and financing

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[60] https://ens.dk/sites/ens.dk/files/Globalcooperation/regulation_and_planning_of_district_heating_in_denmark.pdf

costs, so that the heating companies can be financially sustainable both in the short and long term. The heating cost, concerning the consumer is therefore affected by the following parameters:

- Production facility investment
- DH network investment
- Production facility O&M
- DH network O&M
- Fuel prices
- Efficiency of the production facility
- Heat loss in the DH network
- Taxes and VAT
- Financial support/grants
- Electricity price (relevant for DH production facilities that either use or produce electricity)

The aim of Danish energy policy changed over time and DH systems demonstrated the flexibility to develop and to support the different policy aim. Looking ahead, DH will continue to be an important market and it has a long term ambitious, considering the EU 2020, up to the year 2050. Energy policy goals DH in Denmark expects to play an important role in reaching the following aims:

- ✓ The 2020 expects to have a 20% reduction in CO2 emissions compared to 1990 levels, an increasing in the share of renewables to 20% of the energy (Denmark's share is 30%), and a 20% increasing in energy efficiency
- ✓ In 2020, wind turbines in Denmark will cover 50 % of the domestic electricity supply
- ✓ By 2030 50% of the gross energy consumption will be covered with energy that come from renewables.
- ✓ In the longer term, i.e. 2050, the energy system in Denmark is to be independent of fossil fuels

The policy goals listed before increases among others the challenges of balancing wind power in the power system. Wind power is an intermittent and wind power production cannot be matched with demand. Sometimes wind power only covers the low part of the electricity demand and sometimes it covers a very large part or it could even exceeds the electricity demand. The flexibility of district heating systems can help to balance these fluctuations in the power system and, at the same time, to support the integration of wind power. According to the longterm 2050 goals, a large share of the electricity and heat generation will have to come from renewable energy. In that respect, DH has a real big advantage because it is flexible with with respect to other technologies. In the same time t could improve the other systems and other new technology (for example the storage P2P plant that we are talking about in the present thesis) and DH/CHP systems integrated in wind power generation, especially in Denmark like:

I. Heat storages
II. Electric boilers and heat pumps

III. Bypass of turbines By use of heat storage, which is already common in Denmark, DH plants can decrease their CHP production when there is sufficient electricity from wind turbines in the system and still be able to supply heating from the thermal storage.

By using electric boilers and heat pumps, DH plants can use excess electricity from wind turbines directly for heat production. By bypass of turbines, a CHP plant can avoid generating electricity when there is excess in the system. The flexibility of the DH/CHP system is therefore an important aspect with regard to integrating a large share of wind power into the energy system. Low-temperature DH-systems. In many Danish DH networks, the flow temperature is around 100-120 [°C], and the return temperature is around 40-45 [°C] In the future probably the low temperature could be lower. Lower temperatures have a number of advantages:

- Lower temperature reduces heat losses into the pipeline network.
- A low temperature of return increases the efficiency of the thermal based heat production facility, especially if it is used the flue gas condensation.
- A low flow temperature increases the efficiency of heat pumps in a DH system and increases the possibilities of using different sources of low temperature heating for DH production.

Nowadays in Denmark, the 63% of private house are connected to the district heating. District heating means space and domestic hot water. The whole Denmark has six large areas with the total heat equal to *67 (PJ) in 2014, 56 % of the national DH supply. There are also 400 small and medium district heating zones with an annual heat supply of approximately 53 PJ.*[61]

Another aim is to increase the wind power market which will decrease the thermal power generation (and consequently also the heating production) at CHP plants. When the number of annual full load hours at the CHP plants decreases, the specific costs of producing DH at these plants could increase. The analysis concluded that DH is still very relevant in Denmark and that there may be potential for even more DH.

9.2.1 Greater Copenhagen zone

In the Greater Copenhagen area there are three different heat distributors:

1. HOFOR
2. VEKS
3. CTR

There are two different heat producers:

1. DONG ENERGY
2. HOFOR kvaftvarme (before Vatternfall)

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61 https://ens.dk/sites/ens.dk/files/Globalcooperation/regulation_and_planning_of_district_heating_in_denmark.pdf

The district heating network includes two networks:

- TRANSMISSION NETWORK: the annual loss is 1%, the pressure is relatively high (25 bar). Travel long distances. Generally, energy transport occurs through either water or steam. In our case, so in Greater Copenhagen zone, the transport is only through liquid, with a temperature that goes from 100 to 120 [°C].

- DISTRIBUTION NETWORK: this network is connected to the transmission network through heat exchangers. This has a return temperature (output temperature to be supplied to buildings) equal to 60 [°C]. The losses compared to the transmission grid are greater and amount to about 20%. The input temperature is flexible and varies from 90 to 60 [°C] and varies depending on the location of the distribution network compared to the buildings to which heat is supplied, to the Testerna. If the heat demand is higher, the temperature inside the circuit varies. The required pressure in the circuit in question is equal to 6 [bar].

The person in charge of sending heat to Copenhagen is'Varmelast.dk'. EA (Energy Agency) carried a project focusing on the interaction between district heating and the electricity market under various constraints conditions. In particular, these work have focused on how district heating can contribute to achieving goals related to energy savings, CO_2 reductions, and renewable energy in the future energy system. We have assisted various heating companies in finding methods to reduce CO_2 emissions, for example thanks to the use of biomass and heat pumps.

EA Energy Analyses has been undertaking an analysis of the possible regulation models for the district heating sector that has examined advantages and disadvantages of the various regulation forms in relation to the challenges that the district heating sector is facing today. Ea Energy Analyses is also taking part in the development of a new RD&D strategy for the district heating sector.

Since 2007, the energy analyses developed a tool to control and to dispatch heat energy in the greater Copenhagen area. EA's toll (Varmelast.dk) takes into account the heat load unit for every day for energy production taking in consideration account the local distribution.62

[62] https://ens.dk/en/our-responsibilities/global-cooperation/experiences-district-heating

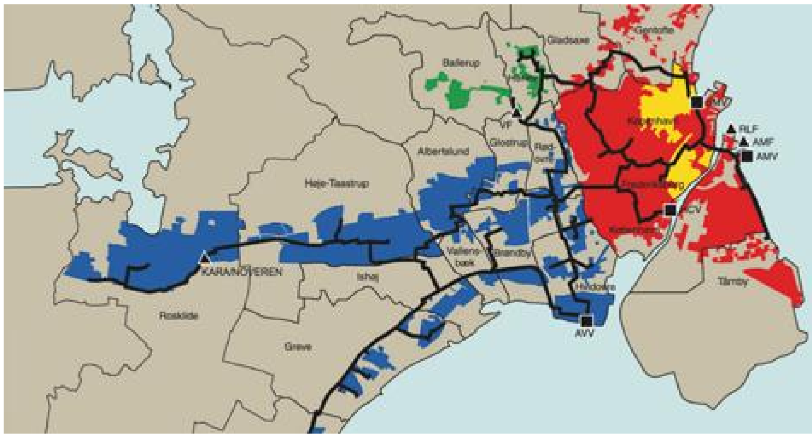


FIGURE 86: THE GREATER COPENHAGEN DH SYSTEM (REFERENCE - REGULATION AND PLANNING DISTRICT HEATING IN DENMARK)

PROCESSING OF THE INVENTION OF HEAT: Varmelast.dk is a company composed of three employees, each of which belongs to the 3 distribution companies: VEKS, HOFOR, CTR. The purpose of this company is to obtain the optimal dispatching between the two Danish suppliers DONG HOFOR. All this determines the monthly price to be paid for the DH. Fixed-cost contracts are fixed and costs vary depending on the quantity: investment cost (fixed) and heat supplied (variable).

SENDING OF DAILY HEAT:

1. At 7:45 am Varmelast.dk sends the heat request the next day

2. DONG and HOFOR say which supply points are available (max 5 for HOFOR and 20 for DONG)

3. Varmelast.dk assuming a linear supply and demand relationship, an offer demand curve is thus constructed

4. Suppliers make a plan on how much heat energy they have to produce

5. Varmelast.dk receives the plan and for the next day you have that energy

6. Variations are allowed no later than 9:30 the day before.

9.3 Data analysis 2017

9.3.1 Data analysis

Considering the data, it was possible to make simulation thanks to the input electricity prices data. It is decided to take the hourly electricity prices of two specific year, one for the future and one for the past.

Concerning past, it was carried a simulation about the 2017. Concerning the plant that it is studying the optimal electricity data useful to have a good profit is to have a high fluctuation of the electricity prices. In this way we could charge the HT-TES storage when the electricity prices are low and immediately discharge the energy stored into a turbine or in a district heating using rapidly this energy without loose it in the storage phase. In Denmark, the data available are in Nordpool.dk website. There it is possible to find the hourly electricity prices for the intraday and for the day-ahead market. In Nordpool.dk site the data are available only for 5 years before the current year; i.e. 2018, so it is decided to choose the best year knowing that the choice are among the years from 2014 to 2017.

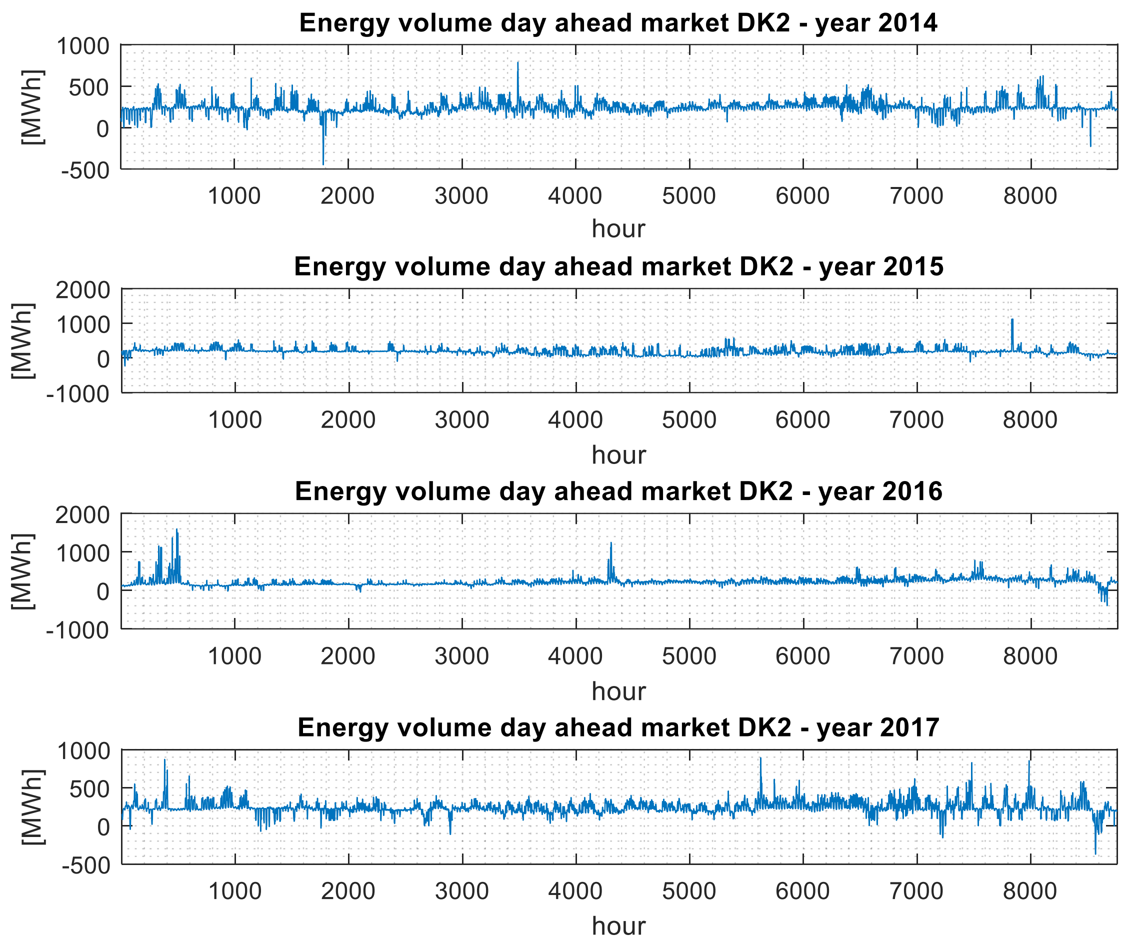


FIGURE 87 ELECTRICITY PRICES DAY AHEAD MARKET DK2[63]

Here it was reported some data concerning the day ahead market. As the figures shows, the year where we have a lot of electricity prices fluctuations is the 2017, so it is a good idea to choose it. The idea, as we said, is to carry a perfect prediction analysis.

The perfect prediction is an analysis that often is carried by companies to know if a new technology or a new process is feasible and advantageous or not the perfect prediction is a good opportunity to know that. As we said before, it is possible to know the day ahead market prices one day before and some hour before the intraday market prices. In the perfect prediction procedure, the solver program that it is developed knows the whole electricity prices during one

[63] https://business.nasdaq.com/trade/commodities/index.html

year in order to find the maximum profit. So the procedure that it is used is the same of the companies to know the feasibility of the HT-TES technology inserted in a power to power plant connected into Danish electric and thermal grid.

There is a reason why the year 2017 is the best year for this type of simulations:

Concerning the day ahead market prices come from the intersection point between demand and offer cumulative. Knowing the demand, there is a certain amount of energy that we have to produce to satisfy the demand for the ahead. Electric energy is produced by conventional plant like:

Conventional plants: steam turbine, nuclear plant, CHP plant: the heat at high pressure is discharged into a turbine that produced a water expansion in order to produced energy throw the alternators. The turbine is a slow fluid dynamic machine: to stop it it is necessary to wait almost ten hours and to switch on it is necessary to wait 12 hours, losing the energy when it is switched off and it is switched on. Therefore, it is a good option to have this machine always on without an intermittent behaviour. There it would be unuseful. So usually we use it for a base electricity supply knowing that this energy is always available and it is usually always on.

Gas turbines: they gives to electrical grid a high amount of energy. They are used usually when we have a peak of electrical energy request. Therefore, this energy quantity is used to peak demand hours.

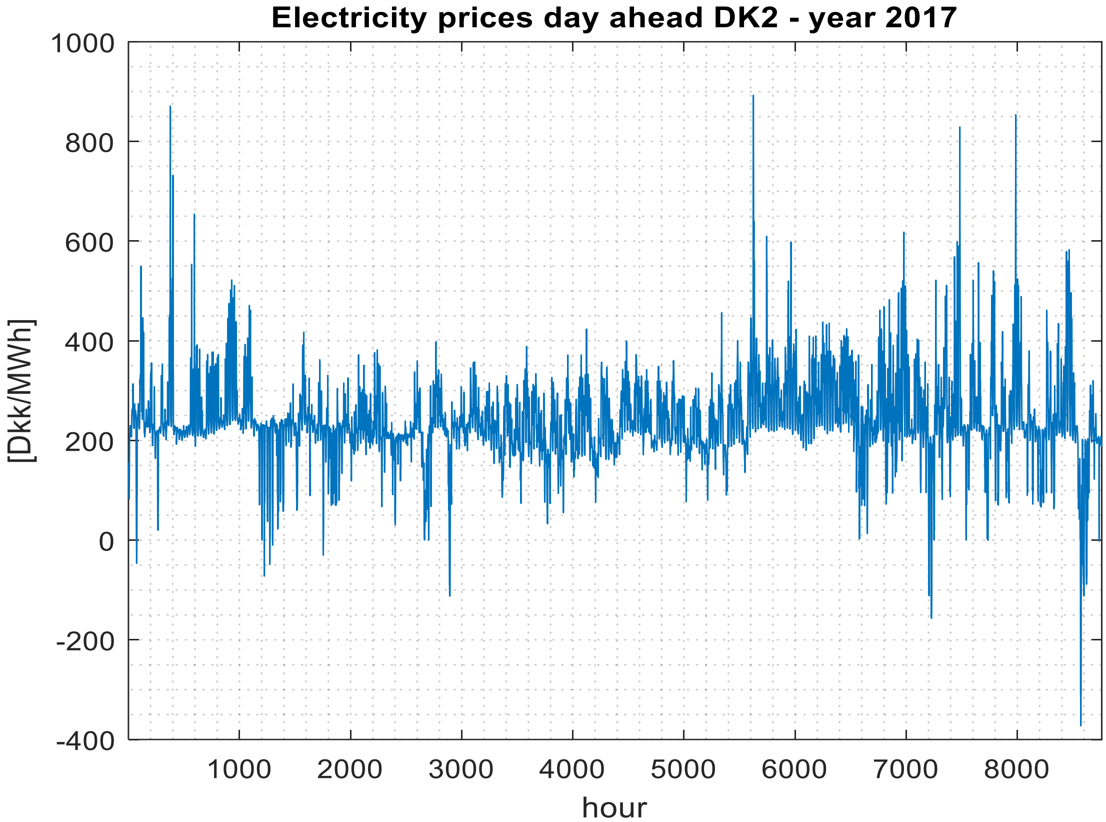
Renewables: the renewable energy are unpredictable: they depend on the sun, on the wheatear, on the wind etc. Without to know when it is produced, we could have a heat amount of energy, if the wind for example went an high velocity or if it was a sunny day etc. at the contrary, we need more energy if the renewables produced a low amount of energy. So this energy is used for energy peaks but it is not trustable.

Concerning the year 2017, there were a lot of amount of energy comes from renewables and, in this case, there were more energy with respect to the demand. Therefore, to force to buy electric energy to consumers the prices went down. As it is shows in a figure, there are a lot of negative electricity price value.

In the 2017, as well there were a lot of period in which there is not energy produced by renewables. So the energy is only sufficient for the electricity demand, so the prices are very high.

Therefore, as we can show in the figure, there were a lot of fluctuations of electricity during this year.

FIGURE 88



As it is said, event the intraday market is considered. It is easy to understand that these two market, so their prices work in parallel. The motivation is that if the day ahead price is high, company prefers to not buy the electric energy on that market. So, the intraday market could use this high prices to propose a better offer, to sell energy at a more convenient price. This type of competition is useful for the markets and for users too. For the same motivation, even the Intraday market had a lot of fluctuation values.

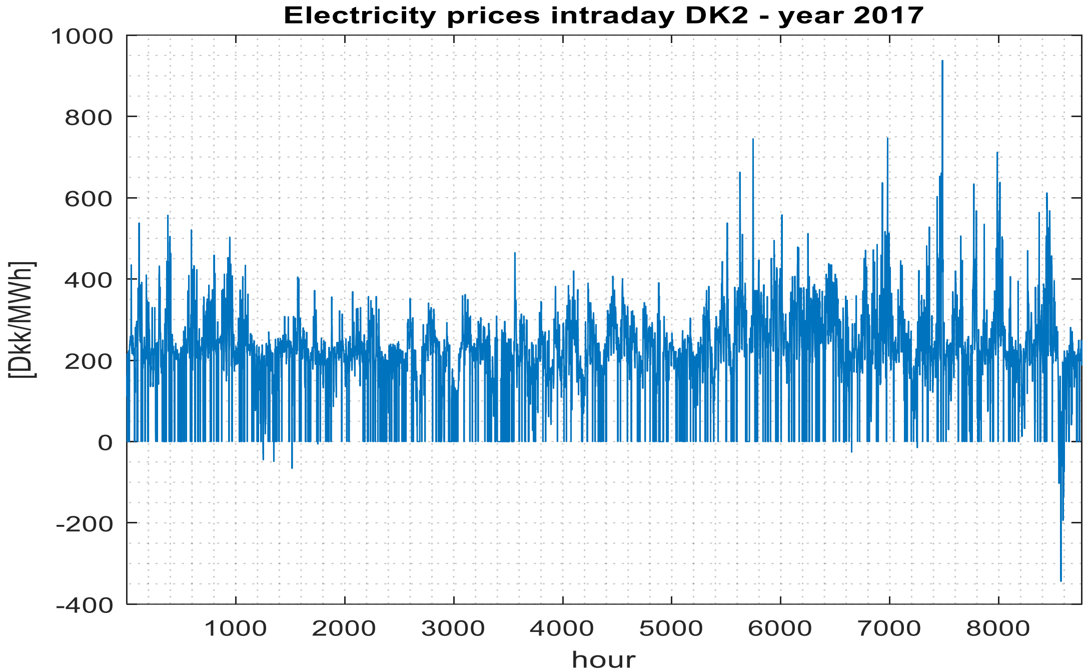


FIGURE 89

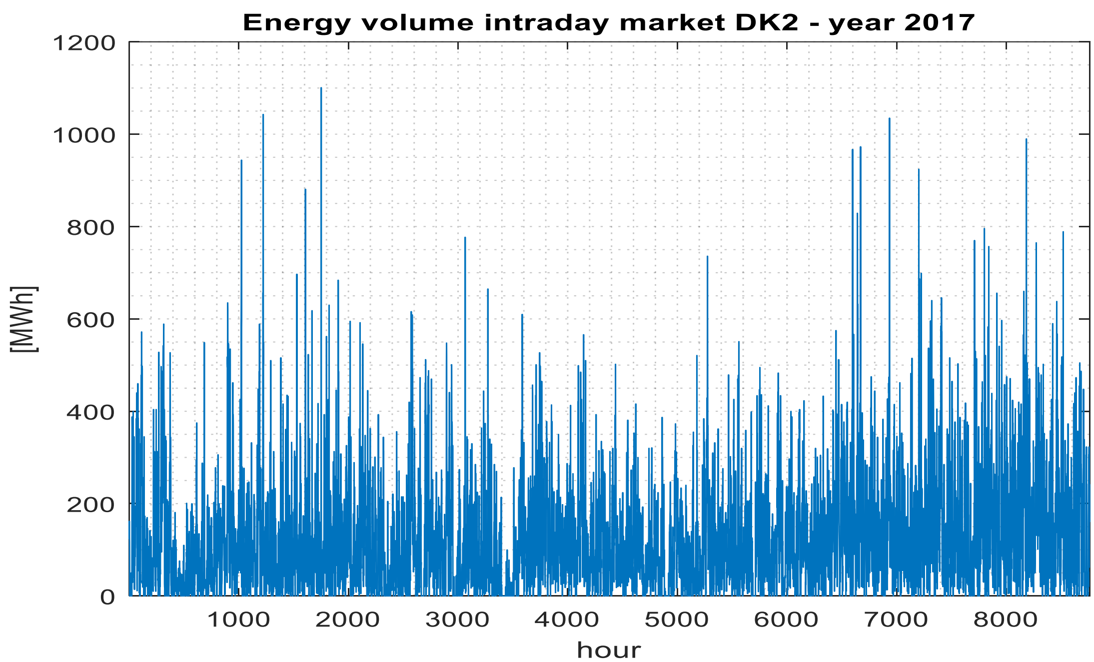


FIGURE 90

9.4 Data analysis 2035

9.4.1 Scenario 2035

For the future scenario, it is chosen the year 2035. This is a prevision in which the prices are conducted as part of Energinet's internal basis for analysis and are a result of model simulations which are based on uncertain assumptions about the future including development of fuel prices, production capacity, electricity consumption etc. Consequently, the prices are very uncertain and should be used with proper reservations. Energinet cannot be held responsible for the correctness of the prices, the use of the prices for investment decisions or any other usage of the prices regardless of the form and extent of the usage[64].

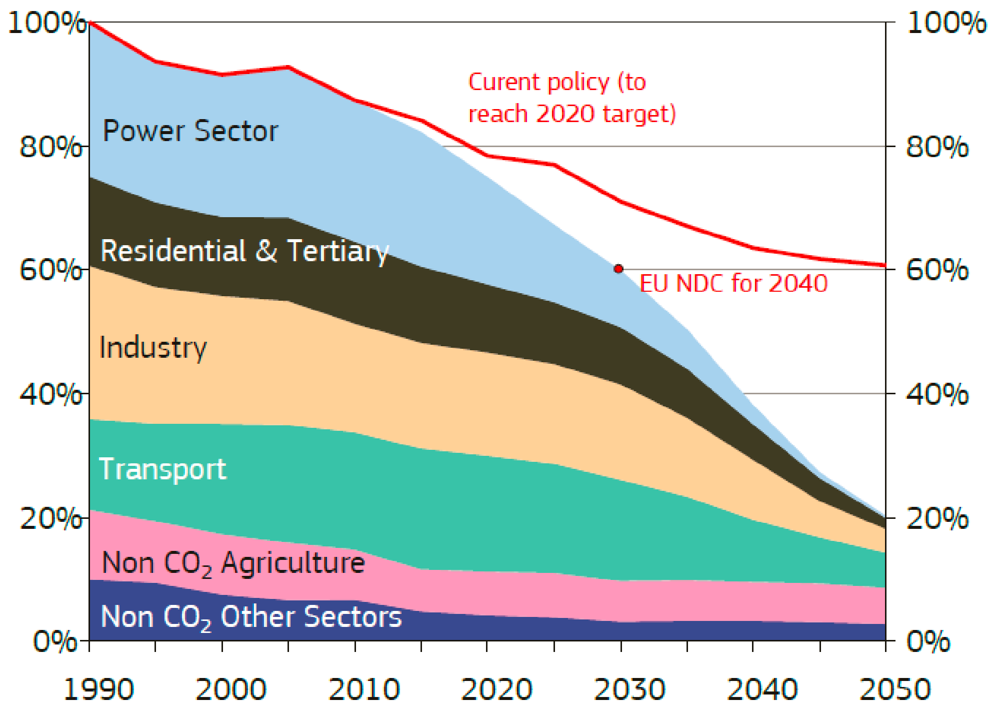


FIGURE 91[65]

ENTSO-E (www.entsoe.eu , the European Network of Transmission System Operators for Electricity) creates energy system scenarios in relation to their TYNDP (Ten Year Network Development Plan) published every second year.

In the year 2018 TYNDP18 works in order to make three different scenarios; Sustainable Transition, Global Climate Action and Distributed Generation. The electricity prices used in this thesis are based on the Distributed Generation scenario. Energinet just recently used the scenarios within our newest analysis (System Perspective 2035, www.energinet.dk/sys35 ,

Considering the 'distributed generation' scenario there is a main assumption: the renewables energy development. It generates a tremendous evolution in the electricity sector. The consequently expectation is that the electricity demand could increase significantly.[66]

64 https://energinet.dk/sys35

65 www.entsoe.eu

66 https://docstore.entsoe.eu/Documents/TYNDP%20documents/14475_ENTSO_ScenarioReport_Main.pdf

Therefore, thanks to storylines and datasheets plus a high level of coordination throughout the process it is possible to create a scenario. This scenario was developed by ENTSO with a best fitted methodologies. ENTSO developed a gas and electricity scenario. Concerning the electricity ones it develops a future scenario using the bottom-up and top down approach thanks to the local knowledge of TSO experience. TSO provides a demand estimation, capacity generation based on European storylines for each scenario using the modelling tools and a consistency correction of the data. In longer-term scenarios (Distributed G it was mainly used the top-down approach generation 2030 and 2040). Considering this assumption, a Thermal and RES Optimisation phase was added with the aim to include peaking units for adequacy, access economic viability of plants and optimise the PV, onshore and offshore wind generation in the scenario.
If we look at this data it is possible to notice that considering the renewables scenario, as we said, it is possible to notice that the fluctuations are very relevant and the highest prices are major with respect to the scenario in 2017, the same for the lowest prices and the fluctuations are more relevant. This is very useful for the power to power plant behaviour in order to maximize the profit. Thanks to the diminishing of the demand, in order to assume that, in the future there will be a energy saving, and the development of the renewable energy in Denmark, it will be the possibility to have a lot of fluctuating electricity prices.

9.4.2 Data analysis

In the graph showed below, it is possible to see that the great renewable introduction could make the prices very high and very low. As it is discussed before, it is very convenient for this type of power-to-power-plant in order to have a good profit and to make this plant feasible in the future scenario.

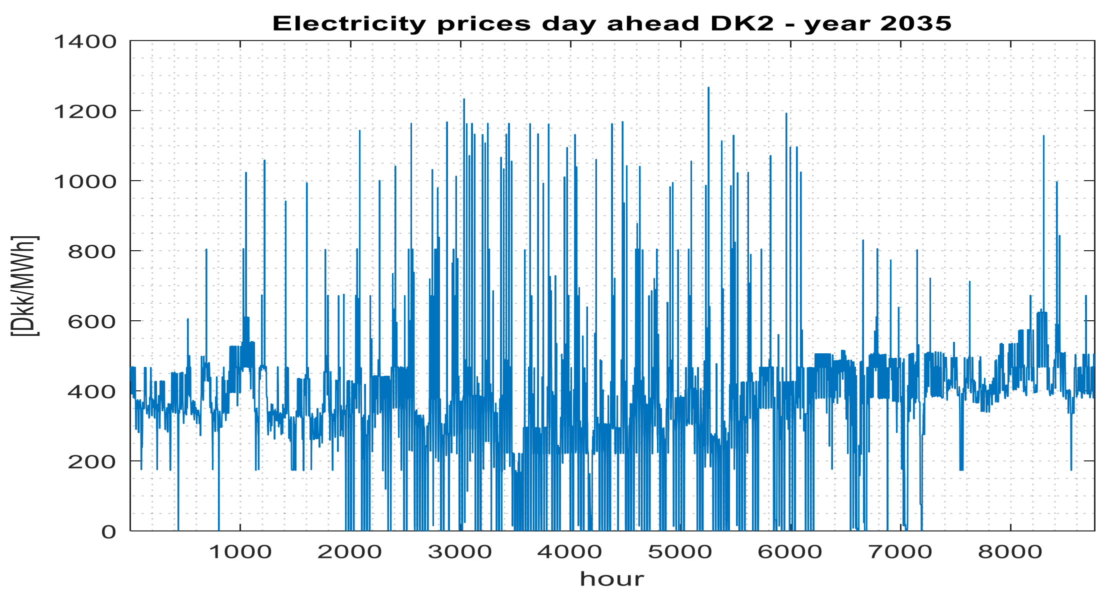


FIGURE 92

This is the scenario for the day ahead market. Considering the electricity prices of the intraday market, we haven't available data. So in order to perform the same simulation it will be possible to have this data considering two things:

1. The behaviour of the curve it will be same of the 2017
2. Considering an inflation rate equal to 2% we suppose that the cost of the electricity could increase about of 2% for each year.

Considering the district heating prices, we haven't sufficient information about this scenario for it. As it is said before, these prices are not the same in the whole Denmark. So, concerning this input data, it is made some assumptions. The 2017 district heating prices are increased by 2% for each year. The motivation is that such prices are supposed to be evaluated with an inflation rate of2% that will increase the price each year.

10. Optimization algorithm

In order to make a feasibility analysis on the HT-TES energy storage inserted in power-to-power plant an optimization algorithm was developed. This final part was performed on Matlab taking as a input the following data and parameters. The tool, thanks to the whole enter data, could show how the plant will work during the year. So it will be possible to know if the plant charge, store or discharge energy. The tool knowing the plant characteristics with the aim to reach the maximum profit on the whole year finds this behaviour.

Firstly this tool receives the outputs of previews function like charge, storage and discharge Matlab function. This function has the aim to calculate all technical parameters and the energy fluxes that is possible to have in this plant. As it is mentioned in the previews chapter, their input are the three input parameters are storage capacity [MWh], turbine power [MW] and heater power [MW].

Secondly the there is another input function that evaluates the total investment cost with NETL methodology and finally there are prices parameters. The prices parameters are electricity, district heating, taxation, operational and maintenance costs, all referred to a specific year. All this function and data are need to compute the maximum profit that it is possible to achieve considering the input parameters and the costs related to that specific year. Knowing the maximum profit, through the optimization algorithm it will be possible to make economical evaluation like Pay Back Time, Net Present Value etc. in order to choose the right sizes of all basic parameters in order to choose the most feasible one from the economical point of view. Thi is the general overview of the done work.

10.1 Introduction

Because of the depletion of natural gas, gas oil and the others not renewables sources, is very important to use them wisely. It is necessary to understand how to use the energy and when to produce it in function of input prices and in function of the demand of each type of energy. Considering this plant like a renewable plant with a not renewable component (heater), it is important and very interesting how to manage correctly it in order to minimize the costs and the resource used and to maximize the final economical gain. This is the motivation for what it is built a program to optimize from the economical point of view the plant when it works. As we know, the aim of the thesis is to build a feasibility analysis of the rock bed HT-TES inserted in a power to power plant.

The aim of this project is to implement a Matlab script that knowing the external input like electricity, taxes, O&M, DH etc said to us what is the best behaviour of the plant, hour by hour in order to maximize the profit and to use wisely the energy bought and stored in the HT-TES.

10.2 Useful data analysis

It is imaged that the power to power plant is in Copenhagen inserted in a Danish electrical grid and connected to a part of the Capital city concerning district heating in order to produce electric energy and heating for houses in Copenhagen, so it is imaged that is connected to a heating network.

The external input parameters for this optimization model are:

1. Electricity day ahead prices from two different markets: day ahead market and intraday market. Considering the day ahead market we know the price from the nordpool.dk and usually it is possible to know it only 24 hours before. The day ahead electricity price is the common point between offer and the demand.

2. The intraday market electricity prices has the aim to adjust the mismatch between the real requests after the 24h. In the market it is possible that the prediction of day ahead market does not correspond to the real demand of energy so 15 minutes an energy company could know the price of the electricity and the energy volume linked to that. If the company has this energy and if it is convenient to sell it the company could gain money. The prices changes hour by hour and the energy volume too. It is imaged that the plant was installed in Copenhagen, so considering that the electricity prices in Denmark are divided into types of data: DK1 and DK2. Copenhagen stays in the region DK2. The electricity prices in these two areas change because the suppliers from this two areas change. In Principle the prices oscillations are quite similar for this two areas but it is different hour by hour.

3. Considering the district heating prices they are constant considering the whole year. It is an hourly price per MWh. As we know the plant is inserted in a DH in Copenhagen, so exists a demand curve in order to put in the injection point the correct amount of heat water. Considering the demand

curve we use the demand curve of Roskilde.[67] The demand curve on Roskilde corresponds at the hourly energy demand on the injection point of a district heating. This demand curve is related to an area with an extension of one fifth of the city of Roskilde. If we want to transpose it in Copenhagen, we could scale the heat demand using the population density of Copenhagen with respect to the Roskilde's one. If we assume that we says that the Copenhagen district heating extension is equal to 1/5with respect to Copenhagen extension. Therefore, if the plant has the sufficient energy to sell it into district heating it could have some money otherwise the plant injects an energy that could vary from zero to the maximum energy that the plant could sell.

To run the model simulation, the operational variables at the injection node have to be known. Roskilde Forsying provided the data for the year 2015 of the injected power, the volume flow rate and the supply and return temperatures at Marbjerg's injection point.

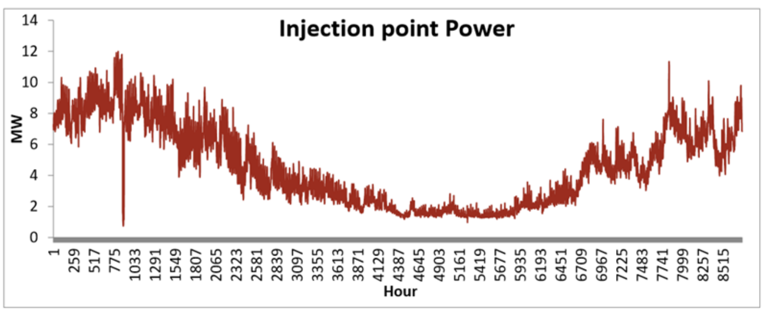


Figure 25 Heating supplied in the network injection point

FIGURE 93 INJECTION POINT POWER ROSKILDE DISTRICT.[68]

The author of this paper made a studies about Marbjerg, that is a Roskilde district (1/5 of Roskilde extention). To find the correct demand curve for Copenhagen I scaled this values with respect to density population in Copenhagen and in Roskilde. Making this assumption i.e. that the district heating extension that I consider in Copenhagen is 1/5 with respect to the whole extension of the Capital city.

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[67] Falcone, A. (n.d.). ANALYSIS OF THE POSSIBILITIES TO OPTIMIZE THE FORWARD TEMPERATURE OF A DISTRICT HEATING SYSTEM COMBINED WITH LOCAL TEMPERATURE INCREASE BY Master ' s Thesis.

[68] Falcone, A. (n.d.). ANALYSIS OF THE POSSIBILITIES TO OPTIMIZE THE FORWARD TEMPERATURE OF A DISTRICT HEATING SYSTEM COMBINED WITH LOCAL TEMPERATURE INCREASE BY Master ' s Thesis.

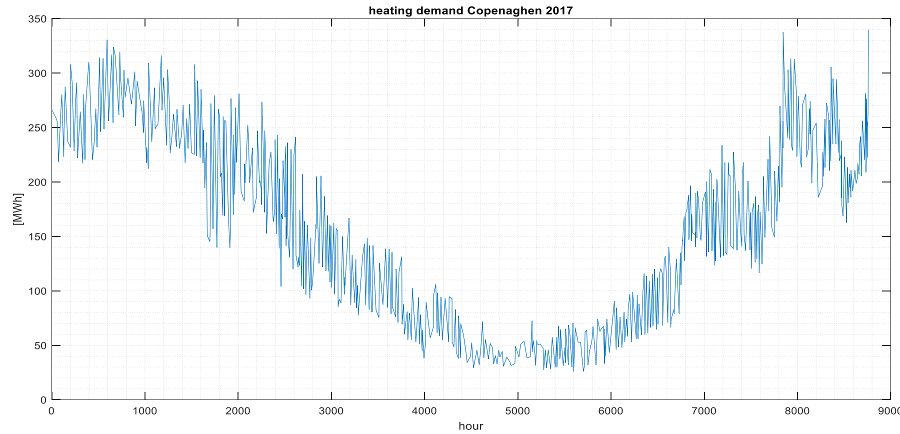


FIGURE 94

The reason why are used this data is that it was not possible to have all data concerning a network district heating in Copenhagen, so making this assumption it is possible to make calculation and finally to have some output results.

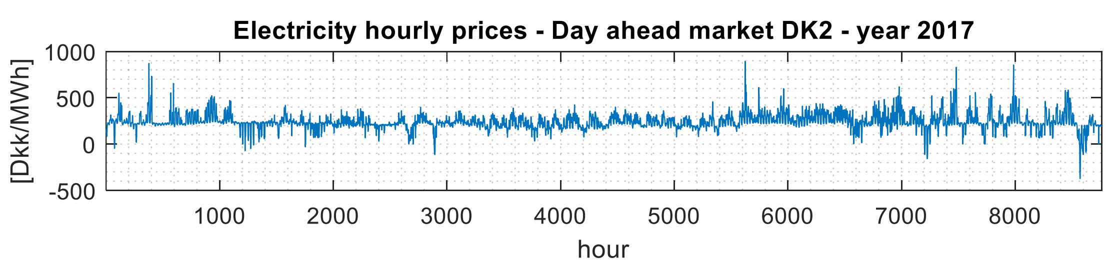
4. Another input data is taxation prices. In Denmark we are electricity taxation either if you buy and either if you sell electricity. They are different obviously but in principle the taxes concerning the energy that you sell is lower that the taxes that you buy because the VAT is not considered in the amount of taxes if you buy. All taxes are proportional to the energy that you buy or sell. For the whole year all taxes are constant except the PSO: it has a trimestral value, so in one year it changes 4 times.

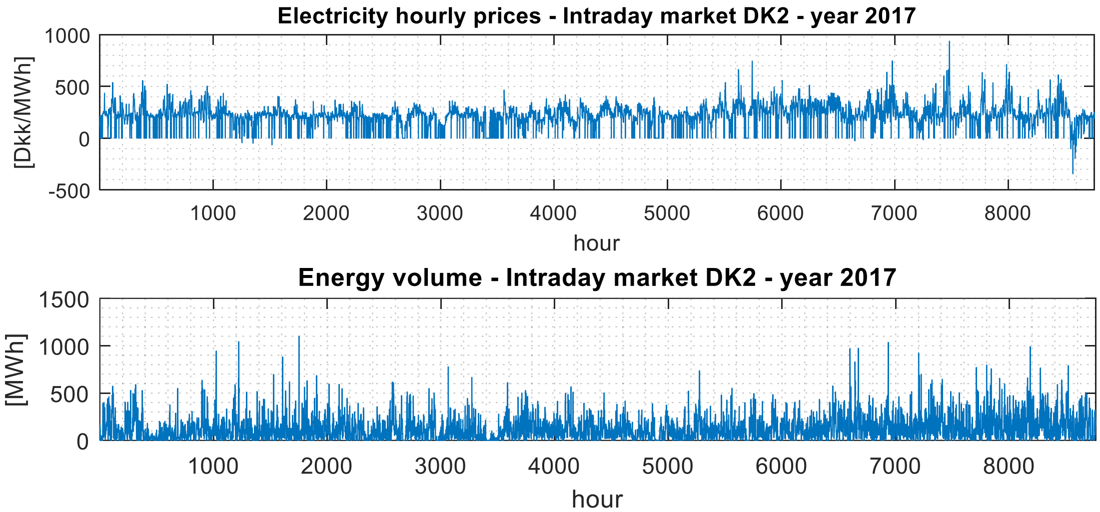
5. The final input data are the operational and maintenance costs. They could depend on the energy that you use like for steam cycle, charge phase and discharge phase O&M or it could be fixed, so independent on the time and on the energy like in storage phase.

10.2.1 year-2017

Having all these data it was possible to make all simulation with this tool developed on MatlabR2017b.

Electricity data from NordPool.dk:





DH prices:

Concerning district heating prices [69] are opaque because there not exits an official web site, like electricity prices, in which it is possible to find available data. The prices depend on the installed capacity and depend who is the supplier and in which area. For example the data available, here will be an example of data of 2017 the district heating hourly prices from Greater Copenhagen since 2008. This is a type of data constant alongside the whole year. To calculate the right price it is mandatory to remove from the available retrieved data prices the 25% of VAT and, through a formula, the district heating prices is scaled with respect to the installed capacity. The graph showed below is an example of prices that a power-to-power plat should sell with a power turbine equal to three [MW] whit a district heating price equal to 496.25 [Dkk/MWh].

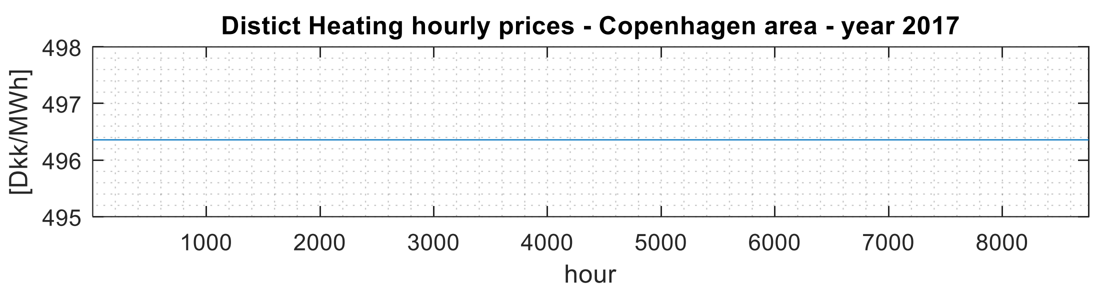


FIGURE 95

Taxation

As it is said in the chapter about taxation prices are available on the website www.Energinet.dk. Taxation is different if the energy is sold or bought. If the energy is sold it is considered three taxes; so transmission, system and PSO, if you sell energy it is mandatory con consider the previews taxes plus the VAT. All this taxes are constant along one year, except PSO that has four trimestral values, and depends on the year and on the energy sold or bought.

[69] https://www.hofor.dk/privat/priser-paa-forsyninger-privatkunder/priser-paa-fjernvarme-2017-privatkunder/

The following table shows the taxes from Energinet considering the year 2017.

TARIFF	[øre[70]/kWh]
PSO	[1.3, 1, 1,0. 9]
Transmission	4.3
System	3.9
Distribution	15

FIGURE 96

Operational and Maintenance costs

Operational and maintenance costs are related to the four parts of the plant. The first one is related to the charge phase and it is proportional to the heater power.

The second one concerns the storage maintenance. The storage is fix and do not need operational costs but only maintenance one, that is why it is the lowest costs. temperature is a fixed cost during the year and it is independent on the storage capacity. The third one is concerning the discharge airside plant. It is proportional to the power of the turbine and it is a fixed specific cost during the whole year.

And finally the last one is concerning bottom steam Rankine cycle. It is the high cost because it is the most delicate part of the plant. This cost concerns the maintenance and operational ones. This is proportional to the turbine power [MW] and it is a fixed specific cost during one year. Below it is shown a table where it is possible to find operational and maintenance prices related to 2017.

OPERATIONAL AND MAINTENANCE COSTS			
CHARGE *[Dkk/MWh]*	DISCHARGE *[Dkk/MWh]*	TURBINE *[Dkk/MWh]*	STORAGE *[Dkk/year]*
0.1	8.44	1.01	65

FIGURE 97

10.2.2 year-2035

ELECTRICITY DAY AHEAD PRICES

prevision of 2035 renewables scenario- www.entsoe.eu (day ahead)

[70] Øre is a 1% of a 1 Dkk.

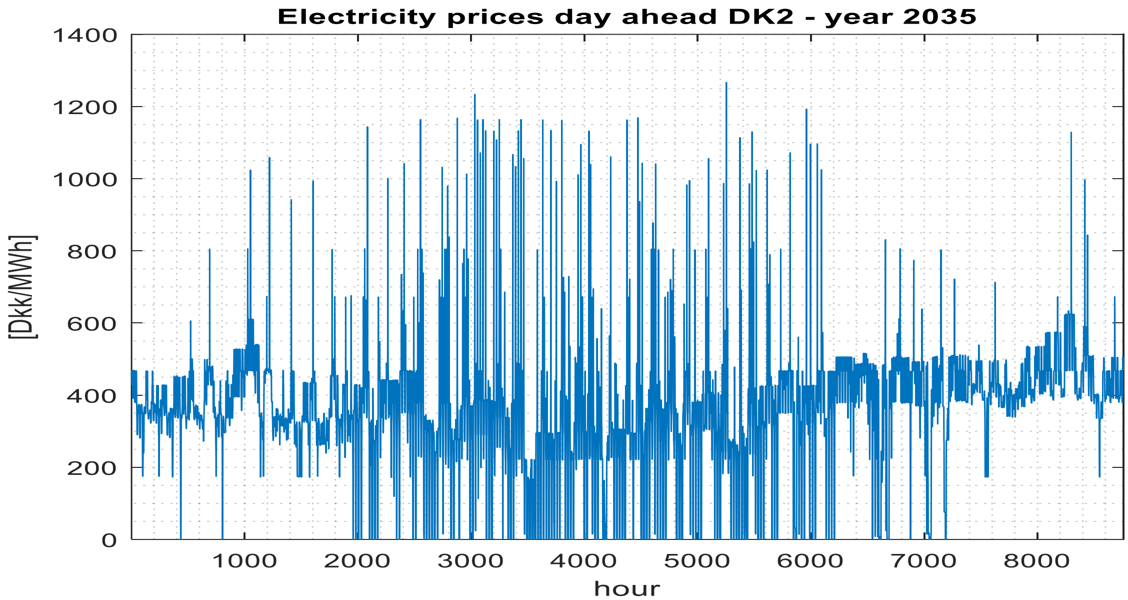


FIGURE 98

ELECTRICITY INTRADAY MARKET PRICES

It was not possible to have some data, that is why assume two following things. The first one is that the trend and the shape of the curve is the same with respect to the 2017 intraday electricity data. The second assumption is that the prices would be significantly increased (as it is possible to see in the day ahead electricity prices of 2017 and 2035) so we assume that we scale the curve considering the median value of 2035 and 2017.

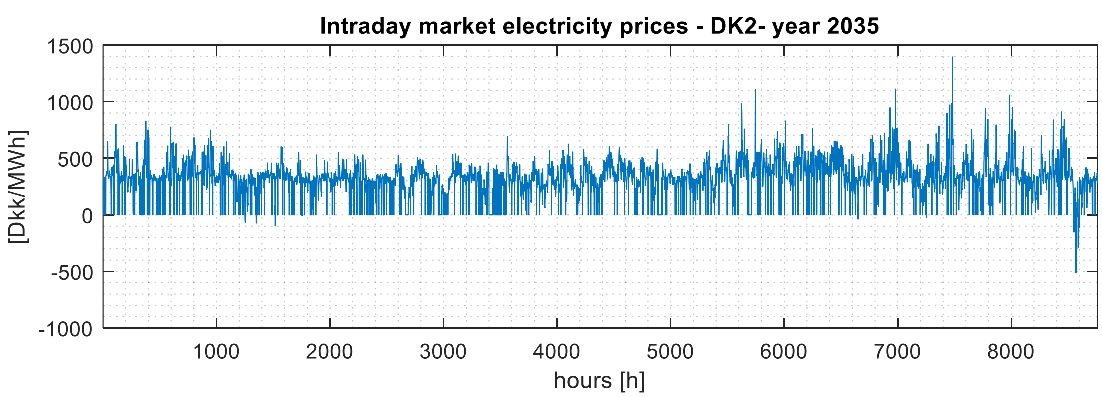


FIGURE 99

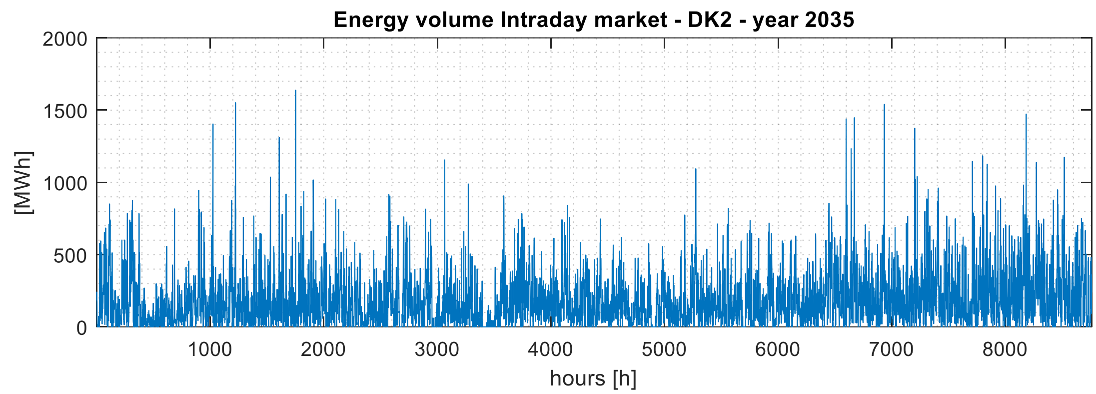


Figure 100

DISTRICT HEATING PRICES

It is assumed a constant price as in the 2017. An assumption is made considering that the district heating prices could increase for each year of 2%. This is a possibility considering that this market is in evolution, so it is a realistic hypothesis the fact that they could increase.

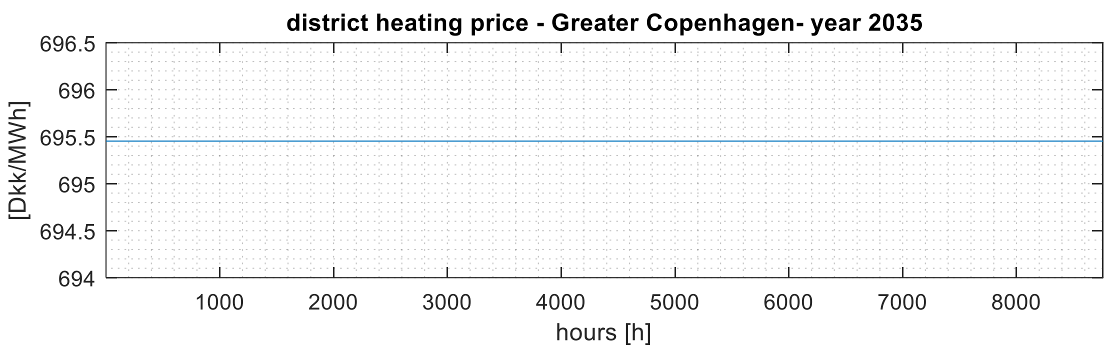


Figure 101

DISTRICT HEATING DEMAD CURVE

We haven't district heating data demand curve considering 2035. Therefore, we have some reference in which the prevision is that the district heating market will increase up to 2020 because the heat demand will increase. From 2020 to 2035, there will be a diminishing of the demand request because we assume that at a certain point there will be a resources savings[71] considering the temperature decreasing and a network optimization of all Copenhagen zone.

As the figure shows, there will be, according to this source, in any way an increase of the heating demand. Interpolating linearly the total load of 2017 and 2035 it is simple to notice that for each year we are an increase of 2% of the total demand for each year. Assuming that the shape of the curve will remain the same considering that in the winter and autumn period we are an huge amount of heat request with respect to the spring and the summer period.

[71] (Af, For, Koordineret, Af, & Og, n.d.)

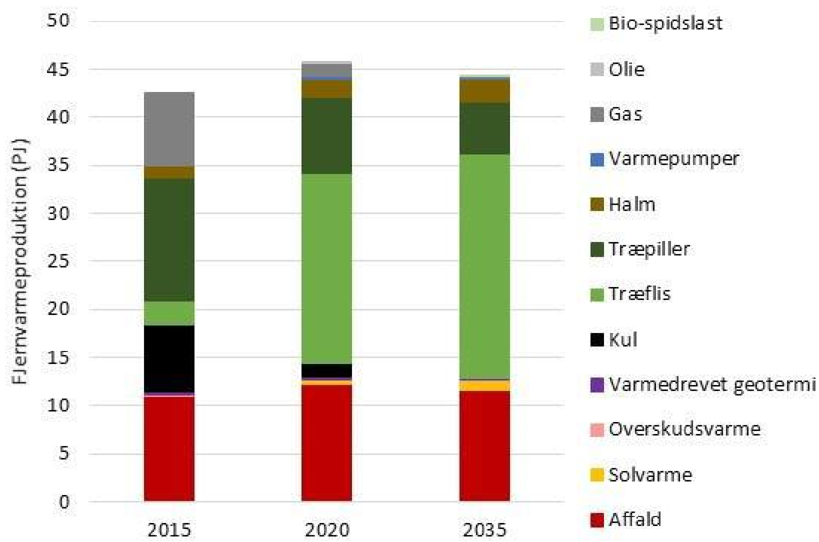


FIGURE 102 TOTAL THERMAL ENERGY CONSUMPTION FOR DISTRICT HEATING IN DENMARK.[72]

The optimization interface that was used is integrated in the optimization toolbox in Matlab. The optimization variables are the heat fluxes and these values could be positive or negative (if it is an energy purchased they are positive if it is a sold energy they are negative) and this value could vary from zero (that part of the plant is off) to their size value (when it is fully operational)

The final aim of this work is to find, knowing the input and defined the optimization variables the maximum achievable annual profit knowing the thermodynamically and technical constraints. The optimization maximizing the vectorial products between the energies [MWh] and the hourly prices [Dkk/MWh]; they could be an intraday or day ahead electricity or district heating prices, a tax or an OPEX and maintenance cost.

Obviously, in order to make this simulation consistent, all data have to be referred to the same year. In this thesis, it is chosen two specific year, 2017 for the past and 2035 for the future scenario. It is chosen the year 2017 because it is a year in which there were a lot of electricity price oscillations. The oscillations are due to a huge renewables energy utilization because in that year there were a lot of wind energy available. The energy that came from renewables, if this energy is a huge value larger than the demand curve the prices fall down. So in that period there were a lot of price oscillations useful for the charge and discharge work of the power to power plant.

Considering the future scenario of 2035, the prices are developed for the Energinet.dk, a Danish electrical company. The data that Energinet gave to me was based on the renewables scenario. In 2035 Denmark wants to use 50% of renewables diminishing the use of coal and gas oil. So, considering this scenario, throw a statistical and probabilistic methods, this company makes electricity prices day ahead future scenario. As it is possible to see in the figure they are very

72 (Af et al., n.d.)

oscillating prices, which the values are higher and lower with the respect to the year 2017.

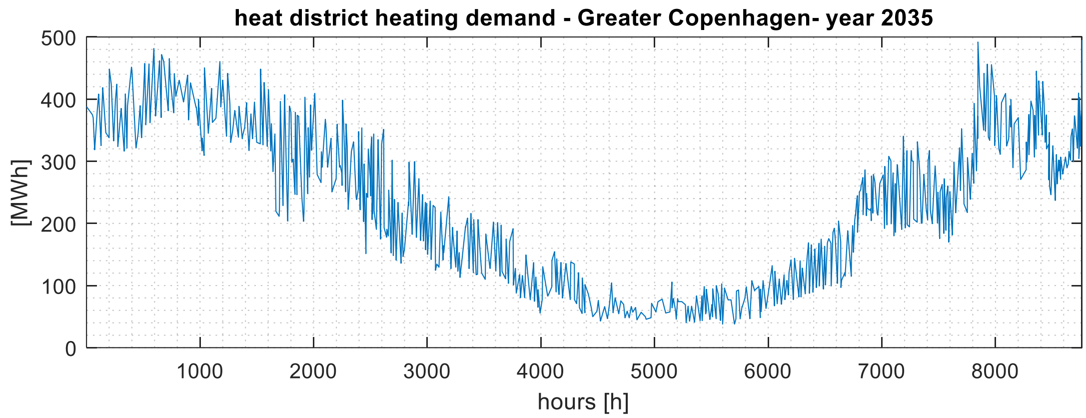


FIGURE 103

Operational and maintenance

Operational and maintenance costs are the same with respect to the 2017, so concerning charge, discharge storage and bottom cycle. We have not available data about taxes for the future scenario, so it was assumed that these prices will increase of 2% for each year, imaging and assuming a general prices increasing.

OPERATIONAL AND MAINTENANCE COSTS			
CHARGE	DISCHARGE	TURBINE	STORAGE
[Dkk/MWh]	*[Dkk/MWh]*	*[Dkk/MWh]*	*[Dkk/year]*
0.14	12.29	1.5	94.69

FIGURE 104

TAXATION

Taxation are the same with respect to the 2017, so PSO, transmission, systems and VAT. The whole tax is different if you buy or sell energy. As in the O&M case, data about taxation in the year 2035 are not available, so it was imaged that this price will increase of 2% for each year, imaging and assuming a general prices increasing.

TARIFF	[øre[1]/kWh]
PSO	[1.9, 1.45, 1.45, 1.31]
Transmission	6,26
System	5,68
Distribution	21,85

FIGURE 105

10.3 Objective Function and model constraints

In this chapter is explained how this algorithm is built. The algorithm used requires the use of limits and indications to make it simulate the correct behaviour of the storage based on the energy flows coming from the charge and discharge part and the behaviour of the electricity and heat market. In the following paragraph, it is describe the whole procedure.

10.4 Model description

As explained previously, the program considers an annual perfect prediction in which it has input the three parameters of the plant such as power of the turbine and the heater and capacity of the thermal storage. The program develops as follows:

The algorithm is designed to limit the workload.

As previously mentioned, the program considers a perfect annual forecast in which access and efficiency of the thermal storage is achieved. The program becomes like this:

- Technical data layout plant,
- the total initial cost of the system referred to 2014 through the NETL procedure
- Energy fluxes

Note all the energy flows of size, that is the maximum flows admissible by the system are established of the optimization variables that will vary over time (hour by hour), continuously (from their size value, in case of maximum flow to zero, when that part of the plant is stationary).

This means that the flow rate is variable while the temperature remains fixed for any flow rate inside the tubes, except of course if this is zero. If the flow rate is zero, this means that the temperature in that part of the system is equal to that of the environment.

In this part of the optimization, the aim is to connect the system created to the Danish electricity and district heating network and see if, considering the information outside the plant such as electricity prices etc., the program simulates the behaviour of the system.

It is built an algorithm where the aim is to maximize the annual profit. Actually, the optimization function used in Matlab wants to minimize the final objective function, so, inserting a minus it is simple to solve the optimization problem.

Considering that, we have three types of plants, the objective functions and the constraints are different. Actually in the second option, (so if we consider the plant that has the possibility to produce heat for district heating using the heat of condensation) has the same equality and inequality constraint and the same term with respect to the first option (considering the steam turbine that produces only electricity) with other constraints. The same thing is valid for the third and second option. So in the chapter it will be explained the first option and then it will be showed the adding equations and optimization variables for the second and third plants. The optimization function is a linear equation where the optimization variables are the energy fluxes [MWh] and the constant values known are the prices [Dkk/MWh] of electricity (e.g. intraday and day ahead market);the energy volume of the intraday market; the district heating, the heat demand of the operational costs, taxations etc.

As follow it is showed the power-to-power plant energy fluxes that are the optimization variables of the maximum annual profit optimization function.

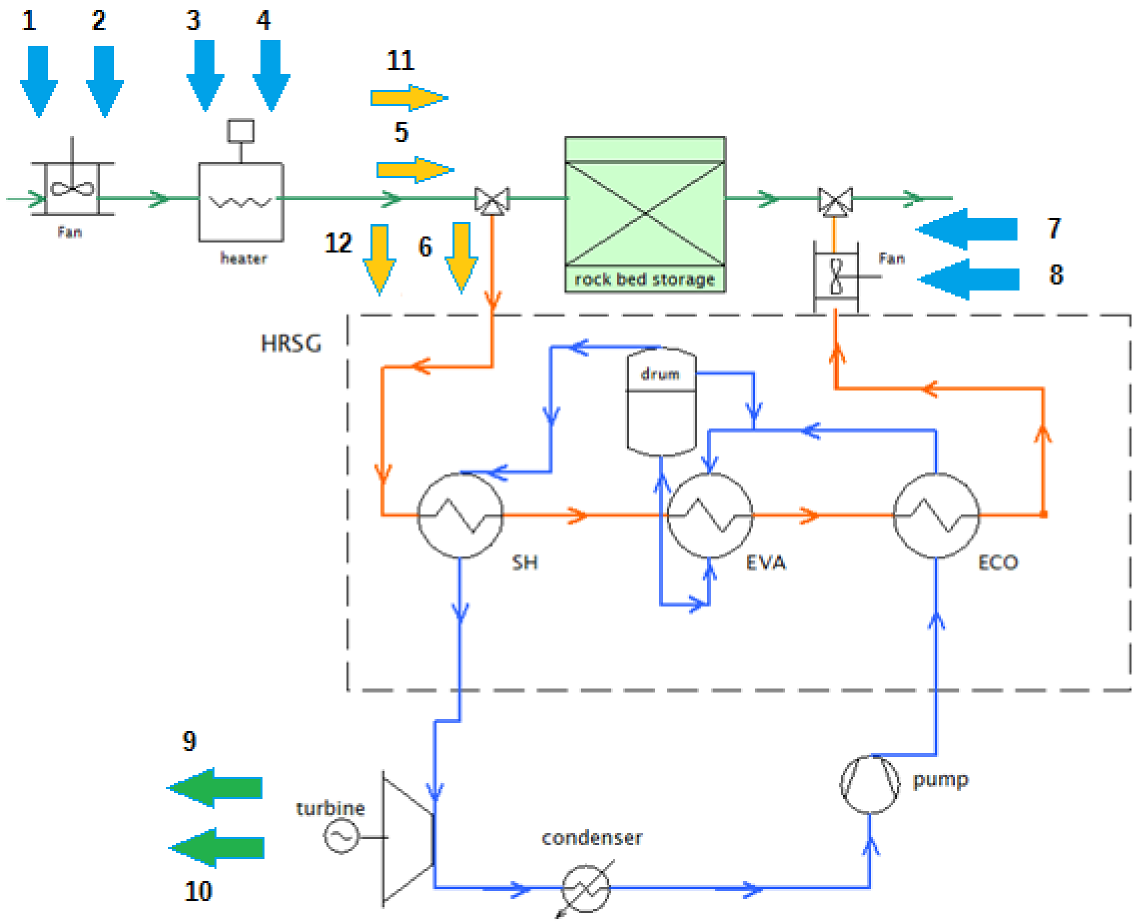


FIGURE 106 ENERGY FLUXES INVOLVED IN OPTIMIZATION ALGORITHM. 1ST OPTION, ONLY ELECTRICITY PRODUCTION.

As it is possible to see in the figure, the energy fluxes involved are the energy linked to an economic expenditure (energy sold (E_turb, E_dh…) or bought(E_h, E_fan_c, E_fan_d…)) or the energy fluxes that communicate with the storage 'E8, E5' and an optimization variables that identify the energy inside the storage 'EN_st' where its values goes from zero to the storage capacity [MWh].

In the following table is summarized the optimization variables. Here, it is possible to find the energy fluxes showed in the previews figure (e.g. Figure 107) and the other optimization variables that defines how the plant works. It is mandatory to underline that these variables are referred to the first option, so the plant that has the only possibility to produce electricity.

TABLE 16 OPTIMIZATION VARIABLES - OPTIMIZATION ALGORITHM

Symbol	Function	type	Upper and lower bounds	Vector components

1 (E_fanc_dayahead)	Energy of the fan dayahead	Continous	[0; Efan_max]	8760
2 (E_fanc_intraday)	Energy of the fan intraday	Continuous	[0; Efan_max]	8760
3 (E_Hdayahead)	Energy of the heater dayahead	Continuous	[0; EH_max]	8760
4 (E_Hintraday)	Energy of the heater intraday	Continous	[0; EH_max]	8760
5 (E5 day ahead)	Energy of the inlet of the storage day ahead	Continuous	[0; E5_max]	8760
6 (E8 intraday)	Energy of the outlet of the storage day ahead	Continuous	[-E8_max;0]	8760
7 (E_fand_dayahead)	Energy of the fan dayahead	Continuous	[0;Efand_max]	8760
8 (E_fand_intraday)	Energy of the fan intraday	Continuous	[0;Efand_max]	8760
9 (E_turb_dayahead)	Energy of the turbine dayahead	Continuous	[-Eturbmax;0]	8760
10 (E_turb_intraday)	Energy of the turbine intraday	Continuous	[-Eturbmax;0]	8760
11 (E5 dayahead)	Energy of the inlet of the storage intraday	Continuous	[0;E5max]	8760
12 (E8 intraday)	Flag of the energy of the outlet of the storage intraday	Integer	[0;1]	8760
EN_storage	Energy inside the storage	Continuous	[0;storage capacity]	8760
EN_storage_ end	Energy inside the storage in	Continuous	[0;storage capacity]	1

	the last moment			
E8_out_intraday	If the intraday market is not on	Integer	[0;1]	8760
CHARGE		Integer	[0;1]	8760
STORAGE		Integer	[0;1]	8760
DISCHARGE		Integer	[0;1]	8760

The optimization function evaluates the energy values [MWh] of this energies considering that their values could go from zero to the size value, calculated in the function of energy analysis. As it is explained before, the energy values of this fluxes is only mass dependent, so if the energy is low, it means that the temperature remains the same, the only thing that could change is the mass flowrate.
As it is possible to see in the table, the total vector of the energy storage (e.g. ENstorage and ENstorage_end) are 8761 vector components. The motivation is that the energy of the storage is the photography of the half of the hour, not, like the others objective variables, that are 8760 vector components.
The objective function written evaluates hour by hour the plants money fluxes. The final aim of the optimization algorithm is to find the maximum annual profit of the plant summing the whole expenditures and the gains during the all 8760 hours. As we know, the prices inserted in this tool are considered row vectors composed by 8760 components, so every optimization variables are column vectors composed by the same amount of components.
Considering the intraday market, it is said before that the prices are linked to an energy volume that could be higher or lower than the size values of te energy optimization variables. So, for the intraday market, others optimization variables are used to evaluate the final maximum profit.
As follow, it is showed the objective function minimized in the Matlab tool.

$$Profit_{max} = c_{el_{dayahead}} * E_{heater_{dayahead}} + c_{el_{dayahead}} * E_{turbine_{1_{dayahead}}} + c_{el_{dayahead}} * E_{fan_{charge_{dayahead}}} + c_{el_{dayahead}} * E_{fan_{discharge_{dayahead}}} + c_{el_{intraday}} * E_{heater_{intradady}} + c_{el_{intraday}} * E_{turbine_{1_{intradady}}} + c_{el_{intraday}} * E_{fan_{charge_{intraday}}} + c_{el_{inraday}} * E_{fan_{discharge_{intraday}}} + opex_{charge} * E_{heater_{dayhead}} + opex_{charge} * E_{heater_{intraday}} + opex_{storage} + opex_{discharge} * E_{turb_{dayhead}} + opex_{discharge} * E_{turb_{intraday}} + opex_{turb} * E_{turb_{dayahead}} + opex_{turb} * E_{turb_{intraday}} + taxes_{bought} * E_{heater_{dayahead}} + taxes_{bought} * E_{heater_{intraday}} + taxes_{bought} * E_{fanc_{dayahead}} + taxes_{bought} * E_{fanc_{intraday}} + taxes_{bought} * E_{fand_{dayahead}} + taxes_{bought} * E_{fand_{intraday}} + taxes_{sold} * E_{turb_{dayahead}} + taxes_{sold} * E_{turb_{intraday}}$$

This is the final equation considering all components of the plant that has only the possibility to produce electricity.
If we consider the others two plants. This equation, in every hour of the year is always respected. As the objective function shows, the energy fluxes for the day

ahead market and for intraday market are different even because we know that to intraday market is linked the energy volume and even because in the plant there is a mutually exclusive condition that imposes that in the same moment a component could sold or buy energy only from one markets.

A fundamental part of the optimization process is to link the energy flows of the plant, in particular storage to the energy flows that consume and produce energy through constraints:

The the energy of the heater and the incoming energy to the storage and the energy of the turbine to the flow coming out of the storage. Considering a 95% heater efficiency and a 2 Kelvin temperature drop. The efficiencies are independent of mass variation and are therefore fixed if the above assumptions are made. The equations that regulate the features of storage are as follows:

$$E_{storage}(t_i) = E_{storage}(t_i - 1) * \eta_{storage} + E_{5_{dayahead}}(t_i - 1) * \eta_{charge} - E_{8_{dayahead}}(t_i - 1) * \frac{1}{\eta_{discharge}} + E_{5_{intraday}}(t_i - 1) * \eta_{charge} - E_{8_{intraday}}(t_i - 1) * \frac{1}{\eta_{discharge}}$$

The energy stored in the storage is regulated by the incoming and outgoing flows to the storage according to very precise efficiencies, considering that the energy derives from the previously stored de-energized energy of a return equal to 0.008%, calculated at National Laboratory in the test facility. The efficiency of the incoming flow is equal to 95% considering the losses from the walls and the loss that comes from the 'cold end'. Same efficiency is that of discharge for the same reasons.

$$E_8 * \eta_{turb8} = E_{turb};$$
$$E_{heater} * \eta_{5heater} = E_5;$$
$$E_{fan_c} * \eta_{heater_{fan}} = E_{heater};$$
$$E_{fan_d} * \eta_{turb_{fan}} = E_{turb}$$

Only if the storage has sufficient energy and if convenient, through the appropriate yields it is possible to discharge into turbine or district heating and turbine or only DH by-passing the turbine and HRSG. The efficiency of HRSG, considering it as a surface heat exchanger, has a variable yield deriving from the flow rate and is dependent on the size of the plant. A different power to be supplied to the network generates a different output temperature from the HRSG based on the power of the turbine and therefore this generates variations in the efficiency of the heat recovery steam generator. A temperature drop of the tubes of two degrees Kelvin is also considered. Remember that while the efficiency of the tubes the efficiency of the Rankine cycle is fixed for any power of the turbine (0.34 for turbine only and 0.28 for turbine and DH), the efficiency of HRSG varies according to the power of the turbine. In general this value is high and does not vary much, generally from 75% to 95%.

If you have only a turbine, consider using the intraday or the day ahead market.

If you have both turbine and turbine and district heating, the solver must choose whether to discharge into the turbine, considering the two electricity markets or turbine and district heating, always considering the two electricity markets.
If you have the three options, or in addition to just the turbine and the turbine with the heat exchanger, the third option is that of the heat exchanger that brings heat to the district heating using the heat downstream of the storage and upstream of the HRSG. The solver will have to choose which exhaust options are cheaper using the three different markets based on hourly prices.

There are inequality constraints linked to the energy capacity of the storage are always lower that the maximum capacity and it is supposed that the first value of the storage capacity is equal to zero, so at the beginning of the year the HT-TES is void.

There are also some mutually exclusive condition of the charge and discharge flows: being a single tube in which the storage communicates with the outside, there is no possibility of charging and discharging at the same time. Therefore, using the whole variables it is possible to insert this option which would otherwise be a non-linear option. This problem of non-linearity is overcome to the binary variables using the mixed-integer linear programming.

$$CHARGE + DISCHARGE + STORAGE = 1$$

This three optimization variables have only two values; 0 or one and to link these variables to the charge, storage and discharge side, there are some inequality constraints showed below:

$$CHARGE >= \frac{E5}{E5 + 0.1};$$

$$DISCHARGE >= -\frac{E8}{E8_{dayahead} + 0.1};$$

$$CHARGE <= E5;$$
$$DISCHARGE <= (-E8_{dayahead});$$

We know that there are even the energy fluxes linked to the intraday market for the charge and discharge. So it is mandatory to add two other integer constraints:

$$E8_{intraday} + E8_{dayahead} + CHARGE = 1;$$
$$E8_{intraday\ out} + E8_{intraday} + DISCHARGE = 1:$$

The first equation describes the fact that if the storage system has sufficient energy and if the price is convenient, the system could be discharged or in day ahead market or in intraday market. It is another mutually exclusive condition that is possible to use the nonlinear equation thanks to the binary auxiliary variables.

The second one says that in every moment the turbine could produce or electricity from day ahead or intraday market or to do not produce anything.

The intraday market carries with us the electricity prices, and the energy volume. This energy volume if it is larger than the power turbine we have to sell to the turbine power; I know the maximum amount of power that is possible to produce.

We could imagine that at zero the energy capacity inside the storage is equal to zero. This is a type of boundary condition.

In the optimization function, the best annual solution from the profit point of view is therefore considered considering:

Electricity purchased from the day ahead market for fans and the heater,

Electricity sold at the day ahead market at the intraday market. The option to sell, at the same time, energy to both markets but not at the same time is also evaluated.

Energy volumes connected to the intraday market.

The optimization algorithm can decide whether to discharge in turbine or to download in turbine and DH or to discharge only in district heating by-passing the HRSG.

When the aforementioned operations are carried out, the tax option is added both during the sale phase and during the purchase of electricity or thermal energy.

At the time the operations are carried out, the operational and maintenance costs of the part of the charge are included, cost proportional to the energy purchased, cost of the part of the discharge and the steam cycle, proportional to the energy sold and the maintenance costs of the accumulation, fixed annual maintenance cost.

In principle the algorithm will decide to charge the storage when the energy cost is low or even negative or when the storage is sufficiently charged and the price of the energy is high the algorithm decides to discharge. Obviously it is quite clear that the profit and the use of storage depends not only on the parameters of the size of the turbine, heater and storage bed rock but it depends a lot on price fluctuations throughout the period and how they are arranged. Subsequently, it will be possible to notice how important and how much the price fluctuations affect this type of industrial plant.

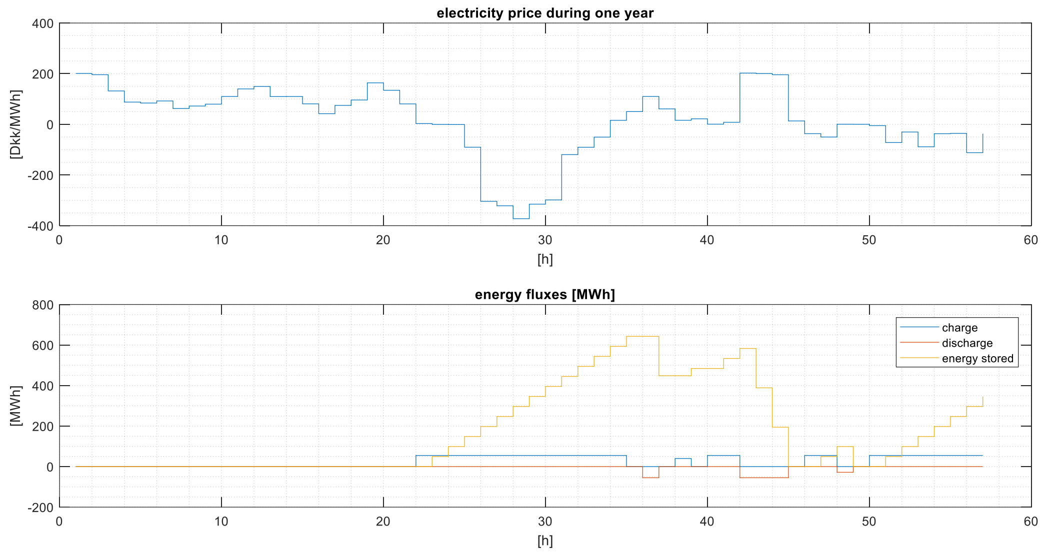


FIGURE 107

As it is possible to see in the figure, thanks to this tool there are the possibility to control the plant behaviour (charge, storage and discharge side) and, as it is possible to notice in every hour we have only one phase (or discharge, or charge or storage) . The red line is the charge part; the blue line is the discharging part and the orange line is the storage capacity. It is very interesting to see that if the price is low, the storage is charge and when it is high the storage is discharged. After making a lot of simulations, if the range if hours changes, the output values changes too.

Considering the second option, so the possibility to have a turbine that could high the low pressure level in order to produce district heating using the heat of condensation, we have to add some optimization variables like:

TABLE 17 ADDING OPTIMIZATION VARIABLES FOR THE SECOND OPTION

Symbol	**Function**	**type**	**Upper and lower bounds**	**Vector components**
Eturb_dh_intraday	Is the energy where the low pressure is equal to P(T=100 [°C])	Continuous	[-Eturb_dhmax; 0]	8760
Eturb_dh_dayahead	Is the energy where the low pressure is equal to P(T=100 [°C])	Continuous	[-Eturb_dhmax; 0]	8760
EDH	Is the energy of the heat for the district heating exchanged in the condenser	Continuous	[-E_DH; 0]	8760
DIS_DH	Is the integer variable that	Integer	[0;1]	8760

	says if the second type of turbine is on.			

E_district heating_day ahead market and E_district heating_intraday market, we have to add another optimization variables concerning the turbine that produce either electricity and either heat for the intraday and the day ahead market. Obviously, we have to insert it in the previews equality and inequality constraints.

There are another equation to describe the fact that the turbine could produce electricity using only one type of turbine and only one electricity market. In this case, is added, like a constant value in the optimization function the district heating price.

$$E8_{intraday\ out} + E8_{intraday} + DISCHARGE + DIS_{DH} = 1:$$

Considering the option to have the district heating upstand to the HRSG, we have to add another optimization variable that has the possibility to simulate the energy inside the heat exchanger. Its value goes from zero to the maximum value of the size energy. There is a control concerning the maximum energy: we know that the district heating in which this plant is inserted has a demand curve. Therefore, the energy that this plant could produce in each hour has to be lower than the heat demand curve in that hour.

$$E8_{intraday\ out} + E8_{intraday} + DISCHARGE + DIS_{DH_{only}} + DIS_{DH_{only}} = 1:$$

TABLE 18 ADDED OPTIMIZATION VARIABLES FOR THE 3RD TYPE OF PLANT.

Symbol	Function	type	Upper and lower bounds	Vector components
EDH_only	Is the energy inside the heat exchanger	Continuous	[-E_HE_max; 0]	8760
E8_DH_only	Is the energy at the outlet of the storage that goes througth the heat exchanger	Continuous	[-E8max; 0]	8760
DIS_DHonly	Is the integer variable that says if the 3rd type of turbine is on.	Integer	[0;1]	8760

The analysis conducted is of the 'perfect prediction' type, i.e. it takes into account the entire lapse of time passed (2017) and the future scenario (2035) and, in relation to the possibilities of the plant, calculates the best performance.
The best performance is calculated by maximizing the annual profit.
The real input data are electricity prices and district heating prices.
As explained in the previous paragraphs, the Danish market taken into consideration is that of DK2, where Copenhagen is located. Furthermore, the possibility of two parallel markets is considered in this optimization, namely the day-ahead market and the intraday market. The first is 'the market of the day before', or the price is established the day before with the possibility of change in the following hours. The resulting price, expressed in Dkk / MWh, is nothing but the intersection of the electricity demand and supply curve.
The intraday market has the task of providing the Danish market the opportunity to provide additional energy to users in case of wrong predictions or in the event that some users need more energy the intraday market provides the opportunity to buy and sell quantities of energy at a certain price, generally different from the main market, or the day ahead market. In the intraday market at any price there is associated a certain maximum energy that can be sold. Considering the plant's performance, it is possible to sell energy on the two markets at the same time.
The intraday market has the opportunity to offer electricity sellers the additional possibility of selling the energy they produce, in general at a more advantageous price. If the seller has that amount of energy from
The analysis conducted takes into account the data for 2017. This choice was made because considering all the years available from Nordpool, from 2013 to now 2017 presents many more price fluctuations than in previous years, fundamental to alternate discharge charge and storage phases in the plant studied.
A further possibility is added to the system, namely that of being able to supply also heat for domestic use. In fact, the plant is expected to raise the low pressure of the Rankine cycle and insert, instead of the condenser, a water-water heat exchanger that carries the condensation heat to the water directed towards the DH.
There is also another option, namely to sell DH thermal energy by inserting a heat exchanger upstream of the HRSG. This will be an air-to-air heat exchangers that will always bring the heat into DH. This represents a greater quantity of heat and therefore more revenue from the economic point of view but represents an extra expense, in fact quite contained, therefore making a budget is very convenient because the energy flows are not separated by the yields of the heat recovery steam generator (HRSG) and bottom cycle, so you can sell that energy as it comes from storage. There is however a exergetic question: heat the air to insert it in the storage at 600 ° C and then sell energy at 100 ° C, bad work from the exergetic point of view. Considering instead the possibility of accumulating energy, the utilization of a 'renewable' technology and the economic cyst point this is very advantageous and as we will see in the following simulations this

configuration is precisely the one that creates more annual revenue, the aim of the thesis.

10.5 Algorithm description

This algorithm has the aim to minimize the objective function which consists of the negative value of the annual profit.

The type of the algorithm used is Mixed Integer Linear Programming (MILP) which there are some integer variables (binary, [0; 1]) and some real variables (from zero to their size value, calculated in another function before, the maximum value that that heat flux could achieve). The optimization problem, so the objective function is a summation of vectorial product between electricity and district heating prices, taxes, operational and maintenance costs and heat fluxes that entering and exiting from the plant. Therefore, this column and raw vectors are a length equal to 8760 components, equal to the hour of one year. The unknowns are the heat fluxes that regulates the storage behaviour in order to maximize the profit.

This analysis is performed inserting as an input three fundamental parameters:

- Heater power [MW]
- Storage capacity [MWh]
- Turbine power [MW]

To do this work is was necessary to build a Matlab program in order to do the following things

1. To know all technical parameters about the plant;
2. To know all heat fluxes and energies in each point of the plant;
3. To conduct an Investment Cost Analysis to know the total cost of the plant in the year 2014

Then, this part is done, it is necessary to know if the profit of this type of new technology is good or not. Therefore, it is necessary to insert the electrical data, district heating data and the heat demand curve of Copenhagen of two different years:

- 2017;
- 2035 (renewables scenario- distributed generation)

The way that we use to carry this analysis is to build a program on Matlab that, knowing the input parameters we could know when it is more convenient to do the following things:

1) Charge the HT-TES: the heater and the charging fan is switched on and the left valve is open in order to carry the heat flux of hot air at T=600°C to charge the storage. In principle, it is convenient to do that when the electricity and heat prices are low, in this way the owner of the plant could buy electricity in a more convenient moment.
2) Store the energy: the right and left valves are closed and the heat is stored inside the rocks. This operation happens when it is neither convenient to charge and neither to discharge.

3) Discharge the HT-TES: the discharging fan and the turbine are switched on and the heat inside the storage goes down in order to produce electricity or thermal heat considering the heat demand of the district heating that is connected in Copenhagen. The solver could choose if it is more convenient to use electricity day ahead or intraday electricity prices or use that heat flux into thermal heat in district heating. The heat flux goes in opposite direction with respect to the charging phase because in order to have a good steam cycle performance it is important to preserve the exergy of the flux that is exiting from the storage.

The solver controls thanks to the constraints, the behaviour of the storage in order to respect all constraints but also to maximize the annual profit.

The solver used to do this analysis is inserted in Optim Toolbox in Matlab and the type of optimization Problem is 'Mixed integer linear programming'. The choice of an optimization problem solver derives to the constraints that it is imposed. More the problem is elaborated; more the solving time is long.

The optimization program has a great industrial interest for the developing of the society and to try to understand is a new technology or a new technology and to predict if a company program could be efficient and winning or not. Therefore, imaging to be a company and knowing that this technology that we are talking about is environmental friendly with respect to conventional plant, it is a good option to see if it could be put on the market and if this technology could be advantageous from the economical point of view.

That is why. It is built an algorithm suitable to all type of hourly annual prices and suitable for all values of input parameters.

Mixed Integer Linear Programming:

The optimization methods depends on the constraints that you have to apply to the Objective function. It is a large field like:

Evolutionary algorithm

Simulated annealing

Newton method

Branch and bound method

Linear programming

Non-linear programming

Mixed integer linear programming

The algorithm that it is chosen to find an optimal solution is the mixed integer linear programming method.

The optimization problem, in general, is of an objective function that the solver could minimize or maximize, a set of optimization variables that the solver uses to optimize the objective function changing their values and considering a set of constraints. Constraints are a set of equations that regulate, in our case for example, the storage behaviour considering the thermodynamic of the heat fluxes, the limits of technical parameters and considering the boundary and external conditions. So the solver have to manage this equations constraints,

variables in order to minimize or maximize the objective function independently regardless of the algorithm used.
Concerning the mixed integer linear programming is a way to solve and manage the problem using this types of optimization variables (continuous or binary) and and linear equality or inequality linear constraints.
This type of problem could be written in this general form:

$$\min_{x_i} f(x_i)$$

Knowing that:

$$Ax \leq b$$
$$A_{eq}x = b_{eq}$$

Where: A is a matrix, b is a column vectors and x is the vectors of the objective variables

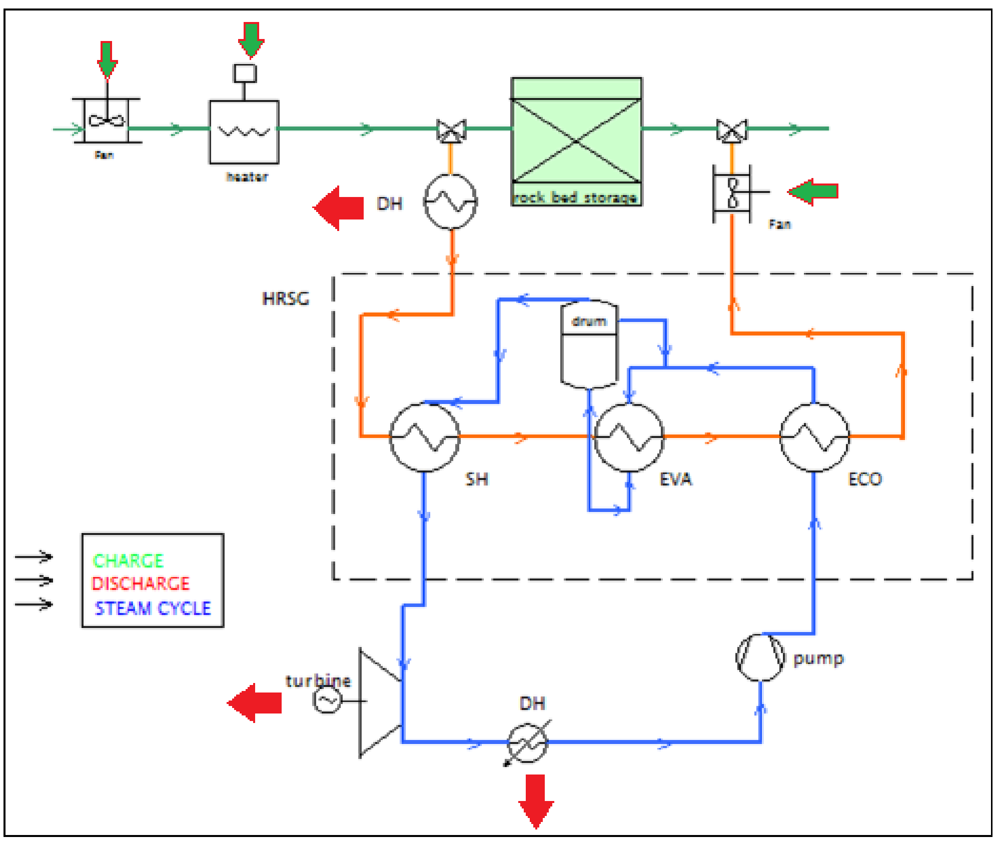
$$x \in \mathbb{Z}^n \times \mathcal{R}^p$$

All optimizations variables x_i have to satisfy the constraints as follow: S={x $\{x \in \mathbb{Z}^n \times \mathcal{R}^p, Ax \leq b\}$, that is called a feasible set and x that belongs to S is a feasible solution.
Concerning the type of solver that is possible to use the three different approaches are:
Branch and bound: it picks a variable and divides the problem in two subproblems. (e.g. if x ∈ {0, 1} solve the problem with x = 0 and the problem x = 1)
Bound Solve the LP-relaxation to determine the best possible objective value for the node. It is built a branch of the tree with the node that could be the feasible solution (i.e. the tree will not be develop any further in this node) if the subproblem is not feasible the best achievable objective value is worse than a known optimum. The optimtool tries to solve a linear problem but if the taking variables violate the optimum binary constraints a branch bound method is applied. The best solution is feasible and found when the tree do not grow further. Branch and bound is an iterative method to find the solution in a mixed integer linear programming optimization. It is possible to find the feasible region to solve the LP and obtain the solution in the best way or adding a new constraints on binary variables (cutting the possible feasible solutions) that removes the fractional solution from that part that is not more feasible.
The second approach is the Cutting plane in order to find the optimal solution we could imagine the solution's domain a space of n coordinates in R^n. Using the constraints this domain is cut every time a constraints is added in a iteratively way in order to cut the domain. Iteratively, some value to optimization variables in that region is put in order to find the best solution
Feasible solution: when it is not possible to find the right solution the alghoritm find a feasible solution, not the best one.

Sometimes the solver could relax the solution from mixed integer linear programming to linear programming only removing the integer constraints on all objective variables. The size of the problem, so the number of the objective variables determines the time of finding a solution and the time of to find all most critical points.

There are a lot of factors that it is mandatory to consider when formulating an optimization problem because they influence the solvability. Relaxations is one of the approaches of the objective when the solution has to be found. So means that if the limit of the bounds are near to the relaxation yields is good. There are a lot of manners to find the narrow bounds, one of this is to keep the constraints in a sparse way. Very complex constraints that contain many variables usually allow more solutions then sparse constraints that only contain very few variables. Moreover, in branch-and bound method only variables with integer restrictions are considered. Thus, the integer variable number determines the size of the search tree in the worst case. It influences the running time of the script in order to find the best solution. To build this algorithm and to simulate the correct power-to-power plant behaviour there is fundamental to identify the correct optimization variables:Firstly is identified the two fluxes that enters and exits into the storage and the energy inside the storage. Considering the storage, it is assumed like a 0D model: we do not know how is the real Temperature inside the storage, so we do not know anything about the thermocline. The other variables are the energy that exits from the DH after the rock bed storage, the energy of the turbine and the energy of the heat of condensation for the district heating. Others optimization variables are the fans energy and the heater one. These are the continuous optimization variables. The binary variables are used only for mutually exclusive constraints. These variables are vectors with 8760 values and, for every hours the optimization constraints have to be respected.

FIGURE 108



So the optimization problem is reduced at an optimization objective function whose the aim is to maximize the annual profit. Choosing the year of interesting (2017 for the past and 2035 considering the renewables' scenario) it is possible to conduct an analysis of the following:

- To know the value for each heat fluxes in the tubes. The energetic analysis is zero dimensional so we know the temperature, the mass flowrate and the energy considering the uniform temperature in the section of the tubes. As we said, if that part of the plant is off, the temperature is equal to the ambient temperature, otherwise is it is on the temperature is set. The plant could works even if the turbine power is not at the maximum value, so the only thing that could change is the mass flowrate that pass throw the plant tubes. Thanks to the Matlab optimization script it is possible to achieve at each hourly value of heat fluxes of the plant for every hours. The unit of measurement is [MWh].
- Storage state: after the simulation it is possible to know the storage state in every moment in relation on how the plant works.
- Where it is more convenient to charge, discharge or to have the pause phase.
- It is really interesting because the program could distinguish on witch market could take revenues like intraday or day ahead market, district heating or electricity market.

The optimization function is simply a linear of the vectorial products of a specific cost (it could be an electricity or district heating price, a taxation or an OPEX cost) whose the unit of measurement is [Dkk/MWh] and an energy that enters of eits from the power to power plant, whose the unit of measurements is in [MWh]. The results is the maximum profit that it is possible to achieve having as a input data the hourly prices is electricity markets, the district heating prices taxation and operational costs.

So the variables that we use to implement this problem are the following: as we know we consider four options, so four Matlab script are built in order to see which are the best feasible. So every scripts has their optimization variables.

The results are the storage behaviour alongside one year, so when it charge, discharge or storage heat. The tool is able to calculate the maximum achievable profit, the thermal and electric energy sold and bought and finally the Payback time.

10.6 Simulation results

In order to see some result and to understand how the power to plant works in the following figure it is shown some output of the program. The entering variables are the three parameters:

1. Turbine power=3[MWh]
2. Heater power=50 [MW]
3. Storage capacity=700 [MWh]

In these simulations, we consider the year 2017

In the following paragraphs it is shown how could change the power-to-power plant behaviour if the add more possibility to discharge, concerning the three options that showed before.

10.6.1 Turbine 2017

This simulation concerns only the possibility to discharge in turbine using the intraday and day ahead market. In this simulation we could consider a turbine tah has the efficiency equal to 0.34[-] discharging at a low pressure steam equal to P(T=30°C).

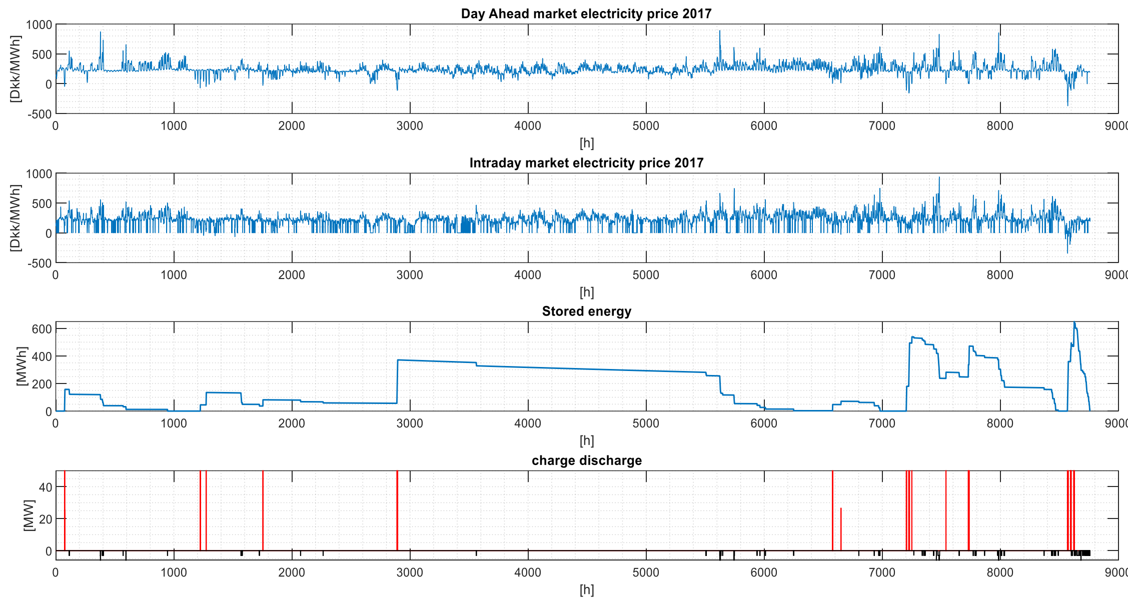


FIGURE 109

As it is possible to show see in the figure, here, it is represented the power to plant behaviour in a perfect prediction in order to have the maximum achievable revenues. In this case it is possible to see four graphs.

The first two graphs are the hourly electricity prices. The solver computes calculations in order to find the maximum profit thanks to this entrance data. The solver coordinates the storage behaviour according to the entrance data.

The third graph is the storage capacity. That value is a photo each hour and 30 minutes plus the final and the initial value, so we have 8761 values for each year. This is a way to represent the energy quantity. Obviously, if the storage is completely void, the value of the capacity is zero and this is the minimum value that the capacity in any case could have. The maximum value obviously is equal to the storage capacity set before like an entrance data.

The fourth and also the last graph indicates which part of the plant is switched on and which is off. As it is said before, the three phases do not work in the same hour, so thanks to binary condition variables. In a specific moment, so in an hour, it has or charge, storage or discharge phase. The graph shows the moment in which it is possible to charge (red line, only positive value) and to discharge (black line, only negative value). If one of that part does not work its value is set to zero.

As it is possible to see in these graphs. If the intraday or day ahead market price is low, it is convenient to charge, so the storage energy increase with an efficiency of 0.95.

If we are in the storage phase, the black and red line are set to zero and the storage capacity remains more or less at the same value except an efficiency equal to 0.008%.

If you are in the discharge phase, so the black line is different from zero, the storage capacity decreases in order to heat up the steam cycle in order to produce only electric energy. The energy that come from the storage is decrease with an efficiency equal to 95%.

As it is possible to see in the graph, to have the maximum profit considering only the possibility to discharge in turbine, so to produce only electricity the power-to-power plant does not work a lot.

In the following graphs it is possible to see the payback time, the portion of energy concerning the intraday market and how many hours, in percentage, the plant could work.

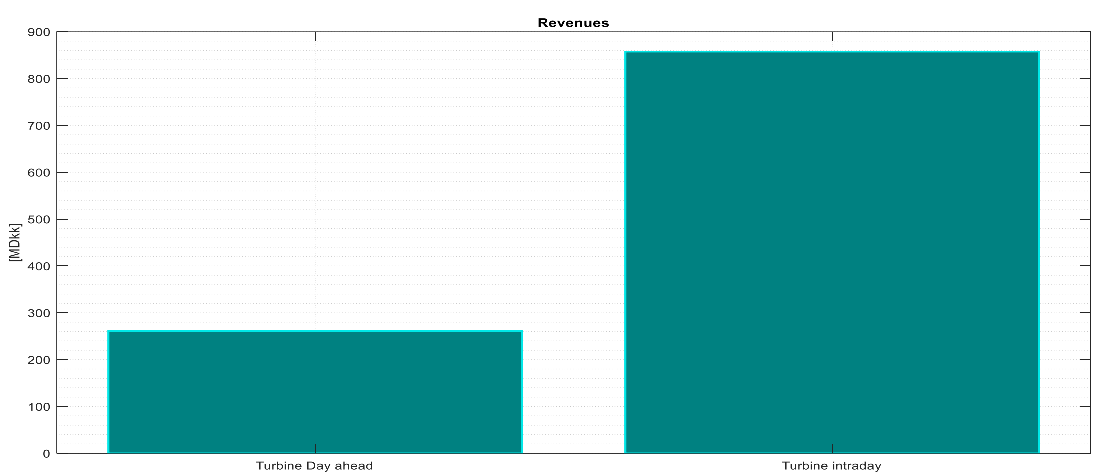


FIGURE 110

In this case the intraday market is more attractive concerning electricity prices as it is possible to see in the previews graph. This is due to the more oscillation of electricity intraday curve. That is why it is more convenient to have two electricity market in order to have a lot of possibility to discharge and charge.

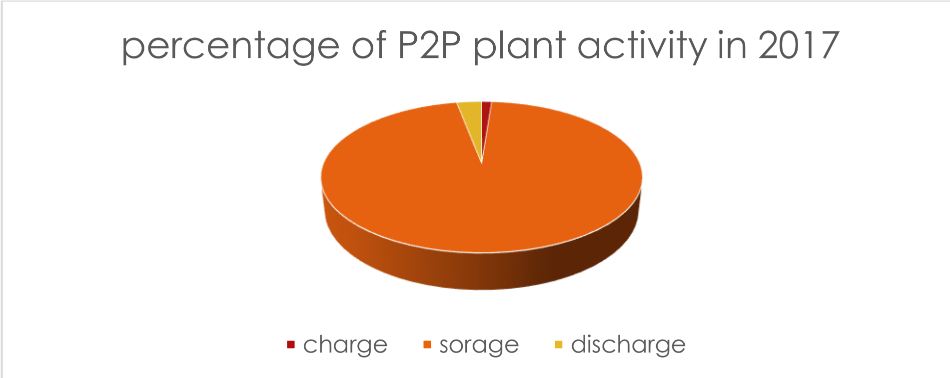


FIGURE 111

As the graph shows the power to power plant in the whole year doesn't work many hours. One of the motivations is that the possibility to discharge is only one and the turbine power is low. Therefore, even if the heater power is higher there is motivated for what to charge the storage in certain time. That is why the charge and discharge percentage hours are low and the main part of the pie chart is storage phase

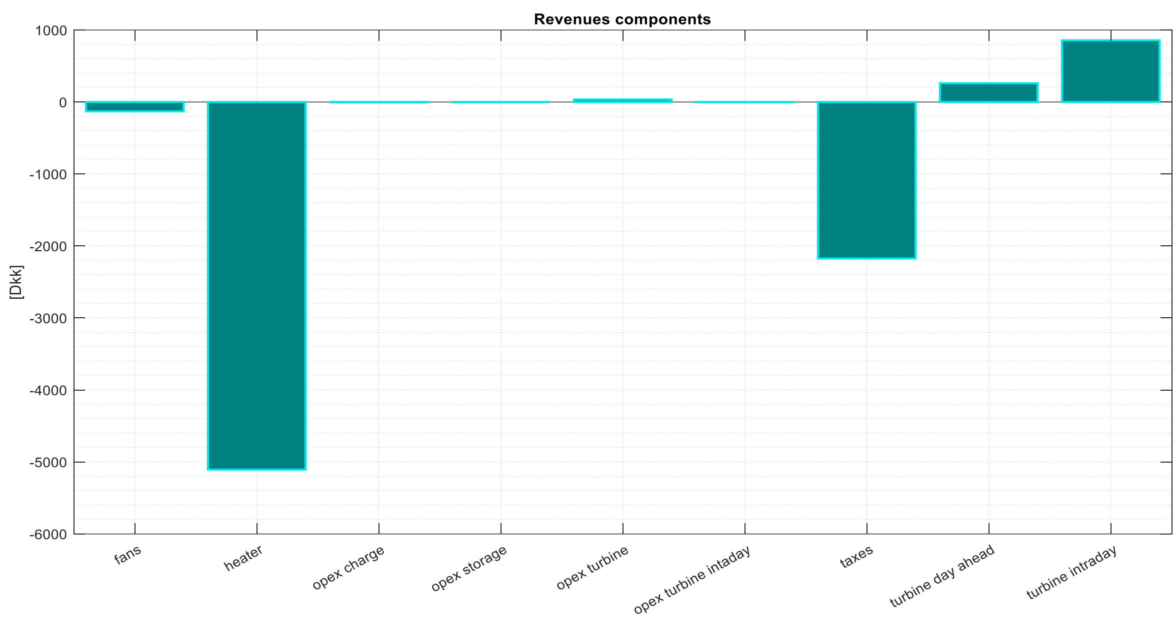


FIGURE 112

The maximum annual plant profit comes from the portion of energy that I buy, and I sell. In this case, so in case we have only the possibility to discharge in turbine, the portion of the energy that you buy are the fans, taxes, operational costs and the main part that is the heater power. The costs is proportional to the energy that you buy, that is why the heater is the main part of the bought money.

Concerning the sold money, there are the electricity prices that came from the intraday and day ahead market as we said before.

The main result for this simulation is the following:

total plant 366.0[year]

charge 27.0[year]

storage 7.0[year]

discharge 43.0[year]

repowering 50 [years]

The annual final profit is 0.225215[MDKK]. Considering that the cost of the plant is very high, this is not sufficient to have good revenues during the whole life time. To see if a new technology is feasible and winner or not it is a good idea to evaluate the payback time in order to understand that. Since the plant is originally divided into three part and in order to see which part is more expensive we calculate the Pay Back time of the charge, storage and discharge part and finally the Payback time total plant. As it is possible to see in the previews table, the amount of year of the total plant is so much, so considering the year 2017, even if is the most promising year considering electricity prices oscillations are the 2017, this type of plant, at the moment is not feasible.

10.6.2 Turbine, turbine and district heating 2017

In this section is considered the plant that has two discharge options like:

- To discharge in turbine with an efficiency of 34% a low pressure level equal to P(T=30°C);
- To high the low pressure level in order to discharge in turbine, in order to produce electric energy and to use the steam cycle heat of condensation to discharge in district heating. This option has an electrical efficiency equal to 28% and a low pressure level equal to P(T=100°C).

Considering the second type of plant in the same year, so in 2017, if we consider the same input data, so the power turbine equal to 3 [MW], the heater power 50 [MW] and the storage capacity 700 [MWh].

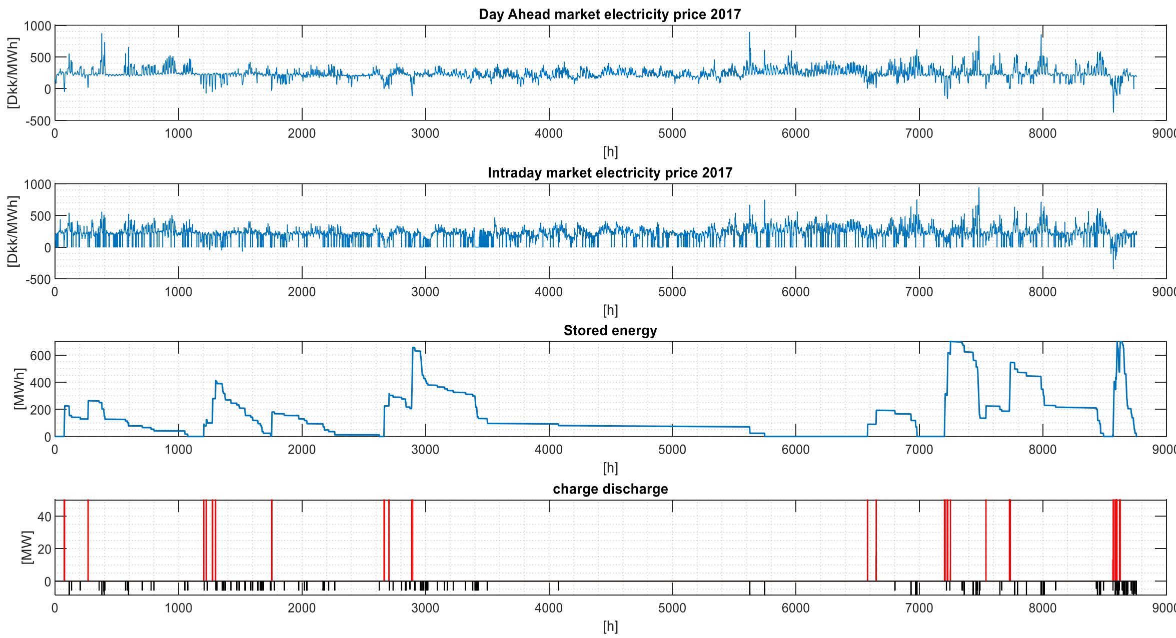


FIGURE 113

As it is possible to see in this figure, the storage is more active. The reason for what there is more possibility to have charge and discharge phase is because there are higher prices. If we consider the district heating prices is higher with respect to the mean value of each price. In certain hours, it is possible to see that all the storage is full. This is a very important data because the money that the owner spent to have that type of storage are useful to have a good power-to-power plant behaviour. If the storage capacity would be never reach, it would be more convenient to have a smaller storage in order to reduce the total investment cost and the use of land.

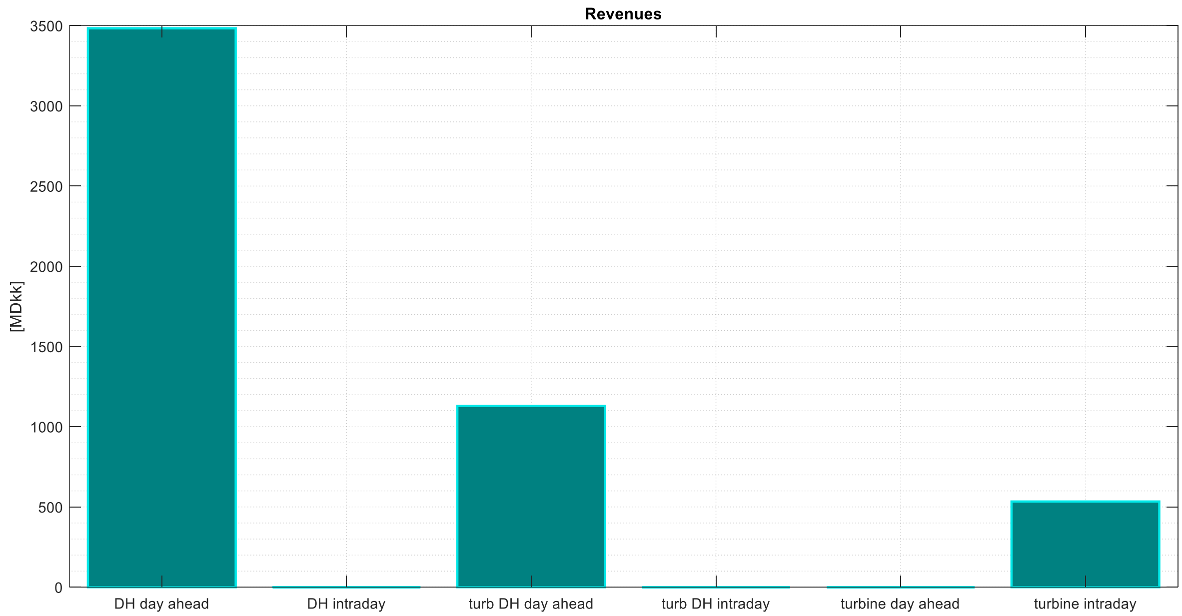


FIGURE 114

Concerning the revenues it is possible to divide the rvenues into six portions:

1. Turbine only Revenue that come from the electricity day ahead market
2. Turbine onlyRevenue that come from the electricity intraday market
3. Turbine and district heating that come from the electricity day ahead market
4. Turbine and district heatingthat come from the electricity intraday market.

Like the figure shows, it is more convenient to use the electricity day ahead prices if you consider the option to discharge only in turbine and sistrict heating or to discharge only in turbine but with intraday market prices. The motivation is that a lot of intraday market prices are bigger than the summation of the amount of money made by the summation of the revenue of the other options. The possibility to have more choice in discharge phase it makes that the maximum annual profit could be higher but make the plant more complex concerning construction, the cost are higher (in this case not so much because it is mandatory to add only an heat exchanger) and the computational cost complexity are higher, even concerning the computational time in running program.

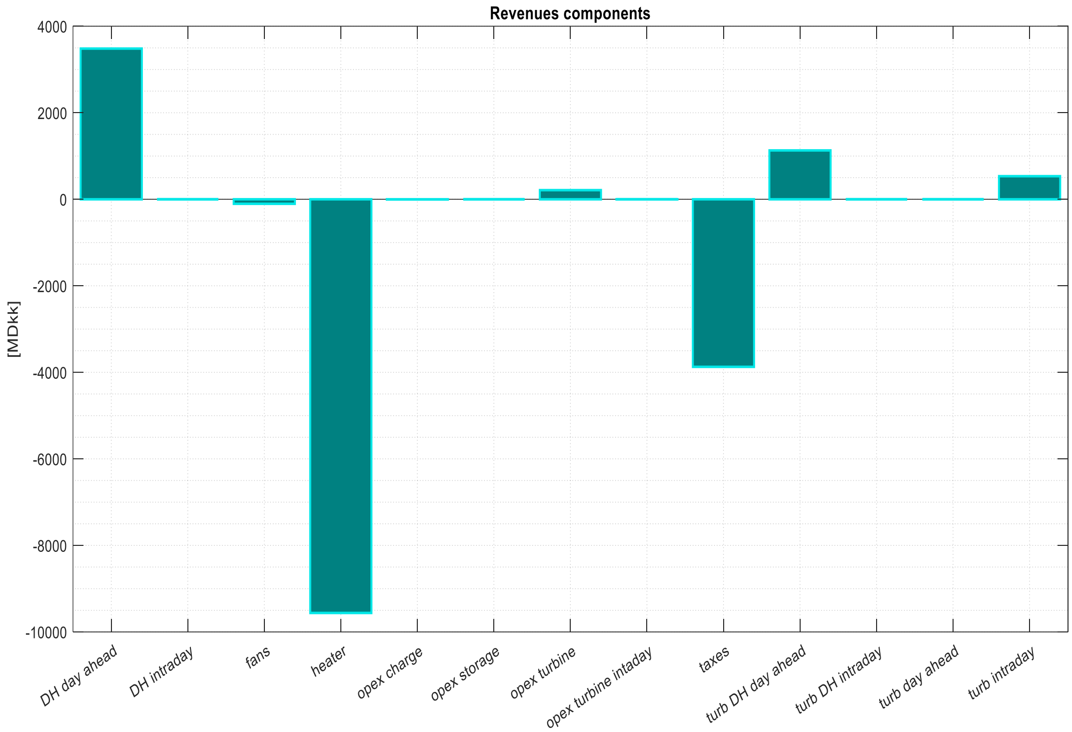


FIGURE 115

In the revenues subdivision si done from the same f the previews case. As in the previews case, the money that we sold is bigger cncerning the heater but even for taxes. The taxes increase because the power topower plant is more active. So the exchange of money increase and even the summation of taxation increase.

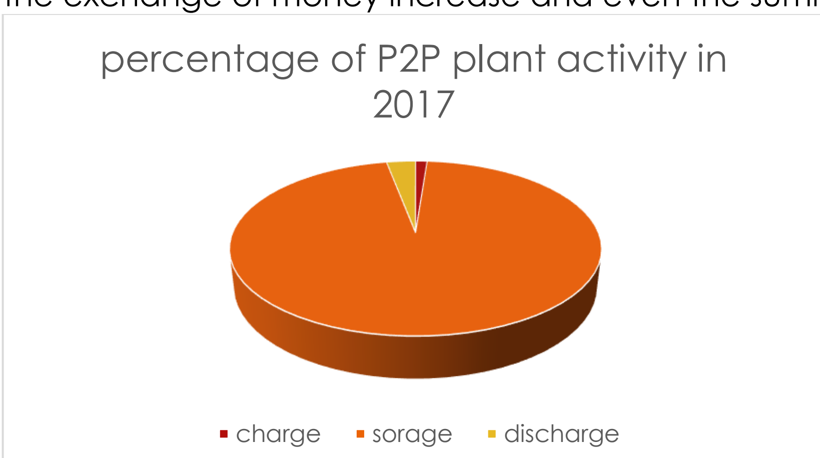


FIGURE 116

It is possible to see that the storage behaviour is more active

The payback time results are the following:

total plant 242.0[year]

charge 18.0[year]

storage 5.0[year]

discharge 29.0[year]

repowering 46.0[year]

10.6.3 Turbine, turbine and district heating, district heating only 2017

In this section is considered the plant that has three discharge options like:

- To discharge in turbine with an efficiency of 34% an a low pressure level equal to P(T=30°C);
- To high the low pressure level in order to discharge in turbine, in order to produce electric energy and to use the steam cycle heat of condensation to discharge in district heating. This option has an electrical efficiency equal to 28% and a low pressure level equal to P(T=100°C).
- To produce energy useful for district heating taking the heat from the heat exchanger put between the HRSG and the storage

Considering this third type of plant in the same year, so in 2017 if we consider the same input data, so the power turbine equal to 3 [MW], the heater power 50 [MW] and the storage capacity 700 [MWh] the following graph shows how the plant behaves with this type of input:

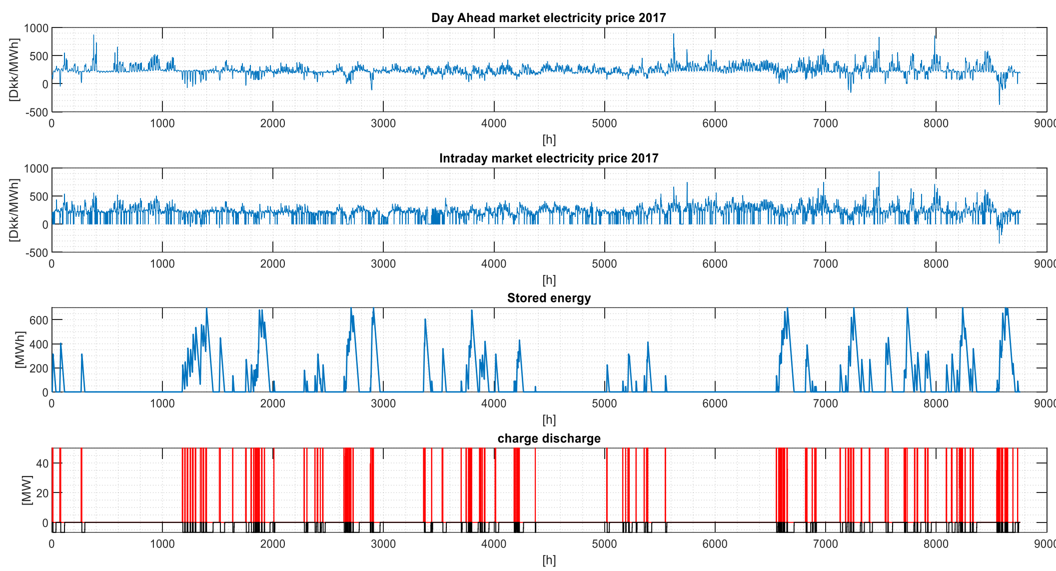


Figure 117

Considering the same electricity markets and the same heating price it is possible to see that the power to plant is more active, the graphs of different options of revenues shows that for the plant it is more convenient to discharge only in district heating trhought the heat exchanger between the storge and the HRSG because the final price is more high with respect t the other options. The motivation is that the specific district heating price is higher that the other markets prices and the energy produced is the highest, because that heat flux must not pass throught the bottom cycle efficiencies, That why it has an higher annual profit, an higher annual revenues and higher performance. As it is possible to see, the charging ohase follows the electricity prices and the discharge phase not because it takes advantage from the district heating markets. Since the heating price are constant, the storage behaviour (plot 3 in the figure …) has the time to charge and immediately it discharge, because it not to wait the best price since that the district heating price are constant.

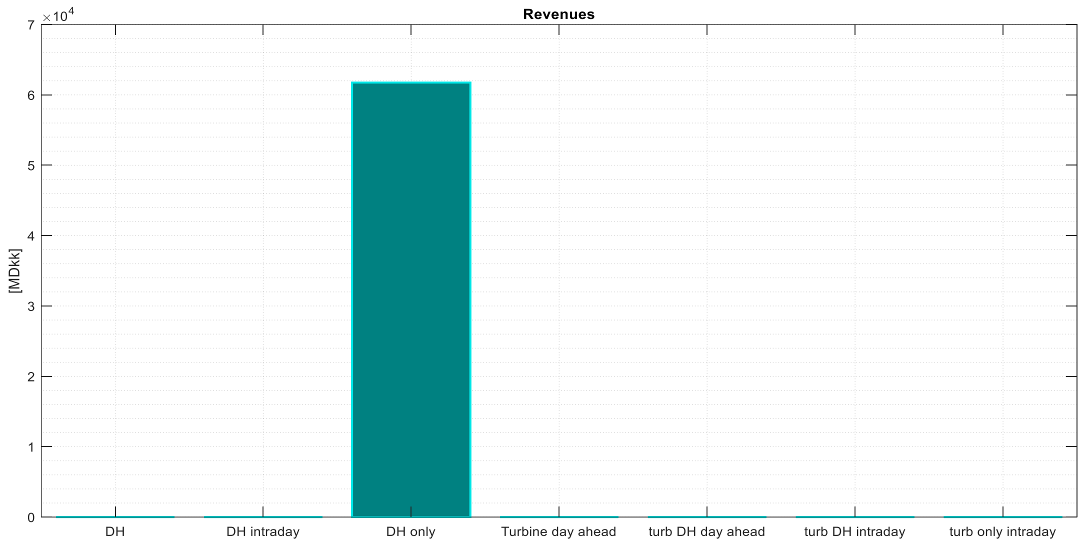


FIGURE 118

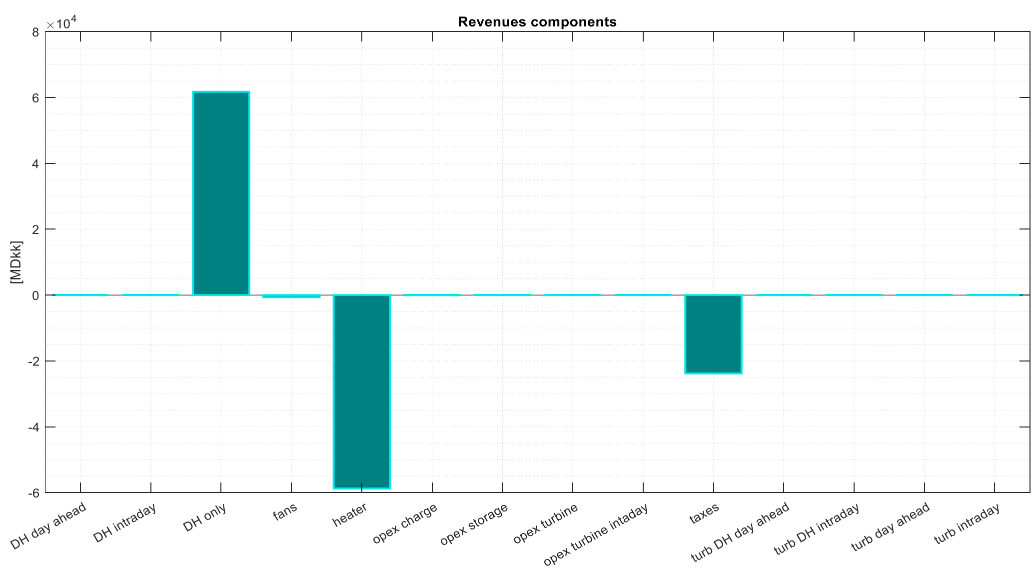


FIGURE 119

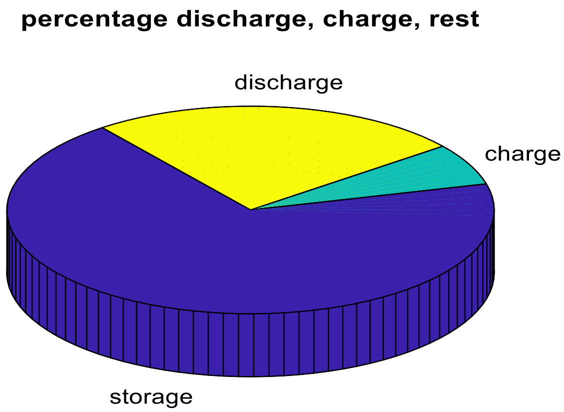


FIGURE 120

As it if possible to see in the pie chart, the plant is more active with respect to the others options. The annual revenue is equal to 2.234722[MDKK]. Only the district heating market, in this simulation could give revenues to this plant. So means that the electricity prices are less attractive from an economical point of view.

The Payback time results are the following:

total plant 49.0[year]

charge 3.0.0[year]

storage 2.0[year]

discharge 15.0[year]

repowering 6.0[year]

Here, it is possible to see that the Payback time is so high to have a make this plsnt feasible. The solution could be to have a repowering of the plant explained as follow.

10.6.4 Fourth simulation- Repowering

It is made another simulation considering the possibility to discharge only in district heating trought the heat exchanger. In this case it is considered only charge and storage phase in order to see, if the discharge phase it eliminate (the huge cost of the plant) which are the annual revenues and what is the behaviour and, finally, the Pay Back Time. The simulation are made only for the year 2017 considering the following input parameters:

Heater power: 55 [MW]

Turbine power: 55 [MW]

Storage capacity: 1000 [MWh]

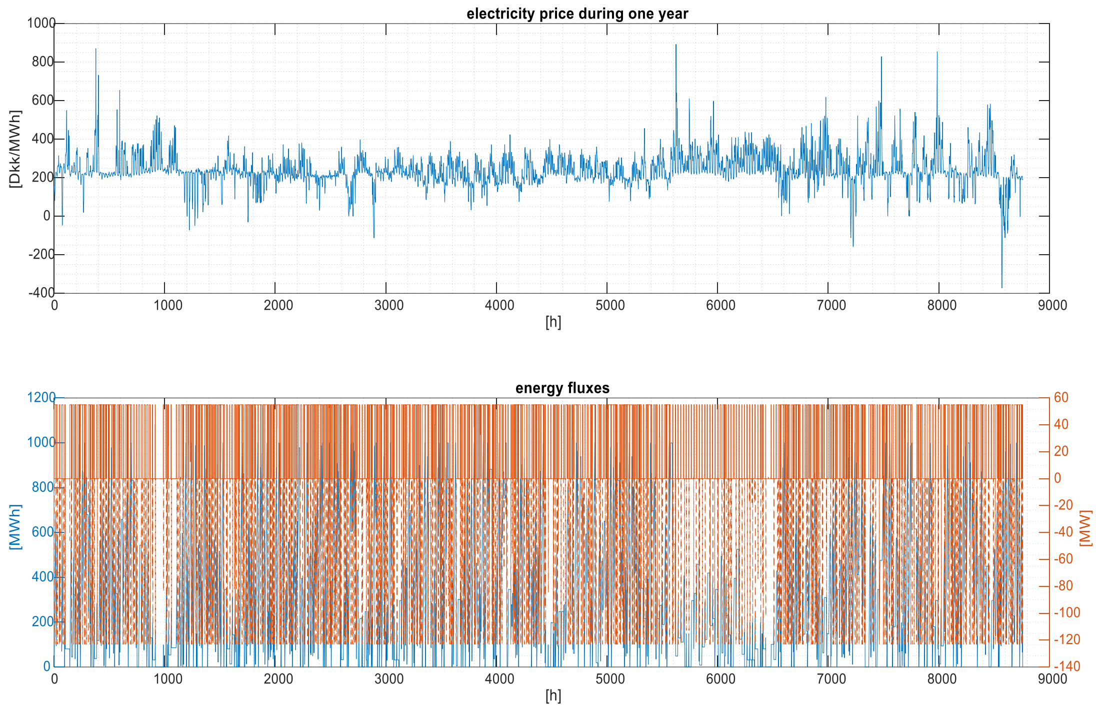


FIGURE 121

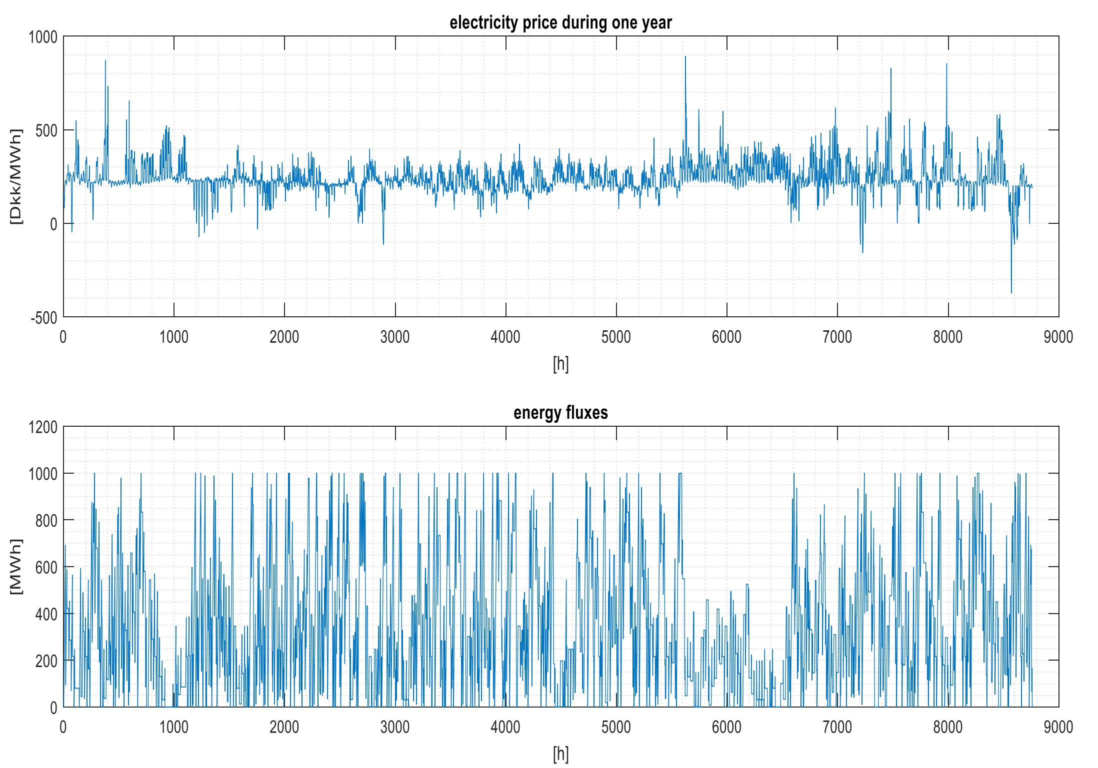


FIGURE 122

As it is possible to see in the graphs, the storage bahaviour is very active and the storage is always full. When the storage reaches its maximum capacity it produces energy. Obviously, only for charge phase the electricity prices are followed. The pay back time calculated here is 18 years, and this is a great result. it is the best result in the year 2017 considering all previews options. It gives an important result. It means that considering this technology, at the moment, so now, the district heating market is fundamental to this technology.

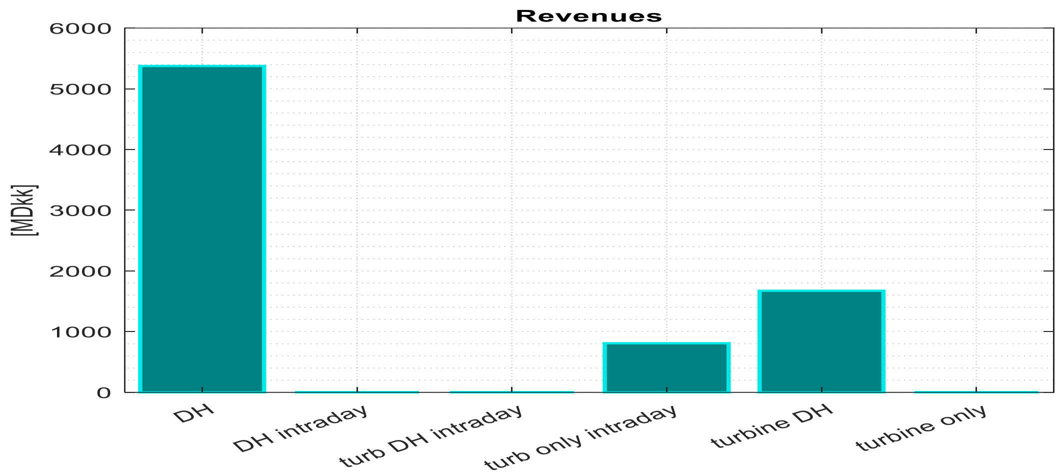


FIGURE 123

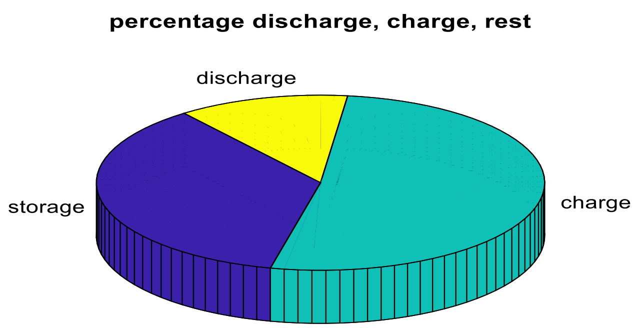


FIGURE 124

In this thesis we insert the option to carry a feasibility analisys in the future. In order to have a great comparison it is convenient to use same entrance parameters like:

Turbine power 3 [MW];

Heater power 50 [MW];

Storage capacity 700 [MWh].

As it is well explained in the previews section this scenario is built considering tha the renewables could increase a lot, so at is is explained before there will be a great electricity prices oscillation.

10.6.5 Turbine 2035

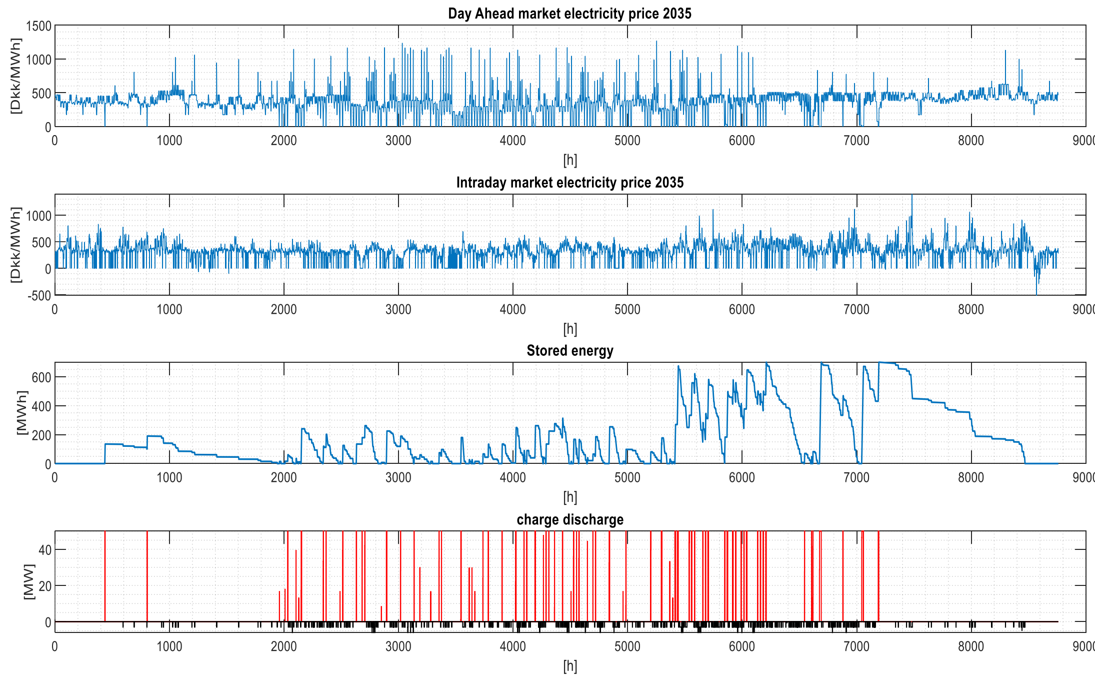


FIGURE 125

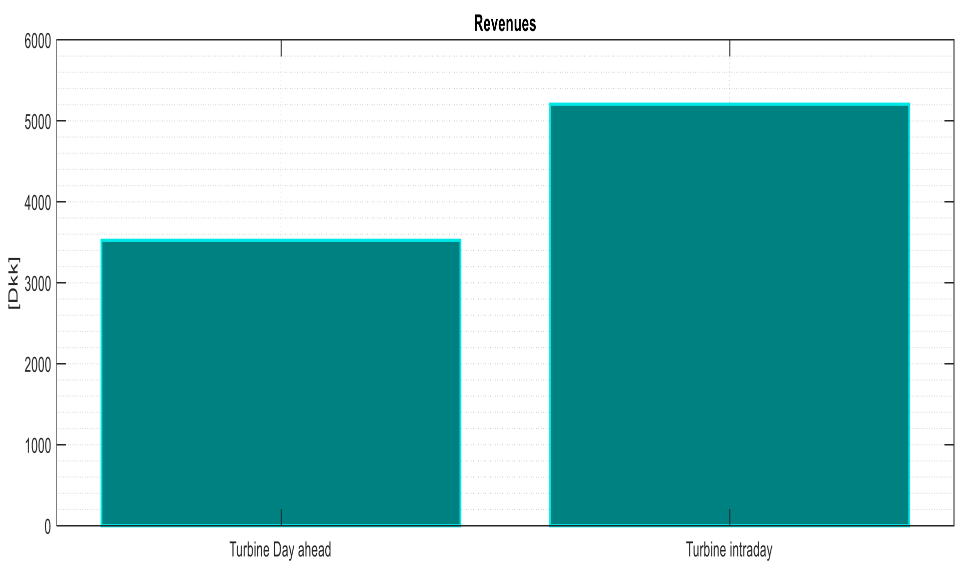


FIGURE 126

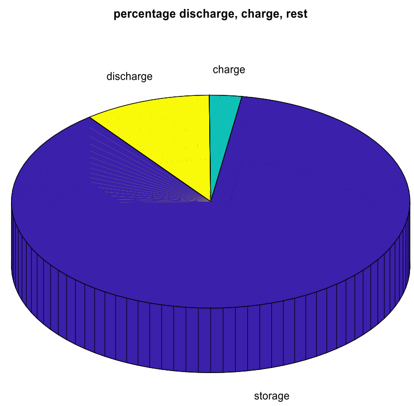


FIGURE 127

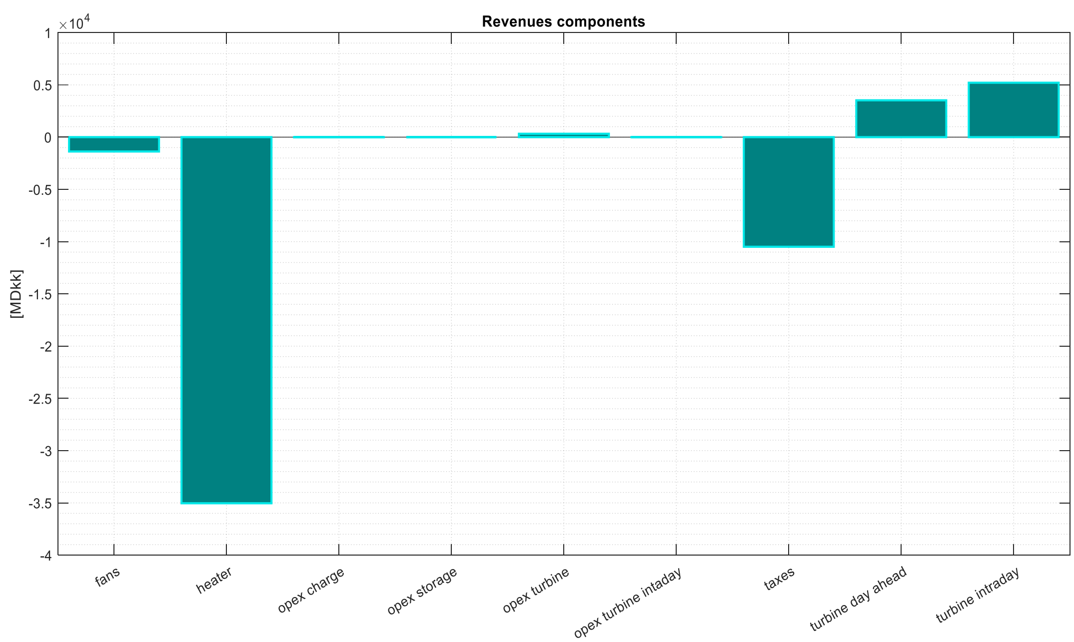


FIGURE 128

This is the output considering only a turbine that produce energy in the future scenario. As it is possible to see, the revenues are higher and the storage is more active with respect to the 2017 electricity prices. Even if in the future there are more revenues, the pay back time of the whole plant, considering this option (turbine only) is very high and it is equal to 200 years. but if we consider the possibility to only buy the charge and storage phase the cost relatively apceptable, and it is equal to 19 year.

total plant 200.0[year]
charge 15.0[year]
storage 4.0[year]
discharge 24.0[year]
repowering 19.0[year]

10.6.6 Turbine And Turbine With District Heating

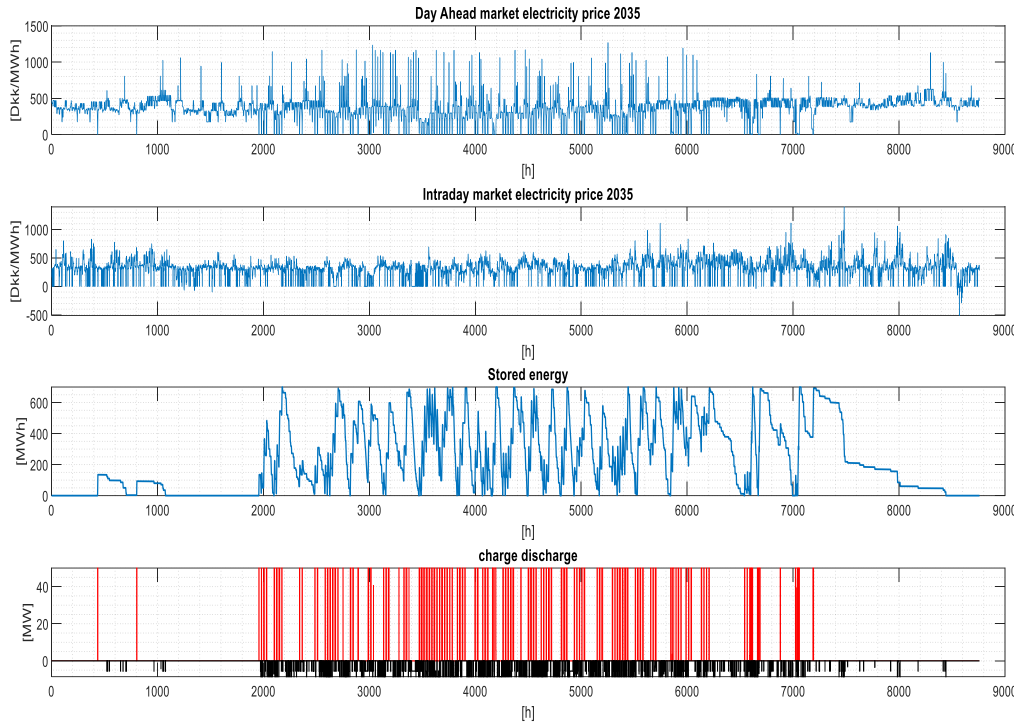


FIGURE 129

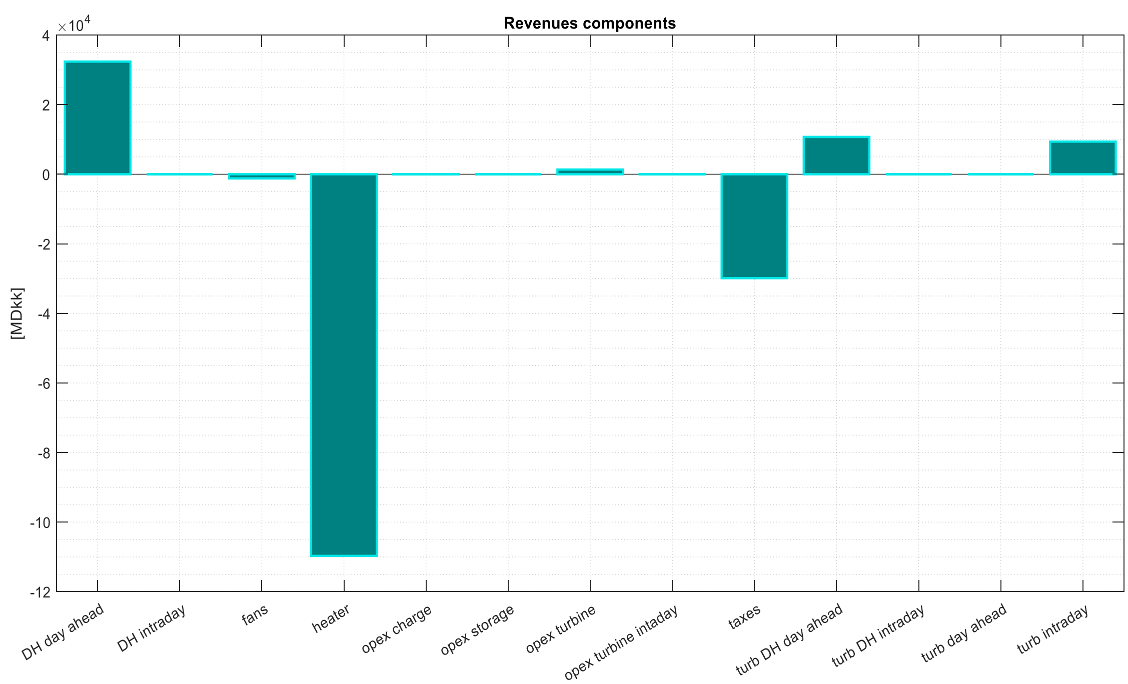


FIGURE 130

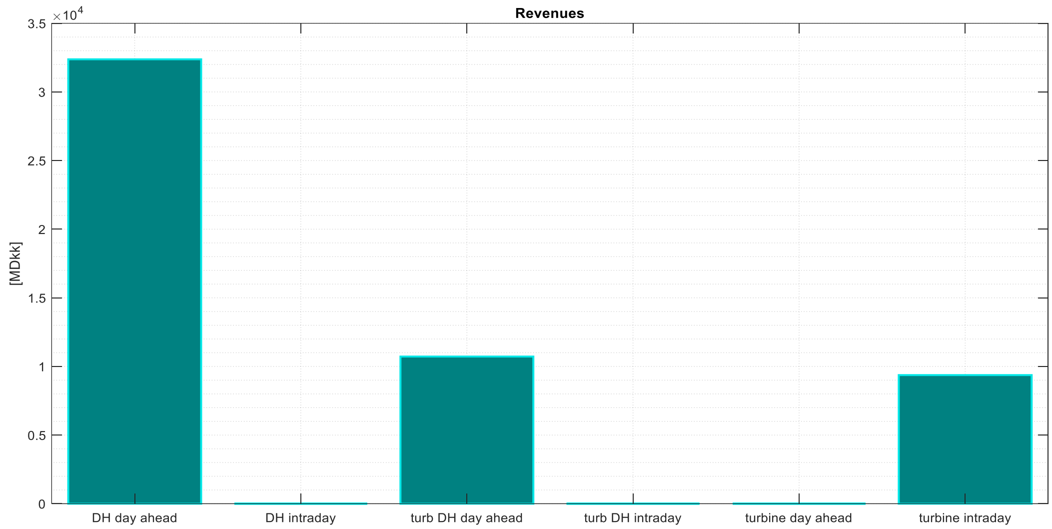


FIGURE 131

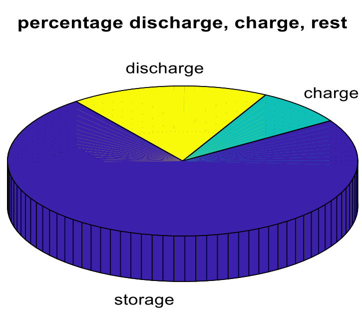


FIGURE 132

This is the results simulation in the year 2035 considering the second option, so the possibility to discharge in turbine and in turbine and district heating taking in consideration the possibility to use intraday and day ahead market. The storage becames more active with respect to the first option. The more interesting way to produce energy are the turbine plus district heating of the day ahead and the turbine only intraday market. The motivation is that the intraday market has more attractive price only for turbine because it reach very hogh specific electicity prices. Considering the final results so the payback time it has a quite high value considering the whole year, it is 45 years. with respect to the previews options it is a good result but 45 year if so much yet. So we have to search a better solution and to find rsults considering the third and last one option.

pay back time:
total plant 45.0[year]
charge 4.0[year]
storage 1.0[year]
discharge 6.0[year]
repowering 5.0[year]

10.6.7 Turbine - Turbine And District Heating – District Heating Only 2035

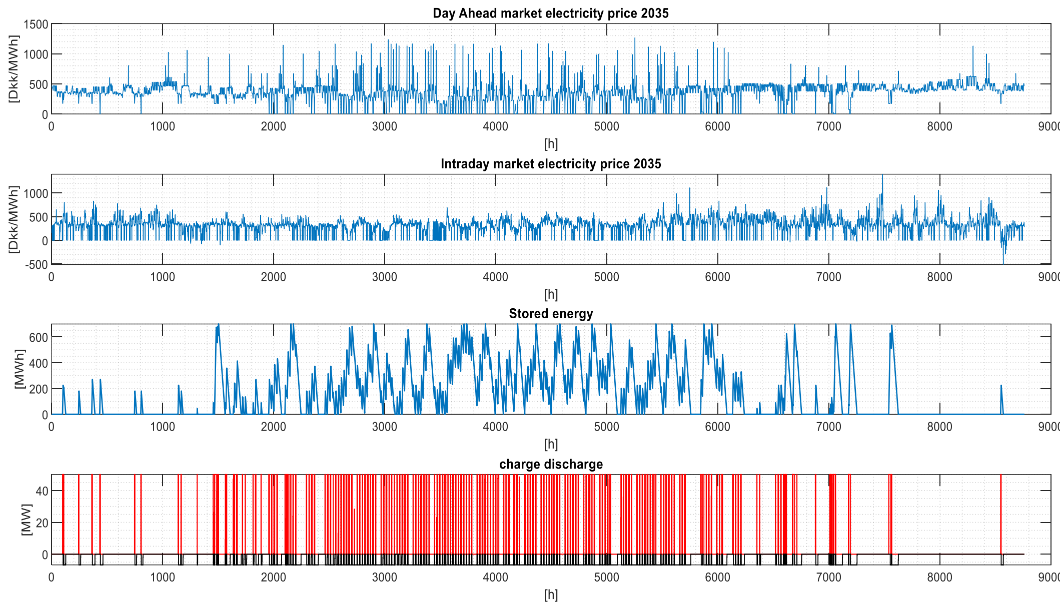


FIGURE 133

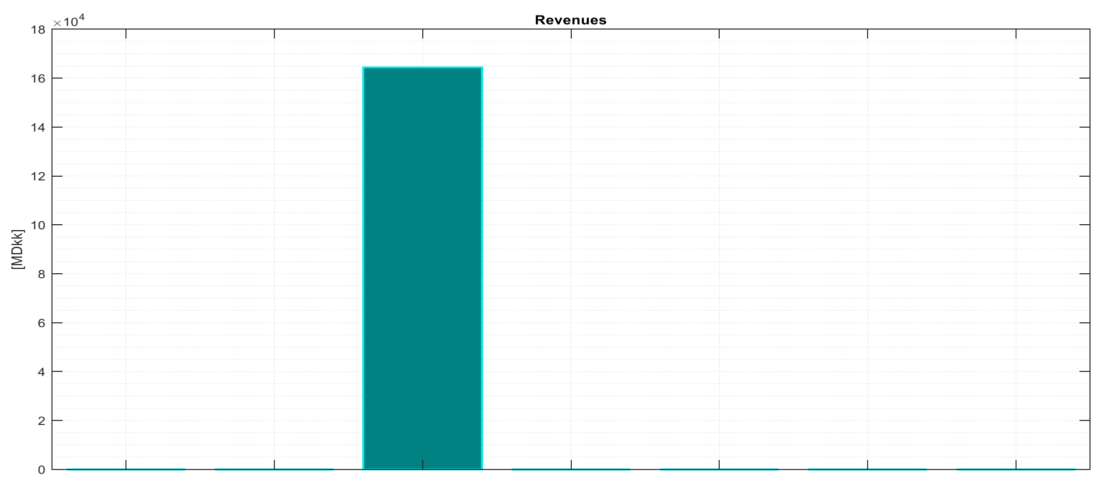


FIGURE 134

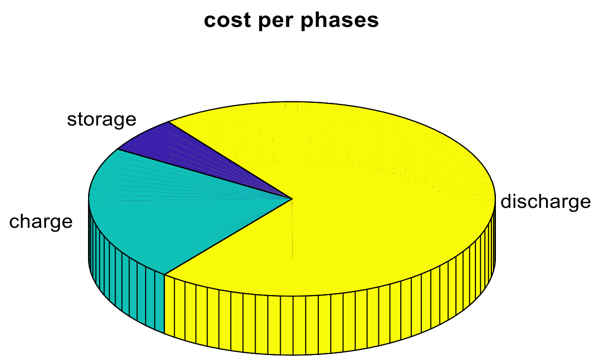


FIGURE 135 COST PHASES

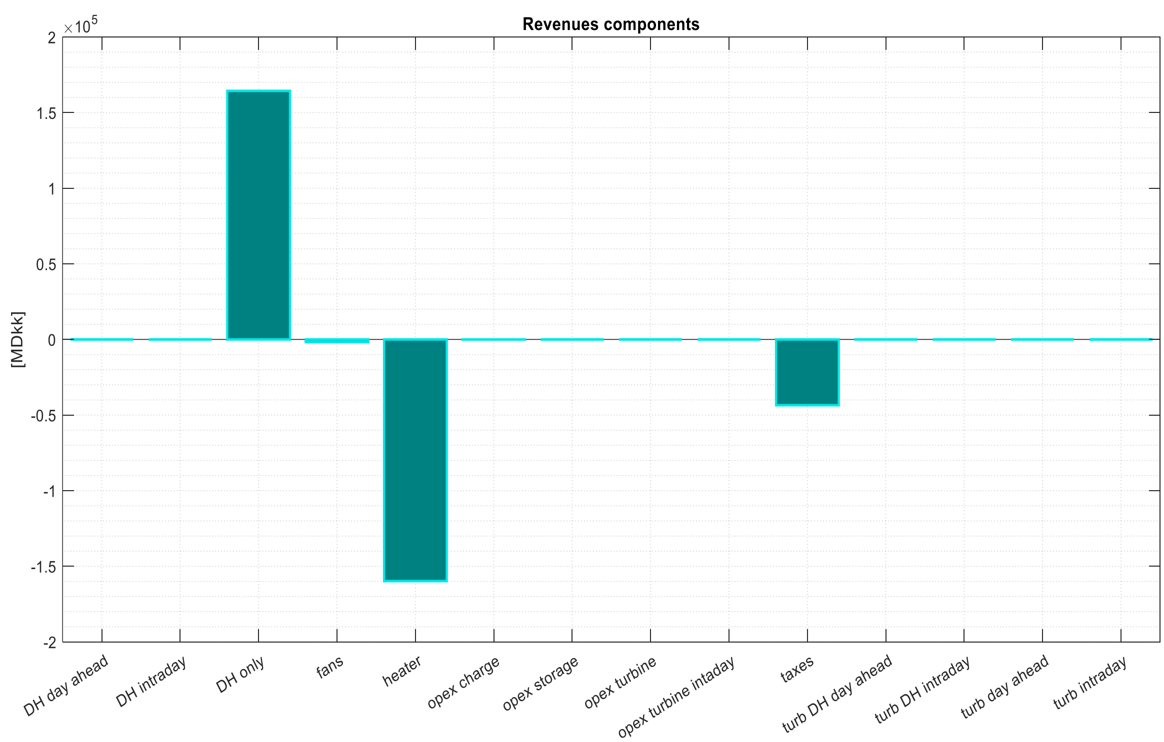


FIGURE 136

This is the final output about the third option about the future scenario in the 2035 where it is considered even the option to discharge heat throught an heat exchanger put between the HRSG and the storage. As it is possible to see in the figure n.136 the only way to reach revenues, so the more convenient way is to

discharge only in DH throght the heat exchanger. The motivation are always the same of the third option in 2017. The storage is more active because the electricity prices are more favour to gives us a lot of opportunity to generate power. the Pay Back Time is calculated and its value is 11 years. it is a great result and this gives us a good hope for the future.
The payback time has the following values:
total plant 11.0 [year]
charge 1.0 [year]
storage 1.0 [year]
discharge 2.0 [year]
repowering 1.0 [year]

This result say to us that this plant in the future, if the renewable future scenario becames reality, it will be feasible. It is a great result for the future. Considering nowadays, the feasibility of this plant is related only to the possibility of to buy charge and storage phase, in the future there will be the possibility to buy the whole plant.

11. Comments

This is the total conclusions about these scenarios

TABLE 19

2017	Pay Back Time whole plant	Yearly Profit [MDkk]
Turbine	366 [year]	0.225215
Turbine, turbine and DH	242 [year]	0.342898
Turbine, turbine and DH, DH	49 [year]	2.234722

TABLE 20

2035	Pay Back Time whole plant	Yearly Profit [MDkk]
Turbine	200 [year]	0.413117
Turbine, turbine and DH	45 [year]	1.856112
Turbine, turbine and DH, DH	11 [year]	10.215691

Here is very simple to see that if the option to discharge energy increase (like in the second and then in the third case). The main motivation is that the round trip efficiency increases adding possibility to produce energy. Another motivation is that the district heating market has price very high, so the profit will increase a lot, and these simulations are the demonstration of it. Even if it is true, so if the round trip efficiency increases, so if the energy sold if high the profit is high, the fact that to have a good profit it will depend also on the electricity prices. The electricity market, if the fluctuation of the prices is very high, the plant is really active and the possibility to use this new technology will increase, considering that this is a way to eliminate the demand the offer mismatch. So, if we compare the fist and the second scenario, the fluctuation of the year 2035 is higher, that it the cause that the final profit is higher and the storage performance are better, and it is depend on how many renewables a country has in their energy mix. And it very interesting to see that if a country has a lot of renewables in its energy mix the electricity prices are a lot of fluctuations and the possibility to insert a storage (carrying with him the possibility to save energy) is reliable.

12.Parametrical analysis

12.1 Introduction

The last step of the thesis is to find, for each type of plant, the optimal size of all components from the economical point of view. This program tool is built knowing that the independent technical parameters of the plant are the heater power [MW], the storage capacity [MWh] and the power turbine [MW]. So in this last chapter, it is performed a parametrical analysis varying these values. The idea is to find the best one for each option from the economical point of view, so considering the annual maximum profit, elaborated by the program tool and the payback time.

The parametrical analysis is done for three types of plant setup which the difference is the discharge phase and the possibility to produce electricity and district heating for two different scenarios, for the past and for the future.

Considering the different types of plant:

a. Possibility to discharge only in simple steam turbine;
b. Possibility to discharge in a steam turbine witch there is the possibility to produce only electricity, like in the first case, and to produce simultaneously electricity and heat for district heating using the heat of condensation;
c. The last option includes the previews one plus the possibility to produce only heat for district heating using the heat that exits from the storage directly.

Using these types of different plant layout it is performed an analysis on two years, the 2017 and the 2035, like a future scenario, considering the 'distributed generation', so the future possibility to have the energy mix in Denmark a large part of renewables energy production.

This analysis is carried varying the three base parameters for five values. The final aim is to understand the optimal size of the plant from an economical point of view considering the Pay Back Time parameter.

The payback time is the amount of years needed to have the initial investment back. The Pay Back time tells us if an investment, in the future could be feasible and a good opportunity to reach money or not.

Concerning this analysis the simulation is done for one year, and, considering that the profit earned in that year would be the same for the following year, it is performed a Pay Back time calculation. To find the Payback time the Net Present Value is calculated. Like in the previews chapters, it is supposed an interest rate, equal to i=2%. The formula used for the Net Present Value is the following:

$$NPV = -INVESTMENT + \sum_{year=1}^{n} \frac{profit}{(1+i)^{year}}$$

The Pay Back time identifies the number of years useful to have that investment back. The analysis performed wants to find, throw this simulation, the best size of the plant considering the three phases, charge, storage and discharge part.
The values used for the parametrical analysis are the following:

TABLE 21 PARAMETRICAL VALUES FOR THE DEVELOPING TOOL

Turbine power	[MW]	100	50	10	1	0,1
Hater power	[MW]	200	70	20	7	-
storage capacity	[MWh]	3000	2500	1500	800	300

As it is possible to notice in the previews table the lowest value of heater power is not considered. Running the simulations and seeing the output value, so the final payback time and the final annual profit, it is clear that in all simulations all types of plant would be unfeasible because the revenues are always equal to zero. That is why in this present thesis this value (heater power equal to [MW]) is not discussed in the following chapters.

12.2 1st option 2017

The results are very different from each other. Concerning the 1st option in the year 2017 the simulation results tell us that the plant is completely infeasible. The lowest return of investment requires almost 200 years. The main problem is that the total cost is high and the production is very low. As we know, the tool gives us information about storage, charge and discharge time in order to reach the maximum profit, so it means that the feasibility of this plant, now it is not convenient. It could be a good option only if we consider a repowering of the plant. Considering this option, the investment requires only the storage and the charge phase, so the initial investment is lower. Considering the repowering option, the best arrangement is a turbine with the same order of magnitude lower with respect to the heater power with a big storage. (H=70[MW], T=50[MW] C=2500[MWh]). Even if it is the best value the Payback time corresponds to 51 years, so it is infeasible anyway. The motivations are the following:
In principle, this type of plant does not operate very often because the possibility to produce energy derives only from electricity. The same plant, considering only this option has a lower energy because the electricity production passes through a lot of efficiencies, lower with respect to the others plant layout studied.
- We said before that the plant does not work a lot, so, it is forced to store energy for a long time. That is why it is very advantageous to have a big storage to store a lot of energy for a long time. . The interesting thing is that if the plant has a heater [70-7] [MW] and a small turbine [1-0.1] [MW] the maximum profit is equal to zero.

12.3 2nd option 2017

The second option in the year 2017 concerns the possibility to produce electric energy and heat for district heating using the steam turbine. The simulations results say that this plant infeasible anyway because the Pay Back time is the same order of magnitude of the previous case. The interesting thing is that if the plant has a heater [70-7] [MW] and a small turbine [1-0.1] [MW] the maximum profit is equal to zero. The motivation is that if the turbine is small it is preferring to not produce energy, otherwise the profit will become negative. The lowest value of Payback time of the whole plant is equal to 156 years with a turbine equal to 1 [MW] an heater of 200[MW] and a storage with a capacity equal to 800 [MWh]. The plant is infeasible anyway. Even here, there is the possibility to make a repowering . it is a good option but the small Payback time is 40 years, so it is infeasible anyway.

12.4 3rd option 2017

Considering the last plant layout in the year 2017 the results are very interesting. The result simulation says us that the lowest Payback time is equal to 33 year with the following data:

T=10 [MW], H=200[MW], C=3000 [MWh]. This is the best result considering the year 2017 for this three plants layout, even if the Payback time is quite high. So if we want to build this plant now, the only possibility is to considering this third option. Considering the repowering, the results are very interesting: for a range of T=50 -1 [MW], H=200 - 20[MW], C=3000 -1000 [MWh], the payback time is below the 50 years. it is an interesting result because this says that this plant is useful, the only problem is that the cost of the HRSG and the steam turbine is very high but to have in a plant a storage it will be a real good possibility to adjust the electricity prices mismatch. It is very interesting to notice that varying the size of the storage the Payback time changes only a bit.

Therefore, this plant is feasible but it is very important to respect the correct size otherwise it will become infeasible and it is really interesting if it is considered the possibility to make the repowering of the plant with a large value of option in relation to the turbine size.

12.5 1st option 2035

Considering the future scenario for only electricity production, the plant results unfeasible anyway. The lowest value is 80 years with a small turbine equal to 1 [MW] and a big heater 200 [MW] and storage capacity 3000 [MWh]. Even if for the 2035 it is not feasible, it is promising for the future. These types of simulation gives us info about the electricity shape. For this type of plant the electricity fluctuation is very useful, so, considering that renewables could increase the electricity prices fluctuation, in a future could be really useful for the feasibility of this plant.

12.6 2nd option 2035

The second plant layout is considered feasible for a lot of heater and turbine power range. It is interesting to verify that the variation of storage capacity do not influence a lot the pay back time of the plant, even if this is true, it is better to have a big storage in this way the energy could be stored for a long time and it could be useful for another moment. The optimum value is T=10 [MW], H=200[MW], C=2500 [MWh] where the lowest Pay back time value is equal to 28 years. The good range is T=10-1 [MW], H=200 -70[MW], C=3000 -800 [MWh]. In this range, the maximum value of payback time is equal to 54 years. Like in the 2nd option of the 2017, its shape is similar to an exponential surface.

12.7 3rd option 2035

This last plant layout in the future scenario the range of feasibility increases a lot. The lowest value of this range 5 five years for the payback time with T=50-1 [MW], H=200 - 7 [MW], C=3000 -300[MWh], and it is a good result. The highest value of payback time in this range is 37 years. This plant is completely feasible, so it will be very interesting to studying it. The optimum value is T=10 [MW], H=70[MW], C=3000 [MWh] where the lowest Pay back time value is equal to 7 years. Considering that varying the storage capacity the final profit does not change a lot, the shape of the surface (so varying only the heater and the turbine power) is like a paraboloid with concavity upward. The minimum is the region that it is explained above.

12.8 Conclusions

Running this simulation, it is possible to notice that the introduction of more options for producing energy in discharge phase increases the profit and diminishes the Payback time. This plant is really dependent on the electricity and district heating fluctuations: more the electricity prices go up and down in a short time more the plant could produce energy and to reach money. The district heating market, even in the future, has a fundamental role to this type of new technology and it will be interesting to studying this market in order to understand how to insert HT-TES in the heating networks. It is interesting to see that the heater is almost one order of magnitude less with respect to the turbine power. It is preferred to have a large storage because it does not cost a lot and it is useful to store more heat. So now, considering the 2017 like a base year the third type of plant right now is the best but it is feasible only considering the repowering. For the future scenario, the plant is feasible considering the repowering in any cases and considering the whole plant it is feasible for the second and the last option and it could give a lot of revenues and a good profit for the future. It is interesting to notice the variation of storage capacity does not change firstly the investment cost, the profit and finally the payback time. It is an interesting thing because if we have to make a plant repowering we have to control very well only the sized of the heater.

It is interesting to see that at constant storage capacity, if the heater and turbine power increase, the payback time increase exponentially in all cases more or less. Considering the first and second option the exponential curve is very rapid, and it has a minimum value quite high. Considering the last option, the shape is blandly exponential and the surface is not rapid like in the previews case, so it seems more like a paraboloid with a concavity upwards.
Finally, the last observation is that the optimum size in all this plant from an economical point of view is that, always, the turbine power has to be one order of magnitude lower than the heater power.

13.Final conclusions

In this present thesis is carried a feasibility analysis on a heat sensible energy storage based on rocks. This is a very interesting technology because it is very useful to mismatch the energy produced in a country useful for energy saving, considering the depletion of energy resources. This type of storage is inserted in a power-to-power plant. The main question of this work is to understand if this plant is feasible from an economical point of view if the plant is connected to an electric and heating grid. Since this is the first time that is carried this analysis it is supposed three types of plants: the first one considers the possibility to produce electric energy through a simple steam turbine, this option considered has an elevated exergy but a low energy produced. In the second one is considered the previews option and the possibility to produce, through a steam turbine either electricity and either heat for district heating. The amount of energy is higher but the exergy is lower if we consider that the temperature of the district heating is around 100 [°C]. The last option considers the previews one plus the possibility to discharge only in district heating.
For all of these plant it is carried a feasibility analysis developed in a tool that receives in input the base parameters. This tool gives us the technical parameters of each part, the total cost of the plant based in the year 2017. After that, it is made a optimization algorithm in order to understand the feasibility of this plant considering two types of scenarios 2017 and 2035 (considering the renewables development scenario in the future), considering two types of electricity markets, one type of district heating market based on Copenhagen it is built a perfect prediction analysis. The algorithm, knowing the whole prices, says to us what is the power-to-power plant behaviour, which the aim is to maximizing the yearly profit. This algorithm knows everything about the plant and about the electrical prices. One of the main assumption is that the storage is a zero dimensional device. It means that we do not know what is the real temperature of the storage at the hot-end. This assumption makes this perfect prediction analysis over estimated because the energy produced is the same but the exergy inside it changes and it is a problem for the steam cycle plant. in fact, the zero dimensionality of the storage is a problem only for the steam cycle because the district heating has a temperature very low, so the reality is respect for the district heating but not for the steam cycle. Even if this is true, the

temperature drop is very low, so it is negligible for big sensible heat storage. Even it is negligible issue it would be very interesting in the future to create a script with a mono dimensional storage in order to understand the real feasibility of the power-to-power plant .The algorithm says to us if this technology could be useful or not, so it was made a lot of simulations to understand what is the final payback time for different power plant arrangement for the year 2017 and for the future scenario in 2035. The main results says to us that nowadays, thanks to the electricity hourly prices shape, there is no feasible plant up to now. It could be put on the market only if we consider the repowering of a plant, so only if we consider the charge and storage phase. the parametrical simulation says to us that in a certain case, (if we put an heater power one order of magnitude lower with respect to the turbine power) the plant do not produce anything. Considering the main results for the future, it would be very interesting to see that the payback time decreases a lot and it is very interesting to notice that the two last option are feasible. Therefore, it says to us that the district heating market is fundamental and very important if we want to put this new technology on the market. Another important thing is that the electricity prices oscillation are fundamental for this power to power plant and it is in line with the renewables exploitation, like in the future scenario.Making all parametrical simulation it is very interesting to notice that to make a feasible power-to-power storage plant it is mandatory to have a heater power one order of magnitude higher with respect to the turbine power.

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