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Sustainable Lanzhou
Design of an Energy System

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1 Introduction

A few years ago, the capital of the province of Gansu located in China was declared at high risk because of the great pollution caused by the constant use of environmentally harmful power plants and heavy industry powered by non-renewable sources. Presently and since a few years, important steps had been taken in Lanzhou, a city with more than 3.5 million inhabitants, in order to reduce this threat to public health and environmental welfare. There are still some outdated power plants running on fossil fuels, like the Guodian Yuzhong coal plant, which is powered by the heat produced in two coal-fired units. Research and analysis of the possibility of replacing this plant with a solar power plant were conducted in an attempt to tackle this problem. This report will present the detailed design of a 100% renewable energy power plant and will consider the thermodynamic aspects of it, the most important material science considerations for two of the components of the power plant and last but not least the environmental impact that the implementation of this plant would imply for Lanzhou by performing a Life Cycle Assessment, some conclusions and recommendations will be drawn.

2 Summary

The following report was written in order to present the results that came out after a detailed analysis of the possibility of replacing the Guodian power plant by a completely renewable energy power plant. The objective of the report is to give a clear overview of the process followed to obtain the best possible replacement and to conclude if this possibility would, in fact, be more beneficial to the Lanzhou problematic. First of all, a thermodynamic analysis is done. Several renewable sources of energy and combinations between these were considered in order to provide Lanzhou enough energy. Three different concepts were further analyzed and among these, the most efficient concept has been selected and analyzed in more detail . At a second stage from a material science perspective, the materials of two important components for the power plant have been selected based on derived performance indices. At the end, the results of the Life Cycle Assesment have been shown and the environmental impact of this new possible power plant can be seen.

3 Thermodynamic Design

3.1 Problem definition

A new sustainable energy system, based on solar power and another renewable energy source has to be designed. The new installation should provide electricity and heat during the whole year. The new installation is compared with the current situation at Lanzhou and advice is given on the suitability of our new design.

3.1.1 Design specifications for the new Power Plant

- The energy system should be based on solar power and another form of renewable energy.
- The new power plant should be able to fully replace the coal power plant in Lanzhou. So the new power plant should produce 220 MW of electricity continuously.
- The power plant needs to provide heat to the Lanzhou district heating system in the form of hot water.
- 130 MW of hot water is required in the winter.
- 65 MW of hot water is required in the summer.
- The hot water must be provided at 14 bars, 120° and the returned is at 4 bar, 90°.
- The power plant needs to be a co-generation plant with adjustable loads.
- The energy should be 100 % renewable.
- The environmental impact should be as small as possible.
- The energy system should avoid unsolvable problems with stakeholders.

3.2 Concepts

3.2.1 General explanation for parts of the concepts

For the district heating another cycle is used because the water coming from Lanzhou will contain some oxygen due to leakage in the district heating system. Water with oxygen will corrode the Rankine cycle which will affect the lifespan of the cycle.

The water cycles are kept simple in the first place, but the cycles can be improved for the detailed design if necessary. Bio-energy is used in addition to solar power for all of our concepts, because of its low investment cost, easy use, and mostly its flexibility, which will be an important aspect in our concepts.

The values shown in the concepts are not the real values for the different flows, but assumptions for the values using the data from the Crescent Dunes Solar Power Station in order to compare the different thermal efficiencies.

The concepts:

- Concept 1: Solar-/Bio-energy alternation
- Concept 2: Bio-energy city heater
- Concept 3: Bio-energy re-heater

3.2.2 Concept 1: Solar-/Bio-energy alternation

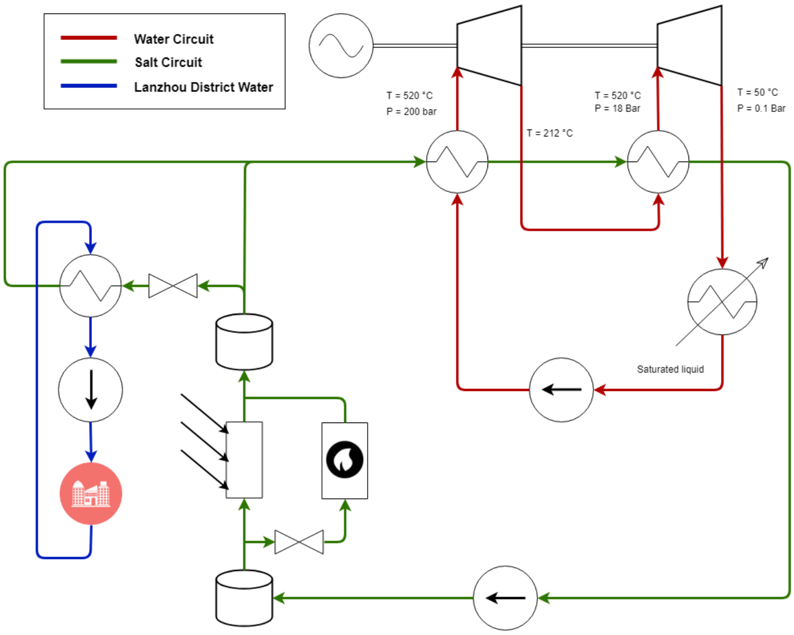

Figure 3.1: Solar-/Bio-energy alternation

Figure 3.1: The burner with bio-energy is placed in the salt cycle and the mass flow through it can be controlled with a valve. This is also the case for the mass flow needed to heat the water of the Lanzhou heating district. This way the power plant can stop using or use less bio-energy if there is enough solar power available at certain periods of time or the other way around.

3.2.3 Concept 2: Bio-energy city heater

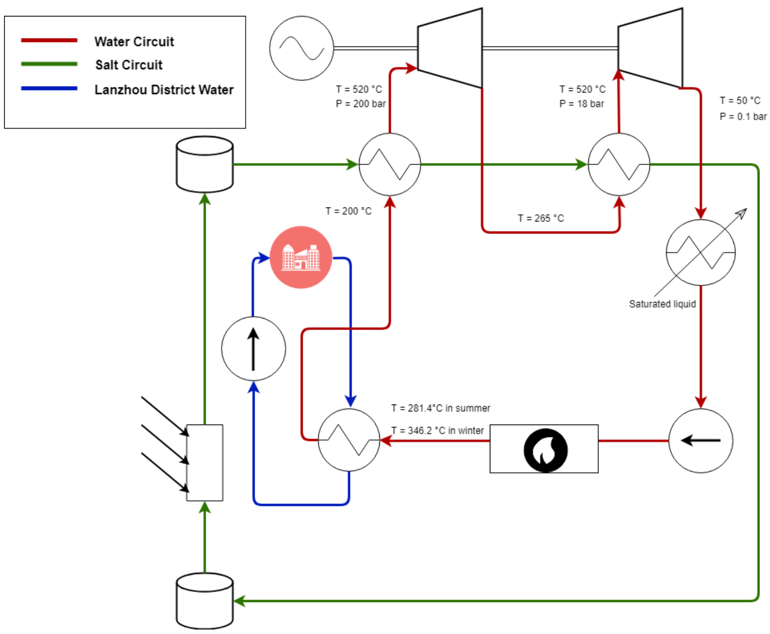

Figure 3.2: Bio-energy city heater concept

Figure 3.2: The burner with bio-energy is placed directly in front of the heat exchanger to the Lanzhou heating district. This way the amount of energy that goes to the district can be controlled by adjusting the amount of bio-energy delivered to the cycle. Then the water is heated again by a heat exchanger before entering the first turbine, so the temperature in the turbine will not be too low and not too much bio-energy will be needed.

3.2.4 Concept 3: Bio-energy reheater

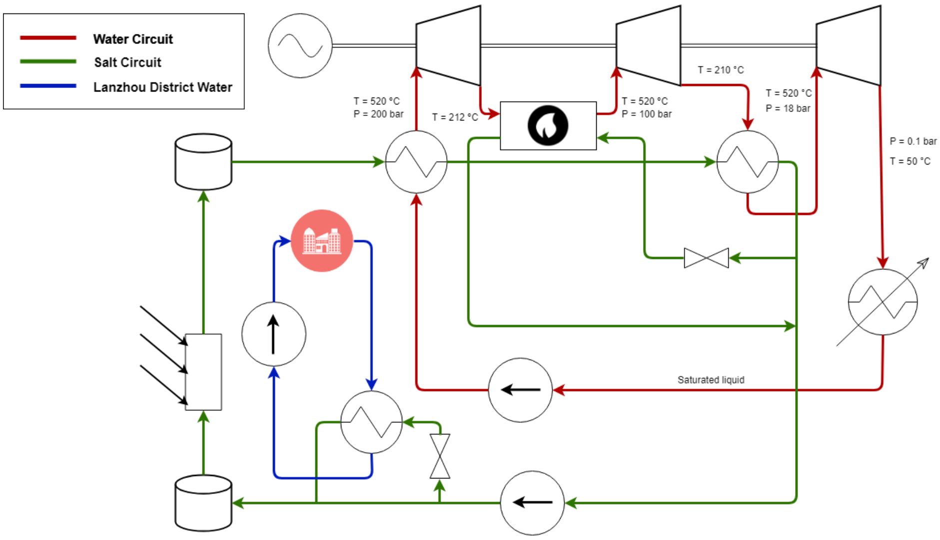

Figure 3.3: Bio-energy reheater

Figure 3.3: For concept 3, the heat exchanger for the Lanzhou heating district is also placed in the salt cycle, but this time at the end. This Rankine cycle consists of 3 turbines with one of the reheaters using bio-energy. This bio-energy can also be used to heat the salt if more heat is needed for the Lanzhou heating district, this can be done by opening a valve to let more salt flow through the burner. The mass flow of the salt through the heat exchanger of the district can also be controlled with a valve.

3.2.5 Concept Analysis

Thermodynamic aspects
Based on the assumptions for certain temperatures and the assumption that all pumps and turbines are isentropic the thermal efficiency for concept 3 is the highest. For the thermodynamic aspect, the thermal efficiency is the most valuable property, because the output for every concept has to be the same. Because of the assumption that there is no heat loss in the piping or heat exchangers, we don't have to take in mind the placing of the burner of bio-energy in the salt circuit instead of the water circuit.

For the rough calculations all the turbines and pumps are taken to be isentropic. Therefore, the thermal efficiency will be higher for all the three concepts. The district heating is neglected for thermal efficiency. Some temperature and pressure assumptions were made using the data from the Crescent Dunes Solar Power Station in order to calculate these thermal efficiency's, just so we could compare the concepts. Full calculations will give other thermal efficiencies.

Thermal efficiency's calculated from assumptions

- Concept 1: 37.3 %
- Concept 2: 35.0 %
- Concept 3: 62.3 %

Materials Science aspects
For all the three concepts all the high pressure turbines operate under a high temperature which affects the material choice. Also all the low pressure turbines of the three concepts are operating under a high temperature however the pressure is lower. Concept 3 has an extra turbine which operates under a intermediate pressure so the material choice could be different than the other two turbines and this should be investigated. Concept 1 and concept 3 have 3 heat exchangers with water and salt flowing through. Concept 2 has 2 heat exchangers with water and salt flowing through and one with only water flowing through. The heat exchanger with also salt flowing through need materials that are more corrosion resistance due to the corrosive nature of salt. The burners of bio-energy for concept 1 and 3 have also salt flowing through them and this is not the case for concept 2. For the Material Science aspects there are no major differences, but there is a slight preference for concept 2. Also the presence of oxygen in the pipes for the district heating which could lead to corrosion should be taken into account. There will be no oxygen in the pipes of the Rankine cycle because this already reacted with the materials and there is no new oxygen coming in unless there is a leakage.

Environmental impact
All 3 power plants use bio-energy as an addition to solar energy, so they all emit gasses and use bio-fuel, biomass, or bio-gas. The transport of the bio-products and the obtaining of it will also impact the environment and need to be taken into account. In concept 2 and 3 it is always necessary to use bio-fuels, but for concept 1 this is not the case. In this concept the use of bio-energy can be stopped or reduced when there are periods with more solar energy making this concept the best environmental choice. The efficiency the burner in concept 3 is high, because the water enters the burner at high temperature, this way also less bio-energy is needed.

Stakeholder considerations
Concept 2 is the easiest concept and thus the cheapest with concept 1 not far behind. So this concept will be more attractive to the government and investment companies in the first place. Concept 3 is more complex and will certainly cost more money. Concept 1 does not always have to use bio-energy or uses less bio-energy than concept 2 and 3, beating concept 2 in the price region over longer periods of time. Less use of bio-energy also pleases environmental activists and local citizens by minimizing emissions and transport. Making concept 1 the best choice taking stakeholders into account.

Final concept choice
For concept 1 the salt will have a temperature that is too low after the district heating. The salt will not be able to heat up the water to 520 °C. It is also not very efficient to have 2 different temperatures of salt meet each other 2 times in the cycle, this will lead to exergy loss even before the energy can be transferred to the Rankine cycle.

For concept 2 the combustion chamber for the biomass is placed in the Rankine cycle in front of the heat exchanger for the Lanzhou heating district. This will not be very efficient, because the water for the district only needs to heat up to 120 degrees Celsius while the burner with biomass heats the water of the Rankine cycle up far above that temperature.

Concept 3 has the highest thermal efficiency based on our assumptions, although this efficiency is not feasible, it can be compared to the other concepts. This concept can also easily adjust to the changing demand for district heat in winter and summer. It loses a bit on the environmental impact and stakeholder aspect, but advantages of the thermodynamic properties of this cycle outweigh the other parts.

So the final concept choice is concept 3 and this concept will be used to further improve for the detailed design.

3.3 Detailed Design

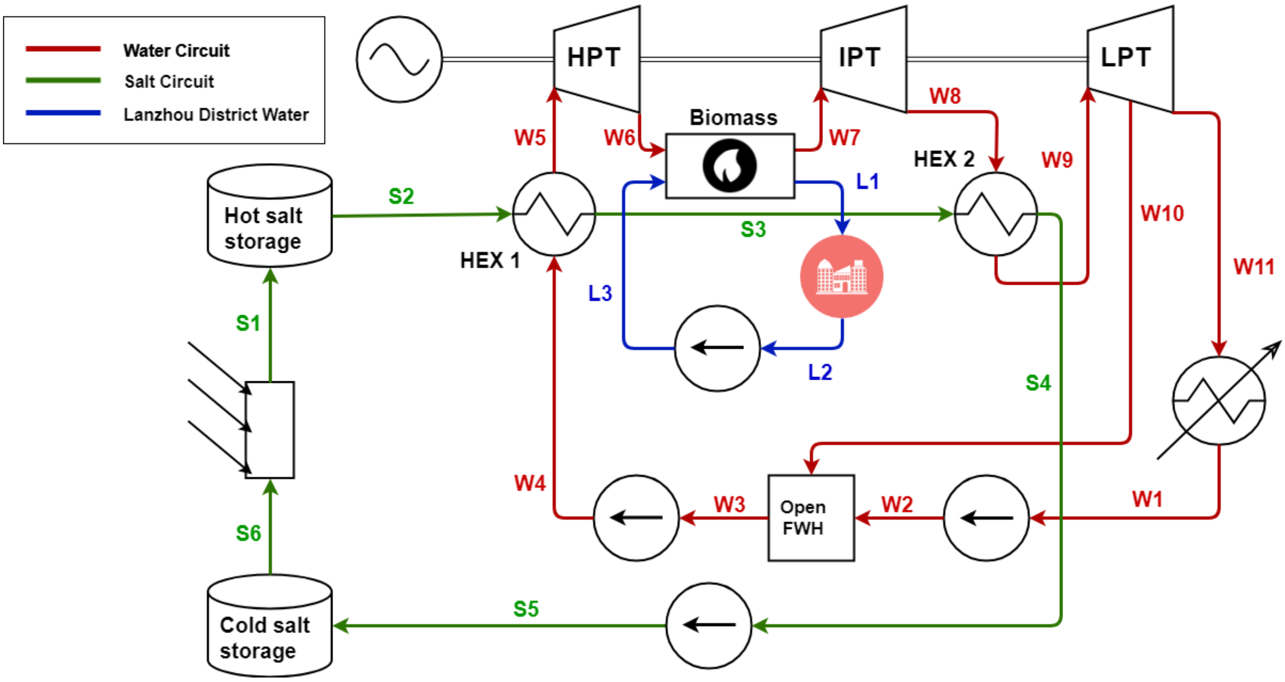

Figure 3.4: Detailed Design

Figure 3.4: A few improvements have been made to concept 3 for the detailed design. The water of the Lanzhou heating district is now directly heated by the biomass. The water does not need to be heated as much as the water from the Rankine cycle and the heat exchanger for the district water will, therefore, be placed at a higher spot in the industrial chimney. The air temperature will be a lot lower there and will only heat the district water to the desired temperature. When more heat is needed for the district in the winter, the water with double the mass flow can pass through a bigger heat exchanger at a lower point in the chimney where the water will be heated up to the same temperature as before.
An open feedwater heater is also added to the Rankine cycle. Hot steam is extracted from the low pressure turbine to heat the water from the condenser up a bit before it passes through the first heat exchanger. The water will therefore be heated at higher temperatures, thus increasing the thermal efficiency of the process.
This design is able to replace the outdated coal plant in Lanzhou and deliver the energy necessary for the Lanzhou heating district, using only renewable energy sources.

Important efficiency's

- Thermal efficiency: 42.1%
- Carnot efficiency: 67.7%
- Electrical efficiency: 41.7%
- Second law efficiency: 62.2%
- Utilization factor (summer): 48.5%
- Utilization factor (winter): 53.6%

3.3.1 Biomass

The biomass that is going to be used to get the desired energy, is waste wheat straw from the province of Gansu. The wheat straw is used dry and ash free for proper operation and to prevent the chemical composition of ash to give rise to problems in the burners, but no further processing is needed. 9.84 kg/s of waste wheat straw is required during summer and 13.30 kg/s during winter to provide the Lanzhou heating district with extra energy.

See Appendix A for the Ts- and hs-diagram of the detailed design and for more information about the biomass selection and efficiency calculations.

3.3.2 Conclusions about the detailed design

Some parts of the cycle will have to endure tough conditions when the plant is operating, for example the intermediate pressure turbine, which will have to endure the highest temperature in the cycle (600 °C) and the high pressure turbine and first heat exchanger will have to endure the highest pressure in the cycle (200 bar). This will be important to keep in mind when selecting materials for these components and will be discussed in the next section (4).

Comparing the Sankey (Figures: A.1/A.3) and Grassmann (Figures: A.2/A.4) diagrams, it is necessary to understand what exactly is happening in these diagrams. In the Sankey diagram the exact energy value per flow is given and in the Grassmann diagram the exergy (useful energy) is given for every flow. Comparing both diagrams gives clear knowledge about the lost energy and well used energy in the cycle. As there are some differences between summer and winter energy requirements (heating district), there are also differences between the summer and the winter diagrams. That is why two Sankey and two Grassmann diagrams are needed.

There are several parts in the cycle that are important to point out:

Condenser:
The condenser is the only place in the cycle, where the cycle loses energy to the surroundings. So it is really important to do not lose to much exergy there. Looking at the energy coming out of the condenser, it looks like that in the Sankey diagram there is a lot of energy going out to the surroundings (268.76 MW), but the Grassmann diagram shows that the energy lost there is mostly useless energy. Just 37.77 MW of useful energy goes away to the surroundings during winter and just 19.73 MW during summer.

Solar receiver:
After the solar receiver the outcoming energy is 2337.5 MW, this can be seen in the Sankey diagram.That seems to be a lot of energy, but the Grassmann diagram shows that just 753.68 MW (in winter) is useful energy, while in the summer it is 689,46 MW. So around one third of the outcoming energy is completely useful. This relation remains the same in the rest of the salt cycle.

Water cycle:
After HEX 1 the useful energy that is coming out is around 50% of all energy. When the cycle has passed all the turbines this value is much lower. After the low pressure turbine this is just around 15%. So a lot of useful energy is used by the turbines and that is exactly the intention. It should be noticed that the low pressure turbine produces about 50% of the total energy going to the generator.

Comparing the winter and summer diagrams, there is just one important difference. At the condenser, in the summer less useful energy (exergy) is lost to the surroundings than in the winter.

See Appendix A for more information about Sankey and Grassman diagrams for winter and summer.

3.3.3 Recommendations

Adding another heat exchanger:
The salt still has a temperature of 447 degrees Celsius when it has passed the two heat exchangers and it can be cooled down without solidifying to approximately 300 degrees Celsius. It would thus be possible to add another heat exchanger at the end of the salt circuit to heat the water up a bit before it enters the first existing heat exchanger. This way the efficiency of the existing heat exchanger will increase, because the water will be heated there at a higher average temperature. This will cause the salt to lose less energy to the water therefore making it possible to increase the temperature of the water even more before letting it enter the high pressure turbine or low pressure turbine. The disadvantage of a lower temperature of the salt at the end of the circuit, is that more solar energy is needed to heat the salt up again to 600 degrees Celsius, but the increase in the thermal efficiency will probably make up for this.

All calculations for the thermodynamic design are performed in Matlab

4 Material Choice

The materials science section aims to find suitable materials for two important components of the designed power plant: turbine and heat exchanger. In order to achieve this, three stages must be worked out.

For the first stage, design requirements have to be translated on the basis of failure modes, working principles and the results of the thermodynamic calculations on temperature, pressure and flow.

For the second stage, performance indices will be derived on basis of their objectives and limiting constraints.

Finally, the material choice for the turbine (housing, axle and rotary blades) and heat exchanger (housing and tubes) will be presented with relevant justifications. The program CES edupack will be used to sort out the most desirable materials on basis of the performance indices.

4.1 Failure modes and production process

Listed below are a number of failure modes, with a description, that could be present in the components of the heat exchanger and turbine.

Subsequently, each component will be looked at in detail. The failure modes relevant to that component will be listed and ranked in order of importance, and the production process needed will also be discussed.

Residual Stress
Residual stresses are caused in materials by the way they are produced. With the manufacturing processes casting and welding uneven cooling can lead to residual stresses, because some parts are solidified and not deformable and other parts are still hot and deformable. After the hot parts are solidified, they shrink, which causes stresses on the already solidified parts which are not able to deform anymore. Residual stresses can lead to unexpected plastic deformation, cracking and fracture. This plastic deformation is unexpected because the external applied stress is smaller than the yield stress.

Stress Concentration
In a material with a hole or crack the local stress can vary a lot. The local stress near a hole or crack is larger than the external applied stress on the material. This local stress can be higher than the yield stress from the material and can lead to plastic deformation. This plastic deformation causes the crack or hole to grow. In the end this will lead to fracture when the crack caused by the stress concentration reaches its maximum crack size.

Brittle Fracture
higher temperature → lower impact energy → Smaller deformation rate → higher opportunity for plastic deformation.

Fatigue
Fatigue occurs under constantly changing load on an object. After a time, depending on the material, it becomes weaker and it will fail. This failure is caused by local structural damage caused by the growth of cracks. If the load reaches a certain level, depending on the material, initial crack growth will occur. After a while the crack growth becomes stable, the second part, and in the third part the crack growth is accelerating and the crack is reaching its maximum crack size before fracture. The chance that fatigue occurs can be minimised by avoiding sharp corners and square corners. Fillets and round holes should be used instead.

Creep
The definition of creep is 'plastic deformation (and fracture) of a structure or material when subjected to a prolonged constant load. This will lead to cracks in the structure of the material and eventually to fracture. The lifespan of a material depends on the environment in which the material is placed. Creep only occurs if the operating temperature is higher than 0.4 times the melting temperature of the material. If that is the case, the higher the operating temperature, the smaller lifetime.

Corrosion
Corrosion is a natural process where a metal react with a liquid and oxygen. This process causes gradual destruction of a material. A way to save a material from corrosion, is to paint it. When a material is painted it can't react anymore with the oxygen in the environment and so it can't corrode.

4.1.1 High pressure turbine

The high pressure turbine does mechanical work on a rotating output shaft by extracting thermal energy from pressurized steam. The high pressure turbine should be able to withstand high pressures and temperatures.

Rotary Blades:

The function of the turbine blades is to take as much energy as possible from the high pressure gases and turn that into kinetic energy by rotating the blades and shaft. Fatigue failure is the main factor that affects the life of the turbine blade, due to stresses caused by the vibrations and resonance caused from the turbulence. Turbine blades operate in conditions of very high temperatures and pressures, which can weaken and limit the performance of the blades. Due to the high speed of rotation of the blades, we must also take into account the centrifugal forces that will be working, to reduce effects of creep of fracture.

Failure modes to take into account (ranked in importance):

1. Fatigue: the rotary blades are subjected to fluctuating stresses due to turbulence that occurs behind the blade. Fatigue occurs very suddenly without any warning, is the most common type of failure, and has catastrophic results. To ensure a long lifespan, the material needs a good fatigue strength.

2. Stress concentration: any small cracks that are created, (in the rotary blades this occurs particularly from the small liquid droplets that drop onto the blades) creates a concentration of stress locally around the crack that is higher than the stress being applied. If the stress concentration at a point exceeds the yield strength of the material, then the material will plastically deform, so we must consider stress concentration as a failure mode.

3. Brittle Fracture: we don't want the fracture of the blades to be brittle. We want to have some warning before that comes from seeing the plastic deformation, so that we can fix or replace the blades, rather than having parts flying all the way down the turbine and causing more damage than solely the one broken part.

4. Erosion: Erosion occurs, because the blades are subjected to high pressure vapour, the tiny droplets of water inside the vapour can erode the rotary blades.

5. Creep: time-dependent and permanent deformation of materials when subjected to a constant load or stress. This is mostly caused by the constant load of the axle on the root of the blades. Creep only happens for temperatures higher than 0.4*Tm (melting temperature). Since the temperature/pressure change vastly, this failure mode is also important.

6. Residual stresses: can be caused during manufacturing process.

7. Corrosion: Corrosion does not occur after all the oxygen in the water has reacted. If the water is not refreshed and if no leaks occur, the material gets in contact with the oxygen of the water only once.

Production Process:
Made by forging, because forged parts have good strength and toughness, and are very reliable for highly stressed and critical applications.

Axle:

The axle of the turbine is the centrifugal part to which the rotating blades are attached. The axle should be as strong and stiff as possible. Furthermore the axle must be able to withstand high pressure and temperature.

Failure modes to take into account (ranked in importance):

1. Creep: time-dependent and permanent deformation of materials when subjected to a constant load or stress in this case the centrifugal load on the axle, because there are 3 turbines connected to the same axle. This could cause a centrifugal load large enough to cause creep and eventually fracture. Creep only happens only for temperatures higher than 0.4*Tm (melting temperature). Since the temperature/pressure change vastly, this failure mode is also important.

2. Fatigue: the axle is subjected to fluctuating stresses. These stresses occur because of turbulence on the blades. The blades will cause fluctuating stresses on axle in the part where the blade is attached to the axle. If that part of the axle fails it has catastrophic results. To ensure a long lifespan of the axle, the material needs a good fatigue strength.

3. Corrosion and erosion: Erosion occurs, because the axle is subjected to a high pressure vapour, the tiny droplets of water inside the vapour can erode the axle. Corrosion does not occur after all the oxygen in the water has reacted. If the water is not refreshed and if no leaks occur, the material gets in contact with the oxygen of the water only once.

4. Residual stresses: can be caused during manufacturing process.

Production Process:
Made by forging, because forged parts have good strength and toughness, and are very reliable for highly stressed and critical applications (Might be round forming). Another process could be (hot) extrusion, because extruded parts can withstand large deformations without fracture, typically have a constant cross-section, and have low tooling costs.

Housing:

Non-centrifugal part which is used as protection of the inner part of the turbine (axle and blades), and making sure that the process is not interrupted by effects from outside (i.e outside temperature). Due to its functions as a protector, strength is of great importance for the housing.

Failure modes to take into account (ranked in importance):

1. Creep: time-dependent and permanent deformation of materials when subjected to a constant load or stress in this case the centrifugal load on the axle, because there are 3 turbines connected to the same axle. This could cause a centrifugal load large enough to cause creep and eventually fracture. Creep only happens only for temperatures higher than 0.4*Tm (melting temperature). Since the temperature/pressure change vastly, this failure mode is also important.

2. Corrosion and erosion (mainly from inside): Erosion occurs, because the housing is subjected to a high pressure vapour, the tiny droplets of water inside the vapour can erode the housing. Corrosion does not occur after all the oxygen in the water has reacted. If the water is not refreshed and if no leaks occur, the material gets in contact with the oxygen of the water only once.

3. Residual stresses: can be caused during manufacturing process.

Production Process:
The housing is being made by sand casting. Almost any metal can be cast; no limit to part size, shape or weight; low tooling cost; uses risers. Limitations are that some finishing is required, relatively low surface finish and has wide tolerances.

4.1.2 Heat Exchanger

Shell and tube heat exchangers are typically used for high-pressure applications (with pressures greater than 30 bar and temperatures greater than 260 °C).

Pipes:

The pipes are the main part of the heat exchanger. Capillary tubes that allow heat transfer between them, through radiation without the interaction of the fluid streams.

Failure modes to take into account (ranked in importance):

1. Creep: The pipes could fail due to creep, as there is a constant pressure and load on each section of the pipes over a prolonged duration of time. To make sure creep does not occur, we need to find a material which has a melting temperature which is less than 0,4*working temperature.
2. Corrosion and Erosion: Erosion from the streams flowing through at velocity. Corrosion does not occur after all the oxygen in the water has reacted. If the water is not refreshed and if no leaks occur, the material gets in contact with the oxygen of the water only once.
3. Residual stresses: can be caused during manufacturing process.

Production Process:
The tubes are drawn with a tube piercer, to create a uniform hollow shape. High pressure hydraulic expansion is then used to expand the heat exchanger tubes using direct hydraulic pressure to form the tube to tubesheet joint.

Housing:

The purpose of the housing is to protect and enclose the internal components of the heat exchanger and offer some insulation.

Failure modes to take into account (ranked in importance):

1. Corrosion and erosion (mainly from inside): the housing will experience flowing streams moving at a velocity which will cause some erosion. Even though there will be minimal corrosion inside the housing, the exterior will be exposed to oxygen, so unless we have a coating/protector, corrosion could also be a possible failure mode.
2. Residual Stresses: can be caused during manufacturing process.

Production Process:
The housing is being made by sand casting. Almost any metal can be cast; no limit to part size, shape or weight; low tooling cost; uses risers. Limitations are that some finishing is required, relatively low surface finish and has wide tolerances. Luckily, for the housing these limitations are not effective on the objective.

4.2 Performance indices

The performance index will play a key role in the selection of the materials, in particular in the ranking of suitable materials.

The objective(s) and limiting constraints will be shown, followed by a derivation of the appropriate performance index. All variables used will be displayed, as well as their status (free or fixed), any assumptions that were made, and finally a step by step insight into how the indexes were derived.

4.2.1 Housing (Turbine)

- Objective: resistance to leaking
- Limiting constraint: leak before fracture

Fixed	Free
p	σ_y
L	K_{Ic}
r	t
C	material choice

Where
p is the pressure in [MPa]
σ_y is the yield strength in [MPa]
L is the length in [m]
K_{Ic} is the fracture toughness in [MPa $m^{\frac{1}{2}}$]
r is the radius in [m]
t is the wall thickness in [m]
C is a constant

the wall thickness, t , is chosen so that, at the working pressure p , the stress is less than the yield strength, σy, of the wall.

$$\sigma = \frac{pr}{2t} \leq \sigma_y \rightarrow t = \frac{pr}{2\sigma_y} \tag{4.1}$$

The stress required to make a crack propagate is

$$\sigma_f = \frac{CK_{Ic}}{\sqrt{\pi a_c}} \tag{4.2}$$

safety can be assured by arranging that a crack just large enough to penetrate both the inner and the outer surface of the vessel is still stable, because the leak caused by the crack can be detected. This is achieved by setting ac in equation 4.2 equal to t/2:

$$\sigma_f = \frac{CK_{Ic}}{\sqrt{\pi \frac{t}{2}}} \tag{4.3}$$

put equation 4.1 in equation 4.3 and separate the free and fixed variables

$$p = \frac{4C^2}{\pi r} \times \frac{K_{Ic}^2}{\sigma_y} \tag{4.4}$$

The maximum pressure is carried most safely by materials with the large values of:

$$M = \frac{K_{Ic}^2}{\sigma_y} \tag{4.5}$$

4.2.2 Rotary blades (1)

- Objective: resistance to centrifugal loading
- Limiting constraint: operating temperature

Fixed	Free
r	σ_e
L	ρ
A	material choice

Where
r is the distance between all the blades in [m]
σ_e is the fatigue strength at 10^7 cycles in [MPa]
L is the total length in [m]
ρ is the density in [kg/m^3]
A is the cross-sectional area of the blade in [m^2]

The centripetal force at a given distance r with a mass m and a centripetal velocity ω can be described with:

$$F_{cpt} = mr\omega^2 \tag{4.6}$$

Equations for density, volume and stress are shown below:

$$\rho = \frac{m}{V} \tag{4.7}$$

$$V = AL \tag{4.8}$$

$$\sigma = \frac{F}{A} \tag{4.9}$$

To calculate the total force on the blade, the mass per dr has to be calculated, with dr being the distance between two blades.
Mass can be obtained by equation 4.7 and 4.8:

$$m = drAp \tag{4.10}$$

Since A does not change, equation 4.10 can be substituted in 4.6.
Finding the integral gives the total exerted force on a turbine blade:

$$F_{cpt} = \int_{r_{axle}}^{r_{axle}+L} (A\rho r\omega^2)dr = \frac{1}{2}(L^2 + 2Lr_{axle})A\rho\omega^2 \tag{4.11}$$

Now the stress has to be calculated using equation 4.8:

$$\sigma_{cpt} = \frac{F_{cpt}}{A} = (\frac{1}{2}L^2 + Lr_{axle})\rho\omega^2 \tag{4.12}$$

Rewriting with $\sigma_{cpt} = \sigma_e$ and separating the fixed and free variables gives the centripetal velocity:

$$\omega = \sqrt{\frac{\sigma_e}{\rho}} \tag{4.13}$$

By maximizing the centripetal velocity, the performance index can be obtained and simplified:

$$M = \frac{\sigma_e}{\rho} \tag{4.14}$$

4.2.3 Rotary blades (2)

- Objective: maximize fracture toughness
- Limiting constraint: operating temperature

Fixed	Free
w	K_{Ic}
L	ρ
	material choice

Where
w is the uniformly distributed load in [N/m]
K_{Ic} is the fracture toughness in [MPa]
L is the length in [m]
ρ is the density in [kg/m^3]

If we assume that the blade follows the equation of a centre cracked plate with a very large width:

$$K_{Ic} = \sigma(\pi c)^{\frac{1}{2}} \tag{4.15}$$

Where
σ is the applied stress
c is a very small crack

$$K_{Ic} = \frac{wL}{A}(\pi c)^{\frac{1}{2}} \tag{4.16}$$

$$A = \frac{wL}{K_{Ic}}(\pi c)^{\frac{1}{2}} \tag{4.17}$$

An equation for mass is:

$$m = AL\rho \tag{4.18}$$

Put equation 4.17 in 4.18

$$m = \frac{wL}{K_{Ic}}(\pi c)^{\frac{1}{2}}L\rho \tag{4.19}$$

To optimize the performance index, separate the fixed and free variables:

$$m = wL^2(\pi c)^{\frac{1}{2}}(\frac{\rho}{K_{Ic}}) \tag{4.20}$$

To minimize the mass, and with it maximize the fracture toughness, the following performance index can be determined:

$$M = \frac{K_{Ic}}{\rho} \tag{4.21}$$

4.2.4 Axle

- Objective: minimize mass
- Limiting constraint: strength

Fixed	Free
M	ρ
L	τ
	material choice

Where
M is the bending moment of the axle in [N m]
L is the length of the axle in [m]
ρ is the density of the axle in [kg/m^3]
τ is the shear stress of the axle in [MPa]

For this performance index, two equations are needed:

$$\tau = \frac{Mr}{I_p} \tag{4.22}$$

$$I_p = \frac{\pi r^4}{2} \tag{4.23}$$

Filling in equation 4.23 in 4.22 will give the following formula:

$$\tau = \frac{2M}{\pi r^3} \rightarrow r = (\frac{2M}{\pi \tau})^{\frac{1}{3}} \tag{4.24}$$

An equation for mass is

$$m = \rho V = \rho \pi r^2 L \tag{4.25}$$

Put equation 4.24 in 4.25

$$m = \rho \pi (\frac{2M}{\pi \tau})^{\frac{2}{3}} L \tag{4.26}$$

By separating the free and fixed variables, the following performance index can be determined:

$$M = \frac{\rho}{\tau^{\frac{2}{3}}} \tag{4.27}$$

4.2.5 Pipes (1)

- Objective: maximise the allowed pressure
- Limiting constraint: leak before fracture

Fixed	Free
r	σ_y
C	K_{Ic}
	t
	material choice

Where
p is the pressure in [MPa]
σ_y is the yield strength in [MPa]
K_{Ic} is the fracture toughness in [MPa $m^{\frac{1}{2}}$]
r is the radius in [m]
t is the wall thickness in [m]
C is a constant
a_c is the critical crack size

the wall thickness, t , is chosen so that, at the working pressure p , the stress is less than the yield strength, σy, of the wall.

$$\sigma = \frac{pr}{2t} \leq \sigma_y \rightarrow t = \frac{pr}{2\sigma_y} \tag{4.28}$$

The stress required to make a crack propagate is

$$\sigma_f = \frac{CK_{Ic}}{\sqrt{\pi a_c}} \tag{4.29}$$

safety can be assured by arranging that a crack just large enough to penetrate both the inner and the outer surface of the vessel is still stable, because the leak caused by the crack can be detected. This is achieved by setting a_c in equation 4.29 equal to t/2:

$$\sigma_f = \frac{CK_{Ic}}{\sqrt{\pi \frac{t}{2}}} \tag{4.30}$$

put equation 4.28 in equation 4.30 and separate the free and fixed variables

$$p = \frac{4C^2}{\pi r} \times \frac{K_{Ic}^2}{\sigma_y} \tag{4.31}$$

The maximum pressure is carried most safely by materials with the large values of:

$$M = \frac{K_{Ic}^2}{\sigma_y} \tag{4.32}$$

4.2.6 Pipes (2)

- Objective: maximize heat transfer
- Limiting constraint: minimise thickness

Fixed	Free
D	t
p	λ
c	material choice
ΔT	
A	

Where
J is the heat flux of the tube in [W/m^2]
D is the diameter of the tube in [m]
Q is the heat transfer in the tube in [W]
c is a constant
A is the surface of the tube in [m^2]
ΔT is the temperature difference in [°C]

To maximize the heat transfer (W), the following equations are needed:

$$J = -\lambda \frac{\Delta T}{\Delta x} \tag{4.33}$$

$$Q = AJ \rightarrow Q = -\lambda A \frac{\Delta T}{\Delta x} \tag{4.34}$$

$$\sigma = \frac{pD}{ct} \leq \sigma_y \rightarrow t = \frac{pD}{c\sigma_y} \tag{4.35}$$

Put equation 4.35 in 4.34 with t as Δ x

$$Q = -\lambda A \frac{\Delta T}{\frac{pD}{c\sigma_y}} \rightarrow Q = \frac{-\lambda \Delta T A c \sigma_y}{pD} \tag{4.36}$$

When separating free and fixed variables in equation 4.36, the performance index can be derived:

$$M = \lambda \sigma_y \tag{4.37}$$

4.2.7 Pipes (3)

- Objective: minimise cost
- Limiting constraint: minimise mass

Fixed	Free
D	ρ
t	C
L	material choice

Where
EURO or € is the cost in [€]
m is the mass in [kg]
C is cost per kg in [€/kg]
ρ is the density in [kg/m^3]
D is the diameter in [m]
t is the wall thickness in [m]
L is the length in [m]

A simple performance index to minimise cost (€) and minimise mass (kg), the following equations are needed:

$$EURO = Cm \tag{4.38}$$

The formula for the mass of the tube:

$$m = \pi D t L \rho \tag{4.39}$$

The combined formula:

$$EURO = \pi D t L \rho C \tag{4.40}$$

When separating free and fixed variables in equation 4.33, the performance index can be derived:

$$M = \rho C \tag{4.41}$$

4.2.8 Housing (Heat exchanger)

- Objective: resistance to leaking
- Limiting constraint: leak before fracture

Fixed	Free
p	σ_y
L	K_{Ic}
r	t
C	material choice

Where
p is the pressure in [MPa]
σ_y is the yield strength in [MPa]
L is the length in [m]
K_{Ic} is the fracture toughness in [MPa $m^{\frac{1}{2}}$]
r is the radius in [m]
t is the wall thickness in [m]
C is a constant

the wall thickness, t , is chosen so that, at the working pressure p , the stress is less than the yield strength, σy, of the wall.

$$\sigma = \frac{pr}{2t} \leq \sigma_y \rightarrow t = \frac{pr}{2\sigma_y} \tag{4.42}$$

The stress required to make a crack propagate is

$$\sigma_f = \frac{CK_{Ic}}{\sqrt{\pi a_c}} \tag{4.43}$$

safety can be assured by arranging that a crack just large enough to penetrate both the inner and the outer surface of the vessel is still stable, because the leak caused by the crack can be detected. This is achieved by setting ac in equation 4.43 equal to t/2:

$$\sigma_f = \frac{CK_{Ic}}{\sqrt{\pi \frac{t}{2}}} \tag{4.44}$$

put equation 4.42 in equation 4.44 and separate the free and fixed variables

$$p = \frac{4C^2}{\pi r} \times \frac{K_{Ic}^2}{\sigma_y} \tag{4.45}$$

The maximum pressure is carried most safely by materials with the large values of:

$$M = \frac{K_{Ic}^2}{\sigma_y} \tag{4.46}$$

4.3 Material Selection

CES Edupack was used to make the final selection for our materials. The performance indices that were previously derived to determine what properties would go on either axis of our material selection graphs were used. Also included are price, density, limits of the minimum and maximum service temperature, minimum melting temperature (to avoid creep) and the manufacturing process.

The intermediate turbine operates between temperatures ranging from 328 to 600 degrees Celsius, and the melting temperature must be above 1500 degrees Celsius. For the heat exchanger the temperatures range between 146 and 600 degrees Celsius, so the melting temperature must also be above 1500 degrees Celsius to prevent creep from occurring.

Using the material selection graphs, the top five materials will be selected, and from these materials the most appropriate material will be determined by taking into account the most common failure modes for that part, as well as the CO2 footprint of the materials primary processing and other research on the materials and how suitable it is for use in the component.

4.3.1 Housing (Turbine)

For the housing of the turbine the chosen material to use is Carbon steel, SA216, (Type WWC), cast, normalized tempered. Of the five materials that were highest ranking on the material selection graph for the high pressure turbine housing, three had to be disregarded, as annealing or quenching the casing of the turbine is not very realistic for such a large component.

From the two materials that remained, nothing distinguished them from each other in terms of CO2 footprint, price, thermal conductivity or corrosion resistance. Therefore, having the highest index (from a higher fracture toughness and lower yield strength), the decision had been made to use Carbon steel, SA216, (Type WWC), cast, normalized tempered.

See Appendix B.1, B.2, and B.3 for an overview of the charts made in CES.

4.3.2 Rotary blades

From the top 5 materials, Nickel-Mo-Cr alloy, HASTELLOY C-276 is a perfect choice for the blades. It contains a high fracture toughness, the fatigue strength is high enough to guarantee a lot of cycles. Furthermore, the material has an excellent corrosion resistance and is also able to prevent creep. The only small negative points for this material are the amount of greenhouse gases that will come free and the price, but these points will not have an extremely negative impact on the choice of material.

See Appendix B.4, B.5, B.6, and B.7 for an overview of the charts made in CES.

Note: the service temperature in the Intermediate Pressure turbine results in a melting point that will not meet the requirements for creep resistance for the material that was chosen. This could result in the blades not being creep resistant. To still make sure that the blades can be made creep resistant, we can make little holes on the blades so air can go through and lower the temperature, so creep resistance can still be possible.

4.3.3 Axle

For the axle of the turbine the chosen material to use is Stainless steel, martensitic, AISI 410, hard temper. This material was the highest ranked from the materials selection graph which displayed density against yield strength, with a slope of 2/3.

Stainless steel, martensitic, AISI 410, hard temper has excellent properties for yield strength, density and price. It is also corrosion resistant, has a good fracture toughness and the CO2 footprint for primary processing is not too high.

See Appendix B.8, B.9, and B.10 for an overview of the charts made in CES.

4.3.4 Pipes

It has been chosen to use stainless steel, martensitic, AISI 410, hard tempered for the pipes of the heat exchanger. This ranks highest on the materials selection graph of thermal conductivity against yield strength and also performs well in fracture toughness, is suitable for the temperatures that will be used in the heat exchanger, and also has a reasonable price, density and CO_2 footprint for the primary processing.

See Appendix B.11, B.12, B.13, and B.14 for an overview of the charts made in CES.

4.3.5 Housing (Heat exchanger)

Stainless steel, austenitic, AISI 308L, annealed is the material that has been selected for the housing of the heat exchanger. Although, ranked higher by index was Nickel-Fe-Cr alloy, INCOLOY 800, annealed, we believe that being four times higher in price and having double the CO_2 footprint does not justify the decrease in fracture toughness and increase in yield strength.

The austenitic steel that has been chosen has good values for fracture toughness and yield strength, is acceptable for forging and has excellent salt water resistance (just to cover the possibility that water leaks from the tubes), as well as not being too expensive.

See Appendix B.15, and B.16 for an overview of the charts made in CES.

For a total overview of the Material Selection, see Appendix B.17 and B.18.

5 Life Cycle Analysis

5.1 Goal Definition

5.1.1 Application

This LCA is meant to discuss the analysis of an already existing coal power plant situated in Lanzhou and of a potential replacement of this power plant that uses renewable energy sources. Coal is used everywhere in the world when it comes to energy generation, and thus it is of great importance to know the general impacts this form of power has. The goal of the LCA is to analyse and quantify these impacts and to compare these impacts from the two different power plants.

Electricity generation from coal accounts for a multitude of greenhouse gases. The emitted CO2, but also the sulphur- and nitrous- dioxides and the waste, have certain effects on the environment. Knowing, understanding these effects and the quantity of emissions behind them can help identify ways to minimize them for a different power plant with the same capacity. Comparing these effects to a perhaps more sustainable power plant can also help understand the problem and help find possible improvements for both of the power plants.

The electricity and the heat generated by the power plant will be used by the citizens of Lanzhou. They are the most important stakeholder when it comes to the energy provision of Lanzhou. They, and the other stakeholders, can use this study to find a suitable form of energy provision for the city of Lanzhou.

5.1.2 Depth of Study

To be able to give a meaningful statement about the life cycles of the power plants processes that have a larger contribution to the environment will be included, positive or negative, in relation to each part of the process. Extraction and transportation of the fuel and the emissions, the operation and maintenance of the power plants including waste disposal and material recycling, and the commissioning and decommissioning of the power plants will be considered. All of these will be inventoried in a cradle-to-grave model.

To be able to do this analysis some estimated guesses were done as for example to what materials and manufacturing processes are used during the building of the power plants. It will however, exclude the transport of the parts to the power plants when they are commissioned, since it is not known where they come from. The contribution of the transport is furthermore assumed to be equal for both power plants.

For the solar power plant the transport of the salt to the power plant will also be excluded since it is a one time provision.

For the Coal Power Plant everything up to the mining of coal will be included. The fuel consumption and emissions of the machines and tools used for the mining process are a part of this. The production of these machines and tools will be excluded, as this will make the analysis too complicated and extend the field of study to extremes that are relatively unnecessary to our goal definition.

Now, it is necessary to use some categories to translate emissions into environmental impacts. The impact categories to be used are the 18 midpoint effects following the ReCiPe 1.08 method in GaBi. However, only 16 effects can be analysed, as the exact size of the power plants is indeterminate and therefore two midpoint effects have no answer.

Since the power plant will be located in Lanzhou, it will be functioning in a desert area. The power plants, both coal and solar, will have a performance that may vary from similar power plants in other climates. The solar power plant will likely have a larger power output due to the greater solar availability in certain regions. Because of the higher average outside temperature, it is easier to isolate certain parts of the cycle that need it, which means less heat loss. However, this also means that it is harder to cool down the liquids in the condenser for example. Due to all of these variable factors, the results of this LCA may vary from those of similar power plants in other climates. The results can still be used for power plants located in similar continental climates.

This LCA is expected to be valid from the moment of publishing until about 2025, since the databases are expected to be outdated by then. The values might also change because of technological advances, but this is not expected to be significant until 2025.

5.1.3 Functional Units

Main Function: To provide electricity and heat
Specification: To provide enough heat and electricity for 3.5 million citizens during winter and Summer
Units: 481.800 MWh electricity per year is needed for Lanzhou. 284.700 MWh of heat in the winter and 142.350 MWh during the summer.

Therefore, the derived functional units are:

1. To provide electricity from renewable energy with a power output of 220 MW and a heat output of 130 MW during winter and 65 MW during summer for 3.5 million citizens each year.
   (a) This might not be accurate due to constant output of the plant, MW is a flow, which is not continuous. The output of the plant is not constant. We would rather have to choose a unit that gives the needed annual output of the plant which displays an average flow. Furthermore, this F.U. is not the best option because it states that the electricity provided must come from a renewable source. However, this is not part of the function for the power plant. We will compare the coal power plant and the solar power plant to see which is better, but in the end both will provide Lanzhou with enough electricity which is ultimately the goal.
2. Provide electricity from a power plant using solar energy with an annual output of 481.800 MWh and a heat output of 284.700 MWh during the winter and 142.350 MWh during the summer for 3.5 million citizens.
   (a) This F.U. may not be entirely correct due to the fact that the 3.5 million people may be quite an arbitrary number. Furthermore, it is not as incremental to specify the heat during the summer, as the heat necessary for the winter is supplied, the heat for summer will also be produced, since it is a smaller number. It also may be wise to add a time-span to this F.U. to help identify the life-cycle.

The final and chosen Functional Unit is:

To produce electricity for the city of Lanzhou with an annual output of 481.800 MWh and a heat output of 284.700 MWh for one year.

This is the best approach to tick all the boxes and fix everything wrong with the previous F.U.s.

5.1.4 Subject of Study

The subject of the study revolves around the generation of energy. The electricity will be provided to the grid of Lanzhou and the energy in form of heat will be pumped to the city. 481.800 MWh electricity per year is needed for Lanzhou. 284.700 MWh of heat in the winter and 142.350 MWh during the summer. These values are calculated per annum to get a better overview.

5.2 Analysis

Next, we proceeded to work with GABI, to help us understand the bigger picture of the inner workings of the coal and solar power plant. To show how both the power plants are modelled in GABI an inventory and some process trees were created.

5.2.1 Inventory

The lifespan of a solar power plant is estimated to be roughly the same as a coal power plant, which is about 40 years. This means that both these power plants can fulfill 40 times the stated functional unit. For the assembly phase of the LCA an inventory for all the parts that were to be produced and transferred was made. An overview of which materials were selected for the different parts and how we modelled them in GABI will be given below.
Solar power plant:

- Condenser: for condenser pipes the most common material used are copper-nickel alloys. For the housing steel is a good option. In GABI copper was used for the pipes, as a good model for the copper-nickel alloys, and for the housing we used steel.
- Heliostats: in reality these are often made with glass and silver, as well as stainless steel for the support. However, since GABI does not contain silver as a raw material, instead a stainless steel slab was used as an alternative. The heliostats are expected to last 20 years each, which means they fulfil 20 times the F.U. and 0.5 times the life span of the power plant.
- Pumps: stainless steel is the main material used for the production of the pumps. This was also available in the GABI software so this was used in the LCA as well.
- Chimney: for the burning of the biofuel it was decided that a chimney was needed in order to let all the emissions out. Therefore it was also modelled in our LCA. Since the main material used to build a chimney is concrete, this is also the way it was modelled in GABI.
- The building: Since the building itself contributes significantly to the assembly of the power plant, with the transport of all the materials to the sight, it was taken into account. The materials selected for the structure are concrete, glass and steel, since those are used for the outer building, the interior and the windows, and make up for most of the power plant.
- Generator: the generator was modelled in GABI using steel, iron and copper.
- Salt storage: the salt storage was modelled as a large tank in GABI using stainless steel. The reason for this being that due to the temperatures, a temperature resistant and strong material was needed.
- Heat exchangers: the first component that was analysed from a material science perspective was the heat exchanger. For the pipes it was analysed that stainless steel was the best option. For the housing stainless steel was also selected. Both of these were therefore also used in GABI as the material for the heat exchangers.
- Turbines: the turbine was the second component that was analysed from a material science perspective. The materials chosen were: for the blades a nickle-MO-cr alloy was chosen. For the axle, stainless steel was selected. For the housing carbon steel was used. Due to a lack of availability of these materials in GABI, it was instead decided upon to instead model the entire turbine out of stainless steel.
- Open feedwater heater: the open FWH was modelled in GABI using copper and a steel sheet.
- Pipes: in GABI we used glass wool and steel to create 1 meter of insulated pipe.

Coal power plant:
Most of the components are the same for the coal power plant and the solar power plant, therefore they wont be discussed again. However, some other parts are used in the coal power plant, they are discussed below.

- Pumps rankine: for these pumps bronze and cast iron was used in GABI.
- Conveyor belt: to model this in GABI we used rubber and also steel for the sides.
- Boiler: for the boiler it was necessary to put some inflammable heat resistant material around the boiler for safety. Therefore bricks and steel were used.
- Coal bunker: the coal bunker is modelled in GABI using concrete.

- Cooling tower: the cooling tower is modelled in GABI using concrete and aluminum.

For the use phase of the solar power plant only the bio-fuel was modelled, because it was assumed that the solar energy does not contribute to the environment enough to be significant, after it being set up. For the coal power plant, only the burning of the coal was modelled and taken into account.

For the disposal phase, both the power plants were first divided back into raw materials. It was assumed that some of the materials were already lost due to wear. For example, the heliostats have a lifespan only half the lifespan of the power plant. Thereafter, most of the metal parts were assumed to be recycled. The rest-products, like concrete and glass, were moved to a landfill. This is because the glass of the heliostats can't be recycled due to the metal that was used in it. The concrete also could not be recycled or burnt, therefore it was also moved to landfill. The transport needed to take all the different components away from the power plants was also taken into account and modelled in GABI.

5.2.2 Process Trees

In order to get a better overview of what is required for each power plant, a process tree was made for each situation.

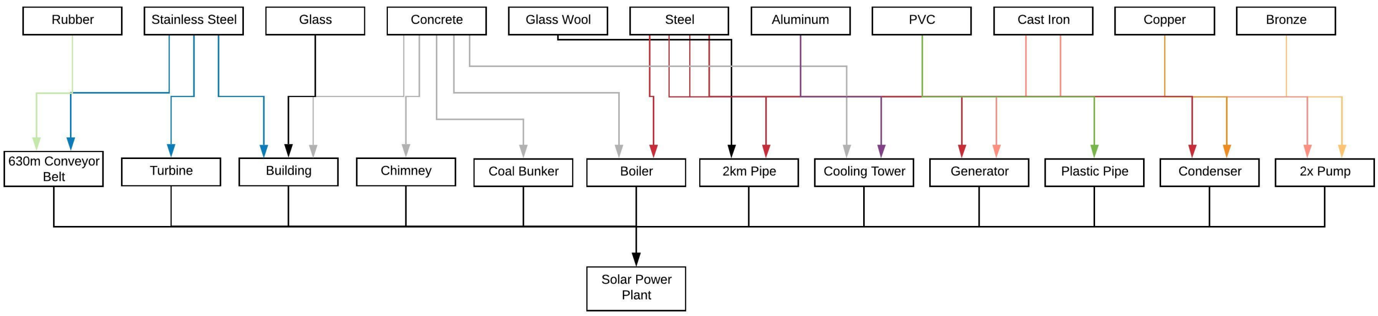

Figure 5.1: Coal Process Tree

As one can tell from the figure above, there are a lot of materials going into the coal power plant. However, due to the colour coding and the easy layout, one can tell which basic materials are required for the creation of a coal power plant.

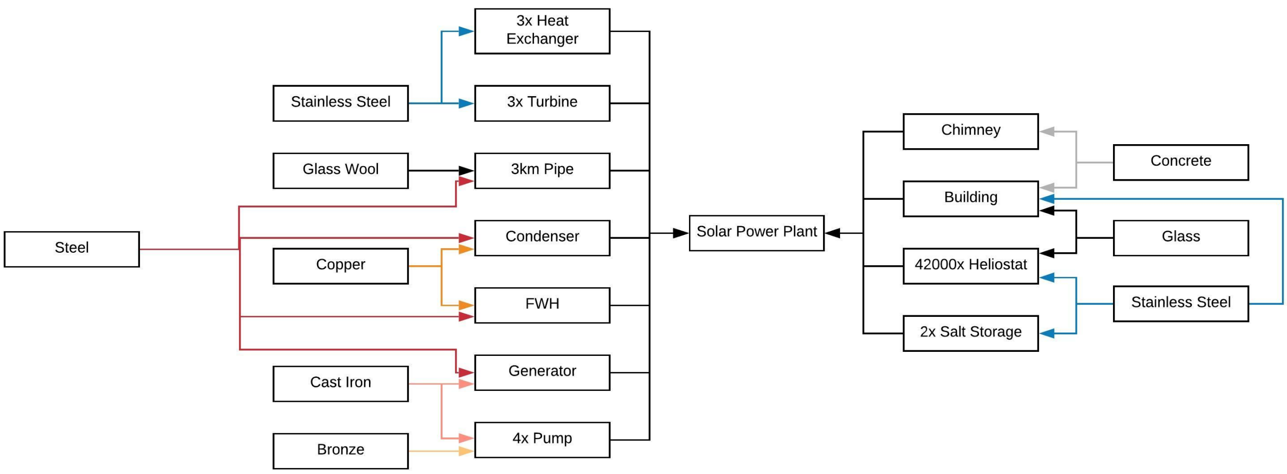

Figure 5.2: Solar Process Tree

This figure on the other hand, shows the materials for a solar power plant. A different structure was decided upon in order to get a different visual aid that may give a different perspective of an organised look over the materials required for the power plant.

5.2.3 Analysing the Graphs

After entering all the data into GaBi, and creating numerous flows and processes, the product was finished. Decided upon were several comparisons were we deemed a comparison was appropriate or even possible. Following are several analyses of the graphs created through GaBi using a the ReCiPe analysis tool for a midpoint targeting different environmental effects. Short descriptions of each term will as well as a complete set of Graphs can also be found in the Appendix C.2.

1. **Climate Change**

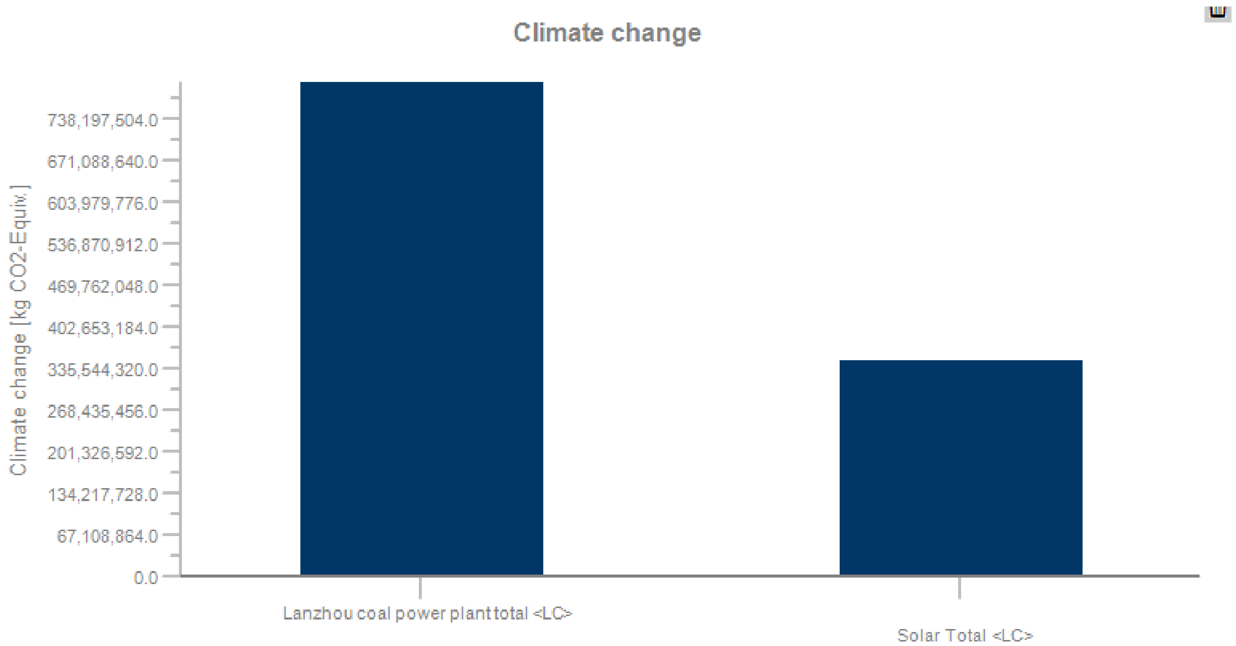

Figure 5.3: Comparison Climate Change

Looking over the graph comparing both power plants, one can tell that the fossil fuel power plant emits more than twice the amount of kg CO2 than the solar plant does. Investigating each plant separately, one finds that both plants emit most their CO2 while the plant is running. The disposal and assembly have lower values. Since the solar plant uses bio-fuel as a supplementary source of energy, it still burns, thus, causing rest products and contributing emissions to the environment. On neither of the power plants does the disposal phase have a big impact, since a lot of the metals are recycled, while the bricks and cement and glass go to a landfill. This does, however, have an impact on the terrestrial ecotoxicity, compared to the other environmental impacts this is not significant. Moreover, because both the power plants use landfills as a way to dispose rest materials and therefore show quite similar impacts, it is not useful to look into this in detail. Looking into the production phase of each plant, as can be seen below, it appears that the structure of both power plants have highest values here. In comparison with each other, the coal structure has five times the value the solar plant does. These values come primarily from the Worldsteel used.

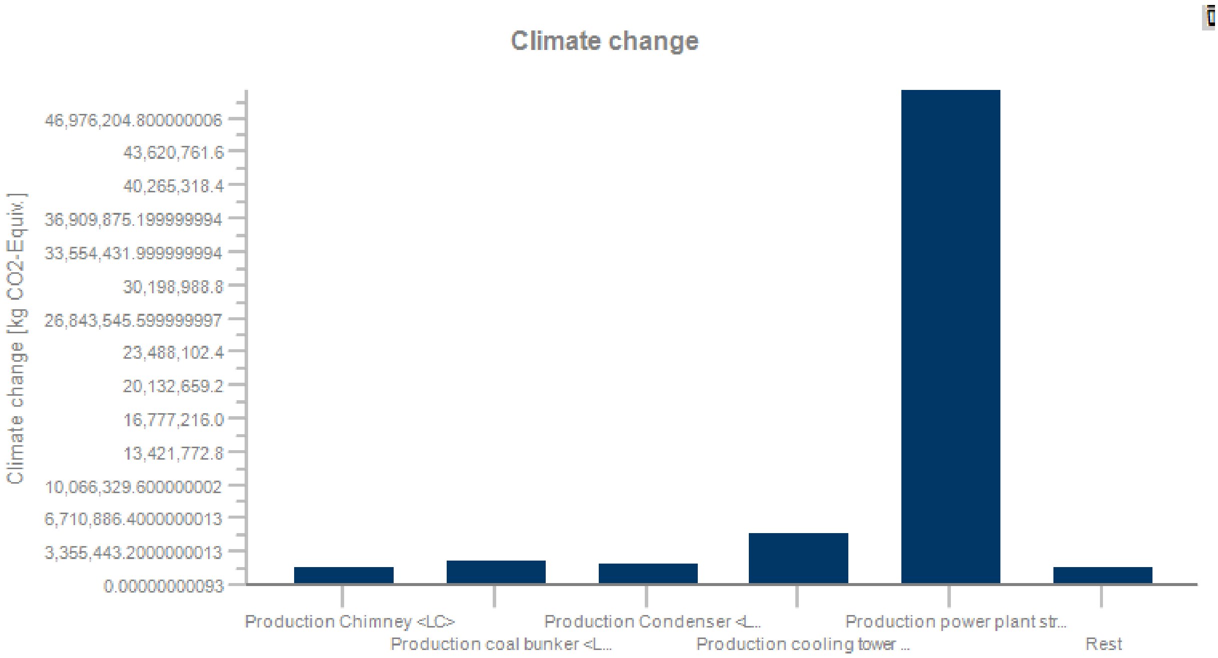

Figure 5.4: Coal Assembly Climate Change

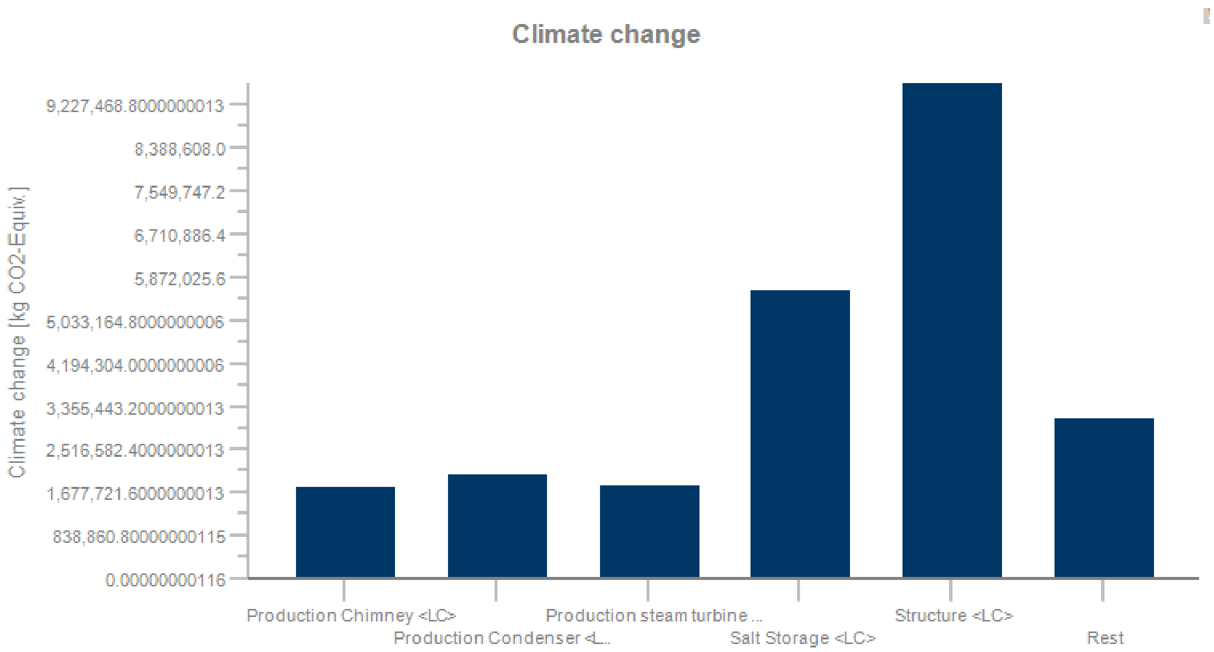

Figure 5.5: Solar Assembly Climate Change

2. **Terrestrial Acidification**

   Right from the start, one sees the solar plant having a higher acidification with values almost three times as much as the coal plant. In the solar plant, however, this comes primarily from the bio-fuel being burned, with only a small amount coming from the assembly, where the main source is the steel from the structure of the building. The coal power plant, while running, produces most CO2 from its coal. However, in the production phase, which accounts for very little CO2 in comparison to the burning of coal, one finds the cooling tower and the structure of the power plant with high values. This is due to the consumption of steel and aluminum in this initial process.

3. **Freshwater Eutrophication**

   This graph is incomparable, as the coal power plant does not produce a comparable amount of kg Phosphorus, half of which comes from the coal, and the other half from the Worldsteel of the plant's structure. In the solar plant, all the eutrophication originates from the burning of bio-fuel.

4. **Ozone Depletion**

   The output of CFC-11 on both plants is very low with the coal power plant even in the negative due to the use of Worldsteel.

5. **Fossil Depletion**

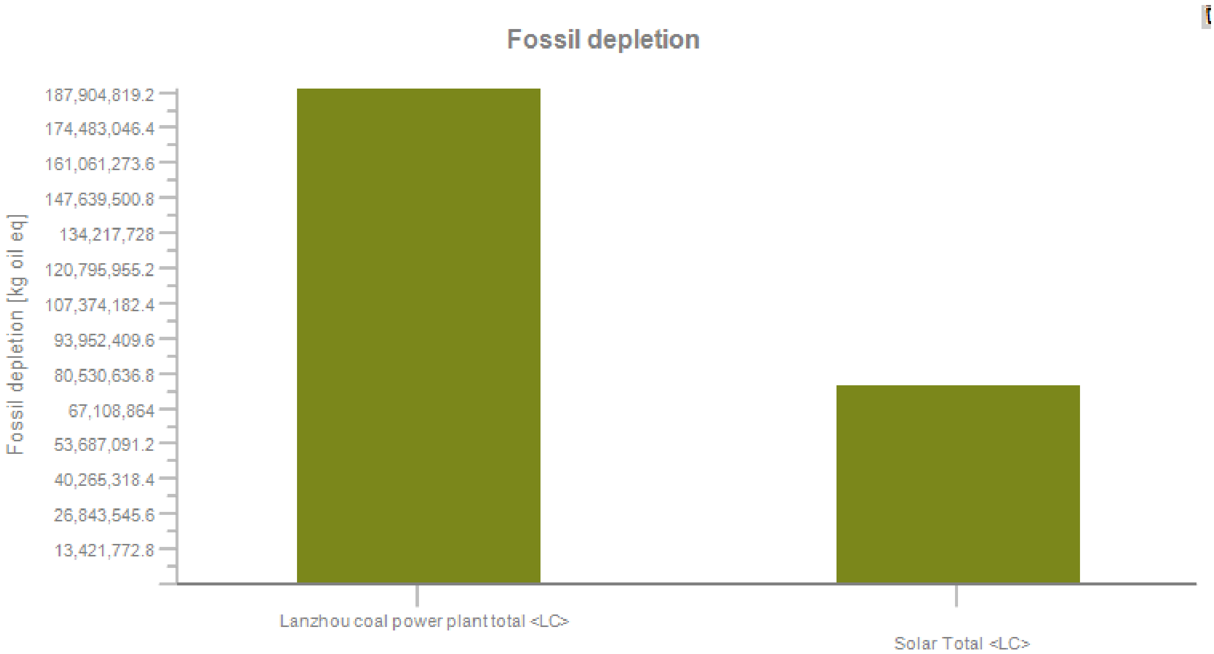

Figure 5.6: Comparison Fossil Depletion

One would expect the coal plant to have much higher values than the solar plant, but this is actually untrue. Even though the coal plant has almost three times the amount of fossil depletion in terms of kg oil, thermal energy from biomass to run the solar power plant is still surprisingly high in this category. Aside from burning coal inside the coal power plant, the steel from the building must also be taken into account for the makeup of the high value in the coal power plant.

6. **Freshwater Ecotoxicity**

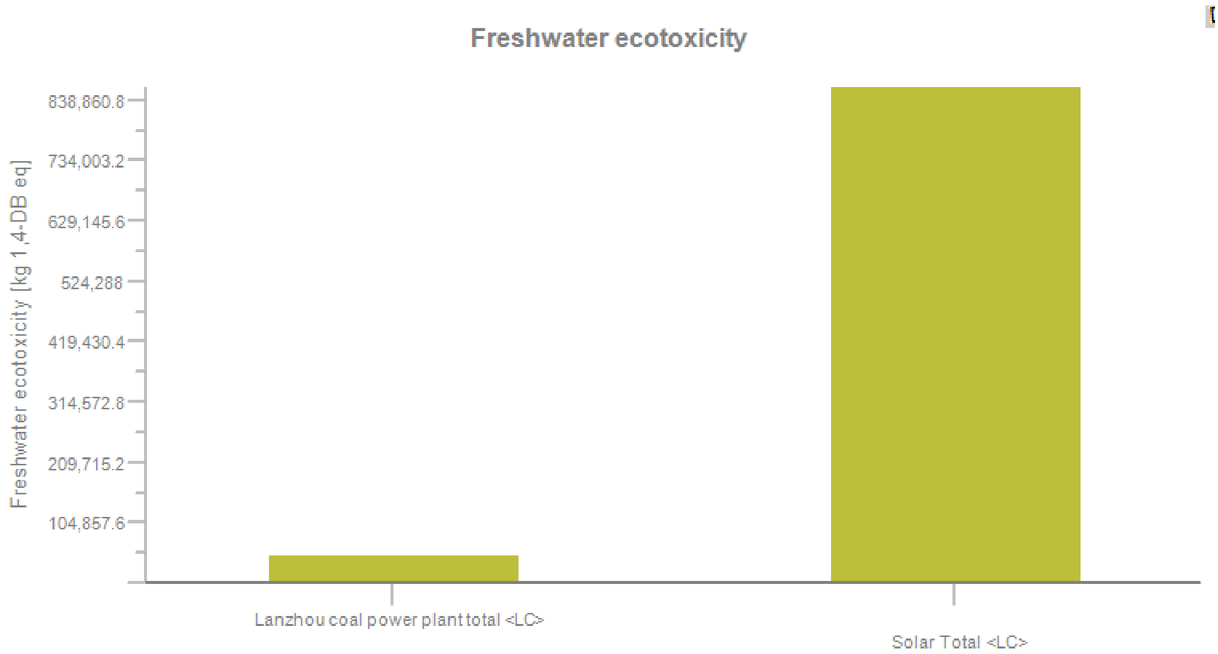

Figure 5.7: Comparison Freshwater Ecotoxicity

For the solar plant, the main contributor in terms of freshwater ecotoxicity, is the consumption of biomass. Whereas in the coal power plant, even though most of the ecotoxicity does come from the burning of coal, a decisive amount also occurs during the construction of the condenser and the structure of the plant, the materials being copper and steel. In total, however, comparing coal power to solar power, the solar plant contributes a lot more to freshwater ecotoxicity than the coal does, due to biomass.

7. **Human Toxicity**

In comparison between both power plants, the amount of human toxicity is almost equal in both scenarios, with the coal power plant just beneath the solar plant. On both plants, the main source of human toxicity emerges from the burning of the coal and biomass.

8. **Ionising Radiation**

In terms of ionising radiation, the solar plant has much higher values due to the use of biomass. The coal power plant on the other hand, has about two thirds of its radiation emerging from the production phase, with the other third coming from the burning of coal. In the production phase most of the ionising radiation comes from the steel from the structure of the power plant.

9. **Marine Ecotoxicity**

The ecotoxicity is comparable between both the solar and the coal plant, as they are relatively similar, with the solar plant being at about two-thirds the amount of the coal power plant. Again, the solar power plant regards these values to the burning of biomass, with a lesser amount coming from the production of the condenser through the use of copper and steel.

10. **Marine Eutrophication**

This is relatively incomparable as the solar power plant has values two magnitudes higher than the coal plant. This primarily comes from the usage of biomass. In the coal plant, most of this comes from the burning of coal to generate electricity, however, some of it also goes to the production and disposal of the plant. This is due to the use of aluminum and Worldsteel.

11. **Metal Depletion**

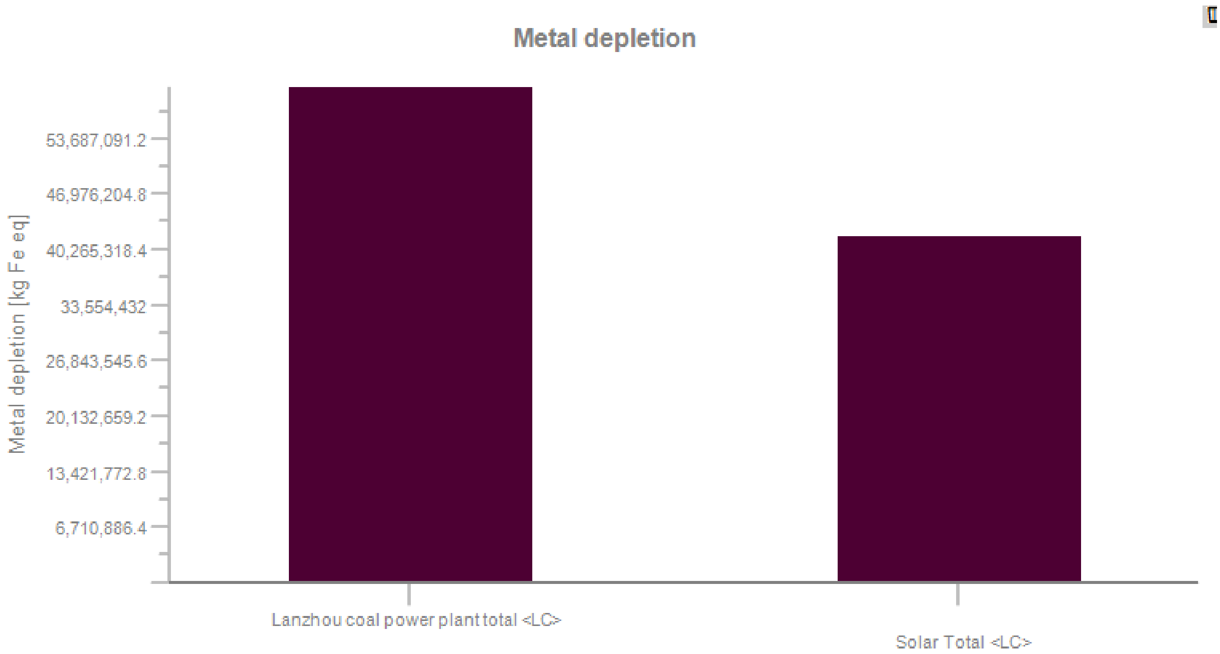

Figure 5.8: Comparison Metal Depletion

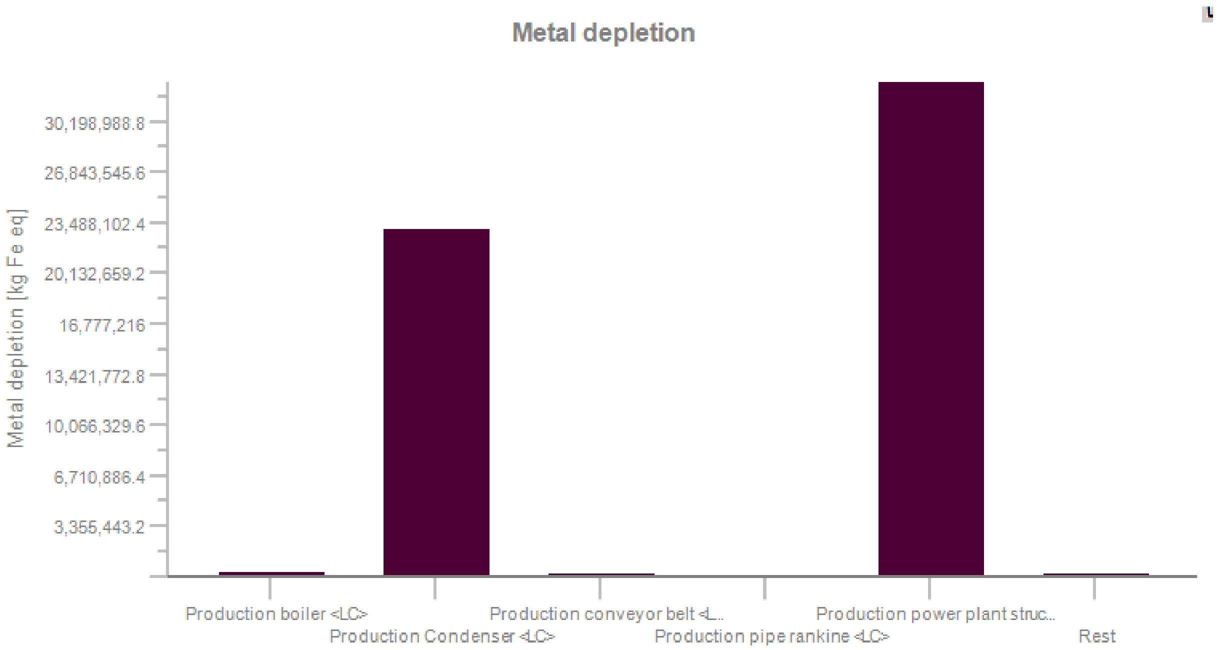

Figure 5.9: Coal Assembly Metal Depletion

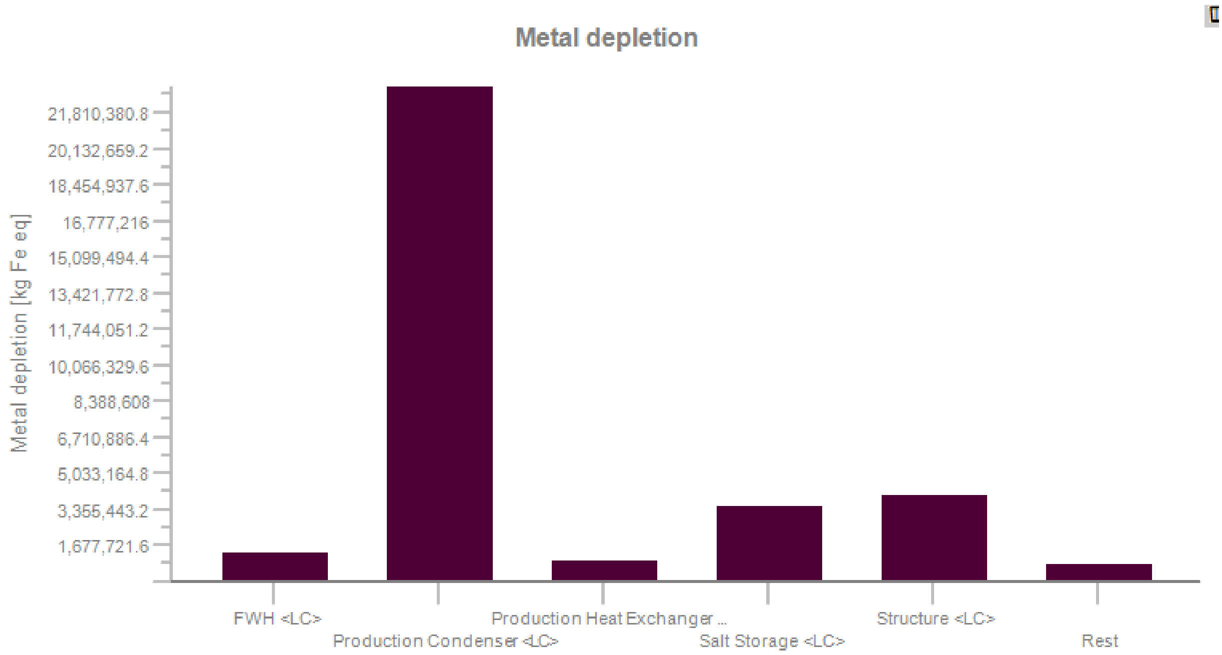

Figure 5.10: Solar Assembly Metal Depletion

The amount of metal depletion is more in the coal plant; by about 42 percent. In the coal plant, most metal is depleted in the construction of the plant due to the use of Worldsteel, with a relatively small amount going to the running of the plant. In the solar power plant, we see a similar scenario with only a small amount going to the burning of biomass and most of the depletion emerging from the construction and production of the condenser due to the amount of copper used for the piping.

12. **Natural Land Transformation**

    This can be compared between both the coal and solar plants as the values are relatively close together. In both plants, the highest amount of land transformation occurs during the production of the power plant, in specific, the condenser and its use of copper.

13. **Particulate Matter Formation**

    In both power plants, the particulate matter formation comes from the burning of both coal and biofuel. However, the amount is a lot larger in the solar power plant.

14. **Photochemical Oxidant Formation**

    The values of the solar power plant are a lot higher than they are for the coal power plant. Both, again, coming from the burning of coal and the usage of biomass.

15. **Terrestrial Ecotoxicity**

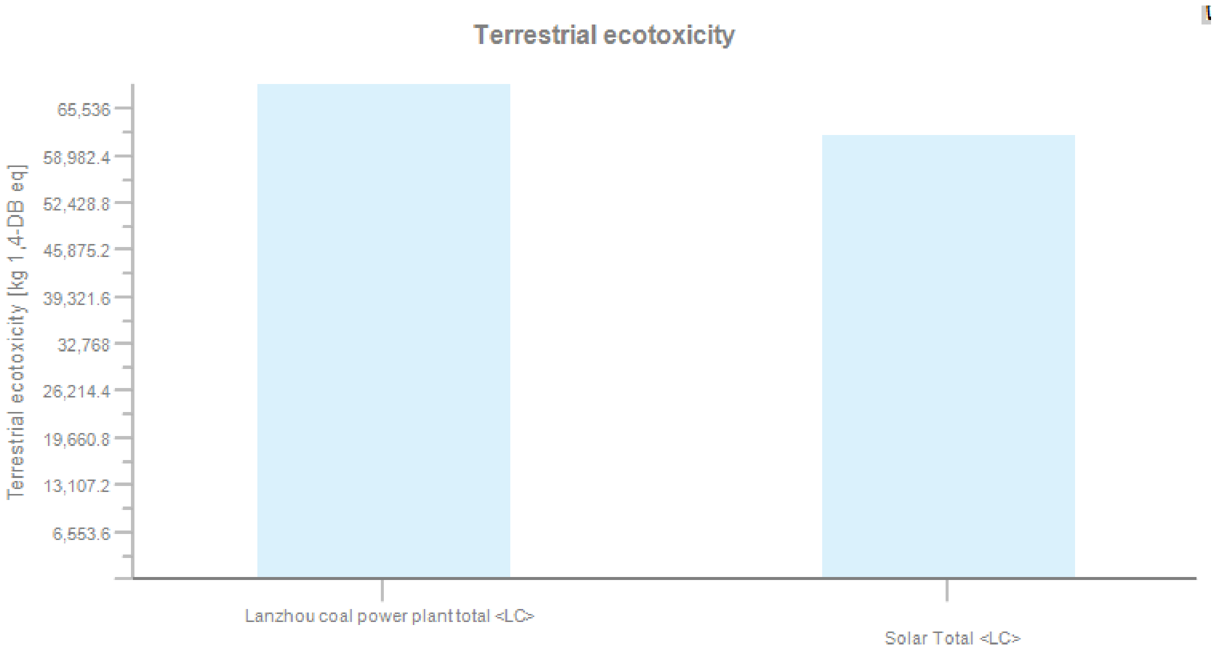

Figure 5.11: Comparison Terrestrial Ecotoxicity

Both the solar plant and the coal plant have about equal amounts of terrestrial ecotoxicity. Both having mainly the burning of biomass and coal to thank. However, a lot of copper goes into the condenser, therefore giving it a viewable position in the graph, other than the rest of the parts in the assembly.

16. **Water Depletion**

The water depletion mostly occurs in the solar power plant due to the biomass being used. Other than that, the assembly of the solar plant has a good spread of water depletion, with the highs emerging from the salt storage and the structure of the power plant due to the use of concrete and steel. In the coal power plant however, the use and production of the plant have relatively similar values, with the use being less. The production phase has such high values due to the structure of the plant and its use of steel.

5.2.4 Comparison

The biggest difference between the 2 scenarios is the use phase when it comes to most of the midpoint effects. This is caused by the fact that, for both plants, the use phase is the biggest contributor when it comes to the environmental impacts. The solar power plant has a use phase of the bio-fuel that is burned in the cycle of the plant. Of course, the solar energy is a large contributor as well when it comes to electricity production. However, since this energy does not account for any emissions and it is completely renewable, it does not show up in the LCA. However, the bio-fuel modelled in GABI shows up quite prominently in the calculated graphs since the burning of these fuels accounts for a lot of greenhouse gasses. One thing that was not modelled in GABI, is the fact that even though a lot of CO2 is released into the atmosphere, those emissions are equal to the CO2 that the crop used for the production of bio-fuel absorbs. However, when the land used for the growing of the crop needs to be cleared of vegetation beforehand this does not apply.

When the coal power plant is considered it can also be seen that the use phase is the largest contributor when it comes to environmental impacts. This is due to the continuous burning of coal. Even though bio-fuel emits various greenhouse gases, the burning of coal in a power plant to produce energy produces far more emissions. Taking into account that both bio-gas and coal are required to produce similar amounts of energy-247MW versus the coal's 220 MW, the burning of coal creates more than twice the amount of kg CO2 equivalent. $(3.2 * 10^8 versus 7.3 * 10^8)$.

When comparing these two scenarios it becomes clear, that when it comes to climate change, the solar power plant provides a better perspective. Since this is arguably the most important midpoint effect when comparing the two power plants it is important to know just how much the difference actually is. When looking at the contribution to the climate change, it can be seen that the coal power plant contributes $7.3 * 10^8$ kg CO2 eq. in the use phase. The solar power plant contributes $3.2 * 10^8$ kg eq. in the use phase(Figure 5.3). When looking at the assembly phase of both the power plants it can be seen that the assembly of the coal power plant has a larger contribution then the solar power plant. This might be too much of a difference to be realistic, since the assembly of the power plants are assumed to be quite similar. However, since the difference is not really significant compared to the use phase of the plants, it does not distort the picture too much.

Other assumptions made, that are relevant to mention because they may cause a difference between the power plants, are the transport of the coal to the power plant. This was not modelled in GABI, but it is worth mentioning it here. There is also some form of transport needed for the bio-fuel to the power plant, but since the main form of energy is solar energy, this is not nearly as much as the coal transport. This means the comparison between the two power plants is not entirely fair, since the transportation of coal indirectly causes more emissions for the coal plant.

Another item that needed to be mentioned, is the fact that the solar power plant does not only provide the city of Lanzhou with electricity, but also with heat. The coal power plant only provides electricity and therefore it does not compare equally to the solar power plant. Since this is not something that is modelled in GABI or reflected in the functional unit this is also something that was kept in mind when comparing the two LCAs.

5.2.5 Impacts in assembly and disposal

Throughout the creation of all the different parts and flows of both power plants inside GABI, and after the analysis through ReCiPe, a few things are worth looking into, because of the unexpected significant contribution that they made within the LCA.

One of the materials that kept appearing was the copper from the condenser. Another material that had a strange contribution to the overall LCA was a material called 'Worldsteel'. Both of these materials were never a leading factor in any of the comparisons made. However, it was too much of an impact to just seemingly ignore. For example, in freshwater ecotoxicity and metal depletion, the usage of copper was evident and large enough to spot and in the ozone depletion, the Worldsteel had a negative impact. This is likely due to the fact that we've overestimated the amount of copper used in the condensers that were used in the power plants. Because the copper was modelled in the disposal phase in GABI to be recycled, the metal depletion is most likely incorrect, since GABI did not take this into account in the assembly phase.

The Worldsteel used in some of the plans in GABI is a material that showed some unexpected things for a steel, as mentioned above. Because it is unclear why this particular type of steel behaves so differently then most steels, it would have likely been better to model it with regular steel in hindsight. In the disposal phase, the biggest impacts on the graphs were always made by the landfills, with one exception: the crushing of concrete in the marine eutrophication.

Overall however, the biggest factors in most graphs came from the running of the plant. This being the burning of coal and the usage of biomass.

6 Conclusion

A new sustainable energy system has been designed to provide electricity and heat to the city of Lanzhou. The system that has been designed is a rankine cycle that consists of 3 turbines, with the bulk of the energy used coming from solar energy and one of the reheaters using bio-energy.

There has been a complete thermodynamic analysis of the new system. During this the efficiencies (including thermal, carnot, electrical, second law) and utilisation factors have been calculated. On top of this a sankey and grassman diagram have been calculated in order to show the exergy and energy flows of the system.

The materials science work concludes in presenting a final choice of materials for the turbine (housing, rotary blades and axle) and the heat exchanger (housing and tubes).

The turbine blades are to be made from Nickel-Mo-Cr alloy, HASTELLOY C-276.
The turbine axle will be made from Stainless steel, martensitic, AISI 410, hard temper.
Carbon steel, SA216, (Type WWC), cast, normalized temper will be what the turbine housing is made from.

The internal pipes of the heat exchanger will be made from Stainless steel, martensitic, AISI 410, hard temper. Finally the housing of the heat exchanger, which will be formed by cylindrical rolling will be made from Stainless steel, austenitic, AISI 308L, annealed

A complete life cycle analysis has been successfully performed. With the use of the GABI software and the ReCiPe 1.08 method various models of the two power plants have been created to compare them with respect to the 18 midpoint effects given.

Most of the results found were in agreement with the expectations, and relatively close to what one would assume to find when performing such a LCA. From these results, it was concluded that the solar power plant has a lower impact when it comes to most of the important effects.

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A Thermodynamics content

A.1 Thermodynamic property tables

S: Summer / W: Winter

A.1.1 Water tables

Point	P (bar)	T (°C)	h (kJ/kg)	s (kJ/kgK)	Phase
W1	0.10	45.81	191.81	0.6492	Sat. liquid
W2	4.00	45.84	192.23	0.6495	Compr. liquid
W3	4.00	143.61	604.72	1.7766	Sat. liquid
W4	200,00	146.17	628.21	1.7823	Compr. liquid
W5	200,00	460.00	3100.60	5.9577	Superheated
W6	60,00	294.16	2863.70	6.0321	Superheated
W7	60.00	600.00	3658.80	7.1692	Superheated
W8	8.00	327.99	3115.90	7.3349	Superheated
W9	8.00	460.00	3395.20	7.7548	Superheated
W10	4.00	370.17	3211.80	7.8058	Superheated
W11	0.10	53.52	2598.70	8.1950	Superheated

Table A.1: Thermodynamic properties detailed design (water)

Point	Energy (MW)	Exergy W (MW)	Exergy S (MW)
W1	24,66	1,78	0,47
W2	24,71	1,82	0,51
W3	90,04	17,55	12,44
W4	93,54	20,81	15,68
W5	461,68	218,60	200,16
W6	426,41	180,29	161,62
W7	544,79	252,28	229,99
W8	463,95	164,68	141,86
W9	505,54	189,14	164,98
W10	65,33	21,82	18,50
W11	334,09	45,41	23,34

Table A.2: Energy and Exergy values (water)

A.1.2 Salt tables

Point	T (°C)	h (kJ/kg)
S1	600,00	1,34e03
S2	600,00	1,34e03
S3	462,51	1,13e03
S4	446,98	1,10e03
S5	446,98	1,10e03
S6	446,98	1,10e03

Table A.3: Thermodynamic properties detailed design (salt)

Point	Energy (MW)	Exergy W (MW)	Exergy S (MW)
S1	2,34e03	753,68	689,46
S2	2,34e03	753,68	689,46
S3	462,51	1,13e03	1,97e03
S4	446,98	1,10e03	1,93e03
S5	446,98	1,10e03	1,93e03
S6	446,98	1,10e03	1,93e03

Table A.4: Energy and Exergy values (salt)

A.1.3 Lanzhou district water tables

Point	P (bar)	T (°C)	h (kJ/kg)	s (kJ/kgK)	phase
L1	14,00	120,00	504,63	1,5267	Compr. liquid
L2	4,00	90,00	377,22	1,1924	Compr. liquid
L3	14,00	90,00	378,38	1,1927	Compr. liquid

Table A.5: Thermodynamic properties detailed design (Lanzhou heating district)

Point	Energy W (MW)	Energy S (MW)	Exergy W (MW)	Exergy S (MW)
L1	514,91	257,45	87,97	29,20
L2	384,91	192,45	51,43	14,59
L3	386,09	193,04	52,53	15,13

Table A.6: Energy and Exergy values (Lanzhou heating district)

A.2 Thermodynamic formulas

Thermal efficiency:

$$\eta_{th} = \frac{\dot{W}_{turbines,out}}{\dot{Q}in} \tag{A.1}$$

Carnot efficiency:

$$\eta_{carnot} = 1 - \frac{T_{cold}}{T_{hot}} \tag{A.2}$$

Electrical efficiency:

$$\eta_{el} = \frac{\dot{W}_{electrical,out}}{\dot{Q}_{in}} \tag{A.3}$$

Second law efficiency:

$$\eta_{2nd} = \frac{\eta_{th}}{\eta_{carnot}} \tag{A.4}$$

Utilization factor:

$$\eta_{\in} = \frac{\dot{W}_{turbines,out} + \dot{Q}_{used,out}}{\dot{Q}in} \tag{A.5}$$

Isentropic efficiency turbine:

$$\eta_{iso,turbine} = \frac{h_{in} - h_{out}}{h_{in} - h_{out,s}} \tag{A.6}$$

Isentropic efficiency pump:

$$\eta_{iso,pump} = \frac{h_{out,s} - h_{in}}{h_{out} - h_{in}} \tag{A.7}$$

Output turbine:

$$\dot{W}_{turbine,out} = \dot{m}(h_{in} - h_{out}) \tag{A.8}$$

Input pump:

$$\dot{W}_{pump,in} = \dot{m}(h_{out} - h_{in}) \tag{A.9}$$

Heat transfer (Heat Exchanger):

$$\dot{Q}_{water,in} = h_{water,out} - h_{water,in} \tag{A.10}$$

$$\dot{Q}_{salt,out} = h_{salt,in} - h_{salt,out} \tag{A.11}$$

Energy input (Solar receiver/Burner):

$$\dot{Q}_{in} = \dot{m}(h_{out} - h_{in}) \tag{A.12}$$

Energy leaving condenser:

$$\dot{Q}_{condenser,out} = \dot{m}(h_{in} - h_{out}) \tag{A.13}$$

Energy (Flow point):

$$E = \dot{m} \cdot h \tag{A.14}$$

Exergy (Flow point):

$$\psi = \dot{m}((h - h_0) - T_0(s - s_0)) \tag{A.15}$$

Exergy destroyed:

$$\psi_{destroyed} = \dot{m} \cdot T_0(s_{out} - s_{in}) \tag{A.16}$$

Exergy leaving condenser:

$$\psi_{condenser,out} = \dot{Q}_{condenser,out}(1 - \frac{T_0}{T_{condenser,out}}) \tag{A.17}$$

A.3 Sankey diagram (summer)

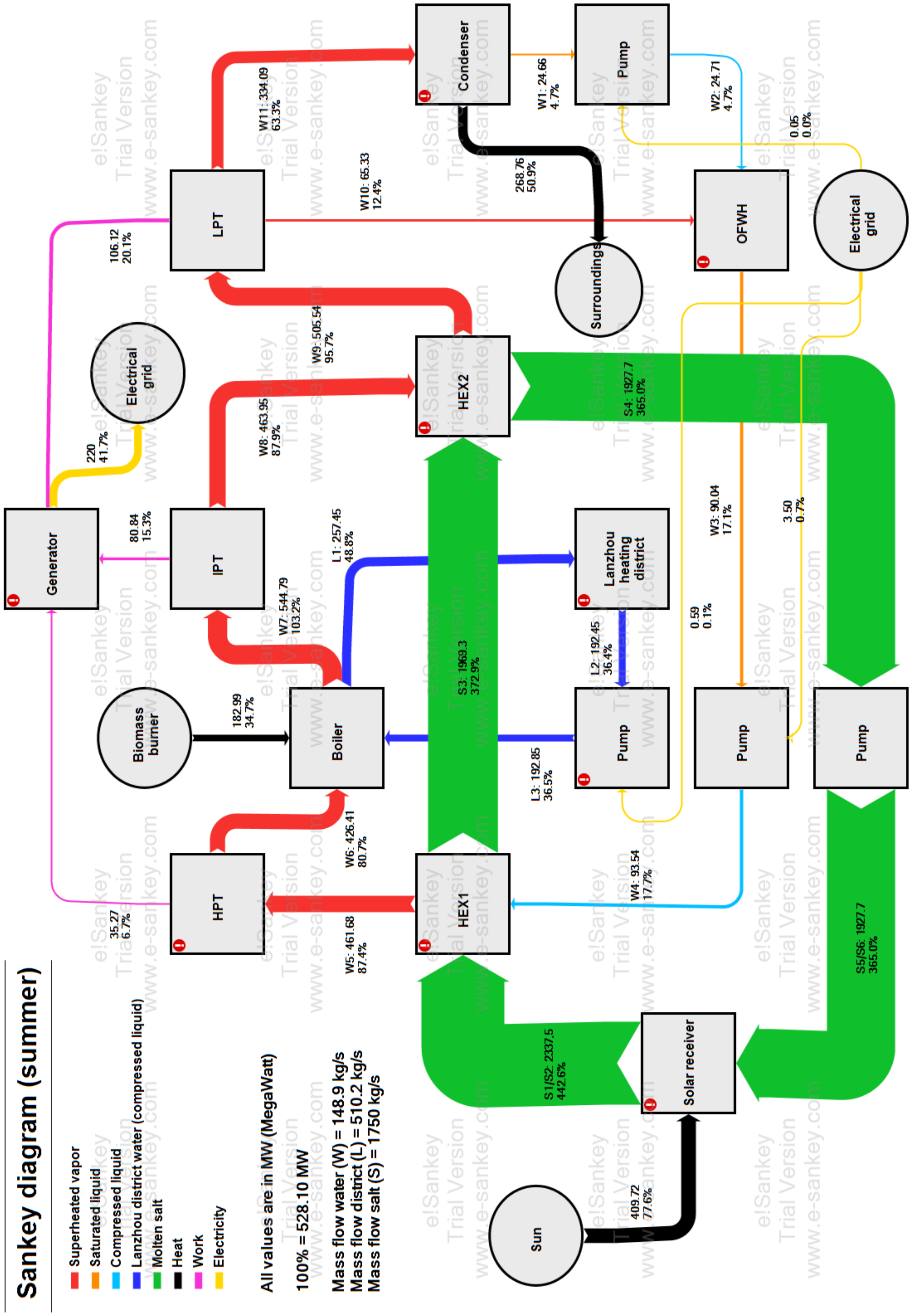

Figure A.1: Sankey diagram (summer)

A.4 Grassmann diagram (summer)

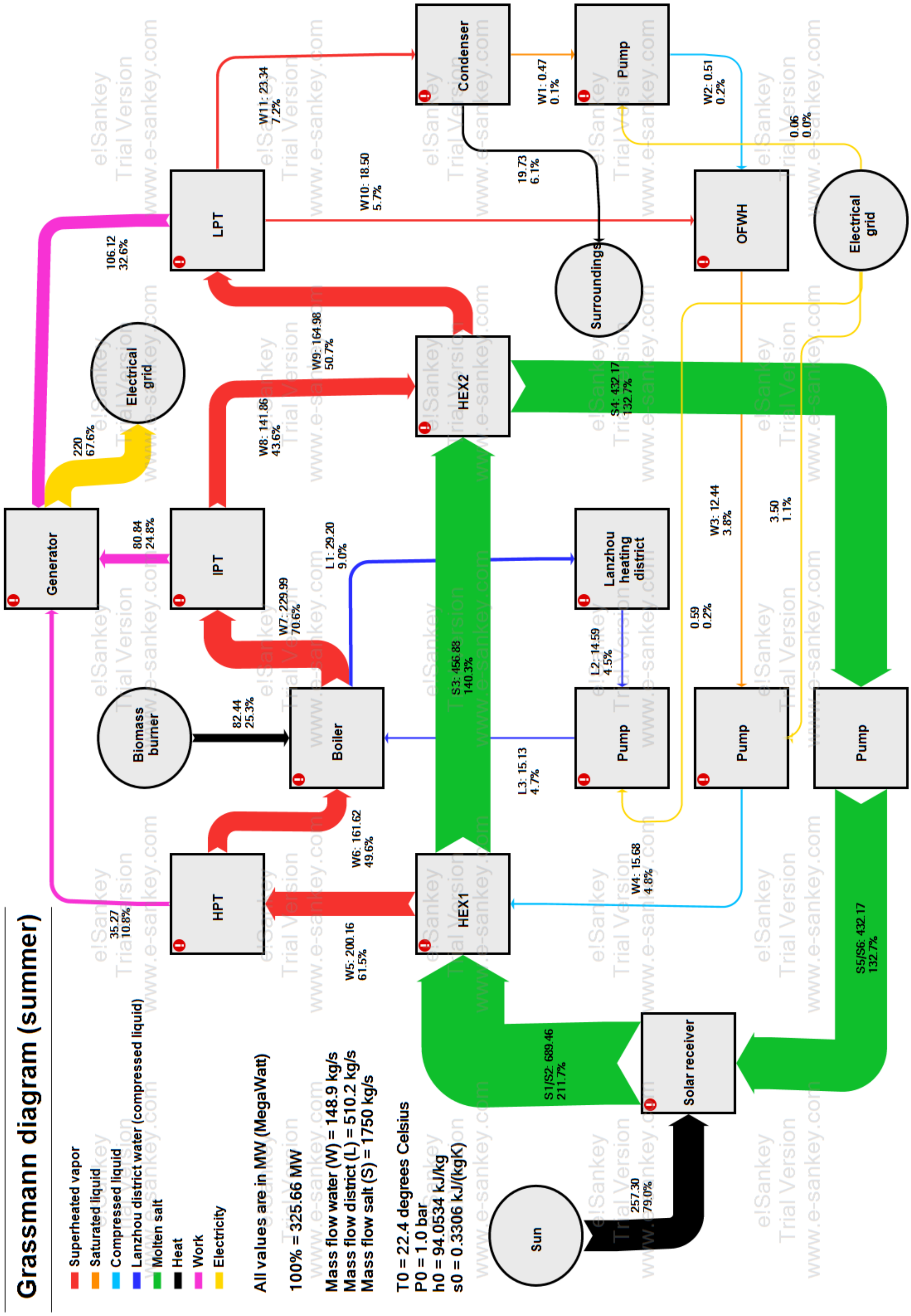

Figure A.2: Grassmann diagram (summer)

A.5 Sankey diagram (winter)

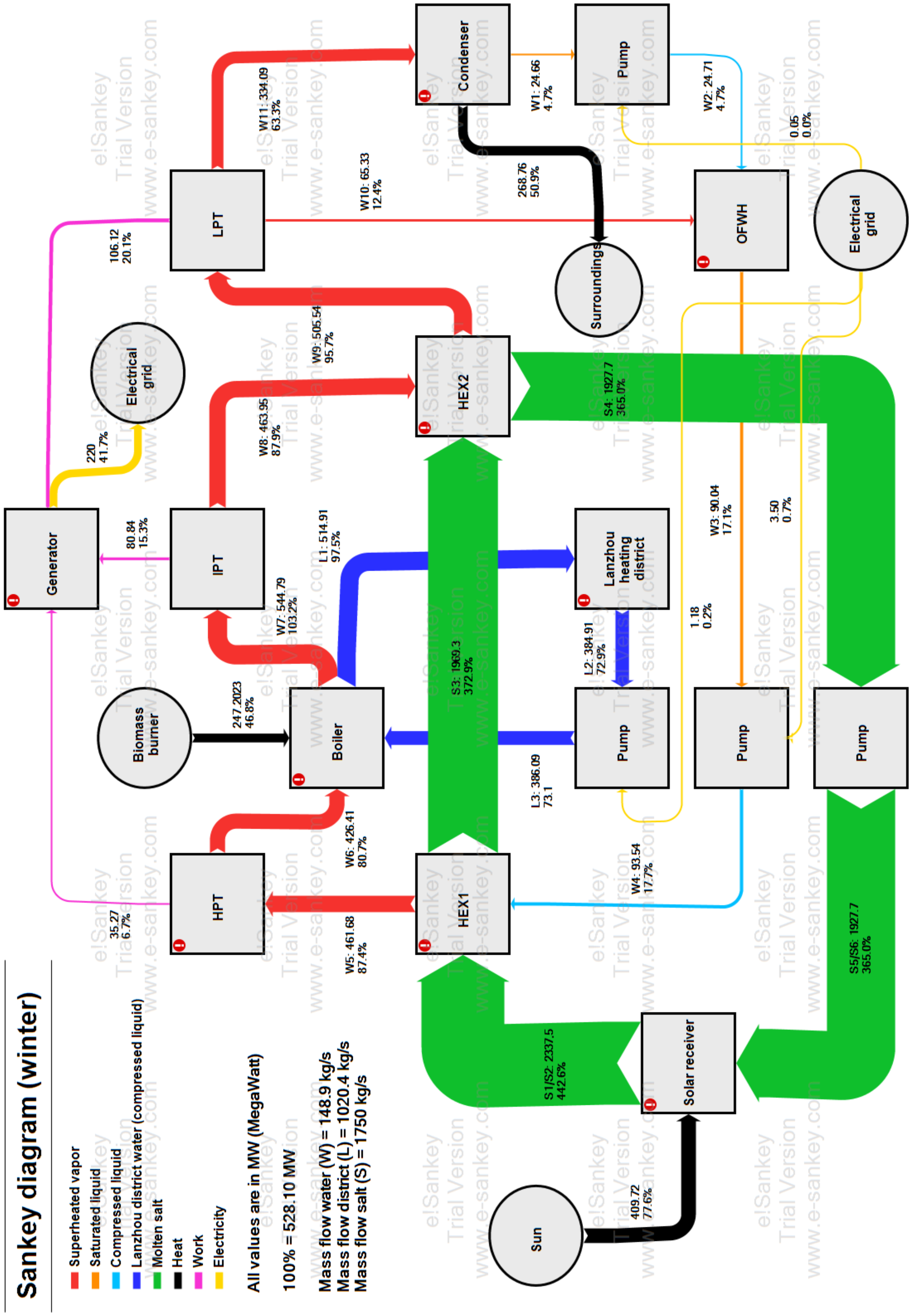

Figure A.3: Sankey diagram (winter)

A.6 Grassmann diagram (winter)

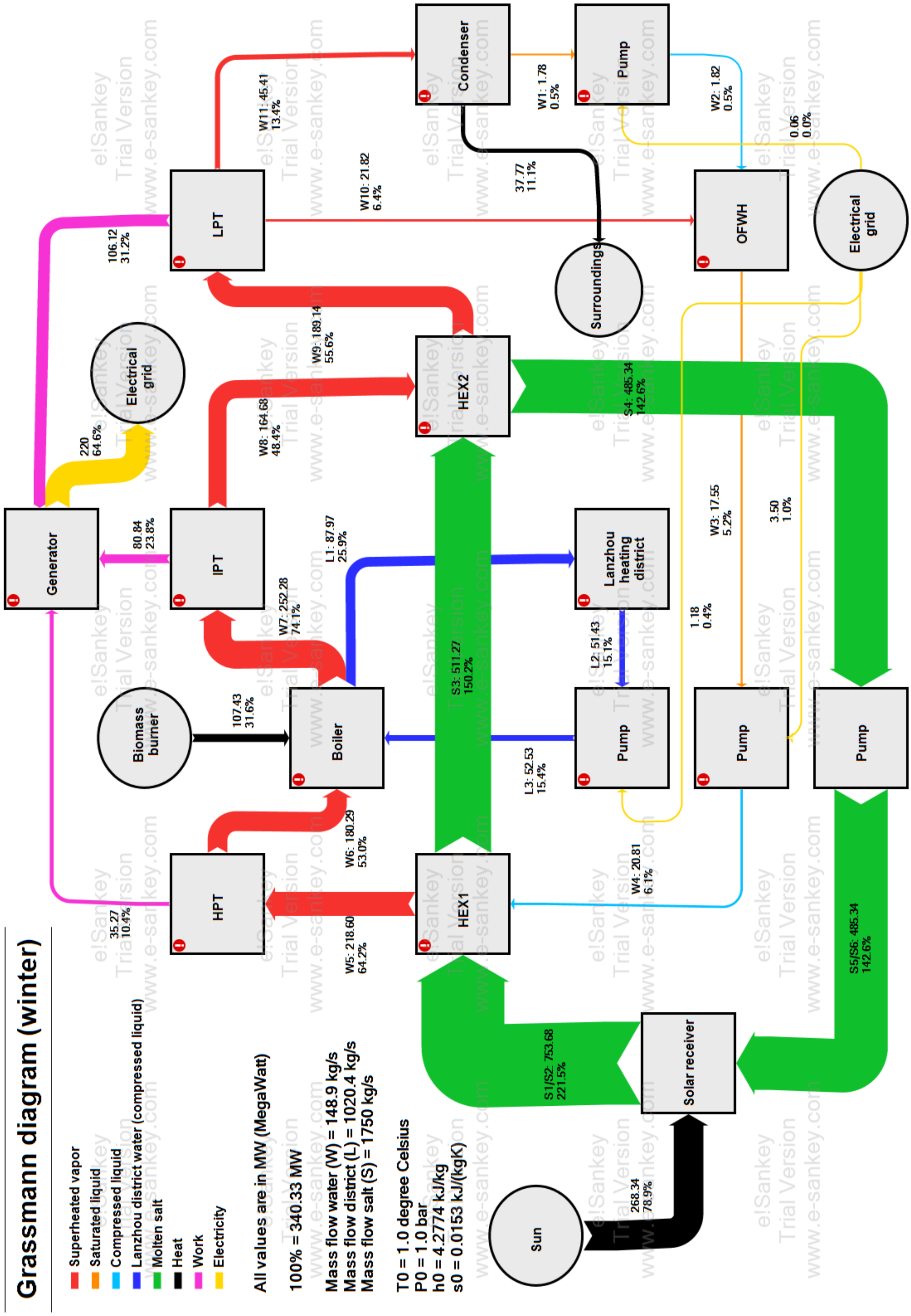

Figure A.4: Grassmann diagram (winter)

A.7 Ts-diagram

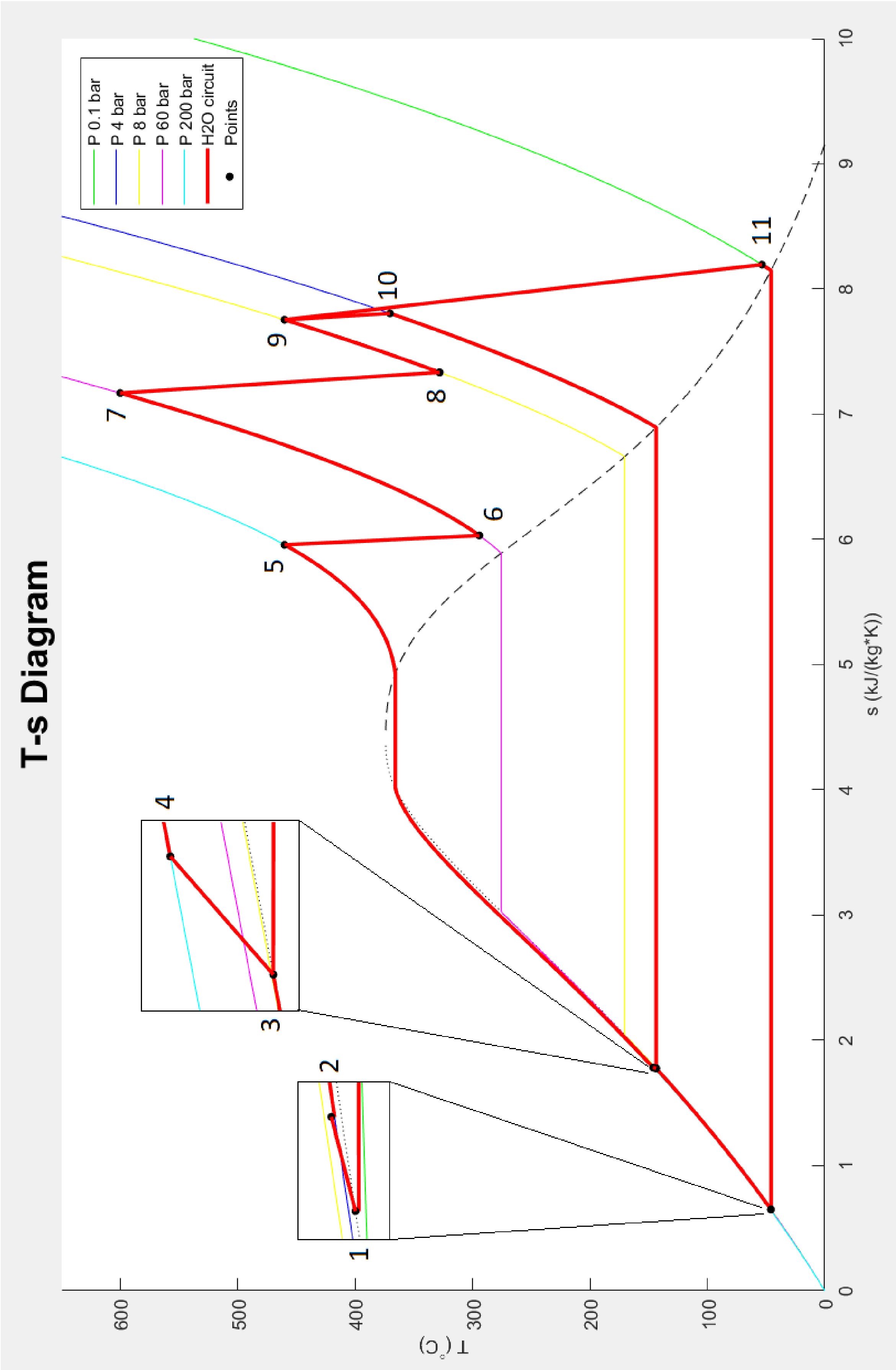

Figure A.5: Ts-diagram

A.8 hs-diagram

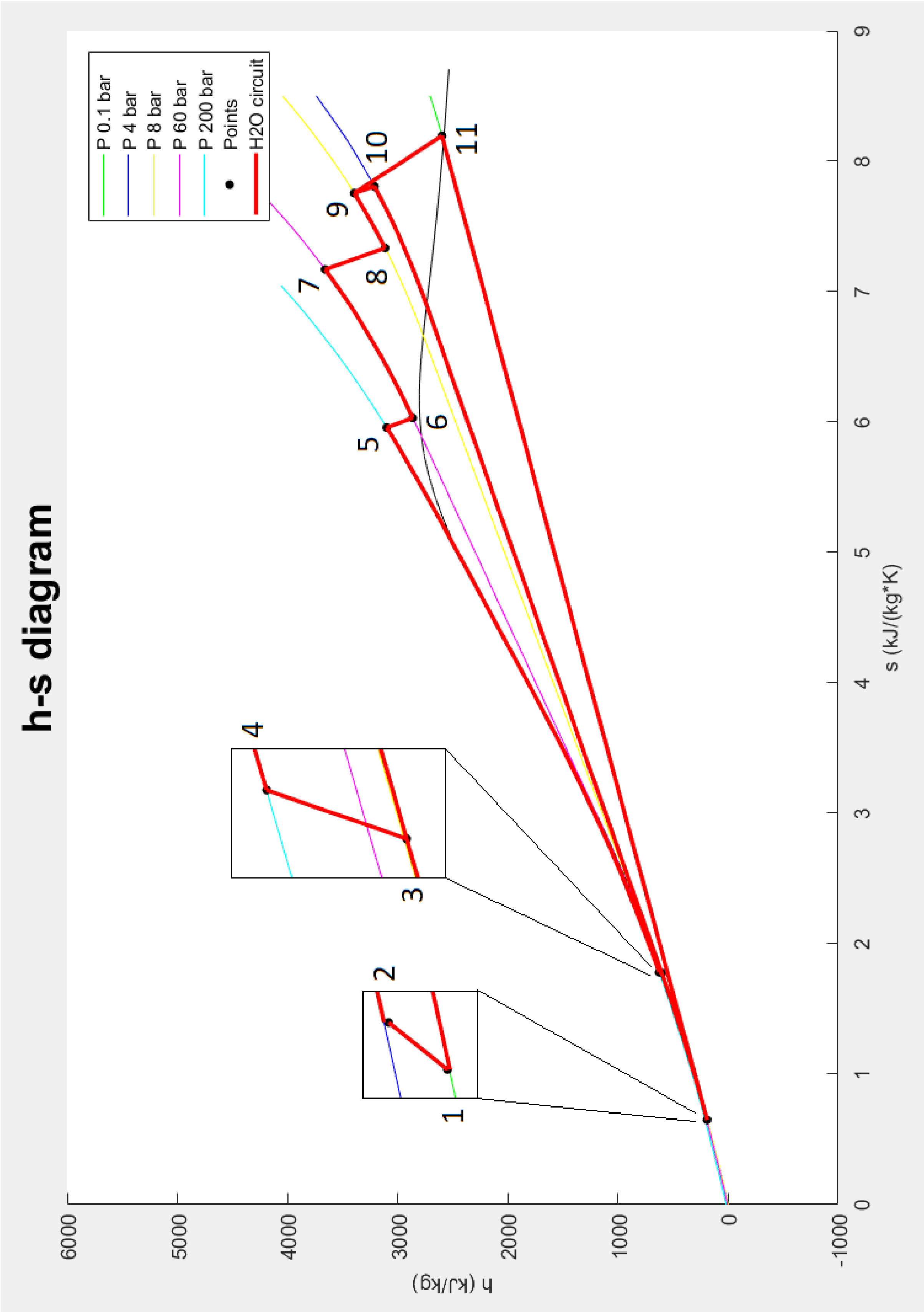

Figure A.6: hs-diagram

A.9 Biomass selection

Important aspects for selecting biomass

- Availability
- Lower heating value
- Ease of transport (solid/liquid/gas)
- Cost (product/transport)
- Competition with the food chain

Biomass resources in Gansu area
There are resources for a total of 115 million tons of agricultural waste in the area of our new power plant. The coal equivalent of this is 36 million tons. So providing the new power plant with the necessary biomass will be no problem.

The spatial distribution of the theoretical energy potential available of agricultural residues in 2003 and 2007 at province level (PJ):

	Rice	Rice husks	Wheat	Corn	Corn cobs	Other grains	Beans	Tubers	Cotton
Gansu	0.42	0.10	32.63	34.09	6.51	13.85	5.12	14.38	7.27

Figure A.7: Agricultural residues Gansu

Figure A.7: Thus the preference goes to wheat and corn as agricultural residues for extra energy production. The energy density of these two products is not high, but because of the local availability of these products this will not greatly increase pollution by transport or transport costs. The products themselves are also cheap as agricultural residues.

Because wheat or corn will be used and we only need heat, combustion is used to heat the water of the rankine cycle and the water of the Lanzhou heating district. This is the easiest process for the application in our power plant and also the cheapest when transport is neglected.

The material will be used dry and ash free (daf). The water content of the biomass needs to be low for proper operation and the chemical composition of ash is a determinant parameter in the consideration of the thermal conversion unit, since it gives rise to problems of slagging, fouling, sintering and corrosion. The lower heating value is used since the water leaves the chimney of the power plant in an evaporated state.

Different types of wheat that can be used:

Waste wheat straw (China) (#2321)

- Net calorific value (LHV): 18.58 MJ/kg
- Moisture content (ar): 10.06%
- Ash content (ar): 16.95%

Wheat straw waste (pellets) (#2332)

- Net calorific value (LHV): 17.90 MJ/kg
- Moisture content (ar): 7.48%
- Ash content (ar): 17.75%

Not much advantages over: Waste wheat straw (China) (2321), except for easier transport and handling, but more processing needed making this the less preferable choice.

Char from wheat straw (#761)

- Net calorific value (LHV): 26.02 MJ/kg
- Moisture content (ar): 4.00%
- Ash content (ar): 36.96%

More processing needed, decreasing the total process efficiency. Very good lower heating value compared to: waste wheat straw (China) (2321). Very low bulk density (although the other densities are not known, the assumption can be made that they are higher, with the pellets close behind), making this the better choice for transport.

Waste wheat straw (China) (2321) will be the cheapest option because, it requires the least amount of processing (only needs to be made dry and ash free). More transport is needed to deliver the required amount of it to the power plant, but because of the large availability of waste wheat in the Gansu area this becomes less of a disadvantage. Overall this will be the cheapest option.

Amount of biomass required during summer: 9.84 kg/s
Amount of biomass required during winter: 13.30 kg/s

B Material selection CES charts

B.1 Turbine: Housing

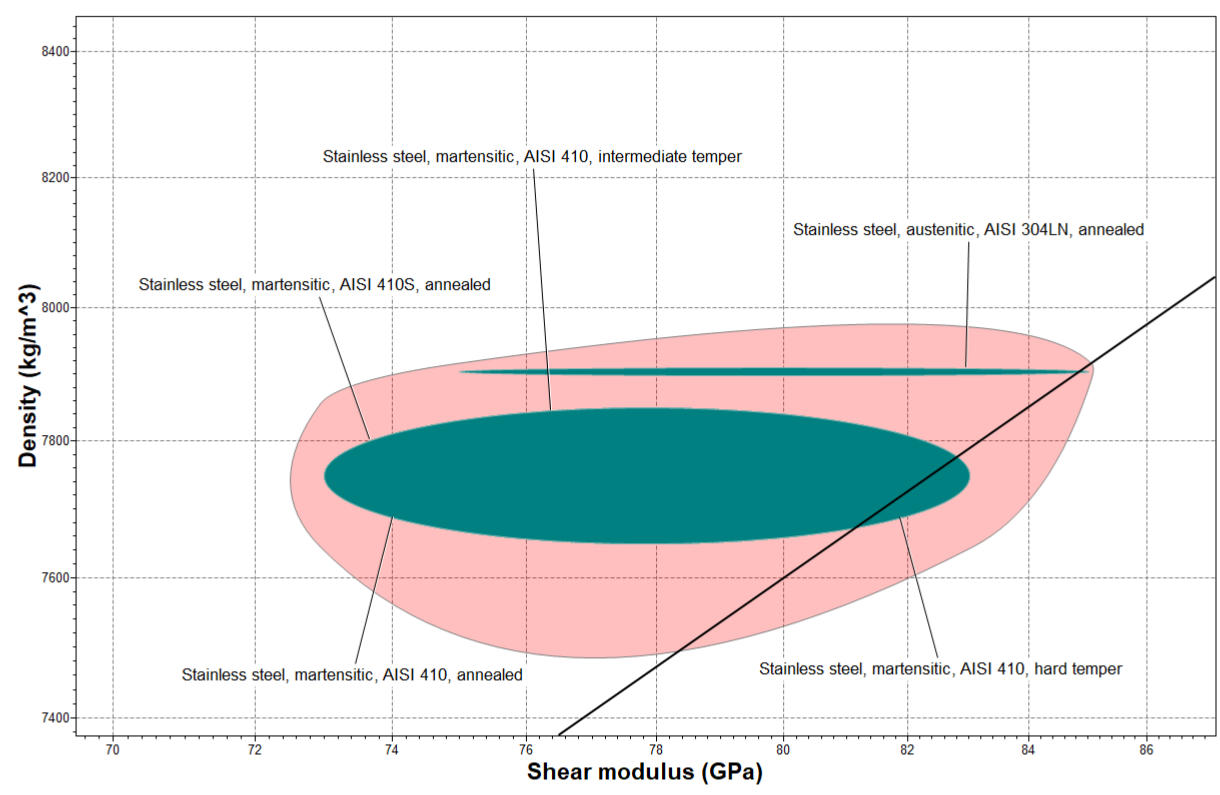

Figure B.1: Turbine Housing (density vs shear modulus)

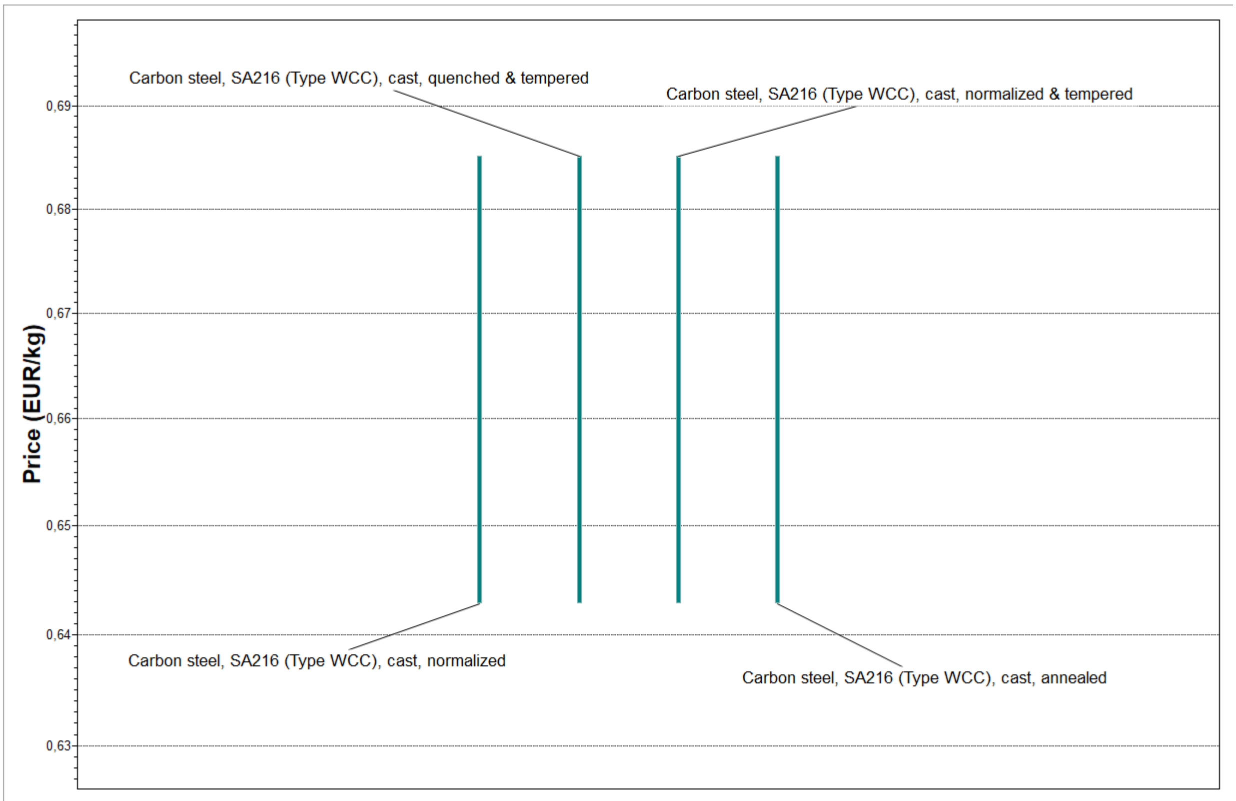

Figure B.2: Turbine housing (price)

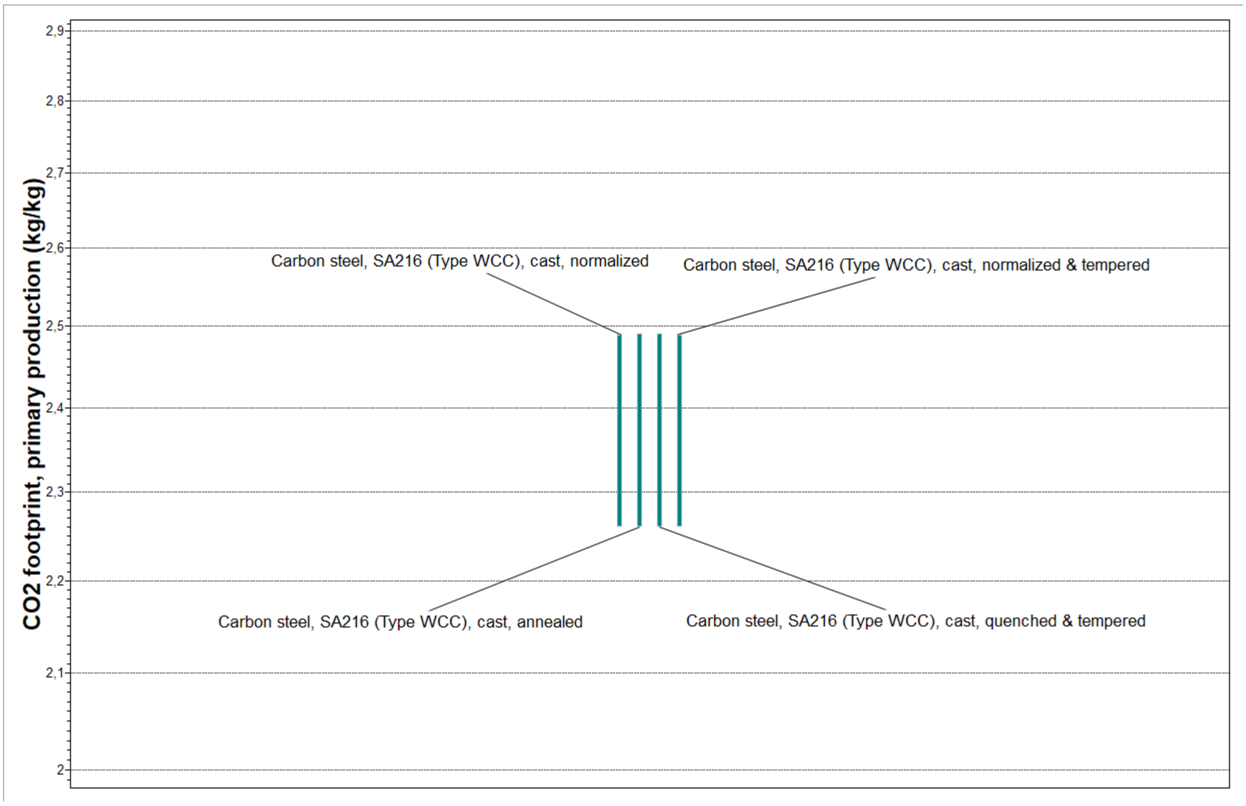

Figure B.3: Turbine housing (CO_2)

B.2 Turbine: Rotary blades

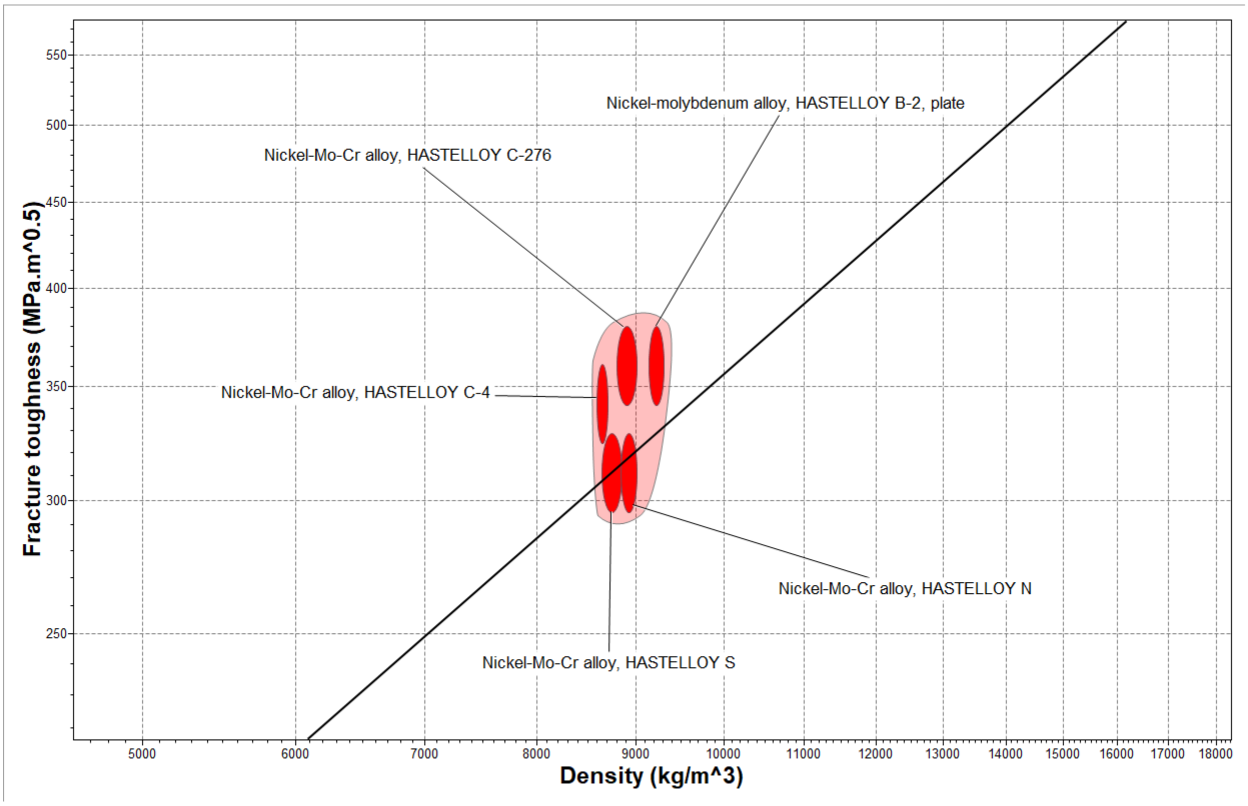

Figure B.4: Rotary blades (Fracture vs Density)

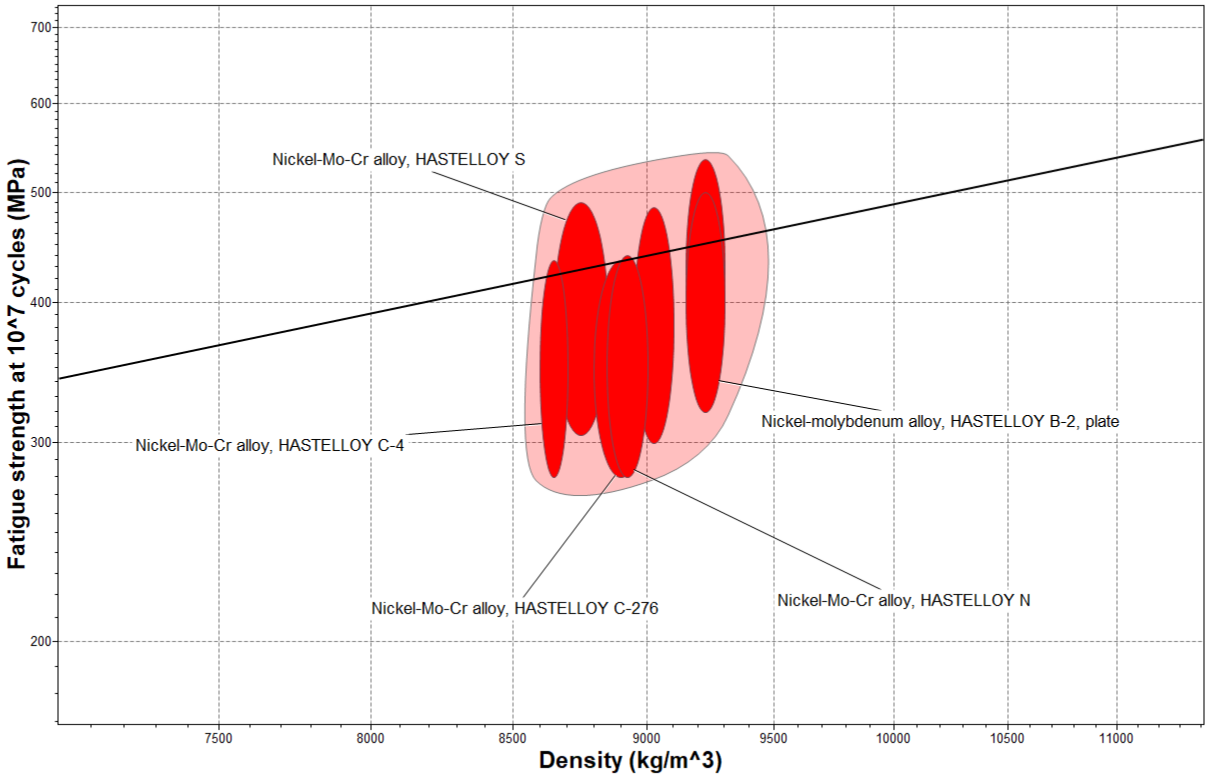

Figure B.5: Rotary blades (Fatigue vs Density)

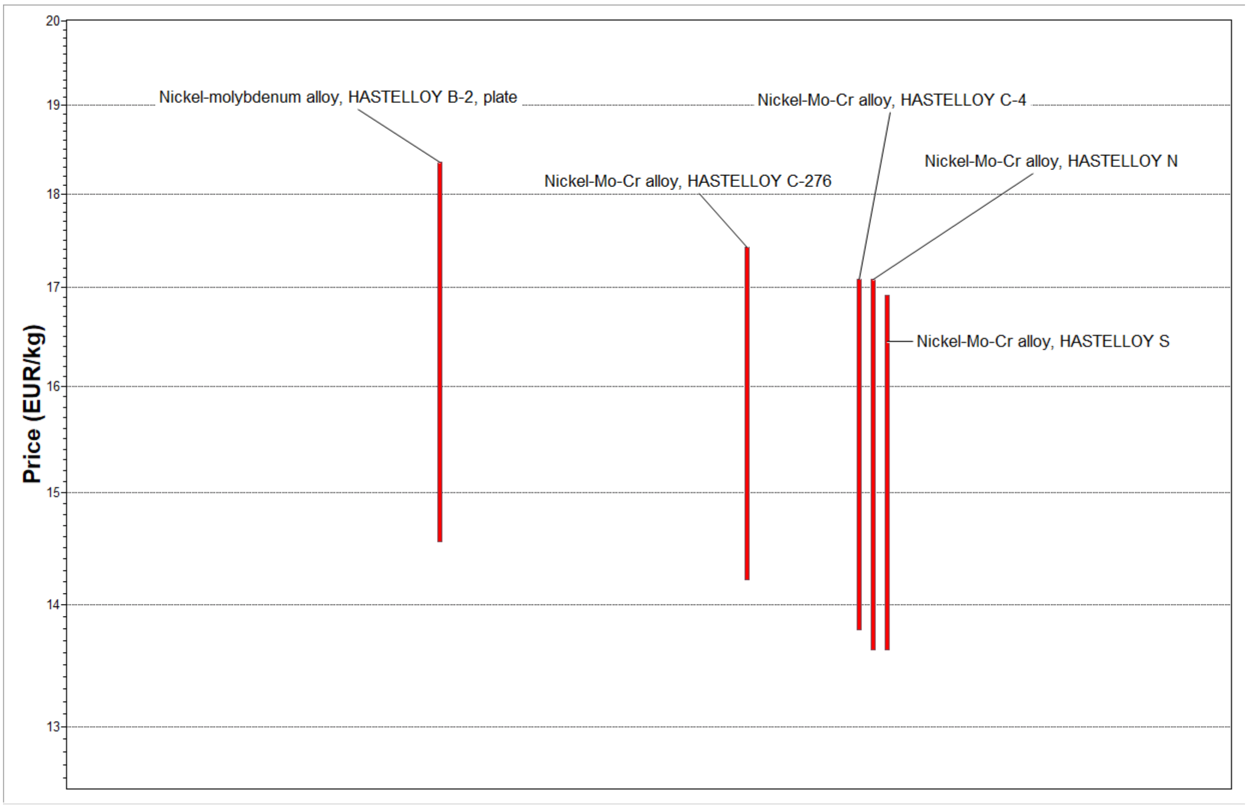

Figure B.6: Rotary blades (price)

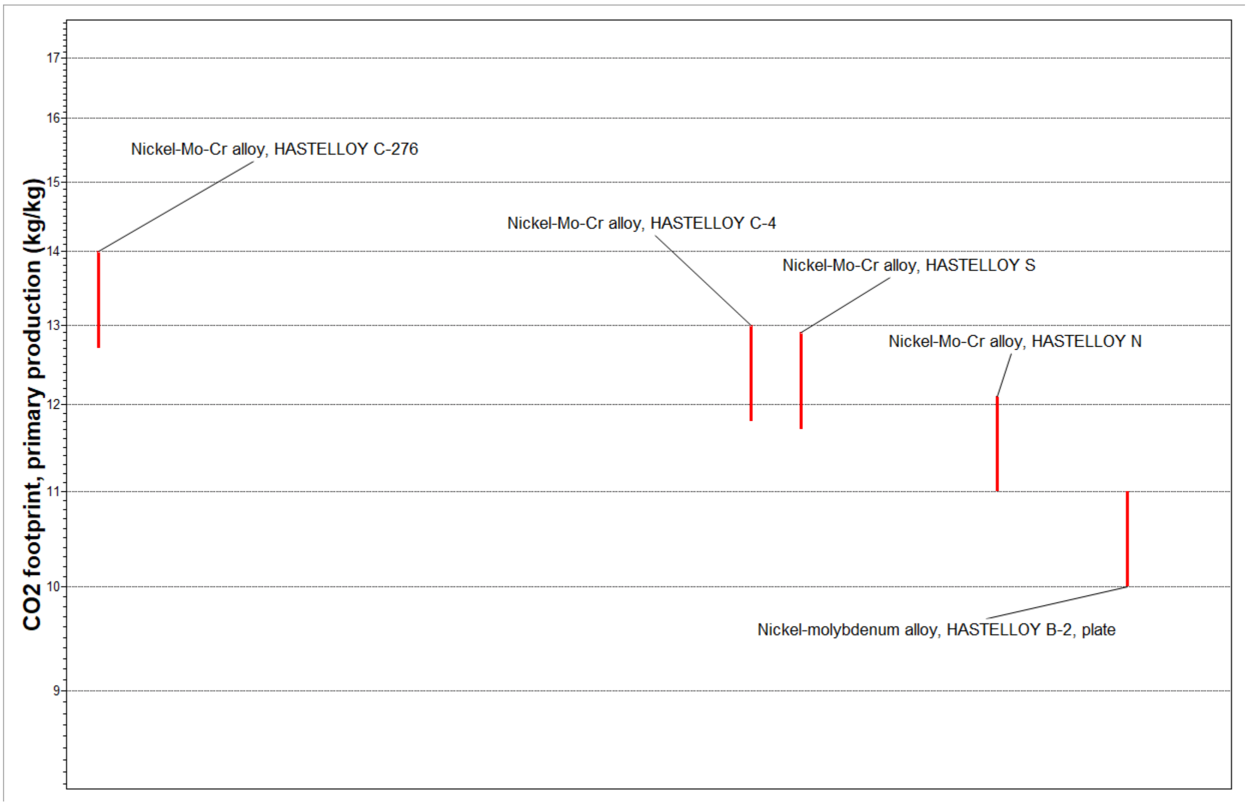

Figure B.7: Rotary blades (CO_2)

B.3 Turbine: Axle

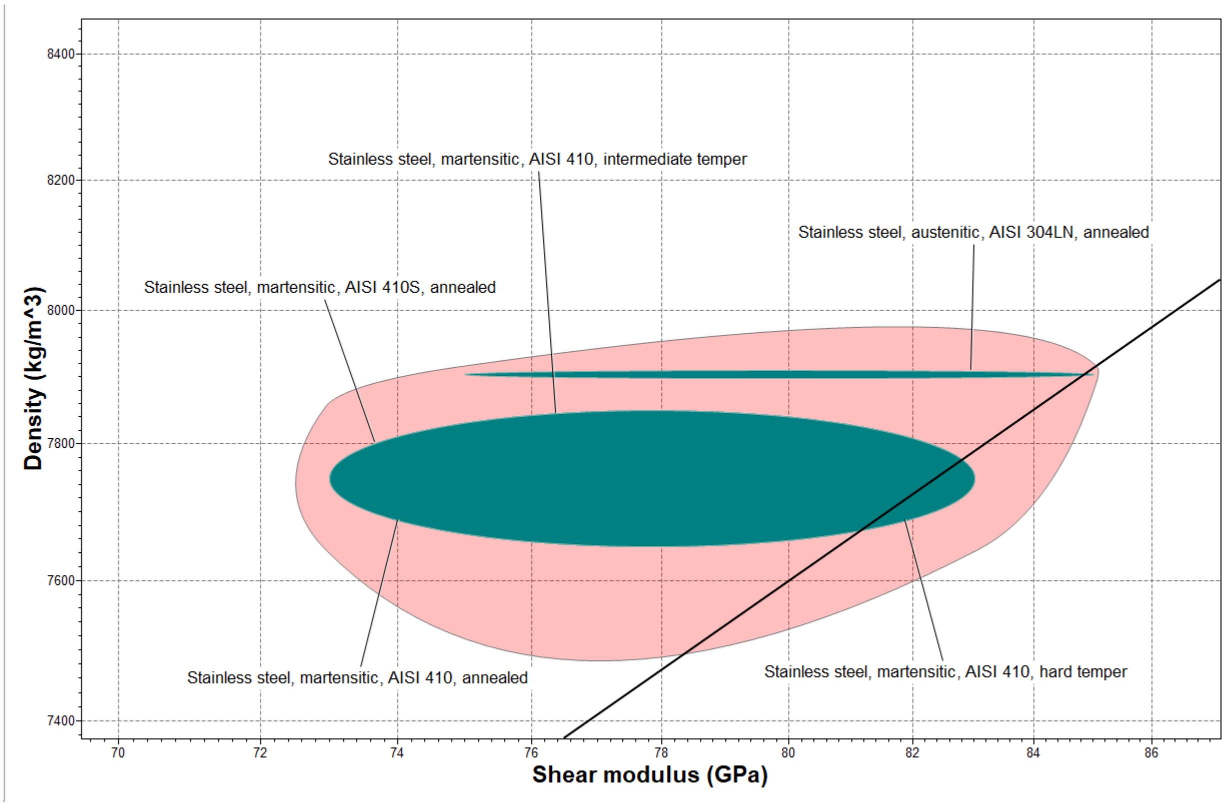

Figure B.8: Axle Turbine (Density vs Shear modulus)

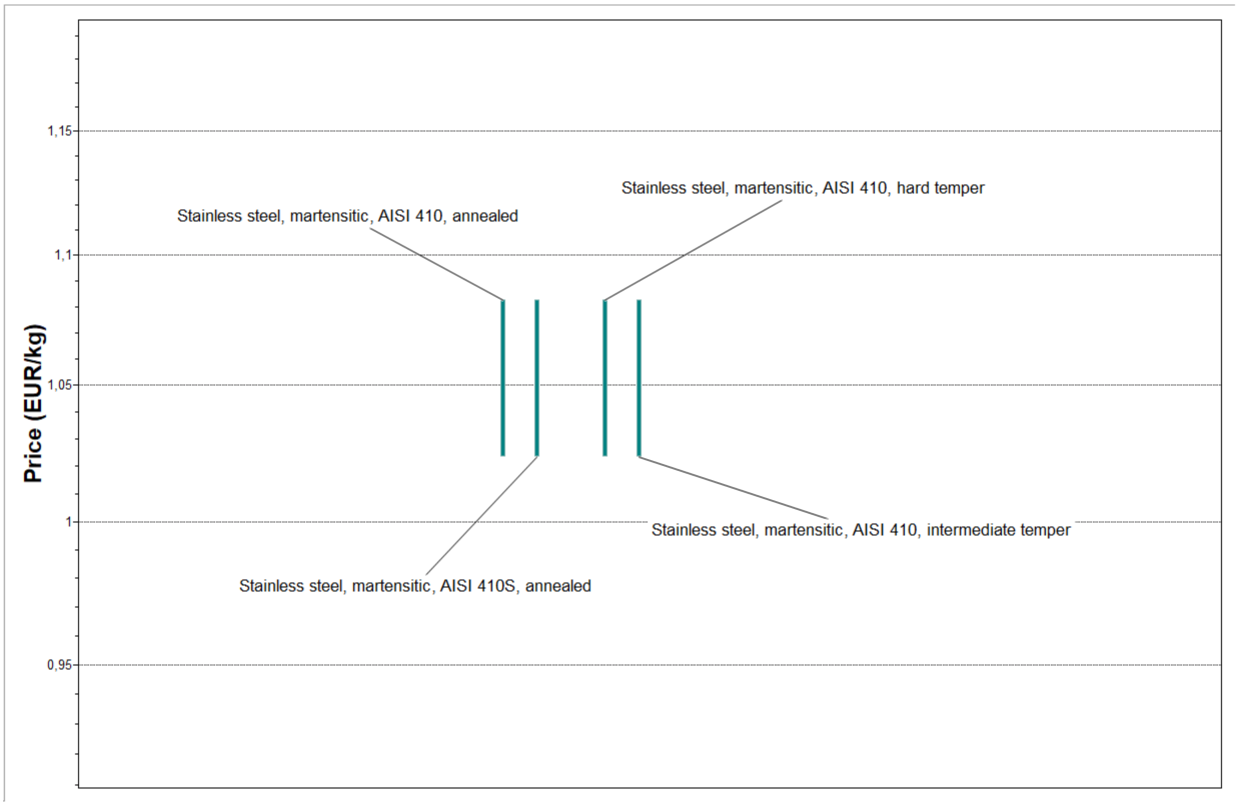

Figure B.9: Axle Turbine (Price)

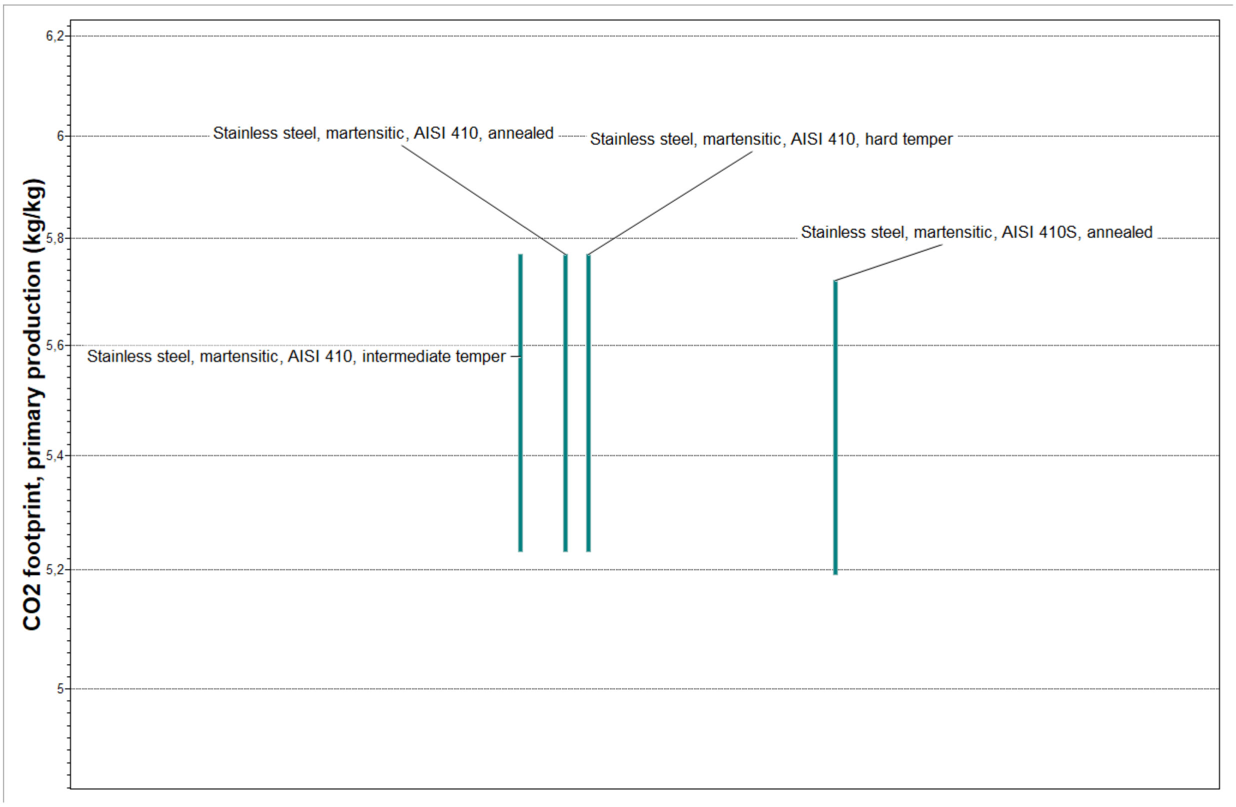

Figure B.10: Axle Turbine (CO_2)

B.4 Heat Exchanger: Pipes

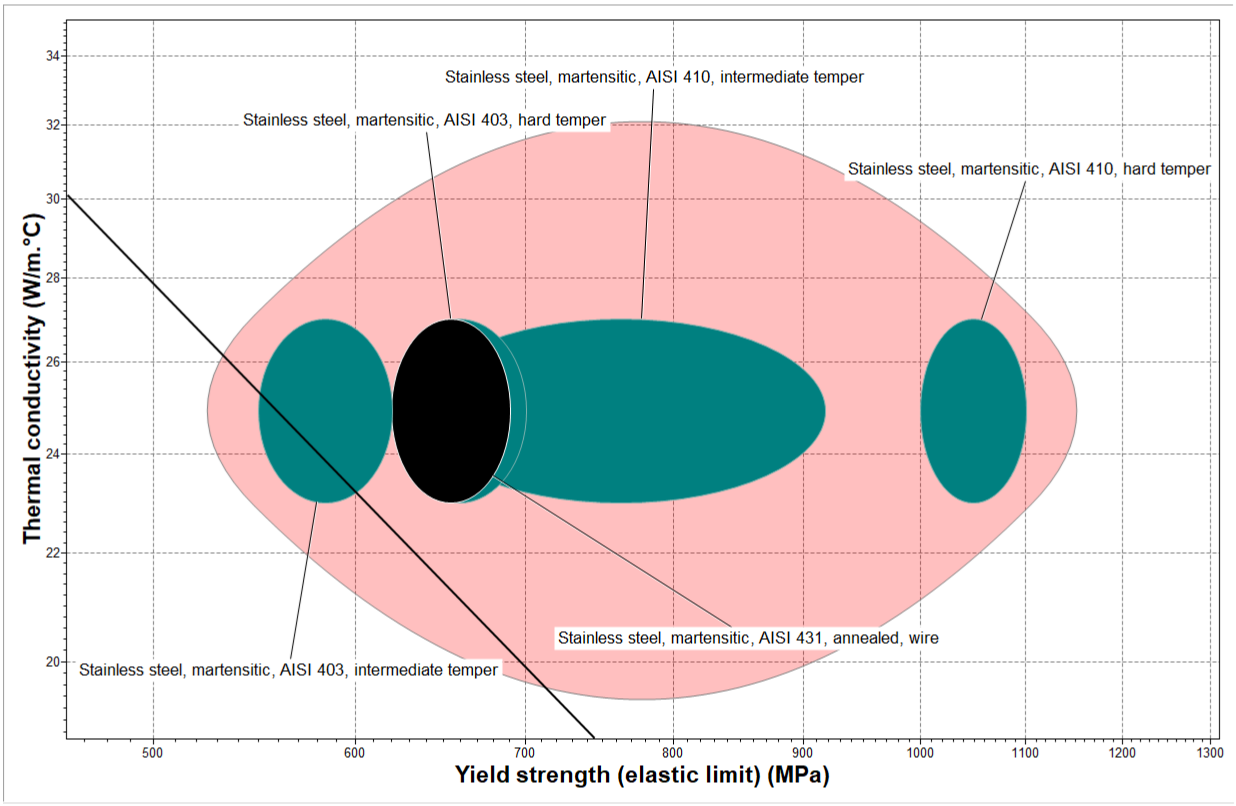

Figure B.11: HEX Pipes (Thermal Conductivity vs Yield Strength)

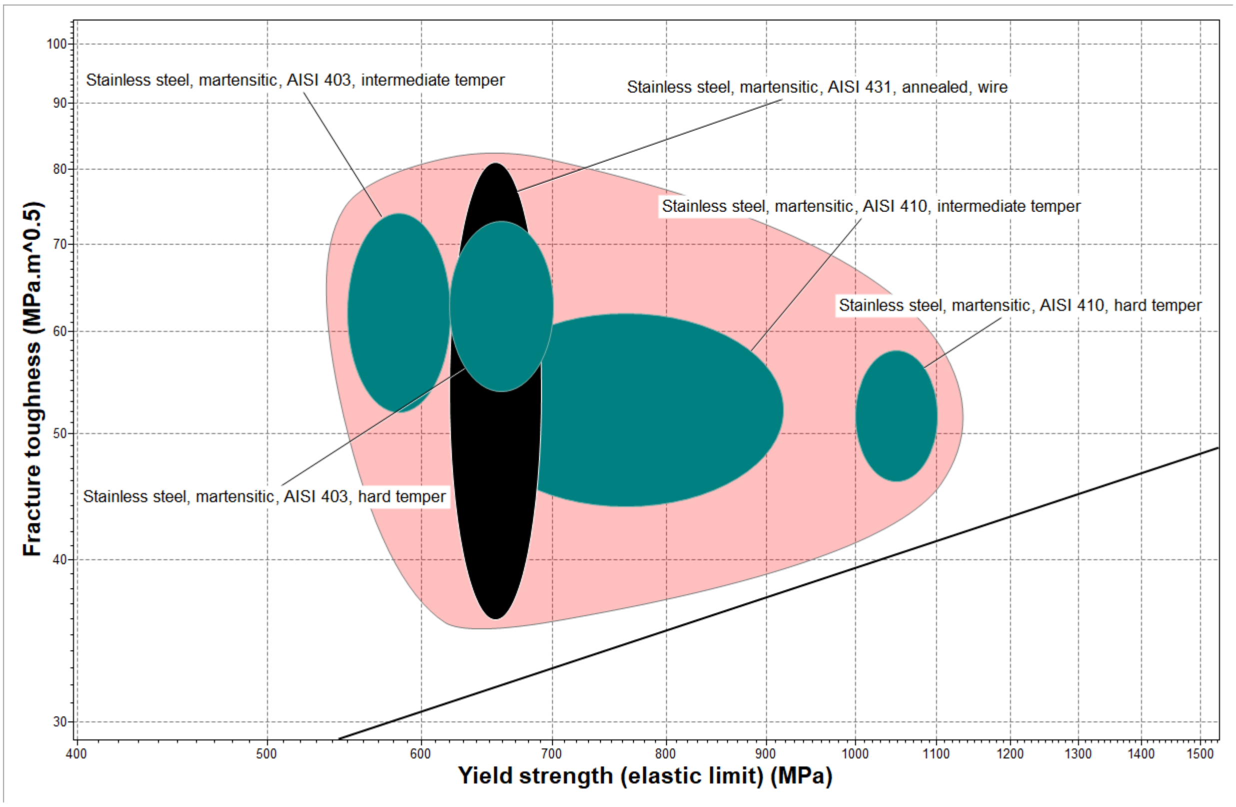

Figure B.12: HEX Pipes (Fracture Toughness vs Yield Strength)

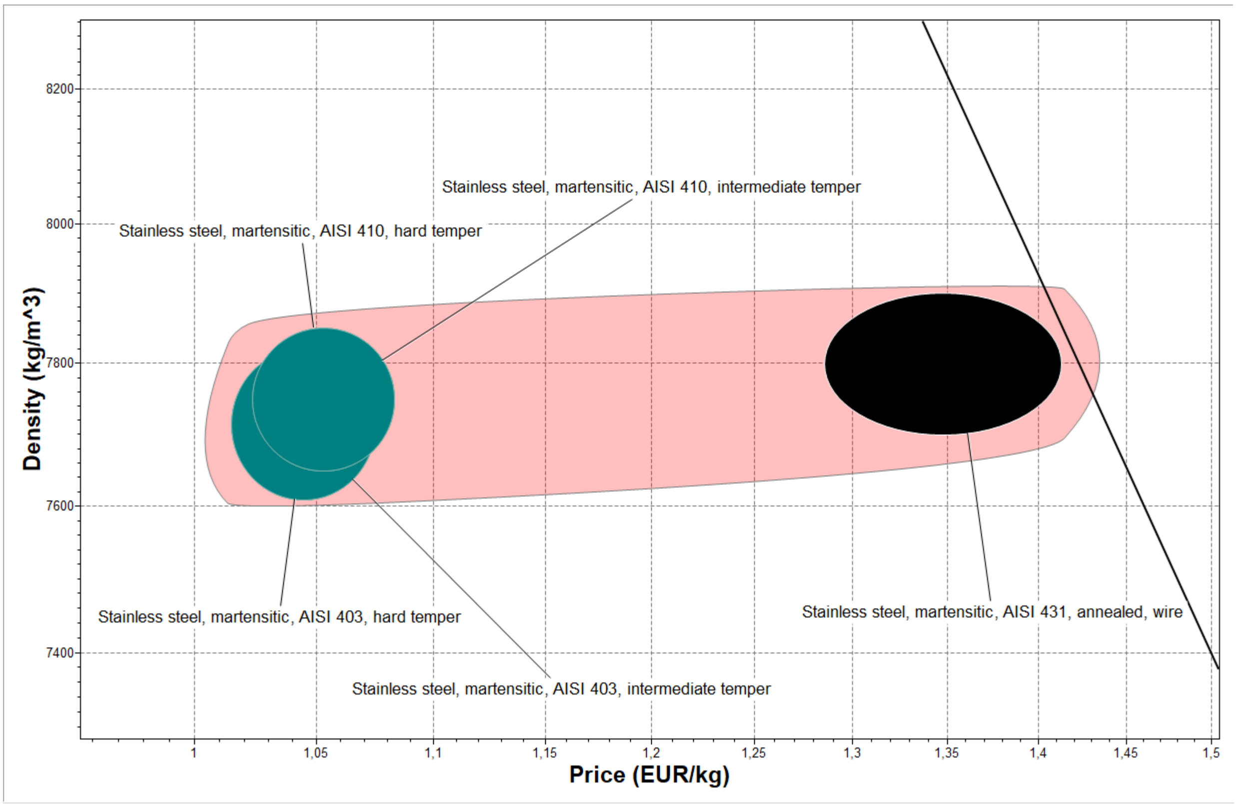

Figure B.13: HEX Pipes (Density vs Price)

Figure B.14: HEX Pipes (CO_2)

B.5 Heat Exchanger: Housing

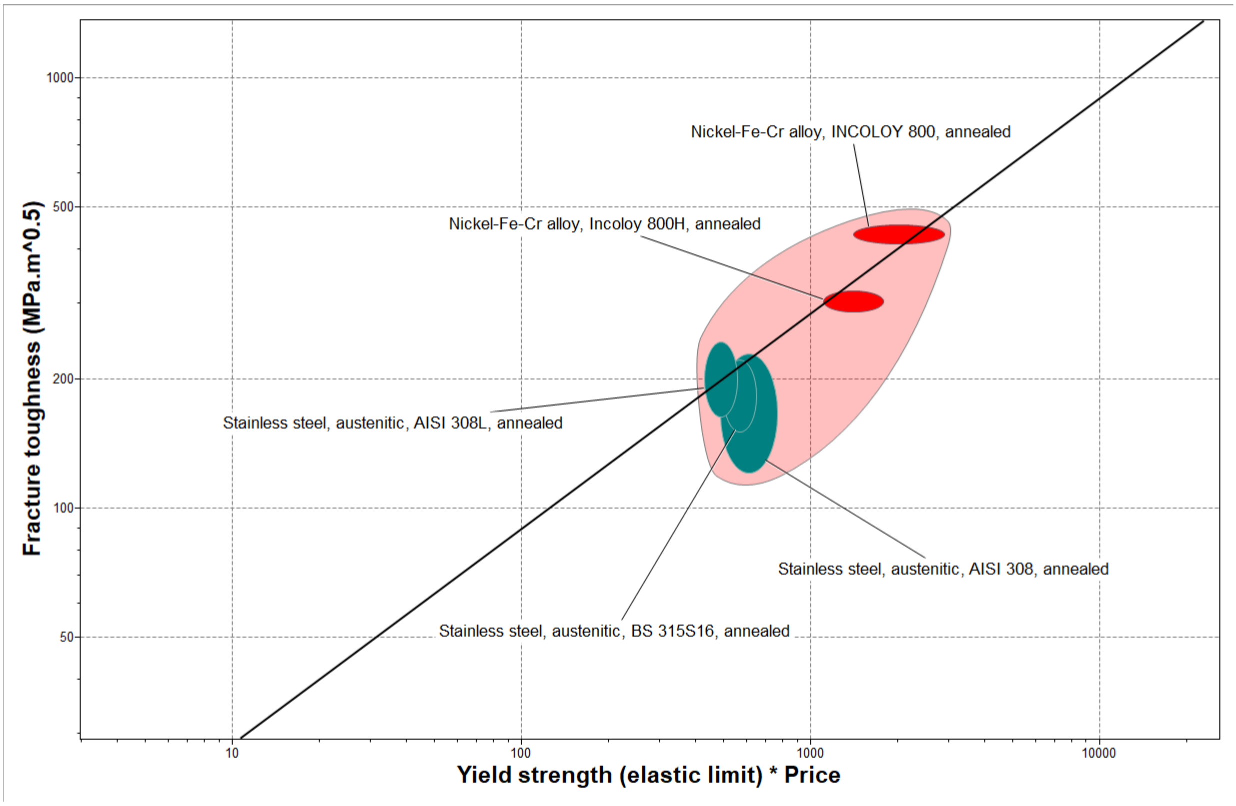

Figure B.15: HEX Housing (Fracture toughness vs Yield Strength)

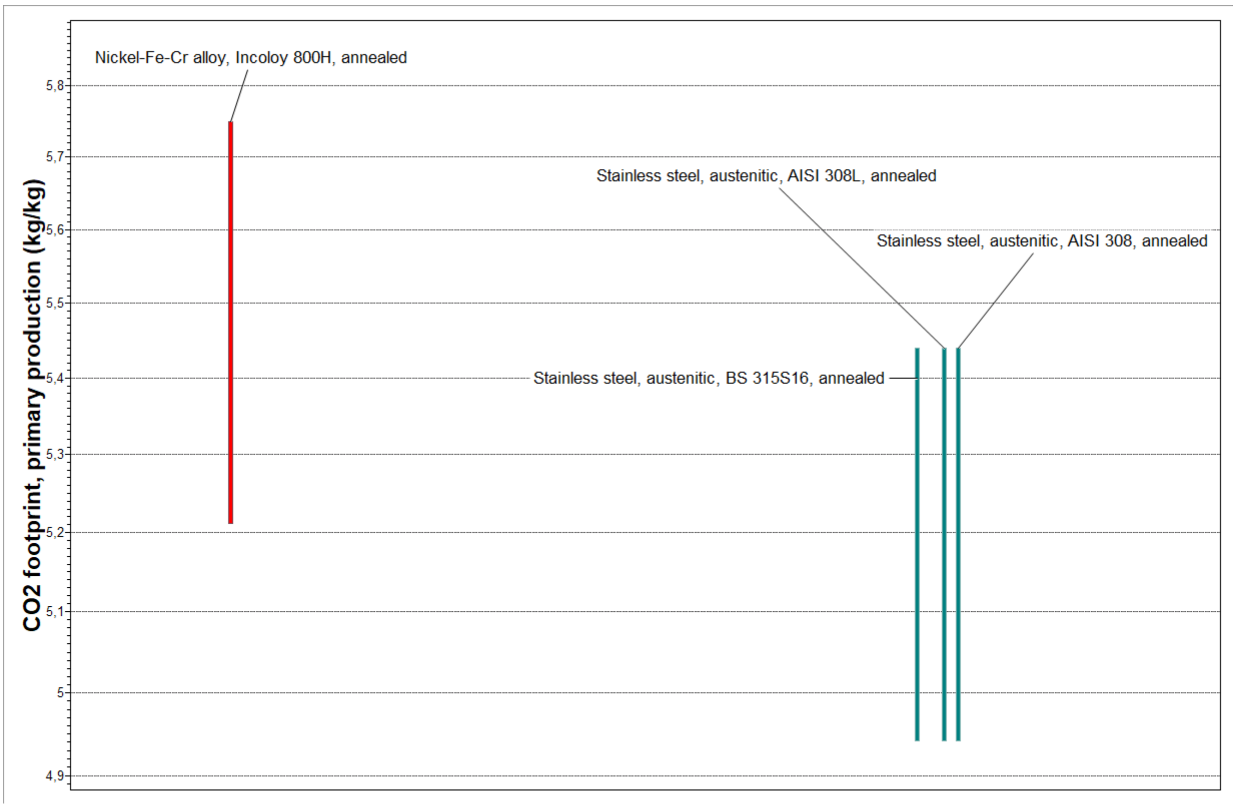

Figure B.16: HEX Housing (CO2)

B.6 Materials selection table

group		Remarks	*turbine blades*	*turbine shaft*
16	Performance index	Please put relevant equation for each of the components	Equation 4.14 & Equation 4.21	Equation 4.27
	Material	Please put selected material here	Nickel-Mo-Cr alloy, HASTELLOY C-276	Stainless steel, martensitic, AISI 410, hard temper
	T (°C)	Please put relevant temperature here	Working temperature 328 to 600 °C. Minimum melting temperature 1500 °C	Working temperature 328 to 600 °C. Minimum melting temperature 1500 °C
	p (bar)	Please put relevant pressure here	Working pressure between 8 and 60 Bar	Working pressure between 8 and 60 Bar
	Deriviation purpose	Indicate in a few words the purpose of the performance index. For example: lowest price, highest specific stiffness, etc.	Resistance to centrifugal loading Maximise fracture toughness	Minimise mass
	Production method(s)	How do you think the part will be produced? What are the major production steps (for example: casting, forging, heat treatment, etc.)?	Forging	Forging
	Important material requirements based on thermomechanical conditions, working principles and manufacturing	Compose a list of the important material requirements. For example stiffness, strength, etc.	Fracture thoughness, fatigue strength, corrosion resistance, price, maximum surface temperature, creep resistance, CO2 footprint	Yield strength, fracture toughness, price, density, maximum surface temperature, creep resistance, CO2 footprint
	Other remarks	Add possible remarks whenever necessary. Keep short	The blades of the intermediate pressure turbine are internaly cooled to prevent creep occurrence	

Figure B.17: Materials Selection Table

turbine housing	heat exchanger internal pipe	heat exchanger housing
Equation 4.5	Equation 4.32 & Equation 4.37 & Equation 4.41	Equation 4.46
Carbon steel, SA216, (Type WWC), cast, normalized & tempered	Stainless steel, martensitic, AISI 410, hard temper	Stainless steel, austenitic, AISI 308L, annealed
Working temperature 328 to 600 °C. Minimum melting temperature 1500 °C	Working temperature 146 to 600 °C. Minimum melting temperature 1500 °C	Working temperature 146 to 600 °C. Minimum melting temperature 1500 °C
Working pressure between 8 and 60 Bar	Working pressure 200 bar	Working pressure 200 bar
Resistance to leaking	Leak before fracture Maximise heat transfer Minimise mass	Resistance to leaking
Sand casting	Hot extrusion	Cylindrical rolling
Fracture toughness, yield strength, thermally isulative (although could be done externally), maximum surface temperature, creep resistance	Fracture thougness, yield stress, thermal conductivity, density, price, maximum surface temperature, CO2 footprint (primary production), creep resistance	Fracture toughness, yield strength, thermally isulative (although could be done externally), maximum surface temperature, creep resistance
The housing has an external insulation layer for minimum heat loss to the environment	The internal pipes are made of finned tubes to increase surface area and thereby heat transfer	The housing has an external insulation layer for minimum heat loss to the environment

Figure B.18: Materials Selection Table

C LCA content

C.1 Definitions midpoint effects

1. **Climate change (cc)**
Climate change is a change in the statistical distribution of weather patterns when that change lasts for an extended period of time. Climate change is caused by factors such as biotic processes, variations in solar radiation received by Earth, plate tectonics, and volcanic eruptions and certain human activities have been identified as primary causes of ongoing climate change, often referred to as global warming. Global warming brings a lot of consequences for the world we live in: More frequent and severe weather conditions, because higher temperatures are worsening many types of disasters, including storms, heat waves, floods, and droughts. A warmer climate creates an atmosphere that can collect, retain, and drop more water, changing weather patterns in such a way that wet areas become wetter and dry areas drier. Increasing temperatures in places where people aren't used to it will also cause severe health problems. It will also worsen air pollution by increasing ground-level ozone. Higher wildlife extinction rates, because species will disappear if they don't adapt quickly enough to the changing environment. More acidic oceans, due in large part to their absorption of some of our excess emissions. Higher sea levels, because the polar regions are particularly vulnerable to a warming atmosphere.

2. **Ozone depletion (od)**
Ozone depletion is the gradual thinning of Earth's ozone layer in the upper atmosphere caused by the release of chemical compounds containing gaseous chlorine or bromine from industry and other human activities. The thinning is most pronounced in the polar regions, especially over Antarctica, which is referred to as the ozone hole. Ozone depletion is a major environmental problem because it increases the amount of ultraviolet (UV) radiation that reaches Earth's surface, which increases the rate of skin cancer, eye cataracts, and genetic and immune system damage.

3. **Terrestrial acidification (ta)**
Terrestrial acidification is the global threat to the diversity of plants and is mainly caused by atmospheric deposition of acidifying compound. Emissions of SO2 and NOx which come mainly from cities and industries causes acidifications of the atmosphere and ecosystems. The pH of the water will be lower. Acificiation threatens aquatic organisms as most cannot exist in water below pH 4.0. These species will disappear due to the acidification. Soils may also be affected if the supply of neutralizing substances declines. Decreased crop production and reduced forest growth rate may result. The balance of nature is disturbed by the present atmospheric pollution of sulfuric and other acids. The unit of terrestrial acidification is kg-SO2 to air. This means that the effect of every substance will be expressed relative to the effect that 1 kg SO2 has to the environment.

4. **Freshwater eutrophication (fe)**
Freshwater eutrophication is caused by plant and algal growth due to the increased limiting growth factors for photosynthesis(sunlight, carbon dioxide and nutrient fertilizers). Freshwater eutrophication is mainly caused by nutrient pollution in the form of phosphorous from agricultural fertilizers, sewage effluent and urban stormwater runoff. Eutrophication takes place over centuries because lakes age and are filled with sediments. Eutrophication reduces water clarity and harms quality. Light penetration is reduced which leads to a reduction in growth and an increase in dying plants and predators that need the light. The high rate of photosynthesis can deplete dissolved inorganic carbon and raise the pH of the water. When the algal dies the, microbial decomposition severely depletes dissolved oxygen, creating a 'dead zone' with a lack of oxygen for most organisms. Most of the organisms will die. The unit of freshwater eutrophication is kg P to fresh water.This means that the effect of every substance will be expressed relative to the effect that 1 kg P has on the environment.

5. **Marine eutrophication (me)**
Eutrophication occurs when there is an enrichment of organic matter to ecosystems. This happens mainly because of an increase in nutrients caused by the discharge of nitrate or phosphate emissions to the atmosphere by fossil fuel combustion. This increase in nutrients causes a great amount of organic matter to grow, consuming a lot of the oxygen of the water body. Specifically, marine eutrophication happens in coastal regions. Ecological and economic effects can be caused, for example through the creation of anoxic zones(areas depleted of dissolved oxygen which means a threat to marine life) and toxic cyanobacteria bloom (Toxic blooms that poison and kill animals or humans).

6. **Human toxicity (ht)**
The emission of some substances can have a negative effect on human health. Human toxicity is the degree to which a certain chemical substance or combination of specific substances can damage an organism, in

this case, a human being. In the LCA, it is useful to weight the emissions in terms of a reference compound which in this case is divided between carcinogens and noncarcinogens.

7. **Photochemical oxidant formation (pof)**
   Photochemical smog is a type of air pollution due to the reaction of solar radiation with airborne pollutant mixtures of nitrogen oxides (NOx) and volatile organic compounds (hydrocarbons). Emission of Nitrogen from car exhausts is the biggest source of the causing emissions. These emissions are Nitrogen oxides and hydrocarbons react with light to create smog. The unit of Photochemical Oxide Formation is kg NOx eq.

8. **Particulate matter formation (pmf**
   Particulate matter forming is an effect because it damages the human health. This damage is caused by emitted NOx, NH2 and SO3 that turn into secondary aerosols. These aerosols are suspensions of fine solid particles or liquid droplets. Intake of these secondary aerosols and other particles such as PM2.5 cause damage to the human health. It shortens the life time and can even lead to death. This effect is measured in kg intake per kg emission.

9. **Terrestrial ecotoxicity (tet)**
   Terrestrial ecotoxicity are the effects of certain substances to terrestrial plants and organisms. Usually, these substances have a negative effect and they have the potential to disrupt an existing ecosystem. Pesticide emissions and sulphuric acid or steam are important substances that have a big terrestrial ecotoxicity. Farmers often use pesticides to protect their crops, but this can have a negative effect on the ecosystem surrounding it. The unit for terrestrial toxicity is kg 1,4-DB eq. (DB is dichlorobenzene). This means that the effect of every substance will be expressed relative to the effect that 1 kg of dichlorobenzene has on the environment.

10. **Freshwater ecotoxicity (fet)**
    These are the effects of emissions on freshwater sources. The unit for freshwater ecotoxicity is kg-DB eq. just like with terrestrial ecotoxicity. Certain substances can change the water's solubility and composition. As a result, the system's life can be altered. For example, certain species will die or thrive with the death of other species as a result.

11. **Marine ecotoxicity (met)**
    This is similar to freshwater ecotoxicity except it focuses around the Oceans. This contains effects such as pollutants and global warming altering life within the ocean, not just for the animals but also for the plants, the soil and the water. This is obviously linked to human activity, and since it can and is endangering a multitude of species, including our own, it is incremental to analyse and examine the changes and effects on the marine environments.

12. **Ionising radiation (ir)**
    Ionising radiation encompasses the types of radiation that have enough energy to detach nuclei from atoms. The particles responsible move at a high speed. This detachment of electrons may cause an element to become unstable, in which case it would become radioactive. The unit for measuring radioactivity is in Becquerel (Bq). This radiation exists everywhere in small quantities, and is relatively harmless in these small quantities. However, being exposed to an increased dose of radiation can cause acute health problems. Skin burns and radiation sickness is common, as well as the evident causes to cancer.

13. **Agricultural land occupation (alo)**
    Agricultural land is defined as the land area that is either arable, under permanent crops, or under permanent pastures. Arable land includes land under temporary crops such as cereals, temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow. Land abandoned as a result of shifting cultivation is excluded. Land under permanent crops is cultivated with crops that occupy the land for long periods and need not be replanted after each harvest, such as orchards and vineyards. This category excludes land under trees grown for wood or timber. Permanent pasture is land used for five or more years for forage, including natural and cultivated crops. This indicator is presented as a total and per type of agricultural land and is measured in hectares and in percentage. Other agro-environmental indicators include Organic farmland and Transgenic cropland.

14. **Urban land occupation (ulo)**
    Urban land occupation happens when land use type is maintained over a period of time, leading to a delay in the recovery of land to its potential natural state. The midpoint effect is measured with the unit m2

15. **Natural land transformation (nlt)**
    NLT is the level of which human-beings changed the landscape of a certain area. This can have various reasons. Think of increasing demand of minerals and water due to population growth or think of mining

for resources in mines. The main cause of this effect are humans. This effect is measured with the unit : m2.

16. **Water depletion (md)**
The most important source of water depletion is groundwater depletion. It mostly comes down that groundwater is used more quickly, for example for drinking water, than it comes back. In the long term this can cause problems if the groundwater resources are depleted completely, as that would mean that water would be scarce and either needs to be imported or it must be used much more scarcely. The main problem is the lack of water caused by over usage as mentioned, or by unusable salt water flowing into freshwater sources. The amount of water depletion can be measured as change in depth of water level below the surface, as this is indicative of the change in volume of water. In the USA this is ft below surface, but in SI-countries this would likely be in m (metres) below surface level.

17. **Metal depletion (md)**
Metal depletion is quite similar to water depletion. Metals can't be made as fast as they are being used, which will cause a shortage over a long period of time. The main danger with metal depletion would eventually be a lack in minerals, relative to this the emission of metal depletion is neglectible.

18. **Fossil fuel depletion (fd)**
Same goes for fuel depletion, fossil fuels are being used a lot faster than fossil fuels are made. Which will and is causing problems concerning shortage of fossil fuels. The depletion of fossil fuels does not cause emission, only the eventual shortage of fossil fuels is the main problem.

C.2 ReCiPe Graphs

1. **Climate change (cc)**

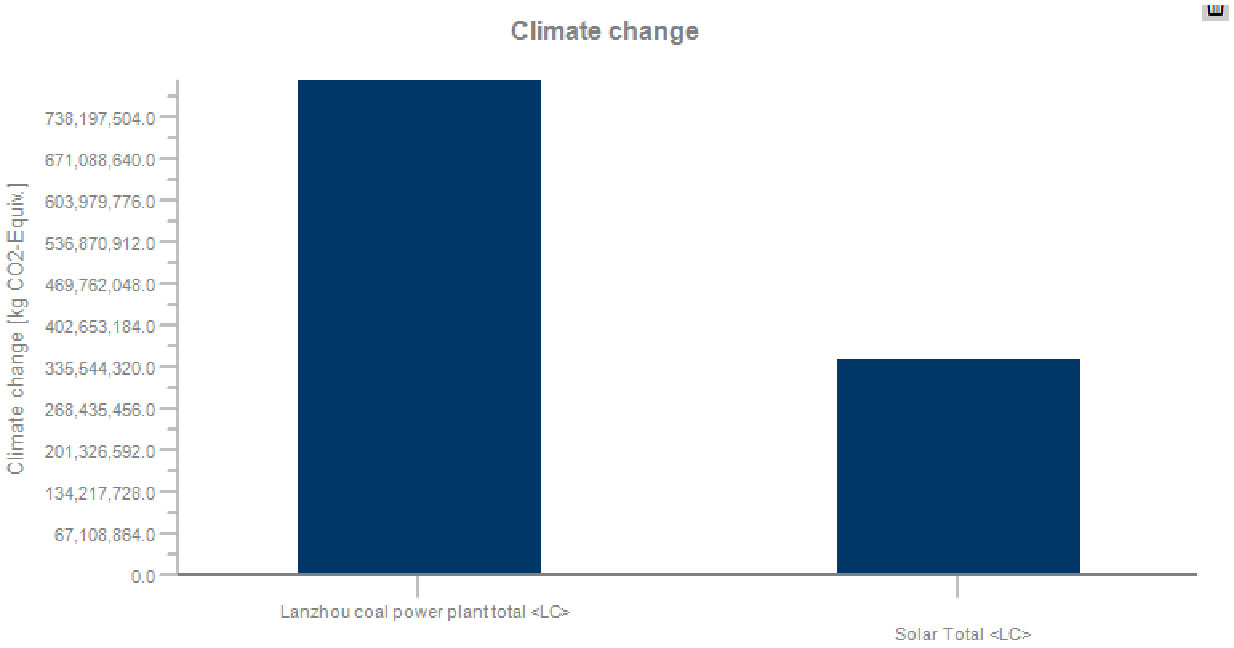

Figure C.1: Climate Change

2. **Ozone depletion (od)**

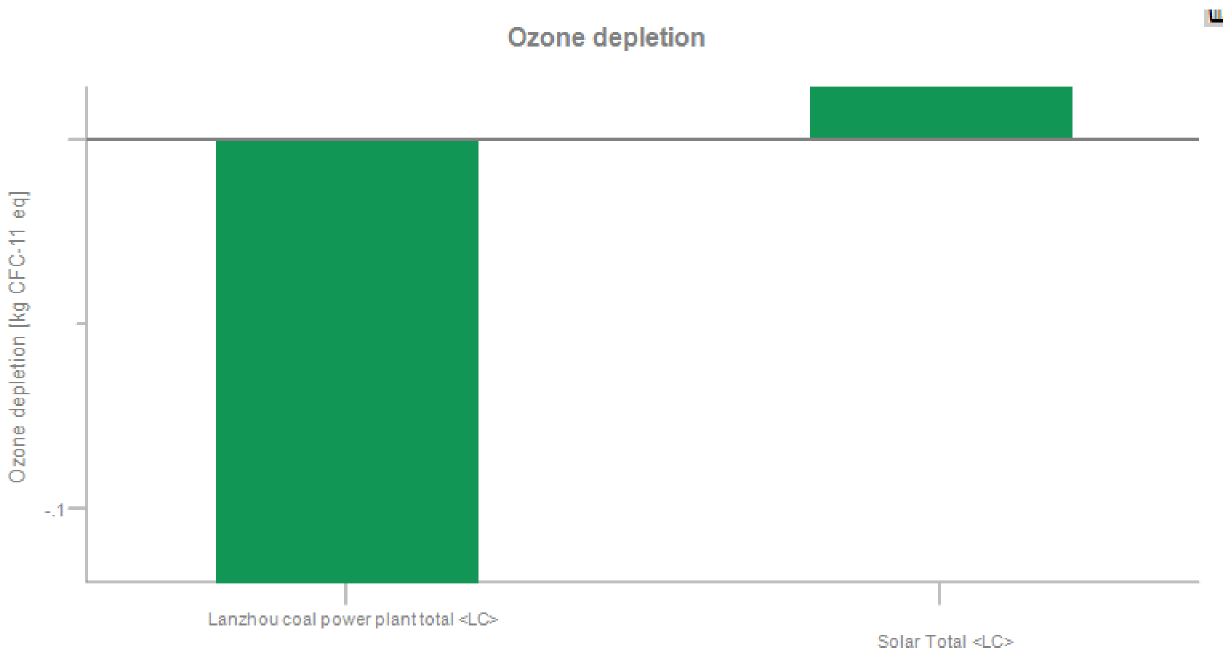

Figure C.2: OzoneDepletion

3. **Terrestrial acidification (ta)**

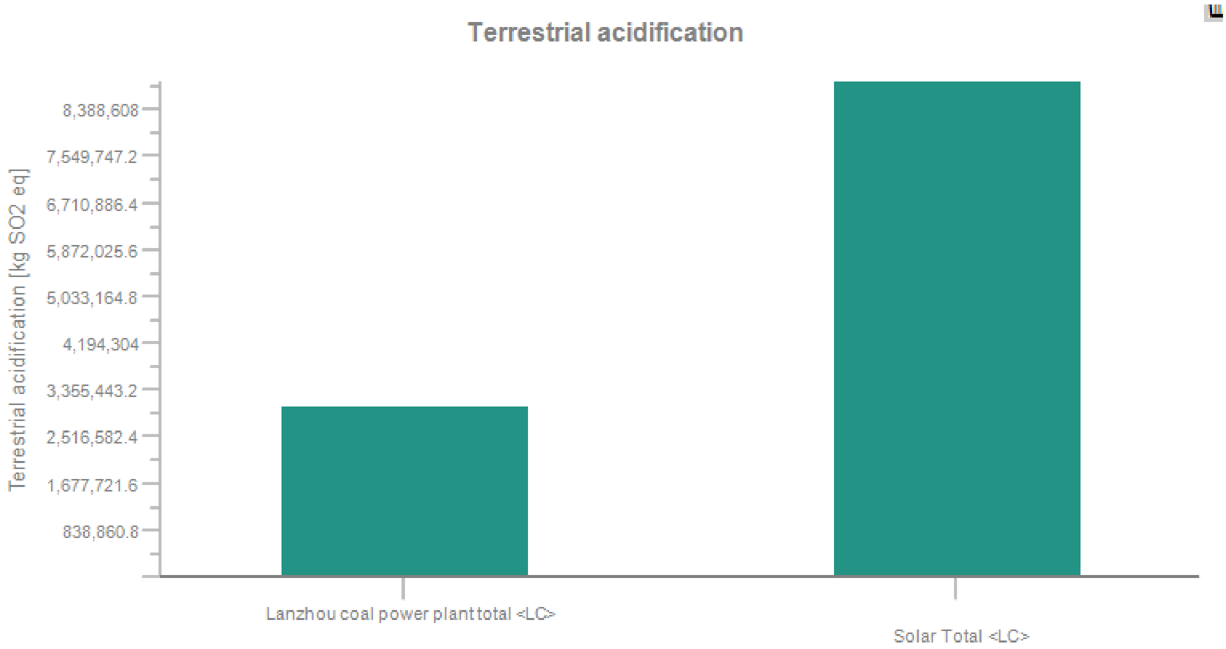

Figure C.3: TerrestrialAcidification

4. **Freshwater eutrophication (fe)**

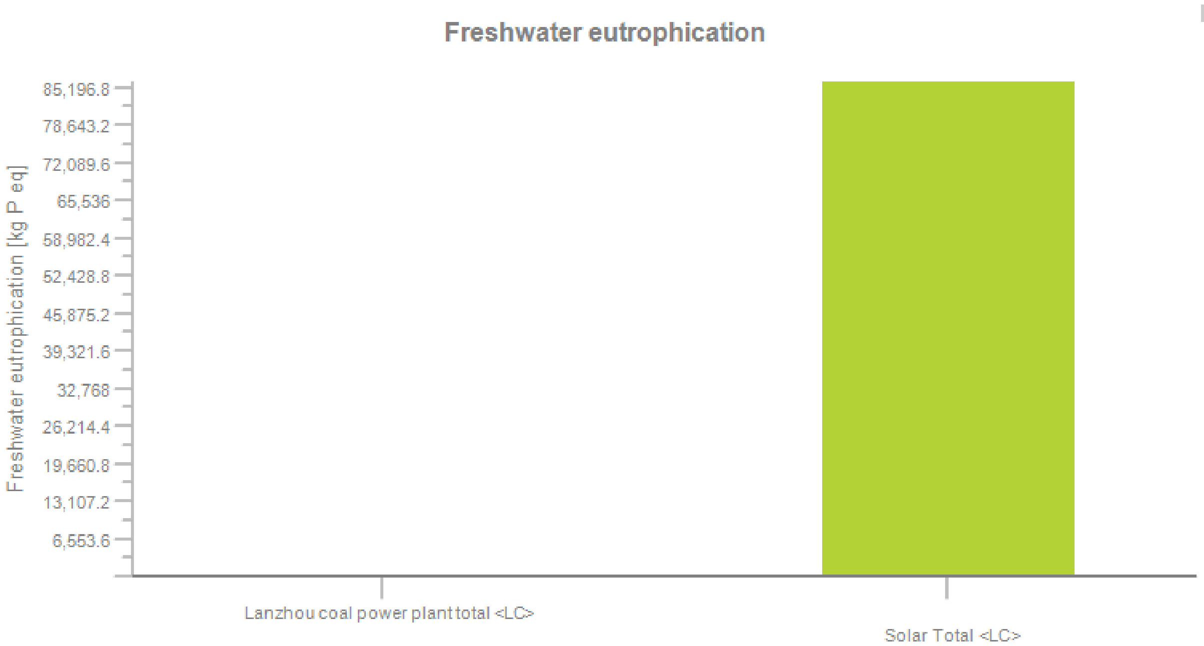

Figure C.4: Freshwater eutrophication

5. **Marine eutrophication (me)**

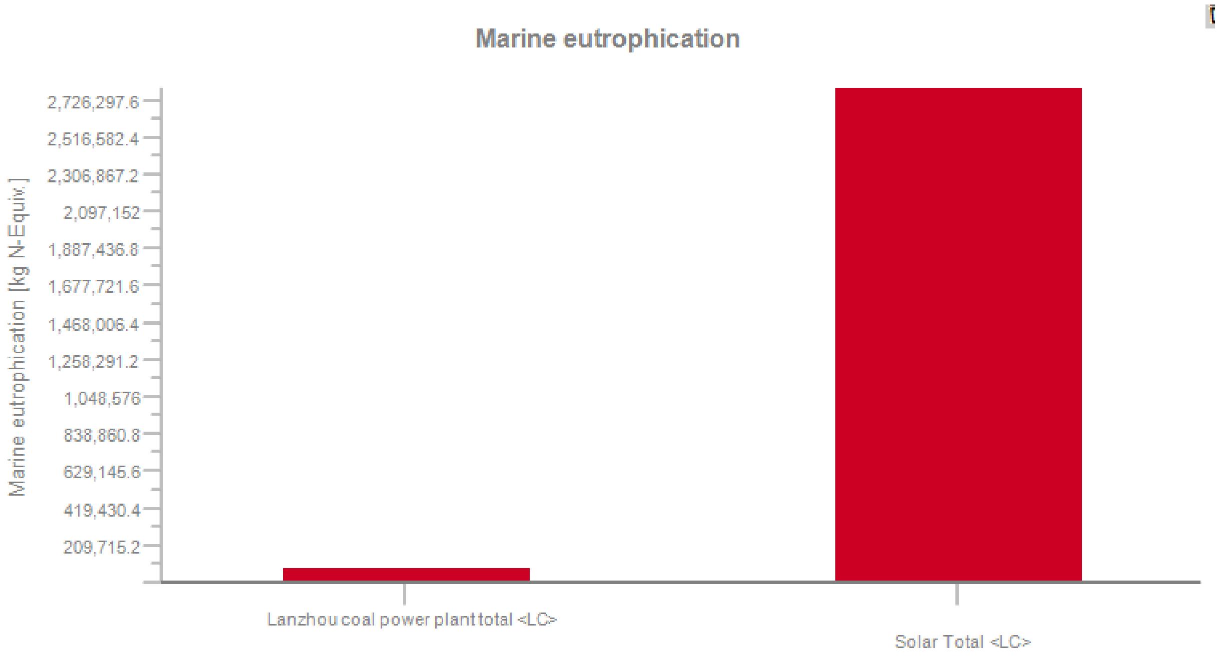

Figure C.5: Marine eutrophication

6. **Human toxicity (ht)**

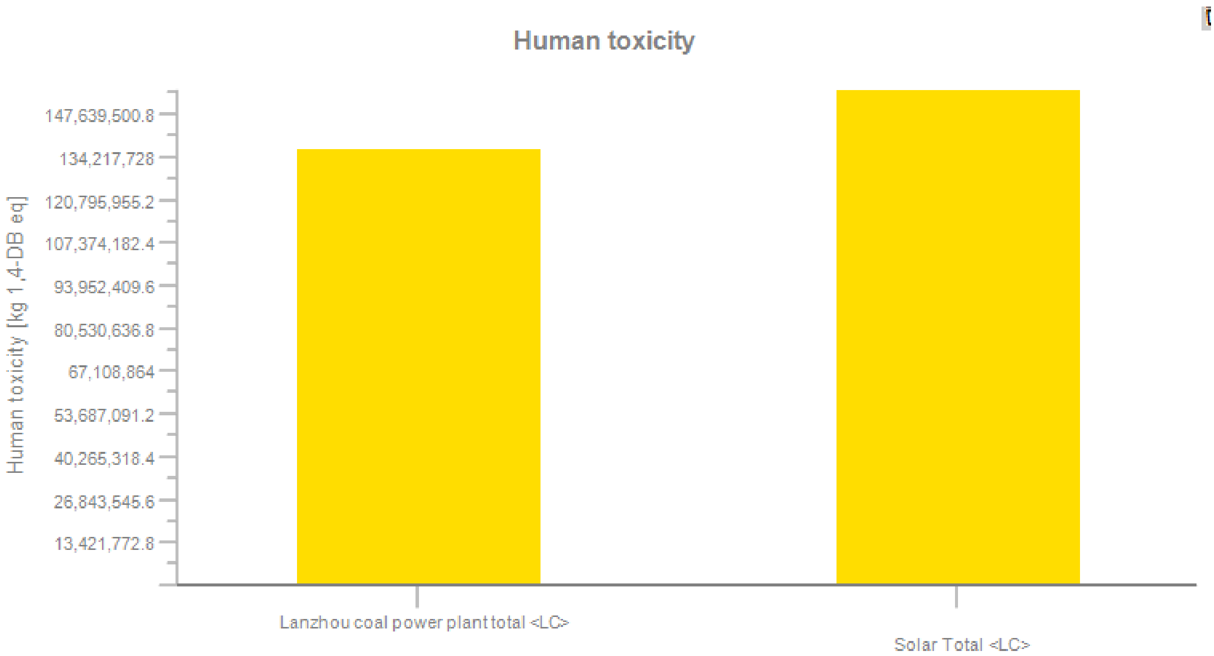

Figure C.6: Human toxicity

7. **Photochemical oxidant formation (pof)**

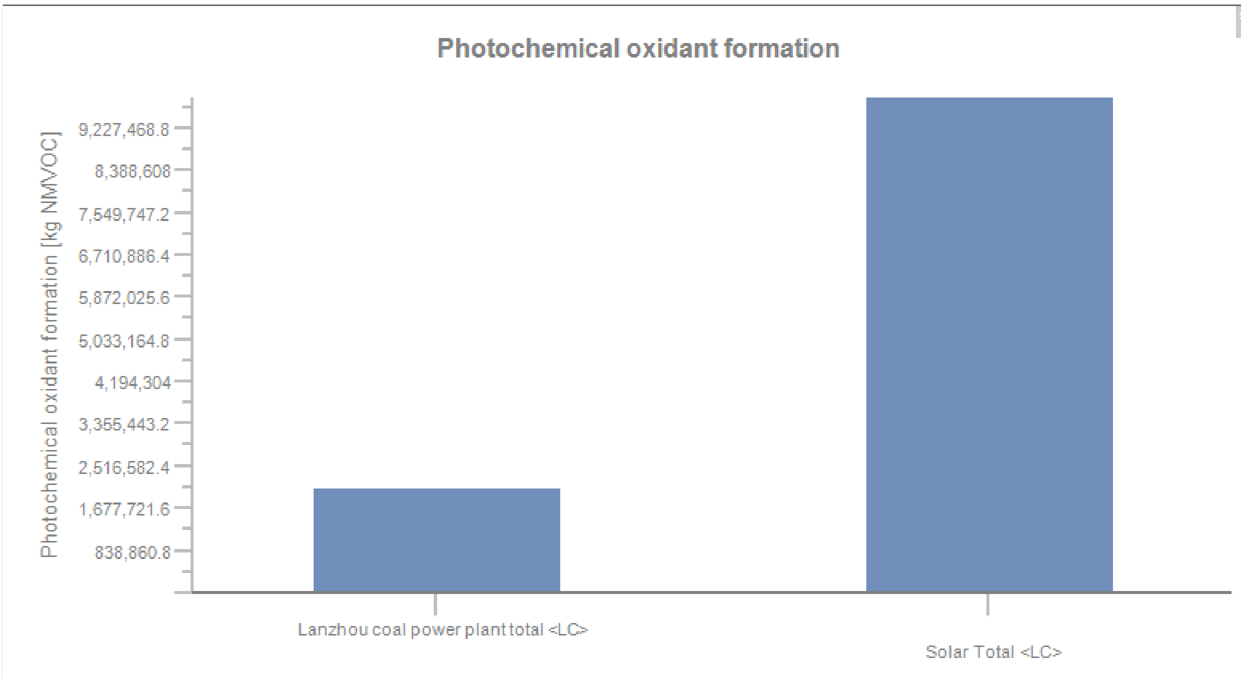

Figure C.7: Photochemical oxidant formation

8. **Particulate matter formation (pmf)**

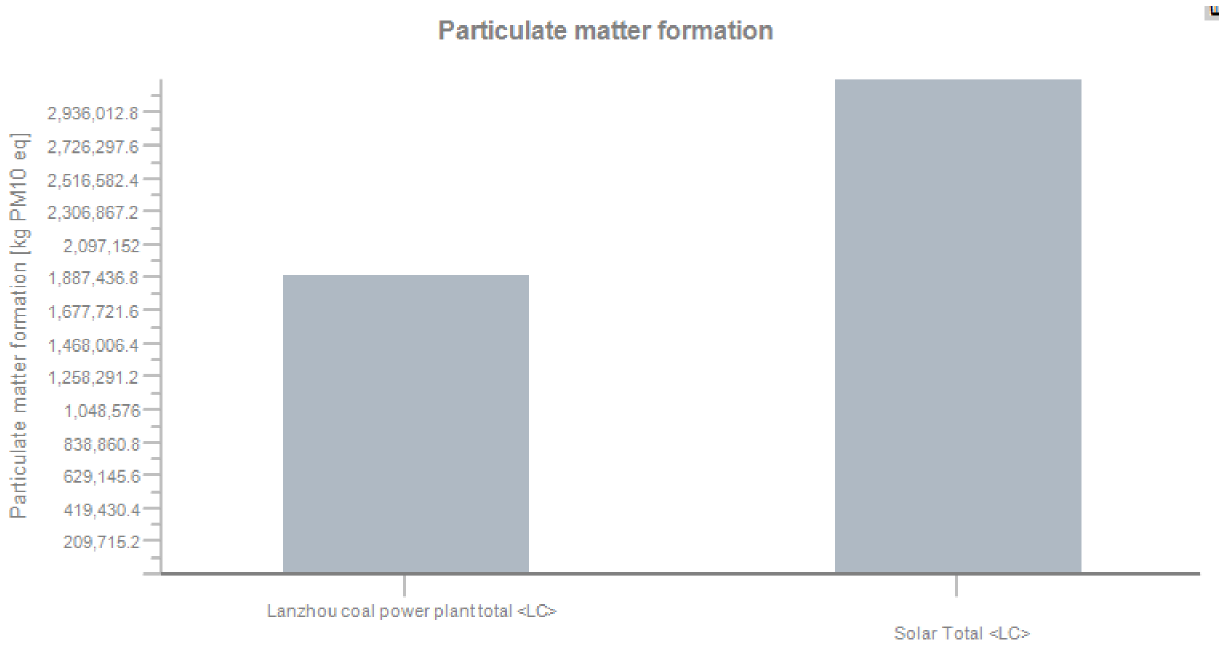

Figure C.8: Particulate matter formation

9. **Terrestrial ecotoxicity (tet)**

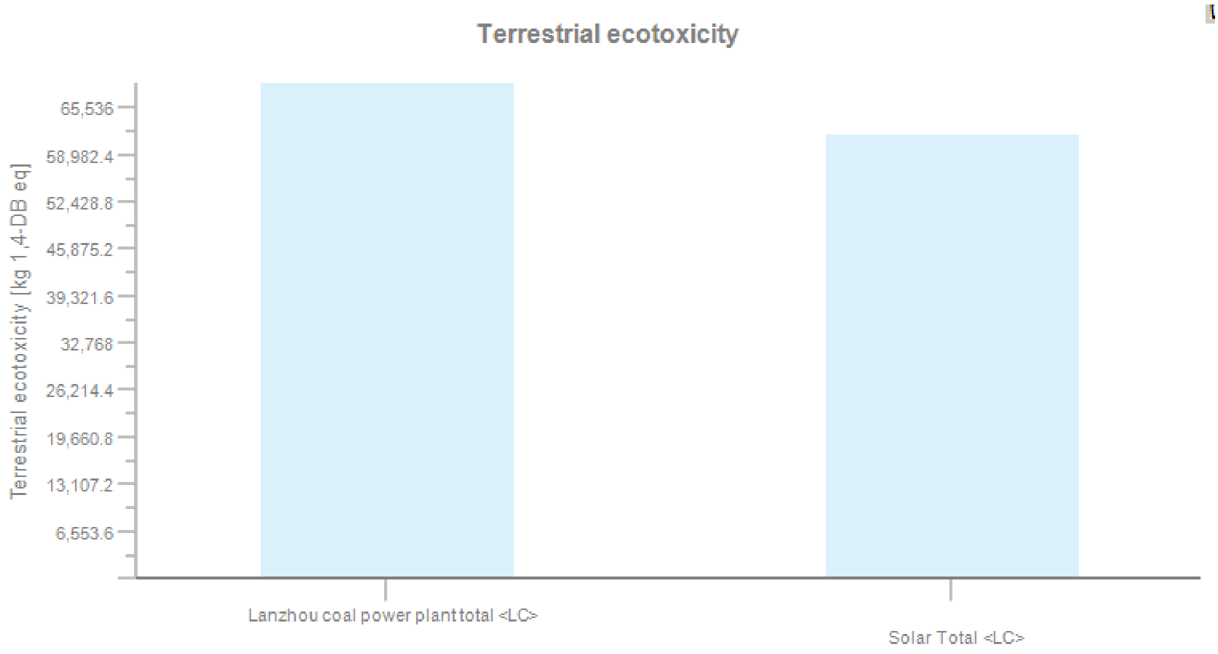

Figure C.9: Terrestrial ecotoxicity

10. **Freshwater ecotoxicity (fet)**

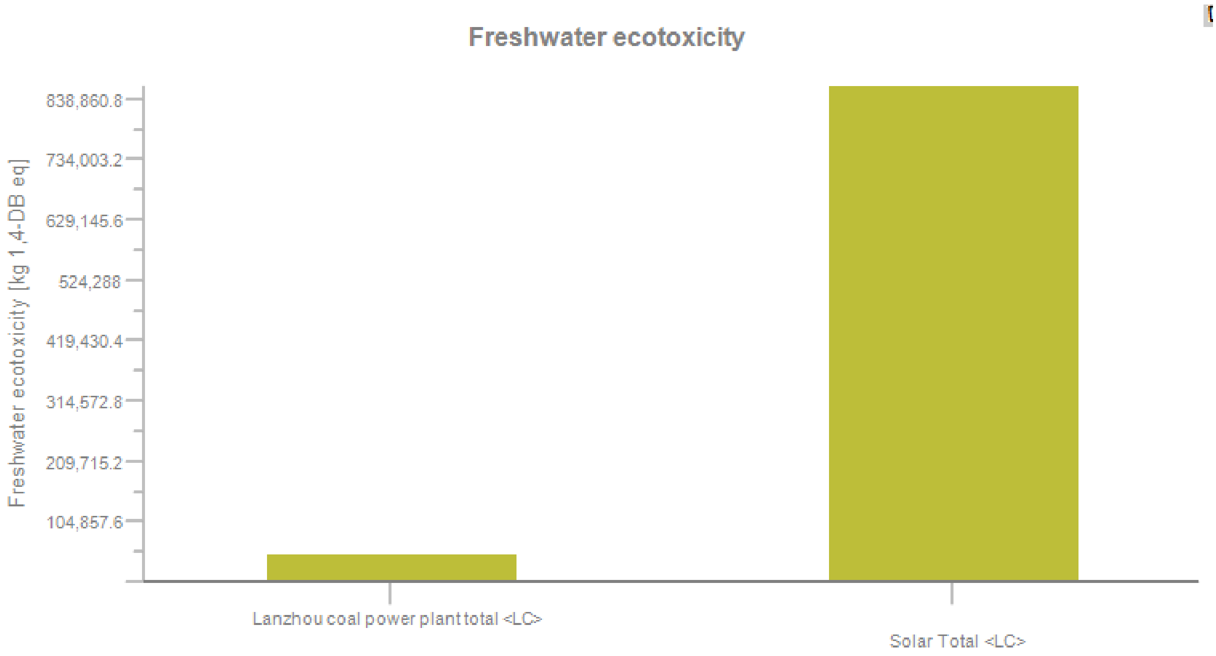

Figure C.10: Freshwater ecotoxicity

11. **Marine ecotoxicity (met)**

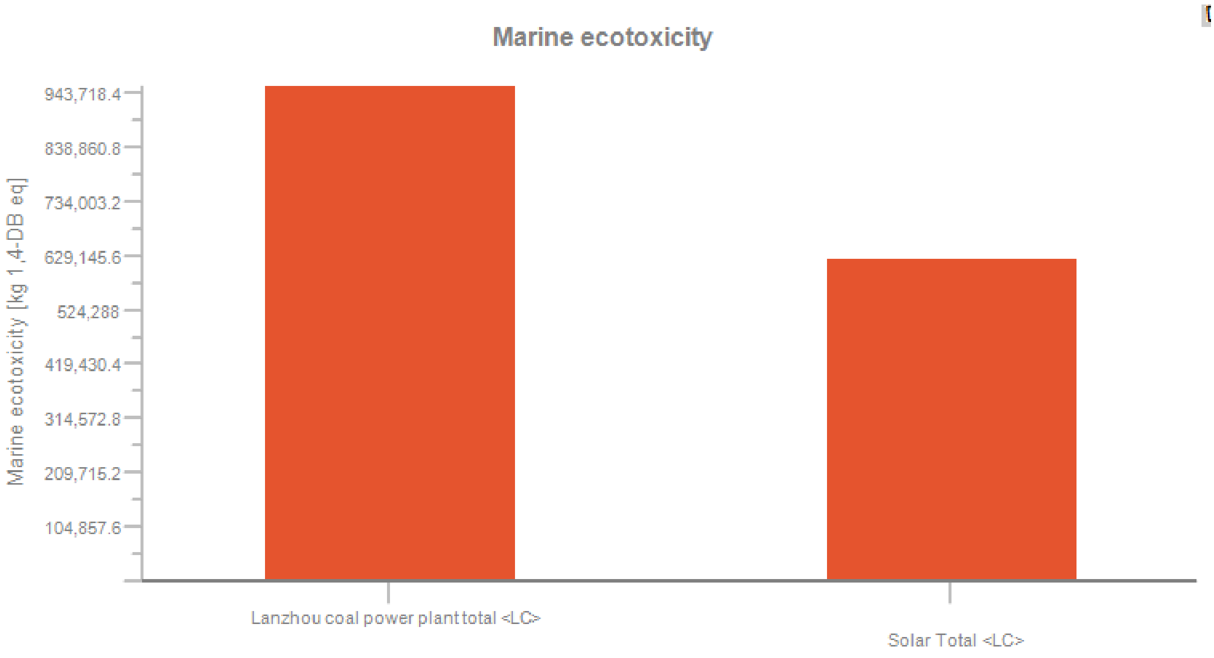

Figure C.11: Marine ecotoxicity

12. **Ionising radiation (ir)**

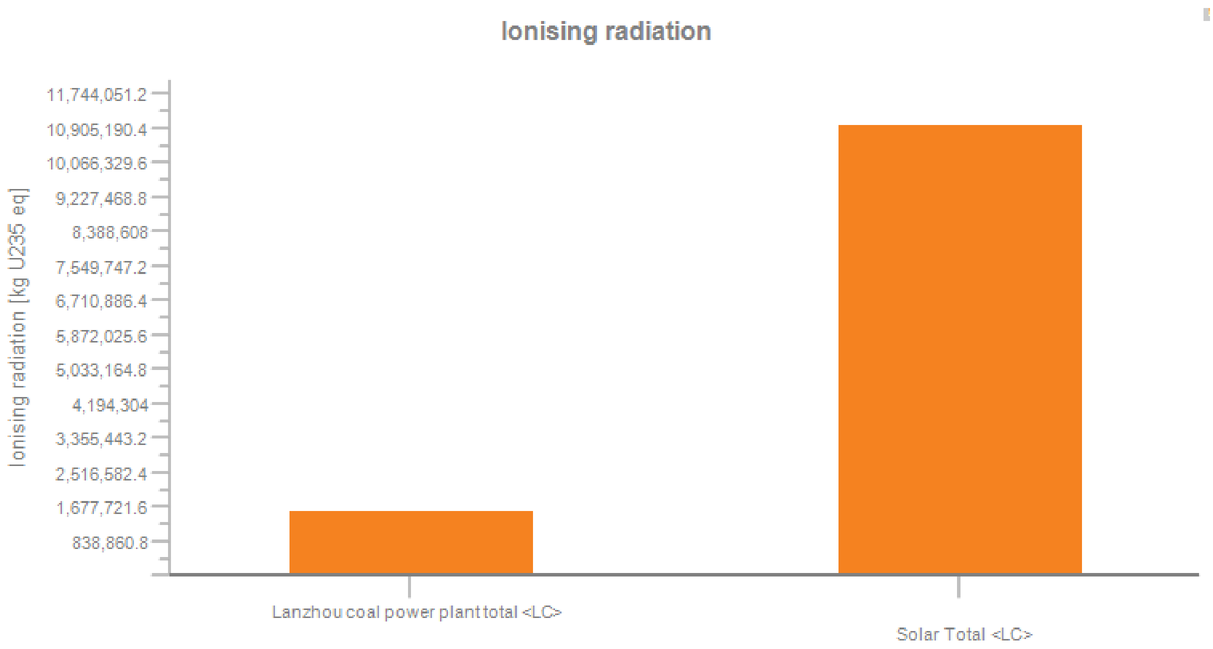

Figure C.12: Ionising radiation

13. **Natural land transformation (nlt)**

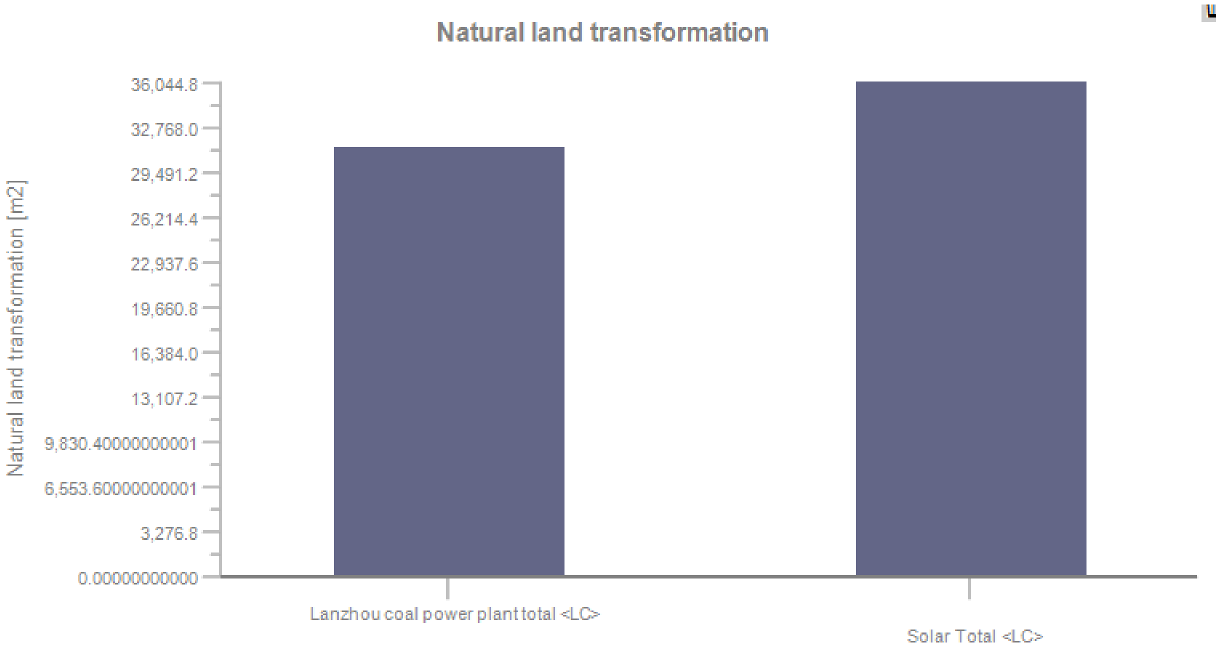

Figure C.13: Natural land transformation

14. **Water depletion (md)**

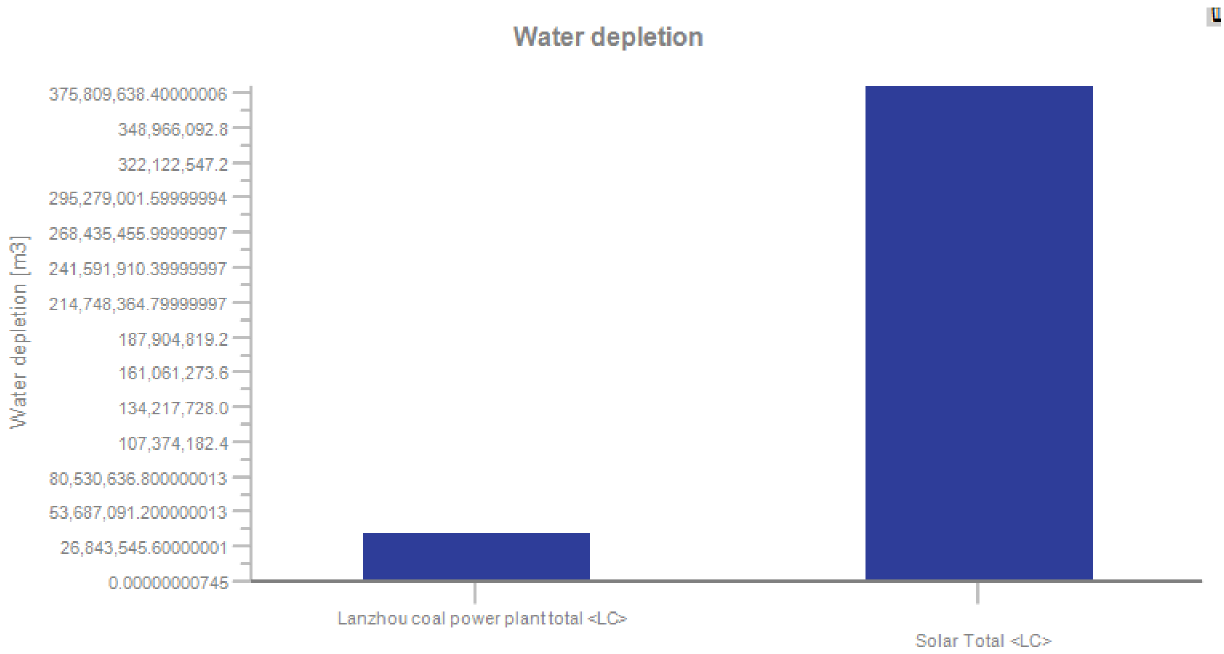

Figure C.14: Water depletion

15. **Metal depletion (md)**

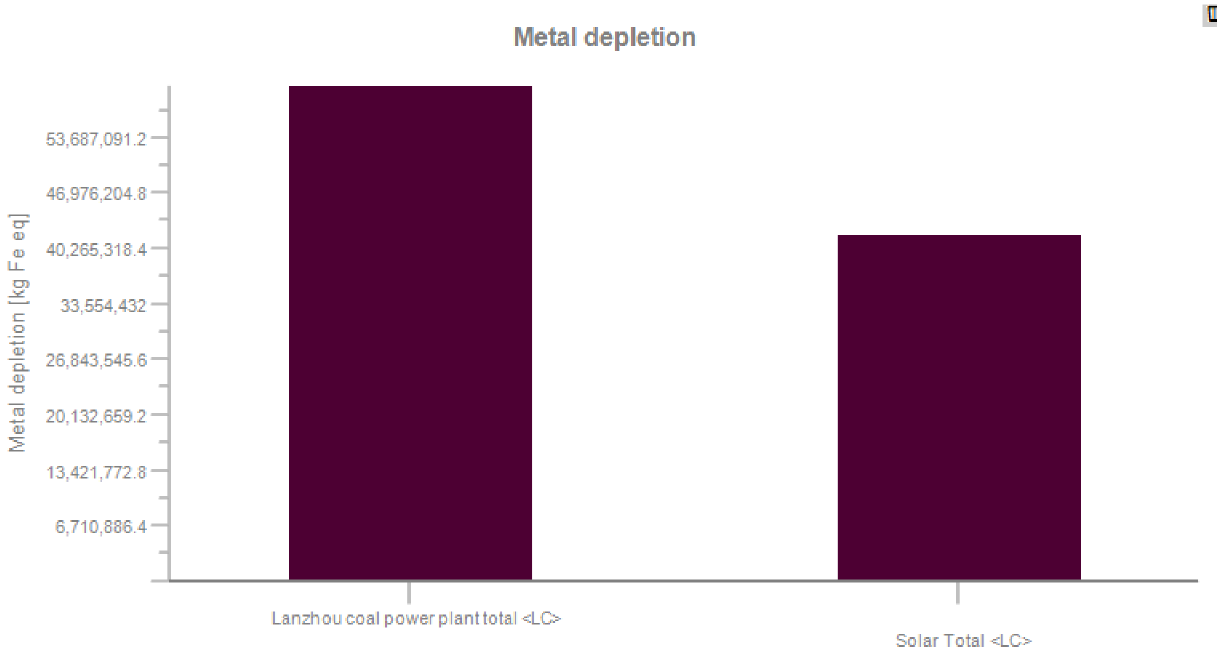

Figure C.15: Metal depletion

16. **Fossil fuel depletion (fd)**

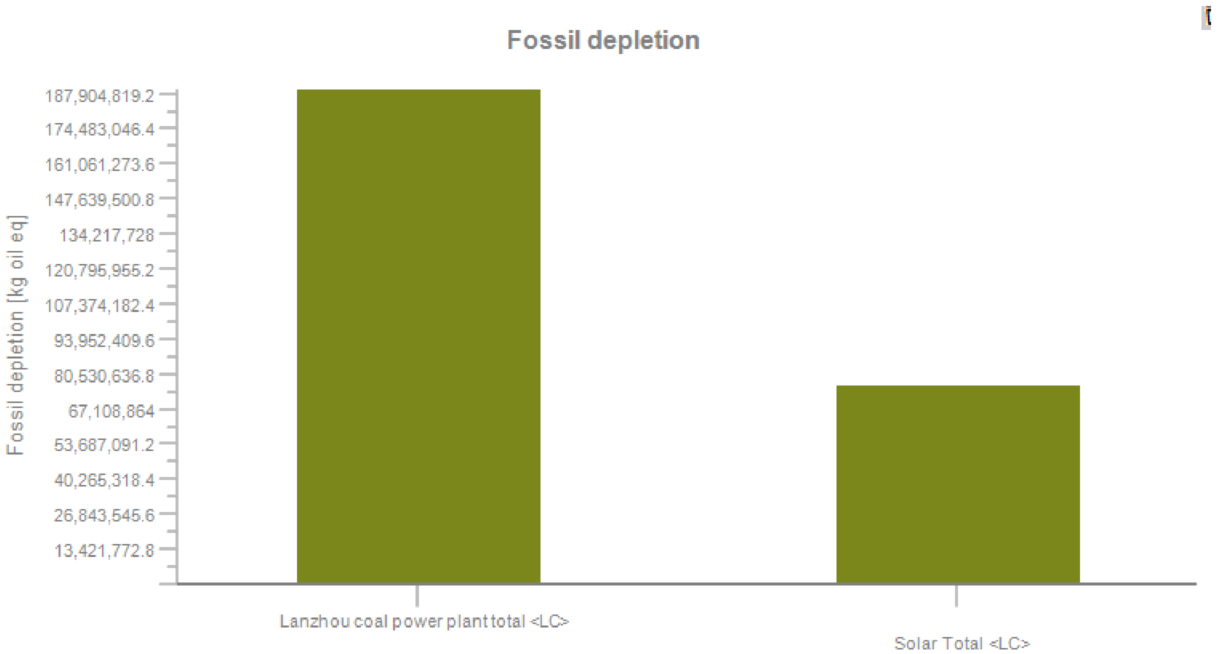

Figure C.16: Fossil fuel depletion