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Sustainable Power plant for Lanzhou

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Summary

Currently the Chinese city of Lanzhou uses a coal-fired power plant for their energy needs. With the life cycle of the old plant ending as well as pollution causing major stress on the environment as well as the population, an alternative was deemed necessary. Through an analysis of thermodynamics, materials science and Life Cycle Assessment (LCA) aspects, it can be seen that a new plant based on renewable energy is an attractive option.

An overview of the proposed cycle is shown in figure 1. Exhaust gasses of biomass are used to heat the water to its maximum temperature of 550°C and to deliver 65 MW of additional heat to the city district heating system in winter.

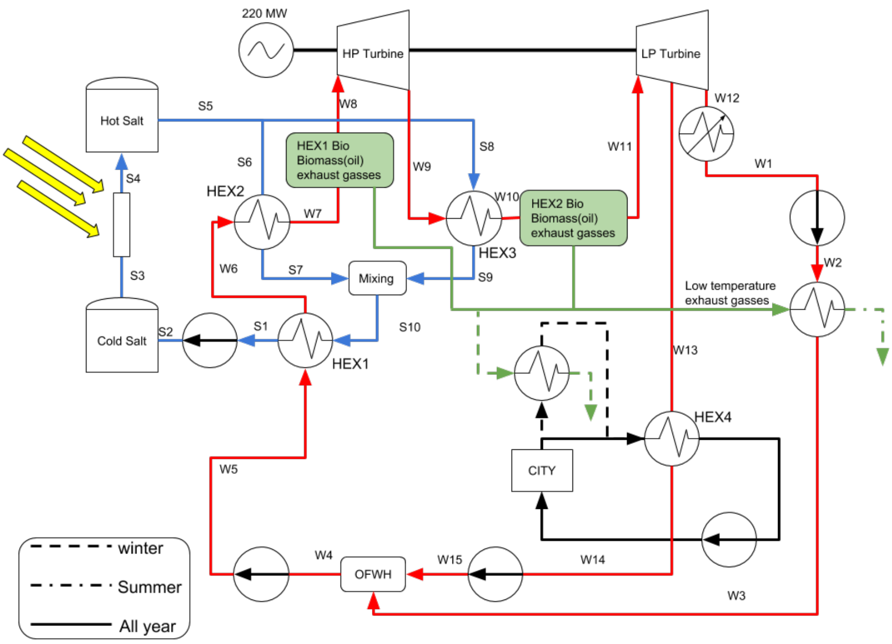

Figure 1: Concept for the new power plant

The area that the power plant will cover is at least 19.4 km^2. The location of the power plant should not be too far away from the city because heat loss will occur during the transportation of the hot water. At the same time, it should not be too close to the city in order to avoid disturbing the inhabitants. A possible place that satisfies these requirements has been found close to the Lanzhou Zhongchuan Airport.

Estimations have been made to calculate the expected efficiency's and power output of the cycle. These values are shown in table 1.

$\eta_{th,summer}$	37.03 %
$\eta_{th,winter}$	36.70%
ε_{summer}	47.90 %
ε_{winter}	58.37 %
η_{Carnot}	64.40 %
$\eta_{SL,summer}$	57.5 %
$\eta_{SL,winter}$	57.00 %
Power production	222.3 MW
Heat to city	65 MW

Table 1: Efficiencies and power production of final concept

In the material section two critical components of the facility were looked at in depth. These are the heat exchanger and the turbine. The materials were selected considering failure modes through performance indexes. The price was also taken into account to ensure the highest profit for investors. For the turbine the materials selected are mostly stainless steel with smalls differences in composition of carbon and other component. The different composition gives specific properties to each part of the turbine. Non-steel metal alloys were chosen for the heat exchanger parts; a copper-chromium alloy for the tubing and a Ni-Cu-Si alloy for the housing.

A Life Cycle Assessment (LCA) was performed on both the conventional coal plant and the newly designed solar plant. First the goal definition was worked out, including the target group, validity and all Recipe effects. This goal definition defined how the LCA was conducted. It also included the functional units that were considered and used for further assessment.

Using the software of GaBi, models were made and resulted in graphs and tables that gave information with respect to the environmental impact of both plants. Using these profiles, the data was evaluated. All profiles were discussed and explained. Following that was the normalization of the results. This was to prepare the graphs for detailed comparison.

For the official comparison between the two plants, a break even point was found. This included changing the best plant to the worst one by altering your assumptions. Also a sensitivity analysis was done to truly see what substances matter. After this, the solar plant was compared with other plants to bring it in a broader context. This included plants in Poland and Norway.

All in all, it is possible to create a new 100% renewable power plant that satisfies the requirements. However the feasibility of actually building the power plant is questionable as it will be very expensive due to the high mass flow rates that are required to generate the desired power output.

Contents

Chapter 1

Introduction

The Chinese city of Lanzhou has long been one of the most polluted cities of the world. A large part of the air pollution is caused by the presence of a coal-fired power plant used to provide energy for the city. In order to improve the situation in Lanzhou, an alternative energy source can be investigated. By means of an analysis regarding thermodynamics aspects, materials science aspects and a life cycle assessment, a design for a new installation will be made and compared to the current power plant in order to replace the highly polluting coal-fired power plant.

First in chapter 2, three different thermodynamic concepts are described and compared in order to eventually design the final concept. The concepts are based on the the thermodynamic cycle of the Crescent Dunes concentrated solar power station, however values of thermodynamic properties have been changed and elements have been added to the cycle. Furthermore, an analysis was done on different energy sources, as well as a potential place for the power plant to be located. When the final concept was designed and all the thermodynamic properties were known, an analysis was done to decide which materials can be used for some critical parts of the cycle. This is done in chapter 3. With the use of performance indices, possible materials for the different parts of the turbine and the heat exchanger were chosen. In chapter 4, a life cycle analysis is done in order to investigate the environmental impacts of the new energy system that has been designed. In the last chapter, conclusions will be drawn, regarding the thermodynamic analysis, the material choice of the different part in the thermodynamic cycles and the life cycle assessment.

Chapter 2

Thermodynamic Analysis

2.1 Problem definition

The Lanzhou Guodian Yuzhong power plant is currently used to provide enough energy for the inhabitansof Lanzhou. An alternative has to be found in order to reduce the pollution within the city caused by the coal-fired power plant, and still provide the city with energy and, in addition, heat should be delivered to the district heating system of Lanzhou. A 100% renewable power plant has to be designed to replace the current coal-fired power plant in Lanzhou. The new power plant should supply a power output, $\dot{W}_{out}$, of 220 MW. Another requirement is that the city of Lanzhou should be provided with heat. A heat output in the winter, $\dot{Q}_{out-winter}$, of 130 MW has to be delivered to the district heating system. In the summer the required heat output is halved, so $\dot{Q}_{out-summer}$ is 65 MW. The hot water is sent to the city at 120°C and has a pressure of 14 bar and the water returns at a temperature of 90°C and a pressure of 4 bar.

The new power plant will be based on the Crescent Dunes concentrated solar power plant (CSP). However, the power output should be twice the power of the Crescent Dunes CSP. Furthermore heat should be provided to the city and, besides energy from concentrated solar, other renewable energy sources are used in order to meet these requirements, improve the efficiency's and minimize the area which the new power plant will cover.

2.2 Energy Source Combinations

During the concept design stage, a number of combinations of concentrated solar power with other sources of renewable energy were considered. This was done because the power output has to be twice as much, but increasing the number of the mirrors would result in a large area needed. Furthermore the yearly solar irradiation in Lanzhou is lower than that in Crescent dunes, 1600 kWh/m^2 compared to 2760 kWh/m^2 [1] respectively, the area will increase even further leading to a very large area. To minimize the area needed for the new power plant alternative renewable energy sources have been considered. These are biomass, geothermal, wind, and hydroelectric power.

However not all of these alternative energy sources are available or are available but not in a large enough quantity that they could be used. Hydroelectric power was quickly dismissed as a possible combination since the Yellow river that runs through the city of Lanzhou lies in a valley, using a dam to utilise this energy would result in that a large part of the inhabited area around the city would become flooded. A different method of utilising the energy from the river is by using waterwheels, but this will require a large area around the river to be available, but this area is already used by the industry.

While geothermal energy provides a relatively higher efficiency, it also releases greenhouse gases to the environment, despite being substantially less than fossil fuels [2]. Furthermore, geothermal energy works best in regions of volcanic and tectonic activity [3]. The desert region of Lanzhou does not suit these conditions for geothermal energy to work at its prime. Finally, a substantial amount of energy goes to waste in a geothermal power plant due to its low heat efficiency [2]. In this case, the number of disadvantages of using geothermal energy outweighs its advantages.

Wind power is a clean energy source with a low maintenance cost and does not produce emissions. However, this power combination might not be feasible enough to provide sufficient power to the city since the average wind hours in Lanzhou is around 3500h [4] yearly, which is not ideal since the power output of the system needs to be constant. There is the chance of a weather condition with limited solar light as well as a low wind speed, which will result in a reduced power supply.

Biomass as a source of energy is cheaper than fossil fuels, and leaves behind an low carbon footprint. Because of its short carbon cycle of only a few year it is usually considered to be carbon neutral. As solid waste can be used as fuel, this reduces the amount of waste and garbage in landfill sites. However, since Lanzhou has a dry arid climate, there isn't a sufficient amount of biomass nearby for the energy system. In other regions of Gansu rice is grown. The rice straw can be used as biomass, but the transportation of this straw is very inefficient since there is not much energy in the straw. This problem can be solved by converting the biomass into bio-oil with pyrolysis. The energy density of oil is much higher than of the straw. The straw is transported to a local pyrolysis plant and the required bio-oil is transported to the site. Due to biomass being more efficient and reliable than wind energy, and geothermal and hydroelectric power not being ideal for the power plant's location, biomass was used as the secondary source of energy.

Thermodynamic concepts

In section 2.3, 2.4 and 2.5 the three substantially different thermodynamic concepts for the new power plant are discussed. After discussing the different concepts, the final concept, which will be worked out further, can be chosen. To be able to compare the different concepts fairly, the maximum temperature in every water cycle is assumed to be 550°C and the maximum pressure is 200 bar. These assumptions are made based on the cycle of the Crescent Dunes Solar power plant. The flow chart of the cycle that is used in Crescent Dunes can be found in the appendices.

In addition, it is assumed that the turbines and the pumps have an efficiency of 85% and the generator has an efficiency of 99%. Also potential and kinetic energy losses in the system are neglected.

2.3 Rankine cycle (1)

The first concept is based on a Rankine cycle with reheating. Molten salt is used for the heating in the Rankine cycle. This salt is heated by concentrated solar energy. Biomass is used to supply additional heat to the city heating district in the winter. An overview of the cycle is shown in figure 2.1

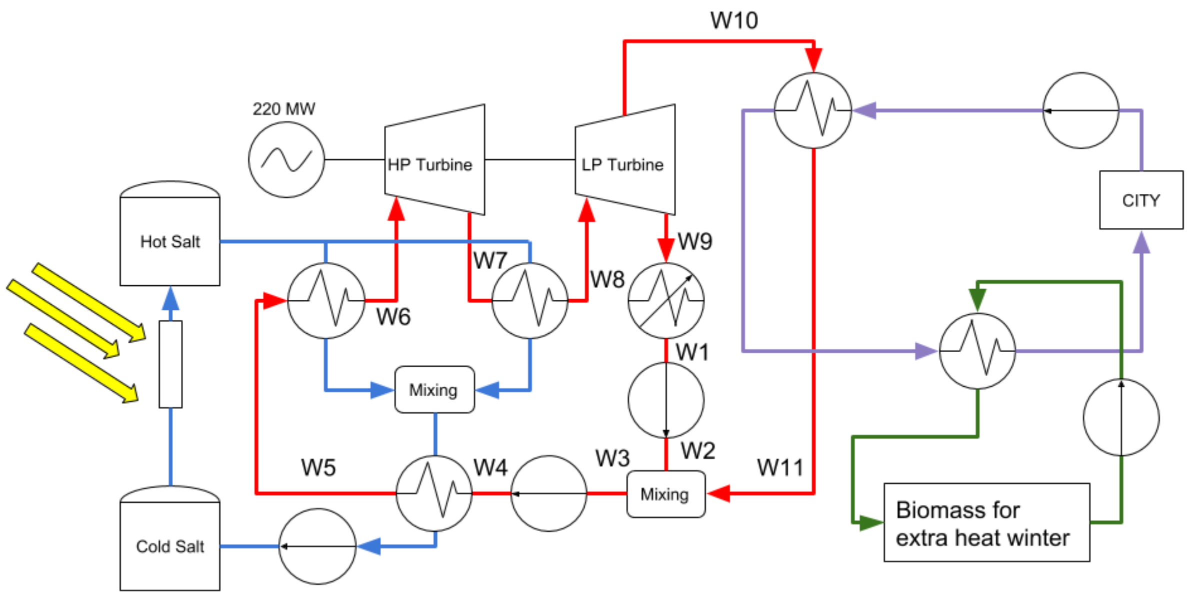

Figure 2.1: Flow chart of concept 1

2.3.1 The cycle of concept 1

After the water is compressed by the pump, the heating in the cycle is done in two steps. First, the stream of flow W4 is heated by the salt in a heat exchanger. After this, the water is heated again by the salt in a heat exchanger after which it is expanded in the high pressure (HP) turbine. The water is heated again by the salt to the maximum temperature, 550°C. Steam from the low pressure turbine is used to heat up the water for the city heating in a heat exchanger. This heat exchanger will provide the heat required in the summer, which equals 65 MW. Biomass is used to deliver the additional 65 MW of heat that is required in winter. The temperature of flow 10 should be high enough to be able to heat the city cycle to the desired temperature. Therefore the temperature of this flow should be at least 130°C, as the water of the city cycle should be heated up to 120°C. The flow that delivers heat to the city is mixed with the part of the stream that expanded to the lowest pressure in the low pressure (LP) turbine. The values of the thermodynamic properties in different parts of the cycle, as well as the mass flow, can be found in the appendices.

2.3.2 Efficiencies of concept 1

Different efficiencies have been calculated to be able to compare the different concepts with each other. The Carnot efficiency can be calculated with the following equation:

$$\eta_{Carnot} = 1 - \frac{T_{cold}}{T_{hot}} \tag{2.1}$$

The maximum temperature in the cycle, T_{hot}, will be 550 ^{0}C and for the minimum temperature, T_{cold}, the outside temperature can be used which is 20 ^{0}C.
The thermal efficiencies and utilisation factor are calculated with equation 2.2 and 2.3 respectively. The results of the calculations are shown in table 2.1.

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \tag{2.2}$$

$$\varepsilon = \frac{\dot{W}_{net} + \dot{Q}_{used}}{\dot{Q}_{in}} \tag{2.3}$$

The second law efficiency has been calculated with the following equation:

$$\eta_{SL} = \frac{\dot{\eta}_{th}}{\dot{\eta}_{carnot}} \tag{2.4}$$

Efficiencies	
η_{th}	36.68 %
ε_{summer}	47.50 %
ε_{winter}	52.61 %
η_{Carnot}	64.40 %
η_{SL}	57.00 %

Table 2.1: Efficiencies of concept 1

The steam of flow W10 does not produce work because it is extracted from the LP turbine to deliver heat to the city district heating system. Therefore the thermal efficiency will decrease compared to a cycle in which the whole stream would be used to generate power. However the utilisation factor will increase due to the fact that more of the heat leaving the low pressure turbine is used. Furthermore, the utilisation factor will be higher in winter than in summer because in winter additional heat is added to heat the city.

2.3.3 Advantages and disadvantages of concept 1

Advantages of this concept are:

- The cycle is relatively simple, which prevents extra costs for additional parts.
- The renewable energy source biomass is used to provide heat to the city in winter. In the case that the cycle cannot deliver enough energy to provide the 65 MW of heat in summer, extra biomass can be used to supply this heat.

Disadvantages of this concept are:

- The biomass is only used to provide heat to the city district heating system. A lot of energy from the biomass will be lost, as the temperature to which the water of the city cycle needs to be heated is relatively low, 120°C.
- The water in flow W5 and flow W7 needs to be heated to 550°C. In order to reach this temperature, the molten salt will have to have a temperature above 566°C, which will largely increase the area that the mirrors of the concentrated solar power plant occupy. If this concept would be worked out further, this problem should be solved, for example by making use of biomass.

2.4 Combined cycle (2)

The second concept is a combined cycle. The cycle consist of a Rankine cycle with reheating and a Brayton cycle. Also biomass is used to supply additional heat in the winter. The cycle is visualized in figure 2.2.

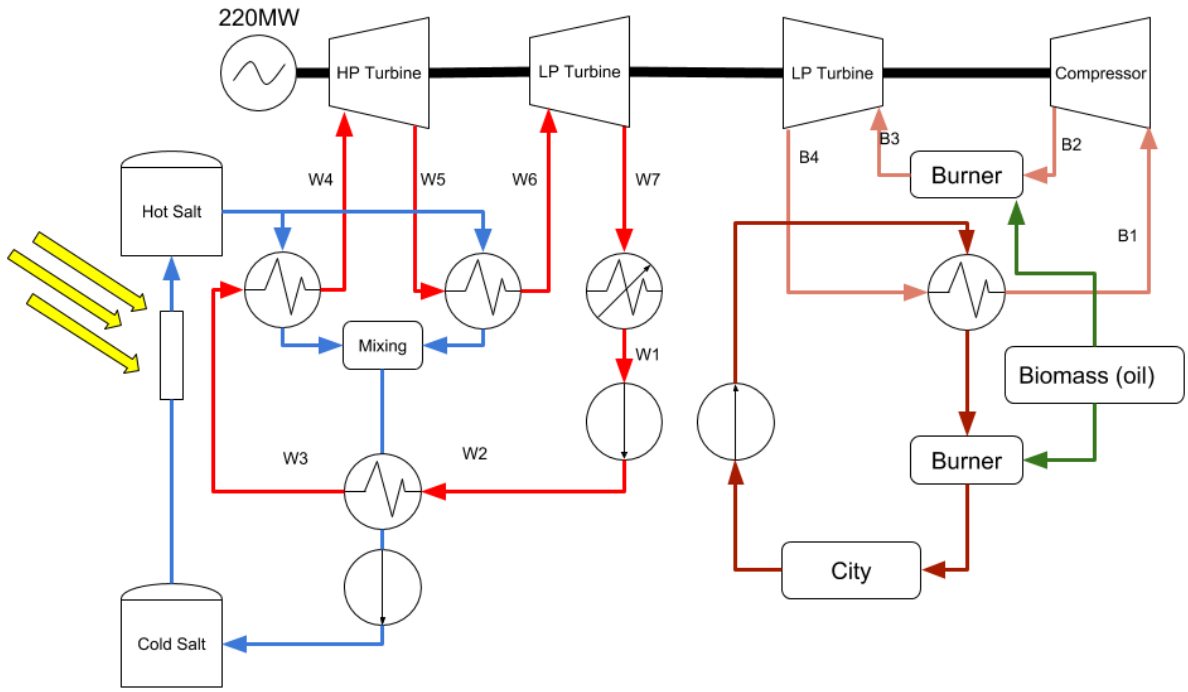

Figure 2.2: Flow chart of concept 2

2.4.1 The cycle of concept 2

In this cycle, a part of the demanded power output is generated by the turbines in the Rankine cycle. The other part is generated by the Brayton cycle. Not only is the Brayton cycle used to generate power, but it also delivers heat to the city district heating system. Biomass is used to heat the superheated vapor as well as to deliver heat to the city. For heating the water in flow W2 and flow W3 in the heat exchangers of the Rankine cycle, heat from the molten salt is used. After this, flow W4 is expanded in the HP turbine and reheated by the heat of the salt to be expanded further in the LP turbine.

The Rankine cycle in this concept is quite similar to the Crescent Dunes Solar power plant, except for the values of the properties in the different parts of the cycle. For example, the maximum temperature of this concept, 550°C, is higher than the maximum temperature of the Crescent Dunes Solar power plant, which is 520°C. The exact values of the thermodynamic properties in different parts of the cycle, as well as the mass flows, can be found in the appendices.

2.4.2 Efficiencies of concept 2

The efficiencies of concept 2, shown in table 2.2, are calculated with the use of equations 2.1, 2.2, 2.3 and 2.4. Because the maximum temperature of this concept is the maximum temperature in the Brayton cycle of 900°C the Carnot efficiency will be higher than the carnot efficiency of concept 1. This can be seen in equation 2.1 that when T_{hot} increases, the carnot efficiency also increases.

Efficiencies	
η_{th}	42.85 %
ε_{summer}	55.53 %
ε_{winter}	61.93 %
η_{carnot}	75.02 %
η_{SL}	57.12 %

Table 2.2: Efficiencies of concept 2

The utilisation factor in summer is higher than in winter. This is due to the fact that extra heat is added in the cycle to deliver the required heat to the city and still make the required power output.
Advantages of this concept are:

- The cycle will have a high thermal efficiency because of the high temperatures in the Brayton cycle.
- Not only the hot exhaust gasses originating from the biomass are used to heat the city district heating system, but they are also used as heat input in the Brayton cycle.

Disadvantages of this concept are:

- In this concept, three turbines are needed to expand the steam of W4, W6 and B3. Furthermore, there are significantly more parts needed for the total cycle compared to the first concepts. It is questionable if the higher efficiencies of this concept weigh up to the investment that needs to be made in order to realise this concept.
- Similar to the first concept, it will be difficult to heat the water to the maximum temperature of 550°C with the molten salt, which has a temperature of 566°C.
- Part of the biomass in only used to provide heat to the city, instead of also using it, for example, to preheat the water in the Rankine cycle. Because of this a lot of exergy is lost from the high temperature exhaust gasses.
- The temperatures in the brayton cycle go up to 900°C, meaning that materials should be chosen that can withstand the high temperatures. Furthermore should the materials be creep resistant as creep is more likely to occur at these elevated temperatures.

2.5 Triple turbine cycle (3)

The third concept is a Rankine cycle and uses the heat of the salt, as well as biomass to heat the water in the cycle. The cycle is schematically shown in figure 2.3.

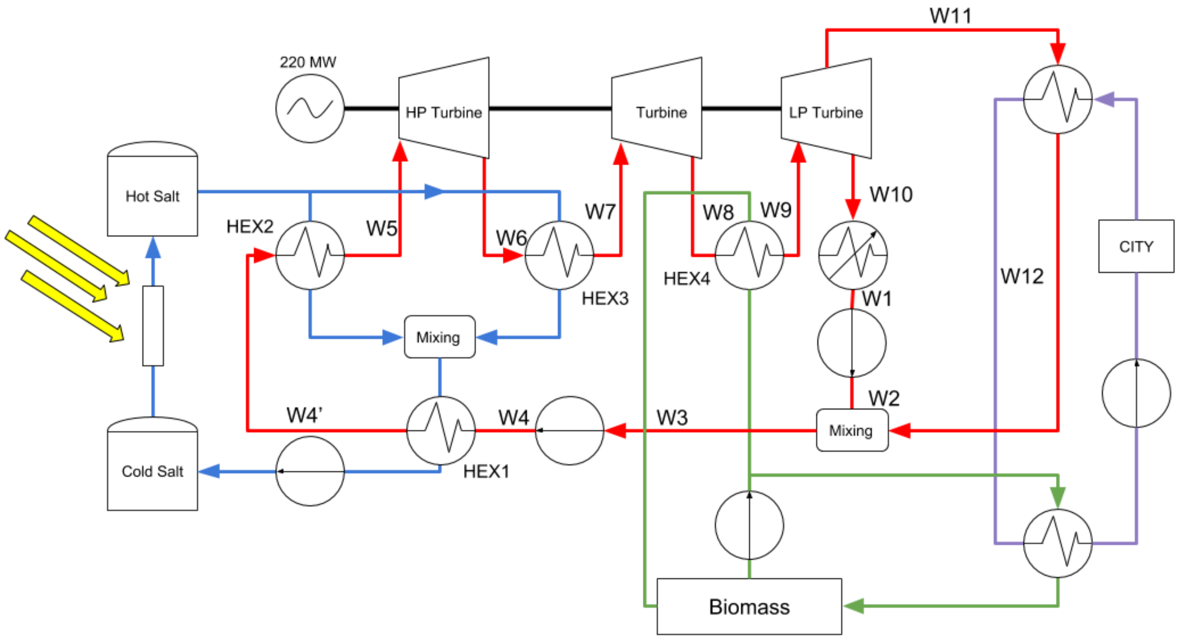

Figure 2.3: Flow chart of concept 3

2.5.1 The cycle of concept 3

In this cycle, the heating is done in two steps. First the compressed liquid in flow W4 is heated in the first heat exchanger to the compressed liquid in flow W4' by the heat originating from the salt. After this, the water is superheated in the second heat exchanger by the hot salt stream, increasing the enthalpy of the steam even further to number W5 in the flow chart.

What also can be noticed is that the cycle makes use of reheating twice, meaning that the superheated steam in flow W5 is first expanded in the HP turbine to produce work, after which it is reheated in the third heat exchanger to increase the enthalpy again in order to be able to expand it in the intermediate pressure turbine again, to produce more work. After this, flow W8 is reheated with the heat supplied by the biomass.

Besides the 220 MW of power that has to be generated, the power plant also has to provide heat to the district heating system of Lanzhou. This is done by using a part of the stream that has entered the LP turbine and use this to heat the stream of the city cycle. Flow W12, which comes from the heat exchanger that delivered heat to the city, and flow W2, which is the flow that is compressed in a pump after it expanded in the LP turbine and rejected heat in the condenser, are combined in the mixing chamber at the same pressure. The values of the thermodynamic properties in different parts of the cycle, as well as the mass flow, can be found in the appendices.

In this concept, the biomass is used to heat the water of the cycle as well as to deliver heat to the district heating system in winter when more heat needs to be delivered.

2.5.2 Efficiencies concept 3

In table 2.3, the efficiencies of concept 3 can be found, which are calculated with equations 2.1, 2.2, 2.3 and 2.4.

Efficiencies	
η_{th}	35.98 %
ε_{summer}	46.71 %
ε_{winter}	51.78 %
η_{Carnot}	64.40 %
η_{SL}	55.87 %

Table 2.3: Efficiencies of concept 3

From this table, it can be seen that that the efficiencies are lower than those of the other two concepts. This is caused by the high temperature of the steam that leaves the LP turbine. Therefore, not all the heat is used to produce work and a lot of heat is lost in the condenser to the environment. Furthermore extra heat is needed to reheat twice but the third turbine produces not enough work for this to be beneficial to the cycles efficiency.

2.5.3 Advantages and disadvantages of concept 3

Advantages of this concept are:

- Biomass is used to reheat the water of flow W8, this decreases the size of the plant since less heat has to be delivered from the salt.

Disadvantages of this concept are:

- The concept makes use of three turbines, a high pressure turbine, an intermediate pressure turbine and a low pressure turbine. This increases the cost and size of the power plant considerably
- Similar to the first and second concept, the salt of 566°C has to heat the water to a temperature of 550°C. This will cause a very high mass flow rate of the salt.

2.6 Final concept

The three different concepts have been evaluated and a final concept is created based on the other concepts. Not only are the efficiencies of the different concepts taken into account in this choice, but also advantages and disadvantages of the cycles.

2.6.1 Concept choice

The efficiencies of the three different concepts are shown in table 2.4. When comparing these efficiencies, it can be noticed that the concept with the combined cycle has the highest efficiencies. However, the difference between the efficiencies of this concept and the efficiencies of the others is not substantially different enough to weigh up to the extra costs that will be made because of the extra parts that are needed for such a cycle, in this case.

Efficiencies	1	2	3
$\eta_{th,summer}$	36.68 %	42.85 %	35.98 %
ε_{summer}	47.50 %	55.53 %	46.71 %
ε_{winter}	52.61 %	61.93 %	51.78 %
η_{carnot}	64.40 %	75.02 %	64.40%
η_{SL}	57.00 %	57.12 %	55.87 %

Table 2.4: Efficiencies of the three concepts

The other two concepts are both Rankine cycles with reheating. When comparing the two cycles, it is noticeable that the main difference between the concept 1 and concept 3 is that concept 3 has one extra turbine. Because of this extra turbine, the temperature of the stream after it is expanded in this last turbine is relatively high, meaning that there will be quite some energy loss in the condenser. An extra turbine would also mean extra costs and since there are no real benefits of a third turbine in this cycle, a concept with two turbines will be more effective.

Based on concept 1, the final concept is created. An overview of the cycle of the final concept is shown in figure 2.4.

2.6.2 The cycle of the final concept

The cycle of the final concept cycle is a Rankine cycle with reheating. The advantage of reheating is that the steam does not need to be heated to a temperature that is too high for the turbine. Furthermore the steam coming out of the low pressure turbine has a better quality, which is also better for the materials. Another advantage is that the average temperature at which heat is supplied increases, which means that the efficiency is higher.

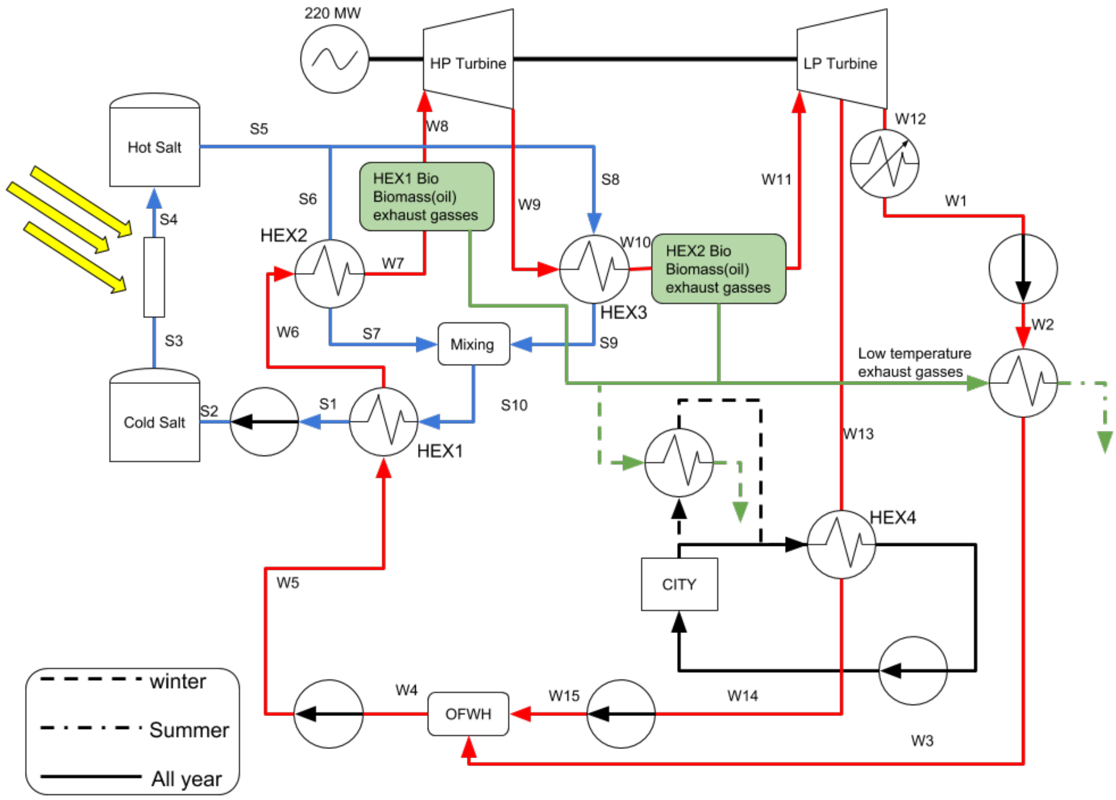

Figure 2.4: Flow chart of the final concept

In order to heat the stream before it enters the high pressure turbine, the heat of the molten salt is used to heat the water to 470°C. This is done in two steps. First, flow W5 is preheated in the first heat exchanger and subsequently, flow W6 is heated up to 470°C. The rest of the heating is done with the use of exhaust gasses of biomass, due to the fact that the temperature of the salt, 566°C, is not high enough to heat the water enough to reach the desired temperature of 550°C. Nevertheless, the exhaust gasses of the biomass are hot enough to do this. After the water has reached the maximum temperature, it is expanded in the high pressure turbine. The water is reheated, first by the salt and then by the exhaust gasses of the biomass. Similar as in the heating before the high pressure turbine, the stream is first heated to 470°C by the molten salt, after which it is further heated to the maximum temperature by hot exhaust gasses.

A part of the stream is taken from the LP turbine in order to be used for delivering heat to the city district heating system. 65 MW of heat is delivered by the water to the city cycle. The other part of the stream is expanded to the lowest pressure of 0.1 bar. The warm exhaust gasses, which are already used to heat the superheated vapor to the highest temperature, will deliver the additional 65 MW of heat to the city district heating system in winter.

In this concept, biomass is burned after which the exhaust gasses are used to heat the water of the cycle and to deliver heat to the system. The biomass could, for example, also be used to heat the salt in the salt cycle, in order to reduce the amount of mirrors needed. However, it is more effective to use the biomass to immediately heat the water instead of using it to heat the salt that would eventually heat the water, as energy and exergy will be lost during this process. That is why the use of biomass is implemented to heat the water in the cycle.

In order to optimize the cycle, the warm exhaust gasses of the biomass, which are used to heat the water in the cycle to the maximum temperature and to deliver heat to the city system in winter, will be used to preheat the water of flow W2. Currently, there are two different scenarios for the exhaust gasses which have been used to heat the water to the maximum temperature before it is expanded. In winter, the exhaust gasses of both bio heat exchangers, that still will have a temperature of approximately 470°C, are used to deliver heat to the Lanzhou district heating system in order to supply the additional 65 MW of heat that is required in winter. Not all exhaust gasses are needed to heat the water of the city cycle to the desired temperature of 120°C, so the other part of the exhaust gasses are used to preheat the water of flow W2. In summer, the exhaust gasses that are used to heat the water before it is expanded in the turbines, are all used to preheat the water of flow W2. However, as the exhaust gasses of the biomass will have a higher temperature because they did not deliver heat to the city, they can heat the water of flow W2 to a higher temperature than in winter. Flow W15 and flow W3 are combined in the open feed water heater. In this way, the water will already have a slightly elevated temperature when it reaches the first heat exchanger, causing a lower heat input by the salt.

Furthermore, the pressure during the reheating of the steam in between the high pressure turbine and the low pressure turbine was set to 18 bar in the Crescent Dunes concentrated solar power plant. However, in this newly designed cycle, this is not the ideal pressure for reheating. With the use of Matlab, the reheating pressure, which causes a thermal efficiency as high as possible, is determined. This resulted in a pressure of 34 bar during the reheating of flow W9 and W10.

To realise this concept, the total mass flow of the water needs to be 162 kg/s. Although this is significantly more than the mass flow of of the water in the Crescent Dunes concentrated solar power plant, which is 78.42 kg/s, it is necessary to have a high mass flow in order to generate the desired work output of 220 WM. The mass flow of the salt is also almost twice as big relative to the mass flow of the salt in Crescent Dunes. The required mass flow will be 1210.3 kg/s in winter, which is significantly more than the mass flow of 699.6 kg/s in Crescent Dunes. The mass flow is this big because the work output twice as big compared to Crescent Dunes. Furthermore, the maximum temperature to which the water will be heated is also higher. The reason that the mass flow of the salt is not a bit less than twice the mass flow of Crescent Dunes, is because biomass is used to heat the water to the maximum temperature. Another advantage of using biomass is that mass flow of the salt will be less than it would have been in the case that the salt had

to heat the water to the maximum temperature. Therefore, the use of biomass reduces the area required for mirrors. As a result, the power plant will take less space and will therefore affect the surrounding region less. The mass flow of the biomass will be 4.45 kg/s in total. The mass flow will remain constant since the hot exhaust gasses are either used to preheat the water in the cycle or in the city heating.
An overview of the different mass flow rates is given in table 2.5.

Mass flow rates

mass flow rate W4	162 kg/s
mass flow rate W2	135 kg/s
mass flow rate W13	27 kg/s
mass flow rate S1 (winter)	1201.3 kg/s
mass flow rate S1 (summer)	1044.5 kg/s

Table 2.5: Mass flow rates of final concept

Note that $\dot{m}_{W4} = \dot{m}_{W5} = \dot{m}_{W6} = \dot{m}_{W7} = \dot{m}_{W8} = \dot{m}_{W9} = \dot{m}_{W10} = \dot{m}_{W11}$. In addition, $\dot{m}_{W2} = \dot{m}_{W1} = \dot{m}_{W12}$, and $\dot{m}_{W13} = \dot{m}_{W14} = \dot{m}_{W15}$.
The mass flow rate of the salt is lower in summer, because the water is already preheated by the exhaust gasses of the biomass. Therefore the heat input of the molten salt is lower.

2.6.3 T,s-diagram of the final concept

To give a better insight in the cycle a T-s-diagram can be made. For the final concept all the specific points were calculated. The temperature, pressure, enthalpy and entropy have been calculated with the use of Matlab and XSteam. The energy in the flows have been calculated with the following equation.

$$E = \dot{m} \cdot h \tag{2.5}$$

For the exergy the equations 2.6 till 2.8 are used for the exergy in flow, heat exhangers and condensers respectively.

$$\psi = \dot{m} \cdot (h - h_0 - T \cdot (s - s_0)) \tag{2.6}$$

$$\psi = \dot{m} \cdot c \cdot (T_{in} - T_{out}) - T_0 \cdot ln\left(\frac{T_{in}}{T_{out}}\right) \tag{2.7}$$

$$\psi = \dot{Q} \cdot \left(1 - \frac{T_0}{T}\right) \tag{2.8}$$

The values of the different thermodynamic properties in the different parts in the cycle in the winter scenario are shown in table 2.6.

	T (°C)	P (bar)	h (kJ/kg)	s (kJ/kgK)	Energy (kW)	Exergy (kW)
W1	45.8	0.1	191.8	0.649	25901.0	614.5
W2	46.1	34.0	195.8	0.651	26442.3	1079.1
W3	70.2	34.0	296.7	0.659	40058.7	2651.6
W4	80.9	34.0	341.4	1.084	55305.2	4340.8
W5	82.5	200.0	364.4	1.092	58545.0	7187.5
W6	349.5	200.0	1641.6	3.722	265942.8	89765.1
W7	470.0	200.0	3137.8	6.008	508317.9	223618.3
W8	550.0	200.0	3396.2	6.339	550191.1	249784.2
W9	300.6	34.0	2983.3	6.469	483291.5	176711.6
W10	470.0	34.0	3384.6	7.084	548309.7	212547.6
W11	550.0	34.0	3565.9	7.315	577688.2	230912.72
W12	45.8	0.1	2505.2	7.902	338288.9	26037.0
W13	251.9	3.0	2971.9	7.526	80140.5	20759.3
W14	133.5	3.0	561.5	1.672	15140.5	2011.4
W15	134.0	34.0	565.4	1.673	15246.5	2104.5

Table 2.6: Thermodynamic values in the winter

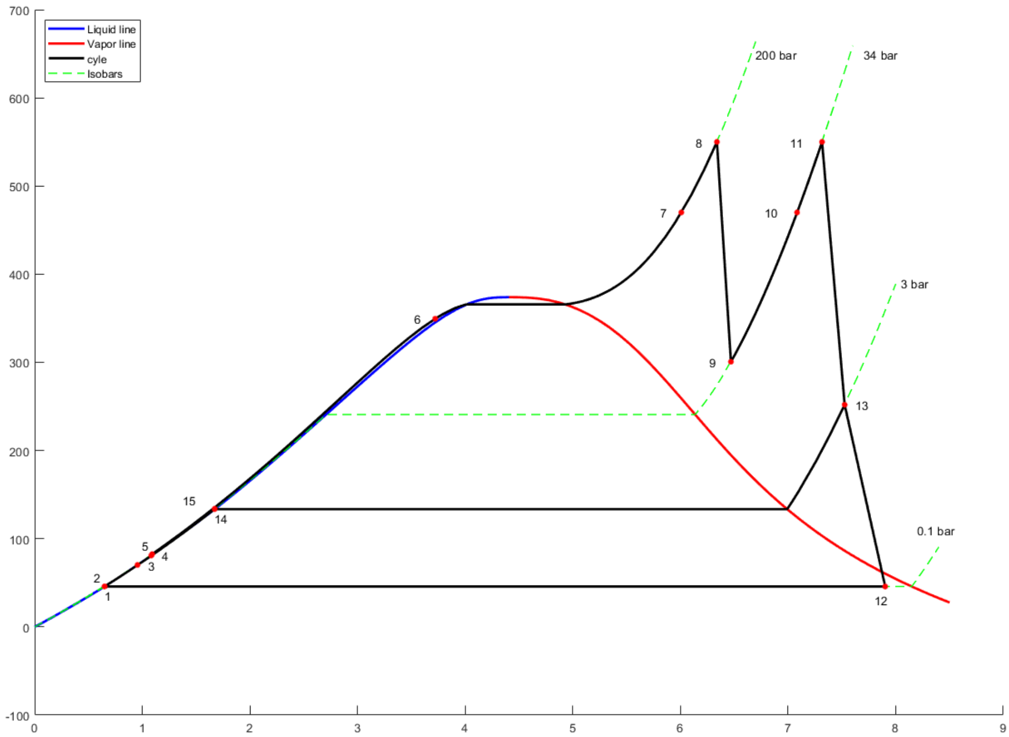

Figure 2.5: T,s-diagram of the final concept in the winter

The T,s-diagram is shown in figure 2.5. From the diagram it can be seen the all the pumps require a very small amount of work input. The stream leaving the low pressure turbine is not a superheated vapour anymore, but a mixture with a vapour fraction of 0.97. This might cause a higher corrosion rate in the turbine, because small water droplets might be formed in the turbine. However, the quality of the mixture is better than it would have been without the reheating.

From the diagram is can be seen that all the (re)heating is done in multiple stages. Furthermore the steam that is used to heat the city can be seen between the point W13 and W14.

The values of the thermodynamic properties for the summer scenario are given in table 2.7.

	T (°C)	P (bar)	h (kJ/kg)	s (kJ/kgK)	Energy (kW)	Exergy (kW)
W1	45.8	0.1	191.8	0.649	25901.0	614.5
W2	46.1	34.0	195.8	0.651	26442.3	1079.1
W3	191.8	34.0	816.4	2.250	110246.3	21640.2
W4	182.3	34.0	774.6	2.159	125492.8	23494.0
W5	185.4	200.0	796.7	2.166	129059.4	26712.0
W6	365.7	200.0	1901.5	4.132	308048.5	112404.2
W7	470.0	200.0	3137.8	6.008	508317.9	223618.2
W8	550.0	200.0	3396.2	6.339	550191.1	249784.2
W9	300.6	34.0	2983.3	6.469	483291.5	176711.6
W10	470.0	34.0	3384.6	7.084	548309.7	212547.6
W11	550.0	34.0	3565.9	7.315	577688.2	230912.72
W12	45.8	0.1	2505.2	7.902	338288.9	26037.0
W13	251.9	3.0	2971.9	7.526	80140.5	20759.3
W14	133.5	3.0	561.5	1.672	15140.5	2011.4
W15	134.0	34.0	565.4	1.673	15246.5	2104.5

Table 2.7: Thermodynamic values in the summer

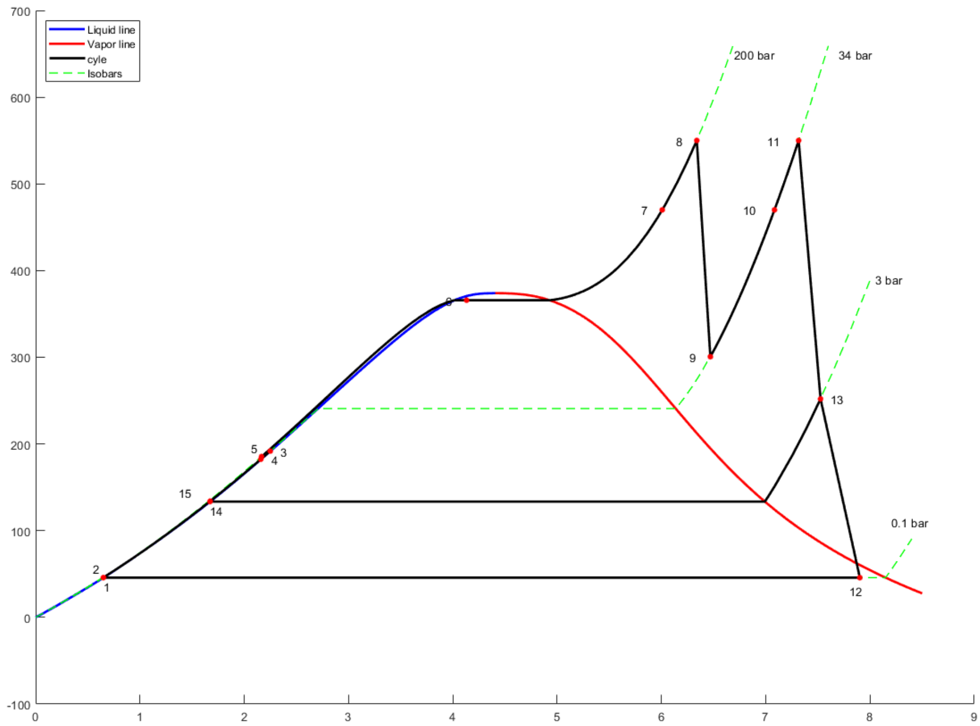

Figure 2.6: T,s-diagram of the final concept in the summer

When comparing figure 2.5 with figure 2.6 is can be seen that only on the left part of the T,s-diagram the thermodynamic values change. Since the exhaust gasses from the biomass do not have to heat up the city, the mass flow that is used to preheat the water increases. Therefore point W3 has a considerably higher temperature than in the winter scenario. But since the maximum temperature and pressures in the turbines do not change the right side of the T,s-diagram will be the same for both the scenarios.

2.6.4 Efficiencies final concept

In table 2.8, the efficiencies of the final concepts are shown. These efficiencies are calculated with the use of equations 2.1, 2.2, 2.3 and 2.4.

Efficiencies of the final concept

$\eta_{th,summer}$	37.03 %
$\eta_{th,winter}$	36.70 %
ε_{summer}	47.90 %
ε_{winter}	58.37 %
η_{Carnot}	64.40 %
$\eta_{SL,summer}$	57.50 %
$\eta_{SL,winter}$	57.00 %

Table 2.8: Efficiencies of final concept

In summer the efficiencies are higher than in winter. The main reason for this is that in summer, flow W2 will be preheated to a higher temperature than in winter, and therefore the heat input is reduced, meaning that the thermal efficiency increases. The second law efficiency provides information about how close the cycle is to its ideal cycle. In summer, the second law efficiency is higher, and therefore is the summer cycle closer to its ideal cycle. The utilisation factor in winter is higher because additional heat is exchanged to the city circuit.

2.6.5 Energy and exergy flows in the final concept

For the final concept Sankey and Grassmann diagrams have been made. In the Sankey diagram all the energy flows can be seen. The heat input of the cycle has been taken as 100%, all the arrows are proportional to their magnitude. The energy in the flows have been calculated with the equation 2.5. In the Grassmann diagram the exergy of the flows is shown. This is the useful energy. The useful energy is always compared to the dead state, in this case the environment. Therefore $T_0 = 20°$C, which corresponds to $h_0 =$ 83.92 kJ/kg and $s_0 = 0.2965$ kJ/kgK. The useful energy is always lower than the energy except for work; the exergy of work is 100%. The exergy of the flows have been calculated with the equation 2.6 The exergy in heat exhangers and condensers in equation 2.7 and 2.8 respectively. Bigger versions of the diagrams can be found in the appendices.

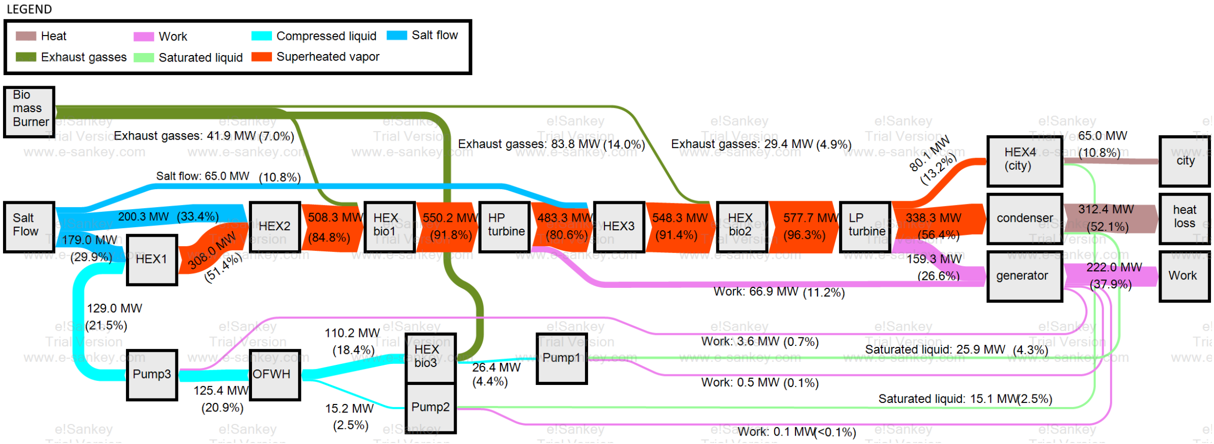

Figure 2.7: Sankey diagram summer

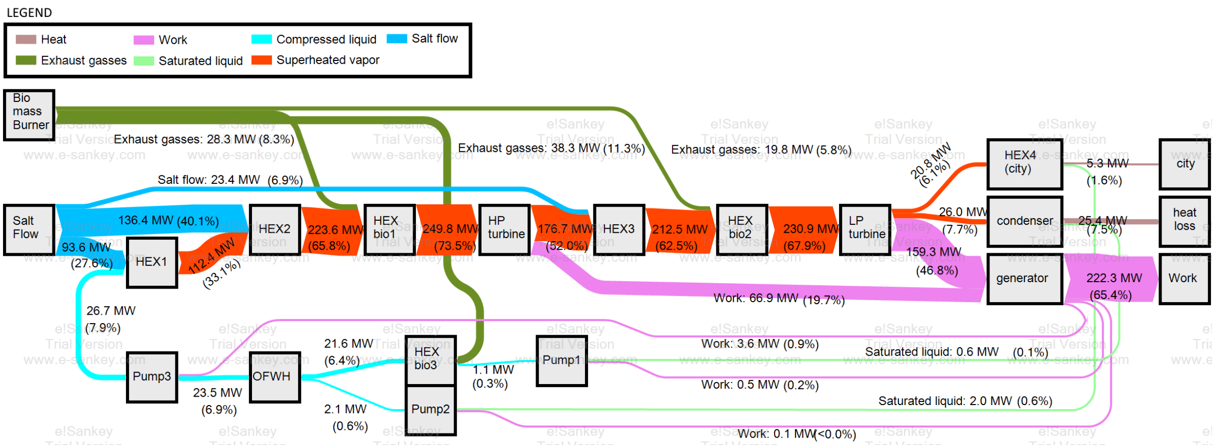

Figure 2.8: Grassmann diagram summer

First of all, in the diagrams it can be seen that the energy flows in every part of the stream are bigger or equal to the exergy flows. The exergy of work is the same as the energy of work, since all work is already useful work. When looking at the Sankey diagram, it becomes clear that the thermal efficiency of the power plant is approximately 37%, since this is the percentage coming out of the generator. This percentage is much larger in the Grassmann diagram, since not all energy that is supplied to the water stream by the salt flow can also be transferred into work, meaning that a bigger percentage of useful energy is in the end converted into work. Another thing that can be concluded when comparing both diagrams is that the energy loss in the condenser seems to be quite large, but the exergy in this stream is a lot smaller, meaning that this is not a place where big losses occur in the cycle. The exergy that is still left in the stream going from the condenser to the pump is also very small, which means that almost all of the exergy present in the stream is released from this stream.

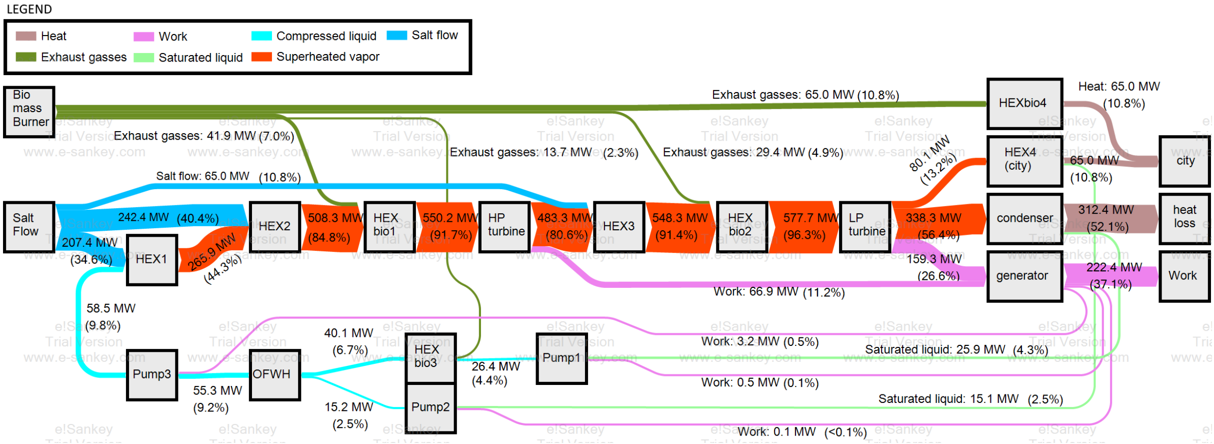

Figure 2.9: Sankey diagram winter

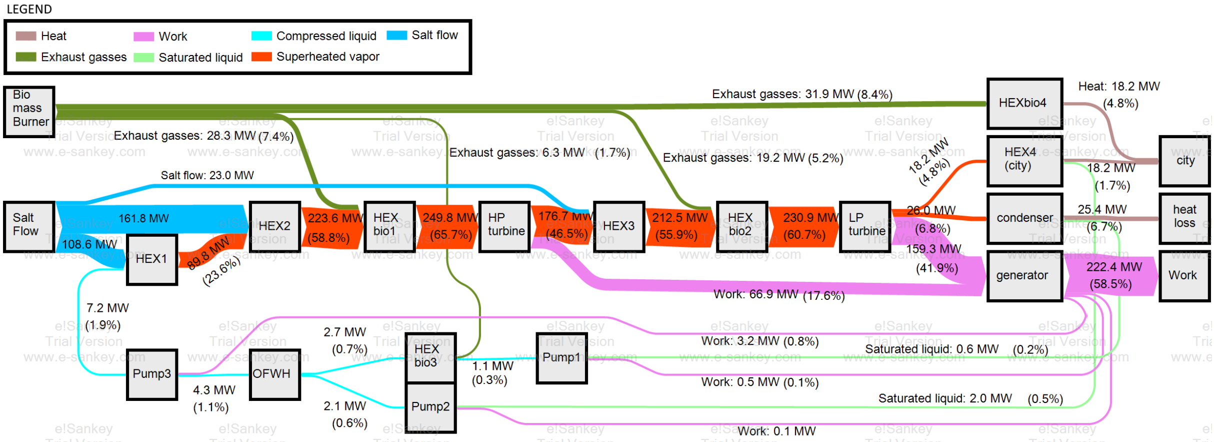

Figure 2.10: Grassmann diagram winter

The Sankey and Grassmann diagrams for winter are quite similar to the ones for summer. The main difference is that a part of the exhaust gasses is used to deliver heat to the city district heating system. Therefore, the part of the exhaust gasses used to preheat the water, is smaller. This also causes a decrease in thermal efficiency because the heat input of the salt increases.

2.7 Possible location for the new power plant

The location of the new power plant should be chosen wisely. The power plant should be located near the city of Lanzhou, since the hot water needs to be supplied to the city and transporting this hot water over long distances will require more work and more heat will be lost. In addition, less materials are needed for the production of cables and pipes to transport the electricity and water to the city. However the plant should not be too close to the city to avoid disturbing the citizens. Furthermore the site should be relative flat, otherwise the mirrors will cast shadows on each other therefore much energy would be lost. Also, the mountains surrounding the site should not be too high relative to the site's altitude because then the time the sun can shine on the mirrors is less than ideal.

The area for the new power plant can be estimated using the Crescent Dunes CSP. The Crescent Dunes CSP covers a total area of 6.76 km^2. From this area 6.1 km^2 is used for the collectors. The mass flow of the salt for the new power plant is 1.78 times larger. Furthermore the solar irradiation in Lanzhou is less than in Crescent dunes as discussed in the section on energy sources. The irradiation is 0.58 compared to that the location of the Crescent Dunes CSP. Therefore the size will increase with a factor of 1.72. It is assumed that the collector area has to increase with these two factors, meaning that the collector area will be 18.7 km^2. Furthermore the buildings are assumed to maintain the same size as the Crescent Dunes CSP. The buildings cover an area of 0.66 km^2. Therefore the total site area should be at least 19.4 km^2.

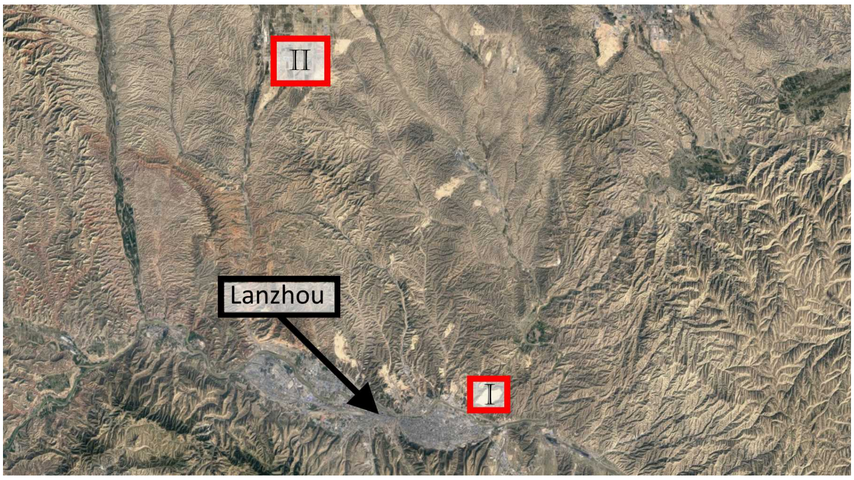

Figure 2.11: Possible locations for the new power plant

The first possible location, indicated in figure 2.11 by I, is a desert north-east to the city. This is a relatively flat area. Also the altitude is high enough to avoid the shadows of the surrounding mountain peaks. The distance to the city is approximately five kilometers. The second possible location, indicated in figure 2.11 by II, is located further away from Lanzhou. However, since this is close to the Lanzhou Zhongchuan Airport the location is good accessible due to the already existing infrastructure.

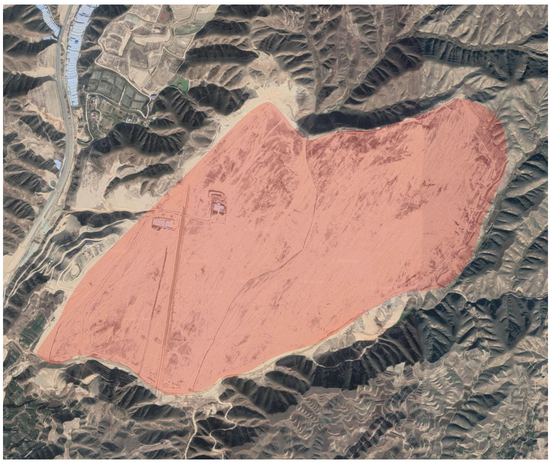

Figure 2.12: Location I

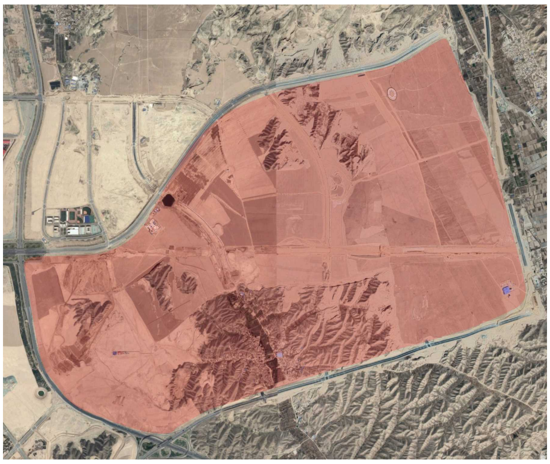

Figure 2.13: Location II

There are other potential locations in Gansus, however these were all more than 60 km from Lanzhou. Because of the extra cost of materials and the heat losses these locations are neglected.

The first location can be seen figure 2.12. One of the advantages of this location is the close proximity to the city, this results in low energy losses in the transport of the hot water to the system heating. Furthermore because of its altitude, which is higher than the city, the power plant will barely be noticeable from the valley. Another advantage is that the land is not actively used. Therefore the price of the area will be relatively low. Furthermore the area is almost flat, which reduces the building costs of the plant and natural land distortion. Unfortunately the area covers only 4 km^2 which is too small to be used to build the new power power plant.

The second location is shown in figure 2.13. This area lies around 50 kilometres from the city of Lanzhou and is area covers 20 km^2. Due to the large distance to the city energy losses in the transport of the hot water to the city are likely to occur. The area contains some considerable height differences which need to be removed in order to ensure that all the mirrors can reflect the sunlight. Furthermore the area consists of agricultural land and partially populated area. The owners of these lands and houses need to be relocated elsewhere and compensated for the loss of land. The area around the site is mostly industrial so no interference with large groups of citizens occurs. However, the location is favourable because of the short distance to the airport and other means of transportation. Because of this the biomass-oil can be easily transported to the power plant.

Although the second location has some drawbacks it is still the best solution. Because of the size of the power plant many locations are too small to be used for the new plant. Subdividing the plant in multiple plants could be a solution, but since this will increase the cost and complexity of the system considerably this option was neglected. To keep the new power plant relatively close to the city and to limit the inconvenience for the citizen as much as possible location 2 is chosen as the building site for the power plant.

2.8 Improvements

Although the final concept satisfies the requirements, there are some improvements that could still increase the efficiency of the cycle. Currently, the pressure of water during reheating is set to 34 bar because this pressure causes the highest thermal efficiency. However, due to this pressure, the stream leaving the low pressure turbine after it expanded is not a superheated vapor anymore, but a saturated mixture. This can cause corrosion in the turbine and the turbine might have to be replaced more often. A lower pressure during the reheating of the water will decrease the thermal efficiency, but it will guarantee that the quality of the stream that leaves the low pressure turbine will be better.

Another improvement could be to increase the maximum temperature, which currently is 550°C, to a higher temperature. In this way, the work output of the turbines will increase as well. Besides that, the problem of having a mixture at the end of the turbine can be solved with increasing the maximum temperature. Furthermore, the exhaust gasses of the biomass, which will have a temperature of 800°C, should be able to heat the water to this higher temperature. Although, the amount of biomass needed might increase. Another factor that should be taken into account is the material choice of various parts in the cycle. Increasing the maximum temperature significantly might cause a different material choice, as it is very important that the materials can withstand the high temperatures.

Besides the possible improvements mentioned above, there could be made some improvements with respect to the used biomass or more specifically, the exhaust gasses of the biomass that are used. Currently, the part of the exhaust gasses that have been used to heat the water of the city cycle, are not further used despite their relatively warm temperature. As the exhaust gasses of the biomass will be cooled down to approximately 130°C after it has delivered heat to the city, it is still possible to use the warm exhaust gasses to preheat the water in flow W2.The same principle holds for the exhaust gasses of the biomass that are used the heat the water to the maximum temperature during the reheating.

Chapter 3

Material Science

3.1 Introduction

After the thermodynamic analysis of the new power plant was done, the next step is to make an analysis of two parts of the total cycle: the turbines and the heat exchanger. These two parts have different inner components, which require an analysis of their own. The subparts to be analyzed for the turbine are the casing, shaft and the blades and for the heat exchanger: the outer casing and the inner tubes. First, an explanation of failure mode must be made for each component and then should be ranked on importance. Also the production process and its effects on the microstructure of the material will be analyzed. Secondly, to choose the right material a performance index must be derived from the failure modes specified in the first stage. Using this, a list of possible candidates can be determined using CES eduPack. Then for the final selection the applicability of each material is discussed, to show that the material selected does indeed have the properties required.

3.2 Material Analysis

3.2.1 Turbine

In order to choose the correct materials for the turbine, some assumptions must be made:

- Turbine has a high pressure section and a low pressure section.
- Material has high thermal resistance, mechanical strength and low cost.
- Clearances between internal parts are extremely small.
- Temperature in the turbine will be 550°C.
- There is a pressure of 200 Bars.
- To choose the correct material, worst conditions and worst case scenarios must be considered.
- Thermal expansion due to high temperature in the casing will be outwards and will not affect the performance of the turbine.

The casing

The casing of the turbine encloses the blades and the other inner components. The main focus for the material selection are the internal forces, which are exerted by the pressure of the steam in the longitudinal direction of the walls. This stress can be calculated with the equation 3.1.

$$\sigma_L = \frac{P \cdot r}{t} \tag{3.1}$$

The internal forces can cause crack growth and consequently failure of the material, crack growth could start either due to the porosity of the material or sharp corners in the casing itself that could have residual internal stress. Also, the high temperature will enhance crack growth, because the creep rate increases as temperature increases.

Consideration:
A function of the casing is to keep the heat inside the turbine that is flowing from the inlet to the outlet with all the heat transferred to work, instead of being released in the environment. In the case of metal; the heat conductivity is high, which is why an outer casing is made with a material that serves as insulator. In this paper the analysis will be focused on choosing the correct material for the inner case of the turbine, which means low heat conductivity is not the relevant importance.

Production:
The shell is casted in two halves divided by a plane parallel to the shaft. This production process is selected, because each half has dimensions that either makes it difficult to produce using other methods, or there is too much wasted material afterwards. For example: machining, investment casting and forging. However, after casting the inside of the casing must be machined to the correct shape and this process must be done carefully, because the clearances between the moving parts are tight. The smaller the clearances the greater the efficiency, because it makes the steam go through the blades and not around it.

Performance Index:

- Function: The casing provides cover for other components and guide the steam towards the outlet. The pressure drop inside the turbine must be smooth and there should not be any leakage of gas.
- Objectives: Material must be strong enough to withstand the pressure of the steam and the heat conductivity must be low to prevent the heat transfer to the surroundings.
- Constraints: The material must be as strong as possible and as cheap as possible.
- Free Variables: The free variables in this case are material choice and thickness.

Assumptions:
Even though it is required that a material also works as insulator; it is not considered for the performance index, because that could eliminate a lot of material that, with the appropriate isolation, could still be very effective and fulfill its purpose.

The axial pressure will not be taken into account for the performance index, because as can be seen in equation 3.2 and 3.3, that it is half of the longitudinal forces.

$$\sigma_{Axial} = \frac{P \cdot r}{2t} \tag{3.2}$$

$$\sigma_{Longitudinal} = \frac{P \cdot r}{t} \tag{3.3}$$

The equation for the mass of the casing is given in equation 3.4, where V(m^3)is volume, $\rho(\frac{kg}{m^3})$ is density, r(m) radius of a cylinder and t(m) is thickness.

$$M = V\rho = 2\pi rt\rho \tag{3.4}$$

Derivation of the performance index:
Equation 3.1 expressed in therms of t is:

$$t = \frac{P \cdot r}{\sigma_y} \tag{3.5}$$

Substitution of equation 3.5 in 3.4 results in equation 3.6:

$$M = 2\pi rt\rho = 2\pi r \cdot \frac{P \cdot r}{\sigma_y} \cdot \rho \tag{3.6}$$

The cost increases when the mass of the casing increases, therefore to include price density ρ is multiplied by the cost, C, in USD per kilogram($\frac{USD}{kg}$). The result is shown in equation 3.7.

$$K = 2\pi rt\rho = 2\pi r \cdot \frac{P \cdot r}{\sigma_y} \cdot \rho C \tag{3.7}$$

Variables	
Free	fixed
σ_y ρC	r P

The variables ρC and σ_y are chosen as free, because these are the properties of the material to be chosen. In the other hand, r is fixed because the dimensions of the turbine are given. The turbine size is influenced by the mass flow of steam. Finally P is fixed and now to be maximum 20 bars.

To minimize price the $\frac{\rho C}{\sigma_y}$ must be as small as possible, therefore the performance index is shown in equation 3.8.

$$P = \frac{\rho C}{\sigma_y} \tag{3.8}$$

Choosing a material:
With the help of CES EduPack 2018 a logarithm graph is plotted with density times price in the y-axis and yield strength in the x-axis. Important limitations are: the material must be castable, the metal must be ferrous, because this type of metals are the cheapest in the market and the maximum working temperature must be a minimum of 550°C. The list below are material that fulfill the requirements.

Materials for casing					
Material	σ_y(MPa)	$\rho(\frac{kg}{m^3})$	$\frac{USD}{kg}$	$P(\frac{\rho}{\sigma_y})$	$P(\frac{C\rho}{\sigma_y})$
ASTM CA-6NM	655	7.65e3	2.02	1.1679e-5	2.3592e-5
ASTM CA-20	240	7.7e3	2.9	2.2083e-5	9.3041e-5
ASTM CF-8A	290	7.7e3	2.9	2.6551e-5	7.7e-5
ASTM CF-8	235	7.7e3	2.9	3.2765e-5	9.5021e-5

The chosen material is ASTMCA-6NM, because it can be seen that this material has the lowest value of P, which means the cost of the casing is minimized, while having the properties to withstand the condition inside.

Reasons:
ASTMCA-6NM is a stainless steel with 11.5-14% of Cr(chromium). This adds resistance to corrosion, because a layer of Cr_2O_3 is created on the surface of the casing. With 0.06% carbon, the hardness of the material would not be enough. Hardening process such as carburization will only improve hardness by a bit a few millimeters inside of the material, therefore to obtain deep hardening 3.5-4.5% Ni(nickel) is added, which also adds resistance to corrosion. Furthermore, together with 0.4-1 % of Mo(molybdenum) its working temperature will also increase up to 700-750 °C . Finally tempering at 590-620°C reduces the amount of bainite that was formed during air cooling. In this way the toughness and also the strength is reduced, but its yield limit is still 625-725 MPa, which is good enough for this application[5].

The shaft

The shaft is constantly rotating and there is a twisting moment for each diaphragm and set of the blades that are attached to the shaft. Therefore, given a certain amount of twisting moment, the shaft should be strong enough to prevent the creation of cracks or undergo deformation during its life cycle.

Given the case that plastic deformation happens (failure) in the shaft; first of all the vibration rate starts increasing due to unequal forces within the shaft; the higher the vibration rate the bigger the deformation will become and at some point the blades could make contact with the casing, which will lead to failure.

Another problem with a shaft undergoing plastic deformation in this case, is the damage to the bearing and other components that are close to the shaft itself.

In other words if the shaft undergoes distortion, it will lower efficiency, make deformation larger and if not fixed on time, complete destruction of the turbine. Therefore the main criteria for choosing the material is a strong material able to withstand the twisting moment for the blades.

Production:
The manufacturing process for the shaft is chosen to be forging, because of the benefits of elongated crystal, high dislocation density and internal stress, which will add strength to the material. In this case the material will already be in the plastic deformation zone and this would help to keep the distortions from forming.

Performance index:

- Function: The shaft allows the transmission of work from the turbines to the generator.
- Objectives: The shaft must be strong enough to not deform plastically during its working life.
- Constrains: The material should be as strong as possible and as cheap as possible.
- Free Variables: Material choice and radius in certain level but it can no be more than 60mm.

Equations to describe the constraints:
The equation for the shear stress is shown in equation 3.9, where M is the twisting moment (Pa), r is the radius (m) and I_p is the polar moment of inertia of area (m^4). The equation for the polar moment of inertia for a circular shaft is given in equation 3.10, where r is the radius (m). The equation for the mass of the shaft is given by equation 3.11 Where r(m) is the radius of the shaft, L(m) is the length and $\rho(\frac{kg}{m^3})$ is the density..

$$\sigma_s = \frac{Mr}{I_p} \tag{3.9}$$

σ_s(shear stress maximum)= yield strength σ_y

$$I_p = \frac{\pi r^4}{2} \tag{3.10}$$

$$M = V\rho = 2\pi r^2 L\rho \tag{3.11}$$

Derivation of the performance index:
Combining the equations 3.9 and 3.10 results in a function of yield strength shown in equation 3.12.

$$\sigma_y = \frac{Mr}{I_p} = \frac{Mr}{\frac{\pi r^4}{2}} = \frac{2M}{\pi r^4} \tag{3.12}$$

This equation can be rewritten in equation 3.13.

$$r = (\frac{2M}{\pi \sigma_y})^{\frac{1}{3}} \tag{3.13}$$

Then 3.13 is substituted in equation 3.11. The result is shown in equation 3.14

$$M = 2\pi(\frac{2M}{\pi\sigma_y})^{\frac{2}{3}}L\rho \tag{3.14}$$

The cost increases when the mass of the casing increases, therefore to include price density ρ is multiplied by the cost, C, in USD per kilogram($\frac{USD}{kg}$). The result is shown in equation 3.15.

$$K = 2\pi(\frac{2M}{\pi\sigma_y})^{\frac{2}{3}}L\rho C \tag{3.15}$$

Variables	
Free	fixed
σ_y ρ C	L M

To minimize cost the the relation between density and σ_y must be as small as possible, from there the performance index is:

$$P = \frac{\rho C}{\sigma^{\frac{2}{3}}}$$

The goal is to minimize the performance index to minimize cost while fulfilling the requirements.

With the help of CES EduPack 2018 a logarithm graph is plotted with density times the price in the y-axis and yield strength in the x-axis. Important limitations are: the material must be accept forging (hot working), the metal must be ferrous because these type of metals are the cheapest in the market and the maximum working temperature must be minimum 520.

Materials for Axel						
Material	Type	σ_y(MPa)	$\rho(\frac{kg}{m^3})$	$\frac{USD}{kg}$	$P(\frac{\rho}{\sigma_y})$	$P(\frac{C\rho}{\sigma_y})$
AISI 410	intermediate temper	634	7.65e3	1.28	1.2066e-5	1.544e-05
AISI 410	annealed	276	7.65e3	1.28	2.771e-05	3.5478e-5
AISI 410	hard temp	1e3	7.65e3	1.28	7.65e-06	9.79e-6

From the list above for all the materials chosen have the same composition of 0.15% of carbon and all of them have the same price per density ratio. The only difference between them is the yield strength for which AISI 410 is the highest, therefore performance index is the lowest.

Reasoning:

The structure of the stainless steel AISI 40 is martensite, according to CES, because it is air cooled during forging, this structure is hard naturally, but the carbon content is only 0.15% (low carbon content), therefore adding 11.5-13.5% of Cr(chromium) adds hardness, because of the formation of chromium carbide during crystallization. Also chromium improves resistance to corrosion on the surface for formation of Cr_2O_3. Furthermore 0-1% of Mn(Manganese), Ni(nickel), Mo(molybdenum) and Si(Silicon) 0-1.5% adds additional strength, because of the carbides formed in the crystallization of ferrite [5]. Furthermore Si improves resistance to oxidation at high temperature and is usually added to heat resisting Cr-Mo (molybdenum) steels[6].

Turbine blades

The purpose of the blades is to extract energy from the hot steam to convert it into useful work. The main reasons which could make the blades fail are; high temperature, high stresses and high rate of vibration. High stresses in the longitudinal direction are due to centrifugal forces. If the material is not strong enough, crack growth could occur, starting from the points where the blades connect to the shaft or in the pores of the surface itself. Also the pressure from the steam perpendicular to the blade will exert an additional stress that could enhance crack growth as well.

The shape of the blades is the crucial for the performance of the turbine. If at some point the material starts to plastically deform, the efficiency might decrease. The requirement for the material then is not only to be strong, but also to be stiff as well, which means a high yield strength and a high Young's modulus.

Additionally, because of the high temperatures, risk of creep also increases. The solution for this problem is to keep the blade as cold as possible. There are different ways to manage creep rate. One of them is to cover the blade with another material with low conductivity and to internally cool down the blade so it stays colder. Another possibility is to chose a material that works better at the temperature of 550°C. In this report the second option is chosen.

Production:
The manufacturing process selected for the blades is investment casting. A process of directional solidification will be used to cast the alloy. The crystals are preferred to be in longitudinal direction with respect to the blade or parallel to the stress due to centripetal force.

Performance index:

- Function: Convert steam with high enthalpy values into useful work by rotation of this shaft.
- Objectives: The blade must be strong and stiff to keep the efficiency of the turbine as high as possible.
- Constrains: Material must be as strong.
- Free Variables: Material choice.

Equations to describe the constrains:
The equation for the Young's modulus is given in equation 3.16, where E is Young's modulus, $\sigma = \sigma_\lambda$ and ϵ is the strain. The mass of the blades is approximated with the equation 3.17, Where V is volume(m^3), b(m) is the base, L(m) is the length and t is the thickness.

$$E = \frac{\sigma_y}{\epsilon} = \frac{\frac{F}{A}}{\frac{\triangle L}{L_o}} = \frac{FL_o}{A\triangle L} \tag{3.16}$$

$$M = V\rho = bLt\rho \tag{3.17}$$

Derivation of the performance index:
In equation 3.16, the force is exerted on the surface face of the blade, $A = bL$ can be substituted the results is equation 3.18.

$$E = \frac{FL_o}{bL_o\triangle L} = \frac{F}{b\triangle L} \tag{3.18}$$

The equation is rewritten in a function of b, the result is equation 3.19

$$b = \frac{F}{E\triangle L} \tag{3.19}$$

Then equation 3.19 is substituted in equation 3.17. The result is shown in equation 3.20.

$$M = \frac{FLt\rho}{E\triangle L} \tag{3.20}$$

More mass represents more cost, therefore to include price density ρ is multiplied by the cost in USD per kilogram($\frac{USD}{kg}$), the resulting expression in shown in equation 3.21

$$K = \frac{FLt\rho C}{E\triangle L} \tag{3.21}$$

Variables	
Free	fixed
ρ,C E	F,L,t $\triangle L$

As can be seen in the equation; to get the lowest cost possible per unit, the relation between density and stiffness, which are the only free variables, must be as low as possible. Therefore the performance index for the blades is:

$$P = \frac{\rho C}{E}$$

the goal is to minimize.

Choosing the material:
With a logarithmic chart in the program EduPack 2018, with ρC in the Y-axis and E in the x-axis. The limitation are: the material must be castable and ferrous, because of the favorable price.

Materials for turbine blades						
Material	Tempered	E (GPa)	$\rho(\frac{kg}{m^3})$	$\frac{USD}{kg}$	$P(\frac{\rho}{E})$	$P(\frac{C\rho}{E}$
ASTM CA-15	650	195	7.56e3	1.29	3.876e-8	5,001e-8
ASTM CA-15	595	195	7.56e3	1.29	3.876e-8	5,001e-8
ASTM CA-15	790	195	9.32e3	1.29	3.876e-8	3.876e-8
ASTM CA-15	315	195	9.15e3	1.29	3.876e-8	3.876e-8

Even though the performance index for each of the materials pres-selected is the same, the tempering temperature affects its maximum working temperature. Even though tempering at 315°C gives the highest strength, its critical temperature is less that 400°C. This is why the chosen material is ASTM CA-15 tempered at °C.

Reasoning:
Because ASTM CA-15 is normalized, the structure of the crystals will be different from the surface to the center; on the surface the structure will be martensite, ferrite and perlite, also some bainite will be present. This makes the material hard and brittle, therefore tempering at 595°C will be performed, which will lower the brittleness and also the hardness. The last one will be high enough to withstand the steam pressure of 200 bars plus the centripetal forces. Tempering to higher temperatures will increase the toughness, but the hardness will decrease. Also stainless steel, being an alloy; its other chemical composition will play a role. Mn(manganese), Ni(nickle) and at some proportion Si(silicon) and Cr(chromium) are to add strength to the material. Si(silicon) 0-1.5% and Mo(0-0.5 %) also increases resistance to corrosion at high temperatures.[6] and [5].

3.2.2 Heat Exchanger

In order to choose the correct materials for the turbine, some assumptions must be made. Here is a list of assumptions that have been made for the analysis:

- For the purpose of this material analysis, only the tubing and the housing will be analyzed, assuming all of the other components run smoothly and without any problems.
- It is assumed that only one form of substance is in the tubing of the heat exchanger at any time (i.e. only salt water, or only water, or only air, etc.)
- The failures that are possible in the part are only during the conditions stated, with only slight deviation, therefore failure is much more likely with extreme values.
- The in- and output flow velocity of the heat exchanger are not a factor in the analysis, this flow velocity is replaced by pressure as it directly correlates to the flow velocity.

The Tubing

The first of the two parts analyzed is the tubing. The main function of the tubing is that it must transfer heat as efficient as possible; it must lose thermal energy as efficiently as possible. Therefore, producing the tubing from a metallic substance is the most efficient for this action. Moreover, this metallic material chosen may then be subject to corrosion, therefore it is important to choose a material that is resistant to corrosion. The production method of the tubing is the most simple and the most successful production-method to produce the desired shape with the desired properties. The tubing should be manufactured by extrusion, since the shape of the tubing is suitable for extrusion, taking into account the size of the tubing. Furthermore, the tubing must also be able to withstand harsh conditions of high pressure and temperatures, which may be a problem with optimizing the use of the tubing, since it must be strong enough to withstand tough conditions, while keeping conductivity at a maximum. Since strength is often increased with thickness, while conductivity is optimized through the kind of material and how thin the material is. This could result in a conflict between the two values.

Performance Index:

- Function: The function of the tubing is the transportation of a fluid under harsh conditions of temperature and pressure.
- Objectives: The main objective is to conduct heat from the fluid being transported to the cooling liquid in the heat exchanger, a secondary objective is the transport of the fluids, this may be assumed to be part of the main objective.
- Constraints: Since the tubing must conduct heat, there may be constraints on the material choice. It must be resistant to corrosion by water and have little to no susceptibility to cracking at corrosion. It must be able to accommodate a maximum

temperature of 600°C. Furthermore, the material must be weldable because the tubes will be welded to the housing as well.

The equations for deriving the performance index are given in equation 3.22 till 3.24:

$$J = -\lambda \frac{\Delta T}{\Delta x} \tag{3.22}$$

Where J is the heat flow per second, lambda is the heat conduction coefficient, Delta T is the difference of temperature between the tubing and the housing, Delta x length of the distance the heat has the travel.

$$\Delta P = \frac{2\sigma_y t}{D} \tag{3.23}$$

Barlow's Formula, where the change in pressure is equal to twice the yield strength by wall thickness over the tube's diameter.

$$Q = A * J \tag{3.24}$$

Rewriting equation 3.23 we get:

$$\frac{1}{\Delta t} = \frac{\sigma_y}{\Delta P r} \tag{3.25}$$

Obtaining an expression for wall thickness. With substituting equation 3.22 and equation 3.24 into 3.23 we get:

$$Q = A * -\lambda * \Delta T * \frac{\sigma_y}{\Delta P r} \tag{3.26}$$

Variables	
Free	fixed
σ_y	ΔT
λ	ΔP, r

The performance index aims to maximize heat transfer per area (Q/A) and from this equation and the free variables we can derive that the performance index (M) is:

$$M = \lambda \sigma_y \tag{3.27}$$

Materials for tubing					
Material	Type	σ_y (MPa)	$\lambda(\frac{W}{M.°C})$	$\frac{USD}{kg}$	$P(\lambda\sigma_y)$
Copper-Beryllium Alloy	half hard	1.14e3	107	15.8	1.21e11
Copper-Beryllium Alloy	whp	1.15e3	107	15.8	1.23e11
Copper-Chromium Alloy	whp	380	300	6.35	1.14e11
Copper-Chromium Alloy	wph	370	300	6.35	1.11e11
Copper-Co-Be Alloy	whp	590	206	9.96	1.21e11

A logarithmic graph was plotted in CES EduPack with yield strength in the y axis and thermal conductivity in the x-axis. The limitations applied were cast-ability of the metal, it must be no higher than 100 dollars per kilogram, little or no susceptibility to cracking at corrosion and the maximum working temperature must be minimum 600°C. The material chosen is Copper-Chromium whp, because it is the cheapest of the other alloys while also being not susceptible to corrosion, unlike the other alloys, which are slightly susceptible.

The Housing

The housing is one of the two parts to be analyzed in the heat exchanger analysis. The purpose of the housing is to provide insulation with maximum efficiency, whilst being able to withstand high pressure and temperature conditions. The pressure and temperature are considered constant and thus do not need any calculation, this has been stated previously in the assumptions. It is important that the material is strong enough to withstand these conditions, otherwise failure is imminent in the form of plastic deformation leading to fatigue. The manufacturing of the housing must be made by casting, due to the size of the heat exchanger it is not possible to manufacture the the housing by extrusion. Therefore, it must be casted in two parts and connected. The parts produced must also be machined and heat treated to provide additional strength and to remove any imperfections. The housing will most likely be produced with a metallic base to withstand the pressure, whilst having a coating to prevent heat loss and minimize the likelihood of corrosion.

Performance Index:

- Function: To contain the tubing, while being strong enough to withstand the pressures from the fluids within.

- Objectives: The purpose of the housing is to minimize heat loss by insulating the tubing and the fluids from the surroundings.
- Constraints: Corrosion resistance to water and little or no susceptibility to cracking at corrosion.

Formulas: The equations used for the housing are the same, the difference is that the objective and functionality differs, making each action the polar opposite of one another, from this we can derive that the performance index (M) for the housing is:

$$M = \frac{1}{\lambda \sigma_y} \tag{3.28}$$

Materials for housing					
Material	Type	σ_y (MPa)	$\lambda(\frac{W}{M.^{\circ}C})$	$\frac{USD}{kg}$	$P(\frac{\lambda}{\sigma_y})$
Ni-Cu-Si Alloy	age hardened	900	20.5	15.7	5.42e-11
Ni-Cu-Si Alloy	annealed	625	20.5	15.7	7.8e-11
Ni-Cu-Si Alloy	cast	900	20.5	15.7	5.42e-11
Ti-$\alpha - \beta$	annealed	1.05e3	5.96	22.1	1.6e-10
Nickel-Titanium Alloy	austenitic	690	18.9	17.4	7.67e-11

Again, a logarithmic graph was plotted with yield strength in the y axis and thermal conductivity in the x-axis. The limitations applied were the same as the ones applied to the graph for the heat exchanger tubing. The chosen material is annealed Ni-Cu-Si, because this material has the lowest price point of the alloys and has the best performance index among the nickel alloys.

Chapter 4

Life Cycle Assessment

In this chapter the Life Cycle Analysis (LCA) is presented and the ways of thinking and reasoning on particular choices. The LCA was performed on the coal-fired power plant in Lanzhou and its possible renewable successor, which is a plant based on the Crescent Dunes concentrated solar power plant. Using this LCA, comparison can be done between these facilities.

4.1 Goal Definition

4.1.1 Determining the application

Defining the goal

The goal for this LCA is to get a clear overview of the environmental effects that could occur as a result of the operation of a power plant. This will also allow for a comparison between the suggested power plant and the old Lanzhou plant. In this way, a well informed decision to replace the plant in a quantitative way can be made.

Defining the target group

The target group will be the government of Lanzhou as well as the technical staff around the project. This is because the government will have the final say on if the project can commence. The technical staff were also chosen because they will inform the government of their opinion based on the LCA.

Defining the initiator

In this case the initiator is the population. Since the current power plant is not environmentally friendly, and in particular affected their health, the group proposed the idea to create a new sustainable power plant to supply power for Lanzhou.

4.1.2 Determining the depth of the study

Exclude and include specific components

It is important to exclude multiple parts within the LCA to ensure that only the relevant sections of the assessment are captured. In following section, descriptions will be given of aspects that will be included or excluded. In addition, if a part has a very small contribution to this LCA, it will be omitted as well. This exclusion will be based on percentages; all contributions under 5 percent on impact will be omitted for this LCA.

The relevant environmental effects

The ReCiPe 1.08 method was used to consider processes and environmental effects. This method contains 18 possible effects and all will be considered when it comes to relevancy based on Lanzhou and its location. All 18 effects are listed and the thought process on relevancy of all these effects when it comes to Lanzhou is mentioned. All 18 effects with their description can be found in the Appendix. This table will also give direct information of all effects that will be included and excluded. Explanation to all of these will be after the table.

Included Effects	**Excluded Effects**
Climate change	Terrestrial Ecotoxicity
Human toxicity	Marine and Freshwater Eutrophication
Fossil Fuel depletion	Water depletion
Photochemical oxidant formation	Marine and Freshwater Ecotoxicity
Natural land transformation	Ionising Radiation
Terrestrial Acidification	Metal Depletion
Particulate matter formation	Ozone depletion

Table 4.1: All included and excluded environmental effects

Now that all effects of the ReCiPe method have been listed, the irrelevant effects for the situation in Lanzhou will be excluded. All effects will be considered.
Terrestrial Ecotoxicity is an effect that will be excluded due to the fact that the cause for this is agriculture. In this case this effect does not occur or in very small amounts. Most of the waste of this power plant is not listed among substances that can cause this effect. Also, the waste that is in fact relevant is not released into the ground, but is released via the air.
Two other effects that will be excluded in this LCA are both forms of eutrophication; *Marine* and *Freshwater*. As explained, this process causes a lack of oxygen in water, and therefore causes that organisms in the water will die. The only water present in Lanzhou is the yellow river, and since this is a river and no lake or other sort of water source where water does not flow, eutrophication cannot take place. Due to the movement of the water, algae cannot grow properly and eutrophication cannot occur.
Marine and Freshwater *Ecotoxicity* are excluded, even though the substances are actually present and this is an effect that could in fact occur; since there is no seawater or freshwater close enough to be at risk, this component will be excluded.
Ionising Radiation is not taken into account since no significant radiation is released during the process.
Metal Depletion is also excluded. There is no continuous flow of metal needed or metal extraction at huge rates. From this is concluded that the influence of the power plant on metal depletion is not significant enough to include this effect, and therefore it can be excluded in this LCA.

From the remaining 6 effects, weighing factors will be determined. In this case rated on importance; High and Low. In this LCA, the effects that can be seen as highly important are climate change, chosen because this is currently one of the highest concerns in today's society, caused by the amounts of energy required by communities nowadays. Renewable energy is a possible solution for this problem. Human toxicity; it is already a big problem around the world. CO_2 levels keep rising, and more and more people are diagnosed with lung-problems due to toxic substances in the air. Fossil Fuel depletion; reserves of fossil fuel are already running out and the use of it keeps growing. It is important to take this into account in this LCA. The effects with lower importance are natural land transformation, terrestrial acidification and particulate matter formation.

Defining spatial validity

This LCA will be valid for an area that shows similarity to the situation of Lanzhou based on climate, position with regard to the equator and elevation for example. The climate that will make this a valid LCA for a specific location should be a 'Bsk' climate, referring to the Köppen climate system. This is a cold steppe-climate with hot wet summers and cold dry winters. This is due to the dry monsoon, a wind from the North East that blows across air that has never passed over water, which makes it a dry wind. The temperature difference should not be bigger than 25^0C with -5^0C as the lowest temperature for valid results. The largest amount of rain should fall in summer and shouldn't exceed a maximum of 400 mm over the year, but should have a minimum of 250 mm of rain. [7] The average sunshine on a day should range between an average of 6 hours to 8 hours a day every month.[8] The elevation should also be taken into account. This LCA is based on a power plant with an elevation of 1600 meter. This should be taken into account when valid research using this LCA is to be done.

Defining temporal validity

This LCA Report will only be valid for a limited amount of time. This LCA will be valid for the next two years. After that time has surpassed, the normalization factors have changed in such a way that the results of this LCA Report are not reliable anymore. Also, the situation in the region are always changing, which will make a longer reliability then the given one, highly improbable. Two years is therefore the period of validity for this LCA. Technology is also always advancing, which adds another dimension to this aspect.

Defining level of detail

The life cycle assessments will be done with the program GABI. This program has its limitations in the effects that can be used. In GABI the ReCiPe 1.08 method is used to display environmental effects. However, the agricultural land occupation and the urban land occupation are excluded from the program which has the result that these effects will not be used for the analysis. Furthermore, some effects are excluded from the LCA because these were not relevant for these power plants.
The level of detail that will be covered by the effects, that are chosen in the assessments, will depend on the data that is given by GABI which depends on the input data that is

given to the program. Some parts will be neglected because they will not give a significant difference in the output data. These parts are discussed below in the used ReCiPe 1.08 effects.
Climate Change is the first effect that is taken into account. In the analysis only the greenhouse gasses which are produced during the use and the assembling phase of the plant.
The focus of the Human Toxicity is only on the toxic emissions which are produced during the use of the plant and the emissions and the emissions that are released during manufacturing of the cycle components. For the emissions that cover the Particulate Matter Formation effect, like the Human Toxicity, only the emissions that are released during the use of the plant and the emissions that are released during the manufacturing of the components of the cycle will be covered.
The materials that are taken into account for the Marine Ecotoxicity are from the components of the plants. These components could be solar receivers, mirrors, piping, turbines or condensers for example.
The Natural Land Transformation is the amount of area that is transformed during the life cycle of a product or system. The area that is causing this effect in this case is the space that is needed for the complete installation of the plant. The transformation during the assembling, use and disposal phase are all taken into account.
The data of the Fossil Fuel Depletion will contain the amount of coal that is used for the use of the plant, the amount of fossil fuel that is used for heating processes. The fossil fuel that is used for the building of the plant will not be taken into account.

Determine order level of inventory

In this LCA the first and second level of inventory will be considered. This consists of the process that is happening within the power plant and the build of the plant itself. The build of the plant itself will be considered since its influence on the 18 midpoint effects of ReCiPe is substantial. Even though the second level of inventory is mentioned here as being taken into account, it will be limited. Defining of this limit will happen later on when the system boundaries are defined.

4.1.3 Defining the subject of the study

Define product and product group

In this case, the product relevant in this LCA is a power plant. At this point in time, the power plant in Lanzhou is a coal-fired power plant. It produces 220 MW of power and it operates on a basic thermodynamic cycle using water, with pressures between 4 and 14 bar and a maximum temperature of 450 degrees Celsius. The coal used for the heat supply is the illios coal 6.
The chosen new power plant is a plant that is 100 percent sustainable and runs on concentrated solar power and biomass. Like the coal-fired power plant, it will also produce 220 MW of power. It will rely on a multiple cycles combined. The main cycle, which is a Rankine cycle, is used to generate the 220 MW of power and deliver 65 MW of heat to the district heating system of Lanzhou. There is an additional cycle for the molten salt

that is used to heat the water of the Rankine cycle. Biomass is used to heat the water, as well as to deliver the additional 65 MW of heat that needs to be provided in winter.

Defining system boundary

The system boundary must be set. In this LCA, the boundary is set to the power plant itself and its in going and out going flows of material and energy. The production of the plant itself and its foundation will be included. It will be assumed that all components delivered are in the exact state that is needed (e.g size and weight). The welding or other type of connection processes will be excluded in the LCA. The materials used for the build and the creation of these materials will be taken into account. This includes all processes used to create this material, however the materials and processes used to create the machinery for making that material will be excluded as will the 'pre'-material (ore for example); its creation will be excluded. The transport of the material for the build will be included. This also includes the transport of biomass, which is a constant flow of material that has to be supplied. Within the process of the power plant; the transformer will be excluded.

4.1.4 Defining the Functional Unit

A description of main function and how much this is considered

First, the function of the new designed power plant is captured in order to be able to make a functional unit. For this LCA, three Functional Units will be made and the most appropriate one will be used for the actual assessment. The three Functional Units that are made are listed below;

- *To produce 220 MW of electricity continuously and produce 130 MW of heat for the city of Lanzhou for one year.*
- *To produce 1 TWh of electricity continuously during its life cycle.*
- *To produce electricity for the citizens of Lanzhou for one year.*

These are the functions that will be considered for this LCA. Before considering the functions and the amount of function that is performed, the lifespan of both plants should be derived. The coal-fired Lanzhou power plant has an estimated life cycle of around 40 years [9]. This value is estimated by using information of other coal-fired power plants around the world. 40 Years is approximately the average lifespan of a power plant with comparable power outputs and inputs. However, current power plant in Lanzhou does not provide any heat for the city. In order to be able to compare both plants, it is assumed that more coal is used to heat up water for the city. This will be the amount of 130 MW that is needed. The lifespan of a typical concentrated solar power plant will be approximately 30 years [10]. The lifespan of the new concept will be estimated as around the same lifespan; 30 years. Now that the lifespan is found, the amount of functional units that the coal power plant can perform, can be derived.

Considering the first functional unit; the coal power plant performs 40 functional units in its life cycle. The new concept that is created, performs 30 functional units in its life cycle based on the first function.
This functional unit will not be used for further research. This functional unit is not chosen due to the fact that the coal power plant normally does not provide any heat for the city. By assuming it would, this gives an extra level of complexity which does not result in better results.

For the second funtional unit; The coal fire power plant produces 77.088 TWh of energy in its life cycle. The inhabitants of the city of Lanzhou consume 17.3 TWh in a year, using average numbers for power usage and the amount of people living in Lanzhou and in China [11][12][13]. This gives that the coal power plant performs 4.5 functional units within its life cycle. The new created concept produces the same amount of electricity in its life cycle, but has a different lifespan. This gives a different amount of functional units; The new concept performs 3.3 functional units.
Also this functional unit is not chosen, because the estimation is too rough and there are too many factors either neglected or changing rapidly. When only using citizens as reference, all industry and other energy consuming activities will not be taken into account, even though these might affect results.

Now a look is taken at the third functional unit; The coal power plant produces an amount of 77.1 TWh of electricity in its complete life cycle This means that 1 life cycle produces around 77.1 functional units. The new concept produces about 57.8 TWh of electricity, so 1 Life cycle is equal to 57.8 functional units.
This functional unit is the one that will be used for further assessing. This functional unit represents all processes in the plant in a accurate way. This functional unit specifies to the factory (the producer) and not to the consumer, which is more accurate then referencing on consumer (see second F.U).

Comparison different products

The chosen functional unit could also be used for different products. Because the chosen functional unit only covers the electricity production over a certain amount of time, other products that would use the same functional unit must have the availability to produce electricity.
This is the case for example for windmills. The energy of the wind is converted into rotational energy. This rotational energy can be converted in different kind of energy such as heat and electricity, but the rotational energy can also be used to transport water. For the use of the functional unit only the windmill which produces electricity could be used.[14]
Another example is a nuclear power plant. By a nuclear reactor heat is produced which is used to run a turbine by generating hot steam. The turbine is connected with a generator which produces electricity.[15]
Electricity is also produced by solar panels. The solar power is converted from sunlight into electricity by the photovoltaic effect.[16]

4.2 Inventory Analysis

The following section describes the different components as well as the different processes that will be used to create the power plant. After that, the use and disposal of the plant will be illustrated. Besides the two critical components which are dealt with in detail in the material science section, many assumptions will be explained about the rest of the plant and the equipment used. With these parameters, an estimated environmental impact in the span of "cradle to grave" will be assessed. Overall the idea is to get the mass flows and energy flows into the scope of the functional unit. In this way, the entire plant can easily be assessed and compared to the old coal power plant.

4.2.1 Process Tree

The process tree gives a good idea of the flow of the facility. It is a graphical representation that will eventually culminate in the analysis of the impact to the environment of building as well as running the power plant. pictured below is the overall tree for the plant. A detailed version of each component with mass and energy balances can be found in the inventory section of the appendix.

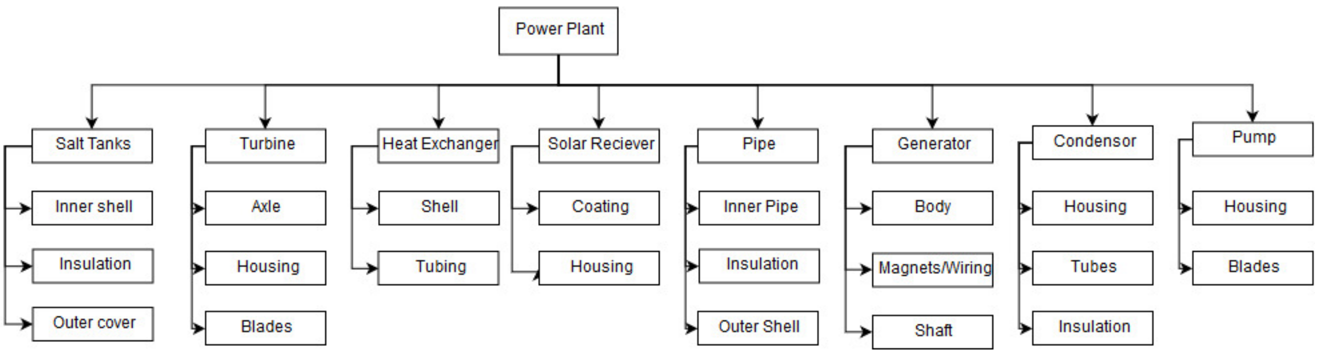

Figure 4.1: Overview of Components

4.2.2 Estimations

This section describes the estimations of all the components that make up the power plant. The data is displayed in totals, or how the total was achieved. The mass will be broken down later in the inventory analysis into a functional unit. There are many assumptions that need to be made when considering the estimates. First, the only components that are considered are ones that will have a large impact on the environment compared to others. For example, the pump, piping, and turbines will be considered versus facility doors, work desks, ect. Secondly, along the same vein, with the individual components, only the major sections are taken into account. For example, in the pump the housing and some internal pieces which are all steel are considered, while gaskets are disregarded. These assumptions are summarized in table below.

Part	Material Considered
Water Pump	Body
Heat Exchanger	Shell, Tubing
Solar Receiver	Main Body
Salt Tanks	Main Body
Turbine	Case, Axle, Blades
Structure	Diagram, Body
Valve	Foundation, Buildings, Piping

Table 4.2: Considered components of equipment

The Pipe and Salt Tanks

The pipe for the plant will be created through Rotary Tube Piercing Process (Mannesmann process). This process allows for thick walled seamless tubing, and so will reduce the number of welds necessary, as well as making the pipe connection to the city much easier to produce. For the kind of heat and pressure expected, a wall thickness of 1.35 cm is needed. The total length of piping is estimated to be at 460 m for the plant. Estimated fiberglass needed for insulation is 10 cm. This would mean about 32 tones of stainless steel would be used for the plant, along with 12 tones of aluminum for the outside cover.

	Pipe	**Insulator**	**Outer Shell**
Material	Stainless Steel	Fiberglass	Aluminum
Density (kg/mˆ3)	7800	40	2500
Inner Diameter (m)	0.20	0.227	0.327
Outer Diameter (m)	0.227	0.237	0.329
Total length (m)	460	460	460
Mass per meter (kg/m)	70.6278723	1.740442	2.576106
Total mass (kg)	32488.8213	800.6035	1185
Volume(mˆ3)	0.009055	0.043511	0.00103

Table 4.3: Pipe estimations

The cold and hot salt water storage must be able to hold the full amount of liquid salt at any given time. This means that the lower limit of the volume must be able to hold 32000 meters cubed. With this in mind, the tanks should have a height of 10 meters with a radius of 25 meters. This means that the wall thickness will be 25 cm thick with an insulated layer of fiberglass 1 meter thick.

	Tank	Insulator	Outer Shell
Material	Stainless Steel	Fiberglass	Aluminum
Density (kg/m^3)	7800	40	2500
Inner Diameter (m)	50	50.5	52.5
Outer Diameter (m)	50.5	52.5	52.7
Total Height (m)	10	10	10
Volume(m^3)	394.588125	1617.62	165.217
Total mass (kg)	3,077,787.38	64,704.6	413,042

Table 4.4: Salt tank estimations

Turbine

The turbine is made up of three parts, the axle, and blade and the housing. Different materials were picked depending on the application (ref to the MS section). Here, the structure is basic. The axle was estimated to need a diameter of maximum 66mm, with a length of 20 meters. This long length is to allow for the connection from the turbine to the generator The housing is estimated to need a volume of about 4 cubic meters per turbine. Lastly, for the blades the shape chosen to represent the structure was a rectangle. For all three components different steel types were chosen as per the performance index in the material science section.

Turbine	**Axle**	**Housing**	**Blades**
Material	AISI 41 (tool steel)	ASTMCA-6NM (Cast SS)	ASTM CA-15 (SS)
Density (kg/m^2)	8100	7650	7560
length (m)	20	5	0.4
Width (m)	-	-	0.05
Height (m)	-	-	0.01
Diameter (m)	0.12	-	-
Inner Diameter (m)	-	1	-
Outer Diameter (m)	-	1.4	-
volume (m^3/m)	0.002232	3.72	0.0002
mass (kg)	1832	28458	1.512

Table 4.5: Turbine estimations

Buildings and Foundation

There is one large tower, and a handful of small buildings. The tower will be a bit taller than the crescent dunes tower: about 300 meters. It will have a diameter of about 20 meters and an average wall thickness of about 40 cm. The small buildings will have about 200 meters squared of walls and roof with a wall thickness of 10 cm.

Structure	Tower	Small building
Volume (m^3)	1184	20
Steel percentage	2	1
Steel density (kg/m^3)	8050	8050
Concrete density (kg/m^3)	2400	2400
Mass concrete (kg)	2,800,000	160,000
Mass steel (kg)	190,000	1,600
amount	1	6
Total mass concrete (kg)	2,800,000	960,000
Total mass steel (kg)	190,000	9,600

Table 4.6: Structure estimations

There is a foundation under the main platform, which has a diameter of around 180 meters. The depth of this foundation will be close to the limit of a practical depth, around 2 meters. The heliostats have a foundation of about 1 cubic meter. The steel percentage is approximately 0.5 percent.

	Heliostat	Platform
Measurements (m)	1 x 1 x 1	d = 180, h = 2
Density steel (kg/m^3)	8050	8050
Density concrete (kg/m^3)	2400	2400
Volume (m^3)	1	50,000
Steel percentage	0.5	0.5
Mass concrete (kg)	2,390	120,000,000
Mass steel (kg)	40	2,000,000
Amount	20,000	1
Total mass concrete (kg)	48,000,000	120,000,000
Total mass steel (kg)	800,000	2,000,000

Table 4.7: Foundation estimations

Heliostat

A heliostat is the structure that reflects the sunlight onto the solar receiver. The numbers in the table are based on numbers from the Crescent Dunes CSP. The number of heliostats is estimated to be about twice as big as the number seen in the Crescent Dunes CSP. This is because of the higher power output of the Lanzhou power plant, the addition of power from biomass, and the lower yearly solar irradiation in Lanzhou compared to Crescent Dunes. A standard thickness for a mirror used in such an application is 6mm. A mirror has a layer of silver of around 100 nm.

Heliostat	Body	Mirror
material	Stainless steel	Glass + silver
Measurements (m)	10.4 x 11.3 x 6.0	glass: 10.4 x 11.3 x 0.006 Silver: 10.4 x 11.3 x 100e-9
Weight Stainless steel (kg) / silver	2000	0.03
Weight Glass (kg)	0	1800
Amount	20,000	20,000
Total mass (kg)	Steel: 40,000,000	Silver: 600 Glass: 36,000,000

Table 4.8: Heliostat estimations

Heat Exchanger

The heat exchanger is a simple shell and tubing type. Here the pipe diameters were implemented so that flow is seamless through the process.

Heat Exchanger		
	Shell	**Tubing**
material	Stainless Steel	Copper
density (kg/m^2)	7500	8960
length (m) outer	5.2	-
width (m) outer	1.7	-
height (m) outer	1.7	-
length (m) inner	5	-
width (m) inner	1.5	-
height (m) inner	1.5	-
Inner Diameter	-	0.2
Outer Diameter	-	0.227
Volume (m^3)	3.778	0.044674875
mass (kg)	28335	400

Table 4.9: Heat Exchanger estimations

Miscellaneous Equipment

In the table below, some very simple components that need to be estimated are stated. Examples were found and the the volume was estimated using length times width times height with a percentage taken out due to internal spacing.

Pump	Stainless Steel
Volume (m^3)	0.10 x 2 x 2 x 4 = 1.6
Density (kg/m^3)	8050
Weight (kg)	13,000

Table 4.10: Pump estimations

The plant will use centrifugal type pumps. The vast majority of the material is stainless steel in the body, and so everything else is disregarded.

	Electric motor
Total mass (kg)	2,000
Mass copper (kg)	200
Mass steel (kg)	1,800

Table 4.11: Electric Motor estimations

The electric motor has a couple pieces taken into account. The frame, as well as the wire components.

4.3 Profiling

In the profiling part of the LCA, all results will be listed. These results were created using the Thinkstep GaBi software and given shape with excel.

4.3.1 Table of Interventions

A Gabi model of both the coal power plant in Lanzhou and our solar power plant design were made. This resulted in data that gave us information relating to environmental impact and relevant emissions and their effects. All the emissions that will be emitted, as the program inquires, were listed in the table of interventions. Note: the table of interventions below is a general table. During evaluation some of these emissions will be analyzed in depth and the table of interventions will be expanded locally for a better overview. The table of interventions can be found in the appendices in figures: (6.25 - 6.28) The Gabi model also created graphs that display these results. These results are displayed using the ReCiPe method, which calculates the effects of all emissions and divides them among the 18 different midpoints. A description of all these midpoints can be found in the appendix too.

4.3.2 Characterized graphs

Characterization was applied to bring these results into perspective. Characterized graphs display the results based on the assembly, the use and the disposal of the plants. As said before, all emissions and other substances are taken into consideration. The characterization part determines how much each substance contributes to a specified effect. Some substances are less dangerous then other substances when it comes to the midpoint effects. The characterization used in this case was the standard ReCiPe characterization, which had weighing factors available per substance. This Characterization was applied to the existing results and this gave characterized results. For both plants there are a total of nine graphs. In this graph 'damage' of the use, assembly and disposal for the plant is displayed.

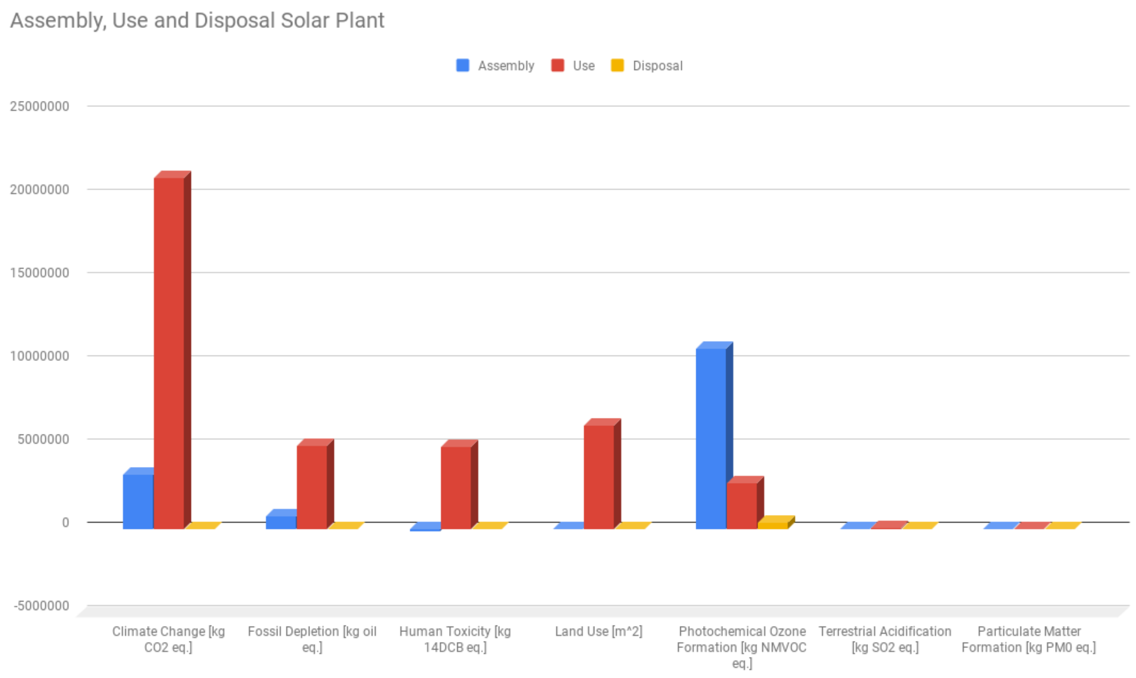

Figure 4.2: Assembly, use and disposal solar plant

Figure 4.2 shows the effect of the assembly, use and the disposal of designed power plant on the ReCiPe effects. Note that the units of all the different effects are stated behind the name of the effect. This means that the vertical axis has a different unit for every effect. It definitely can be seen that the use overshadows most when it comes to impact on an effect. To be able to still see the results of the other effects, the scale of the y-axis is reduced and the use phase from the diagram is removed, shown in figure 4.3.

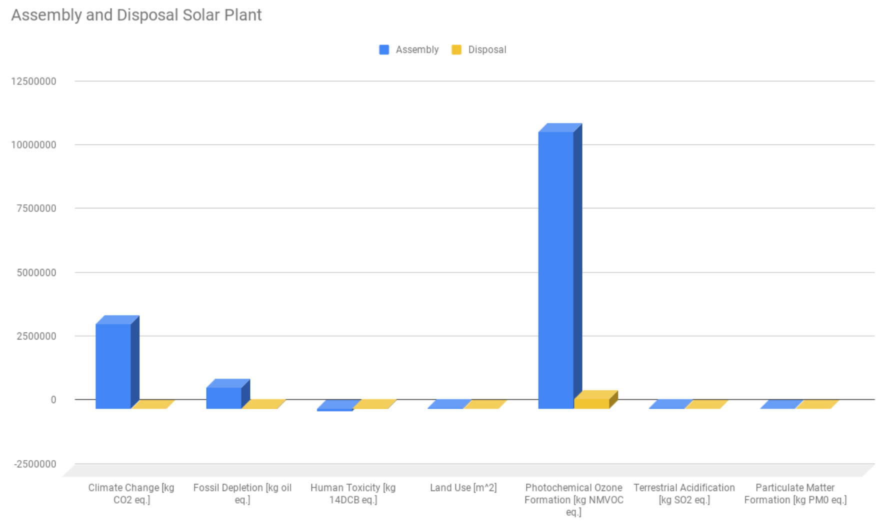

Figure 4.3: Assembly and disposal solar plant

And this will be done again and now only show the disposal in figure 4.4.

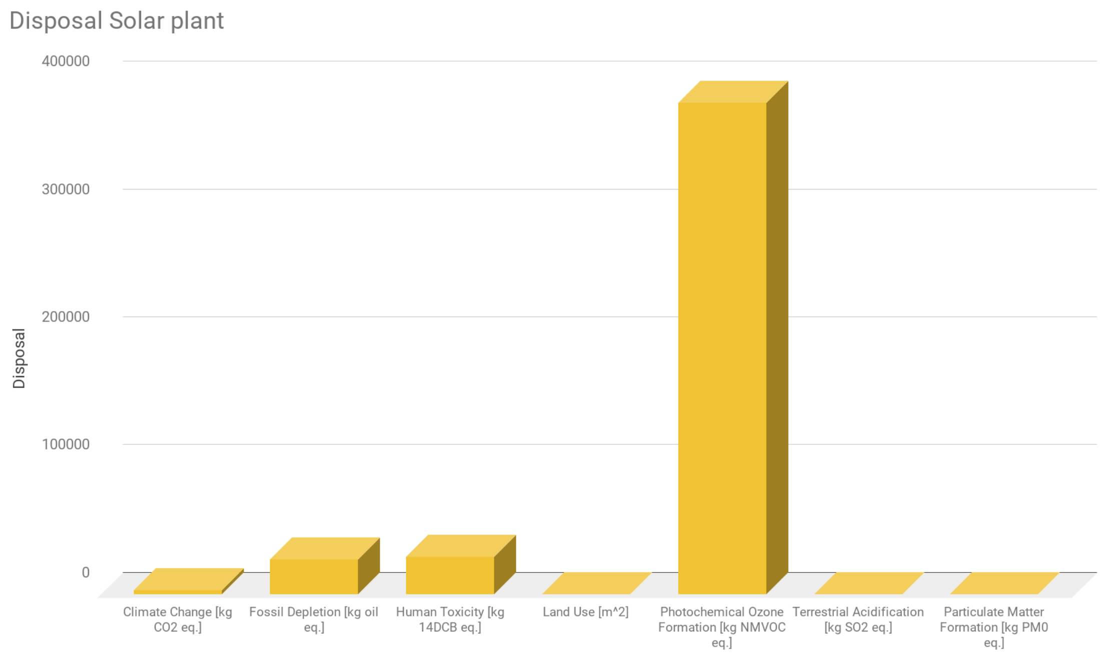

Figure 4.4: Disposal solar plant

These graphs display the results. What is missing still is a detailed look at a single effect. In this case there will be looked at the effect climate change for example in figure 4.5

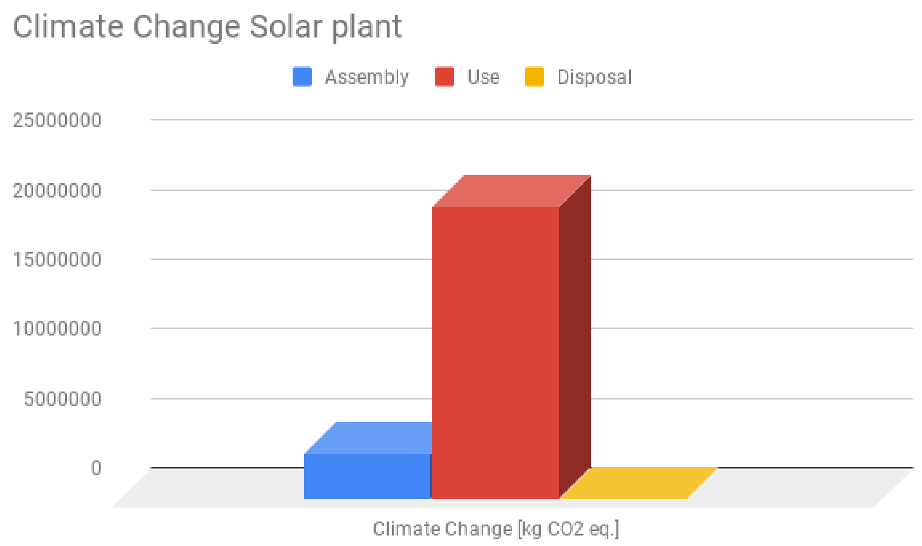

Figure 4.5: Climate change effects

Note that only a brief look will be taken at six of these effects, since the rest is included in the goal definition of this LCA (figure 4.1). Also note that the other five single effects of the solar plant are in the appendix and this same structure of graphs for the coal power plant is also in the appendix in figures 6.29-6.43

4.3.3 Normalization

After the characterization of all graphs it is important to normalize them. Normalization scales these numbers and values so a comparisson is possible. This ensures that comparison can be done between the different midpoint effects. The normalization done within the LCA was based on Personal equivalence of an average European person. The normalized graphs will, like previously, be on 'assembly, use and disposal' AND on 'assembly and disposal' AND on 'disposal'. These normalized graphs can be found in the appendix. (figures 6.44-6.49)

4.4 Evaluation

Now that all profiles have been made and mentioned it is time to evaluate the data that is found. This data will be evaluated in separate sections for the solar plant and the coal plant.

Solar plant

From the input of the GABI model, the following results in environmental effects are given. (figure 4.6). Notice that only seven effects are listed here. The reason only these are displayed will be treated later in Normalization.

Figure 4.6: Assembly, use and disposal solar plant

From figure 4.2 the most remarkable is the effect of Terrestrial Ecotoxicity during the use phase. With an emission of approximately 70,000,000 kg 14DCB eq. Furthermore it is shown that all effects exhaust the most emissions during the use phase except for Photochemical Oxidant Formation (figure 6.31). Here, it is shown that the most emissions of this effect are exhausted during the assembling phase of the solar plant. Furthermore, the emissions to the ecosystems are remarkably higher than the emission regarding human health.

Because of the higher values in the use phase, the differences during the assembling phase and the disposal phase are hardly noticeable. In figure 4.3 the emissions during the assembly phase are more clear. Here it is shown that Photochemical Oxidant Formation and Terrestrial Ecotoxicity are the effects with the highest emissions during the assembling phase. In figure 4.4 the effects of disposal phase are shown more clearly. The most remarkable emissions are the high values for the Photochemical Oxidant Formation.

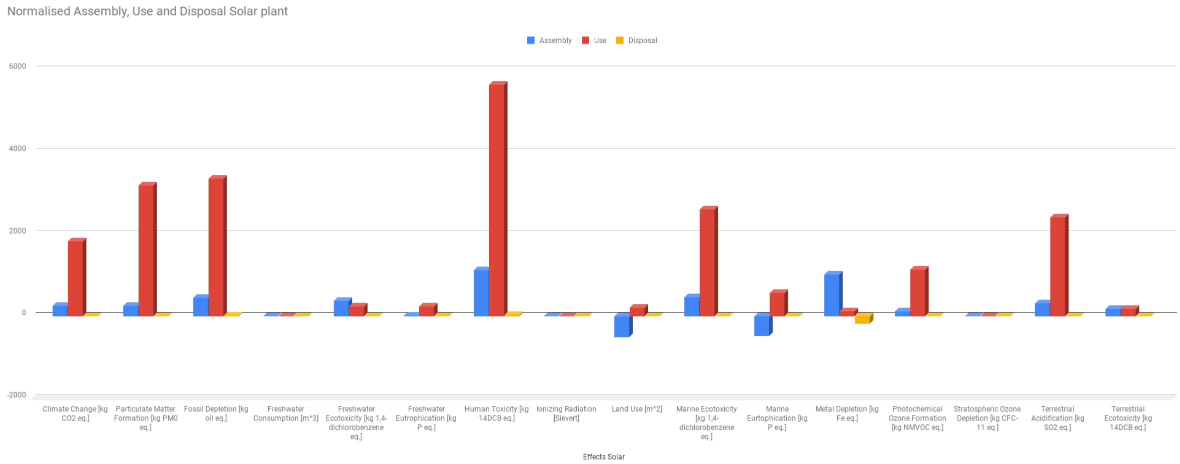

Figure 4.7: Normalised assembly, use and Disposal Solar plant

Since all effects have a different impact on human and environment the values of the emissions can not be compared with each other. The impact of these effects can be compared after the normalization of these effects are done. The unit of the effects is after normalization 'Person Equivalent', which rates the impact of each effect on human and environment.
Regarding to figure 4.7 the comparison of effects with each other on their impact on the environment could be made. Some effects do not have such values that they could make a significant impact compared to the other results. In the goal-definition was stated which effect should be taken into account for the assessment and which were excluded.
The effects can now be compared in normalized graphs. Figure 6.44 conclude that the emissions during the use phase of Terrestrial Ecotoxicity does not have a high impact on the environment in comparison with the other effects. Instead Human Toxicity turns out to have the highest impact followed by Fossil Fuel Depletion and Climate Change.
For the assembly and disposal phase more clear results are displayed in figure 6.45. Here it is shown that Human Toxicity also has the biggest impact in the assembly and the disposal. Furthermore the negative value for Natural Land Transformation during the assembly and the small negative value during the disposal of the Climate Change effect are the cause of production of multiple products. By-products are produced without using these for the power plant. These products could be exported for the production of a different product.

Coal plant

The first thing that will be done is having a look at the results of the GaBi model. All effects will be analysed and given down below in figure 4.9. Also, what should be noticed is that the vertical axis has no specific unit, since every effect has its own unit.

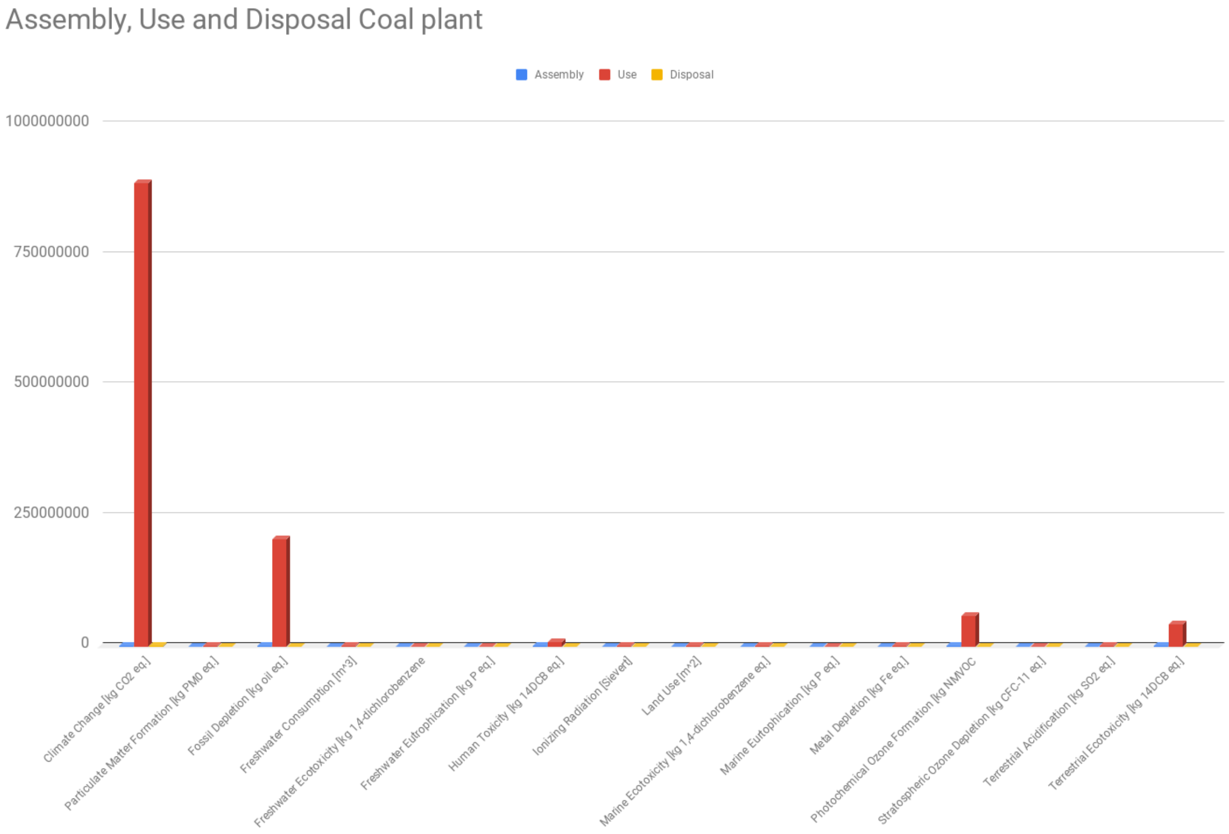

Figure 4.8: Assembly, use and disposal coal plant

What can be seen here is a few effects distinguishing from the others ones. Since this graph is not normalized yet there cannot be made a clear conclusion about how severe the effects truly are. Therefore a normalized graph is created and shown below in figure 4.9.

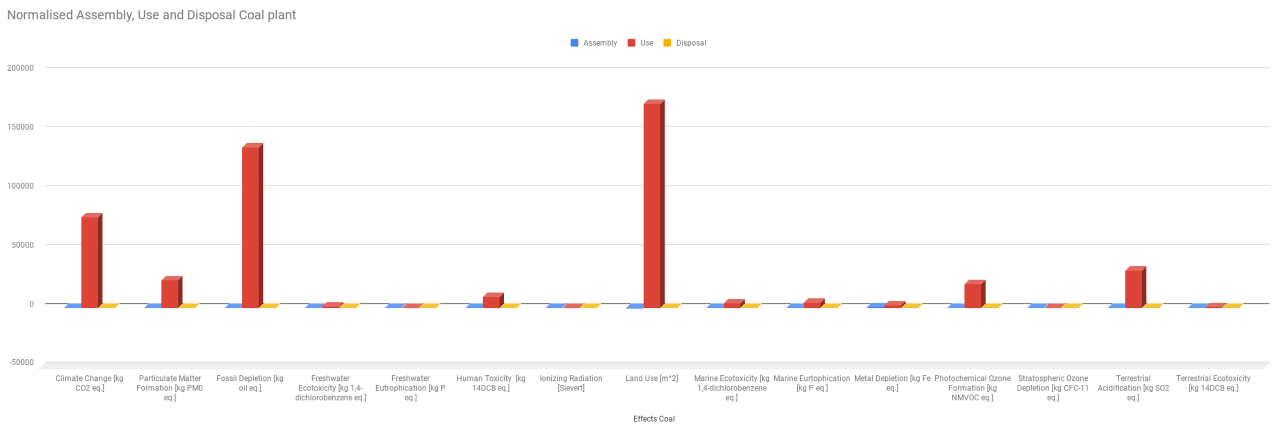

Figure 4.9: Normalised assembly, use and Disposal coal plant

Now the effects that actually matter can be seen. For the following part the effects that matter less will be excluded. Those effects that matter less, were already excluded in the goal definition.

A few things are immediately noticed when a look is taken at the complete life cycle of our chosen effects in figure 6.35. The first thing that is noticed is that the use overshadows all the other phases when it comes to effects. At almost none of the effects, the assembly or disposal phase have an influence as significant compared to use. This makes sense as during production of energy for 40 years, these emissions are emitted to the environment. For assembly for example this is for a short time and apparently a short amount compared to the use. It can also be noticed that the use phase is the biggest within the climate change effect.
Even though climate change seems to be the biggest threat to the environment, the effects to each other cannot be compared to each other. This can only be done after normalizing, which is done and brought into a graph in figure 6.47. When normalization is done, the unit of every effect is personal equivalence. This means that now comparison between effects is possible. And now suddenly it can be seen that the effect 'Land use' is relatively affected the most by the use phase of the coal plant. Besides that, it can also be noticed that climate change has not disappeared from the scale.

The use phase is obviously the biggest 'threat' when it comes to emissions to the environment. For the next part, the use phase will be ignored and a look will be taken at the assembly and disposal in figure 6.36. Here it may be noticed that multiple effects having a strong influence. Notice that the scale of the vertical axis has shrunk compared to the full graph in figure 6.35. It can be seen that the same effects have significant effect, though the proportions have changed compared to the use phase; the effect of the assembly on climate change is not the biggest anymore. Also fossil depletion is now one of the smaller ones. This makes sense as the coal plant uses fossil substances as fuel during its use phase.
Again the results will be normalized to the unit of 1 PE. The results are graphed in figure 6.48. In this figure a few statements can be made. First of all the most remarkable thing is that the huge peak at assembly for Photochemical Oxidant formation in the characterized graph (figure 6.36) has now turned into the smallest amount. This means that the 'amount of effect', in this case in kg NMVOC eq., has now turned to the smallest amount PE in this normalized graph. This is a really nice example of certain substances having less effect then others. Apparently that emission does not affect the environment as much as for example the same amount of another substance would do. What can also be noticed is the negative amount PE on Land use. This is a cause of creation of by-products as it has been explained before. Also can be seen that the amount of human toxicity has now grown to the biggest effect within the assembly phase.

Now for a look at the disposal phase in figure 6.37. Again it can be seen that the climate change is the biggest in this characterized graph. Looking at the normalized graph in figure 6.49 it can be noticed that the climate change has in fact dropped down a spot and fossil depletion is now on top. What should be noticed is the difference in scale compared to the normalised assembly in figure 6.48. That figure runs up to 200 PE while this figure only goes to a maximum of 10, which indicates that the disposal phase does in fact not have a very big normalised impact.

What should also be seen form all of these graphs is the relation between them. When looking at the height of the bars (the amounts of substance eq. emitted), the same bars peeking between them are shown.
In addition, now there will be looked at the assembly, use and disposal phase of the single effects. When analyzing all of these, it can be seen that basically for every effect, the use phase is so much bigger then the assembly and/or use. This is also the only conclusion that will be drawn from these separate graphs.

A few conclusions have been drawn in the previous part about how the biggest effect turns out to be the smallest and about the fact that some effects are way more 'dangerous' then they appear to be. In the following part, not only a look will be taken at the specific effects and the amounts, but also at what processes actually cause these emissions and which ones are the most important,

Emissions Solar plant

Human Toxicity has the highest normalised emissions of the solar plant effects during the assembly phase as it is shown in figure 6.48. Figure 4.10 displays where these emissions come from.

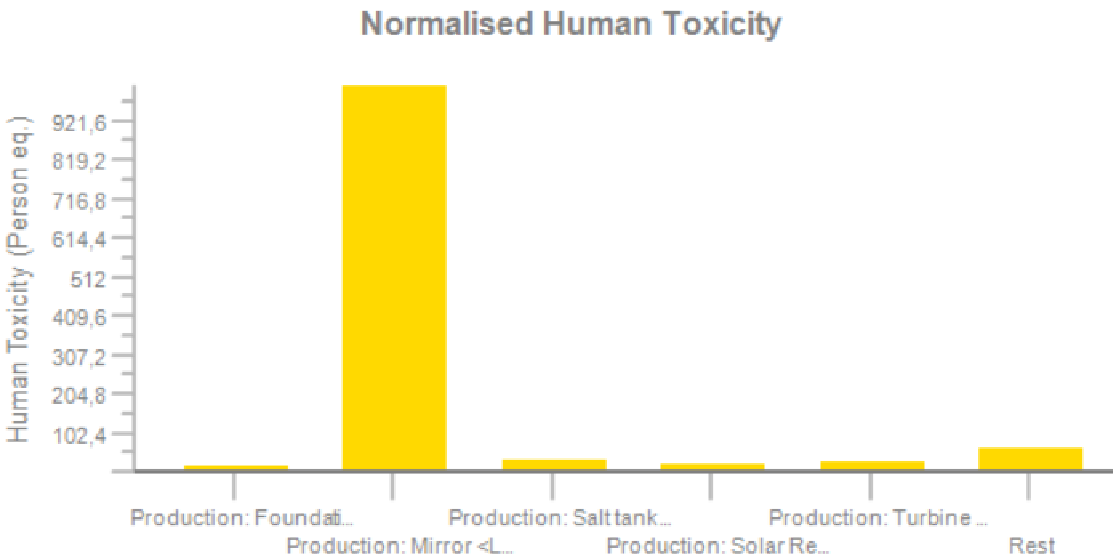

Figure 4.10: Origin emissions Human Toxicity

The major part of the emissions are from the production of the mirrors according to the figure. Which parts of the mirrors actually cause this effect are shown in figure 4.11.

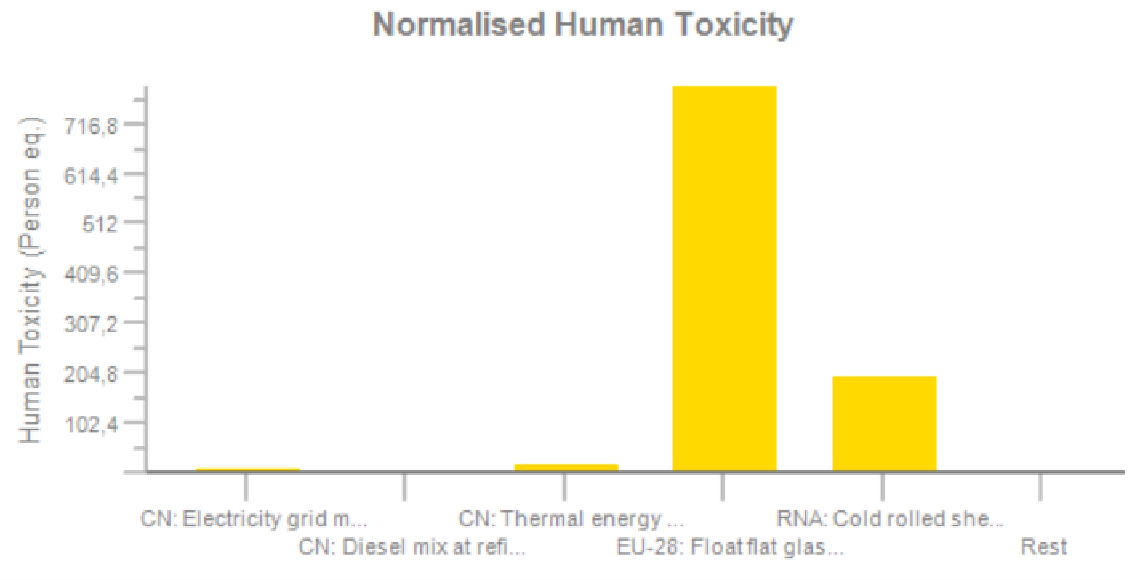

Figure 4.11: Origin emissions Human Toxicity Mirrors

The most emissions are from the glass plate production and the steel production for the Human Toxicity effect. For the Climate Change, Fossil Fuel Depletion, Human Toxicity, Photochemical Oxidant Formation, Terrestrial Acidification and Particulate Matter Formation also has the same major productions which cause these emissions.
In case of the Natural Land Transformation the effects of the assembling have a different major cause. (Figure 4.12)

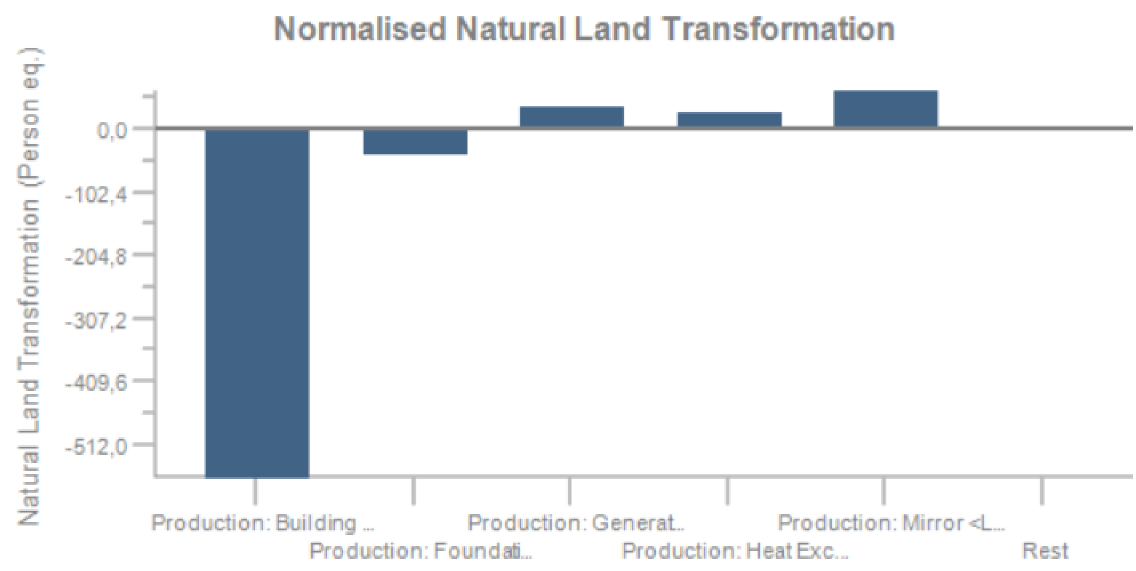

Figure 4.12: Origin emissions Natural Land Transformation

Here is displayed that there is a negative value for the production of the building. By-products are produced during the production of the building. The steel billet production produces these by-products, as it is shown in figure 4.13.

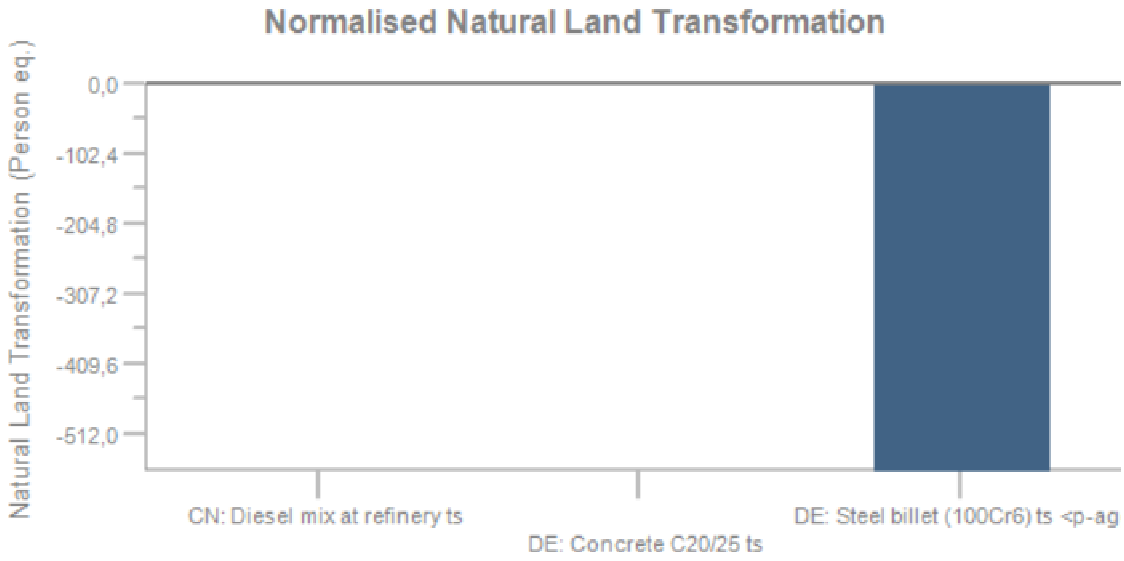

Figure 4.13: Origin emissions Natural Land Transformation Building

For the use phase only the production, transportation and use of the biomass caused environmental effects. (Figure 4.14)

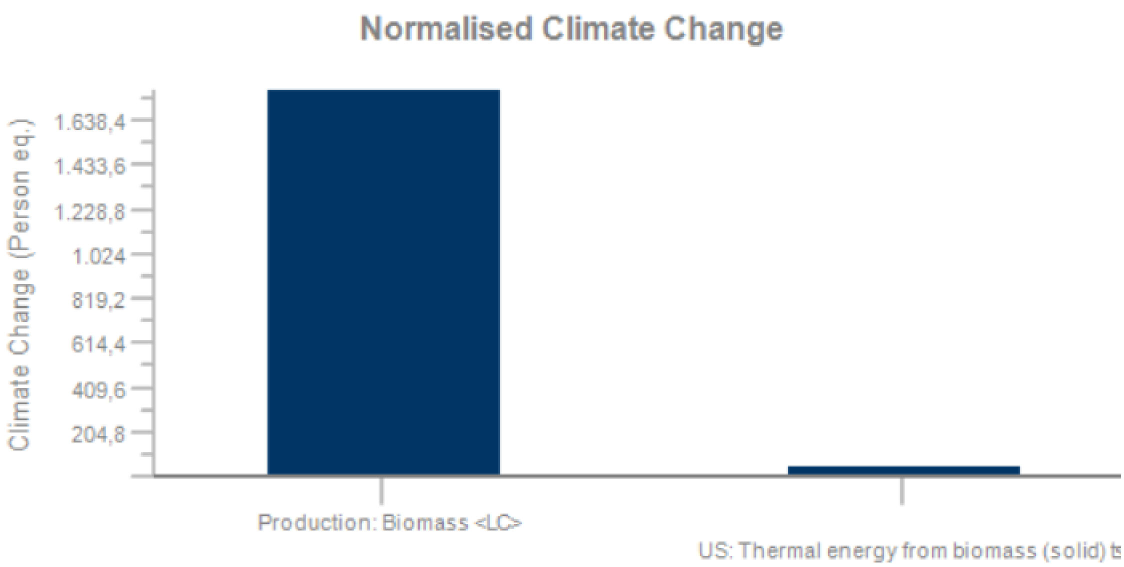

Figure 4.14: Origin emissions Climate Change

The major effect of Climate Change is because of the production of the biomass. A more detailed look on the production of the biomass is shown in figure 4.15. The most of the emission gasses are from the thermal energy that is needed to produce the type of biomass that is used for the solar plant.

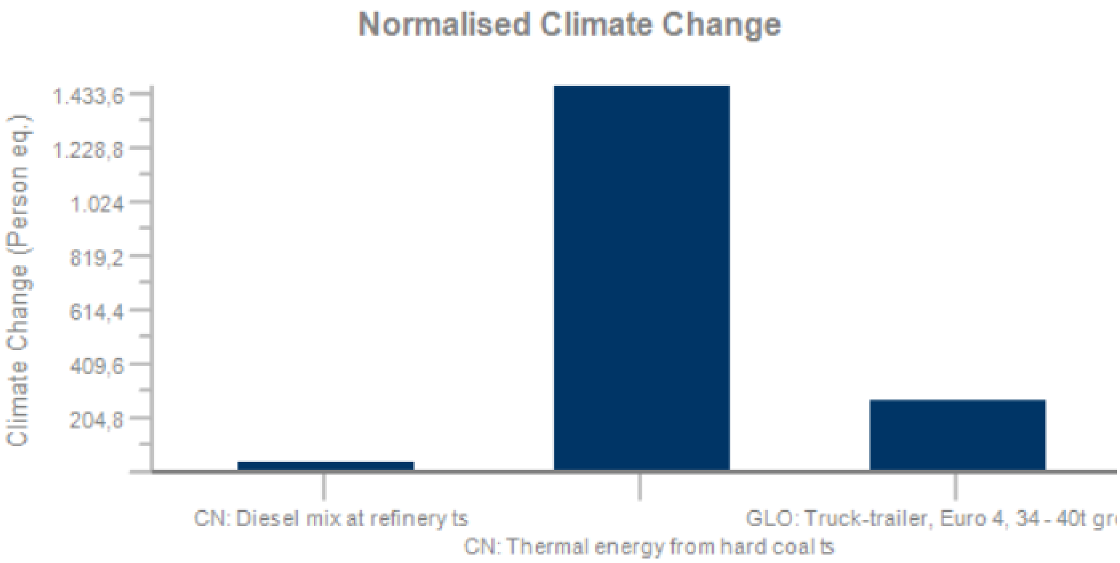

Figure 4.15: Origin emissions Climate Change Biomass production

The CO_2 emissions from the biomass can be neglected, because the biomass that is gained from the environment will be planted back and the CO_2 emissions will be absorbed by the planted biomass.

In the comparison between the normalised disposal effects (figure 6.46) is displayed that Human Toxicity gives the most positive effect (Figure 4.16) and Particulate Matter Formation gives the most negative effect (Figure 4.17).

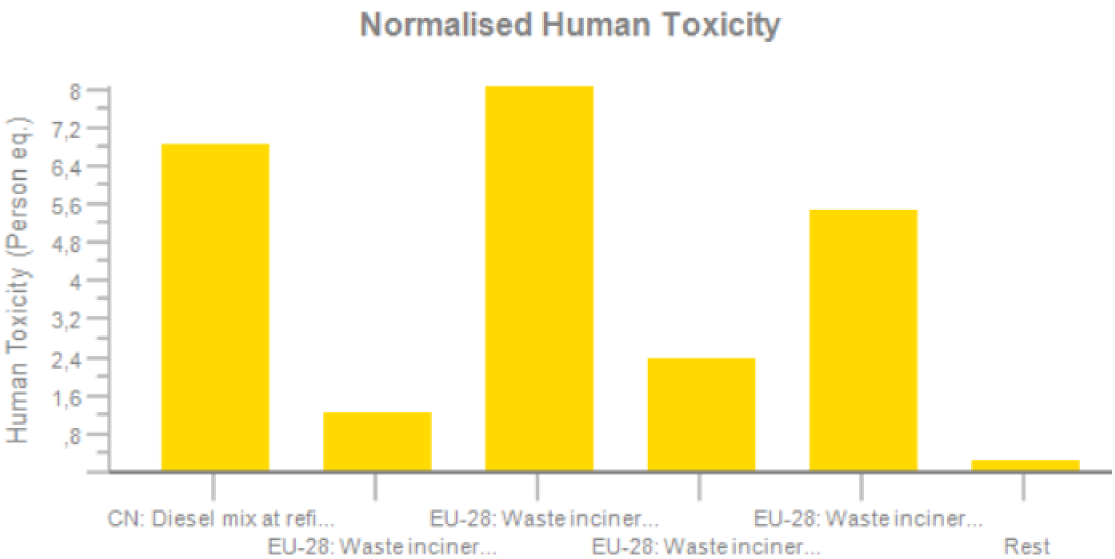

Figure 4.16: Origin emissions Human Toxicity disposal

The diesel that is used and the melting of the metals that will be recycled are giving a positive value which causes the Human Toxicity effect. For the Particulate Matter Formation it is a positive effect for some metals, but for other metals by-products are created which cause the negative effect.

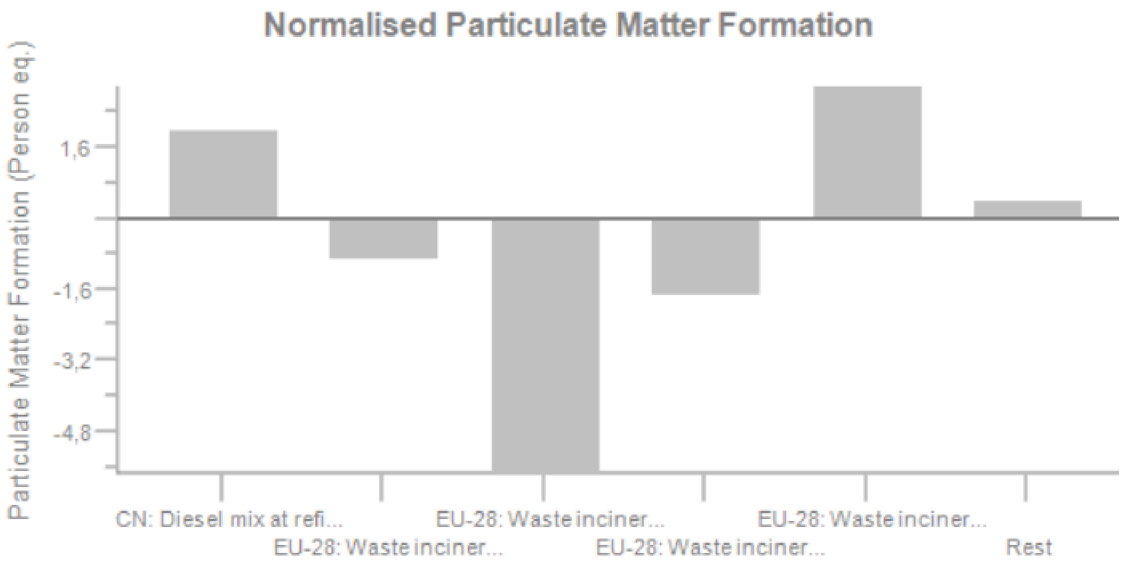

Figure 4.17: Origin emissions Particulate Matter Formation disposal

Emissions Coal plant

Looking at the assembly, there are different processes which cause the emissions per element. In figure 4.18 it shows the origin of the emissions with respect to climate change. In this case the structure is taken as an example.

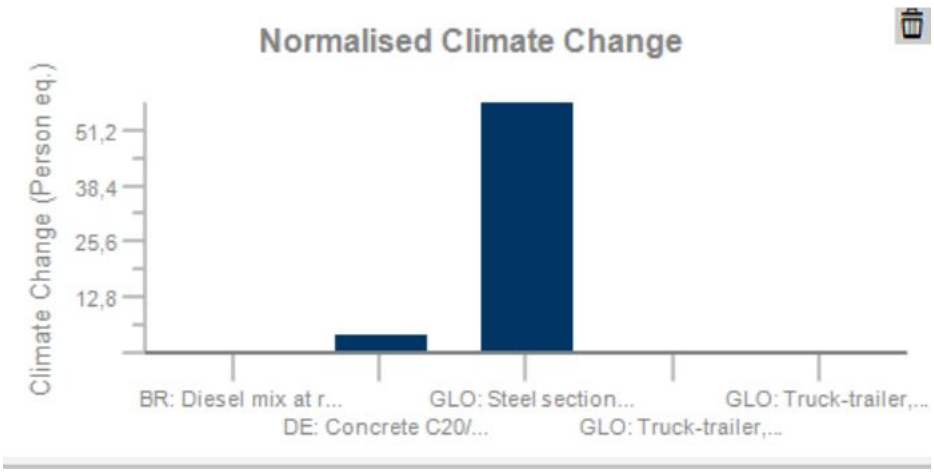

Figure 4.18: Origin emissions Climate Change assembly

Here it can be seen that the major emissions are caused by the creation of steel and concrete. These are the main production processes within the production of the plant,

since almost all elements are made out of steel and concrete. For the other six relevant effects the origin is the same.
What is remarkable to see that for the effect of Human Toxicity it is shown in figure 4.19 and figure 4.20 that stainless steel here is quite a lot more dangerous when it comes to this specific effect.

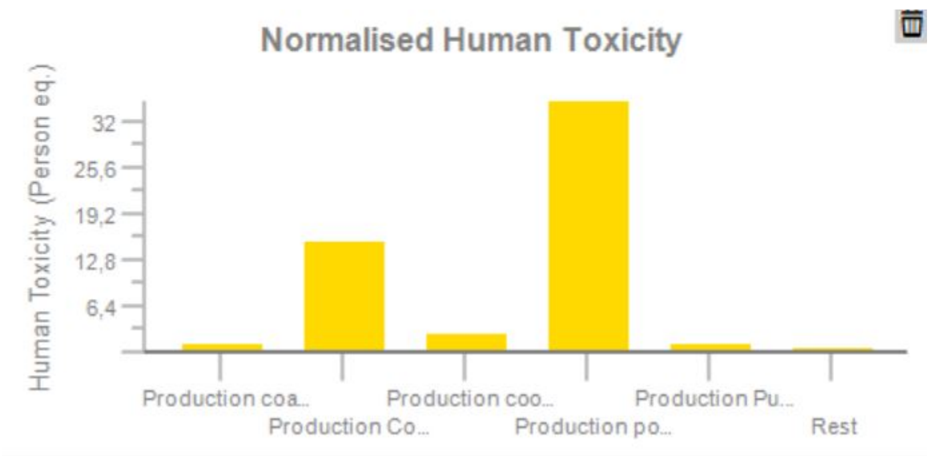

Figure 4.19: Origin emissions Human Toxicity assembly

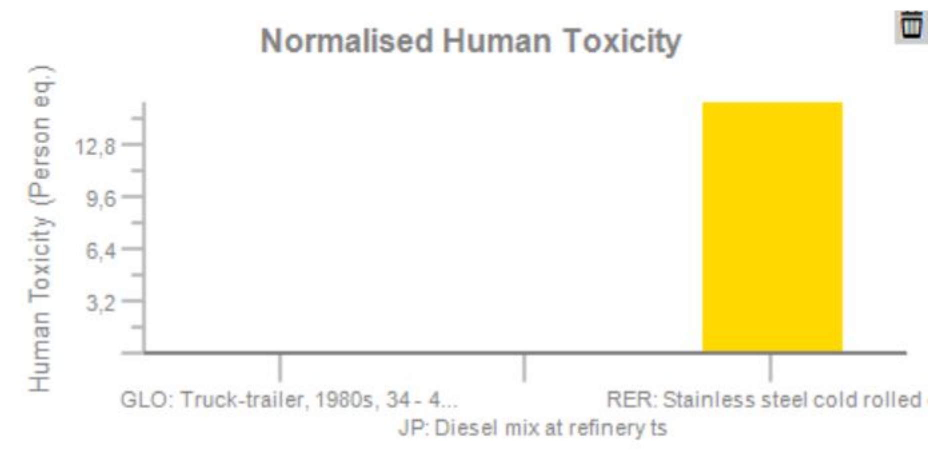

Figure 4.20: Origin emissions Human Toxicity assembly

A big spike in amounts can be seen when it is compared to the other effects and climate change, for example, where stainless steel was not significantly different then regular steel.

When it comes to the use phase of the coal plant; all effects are because of the emission of the substances that release during the burning of the coal. This is because this is the only process within the use phase. This coal burning is then also defined as the origin of the emission within the use phase. In figure 4.23 it could be seen that the thermal energy from hard coal in this case is the origin. This not only counts for this effect but counts for all.

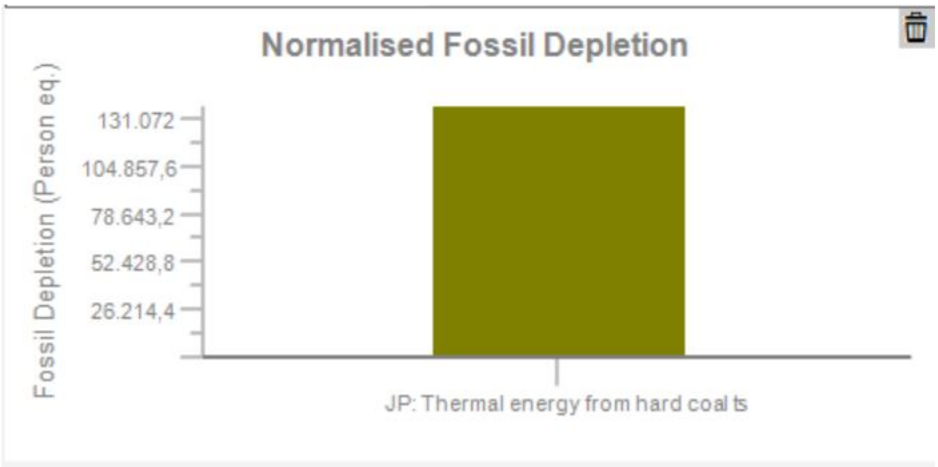

Figure 4.21: Origin emissions Fossil Depletion use

As one can see here there is one origin; The burning of the coal to run the plant.

Now a look will be taken at the origin of emissions for the disposal of the coal plant. When it comes to the origin of the emissions; the biggest origins are concrete crushing and the transport: the trailer and the diesel. This can be seen in figure 4.22.

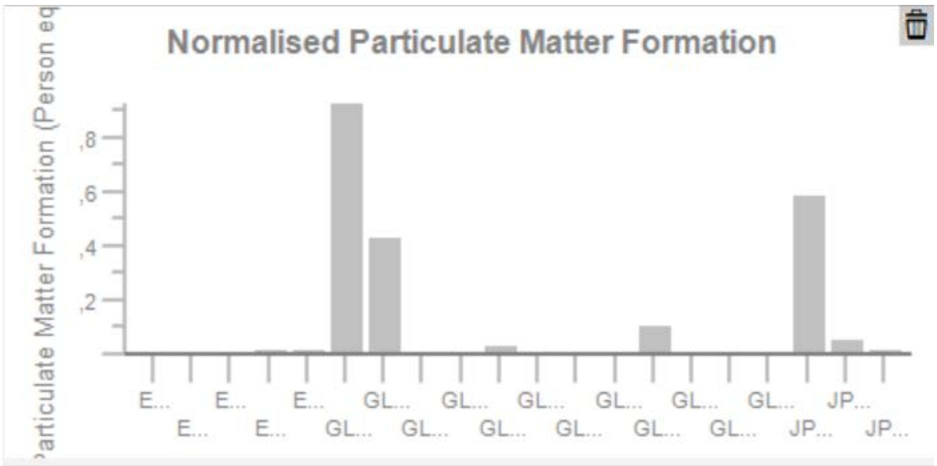

Figure 4.22: Origin emissions Partiuculate Matter Formation disposal

Here it can be seen the concrete crushing as the left peak and the diesel as the right one with the trailer in the middle. This proportion works for most of the effects. A remarkable peak is displayed when there is looked at the disposal phase of fossil depletion in figure 4.23.

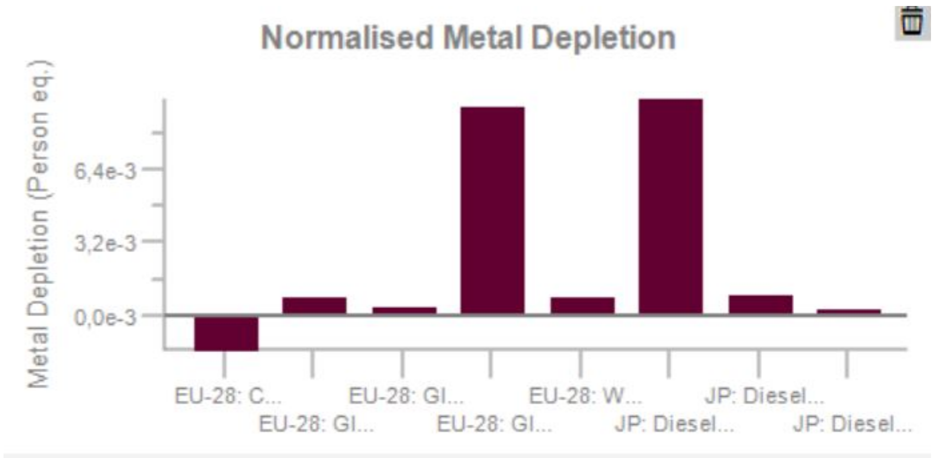

Figure 4.23: Origin emissions metal Depletion disposal

In this figure is show a big peak at the glass. apparently glass plays a major part within the effect of metal depletion.

Validity

When looking at the validity of these results; a lot of assumptions were made on masses and other estimations. Due to the error margin of our estimations the results could slightly differ from what it would be in real life. The exact amount of possible difference between the 2 situations is unknown. Though, there are a lot of estimations done, which should average each other out. But there is still some margin possible.

4.4.1 Break-even

First a comparison between the two scenario's will be done in the break-even. This comparison will be done by looking at a single effect and comparing both the scenarios to each other. This will first be for all phases together and using characterized graphs. As an example all comparisons will be shown below in figure 4.24 to figure 4.30.

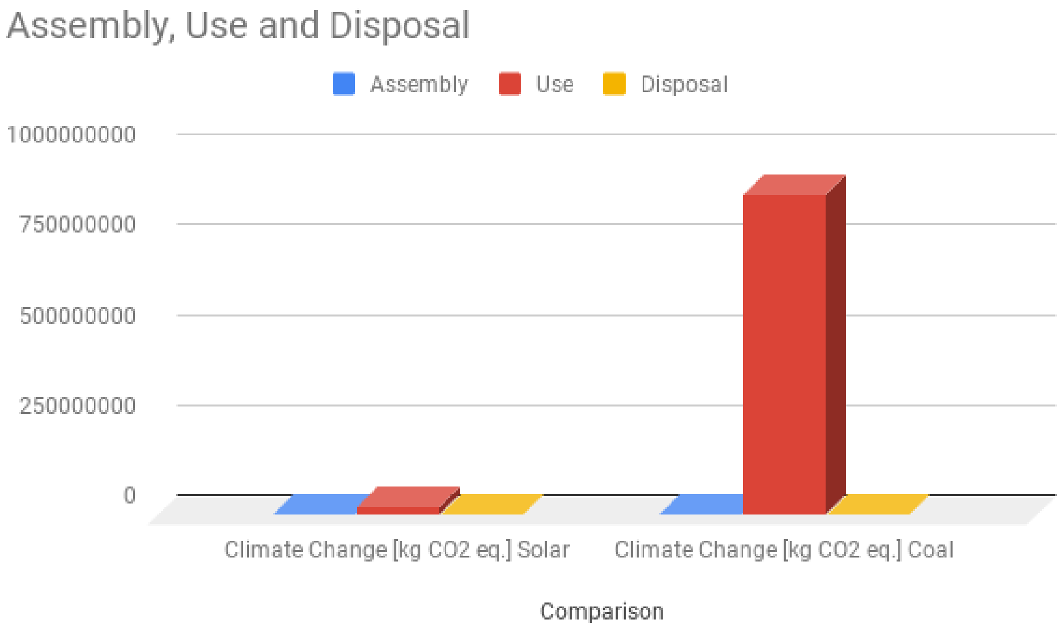

Figure 4.24: Comparison Climate Change

This comparison of figure 4.24 shows the direct difference between running a plant on coal and on solar power. What can immediately be seen that the use phase of the coal plant is multiple times bigger the the use phase of the solar plant due to the use of pure coal as energy source. It makes it very clear how such plants differ in this way.

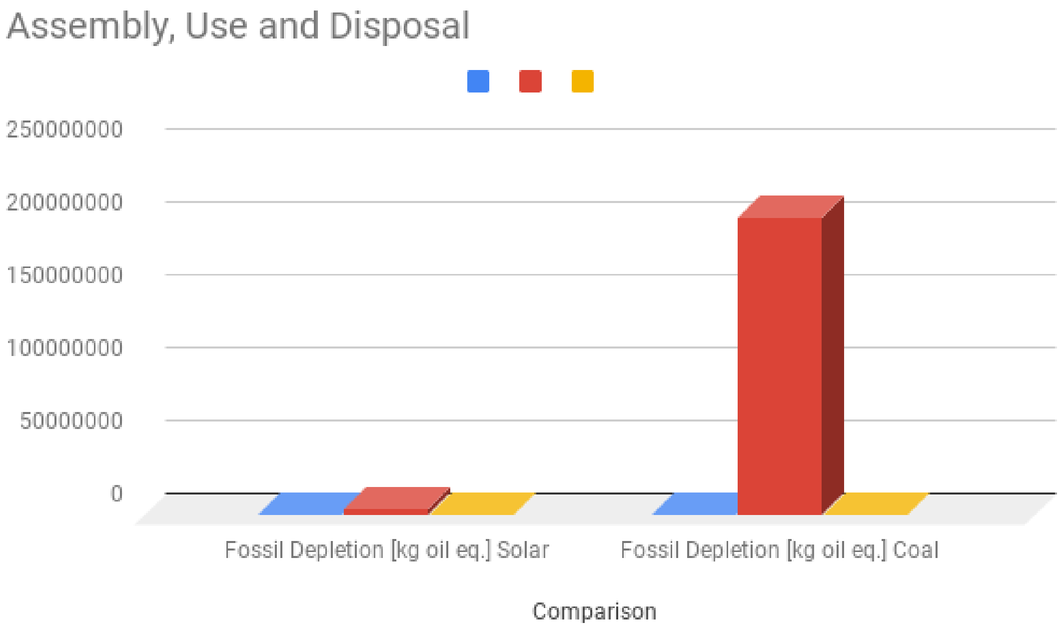

Figure 4.25: Comparison Fossil Depletion

Figure 4.25 basically shows the same as the previous figure. The plant that runs on coal has a big use phase when it comes to fossil depletion due to the fact that is depletes fossil fuel in the way of burning coal.

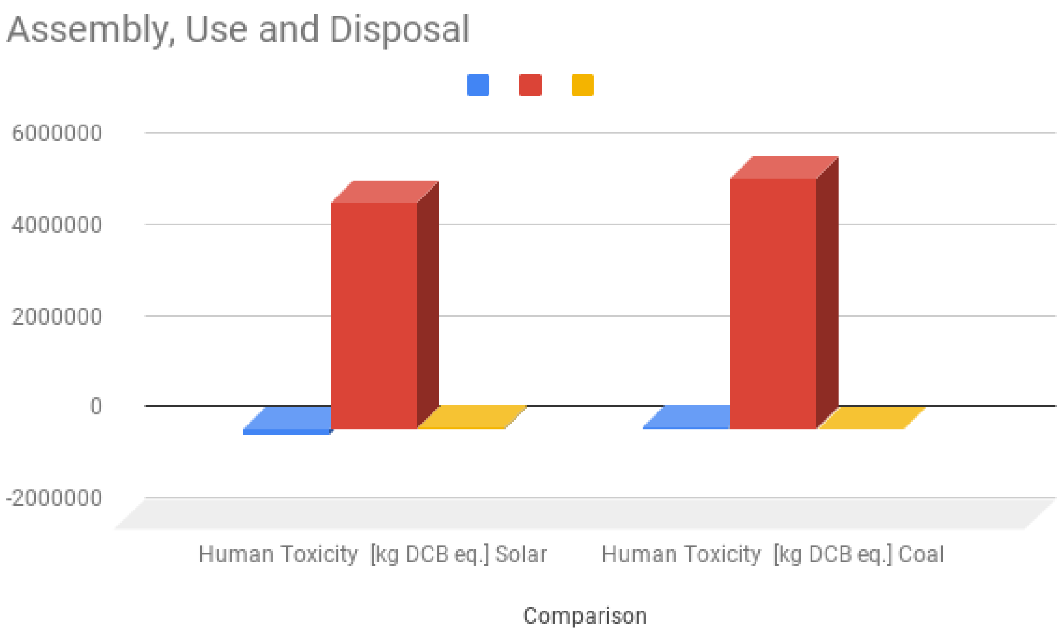

Figure 4.26: Comparison Human Toxicity

What is remarkable here is that the human toxicity of both scenario's do not differ very much from each other. The reason the human toxicity in the use phase is so high is due to the burning of the coal. Then remarkable would be that the use phase of the solar plant is also high, even though we do not emit huge amounts of gasses like that. When analyze deeper it makes more sense. The biomass is first transformed into oil, which takes energy, which indirectly is energy form hard coal. This makes that the human toxicity for the solar plant still has a quite significant value compared to the coal plant in the use phase.

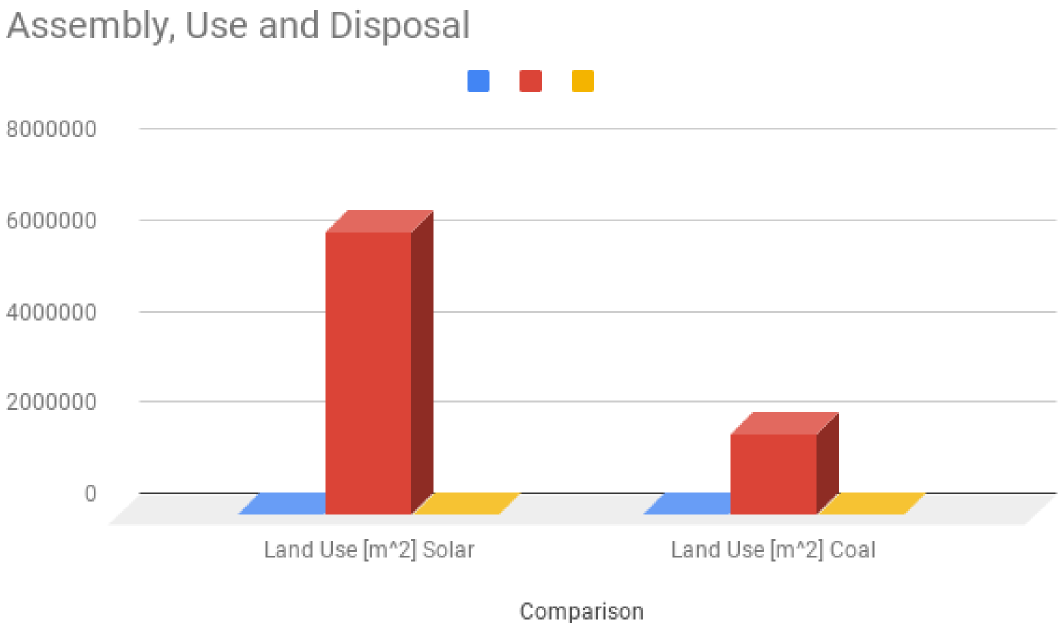

Figure 4.27: Comparison Land Use

Land use again makes sense; the use phase of the solar plant requires a lot of biomass, which must be salvaged. This affects land use in quite a drastic way.

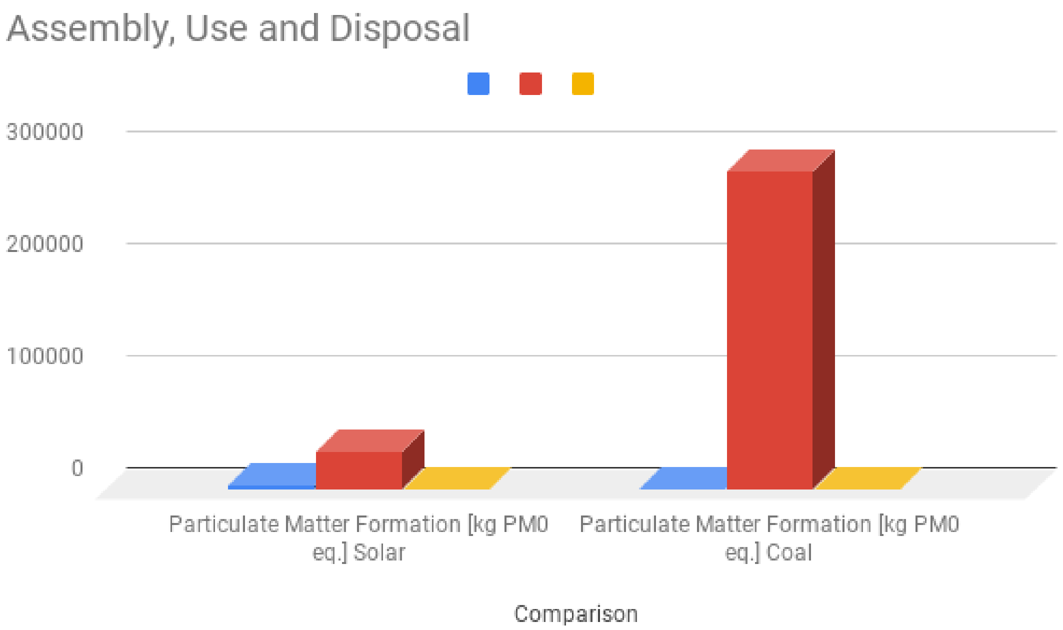

Figure 4.28: Comparison Particulate Matter Formation

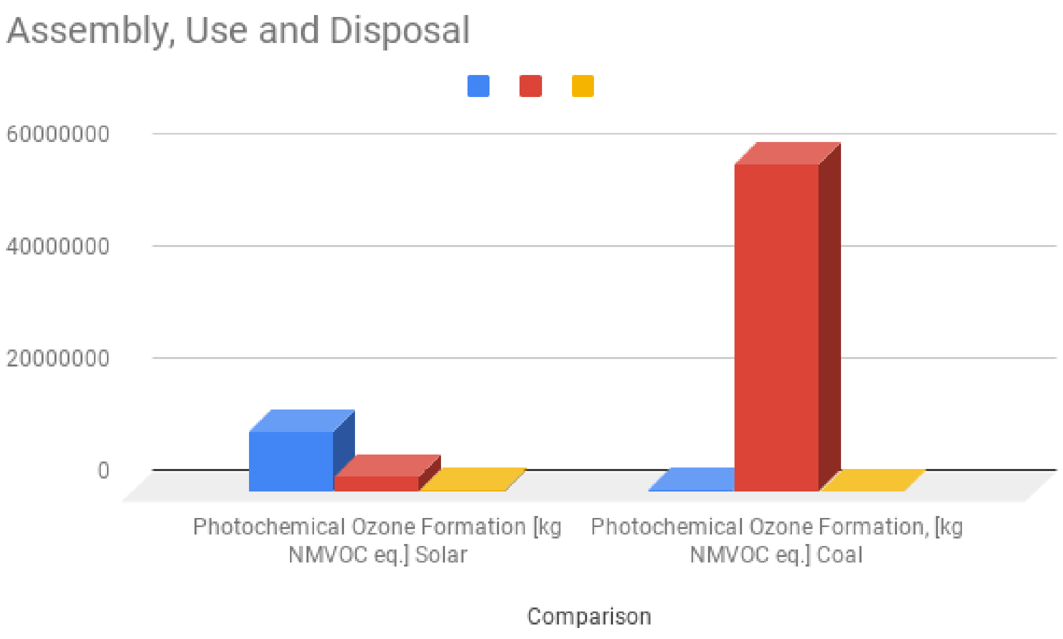

Figure 4.29: Comparison Photochemical oxidant formation

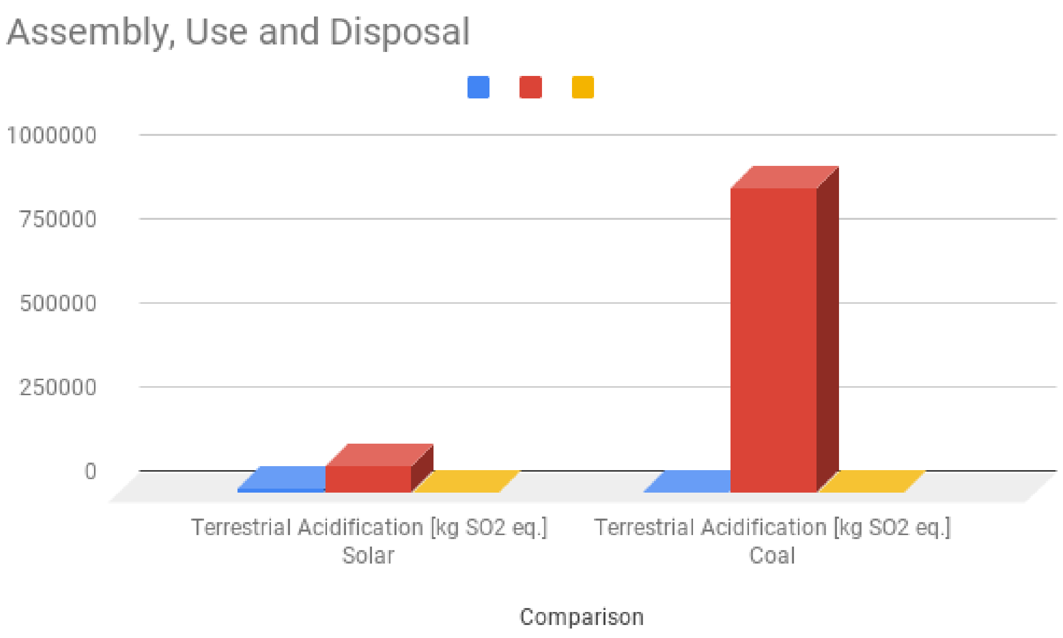

Figure 4.30: Comparison Terrestrial Acidification

Now that all comparisons of the chose effects have been shown, the use phase will be excluded, because it overshadows the assembly and disposal. From figure 4.31 to figure 4.37 we will now look at the comparison of the assembly and disposal phase.

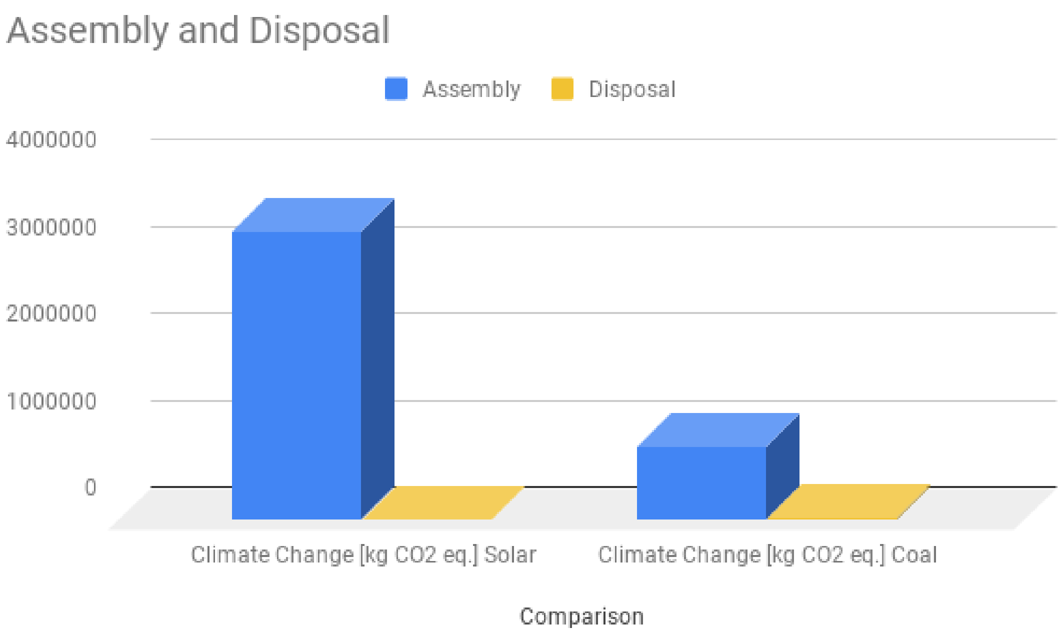

Figure 4.31: Comparison Climate Change Assembly

In figure 4.31 we can see that the solar plant has a bigger impact on this effect. This is due to the size of the plant. As discussed before in the normalization, the size of the plant, including the mirrors and huge foundation cause significant effect, in this case, on climate change.

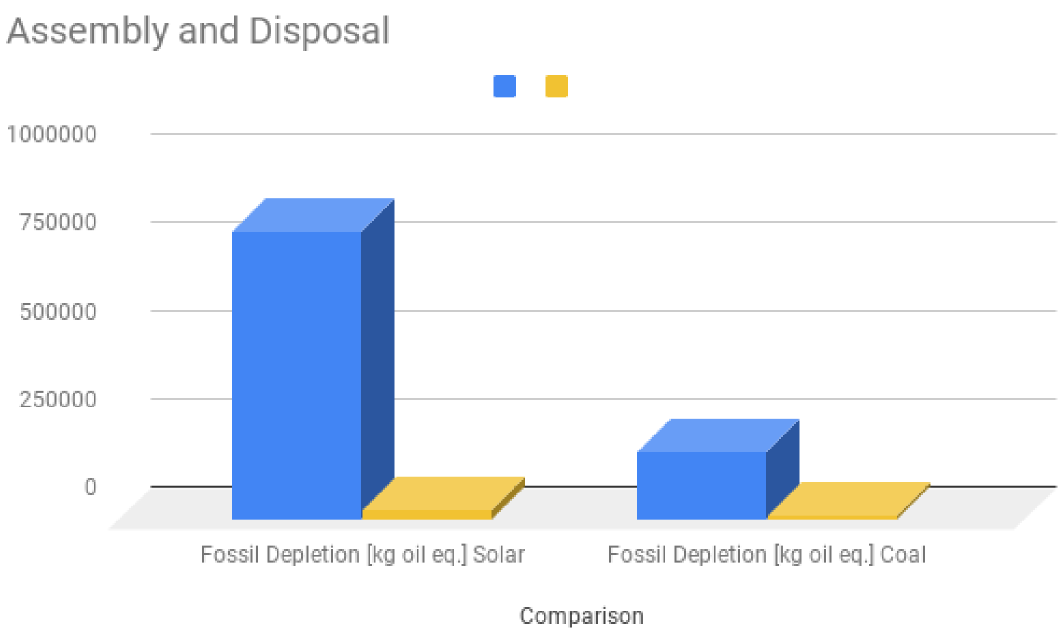

Figure 4.32: Comparison Fossil Depletion Assembly

For figure 4.32 the same will be applied; the size of the plant requires a lot of energy when it comes to assembly. This energy will come indirectly from hard coal which affects fossil depletion. The size of the coal plant is smaller, which means less energy from coal is needed.

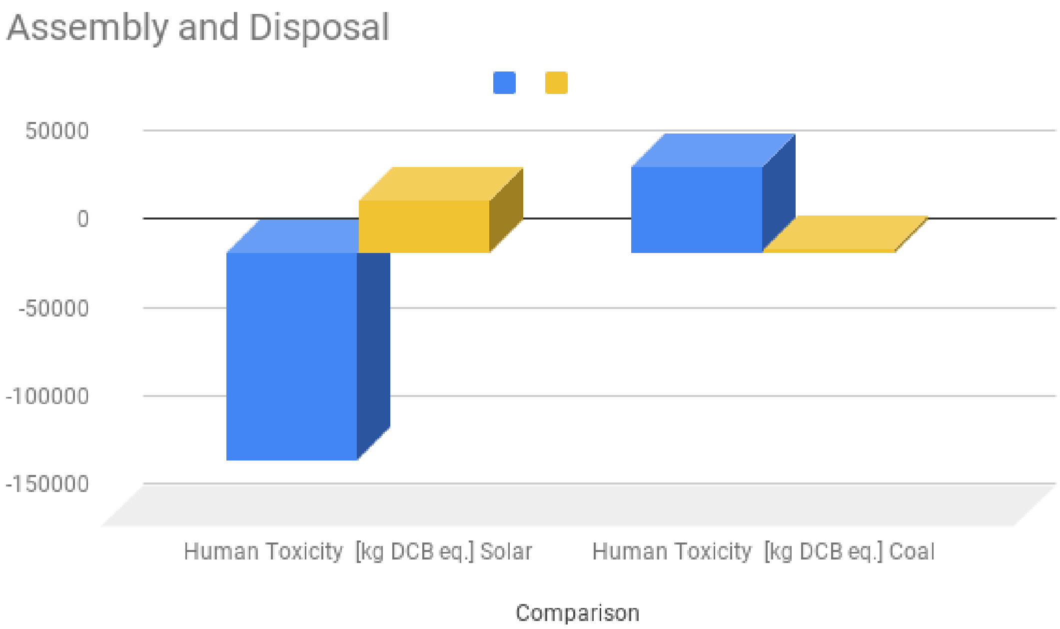

Figure 4.33: Comparison Human Toxicity Assembly

What is remarkable is the big negative value for human toxicity for the solar plant. This value is negative due to the by products that can be used somewhere else, which will then be subtracted, which will result in negative values.

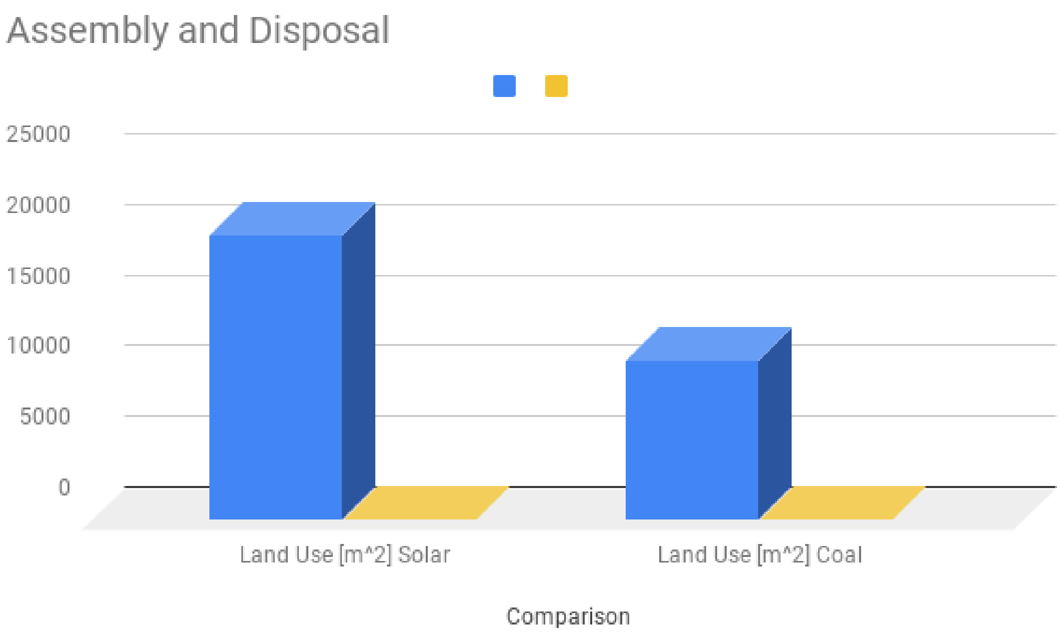

Figure 4.34: Comparison Land Use Assembly

Figure 4.34 tells us that the land use of the solar plant is quite a bit bigger then the value for the coal plant. This again is due to the size of the plant and the area the mirrors cover.

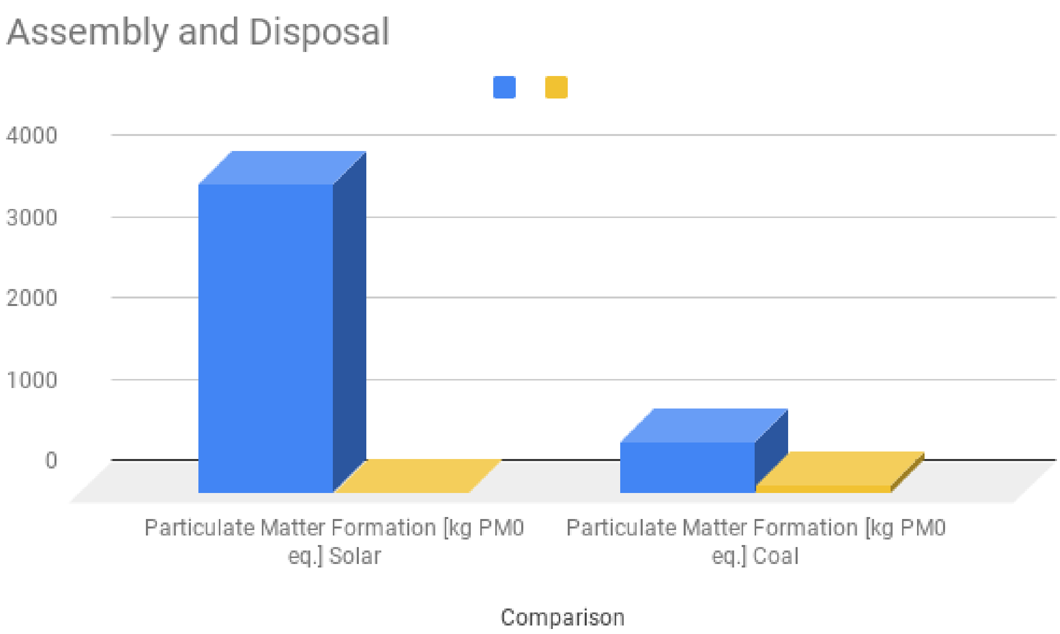

Figure 4.35: Comparison Particulate Matter Formation Assembly

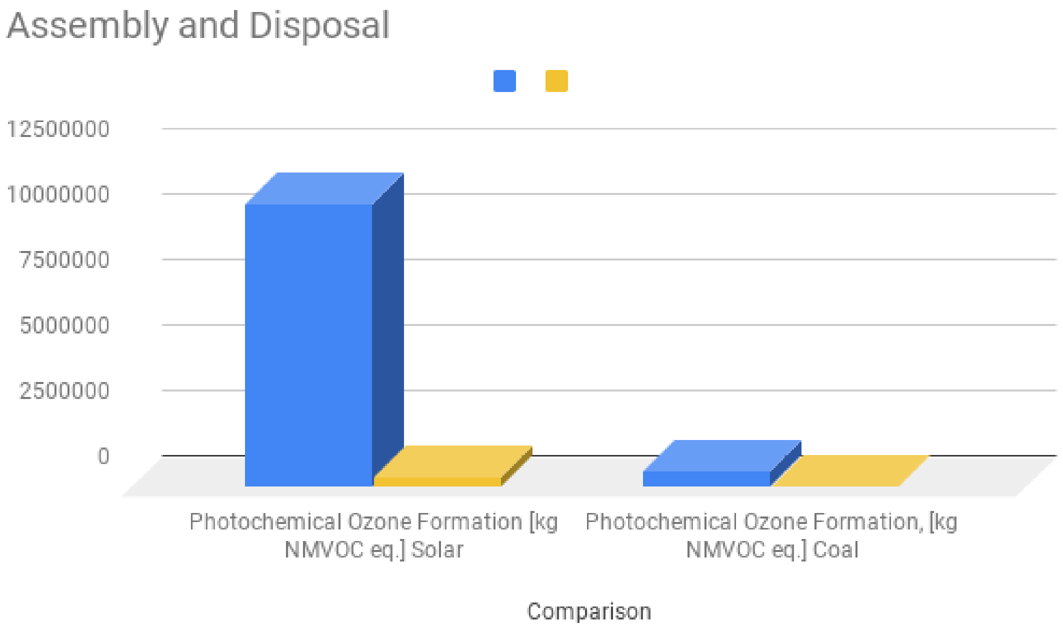

Figure 4.36: Comparison Photochemical Ozone Formation Assembly

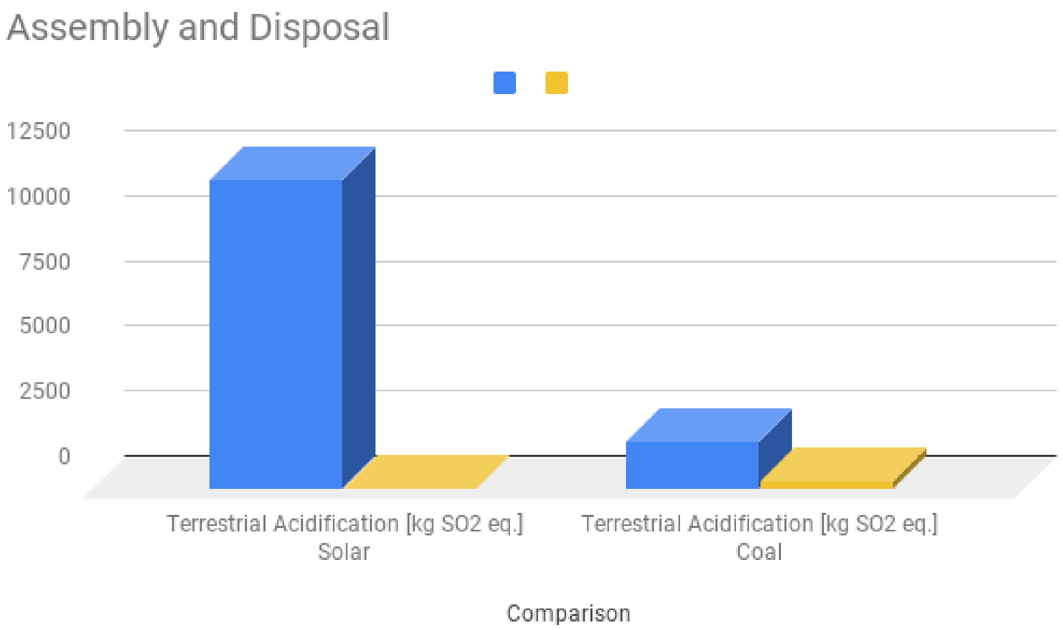

Figure 4.37: Comparison Terrestrial Acidification Assembly

For figure 4.35 to figure 4.37 there can be seen that the solar plant has a higher value for that specific effect. All of these are because of the size of the solar plant compared to the coal plant.

Now it is time to find the break even point. For finding the break even point, the existing model of the solar plant will be changed in such a way that it will turn form best to worst scenario. At first this will be done by changing the lifespan, thus altering the functional unit. For the first break even point an average effect, in this case there will be looked at climate change, since it shows in figure 6.47 that this is a quite average effect. Looking at figure 4.24, there can be seen that the effect in the use phase it quite a bit bigger then the effect of the solar plant. To find the break even point, there has to be analyzed how much the solar plant has to 'change' in order to make it the worst of the two. In this case the changing will be with respect to the functional unit and therefore the lifespan. Changing the lifespan will change the values and using that we can find how short the lifespan of the solar plant should be in order to have a greater effect on climate change then the coal plant.
First to be done is find the difference in scale between the two plants in figure 4.24. Calculating that with the values, we find out that the coal plant has 36 times more influence on the climate change effect then the solar plant. Looking at the functional units; this means that 1 functional unit for the coal plant should be equal to 36 functional units of the solar plant in order to make the solar plant the worst. Since 1 the functional unit, that was given in the goal definition, is basically linear, there can be said that the lifespan of the solar plant has to be around 1450 years in order to be the worst plant. This means that the coal plants 77.1 functional units compares with the new amount of functional unit of the solar plant; 3238 functional units. Doing this alteration, the solar plant has now changed to the worst of the 2 scenarios based on the climate change effect in kg CO2 eq. Performing this scaling gives the following figure 4.38.

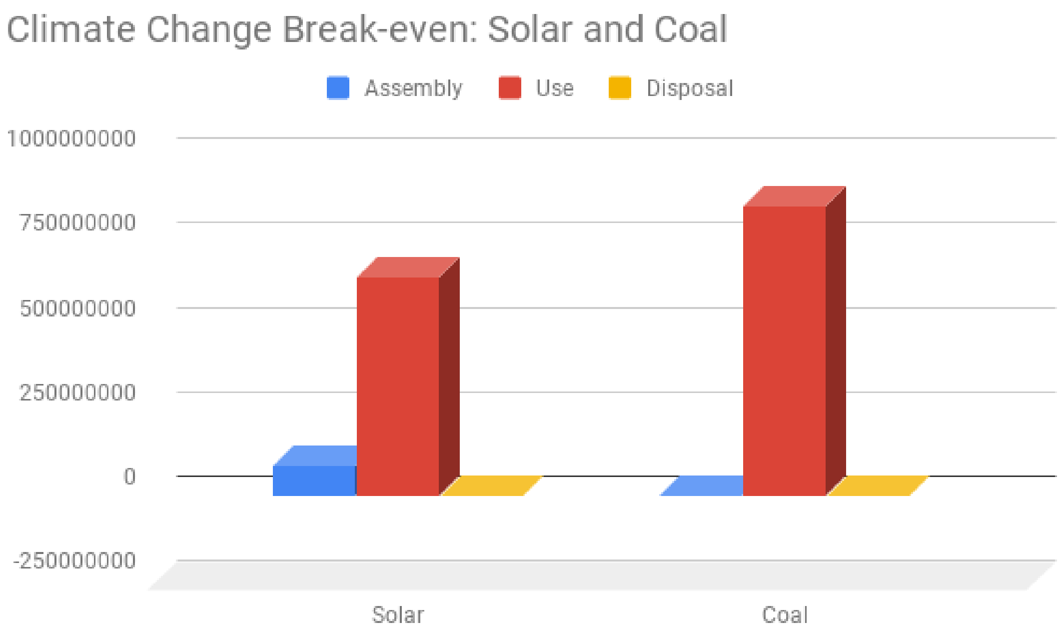

Figure 4.38: Break-even Climate change

Note that the use phase of the coal plant still appears to be the biggest. Though, what can be seen in figure 4.38 is that the assembly phase is quite a bit bigger which results in the fact that the power plant (Figure 4.39), based on the scaling stated before, now creates a solar plant that performs worst than the coal plant in the climate change effect.

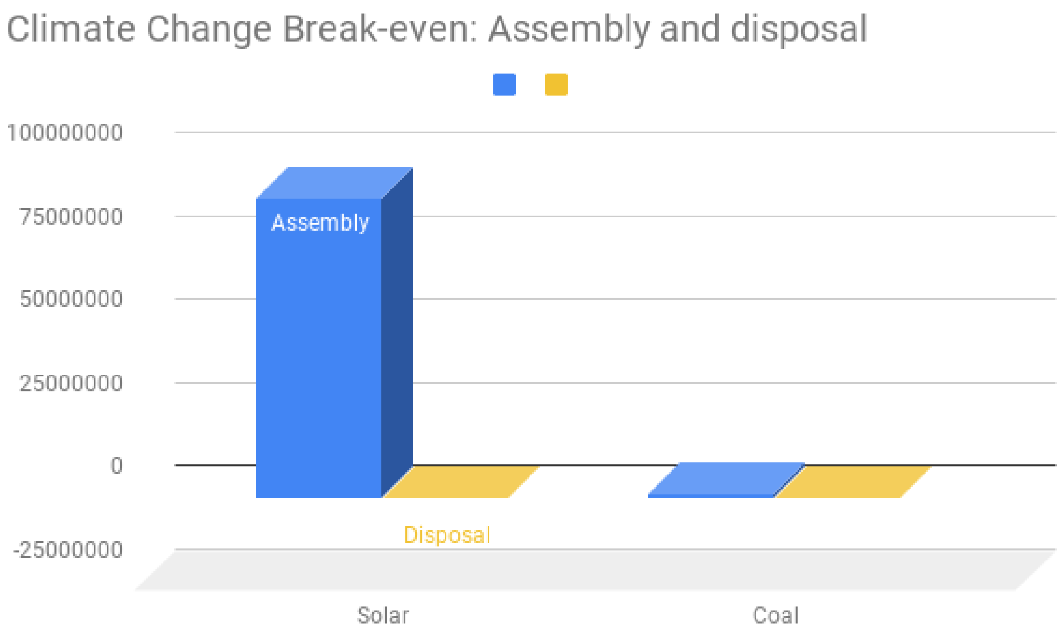

Figure 4.39: Break-even Climate change: Assembly and disposal

Now, there will be looked at a different effect; metal depletion. Down below in figure 4.40 and in figure 4.41 the metal depletion of the assembly phase is displayed.

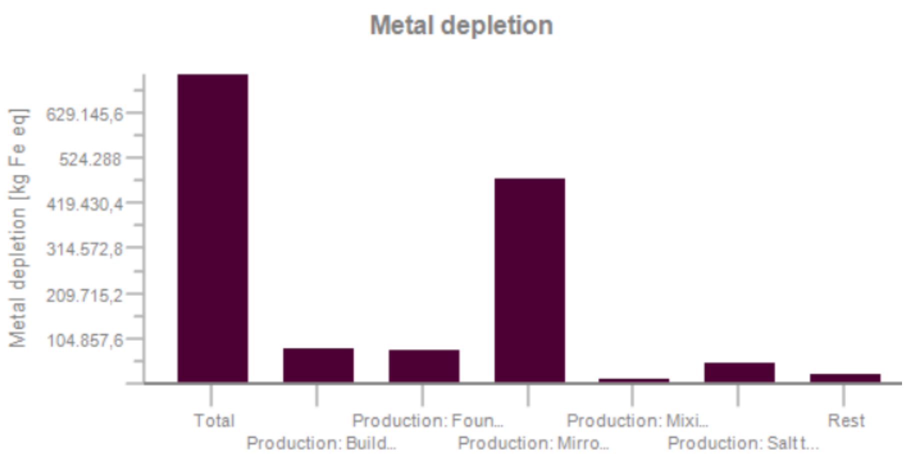

Figure 4.40: Break-even Metal Depletion Solar plant

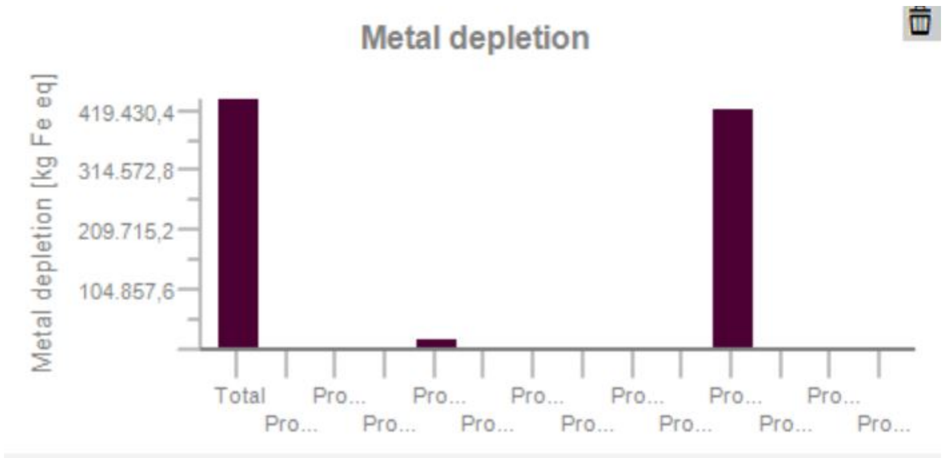

Figure 4.41: Break-even Metal Depletion Coal plant

In figure 4.40 there can be seen very well that the mirrors have a big impact on this effect. In figure 4.41 there can be seen that the biggest impact is within the structure of the coal plant. Please notice the difference in scale and that totals is shown too. To get to a break even point we will change material choice of the mirrors. In that way there will be tried to achieve a break even point. The steel that was used before in the mirrors was now exchange for a thinner layer and a new graph shown in figure 4.42 shows the results.

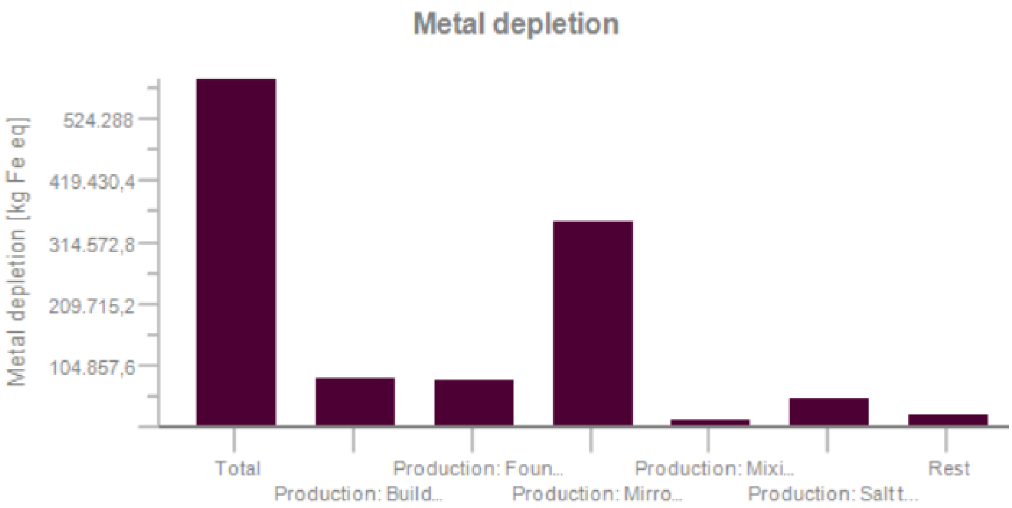

Figure 4.42: Break-even Metal Depletion Solar plant

What can be seen now is that the peak at the total is now around the same size as it is in the coal plant, due to the fact that the material selection of the mirrors were changed. There is still a gap in between the total values of the coal and solar plant; the break even point was not completely reached and the worst scenario (solar plant) has not quite become the better one by swapping materials for the mirror. Of course it could be possible to reach this point by choosing other materials or saving on mass. However this is not practical an in real life it is not feasible.

4.4.2 Sensitivity

The sensitivity analysis of the effects are important for finding the variables in the effects which have a major impact on the results. For example for the solar plant the use of copper in the heat exchangers. How would it change the effects if the amount of copper needed is multiplied by a factor 10,000. Figure 4.43 shows the effect in climate change of the disposal if the amount of copper is as estimated before and figure 4.44 shows the amount of copper for the heat exchangers that is multiplied by 10,000.

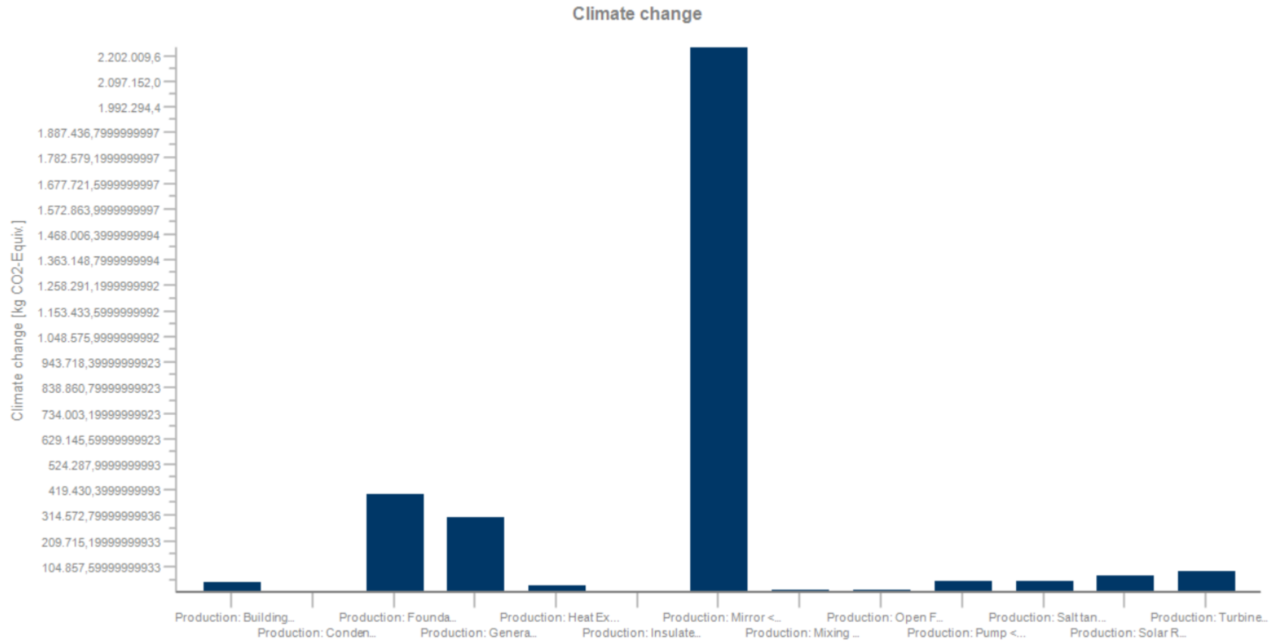

Figure 4.43: Climate change assembling: Normal amount of copper

Figure 4.43 shows the minor effect on climate change in comparison to the other production parts. The value of this emission is 25700 kg CO_2 eq. While looking to figure 4.44 the major emission is the production of the heat exchangers followed by the production of the mirrors. The amount of climate change emissions is 3,160,000 kg CO_2 eq. when 10,000 times the amount of copper is needed for the exchanger pipes. Concluding, while the amount of copper increases with a factor 10,000, then the effect on climate change increases with a factor of 123.

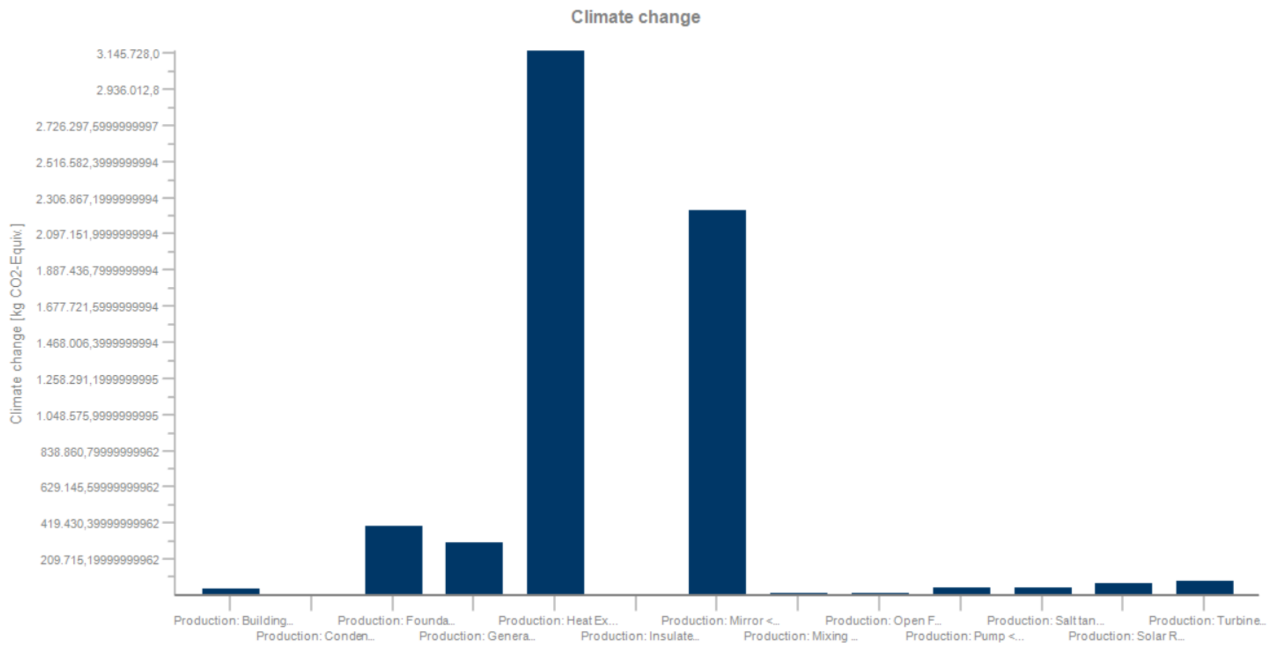

Figure 4.44: Climate change assembling: 10,000 times the amount of copper

An other effect that would change by the increase of copper usage is Natural land transformation. Also here the effects are compared for the estimated copper usage and for the multiplication of the copper usage for the heat exchangers by a factor 10,000.

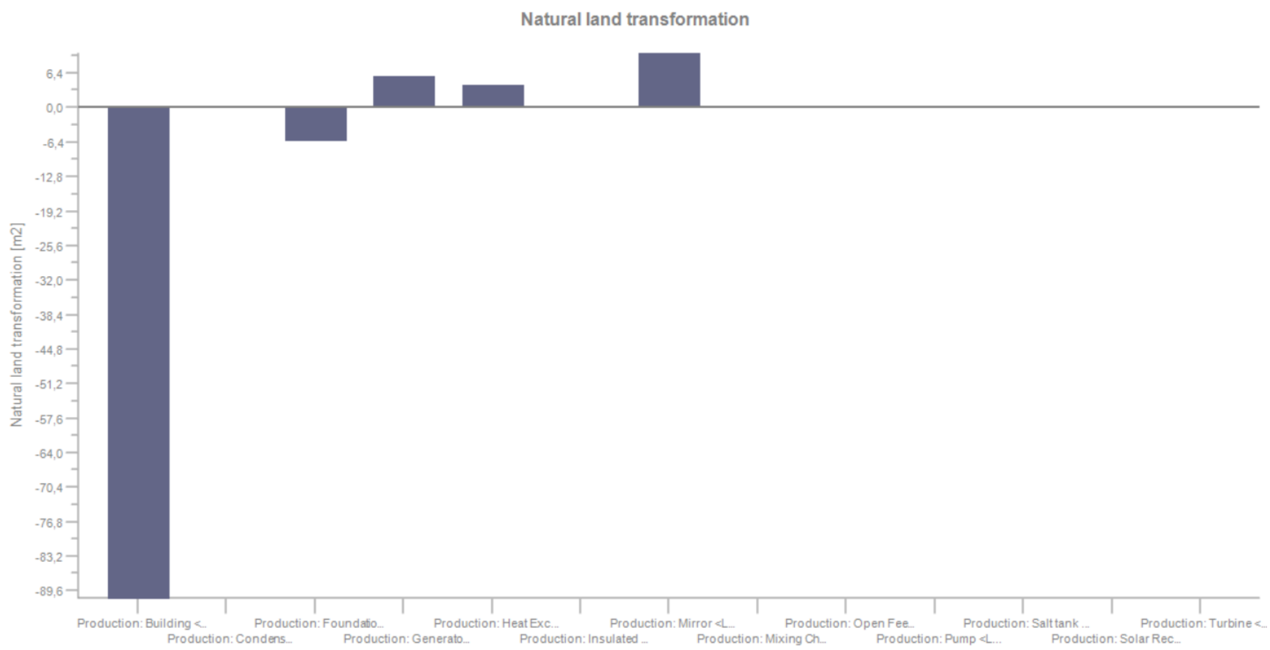

Figure 4.45: Natural Land Transformation assembling: Normal amount of copper

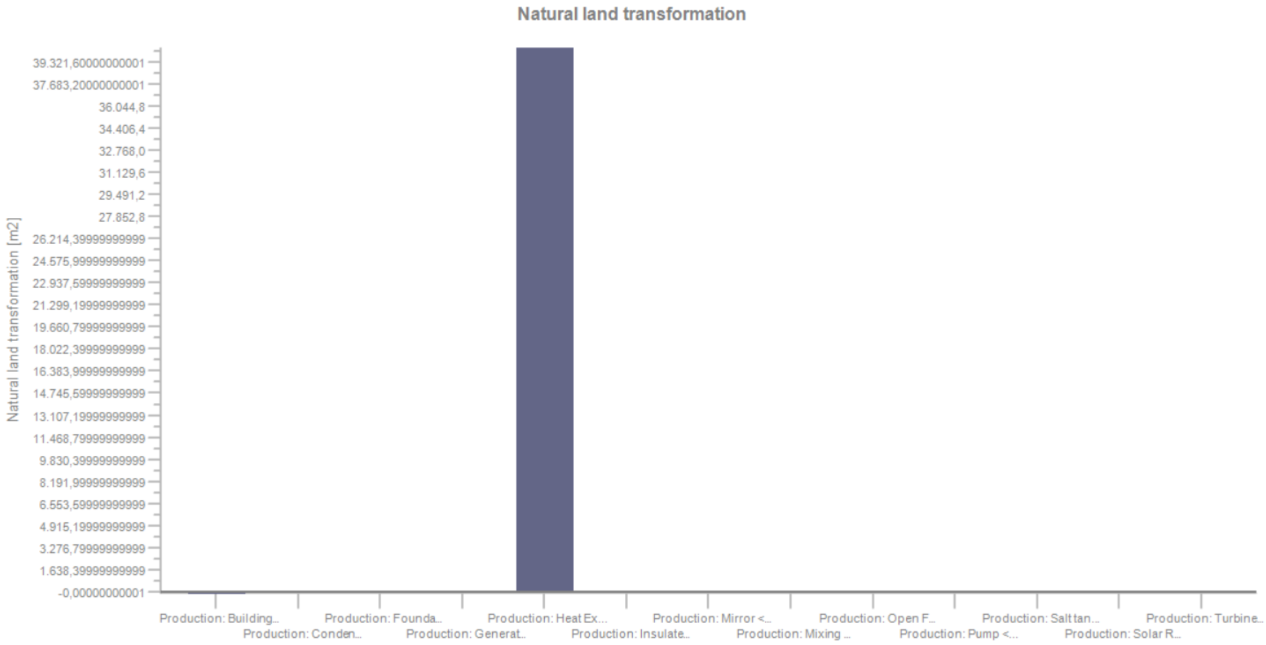

Figure 4.46: Natural Land Transformation assembling: 10,000 times the amount of copper

Figure 4.45 gives a result of 4.11 m^2 on land change, which does not make a big difference in the total effect. Figure 4.46 gives a result of 40400 m^2 which now is the major cause of the total land use effect during the assembling. The Natural land transformation increases with a factor of 9,830, which is close to the 10,000 multiplication of the copper use.

The multiplication of copper seems to have more impact on the Natural land transformation than it has on Climate change. This concludes that not all materials have the same impact on an effect. For example the produced parts for the heat exchanger housings have a bigger impact on Climate change than the copper pipes produced for the heat exchanger, compared to the Natural land transformation.

4.4.3 Compare in Context

To compare in broader context, the solar plant will be compared with an altered version of itself. To do this, certain type of energys will be replaced by energys that are more sustainable or have a higher or lower quality. This will be done for 2 cases. Also worth noting is that for this part only the use phase will be considered. This is because in that part huge differences can be seen. This is mainly because of the energy used to produce energy at this point is energy from coal from china. When changing this specific energy differences can be seen.

Norway

Now, the conventional coal energy to produce biomass will be replaced with energy that comes from a hydro power plant in Norway. The original graph can be found in figure 4.2

and the new graph can be found below in figure 4.47.

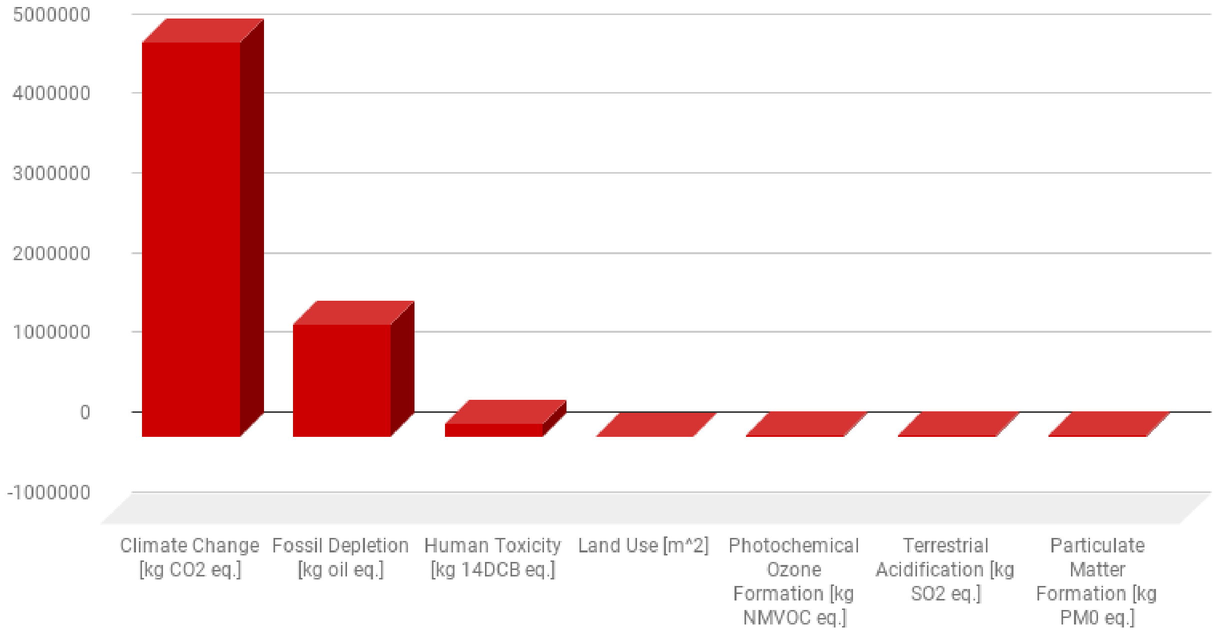

Figure 4.47: Use phase using Hydro power from Norway

Comparing figure 4.2 with figure 4.47, there can be concluded that the use of hydro power will definitely decrease the use phase when it comes to impact on all effects. The profile proportions are quite the same, but the sizes are smaller (note the different size of the vertical axis). This all makes sense as producing biomass from hydro power emits less harm full substances then when energy is retrieved form burning coal.

From these comparisons, it gets clear that choosing sources of energy should be done carefully. This is one of the possible recommendations for building such a power plant. The idea of using biomass is very good, bur if the production of biomass uses energy and that energy is still coming from conventional coal burning, there is just an extra step in the cycle and it will not be as sustainable as it seems to be. By using sustainable energy form hydro, wind or solar power to produce biomass, the cycle can truly be made 100 percent sustainable.

Poland

To gain a broader outlook on the impact, the plant was compared to a situation where it would be in Poland. Here, like with the Norway comparison, the energy is replaced by fossil fuel in Poland. This would be a worst case scenario. As can be seen comparing with 4.2, generally the case gets worse.

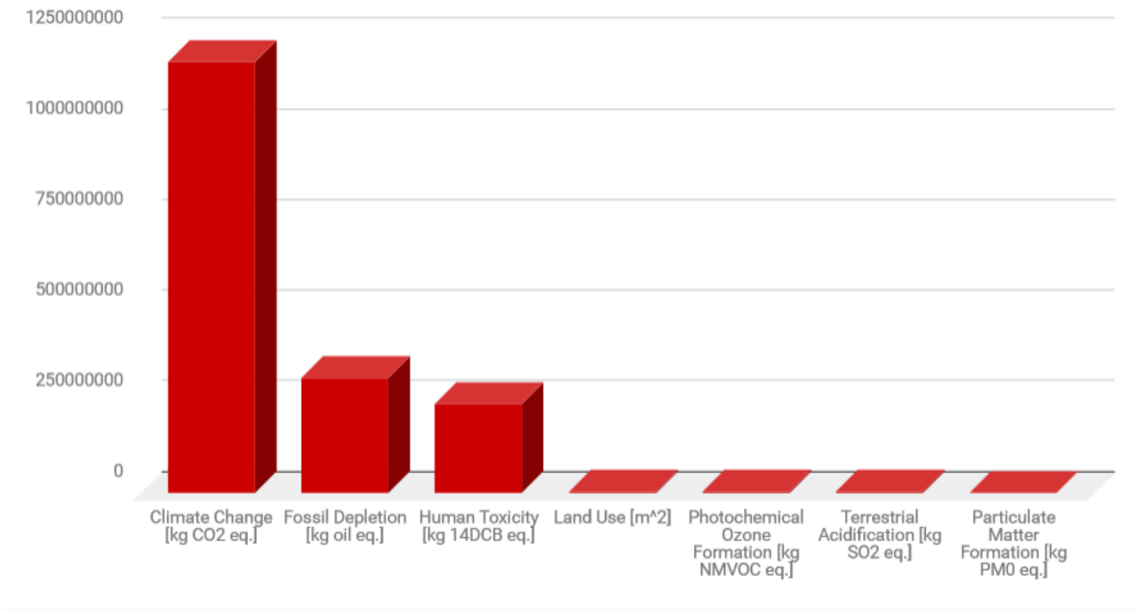

Figure 4.48: Use phase with power plant in Poland

There is about a 50 percent increase in the impact to the climate alone. The other points fair no better with fossil depletion and human toxicity increasing greatly. It is obvious from this how important the energy production is to the affects. Overall, in this situation, the whole project could be scrapped as there would be no improvement to the original plant in Lanzhou.

4.4.4 Conclusions

What can be concluded from the Life cycle analysis is that for both power plants the use phase is the phase with the highest environmental impact. Although, the assembling phase for the solar plant has more environmental impact, for the overall environmental impact it is clear that the solar plant is the best choice regarding the LCA. The overall use phase environmental impacts of the solar plant are much more beneficial in comparison to the coal plant that the higher assembly phase emissions does not affect the overall choice. The higher assembly phase emissions are mostly because of the field of mirrors which are filling a big area.
Both disposal phases can be neglected in the choice of the plant because is has such low values regarding the assembly and the use phase emissions of both plants.
What could be recommended for the solar plant is finding a more environmental friendly way to produce the biomass oil that is needed for the plant. For example a kind of hydro power source could be used instead of hard coal to lower the environmental effects (Figure 4.47).
The biomass oil is produced to make the biomass easier to transport. Because of the low amount of environmental impact compared to the impact of the production of the biomass an analysis could be interesting to research the transportation of biomass without the production of biomass oil.

Chapter 5

Conclusions

Now that all the different aspect of a potential 100% renewable power plant haven been evaluated. Some conclusions can be made based upon this data. Firstly the thermodynamic aspects will be covered, next the material selection we be treated, lastly the conclusion from the LCA can be evaluated.

First of all, it is possible to create a 100% renewable that satisfies all the requirements. The new designed power plant generates 220 MW of power and delivers 65 MW of heat to the district heating system of Lanzhou in summer, and the additional 65 MW of heat in winter. These were the main requirements for the power plant that could possibly replace the current coal-fired power plant. However, the feasibility of actually building the power plant might be an issue. Despite a place is found that might be suitable to build the new power plant, namely close to the Lanzhou Zhongchuan Airport, this might also not be feasible since there is quite a big height difference and the area consist mostly of agricultural land and partially of populated area. Therefore these citizen have to be relocated elsewhere and the loss of land need to be compensated in land or money. Furthermore, the mass flow rates are very large, and therefore large parts are needed. This problem might be solved by, for example, using two very large turbines. However, these are extremely expensive. Another solution could be to use multiple, smaller turbines parallel to each other. However, in both cases the costs to realize the whole cycle will increase considerably.
About the material for the turbine stainless steel was chosen because of its low price comparing with others metal. Another benefit is the layer of Cr_2O_3 that is formed on the surface which helps to protect from corrosion. For the casing the material is ASTMCA-6NM, which has a percentage of carbon of 0.04% and 3.5-4.5%Ni(nickel) mainly , the result is a material with a high strength, high resistance to corrosion and high working temperature. For the axle or shaft the material selected is percentage of carbon is 0.15% with manly martensite structure due to air cooling during the hot forming process, other components such as : molybdenum, silicon and manganese are added in small percentage (0-1%) to improve strength and resistance to corrosion. For the turbine blades the material selected is ASTM CA-15 with 0.15% of carbon first normalized and then tempered at 595°C. It has 1.5% of silicon to improve its working temperature.
The heat exchanger is composed of two parts - the tubing and the casing, each with exact opposite purposes for each other, while both requiring a high yield strength. Copper-chromium whp alloy was chosen for the tubing due to its high conductivity and affordability, and annealed nickel-copper-silicon alloy was chosen for the housing due to its relatively low conductivity.
Concerning the life cycle assessment, the most noticeable conclusion that can be drawn is that the solar plant has less impact when it comes to the 18 ReCiPe effects. For the use phase of the plants this holds strongly. There can definitely be seen that the use phase

of the coal plant is bigger in almost all effects. Though, when we look at the assembly and disposal phase there can be seen that this is built up differently. The solar plant has higher values on all effects when it comes to assembly. This is due to the size of the plant, as mentioned before. The quality of this LCA has a error margin, which should definitely be taken into consideration when this LCA is applied. All estimations were done by loose calculations and the true size of the plant might differ a little. This is why the results of this LCA should not be taken for granted immediately, but first considered.

Chapter 6

Appendices

6.1 Flow chart Crescent Dunes concentrated solar power plant

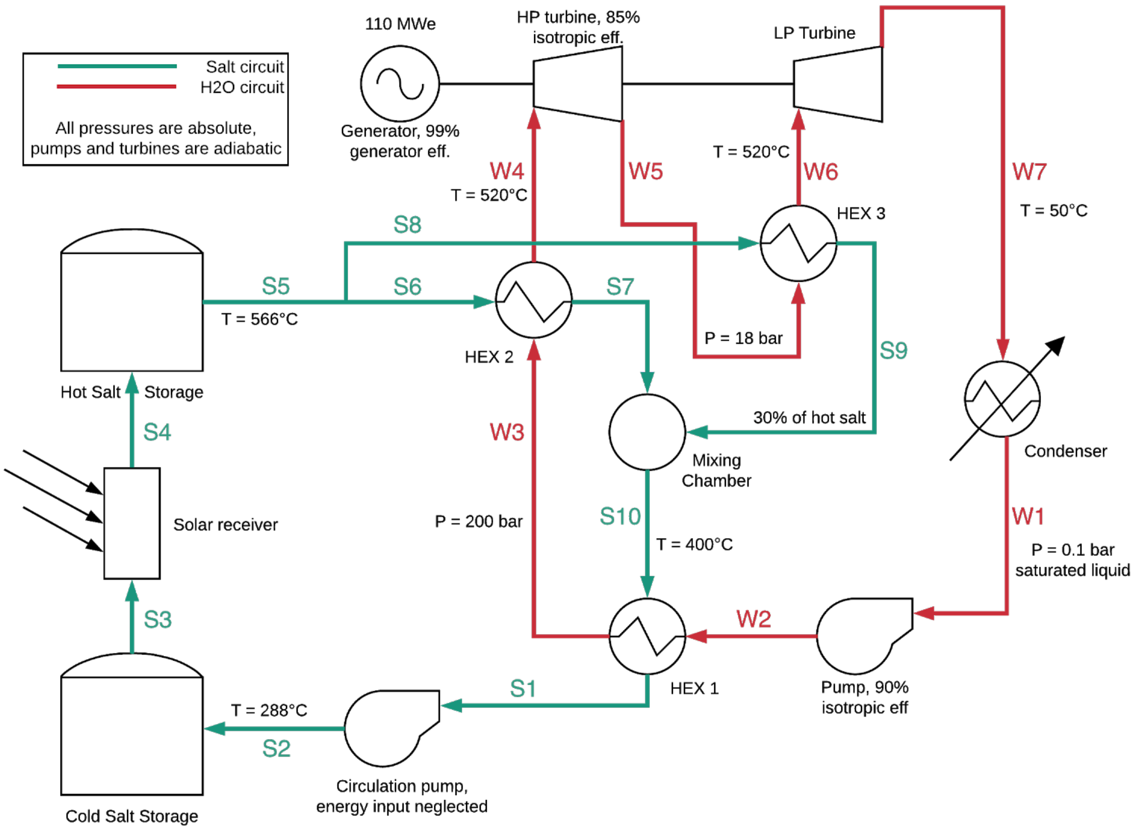

Figure 6.1: Flow chart Crescent Dunes

6.2 Thermodynamic values of the different concept cycles

Thermodynamic values and mass flow rate concept 1

	T (°C)	P (bar)	h (kJ/kg)	s (kJ/kgK)
W1	45.8	0.1	191.8	0.649
W2	45.8	2.0	192.0	0.649
W3	58.0	2.0	242.8	0.806
W4	59.6	200.0	266.4	0.816
W6	550.0	200.0	3396.2	6.339
W7	195.4	12.0	2804.0	6.5653
W8	550.0	12.0	3586.2	7.815
W9	77.0	0.1	2643.7	8.328
W10	319.4	2.0	3111.4	7.961
W11	120.1	2.0	504.7	1.530

Table 6.1: Thermodynamic values of concept 1

It may be noticed that there are no values given voor the properties of flow W5. There are no values given for this flow, because these values do not have a influence on the efficiency of the cycle, and were therefore not necessary in the comparison of the different cycles.

Mass flow rates	
mass flow rate W3	154 kg/s
mass flow rate W2	129 kg/s
mass flow rate W10	25 kg/s

Table 6.2: Mass flow rates of concept 1

Note that $\dot{m}_3 = \dot{m}_4 = \dot{m}_5 = \dot{m}_6 = \dot{m}_7 = \dot{m}_8$. In addition, $\dot{m}_2 = \dot{m}_1 = \dot{m}_9$, and $\dot{m}_{10} = \dot{m}_{11}$.

Thermodynamic values and mass flow rates concept 2

	T (°C)	P (bar)	h (kJ/kg)	s (kJ/kgK)
W1	45.8	0.1	191.8	0.649
W2	47.0	200.0	214.2	0.656
W4	550	200.0	3396.2	6.339
W5	179.9	10.0	2775.3	6.581
W6	550	10.0	3588.1	7.901
W7	89.4	0.1	2667.2	8.394
B1	20	1.0	290	6.85
B2	340	8.0	610	7.00
B3	900	8.0	1250	7.73
B4	540	1.0	835.0	7.90

Table 6.3: Thermodynamic values of concept 2

In table 6.2, the thermodynamic values are shown. It may be noticed that the values of the flows in the brayton cycle are less exact than the values of the rankine cycle. The reason for this is that a mollier for air is used to determine the values of these properties.

Mass flow rates	
mass flow rate water	138 kg/s
mass flow rate air	120 kg/s

Table 6.4: Mass flow rates of concept 2

Thermodynamic values and mass flow rate concept 3

	T (°C)	P (bar)	h (kJ/kg)	s (kJ/kgK)
W1	45.8	0.1	191.8	0.649
W2	45.8	2.0	192.0	0.649
W3	58.5	2.0	244.9	0.812
W4	60.1	200.0	268.4	0.822
W5	550.0	200.0	3396.2	6.339
W6	286.6	30.0	2959.8	6.480
W7	550.0	30.0	3569.6	7.377
W8	293.4	4.0	3053.6	7.544
W9	550	4.0	3593.6	8.329
W10	151.8	0.1	2786.4	8.697
W11	452.2	2.0	3386.1	8.380
W12	120.2	2.0	504.7	1.530

Table 6.5: Thermodynamic values of concept 3

The values of the thermodynamic properties of flow 4' are not given in the table, because they don not influence the efficiency of the cycle and are therefore left out of perspective.

Mass flow rates	
mass flow rate W3	136 kg/s
mass flow rate W2	113 kg/s
mass flow rate W12	23 kg/s

Table 6.6: Mass flow rates of concept 3

Note that $\dot{m}_3 = \dot{m}_4 = \dot{m}_5 = \dot{m}_6 = \dot{m}_7 = \dot{m}_8 = \dot{m}_9$. In addition, $\dot{m}_2 = \dot{m}_1 = \dot{m}_{10}$, and $\dot{m}_{12} = \dot{m}_{11}$.

6.3 Sankey and Grassmann diagrams final concept

Sankey diagram summer

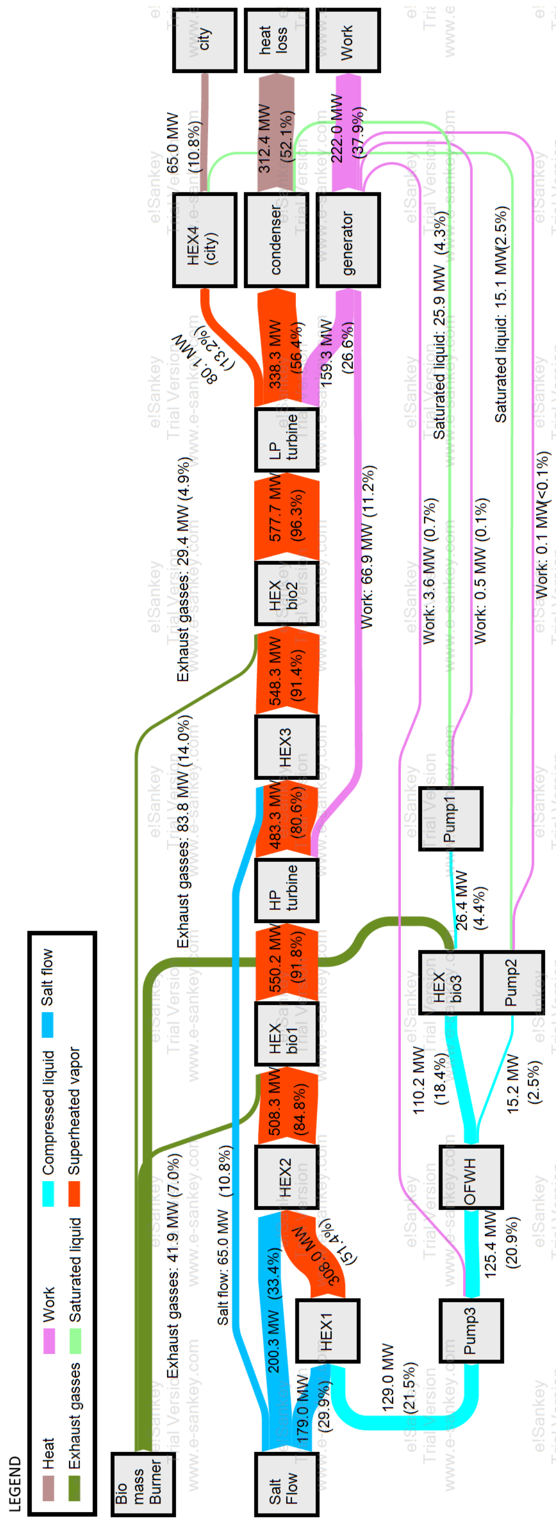

Figure 6.2: Sankey diagram summer

Grassmann diagram summer

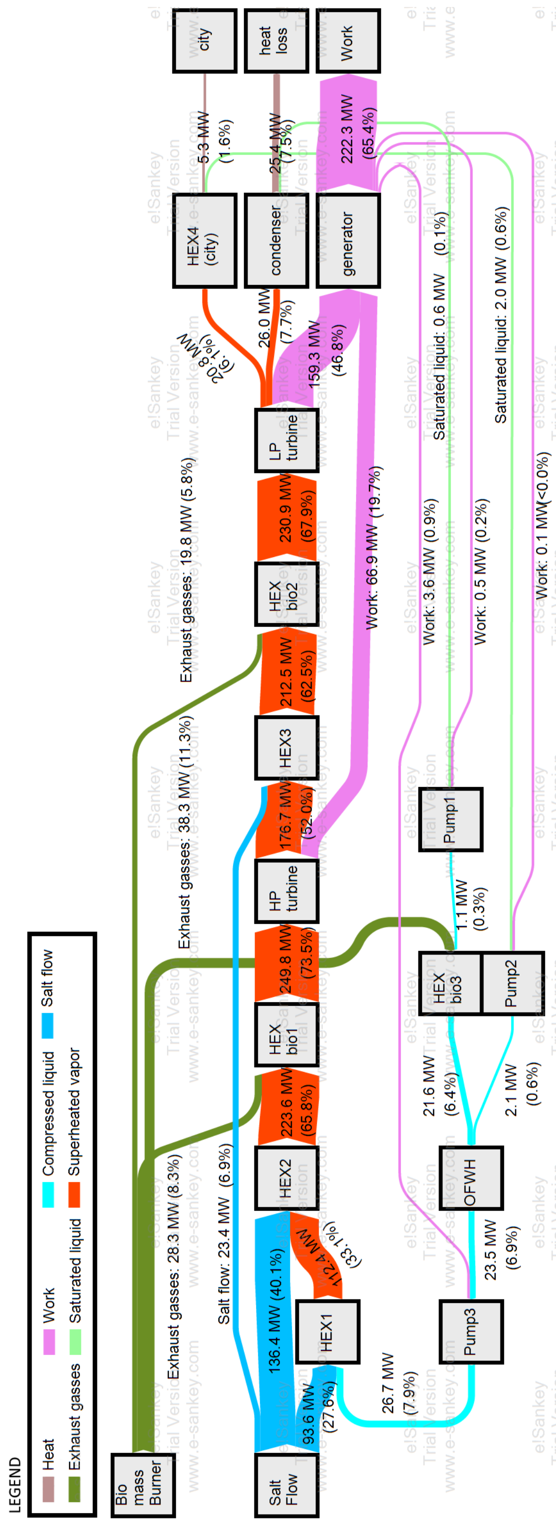

Figure 6.3: Grassmann diagram summer

Sankey diagram winter

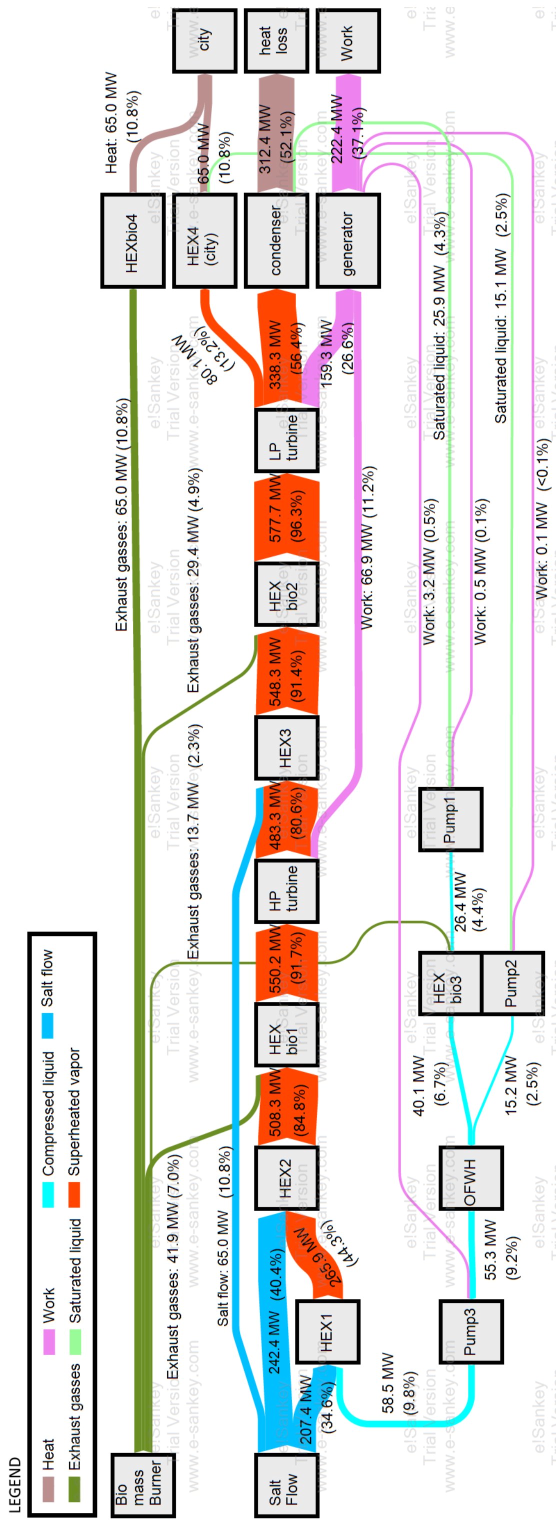

Figure 6.4: Sankey diagram winter

Grassmann diagram winter

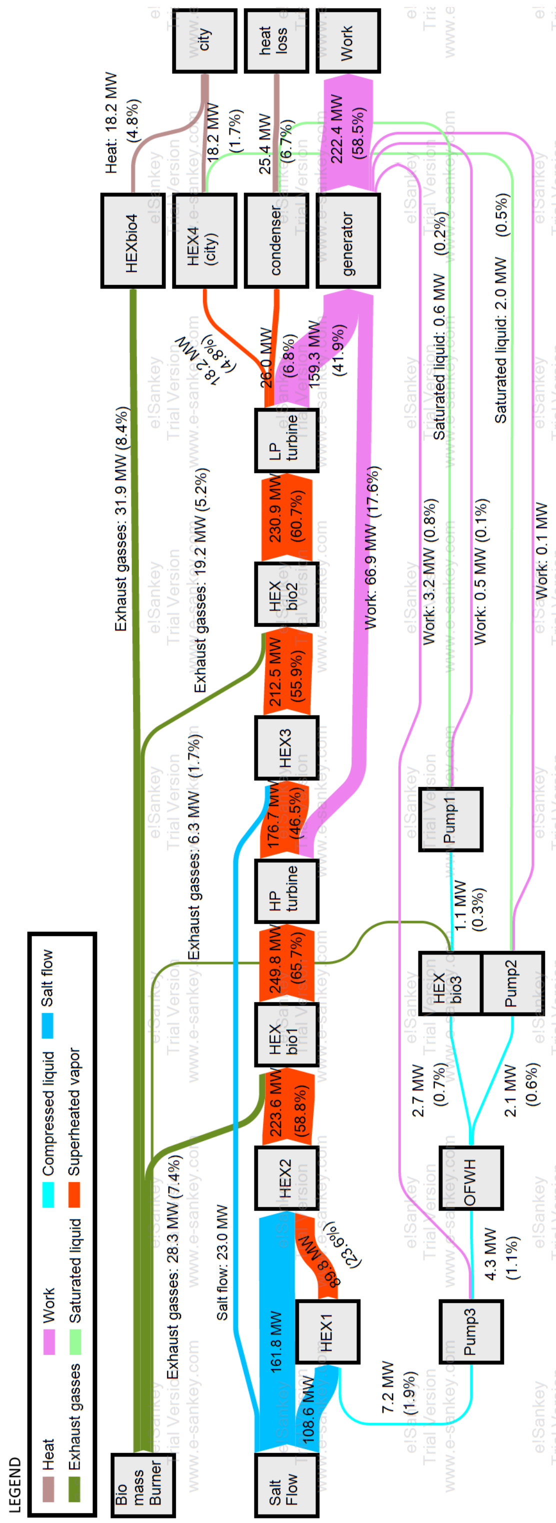

Figure 6.5: Grassmann Diagram winter

6.4 Materials science analysis table

B	C	D	E	F	G	H
	turbine blades	*turbine shaft*	*turbine housing*	*heat exchanger internal pipe*	*heat exchanger housing*	**Remarks**
Performance index	ρC/E	ρC/σ_y^(2/3)	ρC/σ_y	λ*(σ_y)	1/(λ*(σ_y))	Please put relevant equation for each of the components
Material	ASTM CA-15 (Tempered at 595°C)	AISI 410(Hard temepred)	ASTM CA-6NM	Copper-Chromium alloy, whp	Nickel-Copper-Silicon alloy, annealed	Please put selected material here
T (°C)	550			600	600	Please put relevant temperature here
p (bar)	20			200	200	Please put relevant pressure here
Deriviation purpose	As stiff as possible and as cheep as possible	As strong as possible and as cheap as possible	As strong as possible and as cheap as possible	Highest heat transfer per area	Highest insulation	Indicate in a few words the purpose of the performance index. For example: lowest price, highest specific stiffness, etc.
Production method(s)	investment casting	Hot forming(forging)	Sand casting	Extrusion	Casting	How do you think the part will be produced? What are the major production steps (for example: casting, forging, heat treatment, etc.)?
Important material requirements based on thermomechanical conditions, working principles and manufacturing	Castable, working condition 520°C, high Young's Modulus	High yield limit, acceptable to hot working, low price	Castable, working condition 550°C, high yield limit and low price.	High yield strength, corrosion-resistance, high heat conductivity, extrudable, weldable	High yield strength, corrosion-resistance, low heat conductivity, castable	Compose a list of the important material requirements. For example stiffness, strength, etc.
Other remarks	corrosion resitante	corrosion resitante	corrosion resitante	Price must not be more	Price must not be more than	Add possible remarks whenever necessary. Keep short

6.5 LCA

ReCiPe effects

Climate Change
This the first effect taken into account using the ReCiPe method. This is an effect that is described as the change of the natural climate as it should be on earth. Due to its capabilities to influence ecosystems, as an endpoint it could affect human health. Greenhouse gasses, like CO2 or methane, cause this climate change. These are the important emissions for this specific effect. Big sources for these gasses are industry, transportation or variations of agriculture. The most common unit when it comes to these greenhouse gasses is ppm(parts per million). This is a way to display the concentration of these particles in our atmosphere.

Ozone layer depletion
This effect is described as the destruction of Ozone high in our atmosphere due to specific compounds that exist in nature or are created by humans. Ozone layer is vital for life, because of its properties. Ozone absorbs UV radiation, which is a dangerous form of radiation when it comes to humans, and prevents it form reaching the earths surface. The compounds involved in the destruction of the ozone layers are so called CFC's, which is a specific substance with chlorine. Also bromide is responsible for a partly depletion. CFC's are mainly created by devices used by humans like refrigerators and air conditioning. Though recently, laws have reduced the permitted emission of this compound. The unit for measuring the ozone layer depletion is measured in amounts of the actual substance that depletes the ozone layer, CFC-11. The unit to measure this is kg CFC-11 eq.

Terrestrial Acidification
This effect describes the presence of inorganic substance in the ground, such as sulfates, phosphates and nitrates. This effect could result in a shift in ecosystem and a alteration in existing species withing this system. As said before, nitrates, phosphates and sulfates are responsible for this shift. This problem mainly occurs when intensive agriculture is done. Due to the big amounts of manor used, a high concentration of ammonia is present in the soil. Micro organisms feed on this and produce inorganic substances which cause this acidification. For the measuring of this effect, SO_2 is take as the equivalent, so the unit to measure acidification is kg SO_2 eq.

Fresh water eutrophication
This effect is defined as an enrichment of nutrients in fresh water which causes algae and other aquatic plants grow at a high rate. As a consequence, a lot of sunlight is blocked from reaching the ground underwater, which causes micro photosynthesis of certain plants to slow down or stop. These species that no longer receive UV light will die and the organic remains will be consumed by microorganisms that use oxygen for this. Therefore the river will be drained of oxygen and will kill any further life inside the water. This process can substantially impact the ecosystem and biodiversity as well as human health. Mostly

substances like phosphorus and nitrates cause this effect. These substances are nutrients to algae an will cause the mentioned process. These substances are mainly emitted from agriculture, where these are used to improve fertility of the ground used to grow crops. Excess of these substances will leak out to nearby water sources and cause this process. The unit to measure this that is used is kg P eq.

Marine eutrophication
This effect can be compared to the Freshwater eutrophication, but now it occurs in marine ecosystems. This could potentially harm people since humans are often found in contact with potentially eutroficated marine water. This marine eutrophication is caused by the same substances as the previous form of eutrophication and also has the same unit for measurement.

Human toxicity
Human toxicity is an index that measures the potential harm of a chemical that is released into the environment. Due to its capabilities to alter ecosystems and potentially harm people, it is considered in the ReCiPe method. The chemical 1,4-dichlorobenzene was used as a reference for this effect, but there are more chemicals that are part of this effect and cause this harm to people. These substances are mostly coming from human products or processes. Disinfectants and pesticides in agriculture are a big source of a big part of these substances. The unit of measurement used for this effect is kg 14DCB to urban air.

Photochemical oxidant formation
This effect describes the formation of photochemical oxidants like O_3 and SO_2.[17] These substances have been proven to damage plants and with that the ecosystem. These substances are in our atmosphere naturally but amounts can be influenced by human behavior. The unit to measure this effect is kg NMVOC to urban air.

Particulate matter formation
This describes the formation of particulate matter. Particulate matter is the sum of all liquid and solid particles that are present in the air, that are dangerous for human health. Substances like NO_x, NH_3, SO_2 and general PM_X's are to cause this effect. The source of these substances is agriculture and other by human made processes. The unit of measurement kg PM_10 to air.

Terrestrial ecotoxicity
This is defined as the effect of chemical substances in the ground on terrestrial plants or organisms. This effect is taken into consideration because of its capabilities of altering the ecosystem by decreasing biodiversity or changing the composition of the earth, which could lead to problems for agriculture for example. The substances responsible for this are compicated chemical compounds like 14DCB or ECx. These chemicals are usually not found in nature and specifically created by humans. The unit to measure this is kg 14DCB eq.

Freshwater ecotoxicity

Freshwater is essential for various organisms in the world. The pollution of freshwater could have an impact on both environment and humanity. The emissions causing this effect are various chemicals which are polluting the freshwater. The functional unit which is used to calculate this effect is kg 1,4-dichlorobenzene equivalent.

Marine ecotoxicity
For the marine ecotoxicity, the toxic effect of metals in the seawater is taken into account. The metals that are mainly causing this effect are Cobalt, Copper, Manganese, Molybdenum and Zinc. The functional unit of marine ecotoxicity is also kg 1,4-dichlorobenzene equivalent.

Ionising radiation
The exposure of radioactive material in the environment can affect human health. The radiation could cause mutation to the human body.The ionising radiation that is absorbed by human is taken into account by the unit Sievert (J/kg) which is the effective dose of ionised radiation.

Agricultural land occupation
This effect is concerning the effect of the occupation of agricultural land. The amount of land which is used for agricultural purposes is a part of the limited surface of the earth. The more space is used for agricultural goals, the more organisms will extinct because of the lack of space. The impact of the effect is measured in the unit m^2 x year.

Urban land occupation
The Urban land occupation has the same effects on species of animals as the agricultural land occupation. Also the area used for urban purposes is at the expense of the area of nature. Also the functional unit of this effect is measured in m^2 x year.

Natural land transformation
The transformation of the natural land occurs in various ways. In case of a transformation of land, nature- and/or non-nature land are always taken into account. Since the transformation is about a certain area, the unit used for this effect is m^2.

Water depletion
The effect of water depletion describes the total amount of water that is used. Water is a useful resource for the environment and the health of organisms. Water is one of the most important resources to allow life on earth. Losing water could cause a shortage of water. Is case of water depletion a certain volume of water is involved, so the unit used for this effect is m^3.

Metal depletion
Like water also the metal resources can run into a shortage if the use of a metal is faster than the recycling of the metal. The substances that are involved in this effect are all metals. In case of a shortage, the earth cannot supply the amount of minerals that is asked for. The unit used for metal depletion is kg iron (Fe) equivalent.

Fossil fuel depletion
This effect also indicates the amount of resource that is used. Like water and metal, when fuel is used more than it is gained it could lead to shortage. Important fossil fuels are oil and coal. These resources can be gained from in various places under the ground. As unit kg oil equivalent is used to calculate the amount of fossil fuel depletion.

Information from a ReCiPe report [18] was used as example and guide.

Mass and energy balances

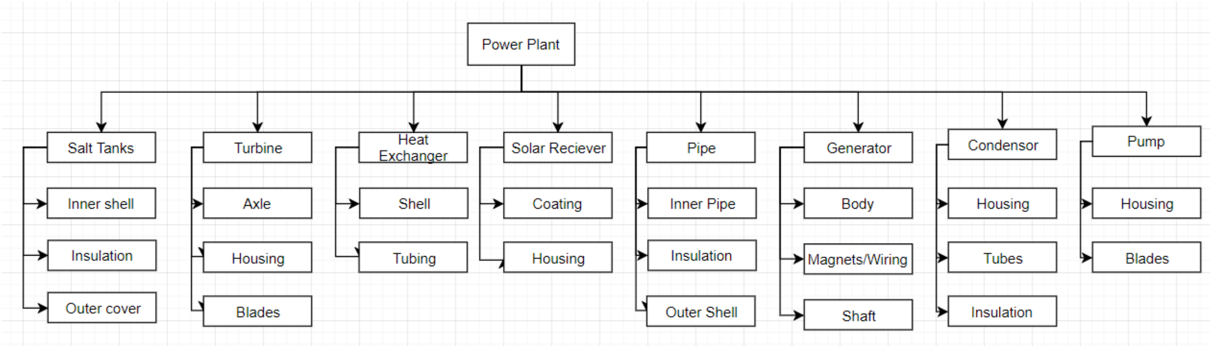

Figure 6.7: The total assembly of the power plant

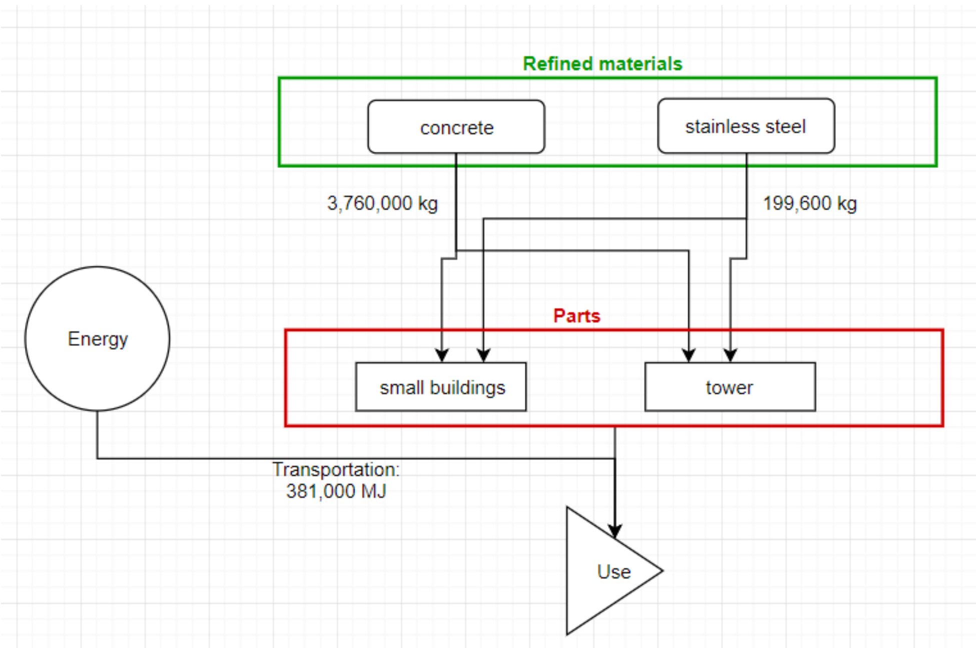

Figure 6.8: Process tree of the buildings

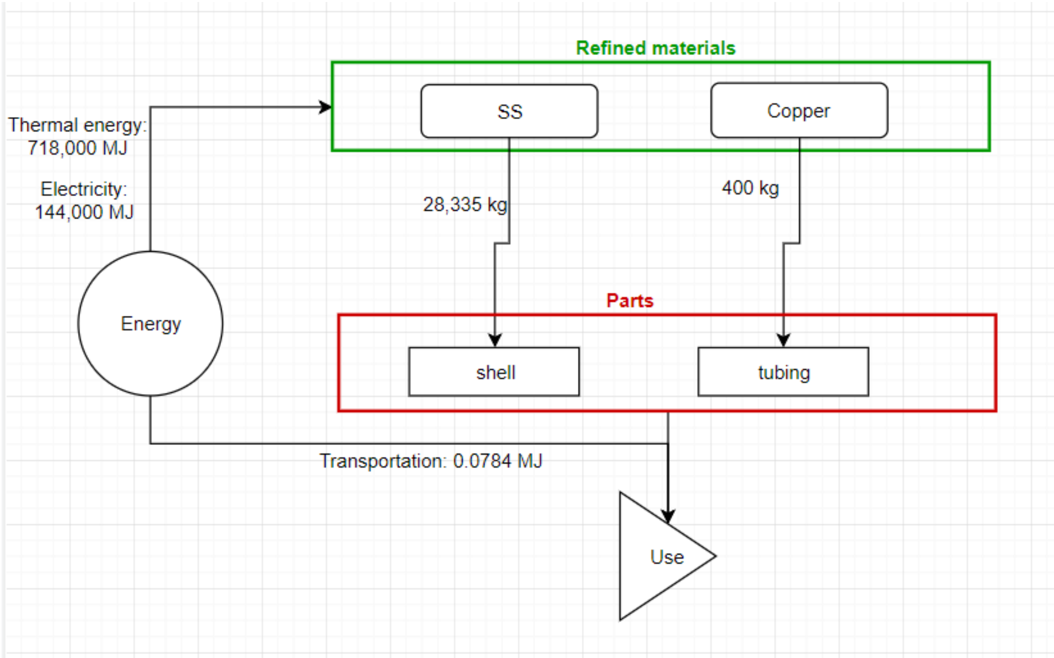

Figure 6.9: Process tree of the condenser

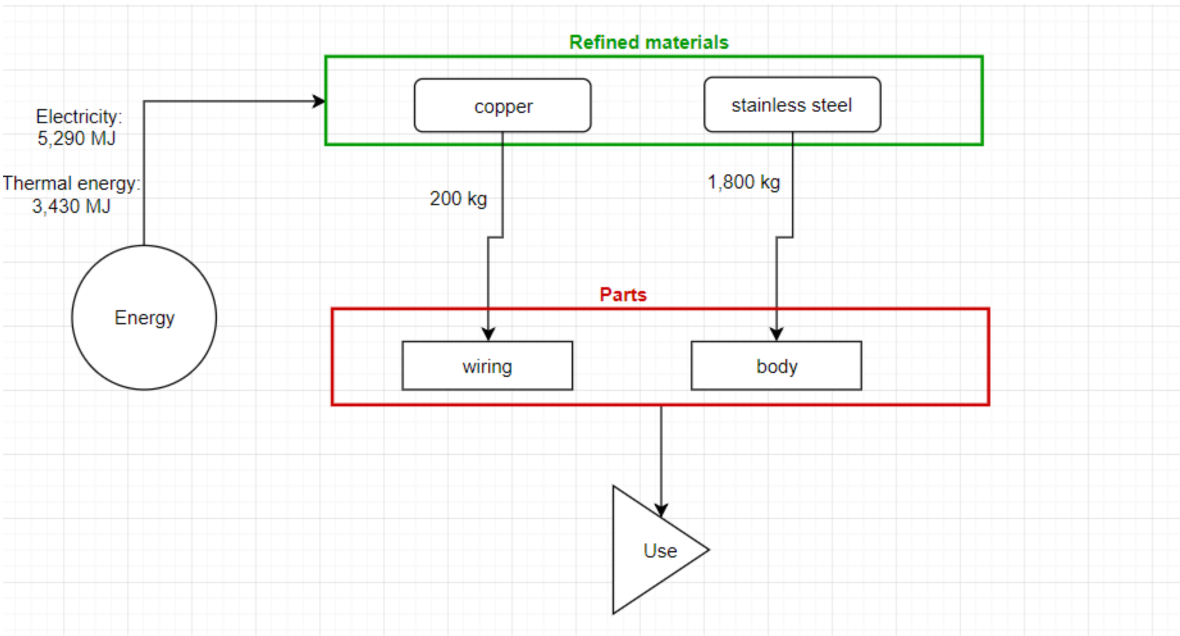

Figure 6.10: Process tree of the electric motor

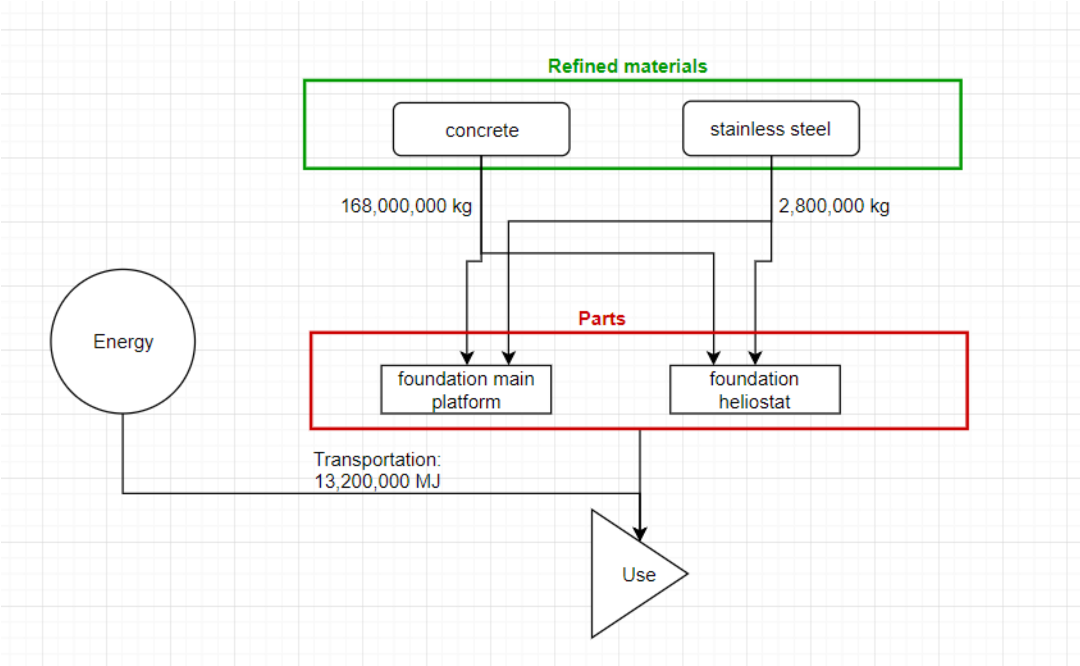

Figure 6.11: Process tree of the foundation

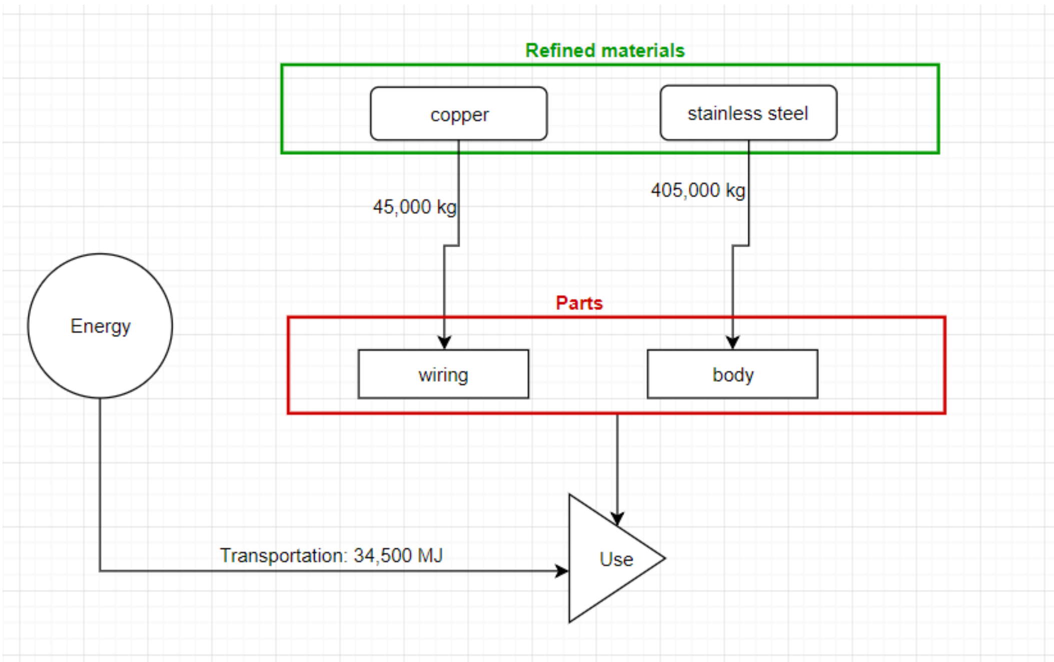

Figure 6.12: Process tree of the generator

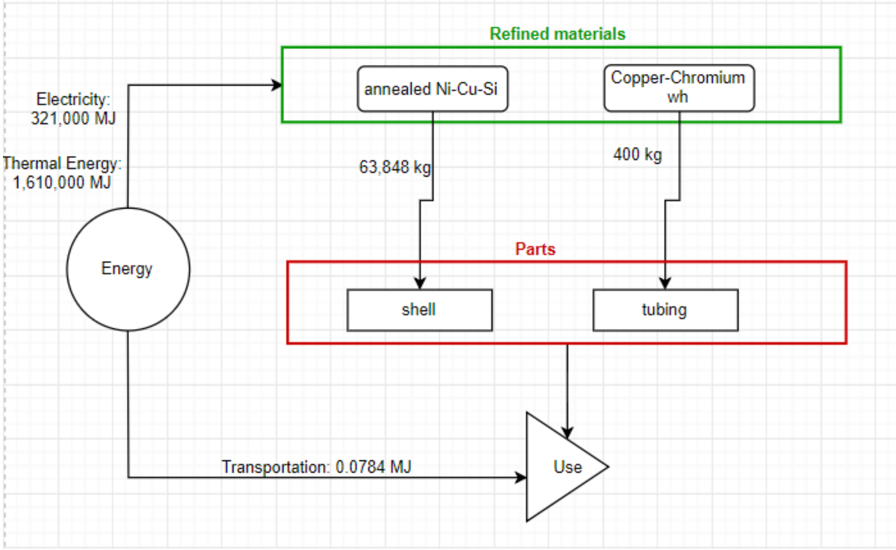

Figure 6.13: Process tree of the heat exchanger

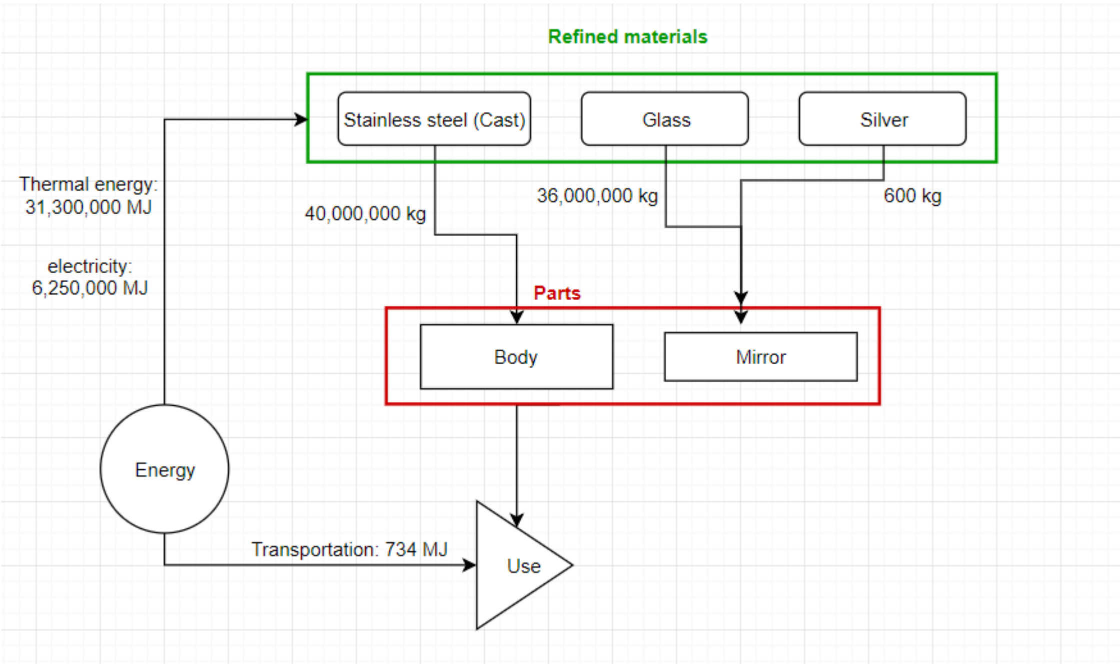

Figure 6.14: Process tree of the heliostats

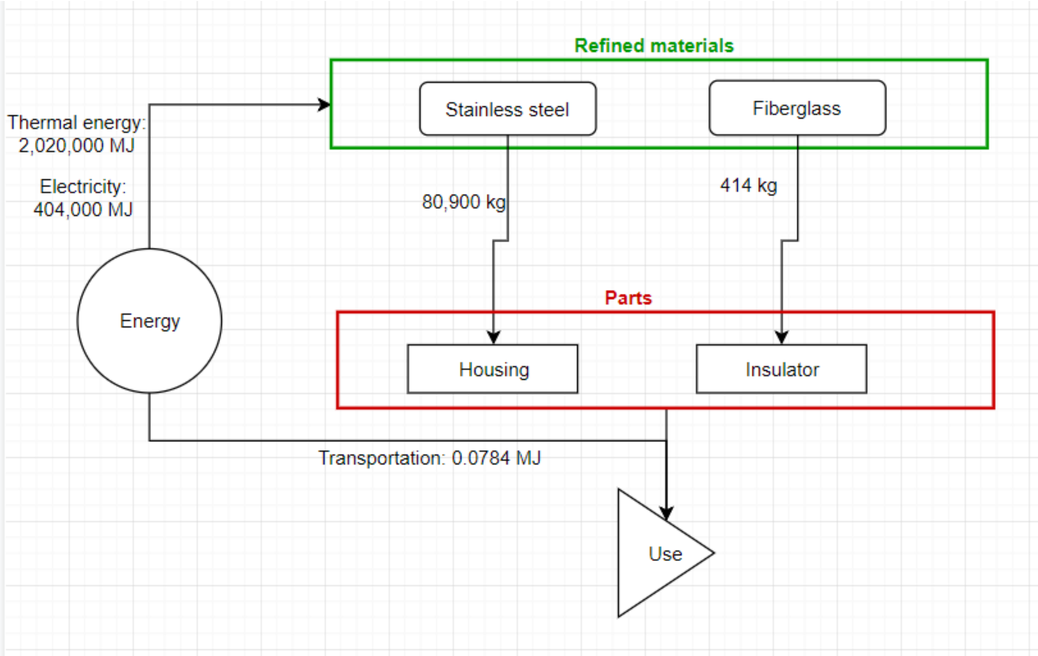

Figure 6.15: Process tree of the mixing chamber

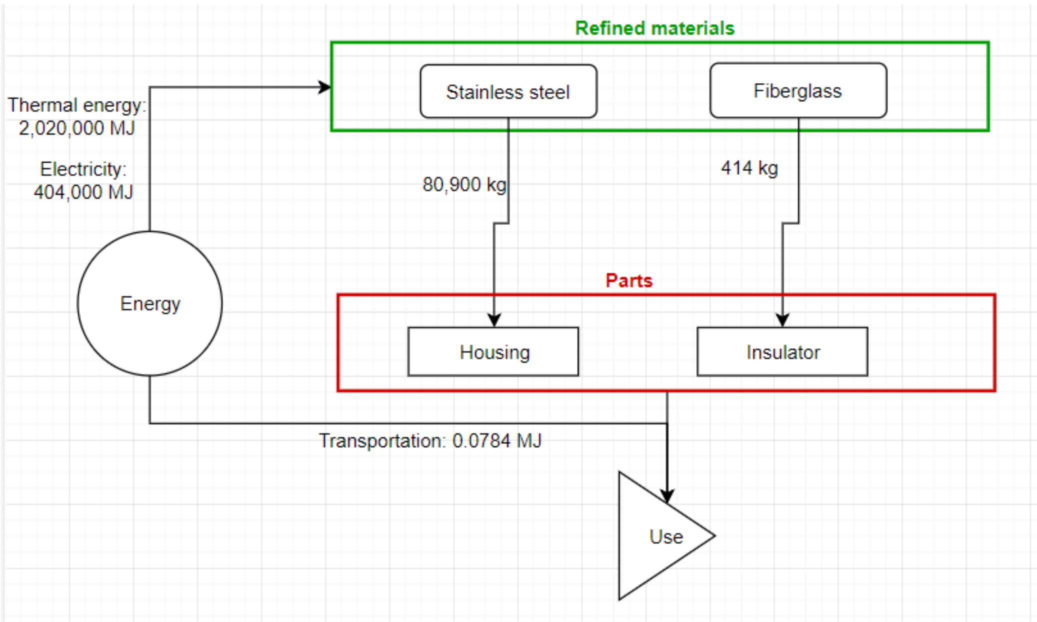

Figure 6.16: Process tree of the open feedwater heater

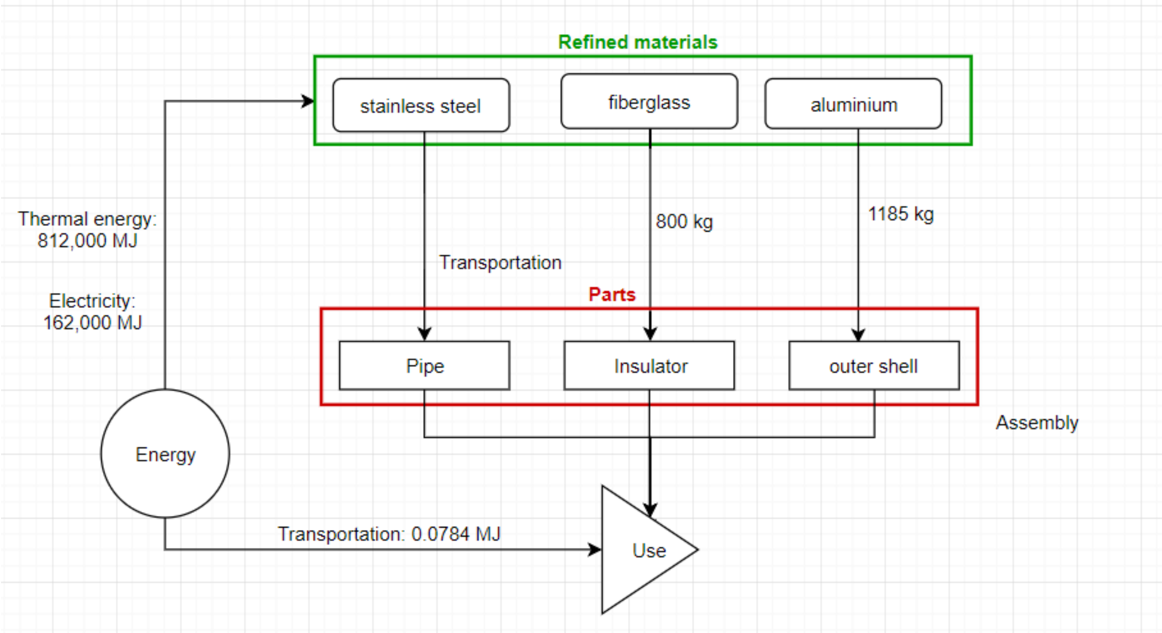

Figure 6.17: Process tree of the pipe

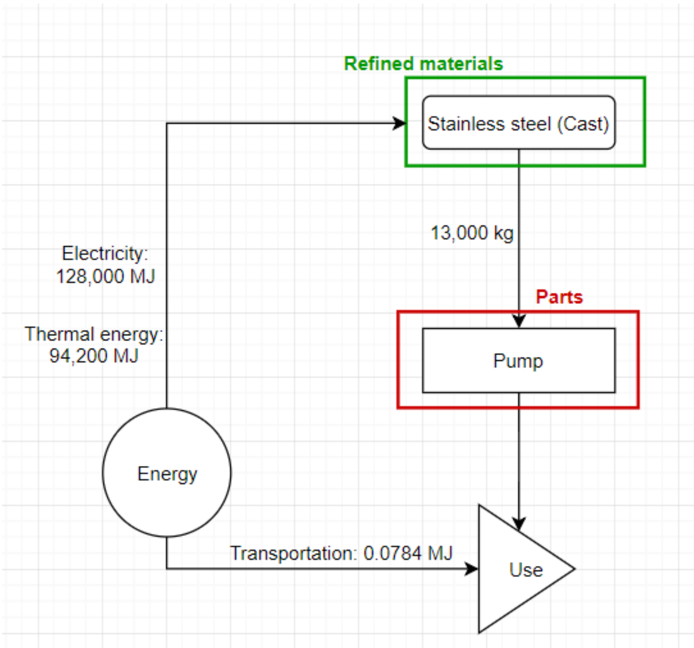

Figure 6.18: Process tree of the pump

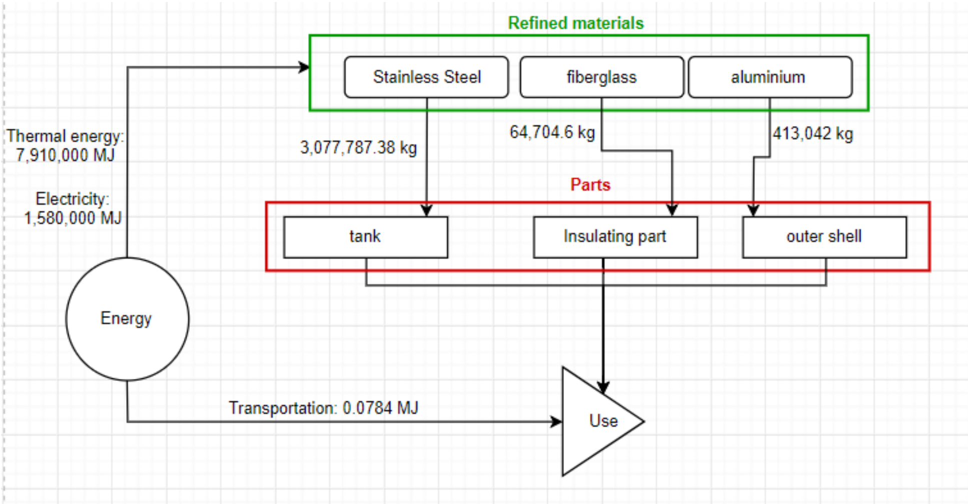

Figure 6.19: Process tree of the salt tanks

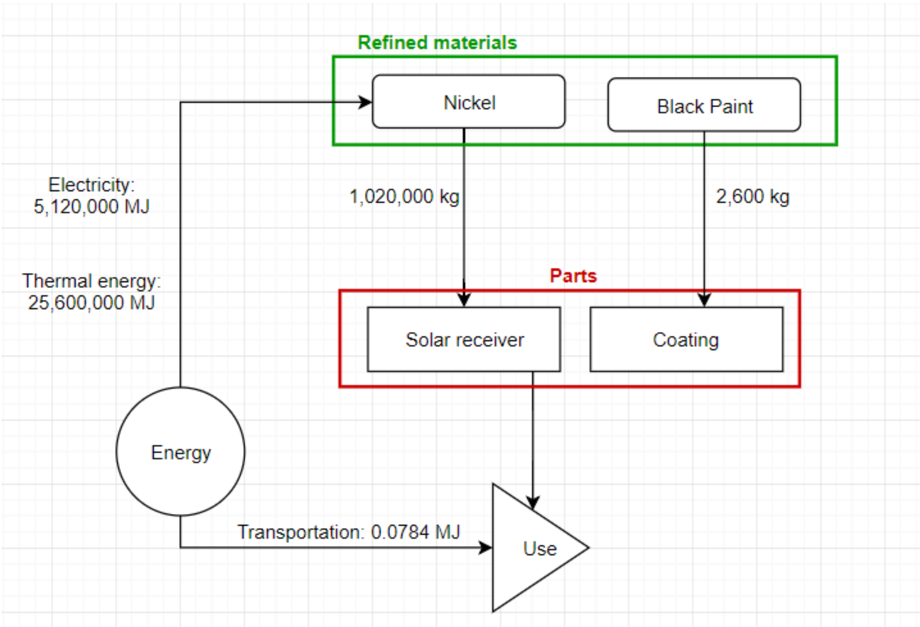

Figure 6.20: Process tree of the solar receiver

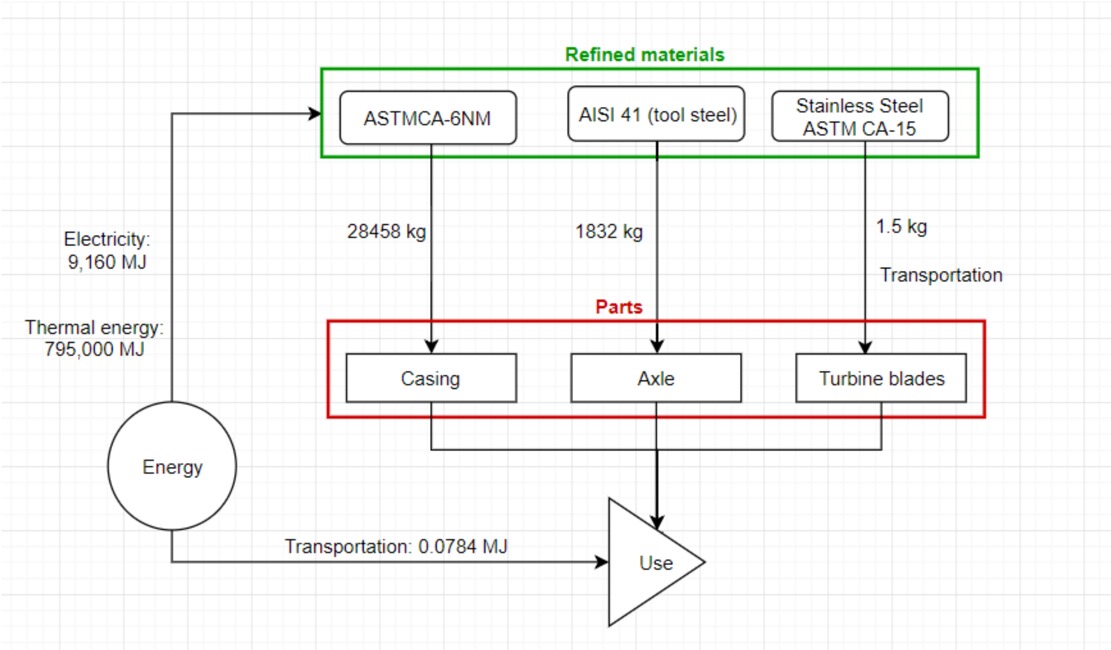

Figure 6.21: Process tree of the turbine

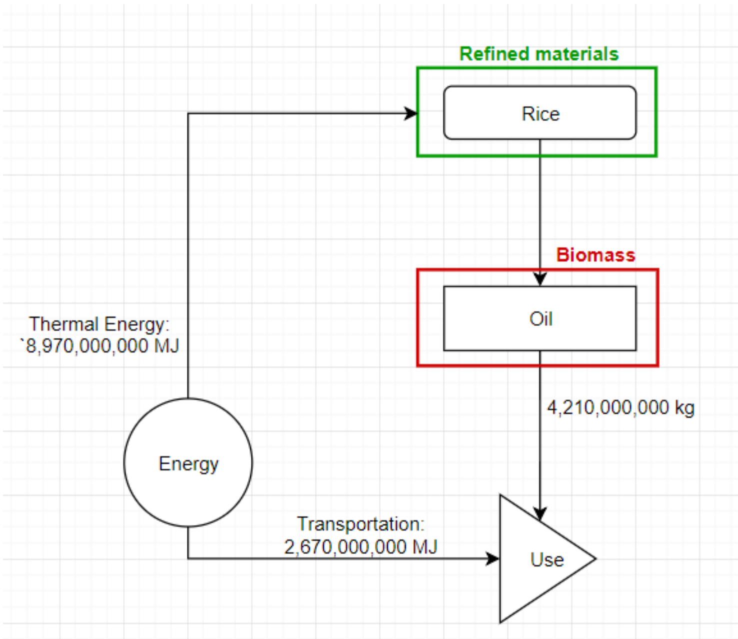

Figure 6.22: Production of the biomass

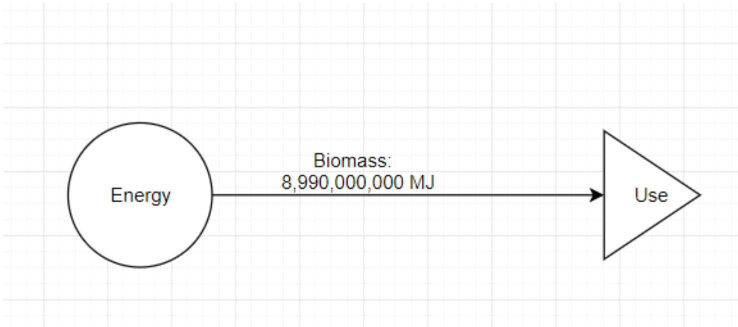

Figure 6.23: Energy requirements for the use

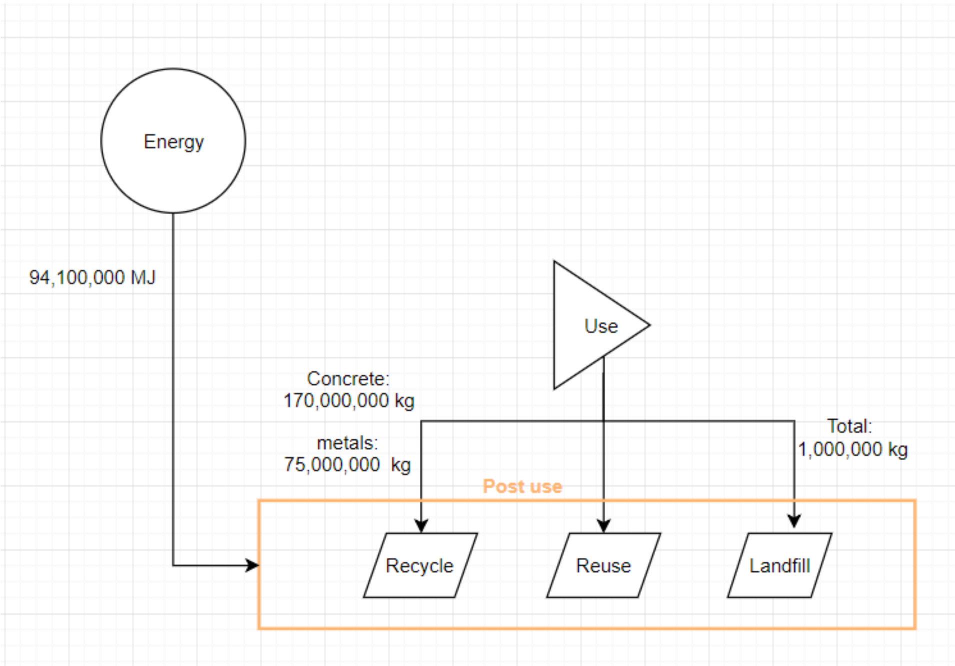

Figure 6.24: Post-use process tree

Table of interventions

	Lanzhou coal p
Flows	2,37E010
Resources	2,37E010
Energy resources	3,32E008
Land use	
Lanzhou coal power plant	5,63E003
Material resources	2,34E010
Non renewable elements	6,83E005
Non renewable resources	4,53E009
Renewable resources	1,88E010
Others	
Emissions to fresh water	

Figure 6.25: Table of interventions: Coal plant input

	Lanzhou coal p
Flows	2,41E010
Resources	23,7
Deposited goods	4,52E009
Emissions to air	4,66E009
Heavy metals to air	384
Inorganic emissions to air	1,36E009
Organic emissions to air (group VOC)	1,35E006
Other emissions to air	3,3E009
Particles to air	1,75E005
Pesticides to air	0,051
Radioactive emissions to air	-4,16E-005
Emissions to fresh water	1,49E010
Analytical measures to fresh water	1,52E004
Heavy metals to fresh water	5,49E003
Inorganic emissions to fresh water	4,04E006
Organic emissions to fresh water	8,52E003
Other emissions to fresh water	1,45E010
Particles to fresh water	1,5E005
Radioactive emissions to fresh water	4,29E008
Emissions to sea water	4,03E007
Analytical measures to sea water	286
Heavy metals to sea water	23,3
Inorganic emissions to sea water	2,47E005
Organic emissions to sea water	146
Other emissions to sea water	4,01E007
Particles to sea water	3,35E003
Radioactive emissions to sea water	
Emissions to agricultural soil	2,67
Heavy metals to agricultural soil	2,67
Inorganic emissions to agricultural soil	1,48E-005
Emissions to industrial soil	40,1
Heavy metals to industrial soil	1,39
Inorganic emissions to industrial soil	38,7
Organic emissions to industrial soil	0,0506

Figure 6.26: Table of interventions: Coal plant output

	Lifecyle: Solar
Flows	**2,23E009**
Resources	**2,23E009**
Energy resources	**9,46E006**
Non renewable energy resources	**9,46E006**
Crude oil (resource)	**3,55E006**
Hard coal (resource)	**4,45E006**
Lignite (resource)	**7,84E005**
Natural gas (resource)	**6,59E005**
Peat (resource)	**2,25E004**
Uranium (resource)	**27,9**
Renewable energy resources	
Land use	
Material resources	**1,98E009**
Non renewable elements	**9,49E004**
Non renewable resources	**-1,8E007**
Renewable resources	**1,99E009**
Solar Power Plant	**2,41E008**
Others	
Emissions to air	
Emissions to fresh water	**17,4**
Inorganic emissions to fresh water	**17,4**
Nitrogen	17,4
Phosphorus	
Emissions to agricultural soil	**0,442**
Heavy metals to agricultural soil	**0,442**
Chromium	0,442

Figure 6.27: Table of interventions: Solar plant input

	Lifecyle: Solar
Flows	2,45E009
Resources	1,26E004
Deposited goods	3,57E006
Emissions to air	5,65E008
Heavy metals to air	962
Inorganic emissions to air	3,38E008
Organic emissions to air (group VOC)	7,79E004
Other emissions to air	2,26E008
Particles to air	4,65E004
Pesticides to air	0,551
Radioactive emissions to air	0,218
Emissions to fresh water	1,87E009
Analytical measures to fresh water	6,7E003
Heavy metals to fresh water	1,63E003
Inorganic emissions to fresh water	8,52E005
Organic emissions to fresh water	2,96E004
Other emissions to fresh water	1,34E009
Particles to fresh water	2,23E005
Radioactive emissions to fresh water	5,34E008
Emissions to sea water	6,4E006
Analytical measures to sea water	71
Heavy metals to sea water	6,53
Inorganic emissions to sea water	6,78E004
Organic emissions to sea water	40,9
Other emissions to sea water	6,33E006
Particles to sea water	418
Radioactive emissions to sea water	
Emissions to agricultural soil	10,9
Heavy metals to agricultural soil	10,9
Inorganic emissions to agricultural soil	1,78E-006
Emissions to industrial soil	9,34E003
Heavy metals to industrial soil	26,9
Inorganic emissions to industrial soil	9,3E003
Organic emissions to industrial soil	5,76
Other emissions to industrial soil	0,000559

Figure 6.28: Table of interventions: Solar plant output

Characterized graphs

Solar plant Characterized graphs

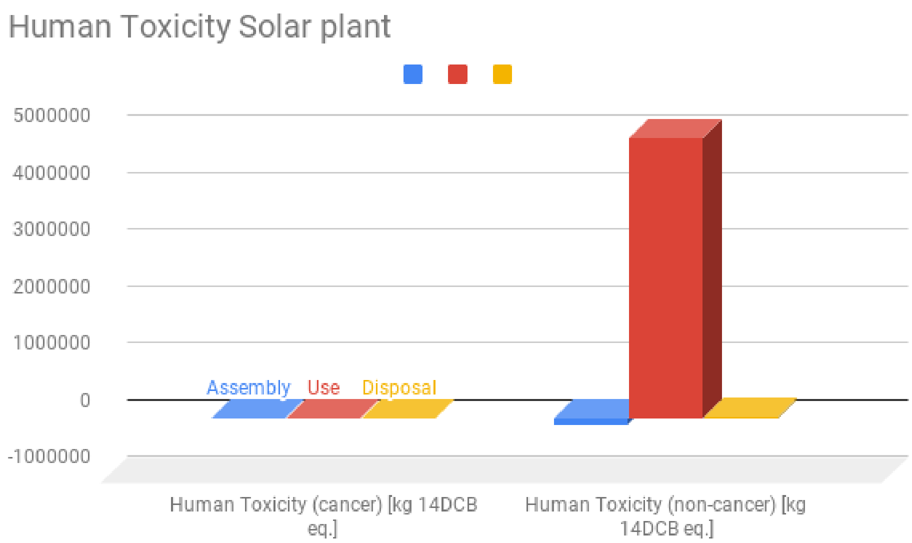

Figure 6.29: Human Toxicity: Solar plant

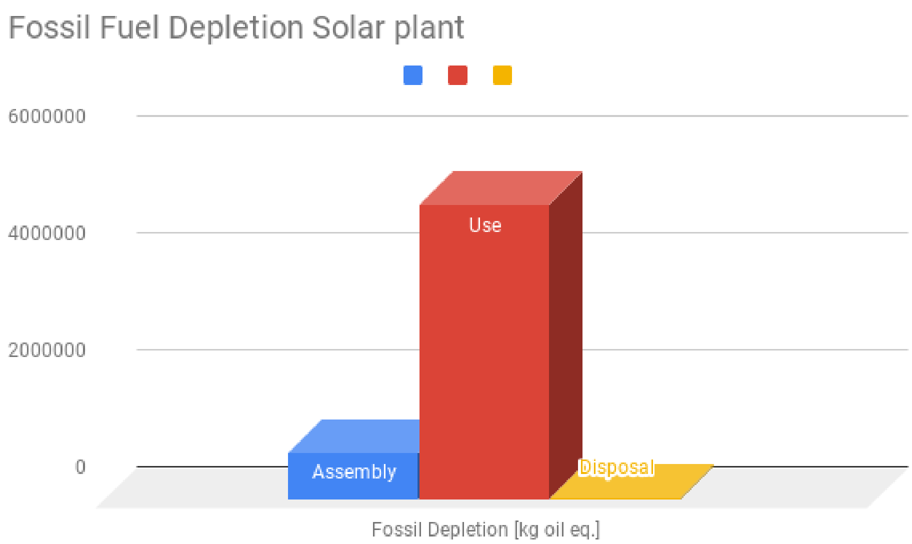

Figure 6.30: Fossil Fuel Depletion: Solar plant

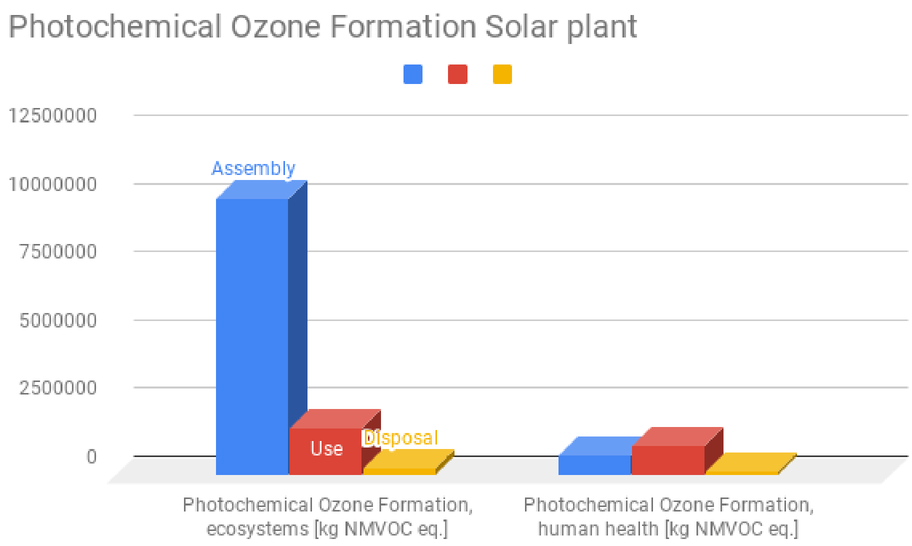

Figure 6.31: Photochemical Oxident Formation: Solar plant

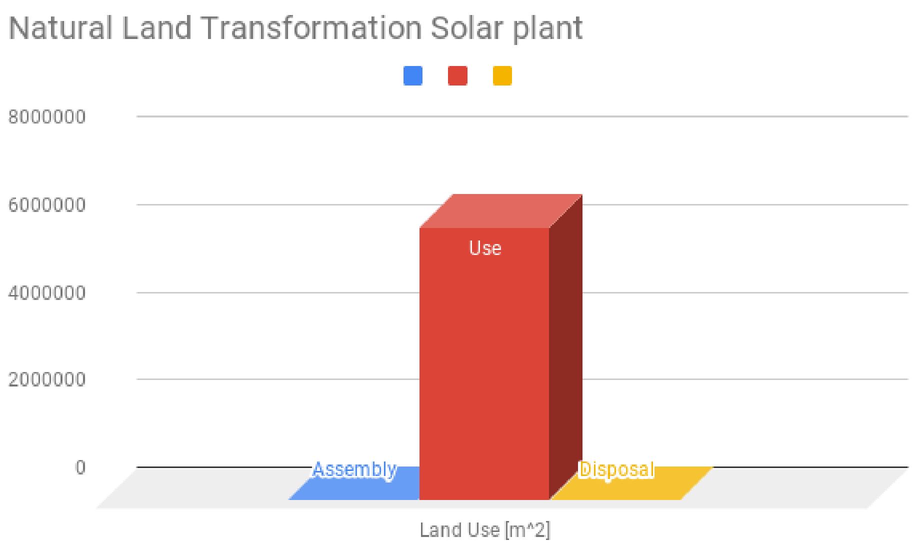

Figure 6.32: Natural Land Transformation: Solar plant

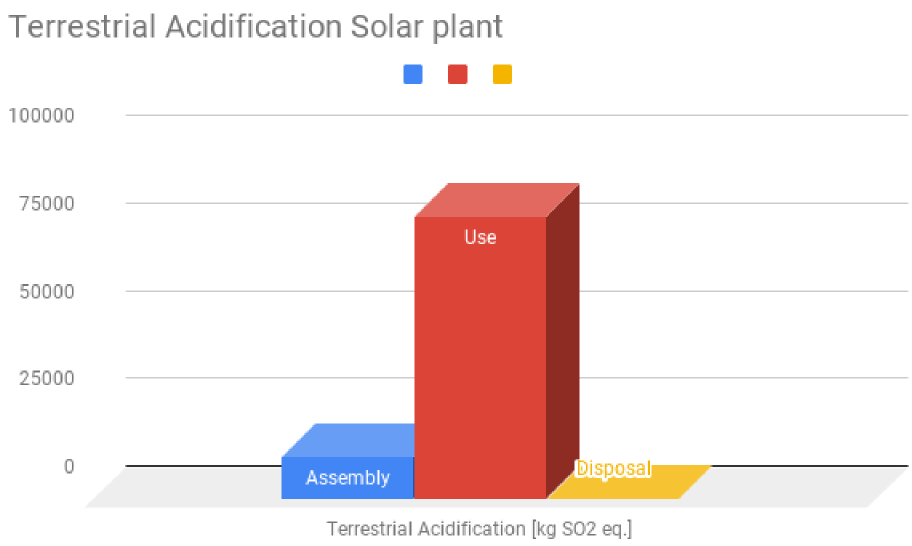

Figure 6.33: Terrestrial Acidification: Solar plant

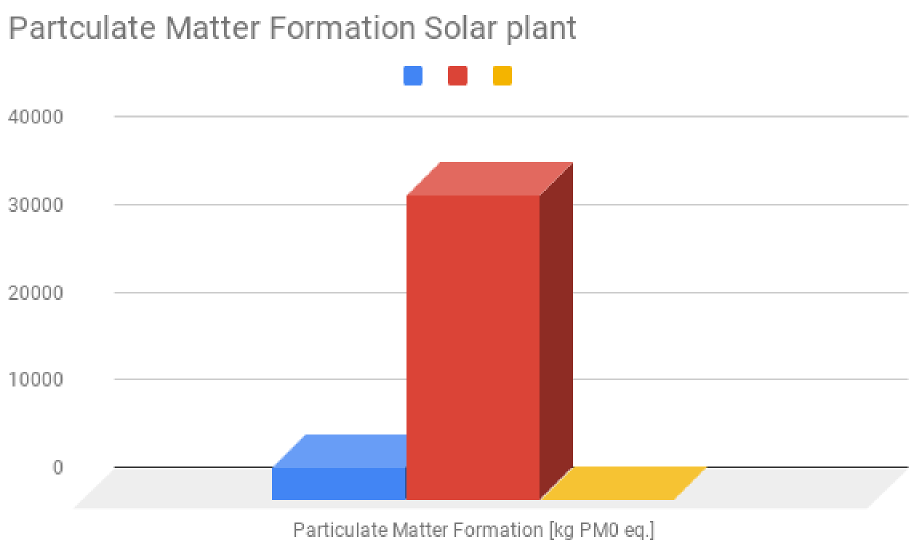

Figure 6.34: Particular Matter Formation: Solar plant

Coal plant Characterized graphs

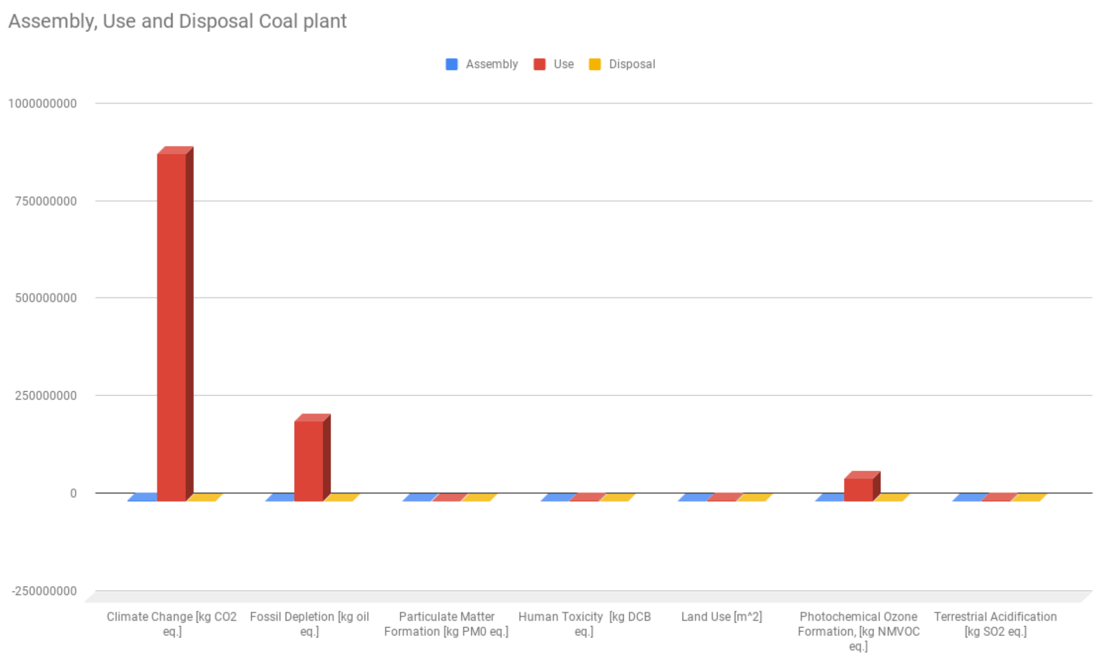

Figure 6.35: Coal plant: Assembly, use and disposal

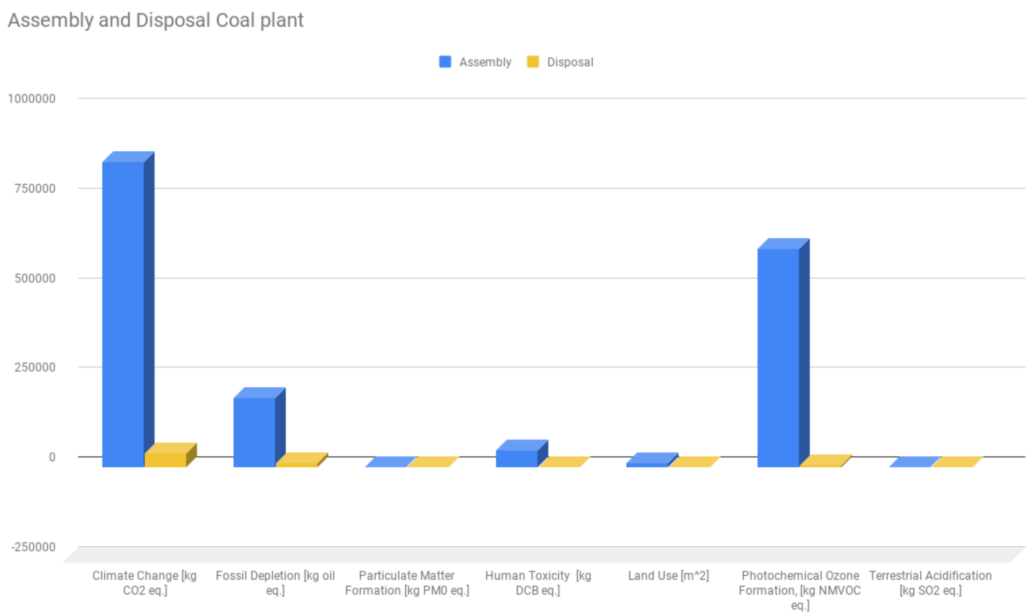

Figure 6.36: Coal plant: Assembly and disposal

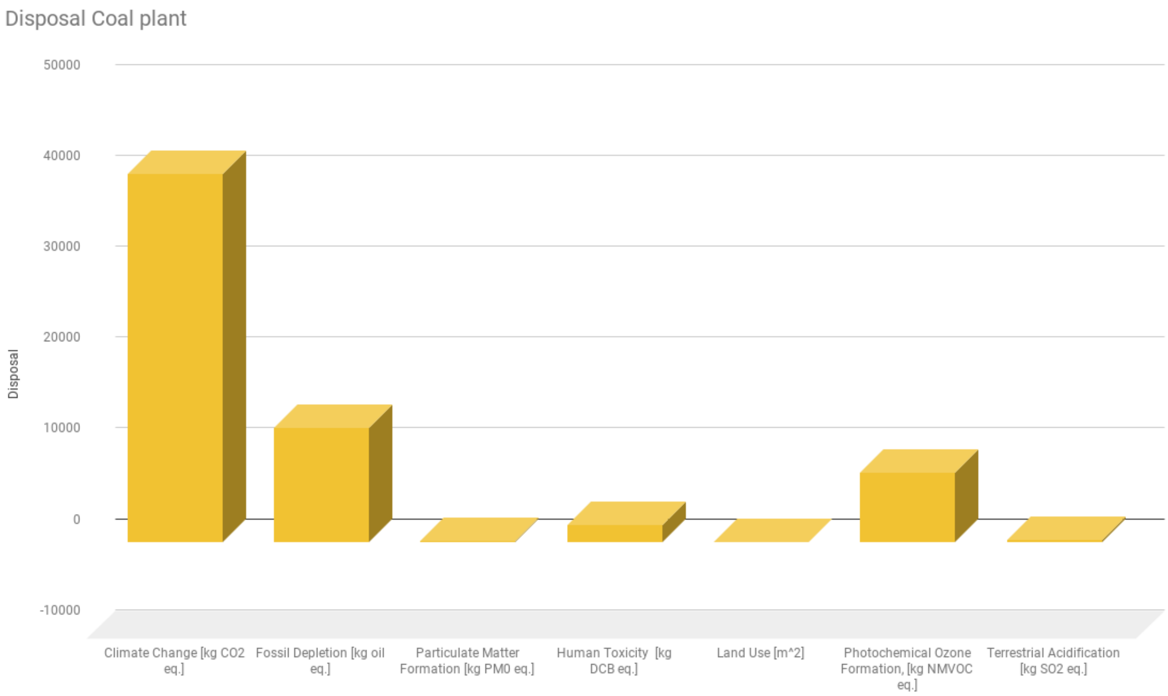

Figure 6.37: Coal plant: Disposal

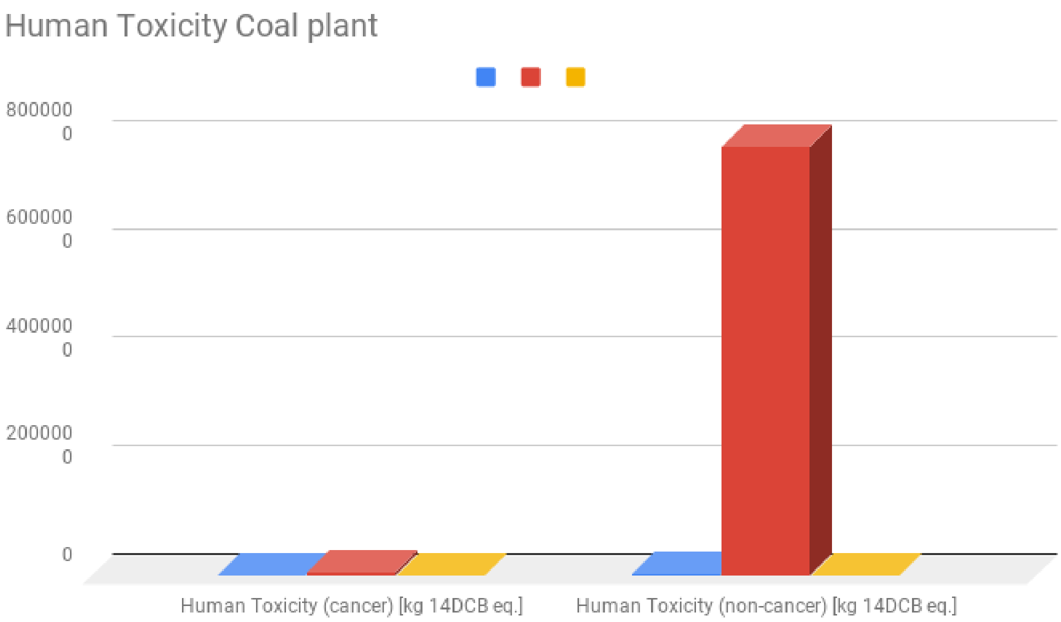

Figure 6.38: Human Toxicity: Coal plant

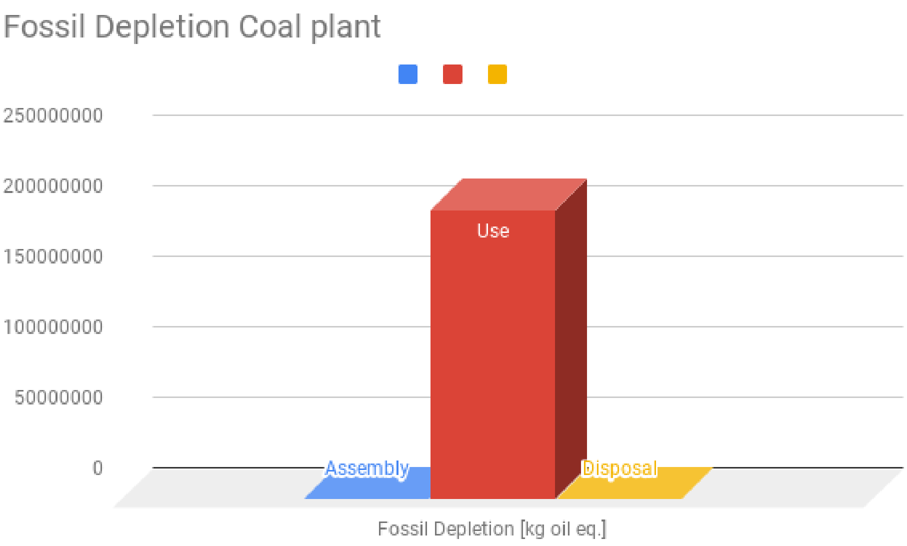

Figure 6.39: Fossil Fuel Depletion: Coal plant

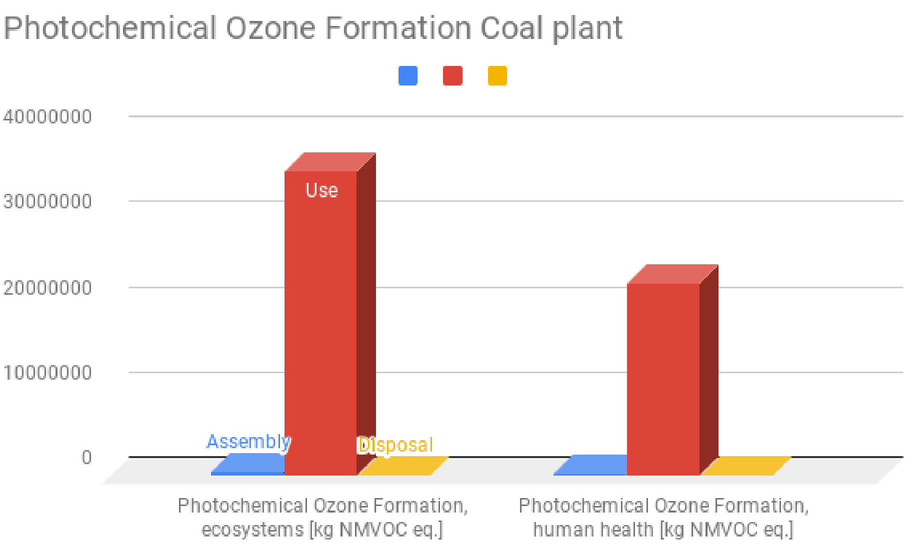

Figure 6.40: Photochemical Oxidant Formation: Coal plant

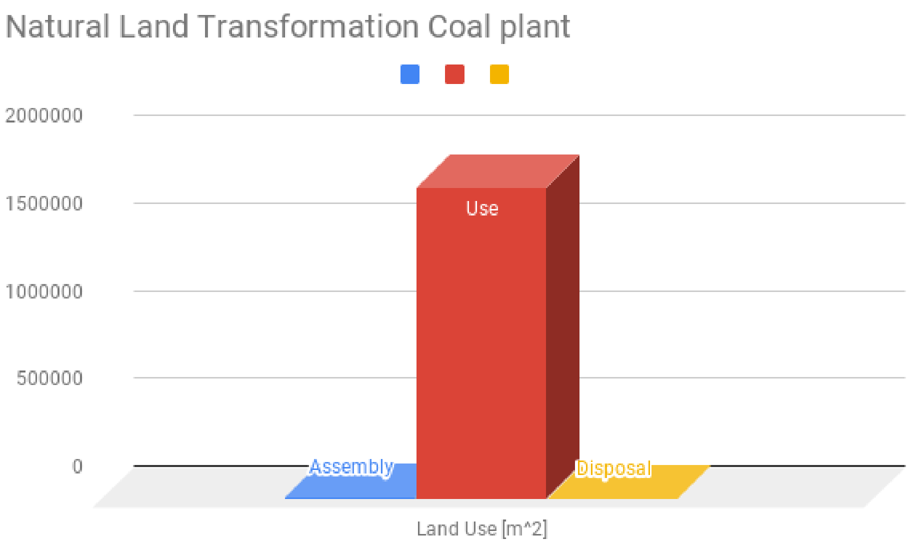

Figure 6.41: Natural Land Transformation: Coal plant

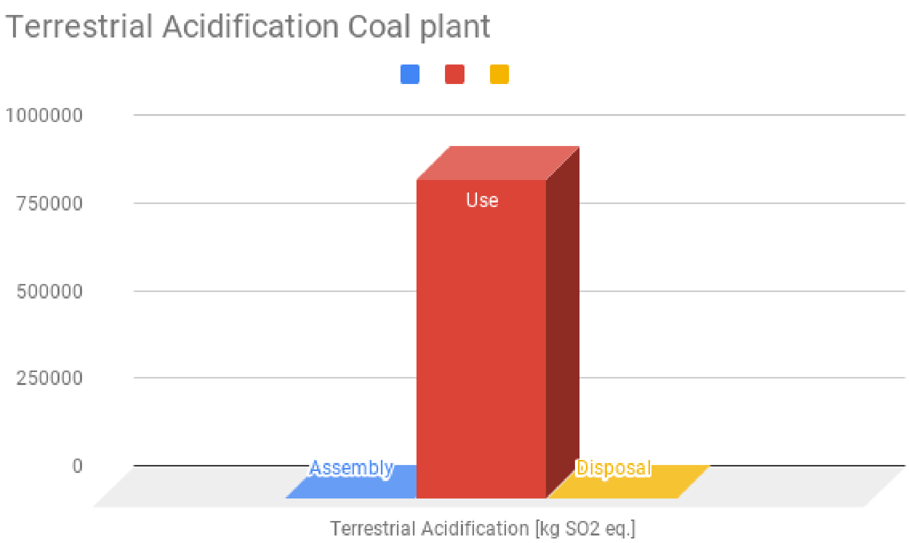

Figure 6.42: Terrestrial Acidification: Coal plant

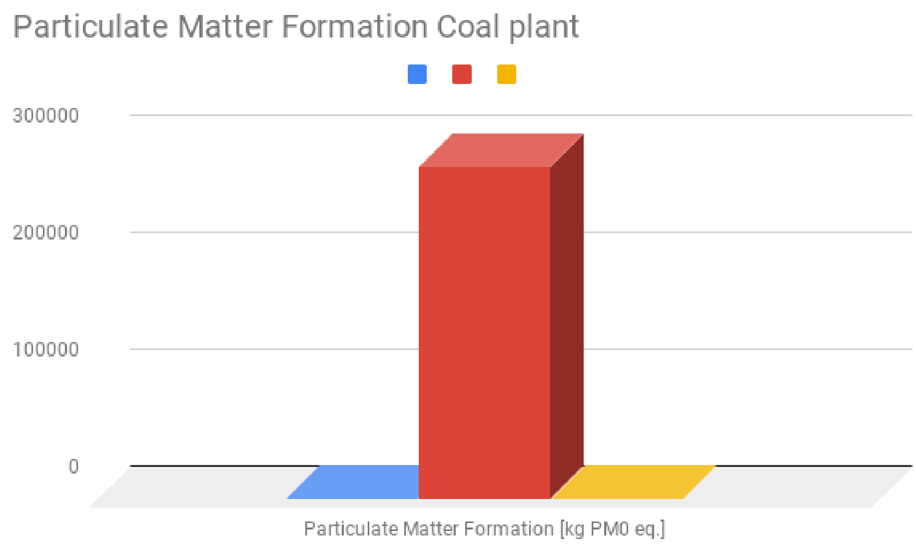

Figure 6.43: Particular Matter Formation: Coal plant

Normalized graphs

Solar plant Normalized graphs

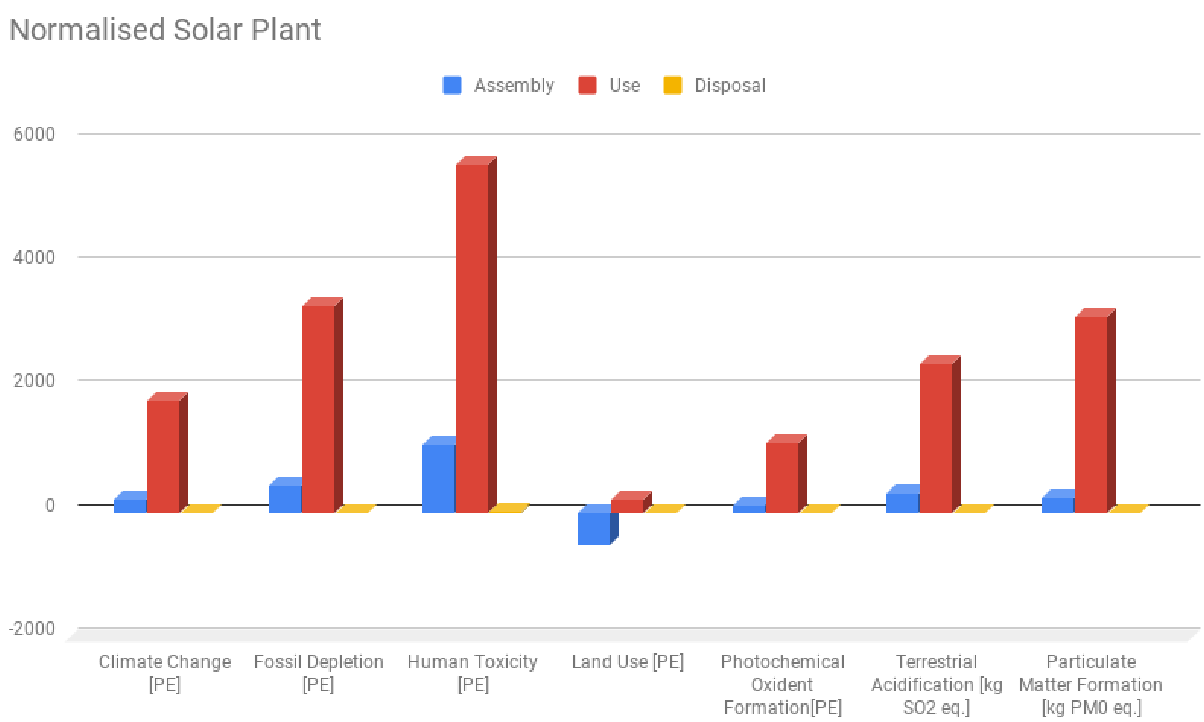

Figure 6.44: Solar plant: Normalised Assembly, use and disposal

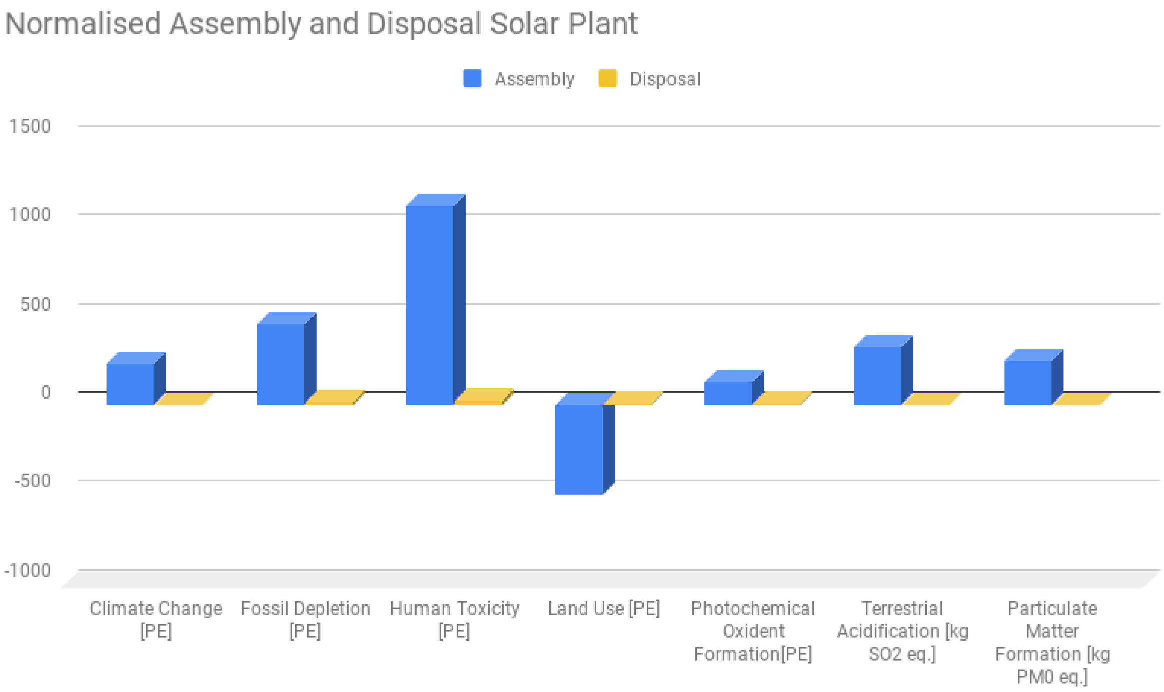

Figure 6.45: Solar plant: Normalised Assembly and disposal

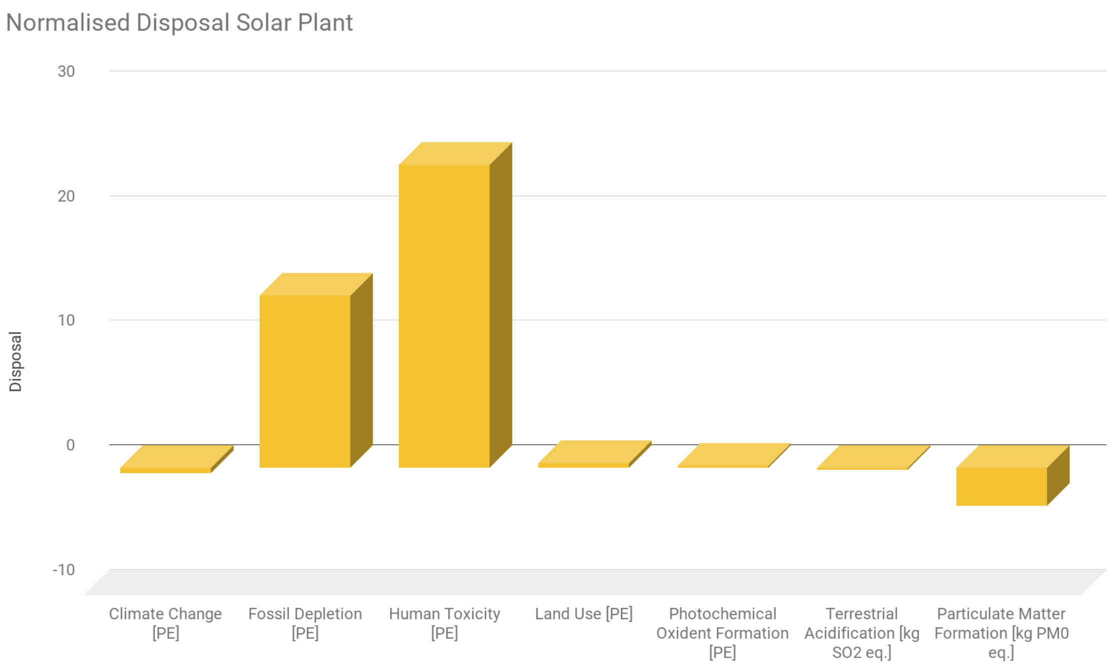

Figure 6.46: Solar plant: Normalised Disposal

Coal plant Normalized graphs

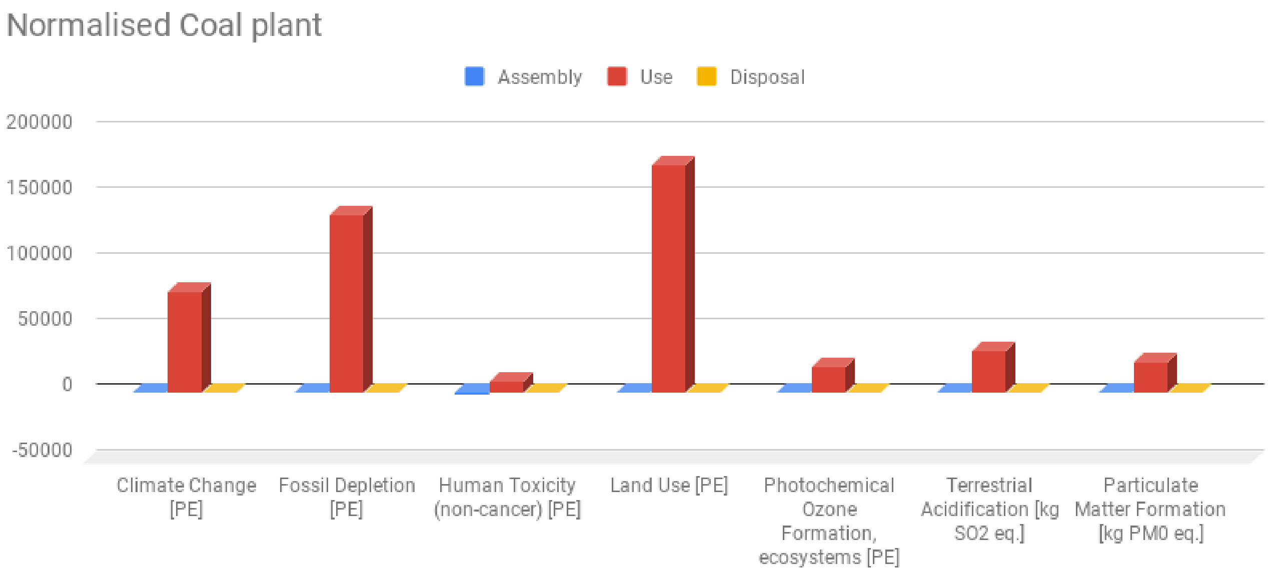

Figure 6.47: Coal plant: Normalised assembly, use and disposal

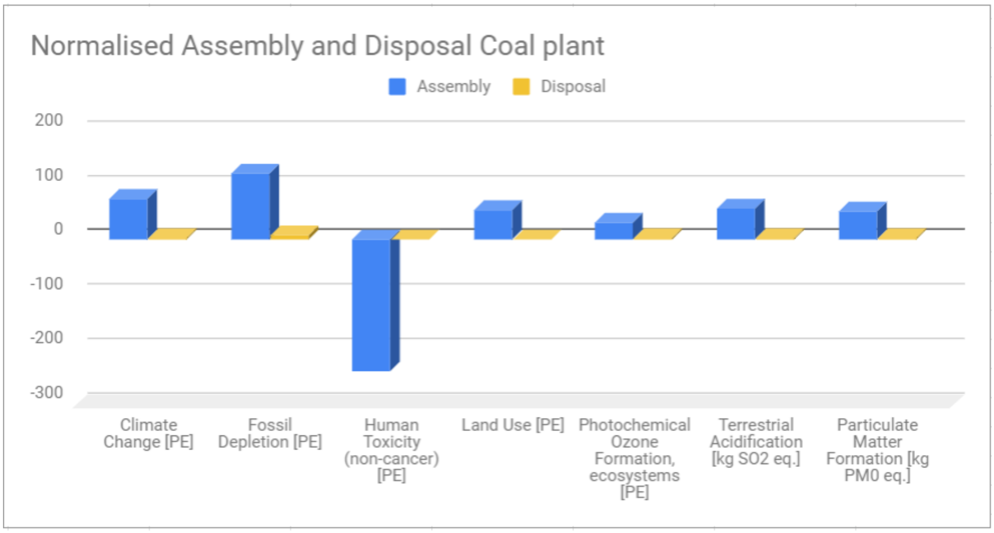

Figure 6.48: Coal plant: Normalised assembly and disposal

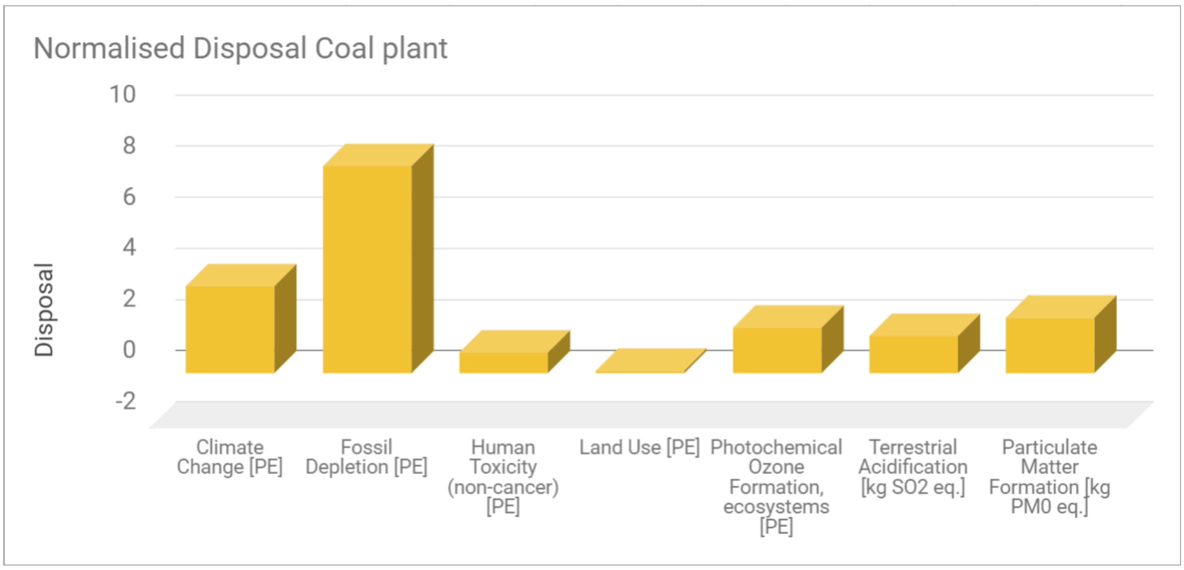

Figure 6.49: Coal plant: Normalised Disposal

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