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Water, Carbon and Land Footprint of Solar Thermal Technologies

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Summary

This research quantifies the impact of solar thermal energy regarding its water, carbon and land footprint. As countries transition to alternative energy production methods, it is critical to take a broad and encompassing approach to avoid trading one problem for another. The appeal of solar thermal energy largely lies in its minimal operational carbon footprint when compared to the operational carbon footprint of coal and gas fire plants. However, if the full supply chain and other environmental indicators are considered, it may be found that switching from coal and gas to solar thermal may only be trading one problem for another.

Two types of solar thermal plants are considered within this research, the solar power tower (SPT) and parabolic trough collector (PT). Each with a high level of detail to pinpoint where in the plant and supply chain emissions are created. Data is gathered using the Ecoinvent database (Wernet, et al., 2016) and supplemented with values from literature when needed. The data used is based on the construction of two solar thermal power plants in South Africa (Telsnig, 2015) but it is assumed modeling a plant will be very similar in all parts of the world. Both the construction and the operation phases are considered and calculated separately to allow for comparison. Each power plant is broken down into its key units and the footprints are calculated for each unit separately so which aspect of the plant causes what emissions can be seen.

The water footprint is separated into the blue and gray footprint, neglecting the green water footprint as there is assumed to be none. The blue water footprint is further separated into the process related blue water footprint and the energy related blue water footprint. This is done because of the different calculation method required. The gray water footprint is determined for 23 different pollutants, but the final footprint is based only the largest pollutant load.

The carbon footprint is calculated using the global warming potential of 5 greenhouse gases including carbon dioxide and methane. This method gives the final footprint in kilograms carbon dioxide equivalence which allows for easy comparison to other technologies. The carbon footprint related to energy inputs, such as electricity or the use of fuels and gases is calculated using known values from literature. The land footprint is calculated in meters squared for both the actual space taken up by the plant and for the land allocated towards the building of the plant from factories and mining.

The results show that the construction phase accounts for a significant part of the overall footprint for both plants. In general, there is little difference between the two plant designs, SPT and PT, for any of the footprints considered. However, the SPT has a slightly lower water and carbon footprint but a larger land footprint. When considered in the context of a specific geographic area with knowledge about what other factors are competing for the same resources, this difference may become impactful. The production of glass for making the solar collectors, a critical aspect of both plants, is identified as a major contributor to the water footprint of each plant, and therefore also a potential opportunity to reduce the water footprint.

This information is useful to compare with other types of energy production to determine which type is best suited for a particular area. It is important to understand how changing to any new form of energy production will affect the natural resources utilization. A full footprint analysis of different energy systems (or energy production technologies) can help decide which mix of energy production technologies will meet power demand while minimizing the strain on the natural environment.

Acknowledgements

This assignment concludes my studies at the University of Twente and the degree program Sustainable Energy Technology. I would like to thank everyone who has helped me along the way. To Arjen Hoekstra and Bunyod Holmatov for their guidance and feedback as they introduced me to the world of environmental footprint. And to Martijn Booij for stepping in as a supervisor offering a new perspective helping me to conclude this research.

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Contents

List of Abbreviations

SPT- Solar Power Tower

PT- Parabolic Trough Collector

LF- Land Footprint

CF- Carbon Footprint

WF- Water Footprint

WFgray- Gray Water Footprint

WFb- Blue Water Footprint

WFbp- Process related Blue Water Footprint

WFbe- Energy related Blue Water Footprint

PV- Photovoltaic

LCA- Life Cycle Analysis

EIA- Environmental Impact Assessment

RQ- Research Question

GWP- Global Warming Potential

1. Introduction

1.1 Background

Solar energy has the potential to become a key player in the transition to cleaner energy forms. Globally, one hour of direct solar radiation is equal to more than the world's energy consumption for an entire year (Viswanathan, 2017). Finding ways to harness this energy has been a topic of great interest for the last decades (Meinel & Meinel, 1977; Sukhatme & Nayak, 2017). The two most common technologies are solar photovoltaic (PV) and solar thermal. PV refers to solar power from photovoltaics which absorb sunlight and transform it into electricity, most commonly by utilizing a silicon based technology (Khanab & Arsalana, 2016). Contrarily, solar thermal technologies collect sunlight and transforms it into heat which is stored and later transformed into electricity (Khanab & Arsalana, 2016). Currently, the footprints of solar PV are being investigated at the water management research group at the University of Twente. Thus, this report will focus on solar thermal technologies and compare two different systems.

Concentrated Solar Power (CSP) is any solar thermal technology that concentrates the sun's energy to heat a working fluid and drives a steam turbine or engine to create electricity (Tian & Zhao, 2013). CSP systems have become increasingly popular in previous years due to their technical simplicity, ability to upscale and potential for integrated storage (Khanab & Arsalana, 2016). The most common types of solar thermal used are Parabolic Trough Collectors (PT) and Solar Power Towers (SPT). More focus has been put on solar thermal technologies in recent years as companies and governments strive to meet emission reduction targets as part of their climate action commitments. The increasing demand for energy in combination with the demand to reduce emissions forces us to look to new energy technologies. Solar thermal technologies are being used to reduce carbon emissions (Mulugetta, et al., 2014); however some concern has been raised over the water demand as solar thermal plants are commonly built in water scarce areas (Carter & Campbell, 2009). Like any thermal technology, solar thermal requires water for system cooling, in addition, the production, transport and maintenance have a water footprint of their own.

Traditionally, the sustainability of a process is measured based on its carbon dioxide emissions or emissions of other greenhouse gasses. Today, a broader definition is used which encompasses other environmental indicators such as water and land usage. Considering the carbon, water and land use gives a more complete picture of how a process uses resources. Furthermore, when assessing technology's impact, the emissions must be traced over the entire life cycle of a product, directly and indirectly. Thus, a footprint method will be applied in this study to determine the land, water and carbon footprint of producing energy via solar thermal technology (Tsoutsos, et al., 2005; Stucki, 2012).

The term 'environmental footprint' encompasses all the different footprints that have been established in literature. These include carbon, water, land, nitrogen, phosphorus, material, biodiversity, chemical and others (Vanham, 2019). Within this report, environmental footprint will only refer to the water, carbon and land footprints due to data availability. These footprints will provide a solid foundation for better quantifying the impact of solar thermal plants and therefore serve as a starting point to investigate the environmental footprint of CSP.

1.2 Literature Review

As solar thermal technologies have grown in maturity and popularity, the academic world has compiled a myriad of information regarding their design, performance and application (Tian & Zhao, 2013). While the business world is dominated by mainly two types of solar thermal technology, the SPT and PT collector with sensible heat storage, the research world is filled with various designs for collectors, storage systems and hybrid plants. Such research aims to find an optimal system that can compete economically with conventional coal fired power plants (Montes, et al., 2009; Powell & Edgar, 2012). Early research boasted about solar thermals ability to reduce carbon emissions and become a key player to solve the climate crisis (Meinel & Meinel, 1977). Later research has started to investigate the broader impact of solar thermal energy (Carter & Campbell, 2009; Lechon, et al., 2008).

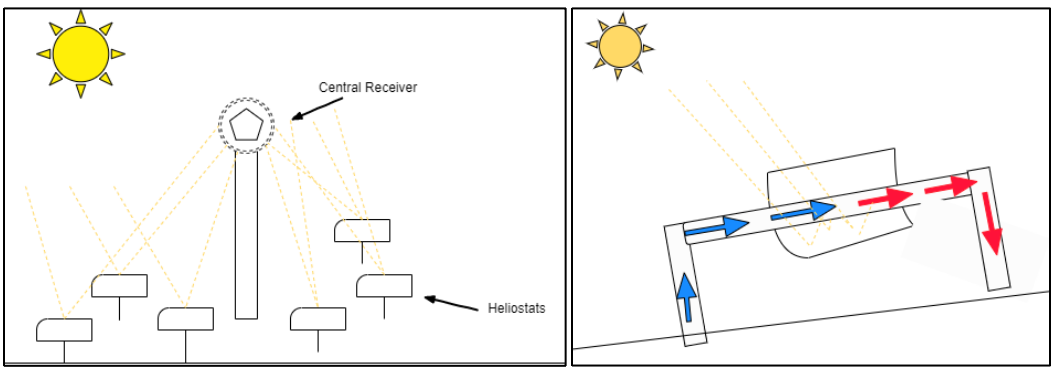

Figure 1 Solar Power Tower (Left), Parabolic Trough Collector (Right)

SPT's have many reflectors fitted with dual-axis tracking called heliostats which focus sunlight onto a central receiver. In the central receiver, a working fluid is heated and used as a heat source for power generation or thermal storage. A PT runs on the same basic principle, however instead of a central receiver, an absorber tube is positioned along the focal line of a "u" shaped reflector. A working fluid runs through the absorber tube which can be used as a heat source for power generation or thermal storage. Other types of solar thermal include flat linear fresnel reflectors and dish stirling. Flat linear fresnel focuses sunlight using a series of parallel grooves where sunlight is refracted at different angles and converges along the lenses focal line which is used to heat a working fluid (Zhai, et al., 2010). Dish sterling systems use dish shaped mirrors to focus sunlight onto a receiver positioned at the common focal point of the mirrors and is used to heat a working fluid (Tian & Zhao, 2013). Both these designs are far less commonly used than the SPT and PT and thus will not be considered within this study.

The most used type of storage is sensible heat storage which stores thermal energy during temperature changes in a phase change material such as molten salts. This method is well developed and relatively inexpensive compared to other methods, such as latent or chemical heat storage. Despite its lower heat capacity, sensible heat storage remains the front runner for solar thermal applications due to its ease of implementation and robustness (Tian & Zhao, 2013).

Environment Impact Assessments (EIA) and Life Cycle Analysis (LCA) studies are common methods to quantify the impact of an activity, process or product. Many EIA (Tsoutsos, et al., 2005; Trieb, et al., 1997) and LCA (Lechon, et al., 2008; Ardente, et al., 2005; Pehnt, 2006) studies have been completed on the topic of solar thermal plants. Such analysis often touches on the water aspect and many assessments name impact on water resources as a potential problem (Ardente, et al., 2005; Tsoutsos, et al., 2005), or one study focused on carbon emissions (Lechon, et al., 2008).

The water footprint concept, introduced by Hoekstra in 2002, allows the water use of a product, process, business or individual to be traced over the entire supply chain, directly and indirectly (Hoekstra, et al., 2011). Water Footprint assessments are commonly used in the agriculture sector to better understand how certain crops and practices affect natural resources. The popularity of water footprints within the agriculture sector is logical as agriculture accounts for 85% of global blue water consumption (Shiklomanov, 2000). There is less research into the water footprint of non-agricultural products and processes and less attention is paid to the gray and green water footprints. As water becomes an increasingly strained resource due to higher consumption and population, it is becoming necessary to understand how other products and processes consume water (Mulugetta, et al., 2014).

The water energy nexus is becoming increasingly considered in research and policy. Policy makers and researchers alike acknowledge the interconnectedness of water and energy and the need to co-manage them (Scott, et al., 2011; Schnoor, 2011). Solar thermal power plants highlight the need for water management within the energy sector. Compared to other energy production technologies, solar thermal is known to have a relatively higher water consumption (Carter & Campbell, 2009; Mekonnen, et al., 2015; Gleick, 1994). This coupled with the geographic restriction of where solar thermal plants can operate, has created the need for a higher level of attention to solar thermal plants impact on natural resources.

While one of the key selling points of a solar thermal plants is its technical simplicity as it uses similar technology to traditional coal plants, the drawback is that this type of technology also requires cooling. Wet cooling uses a stream of fresh water to cool the power plant and dissipate the heat energy to the environment as water vapor. Wet cooling is the largest use of fresh water during operation and the most common type of cooling used in CSP plants today (Carter & Campbell, 2009). More water-efficient cooling methods do exist, but they generally reduce electricity production of the plant and increase the cost of energy. Of all solar thermal plants in operation today, the vast majority use wet cooling (Carter & Campbell, 2009). This coupled with the lack of freshwater availability in sunny areas, where solar thermal plants are commonly built, has the potential to become a dangerous strain on water resources.

A complete footprint analysis that is performed over the entire life cycle of a solar thermal plant, including construction and operation is necessary to understand how solar thermal uses natural resources. Current footprint values (water and carbon in particular) are available from recent literature (Carter & Campbell, 2009; Mulugetta, et al., 2014) but do not provide enough detail to pinpoint where in the plant, construction or operation, these emissions are created. This information will create a better understanding of how installing solar thermal power plants affects the natural environment and is also the starting point towards identifying potential methods to reduce the overall footprint.

1.3 Objective

The purpose of this study is to quantify the water, land and carbon footprint of constructing and operating CSP power plants and to identify where in the life cycle emissions are created. Environmental indicators of water, land and carbon footprint will be considered. The two most common applications of CSP technologies will be considered and compared: SPT and PT. The design for the system will be based on current plants in operation. The two systems are built and operated in one geographic location, but it is assumed that modeling a CSP plant will be very similar in different parts of the world. The data sets used come from research conducted in 2015 (Telsnig, 2015) and thus accurately portray CSP plants in this time period but not necessarily future CSP plants as technology and practices change over time.

While a complete footprint assessment will be conducted within this study, the focal point is on footprint accounting. The resulting values can then be used by the appropriate bodies to formulate policies and targets. Given recent criticism of the water use in Solar Thermal plants (Carter & Campbell, 2009), the water footprint is of most interest.

1.4 Research Questions

The main research question is defined as;

What is the water, land and carbon footprint associated with producing energy from two different Concentrated Solar Power plant designs: Solar Power Tower and Parabolic Trough?

To help answer the main research question, the following sub questions have been defined. A stepwise approach will be used to answer the main research question, meaning investigating the sub questions one by one in order will lead to an answer to the main research question.

1. How are CSP plants constructed and operated?
2. What is the water, land and carbon footprints of construction and operation?
3. What is the water, land and carbon footprint per unit of energy produced via CSP?

1.4 Report Outline

The following sections will expand upon and answer the above research questions. First, section 2, Materials & Methods, will explore the first research question and describe the two production systems, the SPT and the PT. Section 3, Results, will explore questions two and three as the footprint results are presented, first for the construction phase and then for the operation phase. Subsections 3.1 and 3.2 will present the water, land and carbon footprints of construction for the SPT and PT and subsection 3.3 will present the operation phase. Subsection 3.4 will compare the two plants in terms of their total footprints per unit of energy and compare the footprints themselves. Section 4, Discussion, will consider the potential and limitations of this study as well as discussing how the results can be translated into solutions. Finally, section 5, Conclusion, will recap the findings of this report and propose recommendations for future studies.

2. Materials & Methods

This section will describe the two CSP plants investigated in this study including their construction and operation phases (RQ1) as well as the data and calculation methods used (RQ2 + RQ3). Firs the data used will be introduced followed by the scope of the study. A system description is then given including a list of assumptions and specific details related to the construction and operation phases. The calculation methods for each footprint is then presented followed by the footprints related to mining and transport.

2.1 Data and Scope

The primary source of data is Ecoinvent version 3.6 (Wernet, et al., 2016), supplemented by numbers found in literature. Ecoinvent is a well-known data source that has been previously used for water and carbon accounting (Hoekstra, et al., 2011; Buckley, 2017). A life cycle approach is taken for calculations of the water, carbon and land footprint. The supply chain begins with mining of raw materials and ends with an operational plant. Due to data availability and in order to limit the scope of this research, the supply chain is truncated to only include emissions related to mining operation, materials production, plant construction and plant operation. This can be visualized in figure 3. While emissions related to the operation and extraction of raw materials is considered, emissions from the construction of the mining facilities themselves are not.

Ecoinvent provides detailed data on two solar power plants: 'concentrated solar power plant construction, solar tower power plant, 20 MW', and 'concentrated solar power plant construction, solar thermal parabolic trough, 50 MW'. The data is extracted from a detailed life cycle inventory in the dissertation report by Telsnig (Telsnig, 2015). For both plants, the data is based on an operational plant in South Africa. The data is generalized to be global average values as it is assumed that the modelling of a solar thermal plant in other parts of the world would have very similar emissions so the data has been extrapolated to global data without adjusting for uncertainty. This data is used in combination with material and operation data also extracted from Ecoinvent version 3.6. Global values were used for all data unless otherwise noted. A list of special cases can be found in Appendix 1.

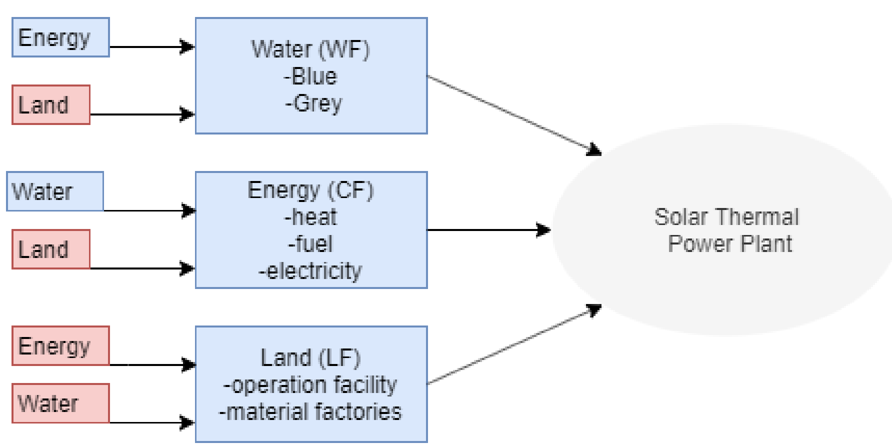

Figure 2 Water, Energy and Land Interconnectedness in Solar Thermal Plant Construction

Water, energy and land are all interconnected. This idea is most clearly shown in the example of energy; water is used during the construction and operation of energy production plants, and the production plants also take up an area of land. The same is true for water; energy is used to pump or to clean water, all these activities take up land. For land; energy and water may be used to transform the land into a usable area, for example by clearing trees or flattening. Therefore, when calculating the water, energy and land footprints one must also consider how the interconnectedness of the footprints affect each other. This research will focus on the water-energy nexus and consider energy used for water, and water used for energy but exclude land. Meaning, land used to provide water or energy (water treatment facilities and energy production sites) will not be included as well as the water and energy needed to create useable land is neglected.

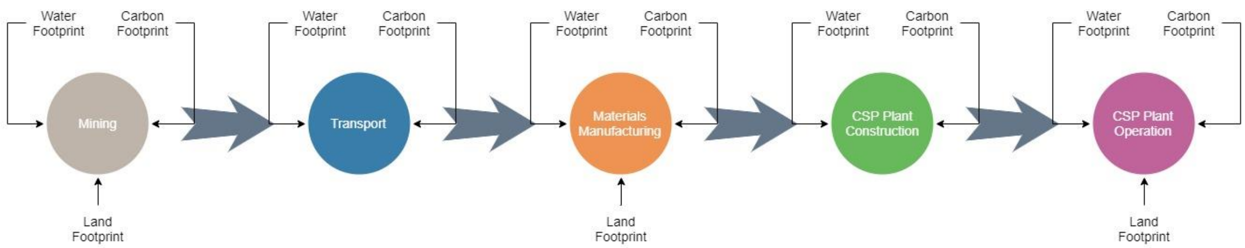

Figure 3 Footprints considered along the Supply Chain

2.2 System Description

There are approximately 130 solar thermal plants in operation across the world as of 2017 (Viswanathan, 2017). The two systems considered here, parabolic trough and solar power tower, will be based on current plants in operation. For calculation purposes, the plant will be considered in two stages, first calculations for the construction of the plant and later for the operation of the plant. System descriptions and calculation methods can be found in the following sections. A comprehensive overview of the system designs can be found in Appendix 2.

2.2.1 List of Assumptions

- Electricity is produced using a CSP plant. Other forms of energy including diesel, petroleum, coke ect. use global averages to calculate the associated footprints.
- Materials are transported an average of 100 km. This is done so the results are comparable with other studies.
- Emissions allocation will be done based on market value. Where there is no price given from Ecoinvent data, no allocation will be assigned.
- The lifetime of the Solar Power Tower plant is assumed to be 30 years as specified in the Ecoinvent data set.
- The lifetime of the Parabolic Trough plant is assumed to be 30 years as specified in the Ecoinvent data set.

2.2.2 Construction

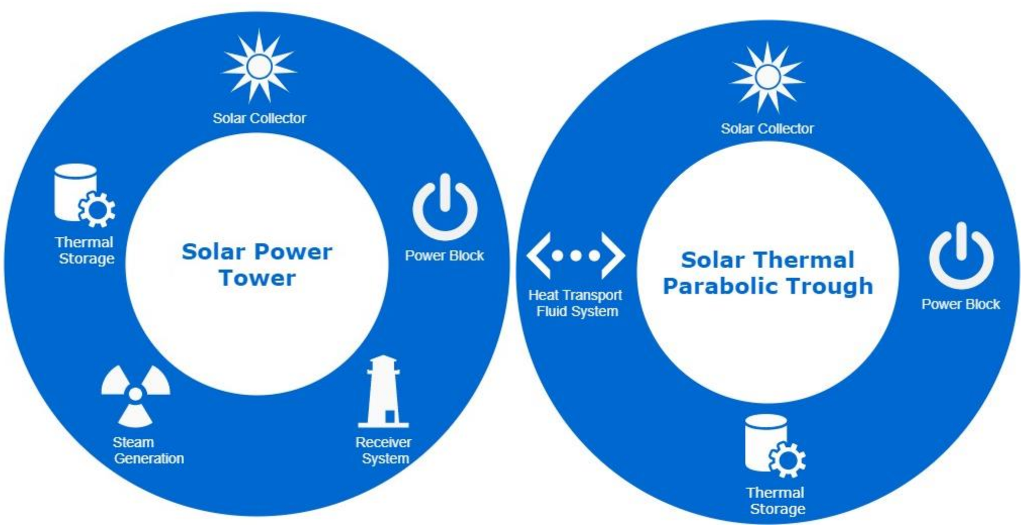

Figure 4 Identification of Key Units in (right) Solar Power Tower and (left) Parabolic Trough

The Solar Power Tower can be broken down into five units that together form the SPT plant: Solar Collector, Power Block, Receiver System, Steam Generation and Thermal Storage. Likewise, the Solar Thermal Parabolic Trough can be broken down into four units: Solar Collector, Power Block, Thermal Storage, and Heat Transport Fluid System. Both plant designs also include site preparation activities, namely: Building Hall Construction, Excavation by Hydraulic Digger, Road Construction, material (Steel, unalloyed) requirement, Water Supply Network construction and Wire Drawing from Steel activity (Telsnig, 2015). For each unit, the footprint will be calculated based on the materials used and an estimation factor to account for transport and mining. Each product has many inputs including materials like steel, concrete, copper or glass, but also operations such as welding or use of electricity or machines. The water, carbon and land footprints of each of these inputs is calculated using data provided from Ecoinvent. The final footprint of the power plant construction is thus the sum of the footprints of each product, plus the footprint related to mining and transport.

In some cases, calculating the footprint of one material requires inputs of other materials that also use the original material as input. This creates a circularity problem in the calculation flow. To solve this problem the calculation chain was cut so that an estimated value from literature or an approximate value calculated with the data available was entered. The chain was cut where the smallest amount of input values would need to be estimated to taken from literature.

2.2.3 Operation

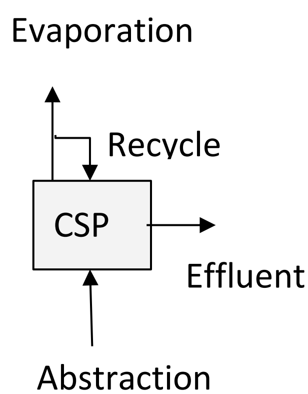

Figure 5 Visualization of Calculation Method

One of the key benefits of solar thermal is absence of any air emissions or waste products during operation. The main consumption during operation is water. There are three main cycles during operation of the plant that influence the water footprint of the plant, namely the cooling cycle, steam cycle and cleaning. Literature research shows that the cooling cycle is the largest consumer as wet cooling is currently the most common type and a lot of water is lost as evaporation (Pelay, et al., 2017). The steam cycle can be a closed cycle meaning virtually no water is lost and cleaning activities (such as cleaning the heliostats) is minimal.

Data from Ecoinvent is used to determine the water, carbon and land footprint during operation per kWh. The Solar power plant is modeled as a 20MW plant producing 105790000 kWh/year and the values for operation do not include any maintenance activities or replacement parts over the 30-year lifespan. The SPT is also fitted with 440 MW heat storage capacity providing 3-6 hours of storage. The capacity factor of a typical SPT plant fitted with thermal storage is typically greater than 40% (Carter & Campbell, 2009). A capacity factor of 50% will be assumed for the SPT. The capacity factor of a plant can vary greatly dependent on the type of thermal storage, type of cooling used and the geographic location of the plant (Carter & Campbell, 2009).

The Parabolic Trough plant is modeled as a 50MW plant producing 239620000 kWh/year and values also do not include any maintenance activities or replacements parts in the 30-year lifespan. The PT is also fitted with 110 MW heat storage capacity providing 3-6 hours of storage. A capacity factor of 60% is assumed for the PT plant as PT plants are known to have higher capacity factories than SPT plants (Carter & Campbell, 2009). Again, there can be large variation in the capacity factor and should be adjusted when looking at a specific plant.

2.3 Footprint Calculation Method

The footprints will be calculated considering the construction and operation phases. The construction phase is defined by the materials used to make the plant and their associated footprint and an estimated factor to account for transport and mining. The operation phase is defined by any cleaning or maintenance activities, cooling of the plant and other cycles during the functioning of the plant such as the steam cycle.

2.3.1 Water Footprint

The water footprint can be further divided into the blue, green and gray water footprints. Blue water footprint refers to the consumptive use of fresh (surface and ground) water. Green water footprint refers to rainwater that does not run off or recharge the groundwater. And finally, gray water footprint measures freshwater pollution as the amount of freshwater required to assimilate the pollutant load. Within this research, only the blue and gray water footprints are of interest as there is no green water footprint (Hoekstra, et al., 2011).

Blue Water

Two calculation methods are required for the blue water footprint, one related to the process water consumption and one related to water for energy consumption. The net blue water footprint is assumed to the sum of the process blue water and energy blue water.

The process blue water, WFb_p, is assumed to be the abstraction minus the discharge. This idea is illustrated with the example below.

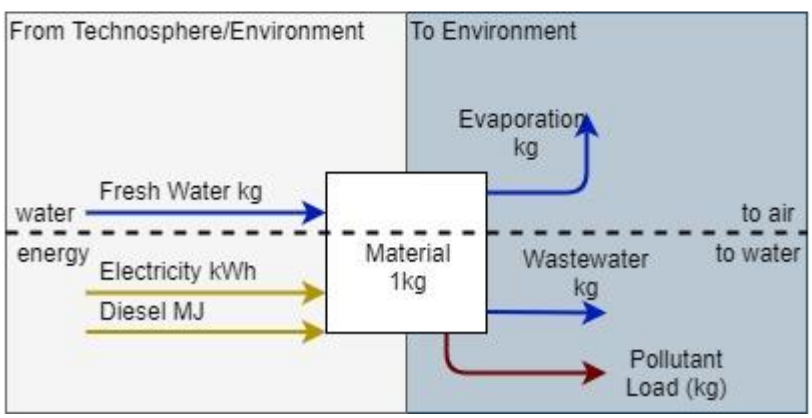

Figure 6 Inputs and Outputs of Material Production, Water Footprint

Blue water footprint, processes related,

$$WFb_p = (a - d)\ x\ f\ [liters] \tag{1}$$

Where, a is the amount of water abstracted and, d, refers only to the discharged water that returns to the same catchment area and is unpolluted, this does not include evaporation. Thus, the abstraction minus the discharge is the amount of water incorporated in the product, evaporated or polluted by the process. And f is a scaling factor applied when there are multiple valuable output products based on their market value.

Value Fraction,

$$f = \frac{p\ x\ w}{\sum_{i=1}^{n} p_i\ x\ w_i} \tag{2}$$

Where, p is an output product and w is the weight of the output product. n is number of materials.

The blue water footprint related to energy, WFb_e, is calculated assuming electricity is produced using a solar thermal plant: SPT for SPT, and PT for PT. An estimation value, W_E, from literature is used to calculate the water footprint. For the SPT, 3.14 l/kWh is used and for the PT, 3.48 l/kWh is used (Carter & Campbell, 2009). Estimation values are also used for other types of energy, including fuels and gas used for machine operation during the manufacturing process of materials. An overview of the estimation factors can be found in Appendix 4.

$$WFb_e = E[kWh]\ x\ W_E[l/kwh] \tag{3}$$

Finally, the total blue water consumption, WFb_{tot}, is equal to the sum of the energy and process water footprints, summed over the supply chain.

$$\mathrm{W}Fb_{tot} = \sum_{i=1}^{n} WFb_{pi} + WFb_{ei}\ \ [liters] \tag{4}$$

Gray Water

The amount of freshwater that is required to assimilate the pollutant load of a product or process is the gray water footprint. For all emissions to water, the gray water footprint was calculated as,

$$WF_{gray}[volume/time] = \frac{Pollutant\ Load\ [mass/time]}{C_{max}\ - C_{nat}\ [mass/volume]} \tag{5}$$

Where, C_{nat}, is the naturally found concentration of a pollutant and C_{max}, is the maximum allowed concentration of a pollutant for environmental standards. In situations where no C_{nat} value is available, it is estimated to be zero. Due to lack of data, this method is used for some C_{nat} values but it should be noted that doing so causes an underestimation of the actual gray water footprint. Appendix 4 details the pollutants considered within this study and their respective C_{nat} and C_{max} values.

Ecoinvent provides effluent data that includes chemical substances and water quality parameters such as biological oxygen demand (BOD) and chemical oxygen demand (COD) [kg/mass output material]. The pollutant load is taken as only the largest pollutant as the volume of freshwater needed to assimilate this load is also enough for other smaller pollutants. Data is provided for all pollutant loads should future research desire a more in-depth gray water footprint picture.

2.3.2 Carbon Footprint

The carbon footprint was calculated using data from Ecoinvent and the Carbon Footprint Standard. The Carbon Footprint standard is an internationally recognized method that includes the leading standards in assessing, reporting and offsetting emissions (Buckley, 2017). The CF measures the global warming of greenhouse gasses in terms of their carbon dioxide equivalence. As a minimum set by the Carbon Footprint Standard, calculations need to include, Carbon Dioxide, Nitrous Oxide and Methane to perform a footprint analysis (Buckley, 2017). Ecoinvent does not give sufficient data to include the Nitrous Oxide in the calculation so it will be neglected. Additionally, at a minimum, all emissions from buildings, fuel and transport that are under the direct control of the entity (product, process, business, ect) must be included.

Within the scope of this research the following greenhouse gases will be considered, with their Global Warming 100-year potential taken from the 5th Assessment Report (AR5) (Myhre, et al., 2013). The global warming potential (GWP) is the measure of the amount of energy 1 ton of a gas would absorb (thereby increasing the amount of energy in earths system) compared to the amount of energy 1 ton of carbon dioxide would absorb. The final CF is thus measured in kilograms carbon dioxide equivalence.

Table 1 Global Warming Potential Values from 5th Assessment Report (Myhre, et al., 2013)

Substance	*Global Warming Potential*
Carbon Dioxide	1
Methane	28
1,1,1,2-tetrafluoroethane	1300
Trichlorofluoromethane	4660
Tetrafluoromethane	6630

For each input the global warming potential, GWP, was multiplied by the mass, m, to determine the amount of carbon dioxide equivalence that should be allocated to the output product and finally summed over all the emissions.

$$\mathrm{CF} = \sum_{i=1}^{n} GWP_i \; x \; m_i \text{ [kg CO2e/kg]} \qquad (6)$$

Carbon emissions related to energy used in the construction and operation of the plant were calculated using estimation factors found in literature for different types of energy input such as electricity, heat and gas. Appendix 3 gives an overview of these estimation factors, C.

$$CF_e = E[kWh] \ x \ C \ [kg \ Co2e/kwh] \tag{7}$$

2.3.3 Land Footprint

The data provided by Telsnig (Telsnig, 2015), includes land footprint information for the construction of the plant. This estimate only includes the direct land use, and does not account for indirect land use through, for example, factories used to produce materials used to build the CSP plant. Therefore, to achieve a more complete land footprint, the footprints from farther down the supply chain are also included using material data from Ecoinvent.

$$LF = LF_{plant} \ + \ (\sum_{i=1}^{n} LF_{mi} \ x \ f_i) \ [m^2] \tag{8}$$

Where, LF_{plant}, is the land estimate from Ecoinvent, LF_m, is the land footprint of materials in the supply chain and f, is the allocation factor for the material as provided in Ecoinvent.

This same allocation approach is also used to account for the land use of mining areas for the extraction of raw materials. The LF is calculated considering land transformations and physical space taken up by the plant, mining and other production facilities as well as land use due to occupation, industrial area or traffic area.

2.3.4 Mining and Transport Factors

In order to take into account the entire supply chain, the emissions due to mining raw materials and transporting them to the plant site must be taken into account. An average distance of 100 km was assumed for the transport of all materials. Data from Ecoinvent for 'transport, freight, lorry >32 metric ton, EURO2' averaged to global values was used. On the water and carbon footprints were considered for transport as the land footprint is assumed to be negligible. The results can be seen in the table below.

Table 1 Transport by Freight Footprint Values

	WFb	WFgray	CF
transport, freight, lorry >32 metric ton, EURO2	1.47E-04 l/kg*km	4.20E-08 l/kg*km	1.23E-05 kg Co2e/kg*km

Mining was also calculated using a similar approach. Because of the quantity of different materials and similarities in mining processes, the water and carbon footprints were not calculated for each material individually. Rather materials were divided into three groups: Metal: non-ferrous, Metal: Iron/Steel, and Non-Metal. It was decided to separate materials into metals and non-metals because of the differences in process and energy requirement between metals and non-metals (BCS, 2007). Data from Ecoinvent was selected for each group to calculate the water, carbon and land footprint from mining.

For the group Metal: non-ferrous, the data set 'mine infrastructure, underground, non-ferrous metal [unit]' was used. For the group Metal: Iron/Steel the data set 'Mine Infrastructure, Iron [unit]' was used and for the final group, Non-metal, the data set 'Mine Operation, Phosphate [unit]' was used. The results can be seen in the table below.

Table 2 Footprint Values related to Mining for Three Classifications of Materials

Classification	*WF [l]*	*WFgray [l]*	*CF [kg Co2e]*	*LF [m2]*
Metal: non-ferrous	9.76E-02	4.21E-04	2.19E-02	2.44E-04
Metal: Iron/Steel	2.81E-03	2.24E-04	1.10E-03	1.13E-04
Non-Metals	2.81E-02	4.69E-10	9.56E-03	1.66E-06

2.3.5 Operation

The above calculations considered the construction phase of a CSP plant. The environmental footprints also need to be calculated for the operation phase of the plant. This is done using data from Ecoinvent, 'electricity production, solar tower power plant, 20 MW' and 'electricity production, solar thermal parabolic trough, 50 MW' which are both derived from the work of Telsnig (Telsnig, 2015). While solar thermal plants are known for their ability to produce electricity with little emissions, some water and energy are required for the operation of the plant.

The blue water footprint comes mainly from the input 'water, deionised' which for both plants has a value of 0.1 l/kWh. There is also an energy related blue water footprint from the 'Heat, district or industrial, natural gas' input which is calculated using an estimated 2.36 l/kWh for natural gas (Mekonnen, et al., 2015). The carbon footprint is mainly related to the required heat input, which is calculated using an estimated 0.415 kg Co2e/kWh (EIA, 2019). The PT design also has an additional carbon and water footprint from the small amounts of benzene and diphenylether-compound. Finally, the land footprint is calculated using the size of the plants which is provided in the original data set from Ecoinvent.

Table 4 SPT Operation Inputs

SOLAR POWER TOWER [1 KWH]	**AMOUNT**	**UNIT**
HEAT, DISTRICT OR INDUSTRIAL, NATURAL GAS	0.111911	kwh
WATER, DEIONISED	0.1	kg

Table 5 PT Operation Inputs

PARABOLIC TROUGH COLLECTOR [1 KWH]	**AMOUNT**	**UNIT**
BENZENE	0.000052	kg
DIPHENYLETHER-COMPOUND	0.000144	kg
HEAT, DISTRICT OR INDUSTRIAL, NATURAL GAS	0.107142	kwh
WATER, DEIONISED	0.1	kg

3. Results

The Results of this research will be presented in four parts, first the footprint results related to the construction phase of the SPT (RQ2). Second, the footprint results related to the construction phase of the PT (RQ2). Third, the results for the operation phase of each plant (RQ2). And finally, a comparison of the two plant designs and the total footprints of each plant per unit of energy (RQ3). An overview of all material, machine, factory and other footprints can be found in appendices 5, 6, 7 and 8.

3.1 Construction Solar Power Tower

Table 6 Footprint Results, 20MW Solar Power Tower Plant

	WF [L]	WFGRAY [L]	CF [KG CO2E]	LF [M^2]
HELIOSTAT	3.45E+08	1.35E+03	1.57E+08	1.35E+03
POWER BLOCK	2.23E+08	7.80E+04	1.27E+08	1.02E+03
RECEIVER	9.36E+07	5.30E+02	2.35E+07	3.95E+02
STEAM GENERATION	8.13E+06	4.55E+01	3.04E+06	4.36E+01
THERMAL STORAGE	5.38E+07	3.03E+01	1.28E+07	5.31E+01
OTHER	2.64E+07	2.95E+04	1.29E+07	1.43E+02
TOTAL	**7.50E+08**	**7.80E+04**	**3.37E+08**	**3.00E+03**

Table 6 gives insight into the location of emissions within the construction of a SPT plant. Only the two water footprints, blue and gray, can be directly compared as they are calculated in the same units.

The following sections will look at the results per footprint to see which parts of the power plant are responsible for which footprints. The SPT has 5 key units (Heliostat, Power Block, Receiver, Steam Generation, and Thermal Storage). Other, is the sum of everything not included in the five key units, namely, Building Hall Construction, Excavation by Hydraulic Digger, Road Construction, material (Steel, unalloyed) requirement, Water Supply Network construction and Wire Drawing from Steel.

3.1.1 Water Footprint

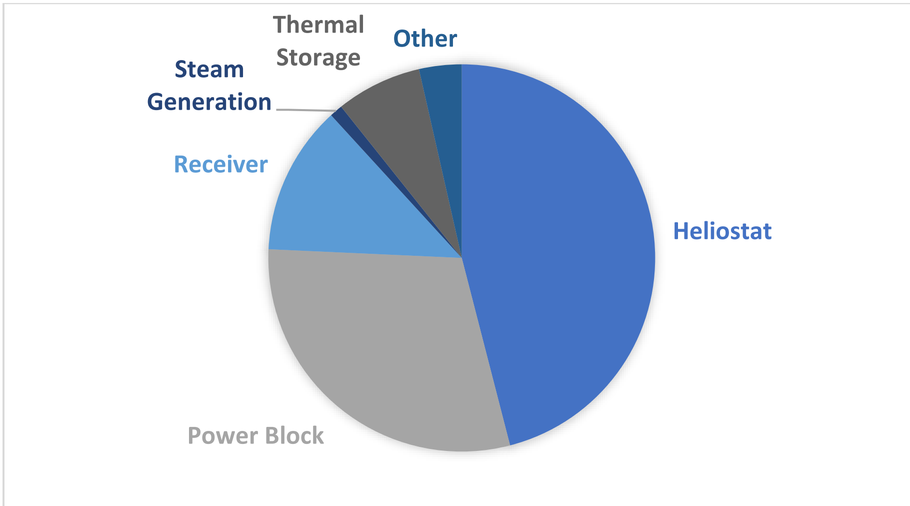

Figure 7 Blue Water Footprint, Solar Power Tower

The largest unit contributing to the blue water footprint (WFb) is the 'Heliostats', accounting for 46% of the total footprint. The main contributor to the large water footprint of the Heliostats is the use of 2179.7 tonnes of 'Flat Glass, Coated'. 'Flat Glass, Coated' has a large process related WF which can be traced back to the blue water footprint of the 'Flat Glass Factory'. Approximately 27% of the WFb of the Heliostats is due to the use of "Flat Glass, Coated'. Reducing the WFb of producing flat glass therefore has the potential to greatly reduce the overall blue water footprint of the 'Heliostats' and thereby SPT plant construction. However, it is not solely the relatively higher blue water footprint of flat glass, but also the large quantities used that cause the footprint.

The second largest contributor is the 'Power Block' accounting for 30% of the total footprint. The 'Power Block' uses 43 different materials during its production which is much more than most other key units. The material that contributes most to its WFb is 'Concrete, normal' which has a relatively low WFb of just 3.4 l/kg but is used in high quantity (26751.95 tonnes). 'Concrete, normal' accounts for 40% of the 'Power Blocks' WFb.

The Gray Water Footprint (WFgray) is predominately related to the 'Power Block' (56%). The high WFgray of the 'Power Block' is from the input 'Silicone, product' whose WFgray can be traced back to the pollutants Mercury during the production of silicone. There is also a portion the WFgray due to mining activities, for non-metal materials, as in the case of 'Silicone, product' this part is negligible but for metals the contribution from mining is more significant. The second largest part is the 'Heliostat' (29%) whose WFgray can be traced back to the input 'Reinforcing, Steel'. The contribution from mining is responsible for the WFgray of 'Reinforcing, Steel' in combination with the high quantity of the material used. Overall, the WFgray is insignificant compared to the WFb.

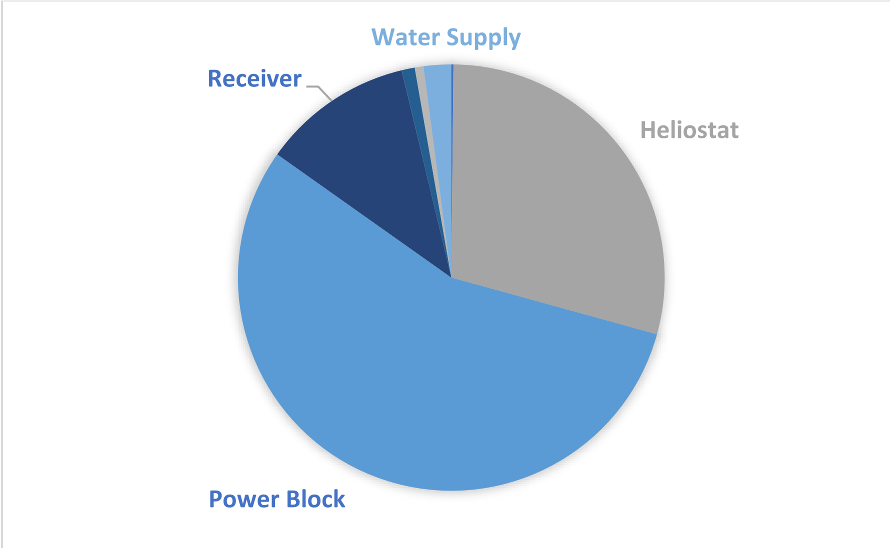

Figure 8 Gray Water Footprint Solar Power Tower

3.1.2 Carbon Footprint

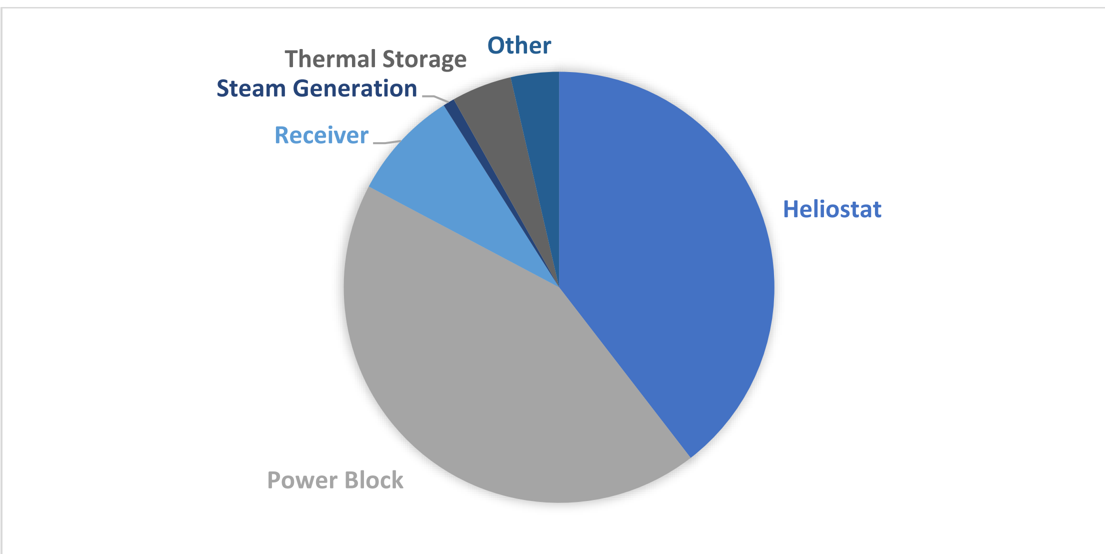

Figure 9 Carbon Footprint Solar Power Tower

The largest contributor to the CF is the 'Power Block', contributing 43% because of the large amount of 'Concrete, normal' required for construction. Most of the CF of 'Concrete, normal' comes from the 'Concrete Mixing Factory' The second largest contributor, accounting for 40% is the 'Heliostats'. The CF of the 'Heliostat' can be traced back to the input 'Reinforcing, Steel' which has a relatively high CF of 10.3 kgCo2e/kg. The high CF is because of the input of pig iron which is made from iron ore. The 'iron ore, crude' must go through a four-step process to be processed into pig iron. Each step requires an additional energy input which increases the CF. This combined with the large amount of 'Reinforcing, Steel' required results in the high net CF. Together, the 'Power Block' and 'Heliostat' account for 83% of the total CF so focusing on the construction of these two units is logical for looking for ways to reduce the overall CF.

3.1.3 Land Footprint

The largest contributor to the land footprint (LF) is the 'Heliostat' (45%), or solar collector field. Examining the construction of the collector field area reveals that most of the LF is from the required 5900 tonnes of 'Reinforcing, Steel' which has a LF of 0.00013 m^2/. The LF can be partly attributed to the area required for mining of steel and partly from the 'blast oxygen furnace' required during production. The 'Power Block' (34%) is also a major contributor towards the overall LF. The LF can also be traced back to the input 'Reinforcing, Steel'. Compared to other materials, 'Reinforcing, Steel' does not have a large LF, but the quantity of material used throughout many parts of the plant cause it to be the main contributor towards the LF of the construction phase.

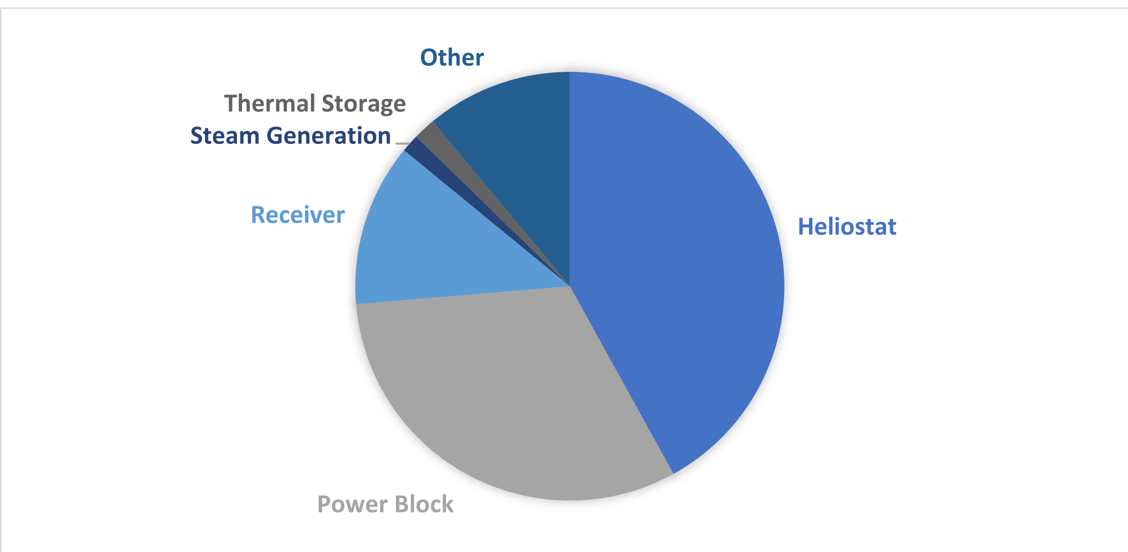

Figure 10 Land Footprint Solar Power Tower

3.2 Construction Parabolic Trough

Table 7 Footprint Results, 50 MW Parabolic Trough Plant

	WF [L]	WFGRAY [L]	CF [KG CO2E]	LF [M²]
HELIOSTAT	1.12E+09	4.08E+03	4.33E+08	3.93E+03
POWER BLOCK	5.13E+08	1.11E+04	1.63E+08	1.44E+03
HEAT TRANSPORT SYSTEM	4.78E+08	3.15E+02	4.16E+07	1.02E+03
THERMAL STORAGE	5.54E+08	3.31E+03	1.35E+08	6.71E+02
OTHER	3.19E+07	1.02E+02	8.49E+06	1.26E+04
TOTAL	**2.70E+09**	**1.89E+04**	**7.81E+08**	**1.97E+04**

Table 7 gives insight into the location of emissions within the construction of a PT plant. Only the two water footprints, blue and gray, can be directly compared as they are calculated in the same units.

The following sections will look at the results per footprint category to see which part of the power plant are responsible for which footprints. The PT has 4 key units (Heliostat, Heat Transport System, Power Block, and Thermal Storage). Other, is the sum of everything not included in the five key units, namely, Building Hall Construction, Excavation by Hydraulic Digger, Road Construction, material (Steel, unalloyed) requirement, Water Supply Network construction and Wire Drawing from Steel.

3.2.1 Water Footprint

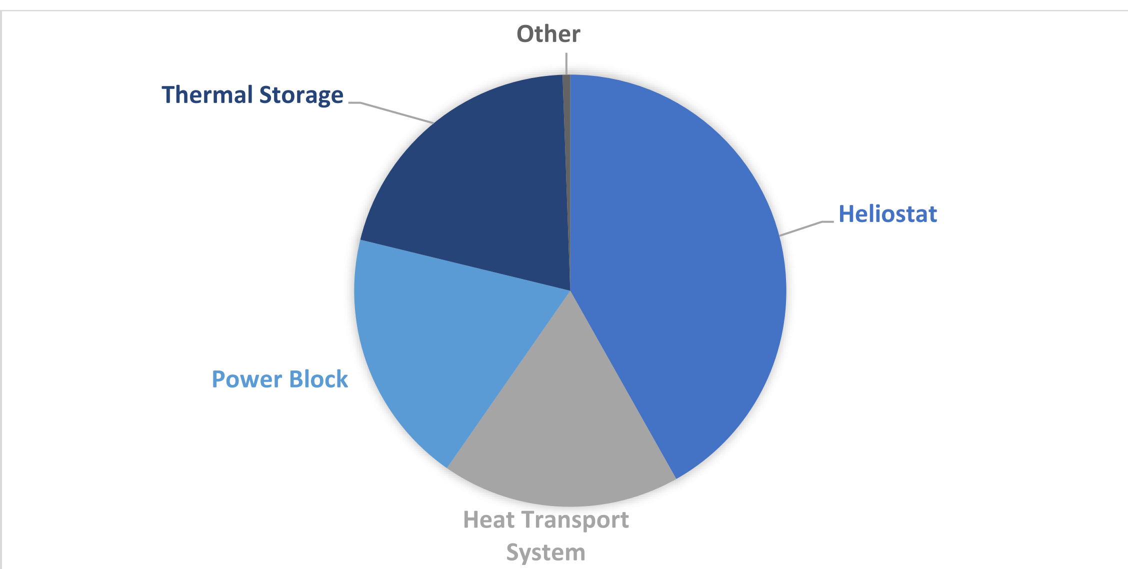

Figure 11 Blue Water Footprint, Solar Thermal Parabolic Trough

The blue water footprint is largely dominated by emissions related to the 'Heliostat', attributing 42%. As with the SPT, 'Flat Glass, coated' is responsible for the 'Heliostat' having such a large blue water footprint. The rest of the footprint is rather evenly spread between the remaining 3 key units: 'Power Block' (19%), 'Heat Transport System' (18%) and 'Thermal Storage' (21%). The input responsible for most the footprint from 'Thermal Storage' is 'nitrate salts, for solar power application' which has a WFb of 7.3 l/kg and requires 29599 tonnes of input. While this has a significant effect on the WFb, having storage capacity is an important aspect to make solar thermal plant competitive with traditional coal or gas fire plants as it allows the plant to continue producing electricity at night and evens out peak loads.

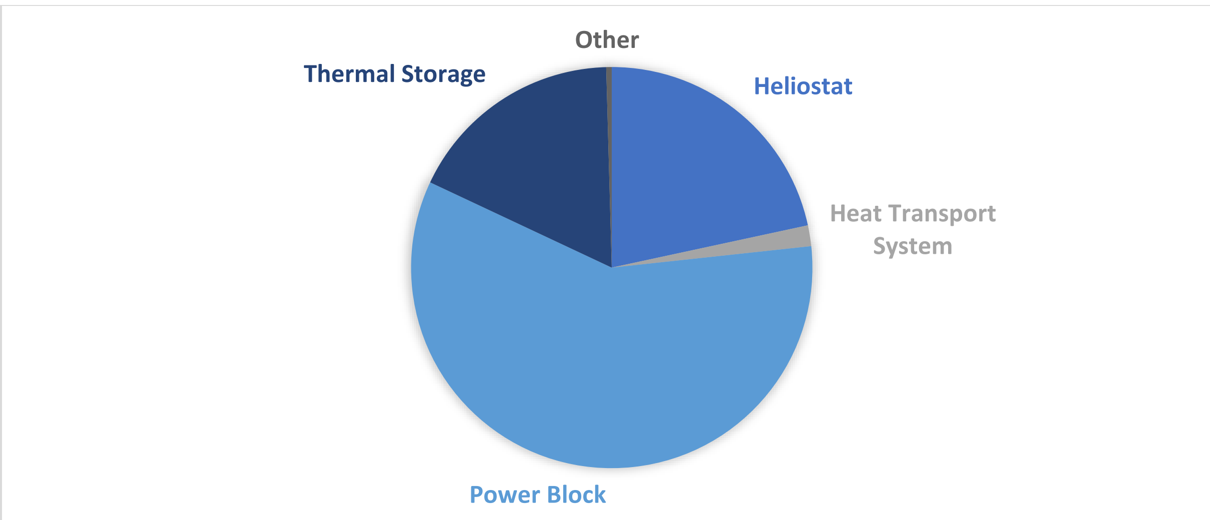

Figure 12 Gray Water Footprint, Solar Thermal Parabolic Trough

The 'Power Block' accounts for 59% of the total gray water footprint and is caused by the input 'Silicone product' and the pollutant 'Mercury'. The 'Heliostat' and 'Thermal Storage' make up the rest of the WFgray with 22% and 18% respectively. As with the SPT, compared to the blue water footprint, the gray water footprint is very small.

3.2.2 Carbon Footprint

The 'Heliostat' accounts for 56% of the carbon footprint. The input 'Flat Glass, coated' causes 17% of the footprint as it is used in high quantity (7231 tonnes) and has a higher than average high CF of 9.9 kgCo2e/kg. The construction of the factory for glass production is responsible for most of the emissions. The 'Power Block' and 'Thermal Storage' also represent a part of the emissions at 21% and 17% respectively. The main contributor towards the 'Power Block' is the input 'Concrete, normal' which has a relatively low CF of 3.3 kgCo2e/kg but accounts for 51% of the total CF of the 'Power Block'.

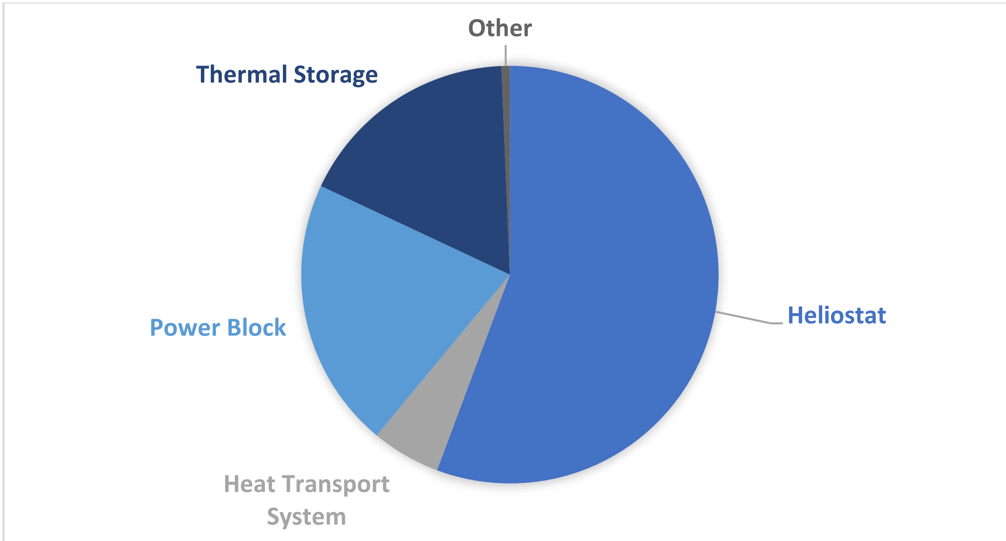

Figure 13 Carbon Footprint, Solar Thermal Parabolic Trough

3.2.3 Land Footprint

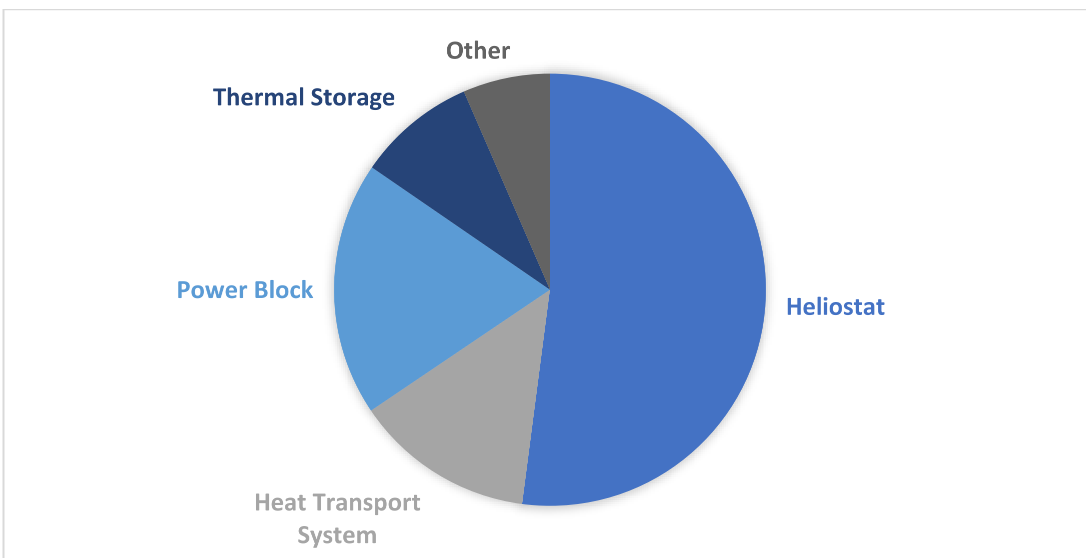

Figure 14 Land Footprint, Solar Thermal Parabolic Trough

The 'Heliostats', or solar collectors, require the largest amount of land accounting for 52% of the LF. This is intuitive as solar thermal plants require vast fields of collectors to generate enough heat for the power plant. The large footprint is explained by the17838 tonnes of 'Reinforcing, Steel' that is required to manufacture the parabolic trough solar collectors. 1 kg of 'Reinforcing Steel' has a land footprint partly from the area required for mining and party from the use of a 'Blast Oxygen Furnace'. The quantity of steel required results in a very large footprint. The other three units account for the rest of the footprint with the 'Power Block' making up 19%. 'Reinforcing, Steel' is again found as the main contributor to the land footprint of the power block.

3.3 Operation Phase

Only the blue water, carbon and land footprints were calculated regarding the operation of the plants and are based solely on data provided by Ecoinvent version 3.6. The SPT has only water and heat inputs, whereas the PT also requires small amounts of 'Benzene' and 'diphenylether-compound'. Despite this difference, there is no significant difference between the footprints for the two plants. The values are based on the operation of a plant in South Africa. Different geographic locations may affect the amount of water required to cool the plant and therefore affect the water footprint.
For the SPT a WF of 129.56 l/MWh, a CF of 46.46 kg Co2e/MWh and a LF of 3.72 m^2/MWh was determined. The PT has a WF of 133.07 l/MWh, a CF of 48.841 l/MWh and a LF of 0.139 m^2/MWh. Table 8, in the following section, displays these values and compares them to the construction phase.

3.4 Total and SPT vs PT Comparison

Table 8 Overview of Footprint Results

		WFb [l/MWh]	WFgray [l/MWh]	CF [kgCo2e/MWh]	LF [m^2/MWh]
Construction					
	SPT	472.98	1.62E-03	172.43	2.03E-03
	PT	621.86	4.37E-03	180.34	1.75E-03
Operation					
	SPT	129.56	0.00E+00	46.46	3.72E+00
	PT	133.07	0.00E+00	46.47	1.39E-01
Total					
	SPT	602.54	1.62E-03	218.89	3.72E+00
	PT	754.93	4.37E-03	226.80	1.41E-01

Table 8 shows an overview of the results. Overall, the construction phase has more significant results than the operation phase for all footprints except for LF. For the SPT, the WFb is 75% from the construction phase and the WFb of the PT is 82% from the construction phase. The CF for both plants is about 80% construction related whereas the LF for both plants is over 98% operation related. The most notable differences are the larger WFb of the PT design and the larger LF of the SPT.

The PT WFb is 20% higher than the SPT, which is a difference of 152 liters of water per MWh. Looking closer at each part of the plants (figure 15), the 'Heliostats' and the 'Thermal Storage' unit both have a higher WFb for the PT design. Furthermore, the PT design requires a 'Heat Transport System' which adds to the WFb while the SPT plant design does not require a 'Heat Transport System' as the working fluid is heated at one central point and does not need to be transported. The combination of the 'Receiver' and

‘Steam Generation System’ of the SPT is comparable to the ‘Heat Transport System’ of the PT, but these units still have a lower WFb.

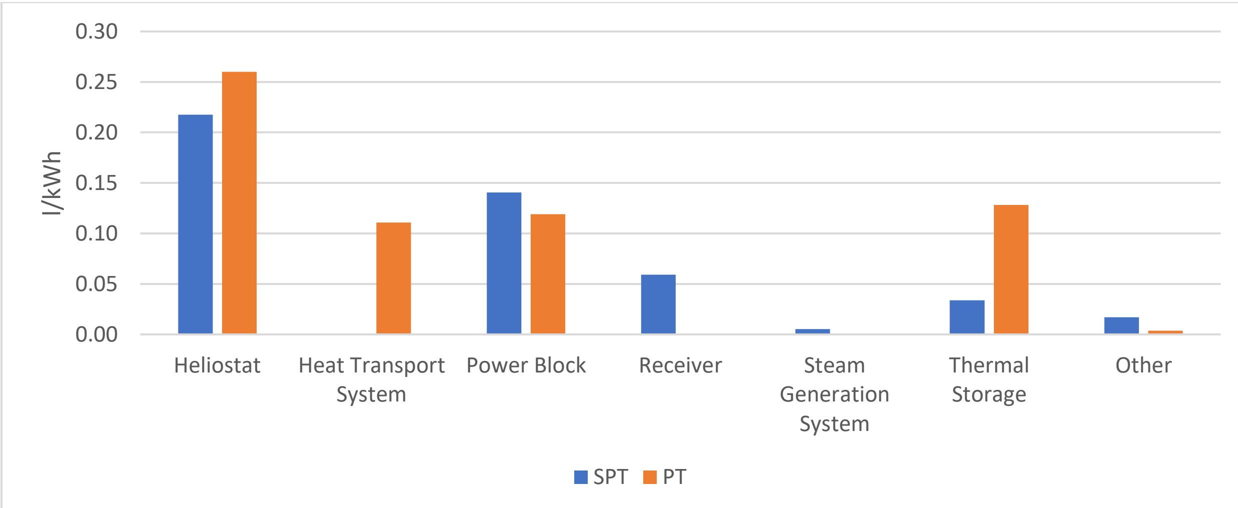

Figure 15 Blue Water Footprint [liters/KWh] per Key unit for the Solar Power Tower and the Parabolic Trough plant designs.

The ‘Thermal Storage’ unit for the PT requires 17.4 tonnes of ‘transformer, high voltage use’ for a 50MW plant design compared to the SPT which requires 0.568 tonnes for a 20 MW design. This is equal to 0.348 tonnes/MW for the PT and 0.028 tonnes/MW for the SPT. The difference explains the discrepancy in the WFb of the two ‘Thermal Storage’ units. Furthermore, ‘Heliostats’ of the PT has a higher WFb. This is a result in the design differences for construction of the plants. The PT design requires more heliostats to produce the same amount of energy. The curved design also increases the complexity for manufacturing. As mentioned in previous sections, the use of ‘Flat Glass, coated’ caused most the blue water emissions for both plants, the higher use of ‘Flat Glass, coated’ in the PT compared to SPT explains the overall higher blue water footprint.

The gray water footprint is dominated by the ‘Heliostat’ and ‘Power Block’ for both the SPT and PT. Compared to the other environmental indicators, the WFgray is significantly smaller, and the overall WFgray of the PT is only higher than the SPT by 0.0028 l/MWh. However, this translates to the PT having a higher WFgray by 63%. Depending on the size of the plant and the availability of water in the area, there could be a large difference in impact when choosing between a SPT or PT design.

Similarly, the ‘Power Block’ and ‘Heliostats’ dominate the CF of the SPT and PT. The CF of the construction phase is again much higher than the operation phase. The CF from operation can be traced to the heat requirement from ‘heat, district or industrial, natural gas’. Meanwhile, the CF of the construction phase is largely due to the ‘Heliostat’ for both the SPT and PT. Overall, the PT has a higher CF, by 7.9 kgCo2e/MWh (4% higher). While this difference is rather small, the cause of the carbon footprint is different for the two plants. The CF of the SPT is traced back to the ‘Power Block’ while for the PT it is traced back to the ‘Heliostat’.

The land footprint is dominated by the 'Heliostat' for both the SPT and the PT. The size of the heliostat field is a critical component of the plant design and affects the system reliability, initial investment cost, and levelized cost of energy. A larger heliostat field typically increases system reliability and investment cost, and decreases the levelized cost of energy (Chen, et al., 2019; Pidaparthi & Hoffmann, 2017). Reducing the amount of land a solar thermal plant directly takes up is therefore difficult. It may be possible to make changes further down the supply chain, such as factory land use, to reduce the overall footprint but as most of the footprint is operational the impact will be minimal. LF is the only category where the PT design has a lower footprint than the SPT. The LF of the PT is 3.6 m^2/MWh lower than the SPT, which is 96% lower.

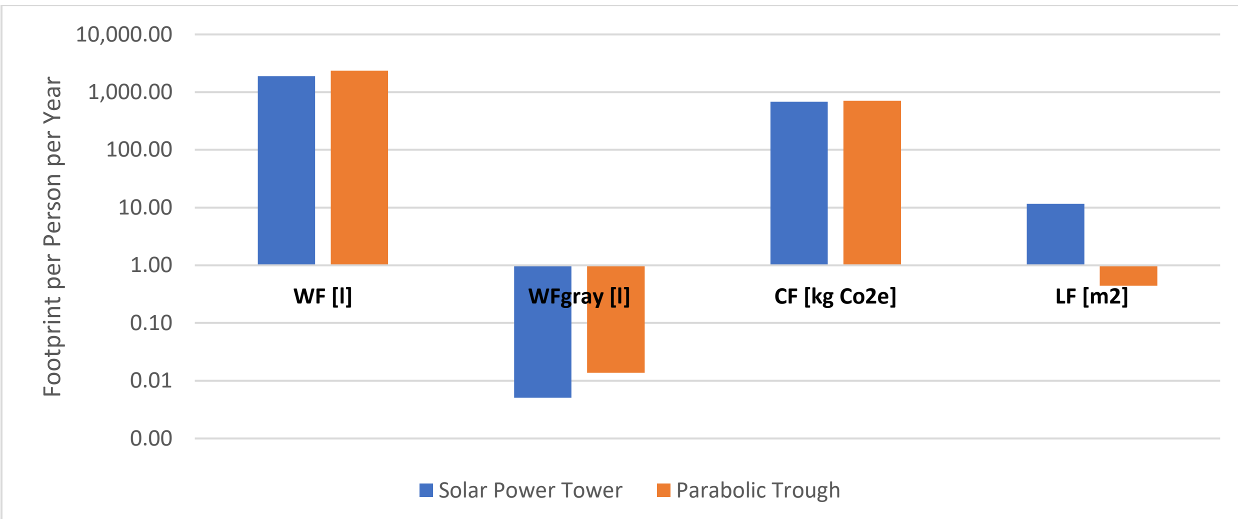

Figure 16 Environmental footprints per person if all energy is produced from Solar Thermal (IEA Statistics, 2014)

Figure 16 shows what the water, carbon and land footprint related to the energy use of a person would be if all energy consumed was produced using CSP. Looking at the land footprints, and area the size of The Netherlands (41543 km^2) could support about 3.5 billion people if a SPT design is used, and about 94 billion people if the PT design is used. The blue water, gray water and carbon footprints would all be very similar.

4. Discussion

The results of this report show three environmental footprints for two types of CSP plants. This information can be used to compare the impact from the two types of plants and to identify where in the life cycle emission are created. While SPT and PT plants are mostly similar in operation, the construction of the plants differ.

It is known that the physical space taken up by a CSP plant is greater than coal, gas or nuclear plants that operate at the same production capacity. Solar PV also has a larger land footprint when compared to traditional coal fire plants (Ong, et al., 2013), however solar PV has the advantage of making double use of space. For example, one can place PV panels on the roofs of building, this option does not exist for solar thermal plants. This limits the potential site locations for solar thermal plants and, in combination with the need for an area with high sun hours, has led to plants being placed mainly in desert areas This line of thought, while logical, overlooks the large water requirement for construction and operation of solar thermal plants and may places them in water scare areas. Appropriate consideration must be given to how the plant will affect all-natural resources, so none are over exploited or become a limiting factor for energy production.

The geographic location of any potential site should be evaluated to see if the area can support a CSP plant. While we can quantify the water, land and carbon footprint per unit of energy, this is not enough to determine if an area of land is suitable for such a power plant. Water scarcity, land availability and current pollution levels must be considered for any potential site in relation to what other factors (industry, agriculture, households) also rely on the same water, land and air.

Most of the blue water footprint is from the factory processes to make materials so it makes sense to focus on how materials are made to find potential strategies to reduce the overall blue water footprint. Factory practices differ around the world and based on geographic location, reducing the water or carbon footprint of the factory may or may not be a priority. Identifying factories that produce the required materials at the lower footprint or in areas with high water productivity and low water scarcity, is something to consider when constructing a CSP plant.

Based on the results of this research, there are differences for all three environmental footprints although the CF has only a very small difference. The PT has a higher water footprint and carbon footprint but a smaller land footprint. Generally, this shows that the SPT is better for an area where more land is available, and water is scarcer. The PT is better in an area with less land available and more water. Looking only at the operation phase, there is no significant difference between the operation of the two plants besides the land footprint. The differences lie mostly in the construction phase, where emissions may not be occurring in the same geographic location as the plant is built (overseas factories). Strategic outsourcing could help reduce the blue water footprint by buying water intense materials from water rich areas and importing them to where the plant will be built.

Understanding where emissions come from also gives the opportunity to identify ways to reduce them. Most footprints reported in this study are dominated by one or two inputs that account for 20-50% of the total footprint. This makes it easy to pinpoint where improvements can be made and prioritize strategies for emission reduction. This can either be done by redesigning the power plant to include less of the high footprint materials or make changes at mining operations or factory practices level to lower the footprint per kilogram material.

Currently it is difficult to compare footprints as there are numerous accounting methods and varied data sources. Within this study, two types of solar thermal plants were investigated using the same methodology and data and thus can be easily compared. As more footprint analyses become available for different energy production technologies, it becomes possible to compare different production methods. This information can be used by policy makers to make informed decisions about how to best meet the needs of the present without compromising the future availability of resources. Current plants in operation, of any production technology, play a huge role in gathering and reporting data so that footprints can be calculated. As more data becomes available more accurate and detailed footprints can be known.

4.1 Limitations

Nearly all data used within this report comes from Ecoinvent. While this has allowed for consistency and conformity within the data, it also leaves room for error. It is assumed that there are no detrimental errors within the data base, but the possibility of error cannot be completely excluded. Efforts were made to cross check data results with known values from literature, but the limited amount of data prevented extensive cross checking. Cross checking was only possible for material footprint values, which are readily available in literature. It is difficult to compare the final footprint values to other studies because of differences in calculation methods and data. The final WFb found in this study is 167.4 m^3/TJ for SPT and 209.7 m^3/TJ which is within the range specified by Mekonnen (Mekonnen, et al., 2015) of 118-2180 m^3/TJ. The final carbon footprint calculated in this study is also similar to those found currently in literature at 0.218 l/kWh for SPT and 0.226 l/kWh for PT compared to 0.227 l/kWh estimated by Mulugetta (Mulugetta, et al., 2014).

This report assumes electricity inputs were produced using CSP plants which have, generally, a higher water footprint and a lower carbon footprint than other production methods. In reality, not all electricity that contributes towards the construction of a CSP plant will come from other CSP plants. This method assumes a future where all electricity is produced as cleanly as possible but as a result may overestimate the water footprint and underestimate the carbon footprint of a CSP plant constructed in present. Because the blue water footprint related to energy is significantly smaller than the process related blue water footprints, it is not thought that this method has significant effects on the results.

All values calculated for mining are done so without any consideration to the geographic location of the mine or any further specifications as to what type of metal or non-metal is being mined. Because of this, there is a lot of uncertainty about the contribution of mining to the construction phase for each plant design. Furthermore, it is likely that the emissions (water and carbon) from factories to produce materials is too high or too low in some cases. Factory emissions were calculated using global data and allocation values from Ecoinvent. Most factories are from the period 1990-2005. In order to have a more reliable estimate of the emissions from factories, more updated data as well as geographic location should be considered.

During the operation of the plant, it is assumed that there is no maintenance activities during the 30 year lifespan of the plant. This is unrealistic and it should be acknowledged that the operational footprints are likely higher due to maintenance.

The results presented here thus can only give an initial indication of how building a SPT or PT plant will impact an environment. One can directly compare the SPT vs PT plant, but caution should be used when comparing to footprint results to other production technologies calculated in other studies. The data used is mostly global values so the results can be applied to any geographic location. Energy production technology is a rapidly changing field and future developments may change the way we build or operate solar thermal plants which in turn could change the footprint values. Furthermore, the data was downscaled from a 440 MW plant (SPT) and a 450 MW plant (PT) to 20 MW (SPT) and 50 MW (PT) plants. Downscaling is a non-linear process, so the results presented here are only valid for plants of a similar size.

5. Conclusion

The results of this research show how a solar thermal plant affects natural resources. The construction of CSP plants requires large amounts of materials which must be manufactured and transported. All these emissions are attributed to the final plant. Secondly, the operation of the plant has emissions of its own. The two plants considered within this study, the Solar Power Tower and Parabolic Trough can each be broken down into four or five key units for which the footprints can be calculated to identify how the construction of the plant contributes to the final footprints. The operation phase of solar thermal plants has very little emissions to air or water except for water vapor from cooling.

Emissions from construction were found to be higher than the operation phase for two footprints, water and carbon. Contrarily, the land footprint is predominantly operation related. The parabolic trough design has a slightly higher blue water footprint at 755 l/MWh compared to the solar power tower at 603 l/MWh. This difference should be considered in relation to the water availability of a potential site location to determine if the site is suitable. The gray water footprints of both plants, SPT and PT, were found to be very similar and of a smaller magnitude than the blue water footprints. The carbon footprints of each plant are also similar at 219 kgCo2e/MWh for the SPT and 227 kgCo2e/MWh for the PT. Finally, the land footprints of both plants were found to have a large difference at 3.7 m^2/MWh for the SPT and 0.14 m^2/MWh for the PT.

For all footprints, the emissions related to factory construction accounted for a large share the total emissions. Therefore, finding ways to produce the required materials at a lower footprint, or strategic outsourcing of material production, can lower the impact of the plant. In order to understand how a CSP plant will affect the natural environment, the numbers calculated in this report must be considered in the context of a specific location and in relation to what other entities (households, businesses, etc.) also compete for the same water, land and air.

5.1 Recommendations

The data used within this research was very detailed which allowed emission to be traced back to a specific part of the construction of the plant. However, more detailed data regarding the operation of the plant would be useful. Currently, the operational data assumes for both plants an input 0.1 kg water per kWh production. It is assumed this is for cooling but if the operation was modeled in more detail and with geographic consideration this value may be higher. Furthermore, this research could be improved through the inclusion of more greenhouse gases in the CF calculation, especially Nitrous Oxide when applicable.

Future studies could quantify the effect of reducing the water and carbon footprint of key materials (metals, glass and others with high water and carbon footprints). It would also be interesting to do a footprint assessment of CSP plants in different geographic locations using the same plant design for each location. This would focus on the availability of resources (land, water) in potential site locations and see how each CSP design would deplete resources in a certain area. Furthermore, this research uses global values for all data. More specific research could be done to see how a plant built and operated in a specific region compares to a plant built and operated in another region. Additionally, a comparison of a CSP plant built with all materials manufactured locally, verse outsourcing and transporting materials from strategic areas, would provide interesting insights to how outsourcing could change the footprint of a plant. On the policy side, the results of this study could be used to explore potential transition pathways towards renewable energy for different areas. Exploration into how introducing stricter water and energy rules for factories and building practices would also be interesting as factories were identified as an important source of emissions.

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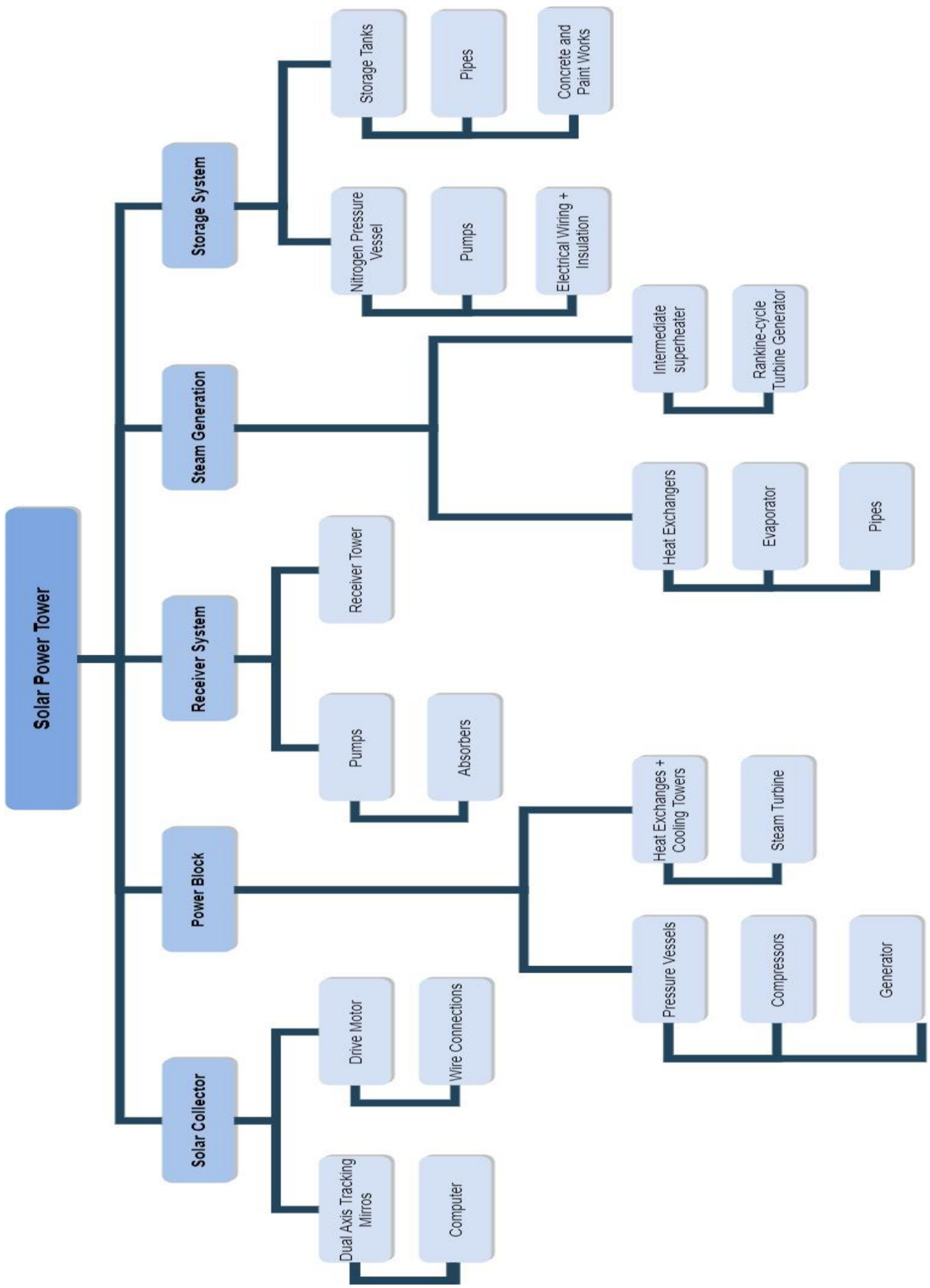
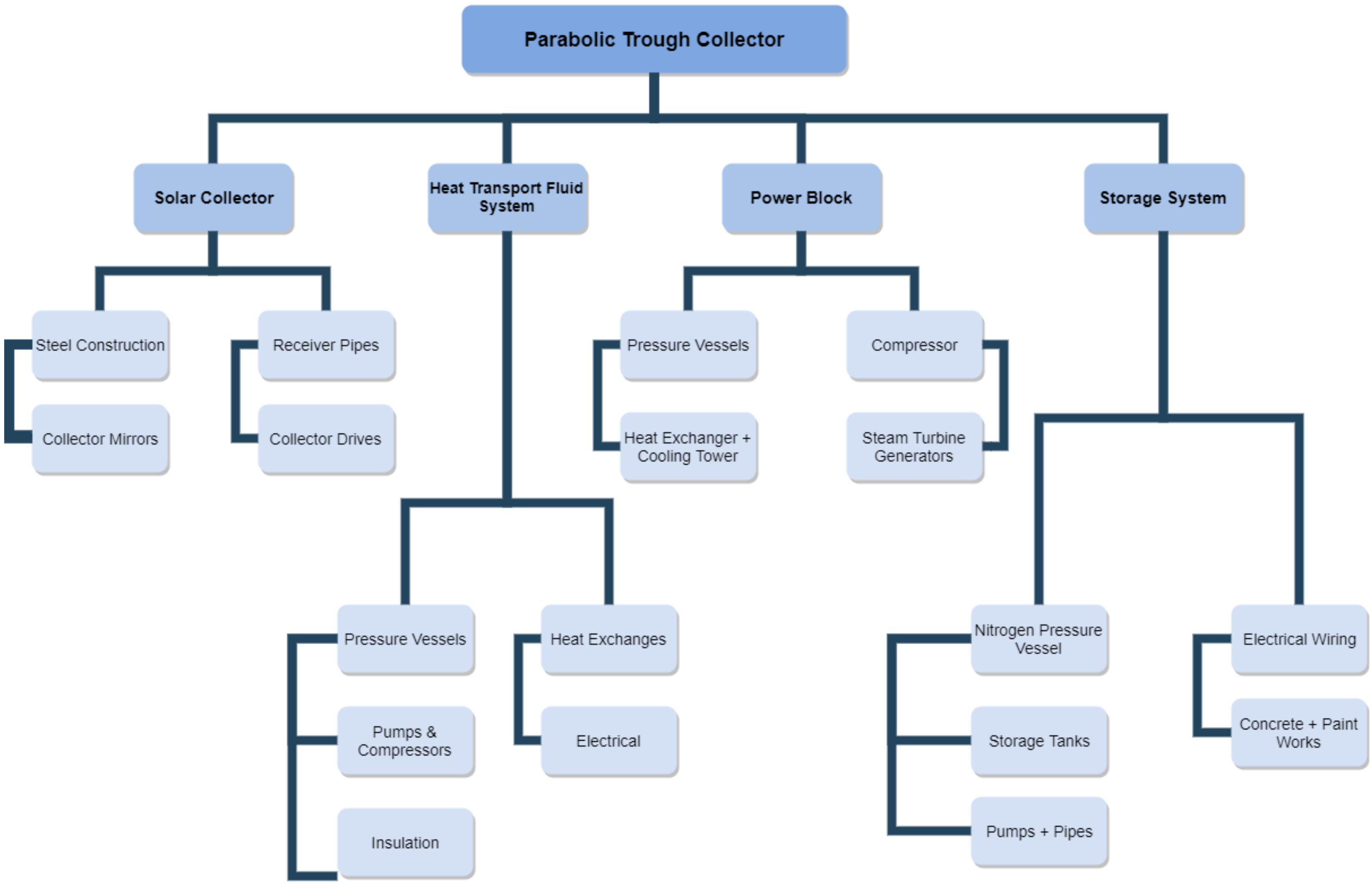
Appendix

Appendix 1: Special Cases Data

DATA	CONSIDERATION	SOLUTION
ALUMINIUM OXIDE, NON-METALLURGICAL [KG]	No data available	Allocate based on mass from production of aluminum oxide, metallurgical. Aluminums oxide, non-metallurgical is a by-product of the production of aluminum oxide, metallurgical.
PARTICLE BOARD, CEMENT BONDED [M2]	No data available	Material not considered in calculations
SAND [KG]	No data available	Allocation based on mass sand and gravel quarry data.

Appendix 2: System Design Flow Sheets




Parabolic Trough Collector
Solar Collector
Heat Transport Fluid System
Power Block
Storage System
Steel Construction
Collector Mirrors
Receiver Pipes
Collector Drives
Pressure Vessels
Heat Exchanger + Cooling Tower
Compressor
Steam Turbine Generators
Pressure Vessels
Pumps & Compressors
Insulation
Heat Exchanges
Electrical
Nitrogen Pressure Vessel
Storage Tanks
Pumps + Pipes
Electrical Wiring
Concrete + Paint Works

Appendix 3: Water and Carbon Footprint Values for Electricity, Heat and Fuel

Water for Energy

	Water Footprint	**Source**
Electricity	830 gal/MWH (solar tower) 920 gal/MWH (parabolic trough)	(Carter & Campbell, 2009)
Gas (Other than Nat. gas)	2.43 kg/kwh	(Mekonnen, et al., 2015)
Natural Gas	2.36 kg/kwh	(Mekonnen, et al., 2015)
Unconventional oil	3.513 kg/kwh	(Mekonnen, et al., 2015)
Conventional Oil	2.527 kg/kwh	(Mekonnen, et al., 2015)
Coal	3.922 kg/kWh	(Mekonnen, et al., 2015)

Energy for Water

	Carbon Footprint	**Source**
Electricity	0.227 kg CO_2/kwh	(Mulugetta, et al., 2014)
Nat gas	0.41511254	(EIA, 2019)
Other gas (based on propane gas)	0.69976165	(EIA, 2019)
Diesel (called Distillate Fuel Oil)	0.8117102	(EIA, 2019)
Coal	0.998	(EIA, 2019)

Appendix 4: Gray Water Footprint Pollutants

Pollutant	Cnat	Cmax
Biological Oxygen Demand (BOD)	n/d	3000
Chemical Oxygen Demand (COD)	n/d	30000
Antimony	n/d	n/d
Arsenic	1	5
Cadmium	0.001	0.04
Chromium Ion	0.1	1
Chromium Unspecified	0.1	1
Cobalt	0.1	n/d
Copper	1.4	2
Iron Iron	50	300
Lead	0.04	1.2
Molybdenum	0.8	73
Manganese	10	n/d
Mercury	n/d	0.026
Tin	n/d	n/d
Nickel	0.4	4
Vanadium	n/d	n/d
Zinc	0.2	30
Aluminium	40	100
Calcium	n/d	n/d
Boron	8	29000
Ammonium	14	6980
Chloride	3900	120000
Cyanide	n/d	5
Flouride	n/d	120
Hydrogen Sulphide	n/d	n/d
Nitrogen	n/d	n/d
Nitrate	100	300
Potassium	1	n/d
Phosphate	10	20
Phsophorus	0	20
Sodium	n/d	n/d
Strontium	100	n/d
Sulphite	n/d	n/d
Sulphate	4800	n/d
Suspended solids, unspecified	150000	155000

(Chapman, 1996)

Appendix 5: Material Footprints- SPT

Material List	WFp	Wfe	WFn	WFgray	CF	LF
alkyd paint, white, without solvent, in 60% solution state [kg]	0.66	0.22	0.89	0.00E+00	0.15	6.61E-05
aluminium, cast alloy [kg]	58.87	0.75	59.62	5.32E-08	7.91	1.54E-04
aluminium hydroxide [kg]	1.20	3.32	4.53	1.53E-08	0.76	3.47E-05
aluminium oxide, non-metallurgical [kg]	2.26	7.36	9.62	0.00E+00	1.69	2.19E-06
aluminium oxide production [kg]	2.12	6.92	9.05	0.00E+00	1.59	2.06E-06
aluminium, primary, liquid [kg]	14.33	44.33	58.66	3.54E-08	8.32	2.25E-04
aluminium, wrought alloy [kg]	60.01	0.75	60.77	5.32E-08	7.91	1.54E-04
bitumen adhesive compound, hot [kg]	0.07	0.78	0.85	0.00E+00	1.00	6.61E-06
bitumen seal [kg]	9.96	0.68	10.64	0.00E+00	0.00	6.61E-05
Benzene [kg]	32.52	59.45	91.97	2.79E-08	20.32	3.28E-07
Brass [kg]	111.18	0.48	111.67	6.86E-02	7.70	4.89E-05
Cast Iron [kg]	16.44	3.51	19.96	0.00E+00	4.48	6.00E-05
cast iron removed by milling, average [kg]	81.50	2.22	83.72	0.00E+00	6.42	1.28E-03
cement, portland fly ash cement 21-35% [kg]	0.06	0.16	0.21	0.00E+00	0.03	2.38E-05
ceramic tile [kg]	2.00	4.66	6.66	0.00E+00	0.89	9.23E-04
chromium [kg]	30.44	200.49	230.93	0.00E+00	25.12	3.34E-04
chromium steel removed by milling, average [kg]	84.50	2.10	86.60	1.28E-03	192.06	1.28E-03
Clay Brick [kg]	0.15	2.94	3.09	0.00E+00	3.26	2.40E-05
Concrete, normal [kg]	3.31	0.01	3.32	1.14E-11	3.32	2.97E-06
Copper [kg]	108.21	9.13	117.34	5.35E-07	3.06	3.27E-04
copper concentrate, sulfide ore [kg]	26.21	3.04	29.25	4.78E-05	0.51	8.72E-05
diesel, burned in building machine [MJ]	0.00	18.54	18.54	0.00E+00	4.37	2.02E-13
diphenylether-compound [kg]	187.51	18.66	206.17	1.79E-04	6.50	4.29E-04
drawing of pipe, steel [kg]	16.59	0.77	17.36	1.48E-06	0.74	1.66E-06
electricity, high voltage [kWh]	0.00	3.14	3.14		0.23	
electricity, medium voltage [kWh]	0.00	3.48	3.48	0.00E+00	0.23	0.00E+00
ethylene, average [kg]	11.78	79.47	91.24	0.00E+00	19.40	0.00E+00
excavation, hydraulic digger [m3]	0.49	5.43	5.92	0.00E+00	1.80	0.00E+00

excavation, skid-steer loader [m3]	0.45	0.38	0.83	2.88E-09	1.79	1.37E-12
expanded perlite [kg]	7.04	5.65	12.70	0.00E+00	1.85	2.40E-05
extrusion, plastic pipes [kg]	7.87	1.71	9.58	0.00E+00	0.55	5.73E-05
fibre cement corrugated slab [kg]	2.32	1.01	3.33	0.00E+00	0.27	1.15E-04
flat glass, coated [kg]	42.18	0.23	42.41	0.00E+00	9.92	1.52E-04
flat glass, uncoated [kg]	3.04	3.40	6.44	0.00E+00	2.00	1.03E-04
Foam Glass [kg]	0.48	12.05	12.53	1.76E-04	0.00	1.76E-04
glass fibre [kg]		4.90	14.62	19.52	0.00E+00	2.33
glass fibre reinforced plastic, polyamide, injection moulded [kg]	4.41	7.67	12.08	6.19E-09	1.55	5.73E-05
glass tube, borosilicate [kg]	6.59	7.78	14.37	0.00E+00	1.45	5.29E-03
glued laminated timber, for indoor use [m3]	619.82	1936.95	2556.77	0.00E+00	757.43	5.19E-02
graphite [kg]	0.03	0.18	0.21	1.41E-10	0.03	1.47E-05
gravel, crushed [kg]	1.38	0.04	1.42	0.00E+00	0.02	8.59E-05
heat, district or industrial, other than natural gas [kWh]		64.72	64.72	4.79E-06	8.90	
Hot Rolling, Steel [kg]		8.67	1.41	10.08	1.06E-06	1.00
injection moulding [kg]	4.41	7.67	12.08	6.19E-09	1.07	5.73E-05
iron-nickel-chromium alloy [kg]	0.09	4.19	4.29	0.00E+00	0.65	6.00E-05
kraft paper, unbleached [kg]	43.65	4.47	48.13	1.00E-06	3.12	4.28E-05
Lubricating Oil [kg]	2.16	5.26	7.42	0.00E+00	8.69	6.61E-05
manganese [kg]	0.00	8.26	8.26	0.00E+00	0.60	3.28E-07
metal working, average for aluminium product manufacturing [kg]			33.18	8.21E-09	2.94	3.24E-04
molybdenum [kg]	5.84	15.74	21.58	3.62E-05	2.46	0.00E+00
nitrate salts, for solar power application [kg]	5.77	1.44	7.20	0.00E+00	1.38	3.86E-07
particle board, cement bonded [m3]	nda	nda	nda	nda	nda	nda
particle board, for indoor use [m3]	777.49	4088.07	4865.56	0.00E+00	279.62	5.19E-02
Perlite [kg]	1.00	0.01	1.01	0.00E+00	0.00	5.27E-04
Pig Iron [kg]	4.93	15.07	19.99	3.80E-07	5.56	0.00E+00
polyethylene, high density, granulate [kg]	97.35	2.42	99.77	4.12E-08	19.89	6.61E-05
polystyrene, high impact [kg]	52.20	84.09	136.29	3.29E-06	28.08	
polystyrene foam slab [kg]	99.27	30.14	125.46	3.15E-06	18.33	0.00E+00

polyurethane, rigid foam [kg]			1.97	0.00E+00	0.23	6.61E-05
polyvinylchloride, bulk polymerised [kg]	113.37	3.75	117.13	2.02E-08	11.08	6.61E-05
potassium nitrate, industrial grade [kg]	3.91	0.72	4.63		0.33	7.84E-08
potassium nitrate, technical grade [kg]	8.55	1.44	9.98	0.00E+00	0.79	1.12E-07
refractory, basic, packed [kg]	0.02	9.54	9.56	0.00E+00	1.73	2.40E-06
reinforcing steel [kg]	35.07	0.07	35.14	0.00E+00	10.33	2.00E-05
Sand [kg]	0.55	0.02	0.57		0.01	2.63E-05
sawnwood, softwood, dried (u=10%), planed [m3]	87.81	52.20	140.01	0.00E+00	29.86	7.20E-06
sawnwood, softwood, raw, dried (u=10%) [m3]	132.17	68.00	200.17	0.00E+00	201.55	2.35E-03
section bar rolling, steel [kg]	7.54	0.35	7.89	6.73E-07	0.00	7.54E-07
sheet rolling, aluminium [kg]	1.98	2.91	4.89	2.63E-07	0.42	4.39E-06
sheet rolling, chromium steel [kg]	6.29	1.47	7.76	4.37E-06	0.64	1.51E-06
sheet rolling, steel [kg]	16.75	1.41	18.15	3.85E-06	1.33	1.51E-06
silicone product [kg]	108.73	10.03	118.76	4.62E-01	4.87	1.39E-04
sodium nitrate, unrefined [kg]	0.00	3.91	3.91	0.00E+00	0.71	2.80E-07
sodium nitrate, technical grade [kg]	3.91	1.44	5.35	0.00E+00	1.78	5.68E-07
steel removed by milling, average [kg]	108.50	1.49	109.99	0.00E+00	13.04	1.28E-03
steel, chromium steel 18/8 [kg]	11.01	0.15	11.16	0.00E+00	7.95	2.00E-05
steel, chromium steel 18/8, hot rolled [kg]	19.68	1.57	21.25	1.06E-06	8.96	2.15E-05
steel, low-alloyed [kg]	27.51	0.15	27.67	0.00E+00	13.49	2.00E-05
steel, low-alloyed, hot rolled [kg]			45.22	1.06E-06	11.33	1.51E-06
steel, unalloyed [kg]	34.81	0.07	34.88	0.00E+00	13.43	2.00E-05
Stone Wool [kg]	4.21	7.18	11.40	0.00E+00	2.36	1.15E-04
stone wool, packed [kg]	11.40	0.11	11.50	1.35E-12	2.38	1.15E-04
synthetic rubber [kg]	53.82	2.26	56.08	0.00E+00	16.60	6.61E-05
tap water [kg]	1.03	0.00	1.03		0.00	5.30E-06
tetrafluoroethylene [kg]	0.66	3.11	3.77	1.23E+00	0.00	6.60E-05
tin plated chromium steel sheet, 2 mm [m2]			313.85	8.57E-05	138.13	3.35E-04
transformer, high voltage use [kWh]		67.87	67.87	5.35E-07	1.28	
urea formaldehyde resin production [kg]	0.84	1.02	1.86	0.00E+00	0.36	6.61E-05
vinyl chloride [kg]	86.27	9.86	96.12	0.00E+00	10.41	6.61E-05

welding, arc, steel [m]	2.43	0.09	2.51	0.00E+00	0.62	0.00E+00
wire drawing, copper [kg]	9.02	2.39	11.40	2.63E-08	0.48	1.33E-06
wire drawing, steel [kg]	15.08	0.70	15.78	1.35E-06	0.68	1.51E-06
Zinc [kg]	75.28	17.85	93.13	3.06E-06	3.20	0.00E+00
zinc coat, coils [m2]	66.00	12.91	78.91	1.93E-06	4.80	2.36E-09

Appendix 6: Material Footprints- PT

Material List	WFp	Wfe	WFn	WFgray	CF	LF
alkyd paint, white, without solvent, in 60% solution state [kg]	0.66	0.25	0.91	0.00E+00	0.15	6.61E-05
aluminium alloy, metal matrix composite [kg]	7.74	14.77	22.51	0.00E+00	2.10	1.54E-04
aluminium, cast alloy [kg]	58.87	0.77	59.64	5.32E-08	7.91	1.54E-04
aluminium hydroxide [kg]	1.20	3.34	4.54	1.53E-08	0.76	3.47E-05
aluminium oxide, non-metallurgical [kg]	7.36	2.26	9.62	0.00E+00	1.69	2.19E-06
aluminium oxide production [kg]	2.13	6.92	9.05	0.00E+00	1.59	2.06E-06
aluminium, primary, liquid [kg]	14.33	48.98	63.31	3.54E-08	8.32	2.25E-04
aluminium, wrought alloy [kg]	60.01	0.77	60.78	5.32E-08	7.91	1.54E-04
bitumen adhesive compound, hot [kg]	0.07	0.78	0.85	0.00E+00	1.00	6.61E-06
bitumen seal [kg]	9.96	0.68	10.65	0.00E+00	0.97	6.61E-05
Benzene [kg]	32.52	59.47	91.98	2.79E-08	20.32	3.28E-07
Brass [kg]	111.18	0.49	111.67	6.86E-02	7.70	4.89E-05
Cast Iron [kg]	16.44	1.48	17.92	0.00E+00	4.48	6.00E-05
cast iron removed by milling, average [kg]	81.50	2.46	83.96	0.00E+00	6.42	1.28E-03
cement, portland fly ash cement 21-35% [kg]	0.06	0.17	0.23	0.00E+00	0.03	2.38E-05
ceramic tile [kg]	2.00	4.75	6.75	0.00E+00	0.89	9.23E-04
chromium [kg]	30.44	215.27	245.72	0.00E+00	25.12	3.34E-04
chromium steel removed by milling, average [kg]	84.50	2.33	86.83	1.28E-03	192.06	1.28E-03
Clay Brick [kg]	0.00	16601.50	0.00	0.00E+00	0.00	0.00E+00
Concrete, normal [kg]	3.31	0.01	3.33	1.14E-11	3.32	2.97E-06
Copper [kg]	108.21	9.32	117.52	5.35E-07	3.06	3.27E-04
copper concentrate, sulfide ore [kg]	26.21	3.37	29.58	4.78E-05	0.51	8.72E-05
diesel, burned in building machine [MJ]	0.00	18.54	18.54	0.00E+00	4.37	2.02E-13

diphenylether-compound [kg]	187.51	19.37	206.88	1.79E-04	6.50	4.29E-04
drawing of pipe, steel [kg]	15.08	0.75	15.83	1.35E-06	0.68	1.51E-06
electricity, high voltage [kWh]	0.00	3.48	3.48		0.23	
electricity, medium voltage [kWh]	0.00	3.14	3.14	0.00E+00	0.23	0.00E+00
ethylene, average [kg]	11.78	79.47	91.24	0.00E+00	19.40	0.00E+00
excavation, hydraulic digger [m3]	0.49	5.43	5.92	0.00E+00	1.80	0.00E+00
excavation, skid-steer loader [m3]	0.45	0.38	0.83	2.88E-09	1.79	1.37E-12
expanded perlite [kg]	7.04	5.68	12.72	0.00E+00	1.85	2.40E-05
extrusion, plastic pipes [kg]	7.87	2.31	10.18	0.00E+00	0.55	5.73E-05
fibre cement corrugated slab [kg]	2.32	1.10	3.42	0.00E+00	0.27	1.15E-04
flat glass, coated [kg]	42.18	0.25	42.43	0.00E+00	9.92	1.52E-04
flat glass, uncoated [kg]	3.04	0.39	3.42	0.00E+00	2.00	1.03E-04
Foam Glass [kg]	0.48	12.56	13.04	1.76E-04	1.77	1.76E-04
glass fibre [kg]	4.90	15.05	19.95	0.00E+00	2.33	1.71E-04
glass fibre reinforced plastic, polyamide, injection moulded [kg]	4.41	8.07	12.08	6.19E-09	1.55	5.73E-05
glass tube, borosilicate [kg]	6.59	8.16	14.75	0.00E+00	1.45	5.29E-03
glued laminated timber, for indoor use [m3]	619.82	1980.90	2600.72	0.00E+00	757.43	5.19E-02
graphite [kg]	0.03	0.19	0.22	1.41E-10	0.03	1.47E-05
gravel, crushed [kg]	1.38	0.05	1.43	0.00E+00	0.02	8.59E-05
heat, district or industrial, other than natural gas [kWh]		64.72	64.72	4.79E-06	8.90	0.00E+00
Hot Rolling, Steel [kg]	8.67	1.46	10.13	1.06E-06	1.00	1.51E-06
injection moulding [kg]	4.41	8.07	12.48	6.19E-09	1.07	5.73E-05
iron-nickel-chromium alloy [kg]	0.09	4.31	4.40	0.00E+00	0.65	6.00E-05
kraft paper, unbleached [kg]	43.65	4.72	48.38	1.00E-06	3.12	4.28E-05
Lubricating Oil [kg]	2.16	5.40	7.56	0.00E+00	8.69	6.61E-05
manganese [kg]	0.00	9.16	9.16	0.00E+00	0.60	6.61E-05
metal working, average for aluminium product manufacturing [kg]		140.12	140.12	8.21E-09	2.94	3.24E-04
molybdenum [kg]	5.84	16.93	22.77	3.62E-05	2.46	0.00E+00
nitrate salts, for solar power application [kg]	5.77	1.45	7.22	0.00E+00	1.38	3.86E-07
particle board, cement bonded [m3]	nda	nda	nda	nda	nda	nda
particle board, for indoor use [m3]	777.49	4442.35	5219.83	0.00E+00	279.62	5.19E-02
Perlite [kg]	1.00	0.01	1.01	0.00E+00	0.00	5.27E-04
Pig Iron [kg]	4.93	15.07	19.99	3.80E-07	5.56	0.00E+00
polyethylene, high density, granulate [kg]	97.35	2.54	99.89	4.12E-08	19.89	6.61E-05
polystyrene, high impact [kg]	52.20	84.12	136.32	3.29E-06	28.08	0.00E+00
polystyrene foam slab [kg]	97.36	32.35	129.72	3.21E-06	19.41	0.00E+00

polyurethane, rigid foam [kg]		2.11	2.11	0.00E+00	0.23	6.61E-05
polyvinylchloride, bulk polymerised [kg]	113.37	3.41	116.78	2.02E-08	11.08	6.61E-05
potassium nitrate, industrial grade [kg]	3.91	0.76	4.67		0.33	7.84E-08
potassium nitrate, technical grade [kg]	8.55	1.45	10.00	0.00E+00	0.79	1.12E-07
refractory, basic, packed [kg]	0.02	9.54	9.56	0.00E+00	1.73	2.40E-06
reinforcing steel [kg]	35.07	0.08	35.15	0.00E+00	10.33	2.00E-05
Sand [kg]	0.55	0.02	0.57	0.00E+00	0.01	2.63E-05
sawnwood, softwood, dried (u=10%), planed [m3]	87.81	57.86	145.67	0.00E+00	29.86	7.20E-06
sawnwood, softwood, raw, dried (u=10%) [m3]	132.17	75.37	140.91	0.00E+00	201.55	2.35E-03
section bar rolling, steel [kg]	7.54	0.37	7.91	6.73E-07	0.34	7.54E-07
sheet rolling, aluminium [kg]	1.98	3.09	5.07	2.63E-07	0.42	4.39E-06
sheet rolling, chromium steel [kg]	6.29	1.62	7.92	4.37E-06	0.64	1.51E-06
sheet rolling, steel [kg]	16.75	1.48	18.23	3.85E-06	1.33	1.51E-06
silicone product [kg]	108.73	10.34	119.07	4.62E-01	4.87	1.39E-04
sodium nitrate, unrefined [kg]	0.00	3.92	3.92	0.00E+00	0.71	2.80E-07
sodium nitrate, technical grade [kg]	3.91	1.45	5.37	0.00E+00	1.78	5.68E-07
steel removed by milling, average [kg]	108.50	1.65	110.15	0.00E+00	13.04	1.28E-03
steel, chromium steel 18/8 [kg]	11.01	0.16	11.17	0.00E+00	7.95	2.00E-05
steel, chromium steel 18/8, hot rolled [kg]	19.68	1.62	21.30	1.06E-06	8.96	2.15E-05
steel, low-alloyed [kg]	27.51	0.16	27.68	0.00E+00	13.49	2.00E-05
steel, low-alloyed, hot rolled [kg]			45.28	1.06E-06	11.33	1.51E-06
steel, unalloyed [kg]	34.81	0.08	34.89	0.00E+00	0.00	0.00E+00
Stone Wool [kg]	4.21	7.28	11.49	0.00E+00	2.36	1.15E-04
stone wool, packed [kg]	11.40	0.11	11.51	1.35E-12	2.38	1.15E-04
synthetic rubber [kg]	53.82	2.50	56.32	0.00E+00	16.60	6.61E-05
tap water [kg]	1.03	0.00	1.03	3.22E-19	0.00	5.30E-06
tetrafluoroethylene [kg]	0.66	3.11	3.77	0.00E+00	1.23	6.60E-05
tin plated chromium steel sheet, 2 mm [m2]			313.85	8.57E-05	138.13	3.35E-04
transformer, high voltage use [kWh]		67.87	67.87	5.35E-07	1.28	
urea formaldehyde resin production [kg]	0.84	1.03	1.87	0.00E+00	0.36	6.61E-05
vinyl chloride [kg]	86.27	9.86	96.12	0.00E+00	10.41	6.61E-05
welding, arc, steel [m]	2.43	0.10	2.52	0.00E+00	0.62	0.00E+00
wire drawing, copper [kg]	9.02	2.54	11.56	4.80E-01	0.00	1.33E-06
wire drawing, steel [kg]	15.08	0.75	15.83	1.35E-06	0.68	1.51E-06
Zinc [kg]	75.28	19.25	94.53	3.06E-06	3.20	0.00E+00
zinc coat, coils [m2]	66.00	13.02	79.02	1.93E-06	4.80	2.36E-09

Appendix 7: Factory Footprints

Factories List	WF	WFgray	CF	LF
Aluminum casting facility [unit]	113983287.9	48673101	12511007	997300
aluminium electrolysis facility [unit]	392526884.8	44187102	50848675	1463200
aluminium oxide factory [unit]	22357402.39	0.2194712	218986.22	82500
Building Hall [m2]	5608.888123	672.90003	2277.991	336.22657
building, multi-storey [m3]	7965.100945	4.537E-06	1536.7724	0
Building Hall, Steel Construction [m2]	5601.408747	4.241E-05	3064.8292	0.0056717
Cement Factory [unit]	1127215085	669751.21	1.56E+10	443600
Ceramic Factory [unit]	380894933	66168500	44400204	230800
Clay Pit Infrastructure [unit]	283639945.8	3.2696302	69355503	120000
Chemical Factory [unit]	42.90279018	0	2.3602579	0
Chemical Factory, Organics [unit]	1860237676	299250.72	7.161E+09	165180
Foam Glass Factory [unit]	366915096.5	1021043.4	2.351E+10	345589
Flat Glass Factory [unit]	950527394.4	1376550.6	3.181E+10	426900
Glas Tube Factory [unit]	496243188	197832600	11669789	528900
gravel/sand quarry infrastructure [unit]	52731053.73	85500.221	1.973E+09	182620
metal working factory [unit]	36243832.74	36339233	615811586	632160
non-ferrous metal smelter [unit]	14722045144	751180737	1.464E+10	30959177
packaging box factory [unit]	64037334.33	273600.63	6.298E+09	40080
Paper Mill, Integrated [unit]	2550924905	6313739.4	7.969E+10	786040
Planning mill [unit]	90712372.79	1548037.1	34929917	13147747
Silicone Factory [unit]	14662188192	65005650	1.496E+12	13857780
Stone Wool Factory [unit]	1841355332	18841200	294599939	258700
Rolling Mill [unit]	1474782.374	2094.7502	48464296	929.32
Technical Wood Drying Facility [unit]	98108.79217		23.717662	45
Water Treatment Faciltiy, 1.6E8 l [unit]	11628000.72	0	9546586.6	2112.12
Wooden Board Factory, organic bonded boards [unit]	1356656584	15877334	72261137	1560000

Appendix 8: Factories, Machines + Other Footprints

Machines + Other List	**WF**	**WFgray**	**CF**	**LF**
Blast Oxygen Furnace Converter [unit]	2985087970	13.501405	13988600	1500000
Blast Furnace [unit]	1098509304	43738514	126598396	2928000
Building Machine [unit]	285013.1357	0.0031731	14320.972	1.505E-06
control cabinet, heat and power co-generation unit, 160kW electrical [unit]	115348.6789	5.778E-06	24854.928	0
Conveyor Belt [m]	18102.16411	0.0005606	429.46268	0
electric arc furnance converter [unit]	1775036333	6.7004808	8495280.9	1500000
Electronics, for control unit [kg]	116.0557754		25.412068	1.233
furnace, wood chips, with silo, 300kW [unit]	226995.512		167989.91	244.8
Industrial Furnance, 1MW oil [unit]	107371.9654		4162.7001	
industrial machine, heavy, unspecified [kg]	32.35564349	6.091E-07	0.4757786	0
metal working machine, unspecified [kg]	13.92415638		1.3872485	
Paper Machine [unit]	115807381		26628844	
Ultraviolet Lamp [unit]	1.84E-09	1.84E-09	4.99E-02	5.30E-06