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Life Cycle Assessment (LCA) of various solar heat technologies

Focus on Heliostat construction and maintenance

Francois Winterbach

15335348

Final year project presented in partial fulfilment of the requirements for the degree of Bachelors of Industrial Engineering at Stellenbosch University.

Study leader: Mr. Dirkse van Schalkwyk

December 2011

Acknowledgements

I would like to express my sincere gratitude to the following people who have contributed to make this work possible:

- Mr Dirkse van Schalkwyk, for his study guidance, patient and always having an open door and a ready ear.
- Mr Paul Gauche, for his provision of information that made this study possible.
- Mr Willem Landman, for his advice and provision of information.
- Inke Rupping, for the training she provided in the use of the GaBi Education software.
- Other staff at the Department of Industrial Engineering who were always willing to answer questions and assist.

After studying environmental impacts, I realised how precious our earth is. Therefore this work is dedicated to God, for creating a paradise for us to live in and care for.

Declaration

I, the undersigned, hereby declare that the work contained in this final year project is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Sign on the dotted line:

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Datum

Date

ECSA Exit Level Outcomes References

The following table include references to sections in this report where ECSA exit level outcomes are addressed.

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Abstract

Energy is an essential part of the world today. It is difficult to imagine a world without it. Modern day households rely on it for daily activities and preservation of food. Industries rely on it for manufacturing and processing. The business world relies on it for ease of transactions and transfers. Media depends on it for the gathering and distribution of information. Night life will be much more difficult without advantage of lights.

The major concern is that the means by which most of the energy is produced causes harm to humans and the environment, including the fauna and flora. Coal fire is the most prominent way of producing energy, but since it creates the most harm to the environment, alternatives ways of energy production must be looked at. Other non-renewable energy sources include oil, natural gas and nuclear energy. All of these have the potential to be very harmful to the environment. That is why renewable sources of energy should be considered. Such sources include wind energy, hydro-energy, solar energy and geothermal energy.

Solar power towers are a solar thermal alternative for energy production. It uses solar radiation as fuel for the energy generation process. The physical components of this technology are the heliostat field, the power tower and various machines used in the power generation cycles. The function of the heliostat field is to intercept, redirect and concentrate direct solar radiation to a receiver which sits at the top of a power tower.

In this project the heliostats that are necessary to fuel a 100 MW power tower is analysed to determine the environmental impact throughout their life time. This is a cradle to grave assessment, which means that the entire life cycle is considered from the acquiring of raw materials to the disposal of the functional unit.

Software was used to do the life cycle assessment of the heliostat field. From the result obtained it could be seen which emissions are produced during which processes and the magnitude of the effect that they have on different environmental categories.

Opsomming

Energie is ŉ belangrike deel van die wêreld vandag. Dit is moeilik om aan ŉ wêreld daarsonder te dink. Moderne huishoudings maak staat op energie vir daaglikse aktiwiteite en om kos te preserveer. Nywerhede maak staat daarop vir vervaarding en prosessering. Die besigheidswêreld maak staat daarop vir die gemak van transaksies en oordragte. Media is afhanklik daarvan vir die versameling en verspreiding van informasie. Naglewe sou moeiliker gewees het sonder die voorreg van ligte.

Die grootste bekommernis is dat die manier waarop meeste energie produseer word skadelik vir die mens en die natuur is, insluitend die fauna en flora. Steenkool is die mees prominente manier van energie produsering, maar aangesien dit die meeste skade aan die omgewing aanrig, moet daar gekyk word na alternatiewe maniere van energie produsering. Ander nie-volhoubare energie bronne sluit in olie, natuurlike gas en kernenergie. Al hierdie het die potensiaal om baie skadelik vir die omgewing te wees. Dit is waarom hernubare bronne van energie oorweeg moet word. Sulke bronne sluit in wind energie, hidro-energie, son energie en geotermiese energie.

Sonkrag torings is ŉ son hitte alternatief vir energie produsering. Dit gebruik radiasie van die son as brandstof vir energie opwekking. Die fisiese komponente van hierdie tegnologie is die heliostat veld, die kragtoring en ŉ verskeidenheid ander masjinerie wat benodig word vir die kragopwekking siklusse. Die funksie van die heliostat veld is om direkte radiasie van die son te onderskep, weerkaats en dan te konsentreer na ŉ ontvanger wat bo-op ŉ kragtoring sit.

In die projek word die heliostats wat benodig word vir die aandrywing van ŉ 100 MW kragtoring geanaliseer om die impak op te omgewing te bereken gedurende hulle leeftyd. Hierdie is ŉ wieg tot die graf assessering, wat beteken dat die hele lewensiklus in ag geneem word vanaf die verkryging van grondstowwe tot die wegdoening van die funksionele eenheid.

Sagteware was gebruik om die lewenssiklus assessering van die heliostat veld te doen. Vanaf die verkrygde resultate kan gesien word watse uitlaatgasse produseer word gedurende watter prosesse en die grootte van die impak wat dit op verskillende omgewings kategorieë het.

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Glossary

Aperture Area	Area of a collector through which the solar radiation enters
Capacity Factor	Ration of solar operating hours per year to total hours per year.
Characterization Factor	Factor used to convert the results of the LCI into a reference unit.
GaBi	Life Cycle Assessment software used to determine the impact of a process or product on the environment.
Lehr	A temperature-controlled kiln for annealing objects made of glass.
Life Cycle Assessment	The investigation and evaluation of the environmental impacts of a given process or product caused by its existence.

List of Abbreviations

AP	Acidification Potential
ATS	Advanced Thermal Systems
CML	Centre of Environmental Science, University of Leiden, the Netherlands
EP	Eutrophication Potential
GWh	Gigawatt-hours
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
MWh	Megawatt-hours
SPT	Solar Power Tower
STE	Solar Thermal Energy

1. Introduction

This final year project forms part of a research area of Industrial Engineering applied in the field of renewable energies, in particular solar thermal energy (STE). Solar thermal power will be discussed in this report but the focus will be on the heliostats which form part of the solar power tower technology. The life cycle of a heliostat field, also known as a collector field, will be analyzed to determine the environmental impact caused by the existence of the heliostats that will provide solar thermal energy to a 100 MW electrical power plant. GaBi is the software that is used for the modelling of the heliostats' life cycle. This chapter provides a brief description of the problem followed by a short discussion of how the problem will be approached.

1.1 Problem Statement

With the current technology available, concentrated solar thermal energy is seen as a viable solution for renewable and clean energy. Although this is seen as clean energy, there is little information available about the effects that solar power tower plants may have on the environment. The environmental effects of the manufacturing, construction, operation and maintenance of the system and its components need to be considered before this renewable energy technology can be claimed as environmental friendly. The entire life cycle, from cradle to grave, of the system must be considered to obtain reliable results that give a true reflection of the environmental impacts.

This report, however, will only focus on one of the components of the solar power tower, namely the collector field, which consists out of heliostats. Other components of the system such as the storing of energy, generation of electricity, and processes such as the Brayton and Rankine cycle will not be discussed in this report.

1.2 Research Approach

The research starts with a literature study. The first part of literature study gives a broad overview of solar thermal energy by mentioning different technologies. The focus will narrow down to solar power tower technologies in general. However, the main focus will then be on one of the components of solar tower power, specifically the heliostats. The different types of heliostats along with their function are described in detail.

The second part of the literature study explains the concept of life cycle assessment (LCA). This consists out of a general description, history and methodology. This then concludes the literature study.

The actual LCA, of the product studied in this report, follows directly after the literature study. This part of the report strictly follows the guidelines that are specified in ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Frameworks. This is where the acquiring of information and assessment of the results are important.

Information will be acquired from previous and present studies that focus on STE, heliostats and LCAs. It is important to have accurate and consistent information to ensure a reliable result. Assumptions are made where there is a lack of information or proprietary issues. These assumptions are stated and justified where necessary.

The results obtained are summarized, interpreted and compared with other sources of electricity. Finally the study is concluded to summarise the outcome of the knowledge gained throughout the study.

2. Solar Thermal Energy

Due to more environmental concerns and more environmental restrictions, renewable energies are developing fast these days. One of the main sources of renewable energy is solar thermal energy (STE). Different technologies are available to harvest this energy. These technologies will be briefly discussed. This is followed by narrowing the focus to solar power tower technologies. Finally this chapter will end with a discussion on heliostats, which will look at different types of designs.

2.1 Different Technologies

Solar thermal technologies can be divided roughly into two groups namely mirror based systems and moving air based systems. The former can be subdivided into (1) dish systems, (2) trough systems and (3) tower systems. Moving air based systems can be subdivided into ascending (up-draught) and descending (down draught) systems. Both of these air based systems fall outside the scope of this report in will not be discussed further. (Groenendaal 2007)

Solar dishes, the first type of mirror based systems, track the sun with a dual axis while focusing its rays on a receiver that is located at the focal point in the front of the parabolic dish. The radiant solar energy is absorbed by the receiver which converts it to thermal energy in a circulating fluid. The thermal energy can then be used to operate a generator that is coupled directly to the receiver or it can be transported through pipes to a central power conversion system. Figure 1 represents a schematic example of a parabolic dish reflector. (Kalogirou 2004)

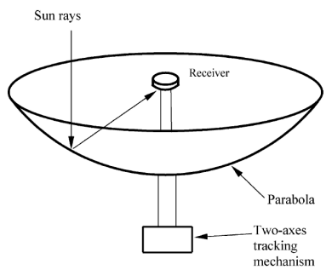

Figure 1: Schematic of a parabolic dish collector

Source: Kalogirou 2004

Solar trough systems, the second type of mirror based systems, consists of a large number of single axis tracking parabolic trough solar collectors made by bending a sheet of reflective material into a parabolic shape. The solar field is modular in nature and is composed of many of these tracking parabolic trough solar collectors. The collectors reflect the solar radiation from the sun directly on a linear receiver located at the focus of the parabola. A heat transfer fluid flows in the linear receiver which absorbs the solar radiation and converts it into thermal energy. The heated fluid returns to a series of heat exchangers in the power block. The heated fluid is then used to generate high pressure superheated steam which is fed to a generator to produce electricity. Figure 2, shown below, is an example of a parabolic trough collector from the PSA (Plataforma Solar de Almeria) DISS (DIrect Solar Steam) test facility located in Spain. (Groenendaal 2007)

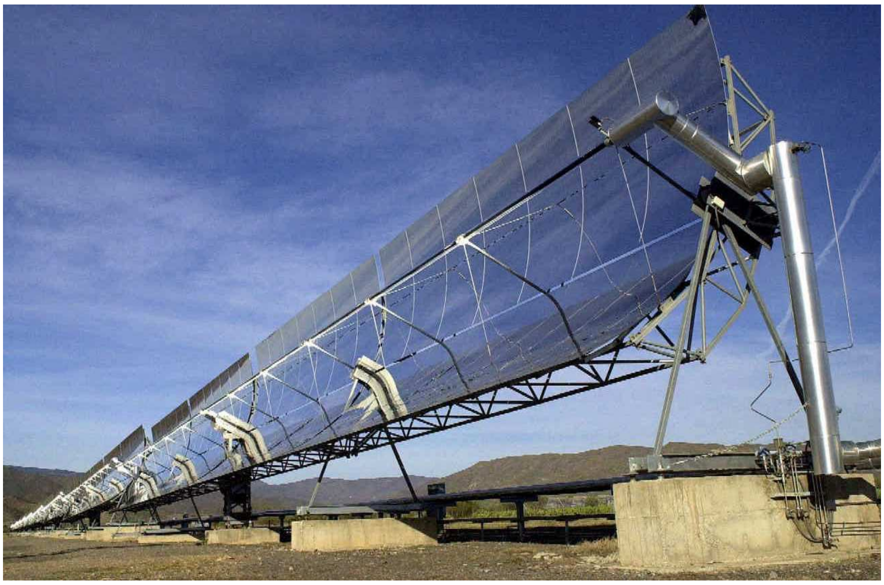

Figure 2: View of the PSA DISS solar field in operation

Source: Zarza et al. 2001

Power towers, the third type of mirror based systems, will be explained in the following section in detail to ensure that the reader understand exactly how the heliostat fit into the concept of solar thermal energy and why it is necessary to do a assessment on the environmental impacts caused by its existence.

2.2 Solar Power Towers

Solar power tower plants, also known as heliostat power plants, use technology for harnessing solar energy and converting it into solar heat. Moveable mirrors, called heliostats, focus concentrated sunlight on a receiver which sits on top of a power tower. This enormous amount of concentrated energy is used for heating water, molten nitrate salt, liquid sodium, helium or air. Systems that use a transport fluid other than water generally require a steam generator in the loop ahead of the generator. The steam produced is then fed through a turbine generator to produce electricity. Air and helium systems are associated with a Brayton cycle turbine. Molten nitrate salt, liquid sodium and water systems are associated with a Rankine cycle turbine. In addition to the turbine and steam generator, other major subsystems include thermal storage and the collector field. (Mavis 1989)

Solar thermal's edge over other renewable energies lies in its storage capacity. Storage ensures that the power output from the turbine generator remains constant through fluctuations in solar intensity until all the stored energy is depleted. Solar thermal energy can be stored in the form of hot nitrate salt or hot sodium which is heated with solar radiation. In the case of a water system the thermal energy can be stored as oil, or other suitable material, which is heated by a steam generator (Falcone 1986). When the plant needs to generate power, the stored fluid is pumped through a steam generating system which produces superheated steam for a conventional Rankine cycle generator system. This basically means that the steam moves through a generator to generate electricity. This method makes the solar tower effective even during nighttimes. Rocks and sand can even be used to store heat from solar produced steam by using oil, air, or any other suitable substance, as the heat transfer fluid.

Solar One, located in the USA, is an example of a plant that uses oil and rocks as a storage medium. A solar tower, located in the California Mojave desert, with energy storage can be designed for an annual capacity of about 65%, which mean that they could potentially operate for 65% of the year without the need for a backup fuel source. Without a storage facility solar tower technologies are limited to an annual capacity factor near 25% (Groenendaal 2007). The capacity factor is defined as the ratio of solar operating hours per year to total hours per year (Müller-Steinhagen 2004).

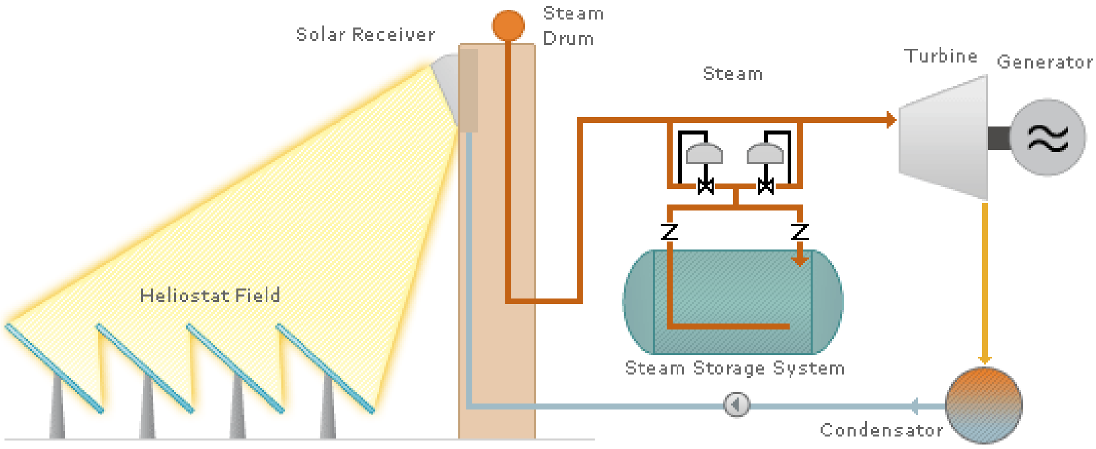

Figure 3: PS10 schematic, Sanlucar la Mayor, Spain, 2007

Source: Osuna et al. 2000

The collector field is has the basic function of intercepting, redirecting and concentrating direct solar radiation to a receiver which sits at the top of a power tower. The field consist of a field of tracking mirrors, called heliostats. A tracking control system ensures that the heliostats maintain continuous focus of the direct solar radiation on the central receiver while energy is being collected.

There are two general field configurations that have been developed, a surround field configuration and a south field configuration (or for plants located in the northern hemisphere, a north field configuration). In the former all heliostats are arranged around a tower usually located to the north of the centre (in the southern hemisphere) to optimize field efficiency. In a south field configuration all heliostats are arranged on the south side of the tower. Selections between the two types of configurations are a function of the receiver configuration, which will not be discussed in this report. (Falcone 1986)

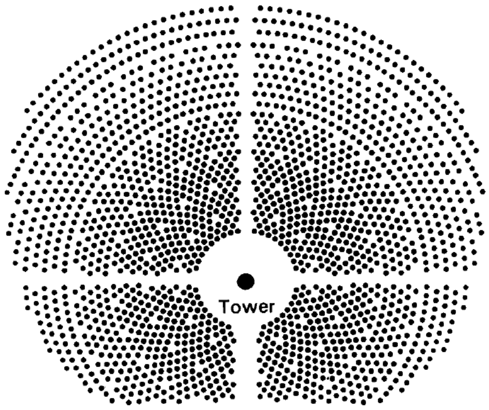

Figure 4: Typical surround field configuration

Source: Falcone, 1986

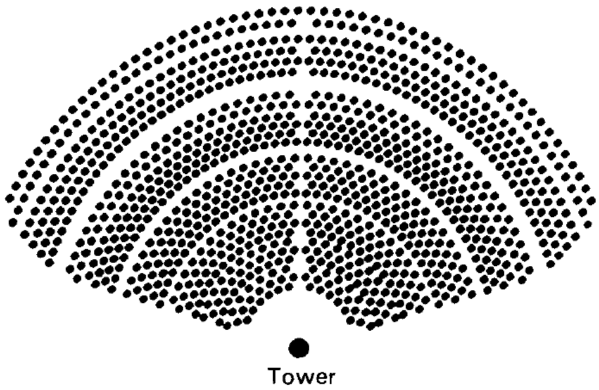

Figure 5: Typical north field configuration

Source: Falcone, 1986

The layout of the field is important to increase the performance, defined in terms of the optical efficiency. Several losses occur that decrease the optical performance. These include the cosine effect, shadowing, blocking, mirror reflectivity, atmospheric transmission and receiver spillage. Below is a visual presentation of these losses. (Falcone 1986)

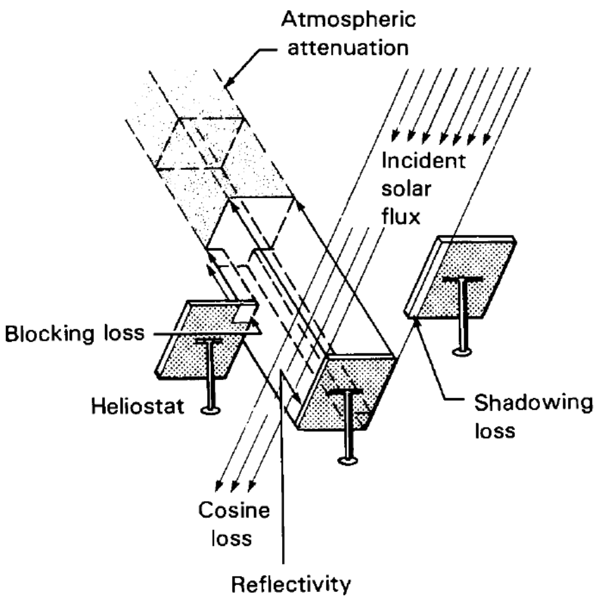

Figure 6: Collector field optical loss processes

Source: Falcone, 1986

Optimization of the shape of the previously mentioned configurations also affects the performance of the field. Heliostats located too far from the tower greatly suffer from atmospheric losses because of the long path that the reflected beams travel to the receiver. The blocking loss is greatest at the inner boundary of the field because of the density of heliostats. The density decreases with radial distance from the tower. Mirror density as a ratio of mirror area to land area is typically 0.20 to 0.25. Figure 7 is a graphical recommendation of the general shapes of a typical field. These field shapes remains relative constant over a wide range of power levels. (Falcone 1986)

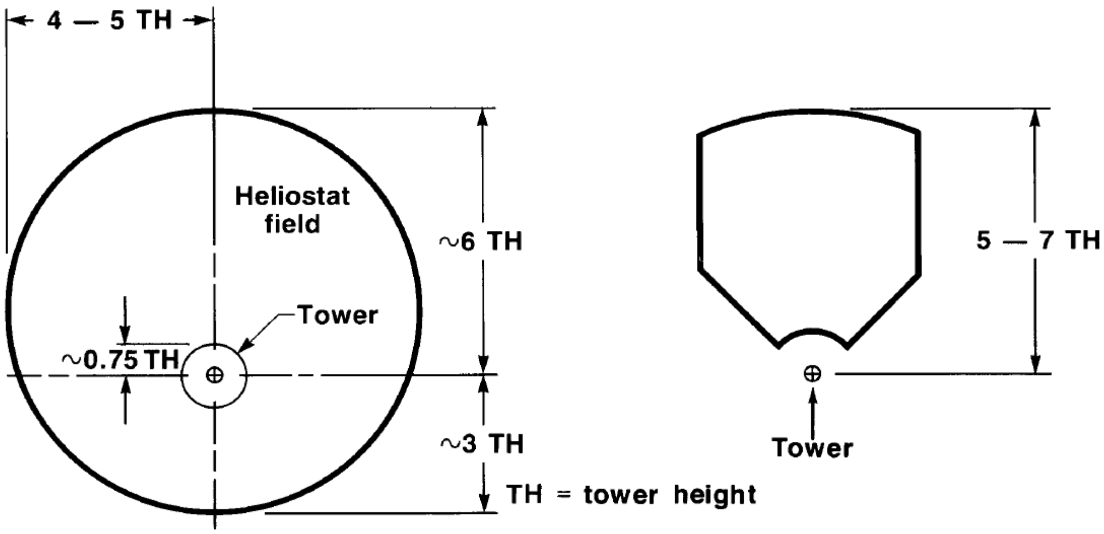

Figure 7: Contours of north and surround heliostat field configurations

Source: *Falcone, 1986*

The collector field represent the largest land area and capital investment of the power plant. A heliostat field can consists of thousands of heliostats. This is why it is important to assess the life cycle of these heliostats to determine where improvements is possible and to calculate the environmental effect throughout their life time. (Meier, Gremaud & Steinfeld 2005)

2.3 Heliostats

The heliostat is the main component of the collector field. Its main function is intercepting, redirecting and concentrating direct solar radiation to a receiver which sits at the top of a power tower. A dictionary definition of a heliostat is "a mirror mounted on an axis moved by clockwork, by which a sunbeam is steadily reflected to one spot" (Falcone 1986). The major components of a heliostat are (1) the reflector, (2) reflector support structure, (3) drive systems, (4) pedestal and foundation and (5) the heliostat control (Mavis 1989). The specifications of these components depend on the type of heliostat, which will be described in the following section.

2.3.1 Heliostat Types

There is no single design or set of specifications for a heliostat because of the various types. Heliostats can be divided into three main types depending on the type of mirror and/or structural arrangement. These types of heliostats are (1) glass/metal, (2) stressed membrane and (3) heliostats enclosed by a bubble. The latter is subjected to nearly no wind loads, since it's enclosed in a bubble, thus can have a lighter support structure. Although this is an advantage over the other types of heliostats, this type is not really popular because the solar energy must past through the bubble material twice, and in so doing can be absorbed and scattered by the bubble material or by dirt on the bubble material. Because of the lack of popularity, heliostats that are enclosed in bubbles will not be discussed further in this report. The following part of this section will discuss glass/metal and stretched membrane heliostats, while considering their differences as well as their similarities. (Falcone 1986)

The reflector of the heliostat is important to ensure high optical performance. The reflector, or mirror module, of a glass/metal heliostat will be discussed first. The modules are usually rectangular and they are ranging in sizes from 0.6 x 3 m to 1.2 x 6.1 m. Multiple mirror modules are used to make up a single heliostats reflective area (Mavis 1989). These modules consist of a silvered glass mirror and some support structure. Usually these are constructed of flat float glass in a sandwich design, silvered glass, backed by float glass for support. Low iron, high transmission glass, is a popular choice for solar applications because it provides a less "greenish" tint due to the relative low iron content. Low iron glass has very similar properties and composition as common soda-lime glass, also known as soda-lime-silica glass, except that the iron oxide content is significantly reduced (Industrial Glass Technologies LLC 2007). The second type of heliostats, stressed membrane, have a reflective silvered polymer coated metal membrane (Mavis 1989). A thin membrane of steel or aluminium is stretched over a structural ring to form a flat, "drum" structure. Thin glass or silvered polymer film are attached to the membrane to give the heliostat its reflective properties (Kolb et al. 2007). The figure below is an example of a stretch membrane heliostat. Notice that round mirror facets are used.

Figure 8: SAIC Heliostat on test at the NRE Laboratory in Golden, Co, USA.

Source: Mancini, 2000

The reflector support structure support the array of mirror modules. This structure typically consists of a main beam, or torque tube, with several cross beams. The mirror modules are attached to the cross beams while the main beam is attached to a drive system. A truss type structure is preferred especially for larger area heliostats because their depth can be varied to provide the required stiffness, with little weight penalty. (Falcone 1986)

Figure 9: Support structure of a glass/metal heliostat (Colon 70).

Source: Mancini, 2000

The pedestal supports the entire heliostat. A single pedestal mounted heliostat is the preferred configuration, as been identified from previous work. By installing both drives at the top of the pedestal the pedestal mount cost can be decreased (Mavis 1989). The size of the pedestal is determined by the dimensions of the heliostat support structure. Three types of pedestals have been identified, (1) a single steel tube, (2) a concrete pillar, made from prestressed concrete grouted in place, integrated with a concrete foundation, and (3) a steel truss frame that heliostats can be mounted on. The latter is not preferred for larger heliostats.

Most modern day heliostats are orientated by a control system. A computer calculates the direction of the sun as seen from the mirror. A control system is needed to position the drive axes independently during plant operation throughout the day. Two types of control systems are identified for heliostat use, (1) open loop and (2) closed loop (Alexis 2001). An open loop system use control computer software with temporal and geometric algorithms to position a heliostat correctly. In a closed loop system feedback is provided by a sun sensor, about whether the heliostat is pointing in the right direction to illuminate the receiver. The open loop system is preferred because of lower costs, but to ensure beam safety the system requires the same accuracy as for tracking (Mavis 1989).

A computer sends a control signal to motors, usually stepper motors, to turn the mirrors to the correct alignment. This is important to provide accurate sun tracking capability. Various different system axes have been considered throughout the years such as polar, equatorial, pitch/yaw and azimuth/elevation. That latter is the proposed system because of its lower cost. Azimuth tracking typically uses a rotary drive because of a larger angular motion, approximately 270°, depending on si te latitude and field configuration. Elevation movement only require 90° of movement. Be cause of this smaller angular movement a linear actuator, such as a screw jack, can provide the required elevation adjustment at a lower cost than a rotary drive. (Mavis 1989)

The drive unit is the main cost driver, as well as the most likely component to fail. The drive system must have the capability of positioning a heliostat to the appropriate position for cleaning, maintenance or operation. It should not drift in elevation or azimuth due to environmental loading or wear. The drive system, including the motors, should be sealed to protect it from mirror washing, rain, wind-blown dust and other environmental factors. (Alexis 2001)

The heliostats that will be used for assessment in this report are discussed in section 4.3 on p. 17 as the Studied Product.

3. Life Cycle Assessment

The focus of this chapter is the Life Cycle Assessment (LCA) and its history and methodology. This technique was developed as a result of the increased awareness of environmental protection, and the possible effect that products, both manufactured and consumed, and services may have on the environment. It is important to understand the methodology because it will give us feedback on what effects a heliostat has on the environment because of its existence.

3.1 Life Cycle Assessment

Life Cycle Assessment is a tool that systematically investigates and evaluates the potential environmental impacts of a product, service or process caused or necessitated by its existence. It quantitatively evaluates the energy and material requirements of a product from initial raw materials acquisition throughout production, maintenance and operation until final disposal. Emissions that are assessed include emissions to air, water and soil.

Although there are numerous application areas of LCA, the main distinction can be made between public and private application. Public studies are used to support the development of environmental legislation and regulation. It also provides consumer information. Public studies should be transparent to ensure that the assumptions made, conclusions and recommendations are clearly represented. Studies in the private sector can be used to support product development or marketing by improving the environmental performance of a product. This can enhance the credibility of the company's environmental policy, or to guide it to act in an environmental friendlier way. (Miettinen, Hamalainen 1997)

3.2 History of Life Cycle Assessment

In the late 1960s LCA started as an exercise to analyse the efficiency of resource use of products and materials. These inventories were made to claim environmental superiority, such as polystyrene over paper packaging. It served as a scientific method to compare different products or systems. The problem was that the LCA didn't provide a clear differentiation between products. Instead it showed that all product systems consume resources and produces wastes and emissions. Most comparisons were inconclusive because of the complex and disparate factors of different products and processes. (Owens 1997)

Initially, practitioners started to explore the instrument of LCA by using inventory data to assess the specific environmental effect of a product throughout its life. This procedure was called impact assessment. This procedure was done by (1) classifying and organizing inventory data into categories, (2) characterizing and modelling the selected inventory data to provide better perspective data about the emissions released, and (3) evaluation of data to rank across different categories. (Owens 1997)

After years of improvement, a broadly recognized structure for the LCA method is available since 1997 as the ISO 14040 standard series. Intensive international standardization efforts ensured clear definitions of the goal and scope as well as the inventory analysis phases. The other two phases, impact assessment and interpretation, are still actively discussed. These phases will be discussed in the next section, the Life Cycle Assessment Methodology. (ISO 2006)

The new improved method allows the assessment of not only products but in principle also the assessment of technical processes. (ISO 2006)

3.3 The Life Cycle Assessment Methodology

There are three primary phases of LCA, (1) goal and scope, (2) inventory, (3) impact analysis, and one secondary phase which is interpretation. It is important to remember that an LCA study has both objective and subjective steps.

The goal and scope, discussed in section 4.1, states the indented application of the study and the reason for carrying it out. The goal is stated along with the objectives which determine how the goal will be achieved. Then the scope should be well defined to ensure the detail of the study is compatible and sufficient to address the stated goal. First the studied product, which is the physical entity that the analysis is based on, will be discussed. This is followed by determining the functional unit so that the results of the study are comparable to various other systems. System boundaries should also be specified in this section and it should include physical and geographical boundaries as well as the time horizon. The detail of the boundaries determines the materials and processes that should be included in the study. Furthermore, the quality of data is also important to ensure that accurate and consistent data is collected which is address the goal of the study correctly. Finally the limitations of the assessment are discussed to ensure the results are interpreted with a fair mind. (ISO 2006)

The life cycle inventory phase, discussed in chapter 5, is a compilation and quantification of all the inputs and outputs, and includes all the material and energy flows that pass the system boundaries. This data is then analysed and the results are interpreted in the impact assessment phase. The data collection process is iterative and the reason for this is that new data and limitations may be identified that require a change in the data collections procedure to ensure that the goals of the study will still be met. Issues may even be identified that require the revision of the goal and scope. The first step is to determine the material specifications, including the type of materials and the quantity. After this is done the manufacturing processes are discussed to determine where the materials fit into the bigger picture. Following the manufacturing of the product the construction process is explained. Then the operation and maintenance of the product, or process, should be calculated to determine the inputs that keep the product, or process, working properly. Finally, at the end of the life cycle, the disposal of material should be considered to minimize wastes. (ISO 2006)

The impact assessment, discussed in chapter 7, uses software to analyse the data collected in the inventory phase. The analysis evaluates the significance of the different potential environmental impacts. The main potential impact that is evaluated is that of the emissions released and this can be divided into two categories, (1) organic and (2) inorganic emissions. Both of these categories are defined, classified and characterised separately in section 7.1. This phase of the LCA mentions other potential environmental impacts in detail. Other relevant impacts, besides emission control, include the impact on water resource and the ecosystem. Visual and noise pollution can also be considered. Even the socioeconomic impact of the power plant should be considered, although this can be discussed in the inventory analysis. Transparency is of critical importance for this phase of an LCA to ensure that assumptions are clearly described and reported since the impact assessment may introduce subjective decisions. This may be a result of insufficient information since some of the specifications may be confidential and the information proprietary. (ISO 2006)

The interpretation phase should be done after each of the three primary phases. This should be done to ensure consistency throughout the assessment. It should reflect the fact that a LCA is a relative approach that indicates potential environmental effects, and that it does not predict actual impacts on category endpoints, the exceeding of thresholds or safety margin or risks. The interpretation also ensure that the information stated is understandable, complete and in accordance with the goal and scope definition of the study. Since a LCA consist of iterative processes, the interpretation phase involves the process of reviewing and revising the scope of the study, as well as the nature and quality of data collected. (ISO 2006)

Figure 10 gives a visual representation of the four phases and shows how it fits into the LCA framework. In addition it shows some of the direct applications of LCA.

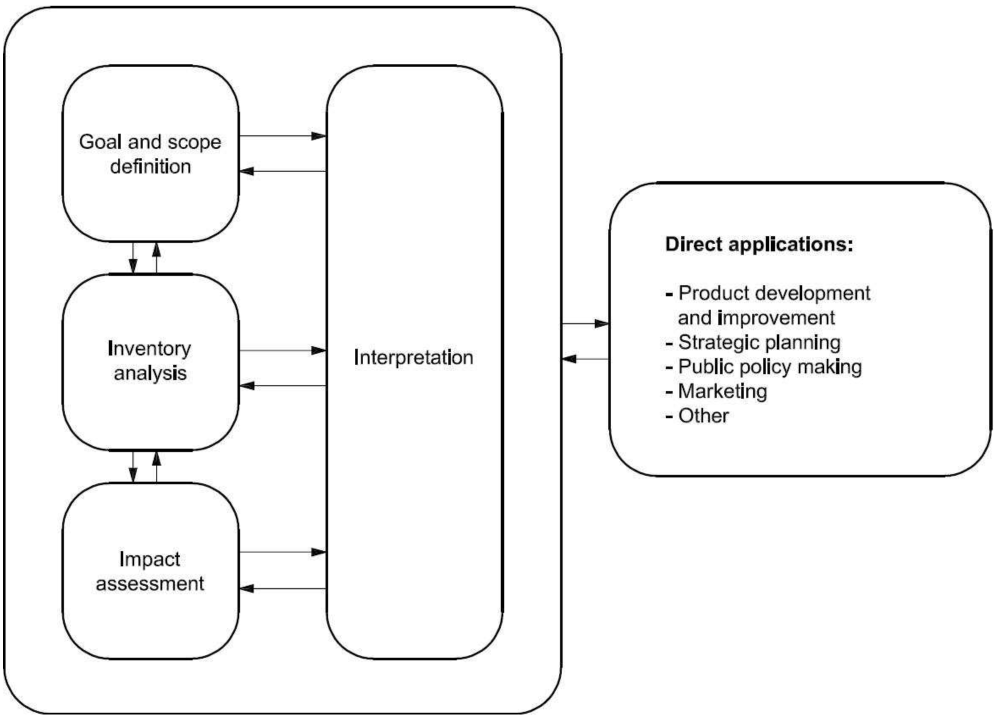

Figure 10: Life cycle assessment framework, the stages

Source: ISO, 2006

4. Goal and Scope

This chapter focuses on the goal and objectives of the study. The studied product is specified as well as the boundaries of the system. Specifications of the required data quality are clarified and the limitations of a LCA study are discussed. This is the first step in conducting a LCA.

4.1 Goal of the Study

The goal of this report is to evaluate the life cycle of a solar power tower with the focus on the heliostats because the heliostat field represents the largest land area and capital investment of the power tower plant. The total emissions throughout the heliostats' entire life should be calculated to determine the total impact that it has on the environment because of its existence.

4.2 Objectives

The objectives of the study need to be completed to achieve the final goal. The amount of organic and inorganic emissions must be determined to reach a conclusion. This is done by using LCA software such as GaBi. The product system, process and material flows, needs to be modelled using the LCA software which will analyse the data and calculate all the emissions. The environmental effects of all the emissions, organic and inorganic, must be determined as well. Finally the amount of emissions, along with their individual effects on the environment, should be evaluated to determine if STE can really be seen as a clean energy source.

4.3 Studied Product

The heliostat design that was chosen for assessment is based on the Advanced Thermal Systems (ATS) H150 heliostat. ATS, a spin-off from ARCO Solar, used the existing 148m^2 ARCO fourth-generation glass/metal heliostat design during the United States Depart Of Energy's (USDOE) large area heliostat development plan in 1985-1986 (Kolb et al. 2007). An existing heliostat was chosen for the assessment discussed in this report, since this report does not focus on the design of a heliostat, but only on the assessment of one. The material specifications and quantities, discussed in section 5.2 on page 24, have been used to do the assessment on for the purpose of this report. This section will continue to discuss the components of the ATS H150, but the manufacturing of the heliostat will be discussed in section 5.3.

The heliostat that is used for assessment in this report has an aperture area of 148.84 m^2. It consists of mirror sections that are adhered side-by-side to form mirror modules. These modules are supported by two racks, made up from trusses, which are attached the main beam. When the final assembly is done the heliostat supports a total of 20 mirror modules, each with an area of 7.44m^2. (Strachan, Houser 1992)

The heliostat features two-stage (two gears in series) worm gears for both azimuth and elevation drives. The drives are mounted on top of a steel pedestal that is placed in an augured hole which is filled with reinforced concrete (Kolb et al. 2007). On-site assembly of the support structure takes place before it’s lifted onto the pedestal. (Strachan, Houser 1992)

It is important to note that 2667 units will be assessed to ensure a large enough total aperture area to supply the power tower with a sufficient amount of solar radiation. Thus, the studied product can be seen as 2667 ATS H150 heliostats.

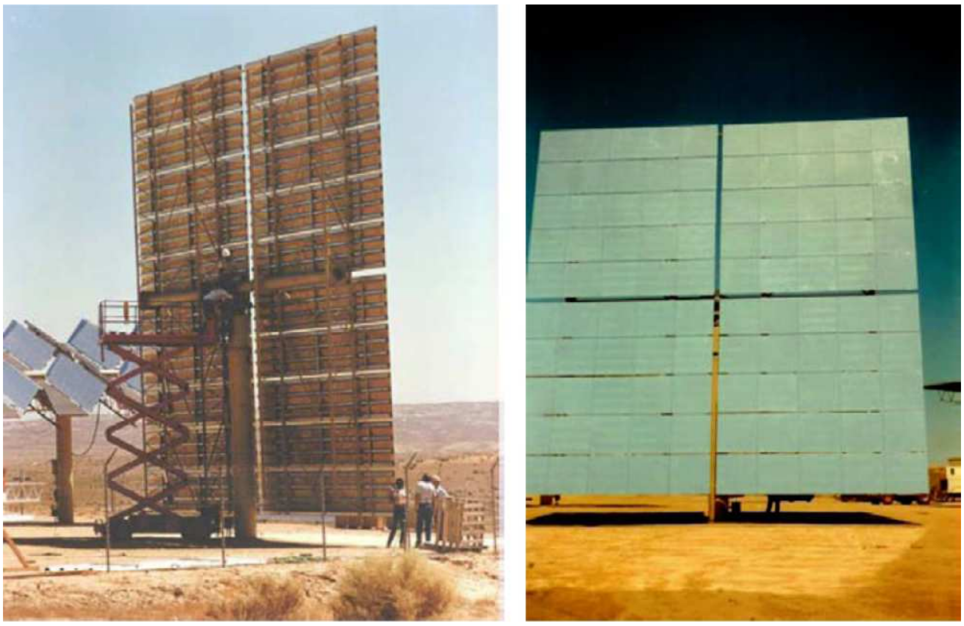

Figure 11: The ATS fourth-generation prototype heliostat.

Source: Kolb et al. 2007

4.4 Functional Unit

The functional unit provides a reference to relate the inputs and outputs. This ensures the results of the study are comparable. Comparability is especially important when alternative technologies with different products and systems are being assessed. (ISO 2006)

The function of the heliostat, as specified for this study, is to redirect and concentrate solar radiation onto a receiver at the top of a power tower, which converts it to thermal energy and ultimately generate electricity. A common measure of electricity is MWh. For simplicity, the electrical power that the power tower plant generates during the estimated life span of the heliostats will be used as the functional unit. The plant used in this report for calculations generates an average of 80.6 MW for an annual output of 706 000 MWh of electricity per year for 25 years, which is the estimated life span of the studied product. This data was obtained from the studies of Paul Julian Harper, 2010. Therefore, the functional unit for this study is 17 650 GWh of electricity. This figure may vary in different sites due to changing weather conditions. (Nalukowe et al. 2006)

4.5 System Boundaries

The boundaries of the system specify which processes should be included in the product system. For this study the boundaries are specified for a complete cradle-to-grave LCA. This includes acquisition of raw materials, manufacturing processes, transportation, construction, operation, maintenance and recycling of material or disposal.

Different approaches for a LCA are possible. In addition to the cradle-to-grave approach, followed in this study, there are other variants of LCA available. The scope of a LCA can specify the boundaries as a cradle-to-gate approach or even a gate-to-gate study

A cradle-to-gate study includes the extraction of raw material to the gate of the factory, before it is distributed to the consumer. The operation, maintenance and disposal of the product are omitted from the study. This type of study is seen as an assessment of a partial product life cycle.

A gate-to-gate study only considers one value added process in the whole manufacturing phase. This is also seen as an assessment of a partial product life cycle, but gate-to-gate studies may be linked together in their appropriate production chain to form a complete cradle-to-grave study.

Other boundaries that can be considered include geographical area and time horizon. Geographical area includes infrastructures such as power supply, waste management and transportation systems. The time horizon, which is the life time of the studied product in this study, must be specified because rapid developing technologies and different pollutants lifespan make it difficult to carry out a LCA and evaluate present environmental impacts and predict future scenarios. (DANTES 2006)

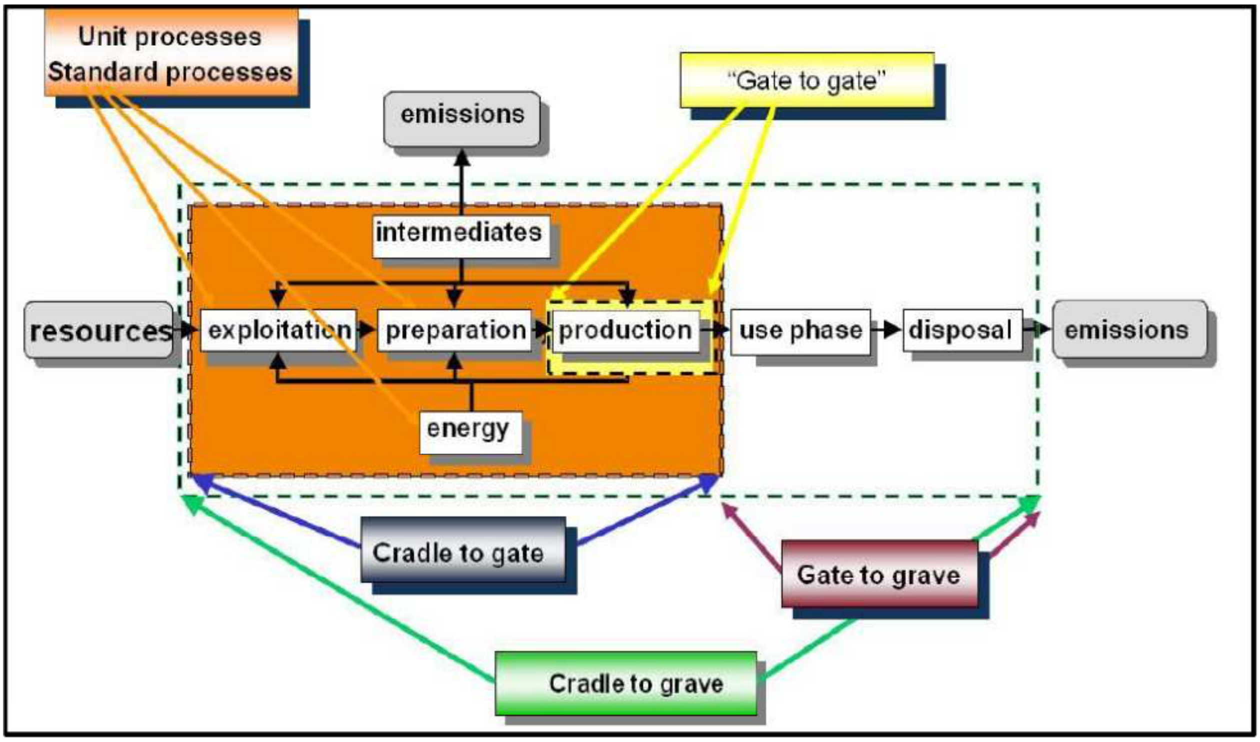

Figure 12: System Boundaries

Source: GaBi Education, 2011

4.6 Quality of Data

The quality requirements specify the characteristics of the data needed for the study. It is important to understand the required quality of data to ensure reliable results that can be used for an accurate interpretation. A truthful interpretation is only possible if accurate and consistent data was used to reach the final results.

The specified boundaries should be taken into account to conform to the goal and objectives of the study. These parameters include system boundaries, geographical area and time horizon.

4.7 Limitations

There are several environmental management techniques available such as LCA, risk assessment, environmental performance evaluation, environmental auditing, and environmental impact assessment. LCA might not always be the most appropriate technique to use in every situation. A LCA, by definition, only considers environmental issues, although there are also other issues such as social, economical, political and technical. The life cycle approach and methodologies can however be use to deal with these issues. (ISO 2006)

Sometimes it is necessary to make assumptions which may be completely subjective. These assumptions, along with the nature of choices, may severely influence the conclusion made if the writer fails to stay objective. (ISO 2006)

The relevancy of data is of high importance. The accessibility and availability of applicable data may affect the relevancy of the results. Results that focus on global or regional issues may not be adequate for local applications (ISO 2006). For this study the availability of data was sometimes a problem because of confidentiality of data and the limited set of databases used by GaBi Education. Suppliers want keep their specifications propriety since they want to ensure that they keep their share of the market by maintaining an edge over competing companies.

5. Life Cycle Inventory Analysis

This chapter discusses the data collection and procedures that was followed to calculate the relevant inputs and outputs of the system. These inputs and outputs are quantified for each phase of the heliostat's life cycle. These phases include manufacturing, construction, operation, maintenance and disposal. The chapter ends with the staff requirements that are necessary to ensure smooth operation of the plant. The data that is collected in this phase of an LCA is used for the final assessment. Since this is an iterative process it is important to do thorough research to ensure accurate and consistent data that are in accordance with the goal of the study.

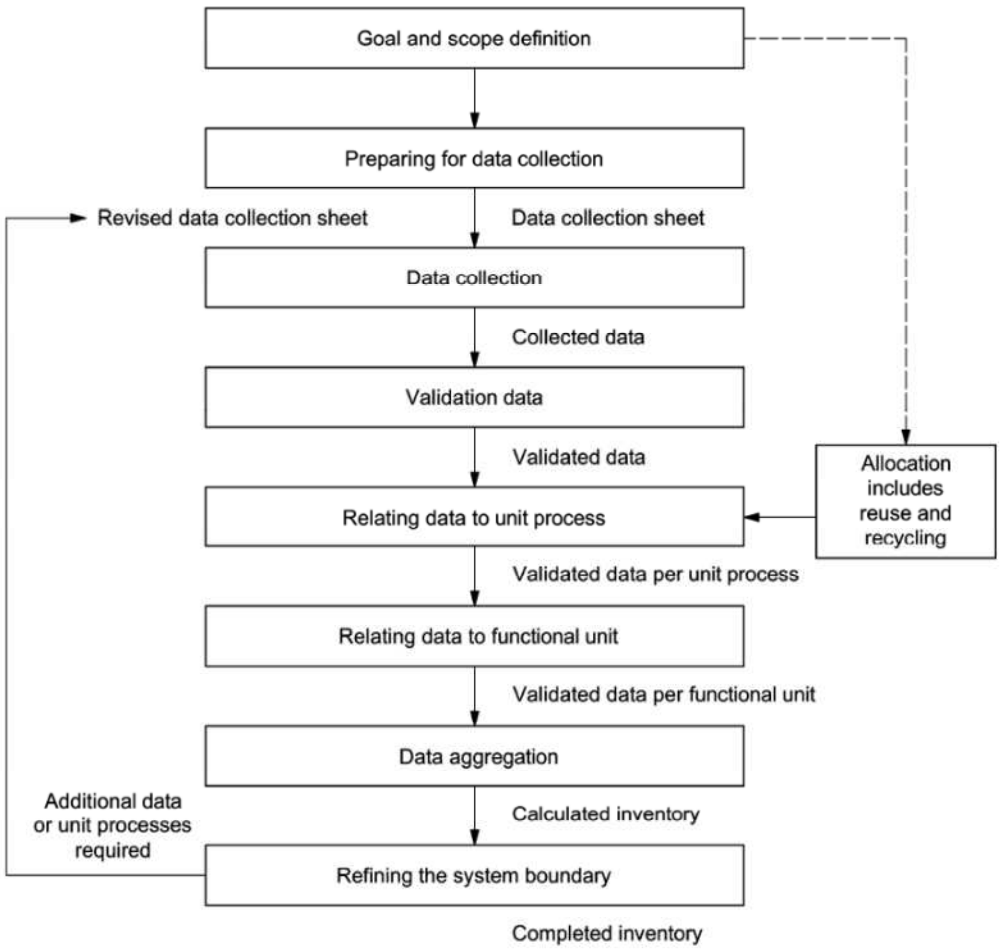

Figure 13: Data Collection and Calculation Process

Source: GaBi Education, 2011

The important components of the ATS H150 heliostat are listed at the start of this section. Since this is an LCA study, not all the potential impacts will be discussed. These omitted impacts include cultural resource, safety, visual & noise, transportation and aircraft interference. This section ends with the socioeconomic impact. Although this usually falls outside the scope of a LCA, it is worth mentioning.

5.1 Components

The main components, and sub components, of the ATS H150 heliostat have been used. The first table, below, is a summary of all the main components of the mirror module along with their quantities and mass. The second table summarise the rest of the heliostat's components. The manufacturing processes of some of these components are discussed later in this chapter.

Table 1: Bill of Material for the Mirror Modules

Components	Quantity	Sub Components Mass (kg)	Sub Totals (kg)
Mirror Module Assemblies:	20		
Glass	100		1496.85
Silvered Glass		374.21	
Low Iron Glass		1122.64	
Steel			716.68
Hat Sections	80	648.64	
Cross Members	60	68.04	
Fasteners	80		36.29
Adhesive			72.57

Source: Kolb et al. 2007

Table 2: Bill of Material for rest of the Heliostat

Components	Quantity	Sub Components Mass (kg)	Sub Totals (kg)
Trusses and Attachment Plates			453.59
Truss Subassembly	4	420.03	
Mounting Adaptor Plate	4	33.57	
Torque Tube Assemblies	2		975.22
Torque Tube Pipe	2	899.93	
Flange	2	64.41	
Fasteners	24	10.89	
Cross Bracing Structure and Attachments	1 set		246.75
Beams	12	149.69	
Long Diagonals	16	52.16	
Short Diagonals	8	16.33	
Stabilizers	16	6.35	
Wing Ties	2	4.99	
Brackets	4	7.26	
Fasteners	44	9.98	
Gear Drives (azimuth & elevation + fasteners)			685.83
Azimuth Subassembly	1	453.59	
Elevation Subassembly	1	226.80	
Fasteners	12	5.44	
Motors & Controls			54.43
Pedestal Assembly	1		1557.18
Pedestal Pipe (Steel)	1	1495.04	
Flange (Steel)	1	62.14	

Source: Kolb et al. 2007

5.2 Material Specifications

The studied product consists mostly out of steel (±63%) and glass (±24%). These materials, along with other relevant materials, will be discussed separately for each of the major components of the heliostat.

To begin with, the composition of the reflectors is important to ensure optimal optical performance. A thin layer, 1 mm, of silvered float glass is bonded to a glass substrate to form a mirror of 1.4884 m^2. A low iron, float glass is used as the substrate. Although it has similar properties and chemical composition, except the iron content is significantly reduced, resulting in a less "greenish" tint (Industrial Glass Technologies LLC 2007). This is a vital characteristic since mirrors for this solar application requires glass with a high transmission value and low coloration.

The reflector support structure consists entirely of structured steel. Structural steel is defined as the structural elements that make up the frame that are essential to supporting the design loads, e.g. beams, columns, braces, plates, trusses, and fasteners (Berman) . The structural steel that is used for this component include carbon steel and cast steel. (Kolb et al. 2007)

The gear drives consist out of two main components, an azimuth subassembly and an elevation subassembly, that is mounted at the top of the pedestal and fastened with steel parts. These drives are made from steel and cast iron. Both of these drives employ 90 VDC, 1/4-hp motors that are mainly made up of steel and copper (Kolb et al. 2007). A rotary drive is used in azimuth because of larger angular motion that is required. A linear actuator can be used for the elevation drive since the rotational requirement is only 90°. Because of this smaller angular moment, a screw jack was chosen since it can provide the required elevation adjustment at a lower cost than a rotary drive. (Falcone 1986)

The pedestal of the heliostat is essentially just a large steel pipe with 0.61 m diameter. A cast steel flange is seam welded onto the pedestal. This pipe is placed in an augured hole with concrete backfill. The hole is than filled with more concrete to create a stable foundation that will be able to support the entire heliostat. A lot of factors should be considered to determine the size of the foundation such as wind loads and the mass of the structure. (Kolb et al. 2007)

5.3 Manufacturing Processes

The reflector mirrors make up about 24% (in terms of mass) of the material requirements of the heliostat, therefore the glass production process will be described in detail in this section.

The float glass that is used for the mirrors uses some of the most abundant raw material on earth. It consists mainly out of silica sand, but other materials are added to determine the properties of the finished glass. To improve the weathering properties of the glass, limestone and dolomite is added. Soda ash and sulphate is added to lower the melting point of the silica sand. Since most glass is recyclable, it is also an important ingredient. The recycled glass further aids the melting process, thus reducing the energy required for melting by up to 20%. All these materials form the batch, which is rigorously checked to insure the purity of the batch. The batch is fed automatically into the filling end of the furnace. (Glass Association of North America)

The batch is melted with superheated air from combustion of fossil fuels to a temperature greater than 1560℃ (Mahrenholtz 2009). Heat is applied inside the furnace from alternate sides at twenty minute cycles. The combustion takes place in the presence of preheated air to assist in fuel efficiency. Glass exist this process at a temperature of about 1040℃ and enters the forming process, a bath of molten tin. The glass is then spread out, into a near perfect flatness on the tin layer, so that the upper and lower surfaces remain flat and parallel. (Glass Association of North America)

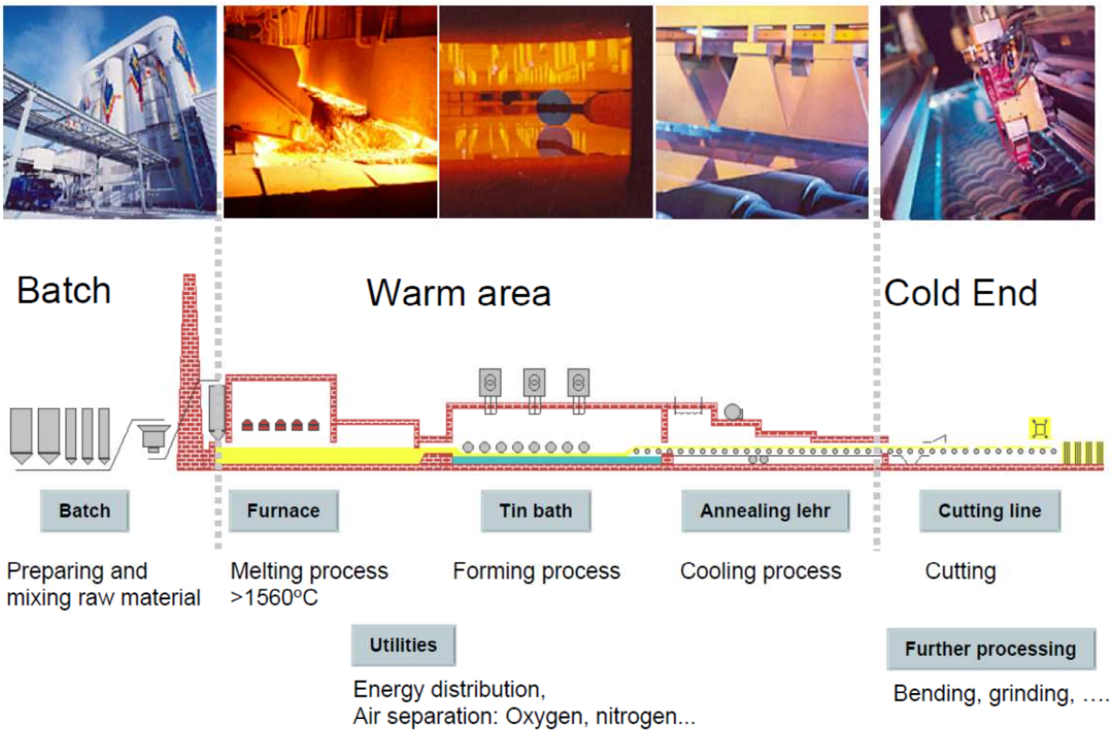

Figure 14: Float glass manufacturing process

Source: Mahrenholtz, 2009

The molten glass can be made thicker by confining its initial outward spread. This process is controlled by the pull of a ribbon, which narrows as the molten glass moves onto the tin bath. The atmosphere is controlled with hydrogen and nitrogen to prevent the tin from oxidizing. Before the glass leaves the tin batch, extremely thin metallic layers can be applied to the glass, while it is still hot, so that special properties can be imparted, including the ability to reflect heat. As the glass exist the forming process, at a temperature close to 600℃, it enters an annealing lehr, where the temperature is taken down to room temperature. The glass is then trimmed to remove the indentations that the top roller left. Glass pieces removed during this trimming process are carried away on conveyors to be reintroduced at the beginning of the melting process. (Glass Association of North America)

Although steel make up approximately 63% (in terms of mass) of the material requirements of the heliostat, various steel manufacturing processes have been used to produce different steel components. These processes include casting, cold drawing, cold forming, extrusion, and machining. Describing all these processes in detail would be redundant. Some of the components may even be produced with different processes. The pedestal is the largest single contributor of steel, contributing approximately 38% of the total steel requirement for the heliostat, and it's basically just a tubular steel pipe. Since it would be redundant to discuss all the different processes, a table has been inserted at the end of this section to show the main processes for steel product manufacturing.

The gear drives includes both steel and cast iron. Machining is used to produce the steel gears. The housing of the gear drive, as well as the motor, is produce with sand casting. This process is used since it can be used to create complex part geometries, including both external and internal shapes. Molten metal is poured into a sand mould, allowing the metal to solidify. The mould is then broken apart to remove the casting. The casting is cleaned and inspected, and sometimes it is required to improve the metallurgical properties through heat treatment. The sand mould utilize a cope (the top half of the mould) and drag (the bottom half). It consists of silica sand, clay and water. The water is added to develop the bonding characteristics of the clay, which is required to bind the sand grains together. The following characteristics should be exhibited by the sand; (1) it should be able to pack tightly around the pattern, (2) strong enough to withstand pressure of molten metal when the mould is cast, (3) it should be permeable to allow gases and steam to escape from the mould during casting.

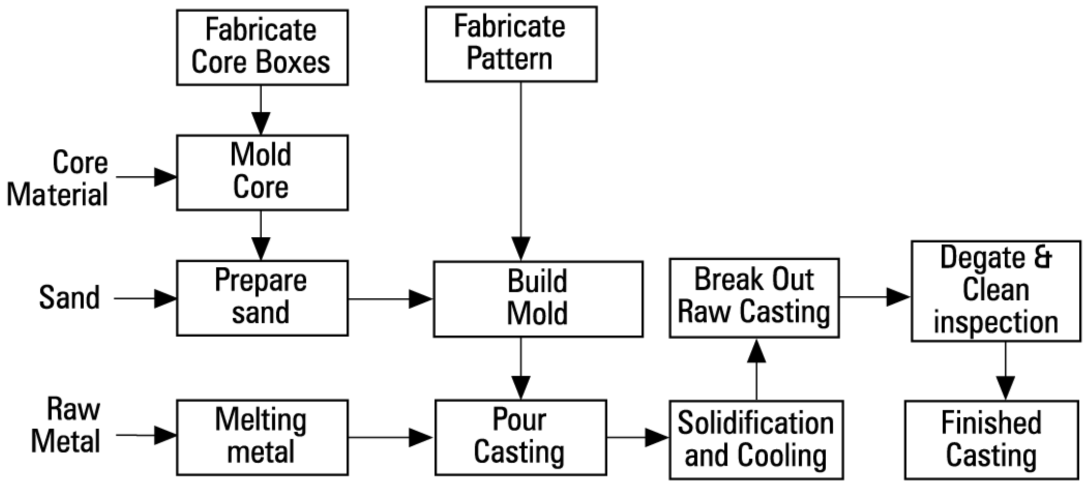

Figure 15: The steps in the production sequence in sand casting

Source: Wang, Conley & Stoll. 1999

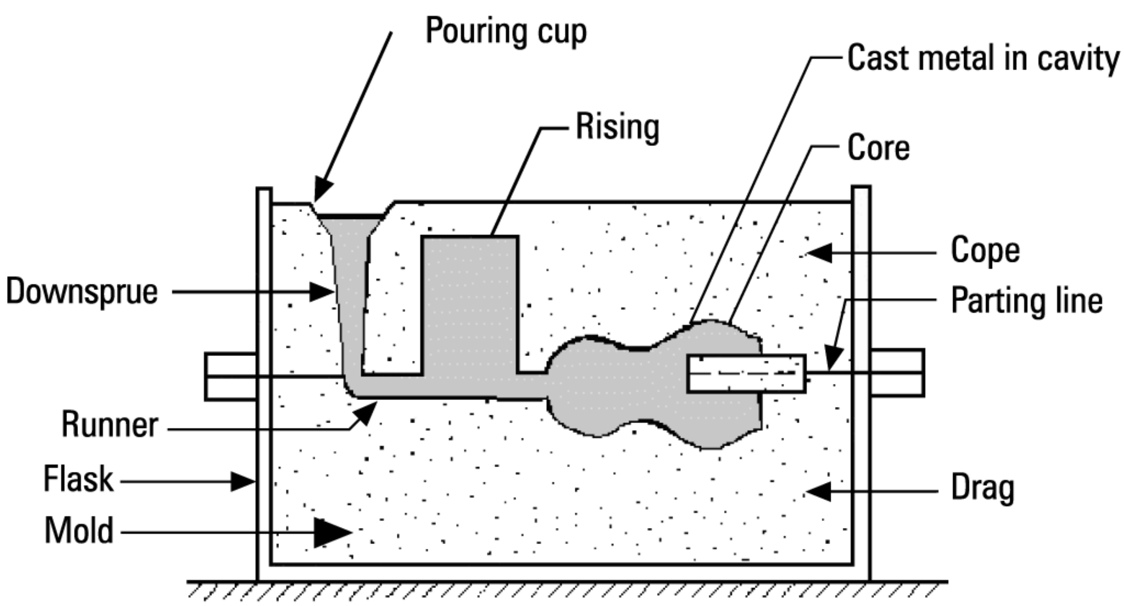

Figure 16: The cross-section view of the typical sand casting mould

Source: Wang, Conley & Stoll. 1999

Table 3: Processes for steel in manufacturing

PROCESS	EXAMPLE OF PRODUCTS
Casting	Gears, engine casings
Powder metallurgy	Gears, bearings, fasteners, sprockets
Forming processes:	
Rolling	Bars, rods, coils, rails, structural shapes
Forging	Flanges, gears, rings
Extrusion	Rods, tracks
Drawing	Bars, tubes, wires
Sheet metalworking	
Shearing, blanking, and punching	Disks, washers
Bending	Brackets, U-shaped parts (and V-shaped)
Drawing	Cylindrical cup, panels
Material removal processes:	
Turning	Cylindrical parts, chucks, collets
Drilling	Piston rings, ring gear pinions
Milling	Fittings, valves

5.4 Assembly and Construction

The first part of the section discusses the assembly of the heliostat, starting at the mirror sections and ending at the mounting of the support structure onto the pedestal. The second part discusses the construction of the heliostat in its fixed position.

5.4.1 Assembly

Since heliostats are custom made for each plant, there aren't any mass produced heliostats that can be compared with the studied product. Therefore the assembly heavily depends on the use of manual labour. Since an LCA doesn't consider the socioeconomic impact of the heliostat, although the operation and maintenance workforce will be discussed later in this chapter, the size of the workforce needed for assembly will be ignored.

The mirror sections of the studied product consist out of 1.22 m^2, 1 mm thick silver glass bonded to 3 mm low-iron glass substrate. Five of these mirror section are adhered to four parallel, aluminized sheet metal hat sections with cross member attached by four threaded studs, to form the mirror hat sections. The four hat sections are fastened together and stiffened by three cross member to form a rectangular mirror module. (Strachan, Houser 1992)

The heliostat has two racks, each constructed from two trusses welded to the heliostats torque tube. There are 10 mirror modules bolted to each rack for a total of 20 mirror modules. The torque tube itself is bolted to either side of the heliostat's elevation drive. (Strachan, Houser 1992)

The gear drives are based on Winsmith low-cost drive systems. Its elevation drive employs a jack screw, while the azimuth drive is a planocentric drive. The drive system is equipped with 1/4-hp motors. These motors are controlled and driven by a local control board that is mounted on the heliostat pedestal. The control board is equipped with an on-board microprocessor. Operator control of the heliostat is via a computer program running on a personal computer that is connected by its I/O (input/output) port to the local control board. (Strachan, Houser 1992)

Assembly of mirror modules, the torque-tube and truss structures take place on-site or near the plant. The final assembly is done when the heliostat is lifted onto the pedestal. (Kolb et al. 2007)

5.4.2 Construction

The constructing of the heliostat requires the entire structure to be mounted on a pedestal and then anchored in the ground.

Each heliostat is planted in an augured hole with concrete backfill. A mobile crane is use to lift the support structure onto the pedestal and ultimately into the augured hole. Once the heliostat is in place, the hole is filled with steel reinforced concrete. This forms the foundation of the heliostat. (Strachan, Houser 1992)

Table 4: Foundation Specification

Material	Amount (kg)
Reinforced Concrete (2 400 kg/m^3)	4 587

Source: Kolb et al. 2007

5.5 Operation

The operation of the heliostat is an automated procedure that depends on the control system that position the heliostat's drive axis independently throughout the day. Three main elements of the collector subsystem control system are identified. These are a heliostat array controller (HAC), a heliostat field controller (HFC), and a heliostat controller (HC) The HAC is centrally located provide information, as the oversight computer, to many HFC's. Each HFC, located through the field, controls a group of heliostats. The HC, located in the pedestal of the heliostat, controls the motors of the individual heliostat.

The major operation factor for this report is the power consumptions of the ATS H150 heliostat's drives. Measurements were made with an AC watt-hour meter during a typical 10-hour day. The all-day power consumption of drives was measured at 292 watt-hours (Strachan, Houser 1992). This figure will be used as the daily power consumption of each heliostat for purposes of this study. The table below show the extended results of the test.

Table 5: Power Utilization of the ATS H150 heliostats

Quiescent Power:	10 W
Avg. Power Draw (both drives)	35 – 75 W
Avg. Power Draw (elev. drive)	22 – 35 W
Typical peak draw (both drives)	175 W
On-sun tracking (average)	80 W
All day power consumption	292 Wh

Source: Strachan, Houser. 1992

5.6 Maintenance

Heliostat maintenance has no parallel in conventional utility or industrial plants. Since heliostat maintenance is dominated by the washing of mirrors, this section will be divided into two subsections, (1) general maintenance, and (2) mirror washing.

5.6.1 General maintenance

Most of the general maintenance consists out of scheduled maintenance. This includes all the activities that should be done at fixed time intervals. Activities that fall in this category include routine inspection, preventive maintenance, cleaning, painting, facet alignment, control adjustment. The last two activities are prepared through testing and calibrating. The facets are aligned during initial assembly, and the control bias for the heliostat is set during the installation of the heliostat. These should be tested regularly, especially after strong wind conditions or maintenance operations such as mirror facet replacement. The system should be calibrated if necessary. This is done to ensure that the reflected solar beam falls within the aim point limits. Since general maintenance consist out of scheduled activities, and some of them happens quite regularly, careful consideration of labour saving equipment, optimum maintenance frequency, and time saving procedures is important because of the large amounts of heliostats that is typical of a commercial power plant. (Mavis 1989)

Other maintenance activities that's not included in scheduled maintenance include major repairs, and repair or replacement of failed components. Major repairs requiring the disassembly of the heliostat may be necessary. The same type of mobile crane used for the installation is used to move damaged heliostats to the shop for disassembly and reassembly. (Mavis 1989)

Repair or replacement is necessary for failed parts. Since all the heliostats are identical, enough parts can be stored to ensure quick replacement. Repairs can be done in the maintenance shop or offsite. Items that typically require repair is electronics, motors, connectors, mirror facets, and drive mechanisms. Cracked mirrors do not require immediate replacement although water seepage will slowly degrade the reflective surface. (Mavis 1989)

5.6.2 Mirror Washing

Optimum plant performance requires maintaining high mirror reflectivity. Soiling is the main reason for reflectivity losses and therefore it's necessary to do periodic heliostat cleaning. The reflectivity is measured in terms of a cleanliness factor. This factor, expressed as a percent of the field's reflectivity, measures the cleanliness of the heliostat field. (Falcone 1986)

There was some speculation that a small amount of total reflectivity of mirror (<2%) may be permanently lost as a result of soiling or damage done to the glass surface by the soiling. Other investigations believed that the losses can be recovered by mechanical scrubbing or by high pressure washing with dilute hydrofluoric or hydrochloric acid.

Previous records from the IEA/SSPS central receiver plant in Almeria, Spain, indicate that water spray and/or rain is sufficient to clean the mirrors to an acceptable levels
(>97% clean). Some amount of mirror washing is probably necessary at most sites, although the Central Receiver Test Facility (CRTF) at Sandia National Laboratories in Albuquerque, NM, USA, relies exclusively on cleaning by natural precipitation (Mavis 1989). Research has indicated that it could be cost effective to wash the field frequently, as often as bi-weekly (Falcone 1986). This will also ensure high mirror cleanliness.

For the purpose of this study, heliostat cleaning will rely on rainfall and high-pressure spraying. For spraying, deionised water is preferred over soft water because of the residue left by the soft water after rinsing. The water requirements for a solar central receiver plant are essentially the same as those of a fossil fuel power plant with comparable electrical output rating and capacity factor. However, for a solar central receiver plant, additional deionised water is required for washing the heliostats. The additional water requirement for heliostat washing depends on the washing frequency but it is typically between 5,000 and 15.000 m^3 (Falcone 1986). Washing frequencies normally range from 10 to 30 per year. The washing frequency for this study is specified as 26 since washing happens bi-weekly. (Mavis 1989).

Heliostat wash trucks, similar to the trucks used at solar one, will be utilize for cleaning purposes. Results from Solar One indicated that one truck operator with a wash rate of

150-170 heliostats per eight hour shift could restore mirror cleanliness to 99% of the clean value, which would provide a 97% average cleanness with biweekly washing. Note that the heliostats implemented at Solar One have a aperture area of about 40 m^2, this is small in comparison with the studied product in this report that have an aperture area of about 148 m^2. This data has been extrapolated to determine the amount of wash trucks required to perform bi-weekly washing of the collector field. (Falcone 1986)

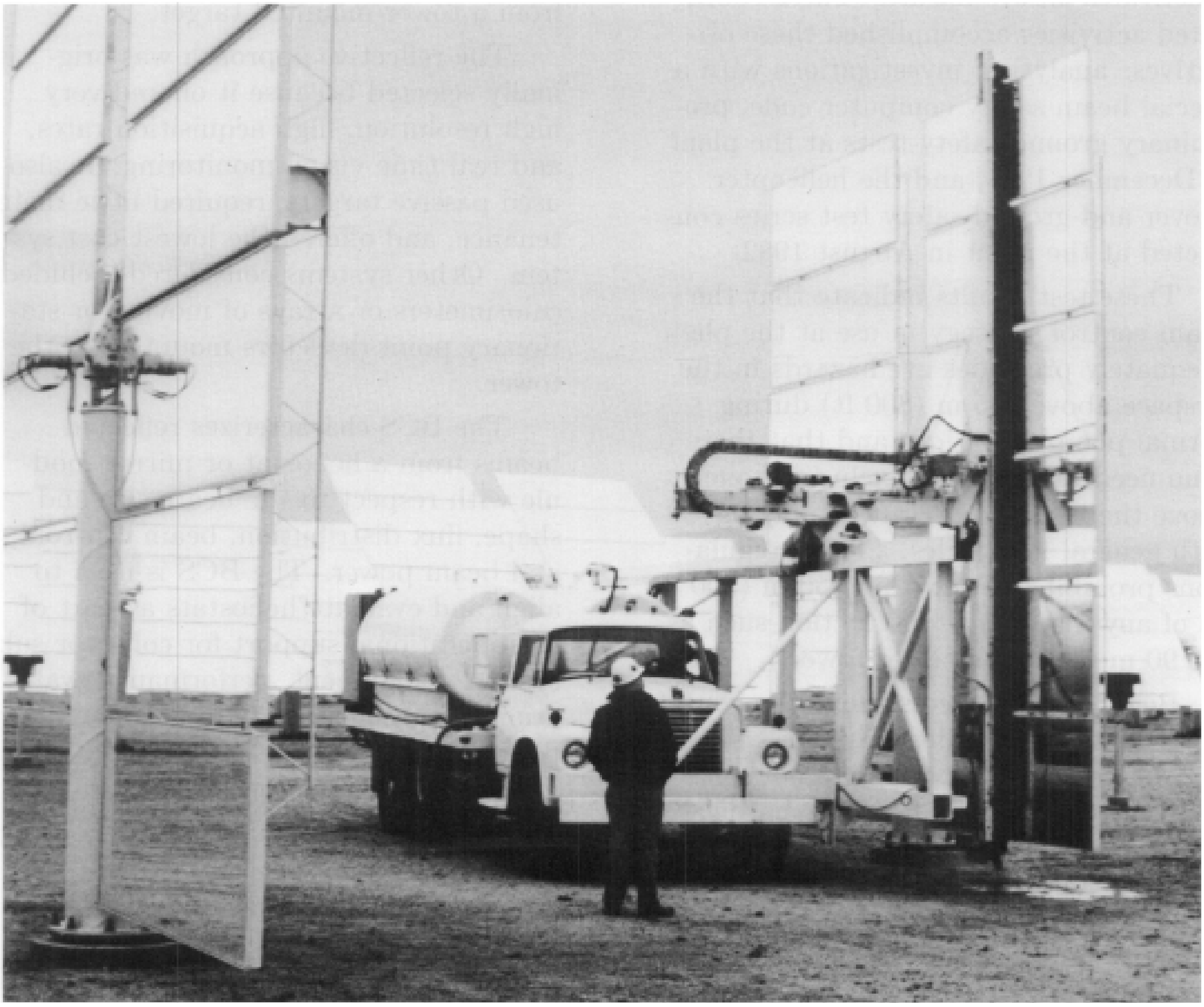

Figure 17: Photograph of the Heliostat Wash Truck at Solar One

Source: Falcone, 1986

5.7 Disposal

The end of a product's life cycle is important to sustain its clean carbon footprint.

When all stages of implementation are considered, from manufacture to disposal, heliostats are among the cleanest energy sources available. Heliostats are primarily composed of steel and glass, both of which are readily recyclable. Neither steel nor glass is considered particularly hazardous to human health or the environment. The concrete used for the foundation is land filled. (NMT)

Steel is 100% recyclable and can be recycled an infinite amount of times. Each time the steel is re-processed it saves energy and raw materials. Most of today's steel has around 20% recycled content. Recycling steel diverts these products from landfill, and enables the material to be reprocessed, thereby conserving raw materials. For every ton of steel recycled, 1131 kg of iron ore, 633 kg of coal and 54 kg of limestone are saved. (Planet Ark)

Since the glass is mostly silicon dioxide, soda ash and limestone, it is relatively easy to recycle it. Producing glass from recycled glass rather than raw materials uses 75% less energy. This is largely due to the much lower production temperature, which is mentioned previously in this chapter. The lower production temperature conserves energy and oil, and extends the life of the furnace. Recycling glass therefore results in a reduction in greenhouse gas emissions. For every ton of glass recycled, there is a saving of 225 kg carbon dioxide. Furthermore, using recycled glass conserves more than 1.1 ton of raw materials per ton.(Planet Ark)

A small amount of copper can also be recovered from the motors. The energy consumption during copper production is 130.3 GJ/ton. Energy consumption for copper recycling is 13% of production. (Nalukowe et al. 2006)

Finally, heliostat arrays do not suffer from the ongoing natural degradation that plagues selenium-based solar panels. They offer a comparatively long service life, minimizing the frequency of manufacturing new heliostats and disposing of old ones. (NMT)

5.8 Socioeconomic Impact

This section takes a look at the socioeconomic impact of the solar power plant. Although this is not normally included in a convention LCA, it is mentioned in this study because of the potential environmental impact that it may have on the surrounding area. (Reilly, Kolb 2001)

The construction of the solar central receiver plant is generally intense, but of short duration while the impact of plant operation tends to be generally mild, but of longer duration. Plant construction may result in a significant, but short term, housing demand. This depends on the ability of nearby communities to supply labour and the level of on-site housing. The operation of the plant may result in addition, permanent on-site housing. (Falcone 1986)

Public facilities such as schools, hospitals, and churches as well as the need for additional police and fire protection may grow. Local traffic congestion may occur as a result of an increase in vehicles, or inadequate number of roadways to the plant site and the temporary addition of construction worker traffic. This may result in the construction of more roadways. (Falcone 1986)

Since the magnitude of these impacts depends on the size of the staff requirements for the operation and maintenance of the plant, it is important to consider the manpower needed. Manpower estimates for a 100 MW commercial power plant (Solar 100) were independently done by ESI and Bechtel, in 1998, and were based on the limited experience at Solar Two. Solar two is a 10 MW solar power tower plant located near Barstow in California, U.S.A. Table 6 compare these estimates made by both companies with the actual staffing at Solar Two. It can be seen that Bechtel's overall manpower is more aggressive than ESI's and that the job categories of the O&M crew are somewhat different, since they assume a non-union labour force is used, unlike ESI. Comparing these estimates with the experience at the 80 MW SEGS VIII and IX plants (~40 to 50 total O&M crew) again suggests that the O&M of trough and tower projects of similar size should be about the same. However, the heliostat washers required might be more for the plant studied in this report since it relies on a frequent cleaning cycle. (Reilly, Kolb 2001)

Table 6: Comparison of estimated Operation & Maintenance Staffing

Staff	10 MW Solar Two (Test & Evaluation)	Solar 100 (ESI)	Solar 100 (Bechtel)
Plant Manager	1	1	1
Secretary	2	2	1
Operations Manager	1	1	1
Senior Operators	5	5	4
Control Operators	4	5	4
Plant Equipment Operators	0	5	4
Assistant Plant Equipment Operators	0	0	4
Maintenance Supervisor	3	6	1
Electricians	0	0	2
Instrument Technicians	7	5	2
Mechanics	0	5	2
Machinist/Welder	2	1	1
Warehouse Clerk	1	2	1
Equipment Mechanic	0	0	1
Heliostat Washers	3	0	6
Engineering	3	5	1
Chemical Technicians	1	1	1
Security	1	1	0
Clerk Supervisor	1	1	0
Test & Evaluation Manager	1	0	0
TOTAL	**36**	**46**	**37**

Source: Reilly, Kolb. 2001

6. Methodology

Although there are many tools available to support the Life Cycle Assessment (LCA) technique, the tool chosen for this specific study is the Educational version of the GaBi software. This is use in addition with the LCA methodology to simplify the data analysis and emission calculations. This chapter will provide a description of GaBi and the flow of materials will be identified.

6.1 GaBi Software

GaBi is a powerful software tool that is used for product and process sustainability. The user builds models for product systems by specifying inputs and outputs for each specific process. Strategic differentiation is made between materials, products and processes. GaBi identifies optimisation potentials by determining what the CO^2 emissions are. It also support environmental monitoring and risk analysis while delivering comprehensive arguments. (GaBi Education, 2011)

A model, which GaBi refers to as a plan, is built that represents the flow of material and the processes involved in the actual life of the studied product. The scope of the LCA determines the boundaries of this model. Flows that enter the product system coming from the natural system (e.g. resources as iron ore) or that leave the system (e.g. CO_2 emissions) are called elementary flows. The inventory analysis, done in the previous chapter, is the input list of all the elementary flows associated with the system. (GaBi Education, 2011)

The most important information of GaBi is the flow information. Flows are characterised by mass and energy with their respective quantities. These flows can contain information for different raw materials, plastics, metals, emissions to air and water and many more. (GaBi Education, 2011)

GaBi analysed the flows specified in the plan and calculated all the outputs. The outputs are categorised and summarised to give a clear representation of the environmental influence caused by the flows. These outputs can then be used to form a conclusion and make recommendations to improve the processes in the future.

6.2 Project, Plans, Processes and Flows in GaBi

The first step in GaBi is to create a project and activate it. This is the main database of the project that contains all the plans, processes and flows. Once the project is active, a plan can be created.

Plans contain processes and flows that were identified in the LCI. A plan can contain other plans, which is then called a subsystem. The subsystem can also contain other subsystems.

The processes contain flows, which represent the inputs and outputs of the system. These flows may already be defined in the database or new flows can be created. Flows that are used by other processes as well are marked with an "X" to show that they should be tracked. Flows that represent the waste of a process are marked with an asterisk (*).

Flows must be specified with material quantity or amount of energy required to produce a product or drive a system. The flows are the links that connect all the processes and that's why it is important to remember that the output of one process is the input of another process.

6.2.1 Heliostat Project

The project created for this study was called "Heliostat", since it describes the life cycle of the ATS H150 heliostat. It consists of three separate plans that contain all the processes and flows that are required for manufacture, maintenance and operation of the heliostats required for the collector field.

The first plan represents the processes and flows required to manufacture the heliostats. The environmental effects resulting from the mining processes involved to acquire the raw materials are automatically considered in GaBi when the material and manufacturing processes are specified. The second plan represents the cleaning of the collector field and consists only of the deionization of water and the water trucks required for spraying the mirrors. The third, and final, plan represents the operation of the heliostats, and only considers the electrical usage of the motors that's use to power the heliostats' drives.

The figure below shows how all the heliostat's components fit together. These flows were used to develop the first plan in GaBi. This figure only shows the component flow and materials, since the masses were already discussed in the LCI.

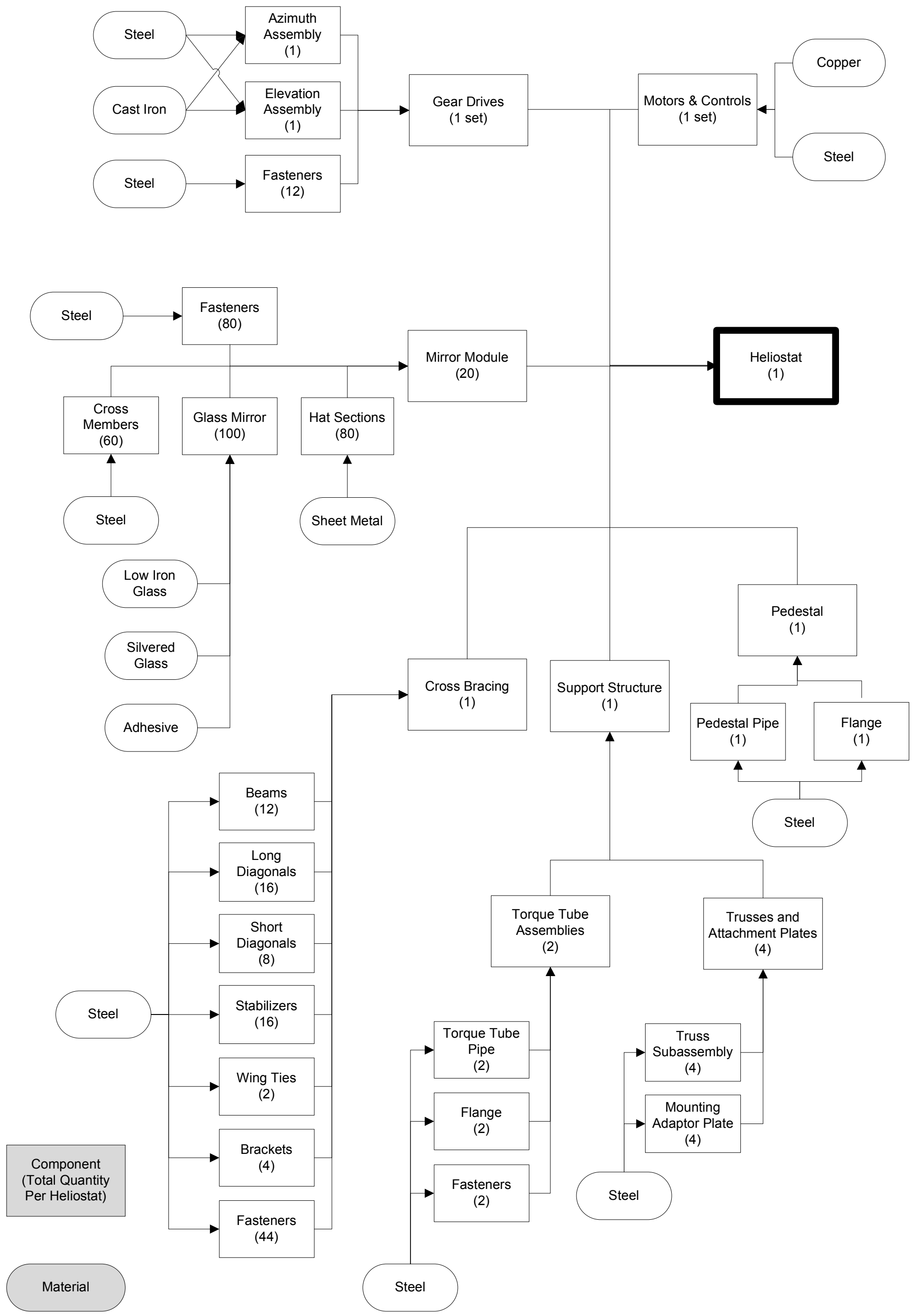

Figure 18: Heliostat's Component Flow

The figure below is a screenshot from GaBi for the second plan, heliostat washing. This is a very simple plan since the only primary flow, that is tracked, is that of deionised water. The flows for the manufacturing process is much more complex, as can be seen from figure 18, which is a flow diagram of all the heliostat's components. This diagram was created in Microsoft Visio, since the plan for manufacturing, which was created in GaBi as well, is too large to display on one page.

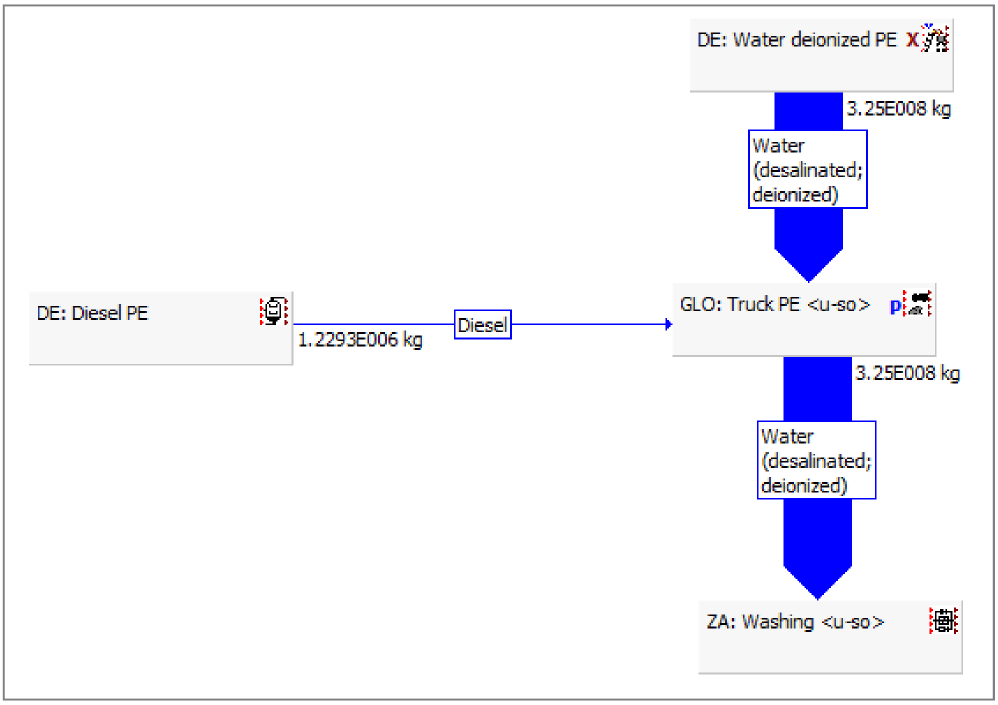

Figure 19: Plan for Washing of the Heliostats

The third and final plan is the simplest of the three since it only consists of the supplying of electricity to the heliostats' motors.

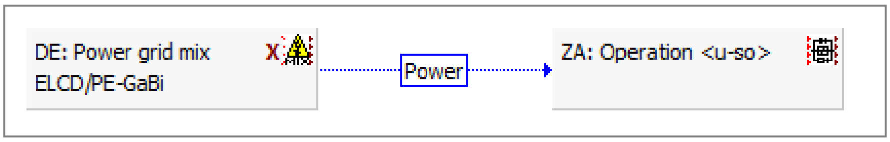

Figure 20: Plan for Operation of the Heliostats

6.3 Assumptions that can be made when working with GaBi

There are certain assumptions that have to be made when working with GaBi education. This might be because of several different reasons that may include the lack of information caused by proprietary materials and processes. It is also important to remember that and LCA has some objective steps that may influence the final results and interpretation.

Four types of assumptions were identified while doing this project. These are (1) construction, (2) installation, (3) decommissioning and (4) operation.
The materials used for construction couldn't be specifically identified, and since different types of steel and glass are available, standard steel and float glass were used for modelling most processes.

GaBi doesn't make provision for auguring the holes that is required for heliostat installation. The assumption was made that auguring contribution to emissions is so small it is negligible.

The problem with the energy consumption of the motors, which are the single largest contributor to operating costs, is that it is based on estimates made more than 15 years ago. The electrical usage and maintenance cost for different motor manufacturers might be different.

The disposal of the heliostats and the decommissioning of the collector area is a topic that many companies haven't considered in their strategic plan. It is difficult to determine the energy use and emissions associated with removing the collector field. Recycling will not be considered in the model, although it was discussed in the inventory analysis.

The final assumption is made regarding the maintenance of the heliostats. Minimum provision is made for broken pedestals or supporting structures. Spare parts will be available on site, but will not be taken into account in the model. These include motors, drives and mirror modules. In reality the amount of spares will be taken as a percentage of the total amount of parts needed for normal operation.

7. Life Cycle Impact Assessment

This chapter use a four step methodology to assess the results of the analysed data. These steps include (1) acquiring and comparison of results, (2) selection of impact categories, (3) classification of results, and (4) characterisation of results. The aim of the impact analysis is to evaluate the significance of different types of potential environmental impacts of the studied product.

The transparency of this chapter is important to give an open, comprehensive and understandable presentation of information. This chapter provide the information for the interpretation phase. (ISO 2006)

7.1 Results

The results that were obtained were the different emissions from the entire life cycle of 2667 heliostats, as calculated by GaBi. It is divided into three plans according to how it was modelled in GaBi. These are (1) manufacturing, (2) washing and (3) operation. The primary outputs that will be discussed are the emissions to air which will be classified, later in this chapter, according to three different impact categories.

Emissions to air consist of two primary types that are organic and inorganic. Organic emissions are chemical compounds that contain carbon (not metal carbonate, hydrogen carbonate or cyanides), whereas inorganic emissions are compounds that do not contain carbon or hydrogen bonds. The organic emissions to air, considered in this study, are halogenated organic emissions to air, methane and Volatile Organic Compounds (VOC). The inorganic emissions are ammonia, carbon dioxide, hydrogen chloride, hydrogen sulphide, nitrogen oxides, nitrous oxides and sulphur oxides.

GaBi's weak point analysis tool was used to filter out insignificant small emission contributors that are not displayed in the results. This is a feature of GaBi that identify the weak points of the life cycle that are that main contributors to the environmental impacts.

Table 7: Organic and Inorganic Emissions for the Entire Life Cycle

Values in kg	Manufacturing	Mirror Washing	Operation
INORGANIC EMISIONS	**42 933 704.114**	**5 592 085.823**	**4 784 148.722**
Ammonia	225.412	68.912	32.777
Carbon Dioxide	42 726 815.438	5 544 850.144	4 774 133.910
Hydrogen Chloride	1 459.770	13.783	41.781
Hydrogen Sulphide	835.187	10.597	3.462
Nitrogen Oxides	99 093.256	43 043.918	4 509.401
Nitrous Oxide	10 454.583	201.207	172.008
Sulphur Dioxide	94 820.468	3 897.261	5 255.384
ORGANIC EMMISIONS	**126 991.134**	**7 942.216**	**8 162.064**
Halogenated organic emissions to air	3.459	0.260	1.062
Methane	126 364.518	7 940.480	8 160.549
VOC (unspecified)	623.157	1.476	0.453

The table above shows the raw results calculated by GaBi. From the table it can be seen that the manufacturing process is responsible for approximately 80% of the total emissions. This is understandable considering that mirror washing and heliostat operation only utilize deionised water and electricity respectively. The potential for decreasing the life cycle emissions is definitively in the manufacturing process, since new, more efficient, manufacturing processes are developing and different heliostat designs can be considered.

Two methods are used in this report to interpret the raw results. The first method simply compares the results obtained with the results from various other power plants that use different technologies. The second method discusses the potential environmental effects of the chosen emissions. This section is concluded with the comparison method while the succeeding sections of this chapter focus on the potential environmental impacts.

The results used for comparison were obtained from GaBi by modelling different power plant technologies using a referent value. The referent value for this comparison is MWh. Since the functional unit for this study is 17 650 GWh of electricity, it was easy to normalise the results to kilogram per MWh. This made it possible to calculate the emissions for various different power plant technologies and compare it with each other.

Table 8: Comparison of Different Power Plant Technologies

	Renewable Energy			Non-renewable Energy			
Values in kg/MWh	**SPT**	**Wind**	**Hydro**	**Nuclear**	**Natural Gas**	**Oil**	**Coal**
Source Nation	**Calculated**	**Germany**	**Germany**	**Global**	**Germany**	**Germany**	**Germany**
Carbon Dioxide	3.005	6.090	24.290	28.838	506.034	869.862	901.212
Nitrogen Oxides	0.001	0.012	0.008	0.050	0.378	0.700	0.944
Sulphur Dioxide	0.006	0.017	0.002	0.118	0.189	1.692	0.812

The table above compare the emissions from solar power tower technology with other power plant technologies. The emissions from the heliostats' life cycle are assumed to be the major contributor to emissions resulting from solar power towers, although the physical tower may have some significant contributions as well. This statement is supported by studies done by current final year students on the other parts of solar power tower technologies. Their studies concluded minimal emission contribution relative to the result obtained in this study. Therefore the SPT emissions are a result of only the heliostats' life cycle's emissions.

All the results for the power plant technologies used for comparison, except the nuclear plant, were obtained from a German database that GaBi uses. The German data was used since most of the processes modelled in GaBi, for purposes of this study, use data from Germany by default. This ensures an accurate comparison since the source of the data is mostly the same.

The table is divided into two types of power plants, those who use renewable energy as fuel and those who use non-renewable fuel as energy source. Renewable energy is energy which comes from natural resources such as solar radiation, wind, tides, geothermal heat, and hydropower, which are naturally replenished. Non-renewable energy comes from natural gas, nuclear power, and more conventional resources such as oil and coal.

From the comparison table it can be seen that solar power towers are indeed a clean source of generating electricity, with only 3 kg of CO_2 released per MWh. Even in comparison with other renewable energy sources this is relatively low. The only non-renewable source of energy that can compete with renewable energy, in terms of emissions released, is nuclear power. Other non-renewable sources of energy, such as natural gas, oil and coal power plants are very environmentally unfriendly with emission as high as 900 kg/MWh released into the air resulting from coal power plants.

There are many factors that can decrease SPTs emission per MWh even more. These include the manufacturing of heliostats, different designs, material specification and washing methods. If these processes improve to increase the efficiency of heliostat field it would be possible to produce energy that is even cleaner than the energy currently generated by SPTs.

7.2 Impact Categories

This section focuses on the different environmental categories that are impacted by the emissions released during the life cycle of the studied product. The quantity of emissions gives a false idea of how clean the energy is if the potential environmental impacts of the different emissions aren't understood. Three impact categories were identified for this LCA study. These categories include (1) global warming potential (GWP), (2) acidification potential (AP) and (3) eutrophication potential (EP).

The identified categories reflect a comprehensive set of environmental issues related to the studied product since the goal and scope of the study was taken into consideration throughout the identification process.

7.2.1 Global Warming Potential (GWP)

Gases that contribute to GWP are known as greenhouse gasses because of the greenhouse effect, which can be observed on a small scale, as the name suggest, in a greenhouse. The GWP of these greenhouse gasses are calculated in carbon dioxide equivalents (CO_2-Eq.). Since CO_2 is the referent unit it has a GWP of 1. The GWP of a greenhouse gas is used as reference of how much heat is trapped by a gas relative to the amount of heat trapped by the same amount of carbon dioxide in a certain amount of time. (GaBi Education, 2011)

The GWP of a gas depends on three factors, (1) the absorption of infrared radiation, (2) the spectral location of its absorbing wavelengths, and (3) the atmospheric lifetime of the gas. A high GWP correlates with a large infrared absorption and a long atmospheric lifetime. The occurring short-wave radiation from the sun comes into contact with the earth's surface and is partly absorbed and partly reflected as infrared radiation. The absorbed part directly leads to global warming while the reflected part is absorbed by the greenhouse gasses in the troposphere and is reradiated back in all directions, including back to earth. This results in the warming effect at the earth's surface. (GaBi Education, 2011)

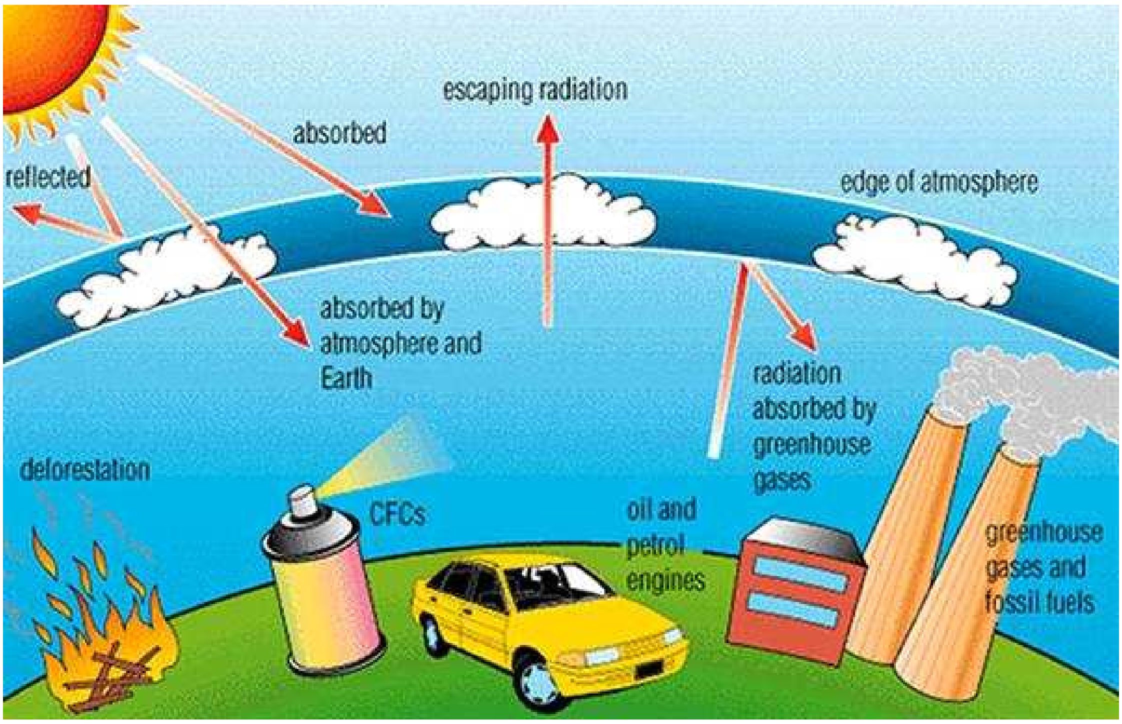

Figure 21: The Greenhouse Effect

Source: Pidwirny, 2006

Since the GWP of a gas depends on its lifetime, the studied time span should be stated to use as reference for the calculation. This is because a greenhouse gas which is quickly removed from the atmosphere may initially have a large effect but for longer time periods as it has been removed becomes less important. An example of this is the GWP of methane which is 25 over 100 years, but 72 over 20 years. A time horizon of 100 years has been chosen for this study since it's commonly used by regulators. (GaBi Education, 2011)

7.2.2 Acidification Potential (AP)

The acidification of soils and waters is a natural process that occurs predominately through the transformation of air pollutant into acids. This leads to the decrease of the pH-value of rainwater and fog from 5.6 to 4 and below. The AP is given in sulphur dioxide equivalents (SO_2-Eq.). Since SO_2 is the referent unit it has an AP of 1. (GaBi Education, 2011)

The AP is described as the ability to of certain substances to build and release H^+-ions. Certain emissions can also be considered to have an AP, if the given sulphur, nitrogen and halogen atoms are set in proportion to the molecular mass of the emission (GaBi Education, 2011). An example of this is atmospheric pollution arising from anthropogenic gasses derived from sulphur and nitrogen. These pollutant depositions enhance the rates of acidification, which may then exceed the natural neutralising capacity of soils. (Pidwirny, 2006)

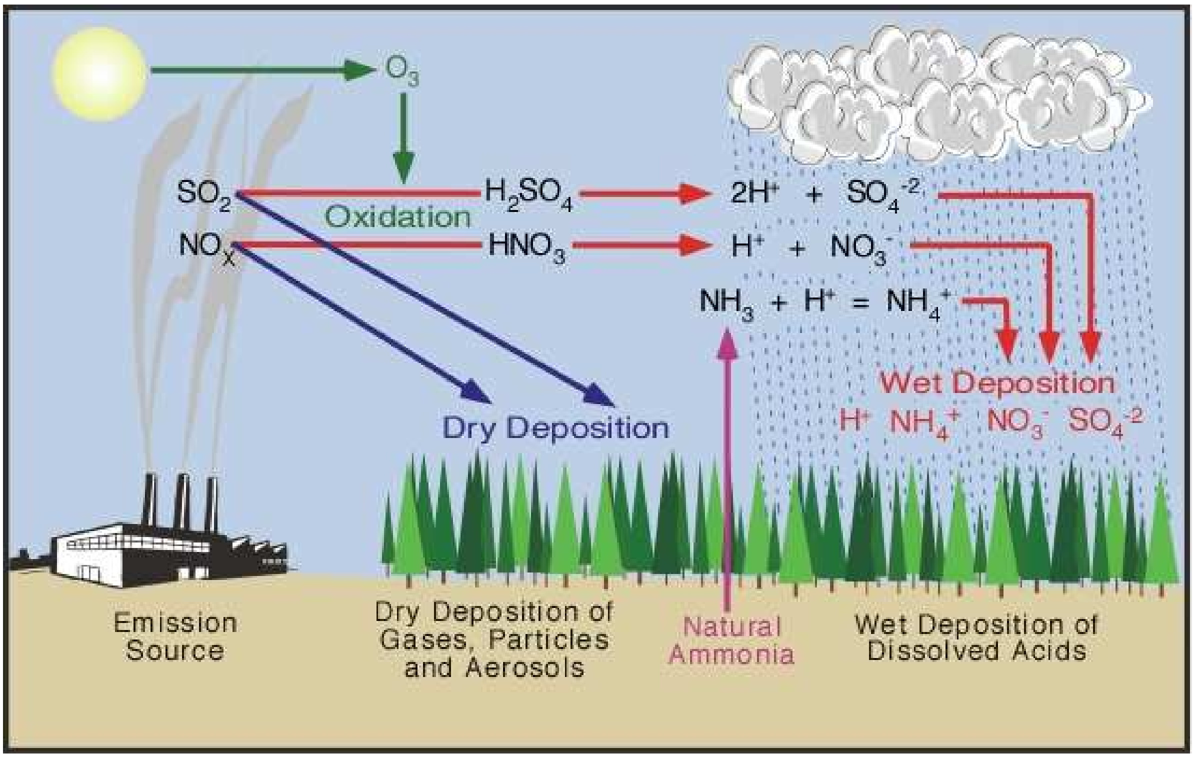

Figure 22: Acidification Potential

Source: Pidwirny, 2006

The environmental impacts of acidification are one of the major contemporary environmental issues. These impacts can be divided into two categories namely direct and indirect impacts. Direct acidification affects all aspects of the natural environment including soils, waters, flora and fauna. Indirect damaging effects include nutrients being washed out of soils or an increased solubility of metals into soil. Even buildings and building materials can be damaged by corrosion or disintegration that is increased by acidification. (GaBi Education, 2011)

7.2.3 Eutrophication Potential (EP)

Eutrophication is the enrichment of nutrients in a certain place. Air pollutants, waste water and fertilization in agriculture all contribute to eutrophication. The EP is calculated in phosphate equivalents (PO_4-Eq.). Since PO_4 is the referent unit it has an EP of 1. (GaBi Education, 2011)

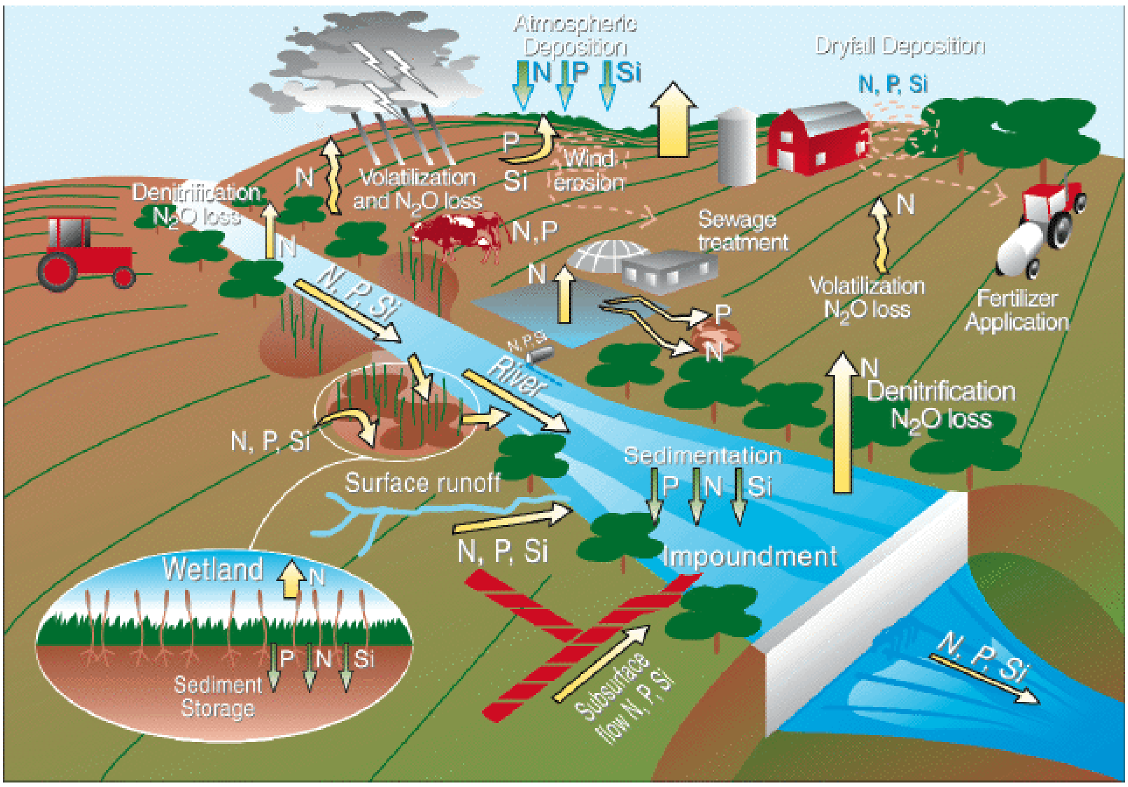

Figure 23: Eutrophication Potential

Source: Joshua, Hoffmeier. 2010

The impacts if eutrophication can be divided into two main categories namely aquatic and terrestrial eutrophication. The result of aquatic eutrophication is accelerated algae grow in water which prevents sunlight from reaching the lower depths, ultimately decreasing photosynthesis which leads to less oxygen production. In addition, oxygen is needed for the decomposition of dead algae. Both of these effects cause a decrease in oxygen concentration in the water, which can lead to fish dying and to anaerobic decomposition. Hydrogen sulphide and methane are thereby produced which can lead to the destruction of the eco-system. (GaBi Education, 2011)

The result of terrestrial eutrophication is an increased susceptibility of plants to diseases and pests. This affects the stability of the fauna in the environment. If the nitrification level exceeds the amounts of nitrogen necessary for maximum harvest, it can lead to the enrichment of nitrate. The nitrate content in the groundwater can increase and also ends up in drinking water. Nitrate at low levels is harmless from a toxicological point of view. However, if the nitrate reacts and form nitrite, it is toxic to humans. (GaBi Education, 2011)

7.3 Classification of Emissions

It is difficult to interpret the results of the LCI when the impact of each emission on the environment is not clear. This is why three environmental impact categories were identified. The impact of these categories has been discussed previously in this chapter. The different types of emissions must be categories to determine their specific environmental impact.

The following table classify each of the emissions, which were selected for this study, according to the impact category that they contribute to. This relevant category is denoted by an "X". The organic emissions contribute only to GWP since its carbon based. It is important to note that some of the inorganic emissions such as ammonia, nitrogen oxides, nitrous oxides and sulphur dioxide, contribute to more than one impact category, thus making it even more harmful to the environment.

Table 9: Classification of the Different Emissions

	GWP	AP	EP
INORGANIC EMISIONS			
Ammonia		X	X
Carbon Dioxide	X		
Hydrogen Chloride		X	
Hydrogen Sulphide		X	
Nitrogen Oxides		X	X
Nitrous Oxide	X		X
Sulphur Dioxide		X	
ORGANIC EMMISIONS			
Halogenated organic emissions to air	X		
Methane	X		
VOC (unspecified)	X		
Reference Unit	**kg CO_2 - Equivalent**	**kg SO_2 - Equivalent**	**kg PO_4 - Equivalent**

7.4 Characterization

This is the final step in the life cycle impact assessment (LCIA). The impact categories have been identified and the emissions have been classified. This section quantifies the magnitude of the emissions in each impact in terms of the reference unit for each category. Characterization factors are applied to the relevant quantities to determine the magnitude of the environmental impact. The table below shows the impact if the greenhouse gasses quantified in terms of kg CO_2-equivalent for the GWP category.

Table 10: Characterization of the Emissions for GWP

kg CO_2-Equivalent	Manufacturing	Mirror Washing	Operation
INORGANIC EMISIONS	**45 842 281.100**	**5 604 809.842**	**4 825 392.146**
Ammonia	-	-	-
Carbon Dioxide	42 726 815.438	5 544 850.144	4 774 133.910
Hydrogen Chloride	-	-	-
Hydrogen Sulphide	-	-	-
Nitrogen Oxides	-	-	-
Nitrous Oxide	3 115 465.662	59 959.698	51 258.236
Sulphur Dioxide	-	-	-
ORGANIC EMMISIONS	**3 195 915.149**	**200 393.451**	**212 028.415**
Halogenated organic emissions to air	26 769.386	1 857.687	8 007.392
Methane	3 159 112.939	198 512.002	204 013.733
VOC (unspecified)	10 032.824	23.762	7.290

From the GWP table it is clear that there are three major contributors to the GWP of the system, with carbon dioxide alone contributing to more than 80% of the total kg CO_2-equivelant. The other two emissions that are a concern are the nitrous oxide and methane emissions with characterization factors of 298 and 25 respectively. The high factors explain the large difference between the original mass and the CO_2-equivalent.

Table 11: Characterization of the Emissions for AP

kg SO_2-Equivalent	Manufacturing	Mirror Washing	Operation
INORGANIC EMISIONS	**167 464.271**	**34 189.610**	**8 516.861**
Ammonia	423.774	129.554	61.620
Carbon Dioxide	-	-	-
Hydrogen Chloride	1 284.598	12.129	36.768
Hydrogen Sulphide	1 570.152	19.923	6.509
Nitrogen Oxides	69 365.280	30 130.743	3 156.581
Nitrous Oxide	-	-	-
Sulphur Dioxide	94 820.468	3 897.261	5 255.384
ORGANIC EMMISIONS	**0.000**	**0.000**	**0.000**
Halogenated organic emissions to air	**-**	**-**	**-**
Methane	-	-	-
VOC (unspecified)	-	-	-

From the AP table above, it is clear that there are two major contributors to the AP of the system, with nitrogen oxide and sulphur dioxide each contributing to almost 50% of the total kg SO_2-equivelant respectively. Sulphur dioxide has a characterization factor of 1 since it's the referent unit, and for nitrous oxide the factor's 0.7.

From the following EP table, it can be seen that there are only three of the selected emissions that contribute to the EP of the system. Nitrogen oxides is the major concern since it alone contributes to more than 85% of the PO_4-equivalent. Although the characterization factor for the nitrogen oxides is only 0.13, the large quantity that is released into the air is alarming.

Table 12: Characterization of the Emissions for EP

kg PO_4-Equivalent	Manufacturing	Mirror Washing	Operation
INORGANIC EMISIONS	**15 783.755**	**5 674.154**	**644.136**
Ammonia	78.894	24.119	11.472
Carbon Dioxide	-	-	-
Hydrogen Chloride	-	-	-
Hydrogen Sulphide	-	-	-
Nitrogen Oxides	12 882.123	5 595.71	586.222
Nitrous Oxide	2 822.737	54.326	46.442
Sulphur Dioxide	-	-	-
ORGANIC EMMISIONS	**0.000**	**0.000**	**0.000**
Halogenated organic emissions to air	**-**	**-**	**-**
Methane	-	-	-
VOC (unspecified)	-	-	-

From these three tables the conclusion can be made that there are three major emissions that are of concern. These three emissions are respectively used as the reference unit for the three different impact categories. The three are carbon dioxide, causing GWP concern, sulphur dioxide, causing AP concern, and nitrogen oxides, causing both AP as well as EP concern.

It is recommended that each part of the heliostats' life cycle is divided into the most basic of processes to find the root cause of these emissions. Although these emissions are the lowest of all power sources discussed in the first part of this chapter, there are still room for improvement since this technology is still not entirely environmental friendly. This creates the opportunity for future research in this field.

8. Conclusion

In this final year project a life cycle assessment (LCA) model was developed in GaBi to determine the impact of a heliostat field for a 100 MW power tower. In the field of energy generation, it is important to considered sustainability and cleanliness of the technology.

Hence; the LCA that was done on the heliostats needed to fuel the power tower can be used to see the magnitude of the environmental impact that implementation of this technology will have. However, the results obtained are mostly based on data from Germany because of the lack of other data sources in GaBi.

In this LCA it can be seen that carbon dioxide, sulphur dioxide and nitrogen oxides are the emissions that have the greatest environmental impact in their different environmental impact categories respectively. The manufacturing of the heliostats contribute to more than 80% of the emissions. This creates the opportunity to look at the improvement of this process.

This LCA forms a basis on which further research and assessments can be done. The assessment can be more in-depth than the current LCA by breaking the three main processes down into their most basic processes. Each process can then be individually assessed to determine the root cause of the majority of emissions.

Reliable data is recommended, because some of the data in this LCA was assumed because of proprietary rights and inaccessibility of data.

Taking all of these factors into account, the conclusion that is made is that the use of solar power towers is one of the cleanest methods of generating energy, relative to other technologies. It is more sustainable and helpful towards the environment. Thus it is indeed a “green” technology.

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