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Life Cycle Assessment of Electricity Production from Concentrating Solar Thermal Power Plants

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A mio padre, mia madre
le mie sorelle

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Nomenclature

CSP	Concentrating Solar Power
CT	Central Tower
DNI	Direct Normal Irradiation
GHG	Greenhouse Gas
GWP	Global Warming Potential
HCE	Heat Collection Element
HTF	Heat Transfer Fluid
IEA	International Energy Agency
LFR	Linear Fresnel
MENA	Middle East and North Africa
O&M	Operation and Maintenance
PT	Parabolic Trough
PV	Photovoltaics
SCA	Solar Collector Assembly
SM	Solar Multiple
TES	Thermal Energy Storage

Abstract

The Electricity and Thermal Energy production trough Concentrating Solar Power (CSP) systems is growing in capacity, technology knowledge and competitiveness. The optimization of their performances are required both at the economic and environmental level. Life Cycle Assessment (LCA) has been proven to be suitable for the environmental assessment of renewable energy technologies since it addresses the potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal. This thesis presents the LCA of electricity production by three different CSP reference plants located in the southern Spain: parabolic trough, central tower and linear Fresnel. Not only the effect of using different technologies and back-up systems is detected but even the impact of increasing the plant scale. A sensitivity analysis of the Direct Normal Irradiation (DNI) influence on the results is as well performed. The obtained results demonstrate that the central tower plant has the lowest GHG emissions, followed by linear Fresnel and parabolic trough. Moreover, 100 MW results the power scale with the lowest emission values and in general the extraction of raw materials and manufacturing of components is the phase responsible for the biggest impact for every technology. When compared with its fossil competitors except for nuclear power plant, CSP has a much lower impact. The sensitivity analysis highlights that the environmental performance of the reference plants rapidly deteriorate if DNI is lower than 1600 $kWh/(m^2yr)$.

Contents

Chapter 1

Introduction

World primary energy demand has grown by an annual average of around 1.8% since 2011, although the pace of growth has slowed in the past few years, with wide variations by country. Growth in primary energy demand has occurred largely in developing countries, whereas in developed countries it has slowed or even declined. In 2016, the power sector experienced the greatest increases in renewable energy capacity, whereas the growth of renewables in the heating and cooling and transport sectors was comparatively slow. The year also saw continued advances in renewable energy technologies, including innovations in solar PV manufacturing and installation and in cell and module efficiency and performance; improvements in wind turbine materials and design as well as in operation and maintenance (O&M), which further reduced costs and raised capacity factors; advances in thermal energy storage for concentrating solar thermal power (CSP); new control technologies for electric grids that facilitate increased integration of renewable energy and improvements in the production of advanced biofuels [28].

Concentrating solar thermal power production is an important topic of interest in the renewable energy sources panorama, electricity and thermal energy production via CSP systems are growing in capacity, technology knowledge and competitiveness. As reported in the 2016 Renewables Global Status Report [29], global operating capacity increased by 420 MW from 2005 to reach nearly 4.8 GW by the end of 2015 (see Figure 1.1) a wave of new projects was under construction as of early 2016 and several new plants are expected to enter operation in 2017.

The first developments of CSP power plants took place during the 1970s when the oil crisis pushed the research about new ways of electricity producion, at the beginning of the 1990s nine plants have been build in the USA but the cheap oil price and high installation cost of this technology deleyed the build-up of next plants for many years. The first European plants have been commissioned and operated in 2008 in Spain: legislation of the country subsidized this renewable electricity production making Spain undoubtedly the leader market.

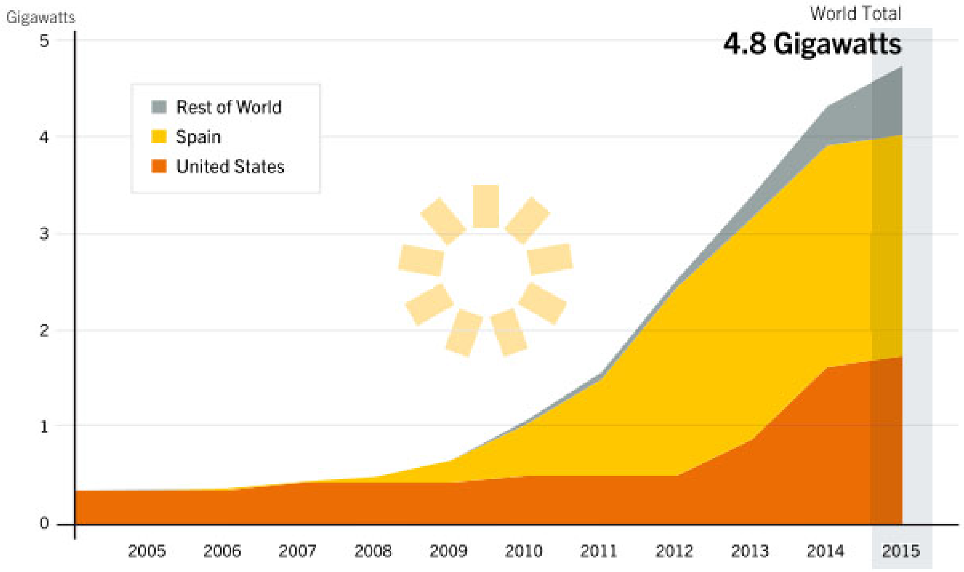


Figure 1.1.: Concentrating Solar Thermal Power Global Capacity, 2005–2015 [29]

However, CSP activity saw a significant shift from Spain and United States to developing countries in 2015, and this trend continued in 2016. The ongoing stagnation of the Spanish market, along with a long-predicted slowdown in the United States, resulted in continuous growth of industrial activity and increased partnerships in new markets, including South Africa, the MENA (Middle East and North Africa) region and particularly China [28]. According to the IEA Technologys Roadmap [19], the regional production will be shared in the World as shown in Figure 1.2.

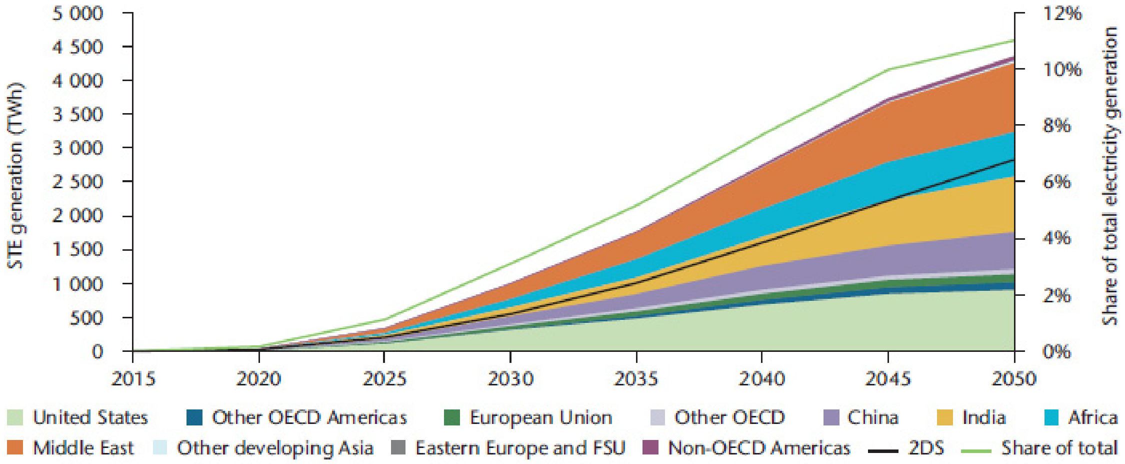


Figure 1.2.: Regional Production of STE envisioned in [19]

This technology uses much of the current know-how on power generation and it can benefit from improvements in steam and gas turbine cycles; in addition, matching the electrical energy production with thermal energy storage in the current plants allows limiting the production variability, covering the evening peak demand and operating as a renewable baseload generator. All of the facilities added in 2016 incorporated thermal energy storage (TES) capacity, a feature now seen as central to maintaining the competitiveness of CSP through the flexibility of dispatchability. For this reason, CSP offers some advantages over PV technology and even though they seem to be in competition, they are indeed complementary.

However, some solar projects have faced public concerns regarding land requirements for centralized CSP plants, perceptions regarding visual impacts, cooling water requirements and land use [4]. Life Cycle Assessment (LCA) studies (and, in general, investigations which include environmental issues) can provide useful information about this technology. Studies based on LCA help for the evaluation of the environmental burdens from cradle-to-grave and facilitate fair comparisons of energy technologies.

1.1. Literature Review

In the literature, there are many studies about the LCA of CSPs, the majority of the publications to date have emphasized on the determination of the life cycle GHG emissions, on the contrary, only few works have detected the life cycle from a broader spectrum such as water consumption with wet and dry-cooling, materials for storage and concentrating device or land use. They have been conducted between 2011-2016 and most of the references are about CSP plants based on parabolic-trough and solar tower technologies, instead, there is a need for more investigations about Fresnel lenses and Dish-Stirling [24]. The majority of the CSP studies defined the LCA boundary conditions to include activities, such as manufacturing, construction, operation and maintenance, dismantling and disposal. From the studies evaluated in the most recent literature review [22], may note that the central receiver CSP electricity generation system had the highest mean GHG emissions (85.67 gCO2e/kWh), followed by the parabolic trough (79.8 gCO2e/kWh) and the paraboloidal dish (41 gCO2e/kWh). These results indicate that the widely used central receiver and parabolic trough CSP electricity generation systems emitted more GHGs than the other technologies. This is mainly due to the material amount needed in the construction of the solar field, which is the prevailing source of emissions of the entire plant, due to its dimension and construction complexity.

1.2. Thesis Scope

The scope of this thesis is the complete environmental analysis of different CSP reference plants, located in the same region and designed following the same general approach, in order to obtain a fair comparison of the results. Indeed, evaluating the results of different studies can show significant discrepancies in the estimated impacts due to discordant assumptions about the scale, the location of the plants and the employed LCA methodology. Therefore, the goal of this analysis is to identify which technology has the best environmental profile as well as the ecological effect of increasing the system scale and using different energy backup systems. The detailed definition of the problem is provided in chapter 4.

Chapter 2

CSP Technology

The following chapter provides an overview about the state-of-the-art of concentrating solar thermal power systems. The main components and technologies involved in the generation of electricity process are detected in order to understand the underlying concepts of this work. Manly commercial level components are reviewed in this section and taken into account in the analysis, anyway possible further technology developments and research topics of interest are cited.

2.1. Collectors

Concentrating solar power technologies produce electricity by concentrating Direct Normal Irradiance (DNI): the amount of solar radiation received per unit area by a surface that is always held perpendicular to the rays that come in a straight line from the direction of the sun at its current position in the sky. Concentrated irradiance allows to heat a liquid, solid or gas that is then used in a downstream process for electricity generation. Concentration is either to a line as in parabolic trough collector or linear Fresnel system or to a point as in central-receiver or dish systems, the latter is not described any further because it is not relevant for this thesis. The line focusing collector tracks the sun along one single axis on a linear receiver, tipically being oriented North-South. Point focusing collectors need tracking systems using two axes to focus the irradiation on the receiver. The receiver is a fixed device which remains independent of the collector assembly during sun tracking while the mobile receiver is connected to the focusing device with respective joints [35]. An important factor to distinguish among the CSP systems is the geometrical concentration factor C which is defined by the ratio between the collector's aperture area and the real receiver area, high concentration factors increase the operating temperature.

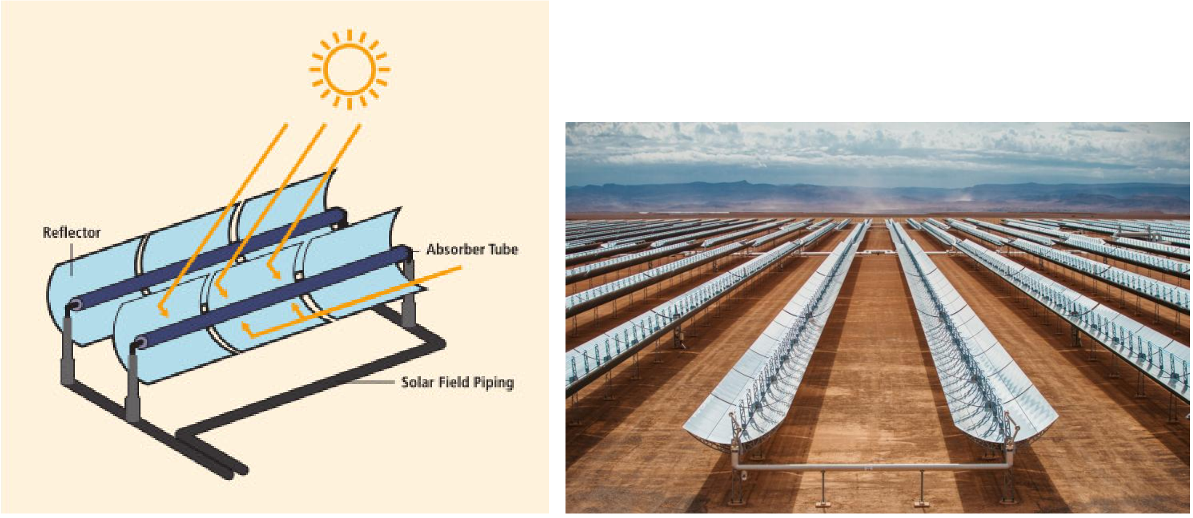
$$C = \frac{A_{ap,c}}{A_{ap,r}} \tag{2.1}$$

Table 2.1.: Concentration factors of the four most common CSP technologies [20]; [34]

Parabolic Trough	**Linear Fresnel**	**Dish-Stirling**	**Central Tower**
C= 70-80	C = 60-70	C >1300	C > 1000

Parabolic Trough Collector

The parabolic trough collector consists of two parallel mirror rows which are fixed to a metal structure on the ground. Although there are ongoing efforts to find alternative materials that could lower the solar field costs, like silver coated polymer films and front side aluminium mirrors, today the majority of commercial parabolic trough power plants use silver coated glass mirrors. They are specially curved in one dimension to focus the solar radiation above the structure to the receiver, also called heat collection element (HCE), which comprises a steel inner pipe fitted with a selective coating and insulated by an evacuated glass tube to minimize the convective heat losses. In fact, the receiver has to be constructed in such a way that high radiation absorption and low thermal losses are realized, low thermal losses refer to radiative, convective and conductive losses. Mirrors are assembled to obtain one module structure and the collector modules are combined to the solar collector assembly (SCA), which is a serial of modules that is moved by one tracking drive unit, located in the centre.



(a) Collector schematics [4]

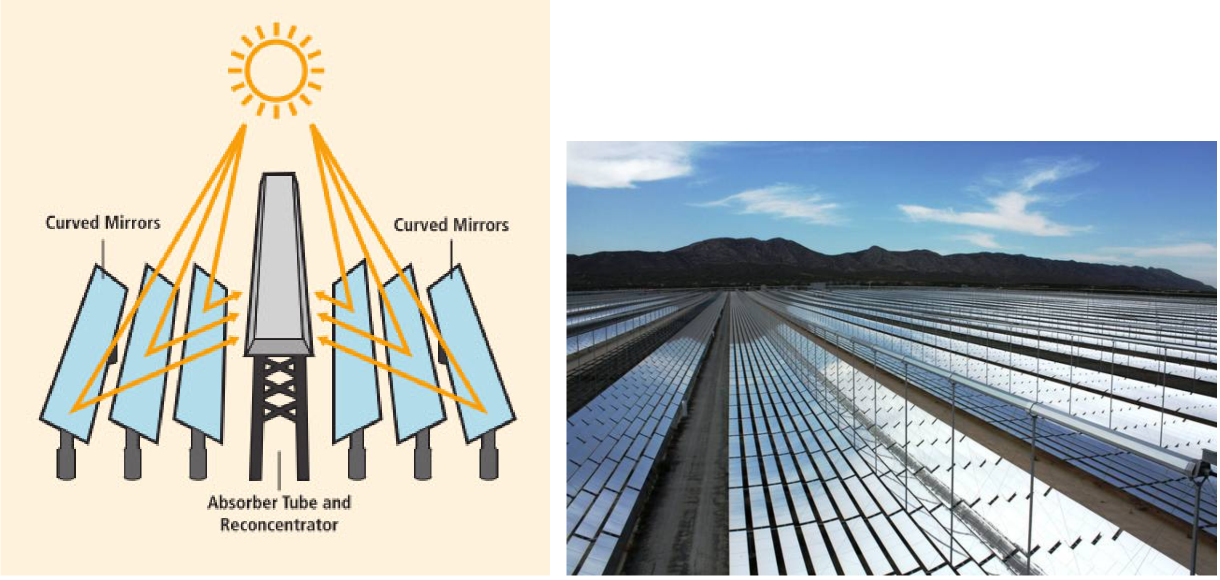
(b) Noor II PT plant, Ouarzazate, Morocco

Figure 2.1.: Parabolic Trough Collectors

Linear Fresnel Collector

Linear Fresnel Collector uses the optical concentration mechanism known as Fresnel lens and is made of several flat mirror stripes which can be orientated independently in order to track the sun and approximate a parabolic concentration on an receiver tube situated above the mirrors. As in parabolic troughs, the reflecting material is silver. Mirrors are smaller and simpler than those used in parabolic trough and they can be placed closer to the ground. As a consequence, the costs linked to the mirrors and to the structure are reduced compare to the previous technology. However, the mirrors in a Fresnel collector can only approximate a parabolic concentration, and the optical efficiency is thus lower [30]. Several realized systems are constructed as solar boilers for direct steam generation, i.e. the steam is generated directly in the solar field without any heat transfer medium in between. Direct steam generation systems can be realized for saturated as well as for super-heated steam generation.

Most systems use a secondary reflector located on top of the receiver pipe which is necessary to mitigate the unavoidable optical inaccuracy of the Fresnel collector and to improve the intercept factor. The secondary concentrator has, hence, principally the task to increase the intercept factor without increasing the absorber diameter, but, thereby it has also the effect that the concentration ratio gets higher. Therefore, the radiation is used more efficiently without generating higher thermal losses at a larger absorber tube.



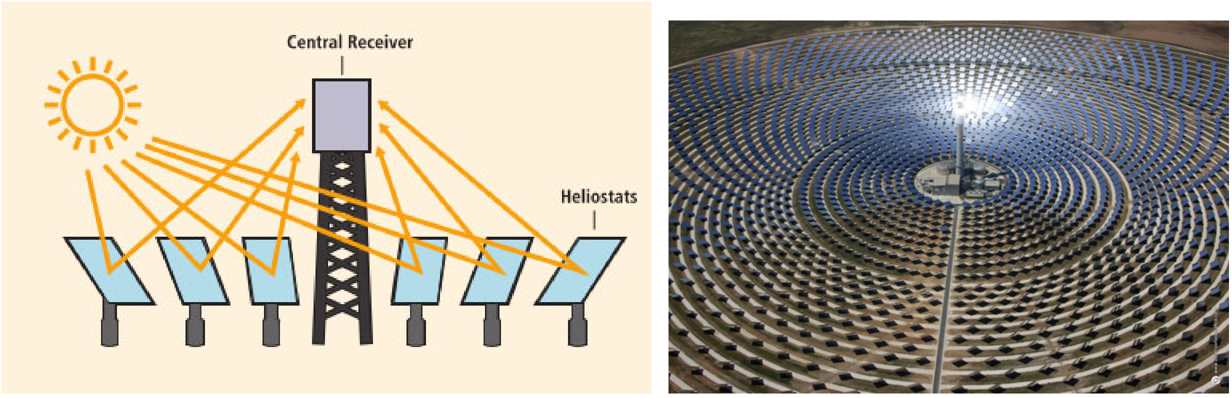
(a) Collector Schematics [4]

(b) Puerto Errado 2 LFR plant, Spain

Figure 2.2.: Linear Fresnel Collectors

Central Tower

In central tower system, the solar irradiation is focused using so-called heliostats to the receiver located on the top of a tower, each heliostat is sun-tracked by a two axis tracking system and reflects the solar image to the fixed receiver. The collectors are mostly positioned in a circular array northwards of the solar tower and are able to generate much higher temperatures than troughs and linear Fresnel reflectors. Major system components include the reflection module, drive mechanism, foundation, structure and controls. The receiver on top of the tower is a key component of the CT system and its design is strongly dependent of the heat transfer fluid applied. The construction is technically challenging in order to withstand the large heat flux densities of 500 - 1000 $kWth/m^2$ caused by the concentrated irradiation [35]. Currently, three different receiver constructions are possible: the water/steam, the molten salts and the volumetric air receiver.



(a) CT Collector schematics [4]

(b) Gemasolar CT plant, Spain

Figure 2.3.: Central Tower Collectors

2.2. Heat Transfer Media

Heat transfer fluid (HTF) is key to CSP success because it carries the heat from the sun collected in the solar field to the power block, where it is converted in electricity. There are three main types of HTF: water, heavy oil and molten salts.

- **Water/steam**: direct steam generation has many advantages but requires a more sophisticated solar field layout, respect to other media. Altough it is free (other than the cost of being de-ionizing) and has a low environmental impact, water can prove unstable and difficult to manage at high temperature and high pressure situations.

- **Synthetic thermal oils**: they are applied in most commercial plants to overcome high pressure issue. One drawback is the limitation of the operation temperature to 400°C, indeed exceeding this temperature causes cracking reactions and the formation of hydrogen destroying the vacuum for thermal insulation in the receiver tubes [35]. Therefore, this limits the temperature CSP plants can operate at.

- **Molten salt**: is the eutectic mixture of 60% sodium nitrate $NaNO_3$ and 40% potassium nitrate KNO_3 which melts when heated above 230°C. It is very suitable for thermal energy storage (further discussed in section

2.3) at high temperature levels, but a technical challenge for being used with parabolic trough is the risk of a freeze event of the salt in the miles of receiver length. There are many research ongoing efforts in order to use the molten salt not only as storage medium, but also as heat transfer fluid in the solar field, which would entail several technical and economic advantages. Unlike oil, molten salts are environmentally friendly, non-flammable, stable fluid, with no degradation of the receiving tube.

2.3. Thermal Energy Storage

A fundamental advantage of solar thermal power plants is the simple integration of a thermal energy storage (TES) which allows decoupling the solar energy from the electricity generation. This introduces more flexibility and allows to sell the electricity not only when the demand is higher, but also when this is more profitable.

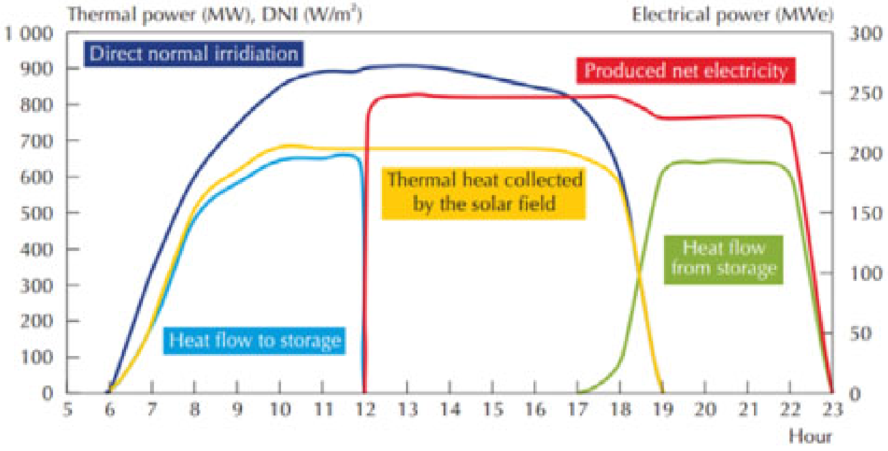


Figure 2.4.: Useful effect of a TES system in a CSP plant [14]

Thermal energy can be stored at temperatures from -40°C to more than 400°C as sensible heat, latent heat and chemical energy using chemical reactions. The current state-of-the-art and commercially proven technology are the molten salt storage systems, which store sensible heat on a day-time basis. Several CSP plants are equipped with such storage systems, dimensioned for about 6-15 hours of full-load operation.

Technical realization can be distinguished by direct or indirect storage systems. In the latter systems, mostly applied together with line focusing collectors such as PT and LFR, a different heat transfer fluid in the solar field compared to the storage media is used. The heat that has to be stored in the molten salt tanks needs to pass through an additional heat exchanger, which causes higher investment costs and lower convertion efficiency. Loading is realized during day time by pumping the molten salt from the cold to the hot tank, unloading occurs during night time by pumping the molten salt through the steam generator to the cold tank. Direct thermal storage systems are characterized by using the same type of heat transfer fluid in the solar receiver and the storage. It can be applied in combination with point focusing systems like the solar tower, where the pipe network is much shorter compared to line focusing systems [35].

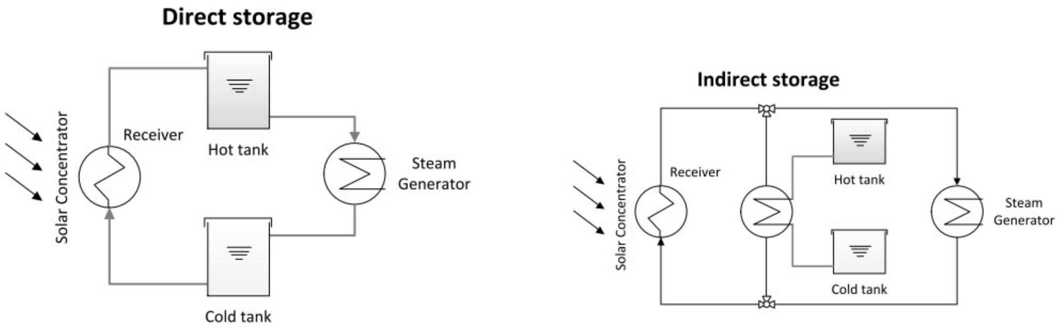


Figure 2.5.: Possibile thermal storage systems [35]

2.4. Power Block

The power block of concentrating solar power plants usually works like conventional fossil fuel power plants, but generally steam turbines need to be designed differently. The reasons are mainly due to the complex cycle conditions, frequent load changes and variable steam conditions. When focusing on annual power production, the short start-up times of the turbines are of great benefit to the CSP plant owner [32]. The steam generation is usually implemented in the process by three process steps: preheating, evaporation and super-heating. When there is not direct steam generation, it is realized by using the molten salt from the hot tank of the thermal storage system. High temperatures and pressure of the steam are favorable for a high thermodynamic efficiency and increased power output. The technical design of the steam generator working with molten salt has some special constraints, the most important is the proper dimensioning of the evaporator because the steam generator has to be able to work with the high pressures and temperatures [35].

Chapter 3

Life Cycle Assessment

This chapter provides a general overview about Life Cycle Assessment methodology as covered by the ISO 14040 and 14044:2006 standards.

3.1. Definition

Life cycle assessment is one of the methods being developed for better understand and address the possible impacts associated with any goods or services ("products"), it quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues.

According to the ISO 14040 [1], "LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)."

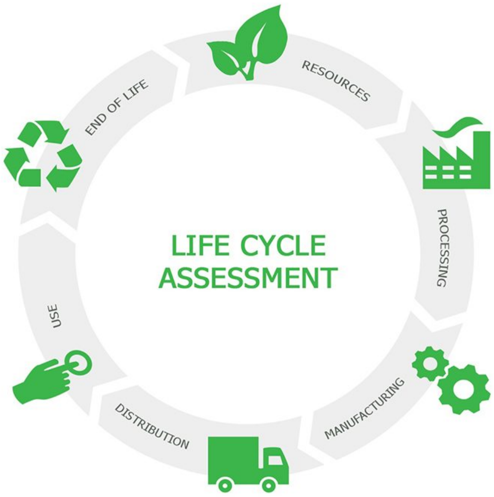


Figure 3.1.: Life Cycle Thinking Schema

Indeed, LCA takes into account a product's full life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste. Critically, LCA studies thereby help to avoid resolving one environmental problem while creating others: this unwanted "shifting of burdens" is where you reduce the environmental impact at one point in the life cycle, only to increase it at another point. Therefore, it helps to avoid, for example, causing waste-related issues while improving production technologies, increasing land use or acid rain while reducing greenhouse gases, or increasing emissions in one country while reducing them in another [10].

LCA can be an assistant tool in:

- improving the environmental performance of products at various points in their life cycle (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign and for development of Integrated Product Policy);

- informing decision-makers in industry, government or non-government organizations;

- marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration)

3.2. Structure

There are four phases in an LCA study:

a) the goal and scope definition;

b) the inventory analysis;

c) the impact assessment;

d) the interpretation.

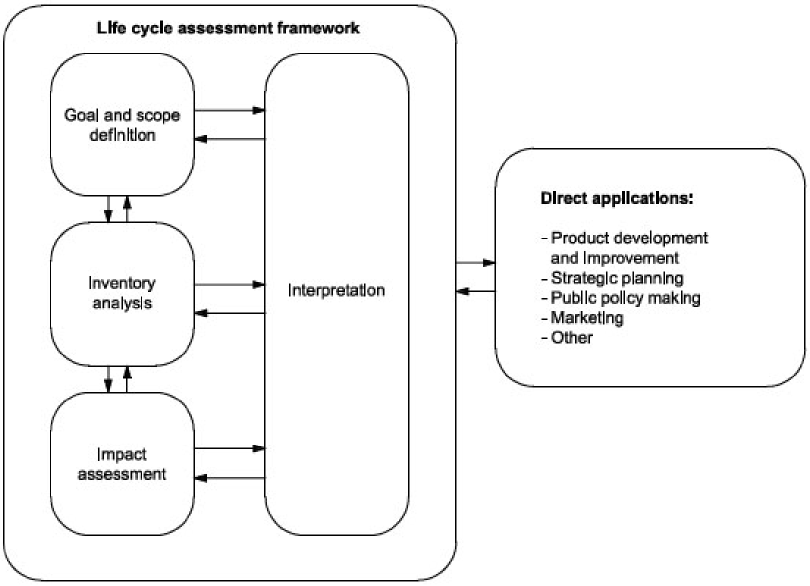


Figure 3.2.: Life Cycle Assessment stages [1]

LCA models the life cycle of a product as its product system, which performs one or more defined functions, the essential property of a product system is characterized by its function and cannot be defined solely in terms of the final products. Product systems are subdivided into a set of unit processes, which are linked to one another by flows of intermediate products and/or waste for treatment, to other product systems by product flows, and to the environment by elementary flows. Dividing a product system into its component unit processes facilitates identification of the inputs and outputs of the product system. In many cases, some of the inputs are used as a component of the output product, while others (ancillary inputs) are used within a unit process but are not part of the output product.

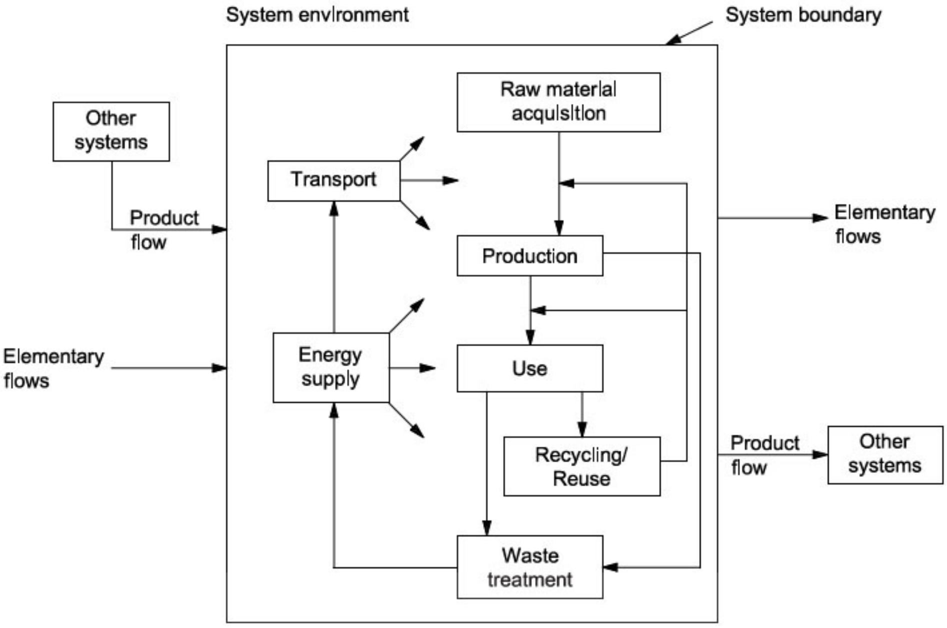


Figure 3.3.: Example of a product system [1]

It is crucial that data used for the completion of a life cycle analysis are accurate and current. There are two basic sources of data for an LCA, primary and secondary in nature. Primary data are derived directly from the process in question. These are the most accurate data that can be applied to an LCA and, as a result, the most desirable. However in many cases, data are proprietary and are not available to the public, thus necessitating the LCA practitioner to seek secondary sources of data, included databases, peer-reviewed literature, etc., that may not be as accurate and are not often accompanied with error estimates.

Goal and Scope Definition

The goal and scope definition is the first phase of any life cycle assessment, during this phase among others the decision-contex and the intended application of the study are identified and the targeted audience are to be named. In the definition shall be detail any initially set limitations for the use of the LCA study and unambiguously identify the internal or external reasons for carrying it out and the specific decisions to be supported by its outcome, if applicable. During this phase, the object of the LCA study (i.e.

the exact product or other system to be analysed) is identified and defined in detail. A clear, initial goal and scope definition is hence essential for a correct later interpretation of the results [10]. The document therefore has to include the functional unit, which defines what precisely is being studied and quantifies the product or service delivered by the product system, providing a reference to which the inputs and outputs can be related. Further, the functional unit is an important basis that enables alternative goods, or services, to be compared and analysed. Moreover, the system boundaries and the allocation methods, used to partition the environmental load of a process when several products or functions share the same process, have to be declared in this phase.

Life Cycle Inventory

Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. Inventory flows include inputs of water, energy, and raw materials, and releases to air, land and water. The process of conducting an inventory analysis is iterative. As data are collected and more is learned about the system, new data requirements or limitations may be identified that require a change in the data collection procedures so that the goals of the study will still be met [1]. The data must be related to the functional unit defined in the goal and scope definition.

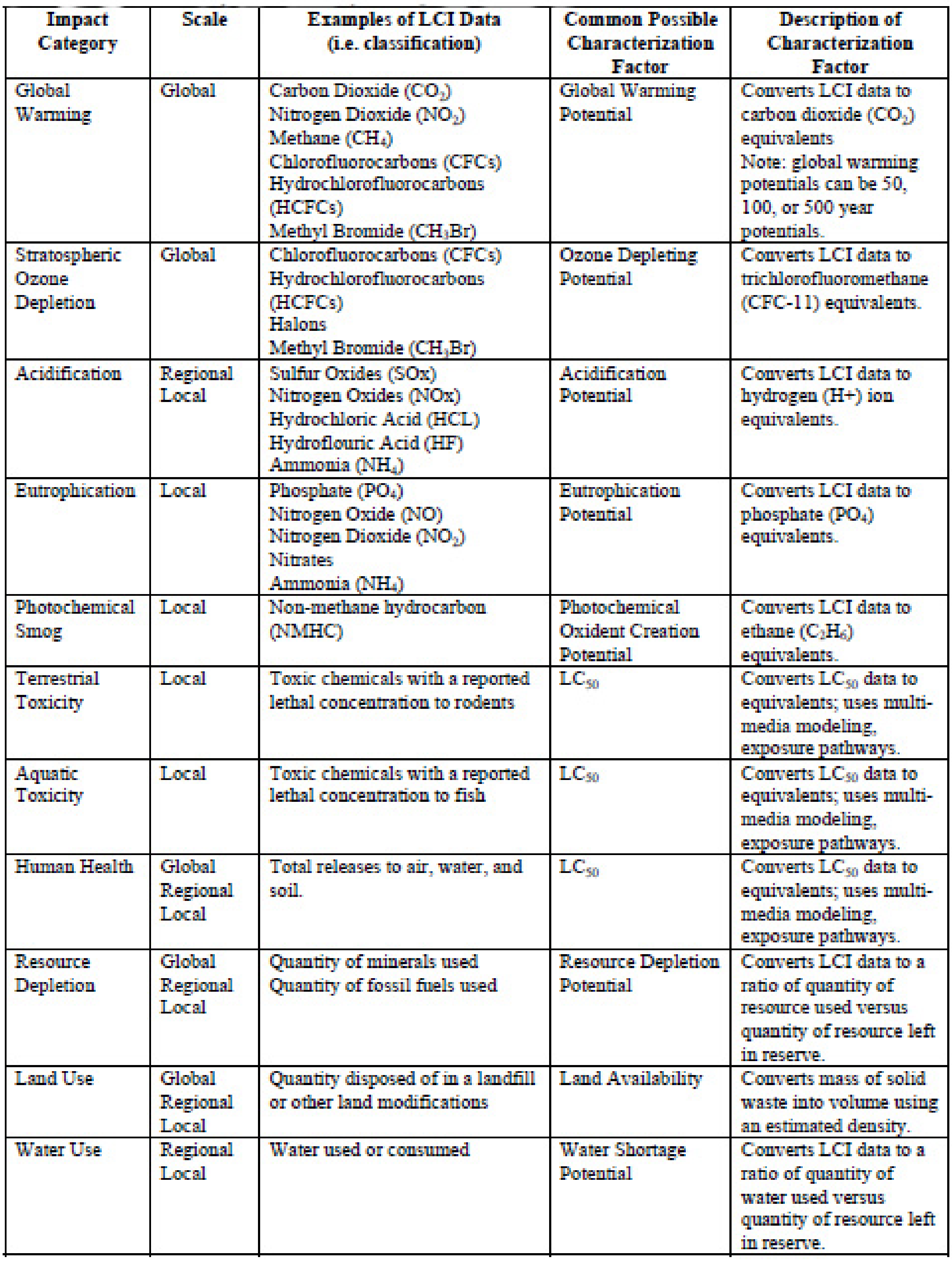
Life Cycle Impact Assessment

The impact assessment phase of LCA is aimed at evaluating the significance of potential environmental impacts using the LCI results. In general, this process involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts.

The following steps, comprise the LCIA:

a) <u>Selection and Definition of Impact Categories</u>

The first step in an LCIA is to select the impact categories (e.g., global warming, acidification, terrestrial toxicity) that will be considered as part of the overall LCA. This step should be completed as part of the initial goal and scope definition phase to guide the LCI data collection process and requires reconsideration following the data collection phase.



Impact Category	Scale	Examples of LCI Data (i.e. classification)	Common Possible Characterization Factor	Description of Characterization Factor
Global Warming	Global	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Methyl Bromide (CH_3Br)	Global Warming Potential	Converts LCI data to carbon dioxide (CO_2) equivalents Note: global warming potentials can be 50, 100, or 500 year potentials.
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH_3Br)	Ozone Depleting Potential	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents.
Acidification	Regional Local	Sulfur Oxides (SOx) Nitrogen Oxides (NOx) Hydrochloric Acid (HCL) Hydroflouric Acid (HF) Ammonia (NH_4)	Acidification Potential	Converts LCI data to hydrogen (H+) ion equivalents.
Eutrophication	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates Ammonia (NH_4)	Eutrophication Potential	Converts LCI data to phosphate (PO_4) equivalents.
Photochemical Smog	Local	Non-methane hydrocarbon (NMHC)	Photochemical Oxident Creation Potential	Converts LCI data to ethane (C_2H_6) equivalents.
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents	LC_{50}	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish	LC_{50}	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.
Human Health	Global Regional Local	Total releases to air, water, and soil.	LC_{50}	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.
Resource Depletion	Global Regional Local	Quantity of minerals used Quantity of fossil fuels used	Resource Depletion Potential	Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve.
Land Use	Global Regional Local	Quantity disposed of in a landfill or other land modifications	Land Availability	Converts mass of solid waste into volume using an estimated density.
Water Use	Regional Local	Water used or consumed	Water Shortage Potential	Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve.

Figure 3.4.: Commonly used life cycle impact categories [31]

b) Classification

The purpose of classification is to assign LCI results to the impact categories (e.g., classifying carbon dioxide emissions to global warming). For some items, which contribute to only one impact category, the procedure is a straightforward assignment. For items that contribute to two or more different impact categories, a rule must be established for classification.

c) Characterization

In impact characterization LCI results are converted and combined within impact categories using science-based conversion factors (e.g., modeling the potential impact of carbon dioxide and methane on global warming). Impact indicators are typically characterized using the following equation:

$$Inventory\ Data \times Characterization\ Factor = Impact\ Indicators$$

d) Normalization

Normalization is an LCIA tool used to express impact indicator data in a way that can be compared among impact categories (e.g. comparing the global warming impact of carbon dioxide and methane for the two options). This procedure normalizes the indicator results by dividing by a selected reference value.

e) Grouping

Grouping assigns impact categories into specific areas of concern (e.g. sorting the indicators by location: local, regional, and global).

f) Weighting

In this last phase, weights or relative values to the different impact categories based on their perceived importance or relevance are assigned. Because it is not a scientific process, it is vital that the weighting methodology is clearly explained and documented.

In some cases, the presentation of the impact assessment results alone often provides sufficient information for decision-making, particularly when the results are straightforward or obvious.

Interpretation

Life cycle interpretation is the last phase of the LCA process, in this phase results from LCI and LCIA are identify, checked and evaluated. Within the ISO standard [1], the interpretation phase should deliver results that are consistent with the defined goal and scope and which reach conclusions, explain limitations and provide recommendations. It is also intended to provide a readily understandable, complete and consistent presentation of the results of an LCA, in accordance with the goal and scope definition of the study.

Chapter 4

Case study

4.1. Goal and Scope Definition

The goal of the following Life Cycle Assessment is to analyse the ecological impact of different CSP technologies in order to identify the most environmentally competitive as well as critical materials and processes involved in the solar thermal electricity production. Three different power scales are considered: small, medium and large of three CSP technologies, the Parabolic Through (PT), the Central Tower (CT) and the Linear Fresnel (LFR) plant. Every reference plant includes a molten salt TES system and in addition, the environmental impact of the natural gas backup system in PT is investigated.

Since the analysis involves many reference plants and different technologies, a first-order design was conducted to obtain information about material requirements and data embodied in the inventory. Mainly, secondary data from other studies are used, following suitable scale methods that will be described in details, as well as information from manufacturer's data-sheets, mean values and consistent suppositions.

To perform a fair comparison, all the plants are supposed to be located in the southern Spain, where annual average direct normal irradiation is[1]:

$$DNI = 2100\,\frac{kWh}{m^2yr}$$

.

The functional unit is 1 kWh of electricity produced at the power plant, which has a lifetime of 25 years. The LCA system boundary (see Figure 4.1) includes the supply of raw materials and manufacture of key system

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[1] http://solargis.com/products/maps-and-gis-data/free/overview/

components, plant construction, operation and maintenance (O&M), plant dismantling and materials disposal.

OpenLCA 1.6.3 modeling software and EcoInvent 3.3 life cycle inventory database are used throughout this study.

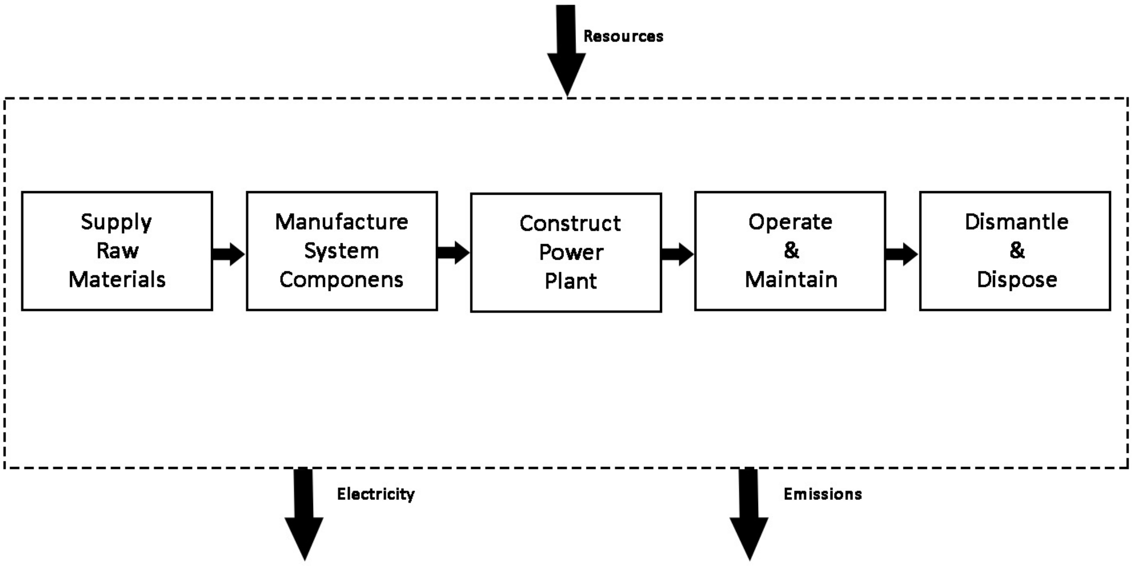

Figure 4.1.: Life Cycle Assessment Boundary

4.2. General Assumptions

The purpose of this chapter is to describe the methodology used to carry out the Life Cycle Inventory of the systems under investigation.

4.2.1. Parabolic Trought Plants

The plant design is based on criteria proposed in [17], [27], [37], [13]. As a general rule, when the mass of a particular component was not given in one of the many data sources used in this study, it was calculated using the material dimensions and an average density.

The reference parabolic trough plant is schematic showed in figure 4.2.

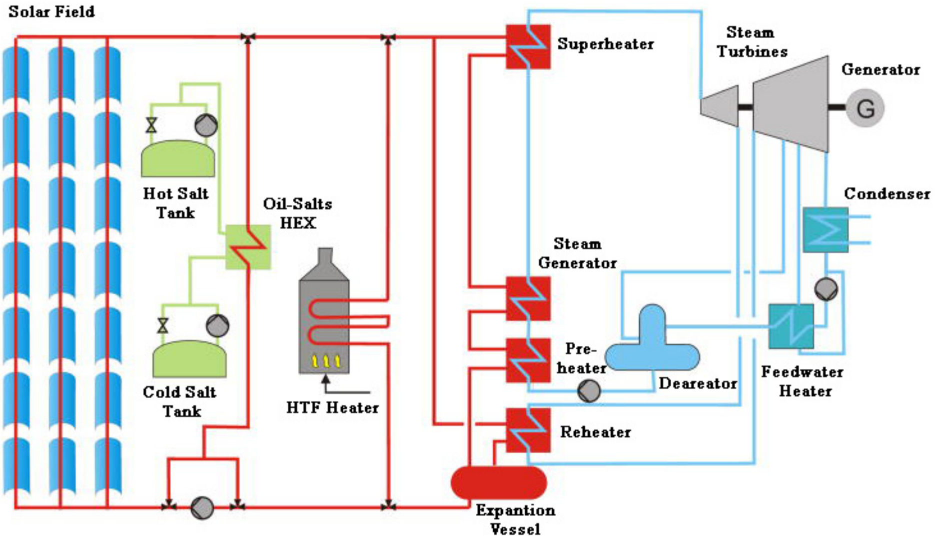

Figure 4.2.: Schematic layout of a parabolic trough CSP plant

As a first-order approach the solar field aperture area is calculated with the following equation:

$$A_{ap} = \frac{P_{el} \cdot SM}{\eta \cdot DNI_d} \tag{4.1}$$

where:

- P_{el} = rated electric power;
- SM (solar multiple) = 2;
- η (overall peak efficiency) = 30%
-DNI_d (direct normal irradiance at design point) = 800 $\frac{W}{m^2}$

The power block is a conventional dry-cooled Rankine power cycle. Dry-cooling system uses a series of fans to transfer heat from feedwater at the outlet of the turbine via forced convection to ambient air at the dry bulb temperature. As demonstrated in [6], this can reduce the life cycle water consumption of a PT plant with TES by 80% (from 5 to 1 l/kWh). Water usage is an important environmental concern to CSP power plants. In fact, although deserts provide the best location for plants to maximise efficiency, increased water consumption in desert areas is an obvious barrier to deploying this technology.

The cycle maximum temperature is limited to about 370°C and the pressure to 100 bar, therefore the power block efficiency is 35%. The annual capacity factor, used to estimate the total electricity production is 36%.

Material Extraction and Manufacturing Phase

Calculations on solar field are based on second generation cylindrical-parabolic collector technology (SENERtrough®-2) installed in NOOR II plant, in Morocco. The collector has an opening that is nearly 25% larger than the current design, reducing the number required to collect the same amount of energy, that gives rise to a global reduction in the solar field total cost, as size has been optimised from the perspective of features and manufacture. Mirrors (RP 2), which have 99,9% intercept factor, are considered in the design of the collectors, as the 90 mm diameter receiver (UVAC 90-7G), which enables more energy absorption, hence increasing the energy output per unit. The bearing structure of the collector is made of reinforcing steel, considering a weight of 17 kg per m^2 of aperture area, meanwhile an amount of 10 m^3 of concrete for every SCA is assumed. Detailed collector features are summarised in table 4.1.

Table 4.1.: Collector Features

Module aperture length	13	m
Module aperture width	6,87	m
Number of modules per SCA	12	items
Number of mirrors per module	28	items
Module aperture area	89,31	m^2
Glass thickness	4	mm
Single mirror area	2,1	m^2
Single mirror weight	21,5	kg
Absorber tube ext diameter	90	mm
Absorber tube int diameter	85	mm
Glass tube ext diameter	135	mm
Glass tube int diameter	129	mm
Tube length	4100	mm

The heat transfer fluid considered is the synthetic oil Therminol-VP1, that is a eutectic mixture of biphenyl ether (23,5%) and diphenyl ether (73,5%), due to lack of information about biphenyl in Ecoinvent 3.3 database, phenol is considered a reasonable alternative in the LCI computation, as supposed in [9]. The oil inlet and outlet temperatures are showed in table 4.2.

Table 4.2.: Heat transfer fluid features

SCA oil inlet temperature	293	°C
SCA oil outlet temperature	393	°C

Specific information about the main hot oil circulation pumps is not available in the literature, therefore this component is not included in the inventory. The mixture of nitrate salts, so called ”solar salt”, which is used as the storage medium for the reference plant design, consists of 60% sodium nitrate and 40% potassium nitrate, see table 4.3 for inlet and outlet temperatures.

Table 4.3.: Molten Salt features

Molten salt inlet temperature	286	°C
Molten salt outlet temperature	386	°C

The oil-salts shell and tube heat exchangers are considered to be made of reinforcing steel and manufactured in Spain. Pipes are supposed to be made of stainless steel and the layout information is obtained from [25] for the 50 MW plant and increased proportional to the plant aperture area for the 100 MW and 200 MW plants.

The molten salt thermal energy storage system is designed for 7,5 hours of full-load operation, the dimensions of the two tanks and the amount of the required molten salt are based on Andasol 1 plant features[2] for the 50 MW plant, from data available in [2] for the 100 MW plant and linearly scaled for the 200 MW plant. Concrete requirement for tanks slab

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[2] https://www.nrel.gov/csp/solarpaces/

is calculated from [23] and the carbon steel amount on data available in [9]. The HTF heater is a natural gas boiler which has an efficiency of 90% and is mainly made of carbon steel and refractory, the mass of the materials is calculated from [9] inventory, scaling the data with the following equation, as suggested in [12]:

$$\frac{m_j}{m_{j,ref}} = \left(\frac{A_j}{A_{j,ref}}\right)^{k_{j,m}} \tag{4.2}$$

where:

- m_j: mass of the process equipment j to be calculated
- $m_{j,ref}$: mass of a reference process equipment
- A_j: functional parameter of the process equipment j
- $k_{j,m}$: exponent calculated from other available LCI data-sets

The functional parameter for boiler is the thermal power and in this case the exponent is $k_{j,m} = 0,80$. When the model includes only the TES backup system, this component is not included in the inventory.

About the power block, data related to the 100 MW scale, from [6], are adapted to 50 MW and 200 MW assuming a direct relationship between the power capacity of the power block and the volume of its components, and a square relationship between the capacity of these components and the mass of raw materials involved in their construction. Transport of mirrors and receivers from the manufacturers to the provider of the collectors are included in the inventory, see table 4.4.

Table 4.4.: Assumed distances for transportation in Manufacturing phase

Collectors	2000	km
Receivers	1700	km

Construction Phase

All the information related to the construction phase are obtained from [9] and properly scaled in relation to the plant aperture area. The amount of material involved in this phase, as well as the specific required activities, such as pipe welding, excavation and fuel consumption for building machines, are considered. Moreover, transport of the main components from the providers to the plant site is also included. The components are supposed to be transported by EURO6 freights and the considered distances are summarised in table 4.5.

Table 4.5.: Assumed distances for transportation in Construction phase

Heat transfer fluid	2000	km
Heat exchanger	550	km
Pipes	650	km
Expansion tank	650	km
Molten salt tanks	650	km
Power block	2200	km
Boiler	800	km

Operation and Maintenance Phase

Since the Spanish legislation allows CSP plants to produce up to 15% of their gross electricity output from auxiliary fuel, this is the maximum percentage considered in the model, when HTF heater is included. The amount of natural gas consumed in the auxiliary boiler is calculated from thermal power and its efficiency and it is not included in the inventory when the molten salt TES is the only backup system.

HTF freeze protection requires an additional consumption of natural gas, which is obtained from [9], and 10% of the HTF total amount is the quantity considered for the replacement during operation. When direct normal radiation can no longer be used to generate power, the CSP plant must consume electricity from the grid to satisfy its parasitic loads, this energy consumption, mirror washing water and steam cycle operation water quantities are extracted from [6]. As a first-order approach, all data are linearly scaled.

Dismantling Phase and Disposal Scenario

The same amount of fuel burned in building machines considered in the construction phase is supposed to be used during the plant dismantling. The waste management scenario: 40% recycling, 30% landfill, 30% incineration of steel, glass and aluminium is based on information from the Spanish National Plan for Management of Construction and Demolition Waste (Spanish Royal Decree 105/2008).

4.2.2. Central Tower Plants

The reference central tower plants are designed following information obtained from [3], [26], [21], [8] and [7]. The system layout is showed in figure 4.3.

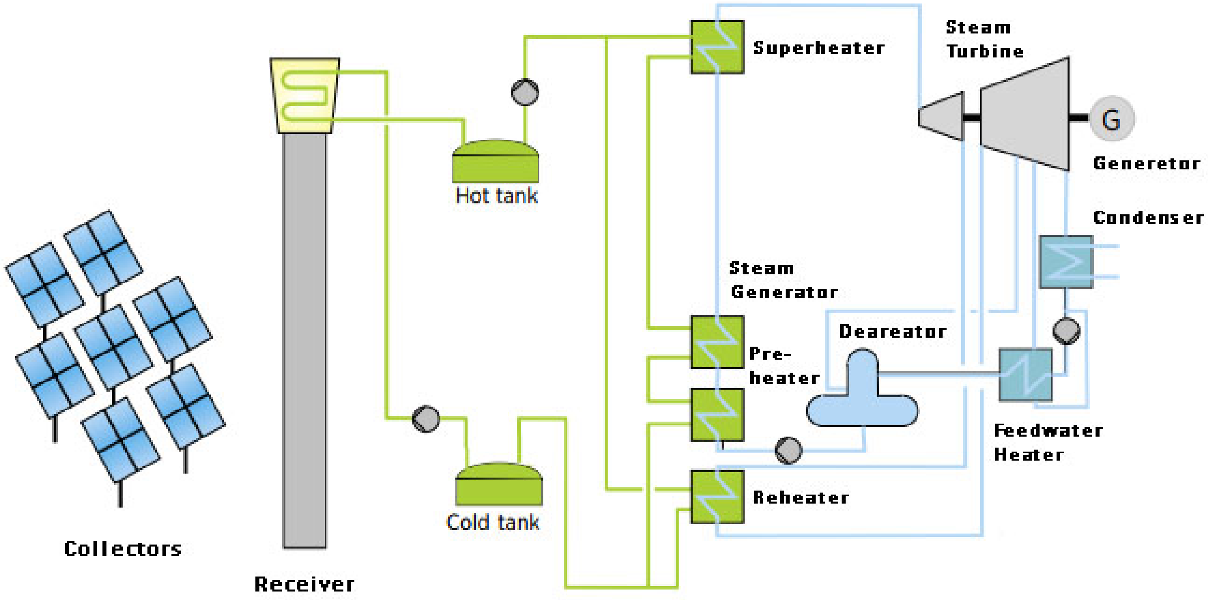

Figure 4.3.: Schematic layout of central tower CSP plant

Unlike the parabolic trough plants considered in the previous section, this reference plant is not provided with any fossil fuel backup system. In order to calculate the aperture area of the plant and than the material requirement for the solar field, equation 4.1 is used with the following parameters:

- P_{el} = rated electric power;
- SM (solar multiple) = 2;
- η (overall peak efficiency) = 16%
-DNI_d (direct normal irradiance at design point) = 800 $\frac{W}{m^2}$

As for the parabolic trought plants, the power block is provided with a dry-cooling system. Superheated steam at 540°C and 150 bar is generated in molten salt heat exchangers and this allows the Rankine power cycle to reach an efficiency of 38%. The estimated solar-only annual capacity factor is 40%.

Material Extraction and Manufacturing Phase

The collector field is considered to be made of large size heliostats, in particular the biggest size that has put into commercial application up till now (designed by SENER and installed in NOOR III plant, Morocco). The heliostat is composed by extra clear 3 mm thick high reflectivity mirrors[3] and it is supported by a frame assembly and a pedestal tube. The pedestal is anchored to the ground with a concrete foundation as usually found in solar power plants using large heliostats, carbon steel and concrete amounts required for structure and foundation are obtained from [36]. Detailed collector features are reported in table 4.6.

Table 4.6.: Collector Features

Heliostat aperture area	178,00	m^2
Glass weight	7,50	kg/m^2
Mirror thickness	3,00	mm
Single mirror area	8,19	m^2
Single mirror weight	61,39	kg
Number of mirrors per heliostat	22	items

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[3] http://www.agc-solar.com/agc-solar-products/solar-mirror/

The plant under investigation is provided with a 7,5 hours of full-load operation thermal energy storage, the molten salt mass requirement as well as steel and concrete amount are obtained from [23]. The "solar salt" minimum and maximum temperatures are showed in table 4.7.

Table 4.7.: Molten Salt features

Molten Salt inlet temperature	290	°C
Molten Salt outlet temperature	565	°C

The receiver, placed at the top of a tower, is of the external type and consist of panels of many small vertical tubes welded side by side to approximate a cylinder. The tubes are supposed to be made of a nickel-iron-chromium alloy (Incoloy 800) and are coated on the exterior with high-absorptance paint. The receiver is designed considering a peak thermal flux of $1\frac{MW_t}{m^2}$.

The tower, which provides support for the solar receiver at the required height above the heliostat field is similar to a tall chimney of conventional fossil power plants and it is supposed to be constructed of reinforced concrete.

Pipes are supposed to be made of chromium steel, in order to avoid corrosion by molten salt and information about material requirement are obtained from [5], scaled in relation to the tower height. Meanwhile, the steam generation system includes water-salts heat exchangers, mainly made of reinforcing steel.

In relation to the power block, data referred to the 100 MW plant, from [36], are adapted to 50 MW and 200 MW assuming a direct relationship between the power capacity of the power block and the volume of its components, and a square relationship between the capacity of these components and the mass of raw materials involved in their construction.

Construction Phase

In the construction phase, excavation and filling activities for the heliostats and tower foundations are included, based on information from [5]. In addition, the diesel consumption for construction machines is extracted from [36] for the 100 MW plant and linearly scaled for the 50 MW and 200 MW plants. Land transport of the main plant components is also included in the inventory of this phase and assumed distances are summarized in table 4.8.

Table 4.8.: Assumed distances for transportation in Construction phase

Heat Exchangers	550	km
Pipes	650	km
Molten Salt Tanks	650	km
Power Block	2200	km

Operation and Maintenance Phase

During the operation of the plant, there are two sources of water consumption: the washing water needed for the mirrors and the steam cycle water, information about these amounts are obtained from [36]. Furthermore, 4% of the molten salt amount is supposed to be replaced once during the plant lifetime and 10% of the gross electricity generation of the plant is consumed as parasitic loads.

Dismantling Phase and Disposal Scenario

As supposed earlier for the parabolic trough plants, during the dismantling of the system the same amount of fuel burned in building machines is considered. The waste management scenario: 40% recycling, 30% landfill, 30% incineration of steel, glass and aluminium is based on information from the Spanish National Plan for Management of Construction and Demolition Waste (Spanish Royal Decree 105/2008).

4.2.3. Linear Fresnel plants

The design of reference Linear Fresnel plants is based on information obtained from [16], [33] and [30]. The system diagram is presented in figure 4.4.

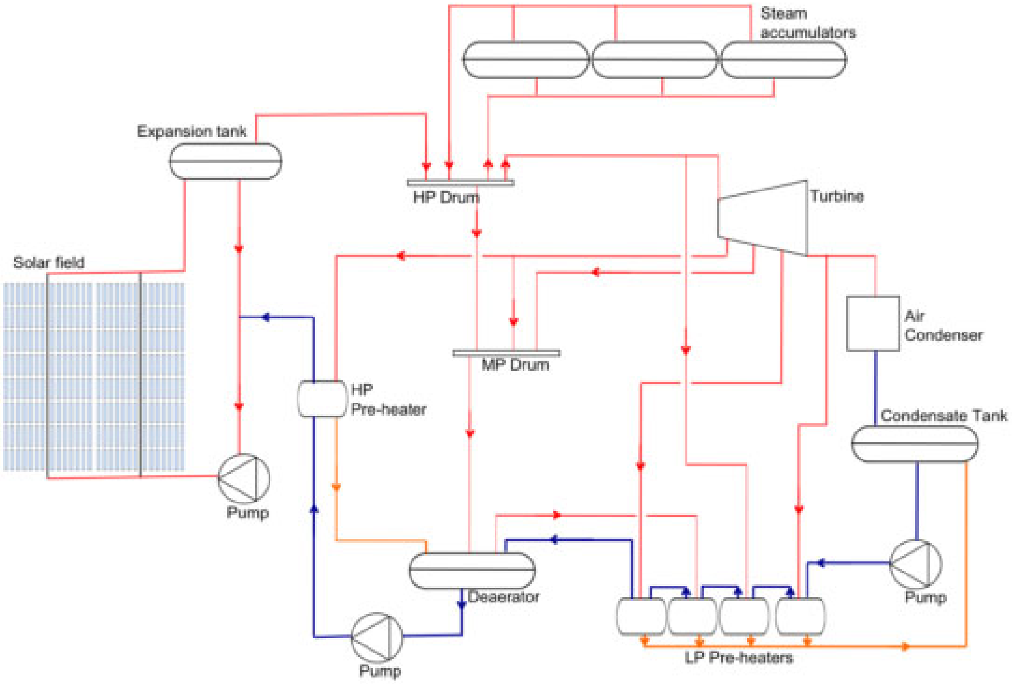

Figure 4.4.: Schematic layout of LFR CSP plant

Considered reference plants are direct steam generation systems, without any fossil fuel backup system and TES. The aperture area of the solar field is calculated from equation 4.1, considering the following parameters:

- P_{el} = rated electric power;
- SM (solar multiple) = 1;
- η (overall peak efficiency) = 20%
-DNI_d (direct normal irradiance at design point) = 800 $\frac{W}{m^2}$

Super-heated steam at 450°C and 90 bar is produced in the collectors. Power block is provided with a dry-cooling system and has a conversion efficiency of 38%, meanwhile the solar-only annual capacity factor is 20%.

Material Extraction and Manufacturing Phase

The solar field is considered to be made of 3 mm flat glass primary reflectors, assembled in modules of 17,5 m aperture width, which is the most cost effective option [16]. Collector features are based on Industrial Solar LF-11[4] technical data and are summarized in table 4.9.

Table 4.9.: LFR collector features

Primary reflector lenght	4,06	m
Primary reflector width	0,5	m
Primary reflector aperture area	2,03	m^2
Number of primary reflectors per module	35	items
Module width	17,5	m
Module aperture area	71,05	m^2
Receiver height	7,5	m
Primary reflector glass thickness	0,003	m
Row lenght	64,96	m
Row aperture area	1136,8	m^2

Modules are supported by stainless steel structure and provided with a 30 cm width secondary reflector, which amplifies the width of the target area of the radiation. The 70 mm diameter receiver (UVAC 70-7G) is an evacuated receiver tube suitable for high temperature application reducing the heat losses by means of the vacuum between the steel tube and the glass tube. The HTF is water for turbine use, the inlet and outlet temperatures are showed in table 4.10.

Table 4.10.: Heat transfer fluid temperatures

HTF inlet temperature	140	°C
HTF outlet temperature	450	°C

A steam/water separator is integrated into the solar field as well as a 0,5 h steam storage tank, material requirements for both the components are obtained from [5] and proportionally scaled with the plant power rate.

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[4] http://www.industrial-solar.de/content/en/maerkte/fresnel-collector/

Information related to the power block are obtained from [36], as considered in the previous cases, data are scaled assuming a direct relationship between the power capacity of the power block and the volume of its components, and a square relationship between the capacity of these components and the mass of raw materials involved in their construction. Transport of primary reflectors, receiver and secondary reflectors are also included in the inventory, see table 4.11.

Table 4.11.: Assumed distances for transportation in Manufacturing phase

Primary reflector	2000	km
Receiver	2200	km
Secondary reflector	2000	km

Construction Phase

In the construction phase, excavation and filling activities needed for the solar field foundation are included, as well as building machines consumption, estimated by scaling by land area a previously published estimate for diesel fuel consumption to construct the Andasol I CSP plant. Land transport of the main plant components is also included in the inventory of this phase and assumed distances are showed in table 4.12.

Table 4.12.: Assumed distances for transportation in Construction Phase

Pipes	650	km
Steam Separator	650	km
Steam Storage Tank	650	km
Power Block	2200	km

Operation and Maintenance Phase

In the operation and maintenance of the plant the water consumption needed to clean the mirrors and the HTF amount are taken into account, data are obtained from [5] for the 30 WM plant and respectively scaled in relation to the aperture area and the power for 50 MW and 100 MW plants. The amount of diesel consumed in cleaner robot is also obtained from [5] and scaled proportionally to the aperture area.

Dismantling Phase and Disposal Scenario

The same assumption made for the parabolic trough and central tower plants is considered in the linear Fresnel case, the dismantling phase includes the amount of diesel consumed in the construction of the plant. Likewise, the waste management scenario: 40% recycling, 30% landfill, 30% incineration of steel, glass and aluminium is based on information from the Spanish National Plan for Management of Construction and Demolition Waste (Spanish Royal Decree 105/2008).

4.3. Life Cycle Inventory

Data related to the mass of embodied materials included in the Inventory are shown in Appendix A, meanwhile here the amount of emissions to air of three main pollutants are reported. In particular, carbon dioxide, nitrogen oxides and sulfur dioxide are considered.

4.3.1. Parabolic Trough Plants

Table 4.13.: Emission to air, low population density

	50 MW		**100 MW**		**200 MW**	
	HTF Heater	**NO HTF Heater**	**HTF Heater**	**NO HTF Heater**	**HTF Heater**	**NO HTF Heater**
Carbon Dioxide (kg/kWh)	2,48E-02	2,23E-02	1,61E-02	1,03E-02	1,93E-02	1,28E-02
Nitrogen Oxides (kg/kWh)	6,54E-05	4,02E-05	4,75E-05	2,61E-05	5,61E-05	3,22E-05
Sulfur Dioxide (kg/kWh)	1,02E-04	1,03E-04	6,87E-05	4,86E-05	8,30E-05	6,06E-05

4.3.2. Central Tower Plants

Table 4.14.: Emissions to air, low population density

	50 MW	100 MW	200 MW
Carbon Dioxide (kg/kWh)	6,37E-03	9,39E-04	5,52E-03
Nitrogen Oxides (kg/kWh)	1,66E-05	3,11E-06	1,41E-05
Sulfur Dioxide (kg/kWh)	2,98E-05	5,96E-06	2,57E-05

4.3.3. Linear Fresnel plants

Table 4.15.: Emission to air, low population density

	30 MW	50 MW	100 MW
Carbon Dioxide (kg/kWh)	6,79E-03	6,66E-03	5,96E-03
Nitrogen Oxides (kg/kWh)	1,75E-05	1,71E-05	1,55E-05
Sulfur Dioxide (kg/kWh)	2,69E-05	2,63E-05	2,39E-05

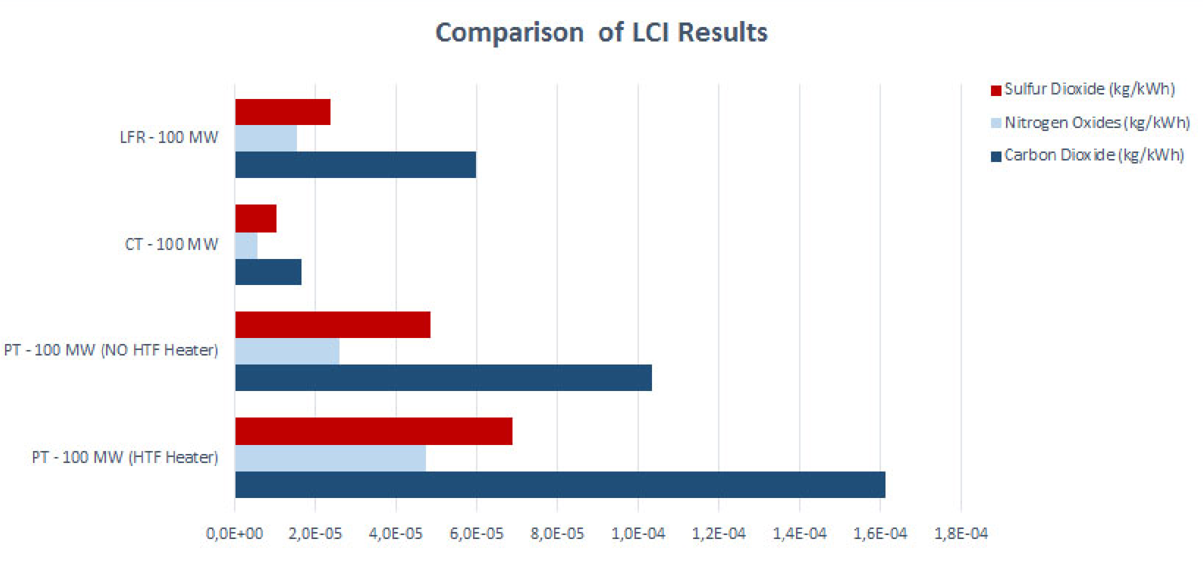

Figure 4.5.: LCI results comparison of 100 MW plants. Carbon dioxide reported values are scaled by $10^{-}2$

4.4. Life Cycle Impact Assessment

In the present study, the CML (baseline) impact method [15] is used to measure the effects of midpoint categories, meanwhile, the Cumulative Energy Demand (CED) was applied to determine primary energy demand of each case.

The Energy Payback Time (EPBT) is the length of time the CSP system must operate before it recovers the energy invested throughout its life time and is calculated using the following equation:

$$EPBT\ (years) = \frac{Embedded\ primary\ energy\ (MJ)}{Annual\ primary\ energy\ generated\ by\ the\ system\ (MJ\ yr^{-}1)} \tag{4.3}$$

Since The European Commission had proposed for the discussion to revise the Primary Energy Factor (PEF) for electricity generation from 2.5 to 2.2 [11], the latter value was considered in order to calculate the EPBT of the plants under investigation.

4.4.1. Parabolic Trough Plants

Table 4.16.: Life cycle impacts of 50 MW PT reference plant per kWhe

50 MW			
Impact category	**Reference unit**	**HTF Heater**	**NO HTF Heater**
Acidification potential	kg SO2 eq/kWh el	1,05E-03	7,36E-04
Climate change - GWP100	kg CO2 eq/kWh el	1,70E-01	8,57E-02
Eutrophication	kg PO4 eq/kWh el	1,86E-04	1,88E-04
Freshwater aquatic ecotoxicity	kg 1,4-DB eq/kWh el	2,46E-02	2,53E-02
Human toxicity	kg 1,4-DB eq/kWh el	1,98E-01	2,09E-01
Marine aquatic ecotoxicity	kg 1,4-DB eq/kWh el	8,64E+01	9,02E+01
Ozone layer depletion - ODP steady state	kg CFC-11 eq/kWh el	2,93E-08	2,82E-08
Photochemical oxidation	kg ethylene eq/kWh el	5,41E-05	3,40E-05
Terrestrial ecotoxicity	kg 1,4-DB eq/kWh el	9,58E-04	1,35E-03

Table 4.17.: Life cycle impacts of 100 MW PT reference plant per kWhe

100 MW			
Impact category	**Reference unit**	**HTF Heater**	**NO HTF Heater**
Acidification potential	kg SO2 eq/kWh el	7,25E-04	2,41E-04
Climate change - GWP100	kg CO2 eq/kWh el	1,52E-01	4,69E-02
Eutrophication	kg PO4 eq/kWh el	1,17E-04	9,69E-05
Freshwater aquatic ecotoxicity	kg 1,4-DB eq/kWh el	1,79E-02	1,22E-02
Human toxicity	kg 1,4-DB eq/kWh el	7,16E-02	5,22E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq/kWh el	6,17E+01	4,01E+01
Ozone layer depletion - ODP steady state	kg CFC-11 eq/kWh el	2,55E-08	8,08E-09
Photochemical oxidation	kg ethylene eq/kWh el	3,86E-05	1,07E-05
Terrestrial ecotoxicity	kg 1,4-DB eq/kWh el	8,03E-04	7,31E-04

Table 4.18.: Life cycle impacts of 200 MW PT reference plant per kWhe

200 MW			
Impact category	**Reference unit**	**HTF Heater**	**NO HTF Heater**
Acidification potential	kg SO2 eq/kWh el	8,34E-04	2,94E-04
Climate change - GWP100	kg CO2 eq/kWh el	1,76E-01	5,91E-02
Eutrophication	kg PO4 eq/kWh el	1,46E-04	1,24E-04
Freshwater aquatic ecotoxicity	kg 1,4-DB eq/kWh el	2,11E-02	1,48E-02
Human toxicity	kg 1,4-DB eq/kWh el	8,33E-02	6,16E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq/kWh el	7,30E+01	4,90E+01
Ozone layer depletion - ODP steady state	kg CFC-11 eq/kWh el	2,88E-08	9,37E-09
Photochemical oxidation	kg ethylene eq/kWh el	4,38E-05	1,27E-05
Terrestrial ecotoxicity	kg 1,4-DB eq/kWh el	9,43E-04	8,63E-04

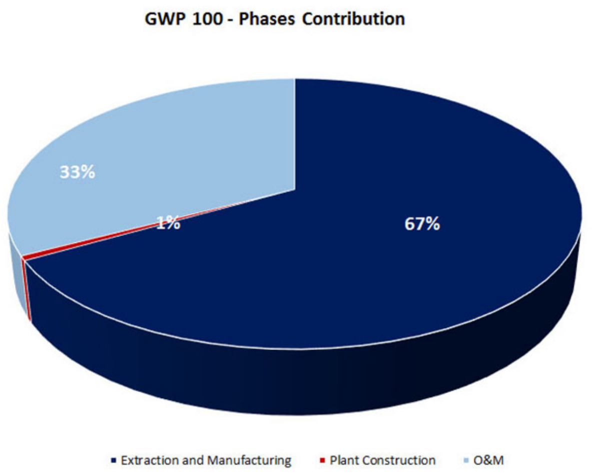

Figure 4.6.: GWP 100 phases contribution - PT plant without HTF heater

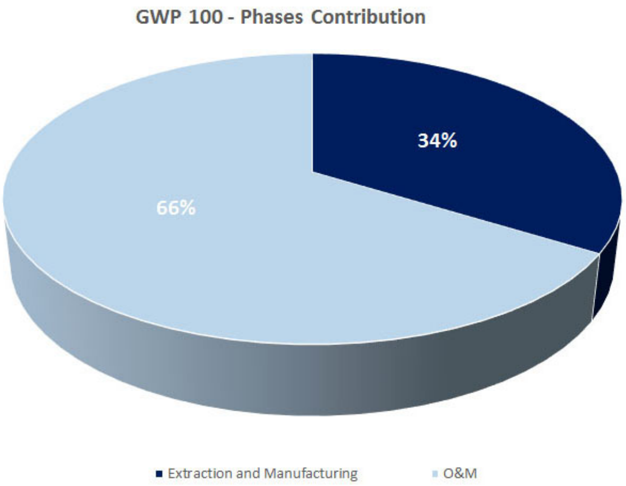

Figure 4.7.: GWP 100 phases contribution - PT plant with HTF heater

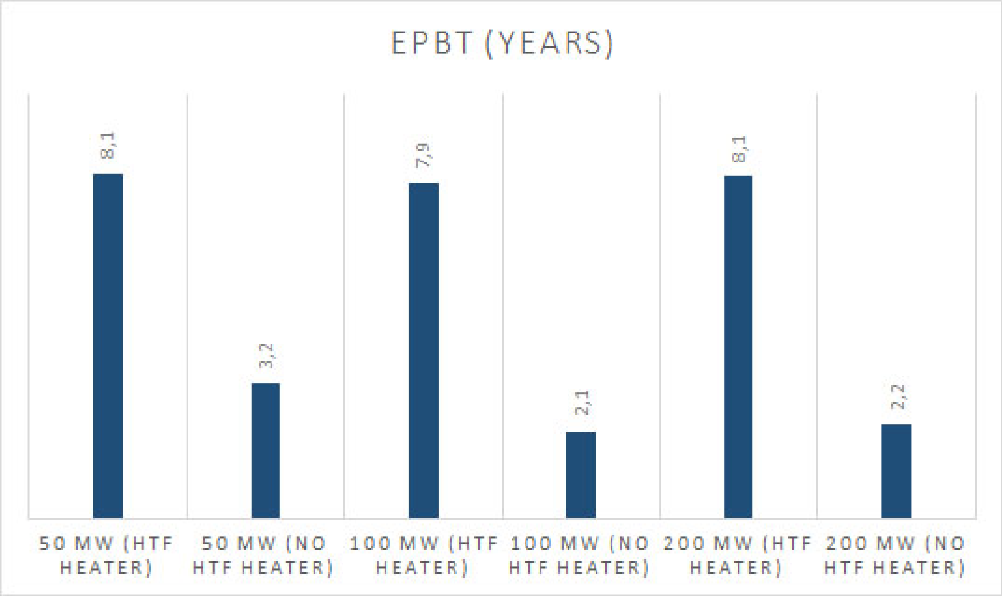

Figure 4.8.: Energy Payback Time of PT reference plants

4.4.2. Central Tower Plants

Table 4.19.: Life cycle impacts of 50 MW CT reference plant per kWhe

50 MW		
Impact category	**Reference unit**	**Result**
Acidification potential	kg SO2 eq./kWh el	1,34E-04
Climate change - GWP100	kg CO2 eq./kWh el	2,59E-02
Eutrophication	kg PO4 eq./kWh el	4,73E-05
Freshwater aquatic ecotoxicity	kg 1,4-DB eq./kWh el	1,78E-02
Human toxicity	kg 1,4-DB eq. /kWh el	8,46E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq./kWh el	3,28E+01
Ozone layer depletion - ODP steady state	kg CFC-11 eq./kWh el	5,06E-09
Photochemical oxidation	kg ethylene eq./kWh el	6,82E-06
Terrestrial ecotoxicity	kg 1,4-DB eq./kWh el	2,57E-03

Table 4.20.: Life cycle impacts of 100 MW CT reference plant per kWhe

100 MW		
Impact category	**Reference unit**	**Result**
Acidification potential	kg SO2 eq./kWh el	1,10E-04
Climate change - GWP100	kg CO2 eq./kWh el	2,27E-02
Eutrophication	kg PO4 eq./kWh el	4,31E-05
Freshwater aquatic ecotoxicity	kg 1,4-DB eq./kWh el	1,54E-02
Human toxicity	kg 1,4-DB eq./kWh el	7,28E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq./kWh el	2,77E+01
Ozone layer depletion - ODP steady state	kg CFC-11 eq./kWh el	3,12E-09
Photochemical oxidation	kg ethylene eq./kWh el	5,56E-06
Terrestrial ecotoxicity	kg 1,4-DB eq./kWh el	2,24E-03

Table 4.21.: Life cycle impacts of 200 MW CT reference plant per kWhe

200 MW		
Impact category	**Reference unit**	**Result**
Acidification potential	kg SO2 eq./kWh el	1,09E-04
Climate change - GWP100	kg CO2 eq./kWh el	2,24E-02
Eutrophication	kg PO4 eq./kWh el	4,27E-05
Freshwater aquatic ecotoxicity	kg 1,4-DB eq./kWh el	1,47E-02
Human toxicity	kg 1,4-DB eq./kWh el	6,89E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq./kWh el	2,68E+01
Ozone layer depletion - ODP steady state	kg CFC-11 eq./kWh el	3,11E-09
Photochemical oxidation	kg ethylene eq./kWh el	5,48E-06
Terrestrial ecotoxicity	kg 1,4-DB eq./kWh el	2,11E-03

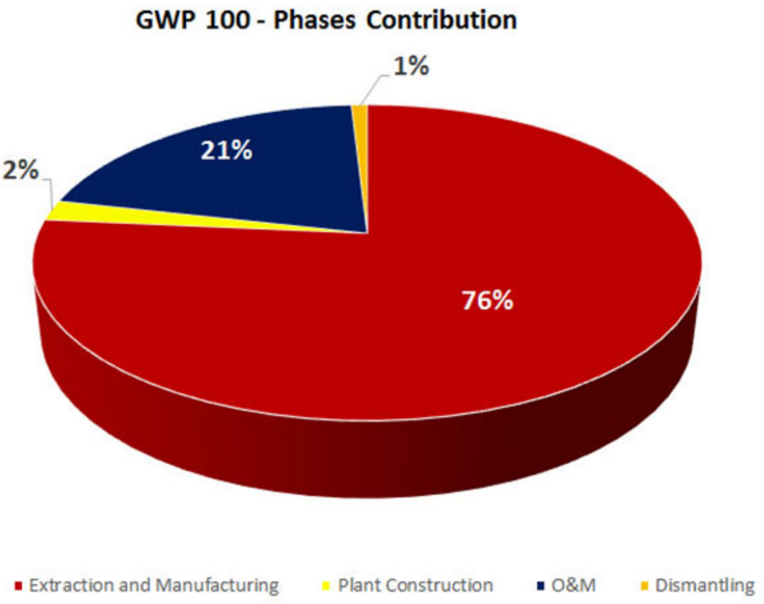

Figure 4.9.: GWP 100 phases contribution - PT plant with HTF heater

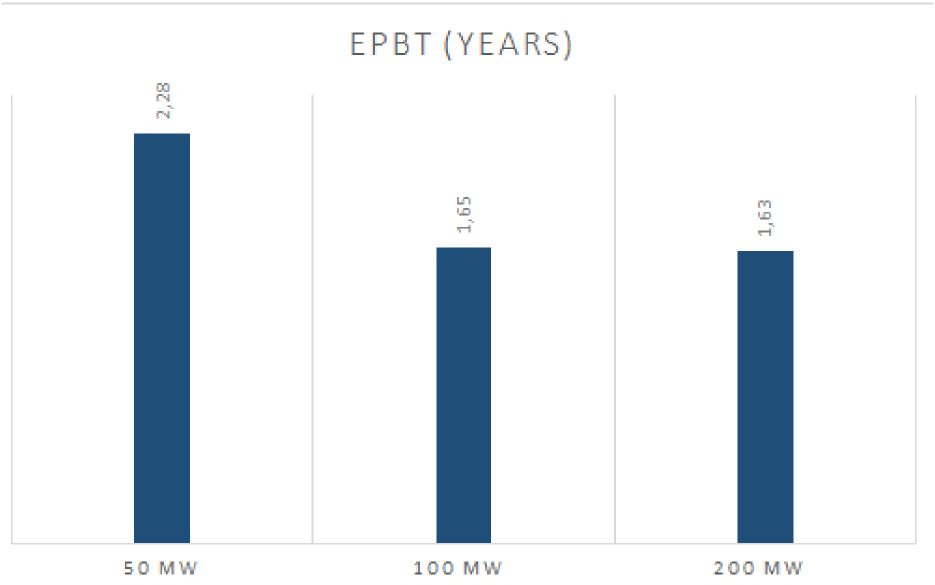

Figure 4.10.: Energy Payback Time of CT reference plants

4.4.3. Linear Fresnel Plants

Table 4.22.: Life cycle impacts of 30 MW LFR reference plant per kWhe

30 MW		
Impact category	**Reference unit**	**Result**
Acidification potential	kg SO2 eq/kWh el	1,17E-04
Climate change - GWP100	kg CO2 eq/kWh el	3,73E-02
Eutrophication	kg PO4 eq/kWh el	3,82E-05
Freshwater aquatic ecotoxicity	kg 1,4-DB eq/kWh el	1,76E-02
Human toxicity	kg 1,4-DB eq/kWh el	6,73E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq/kWh el	3,18E+01
Ozone layer depletion - ODP steady state	kg CFC-11 eq/kWh el	2,31E-09
Photochemical oxidation	kg ethylene eq/kWh el	8,65E-06
Terrestrial ecotoxicity	kg 1,4-DB eq/kWh el	2,09E-03

Table 4.23.: Life cycle impacts of 50 MW LFR reference plant per kWhe

50 MW		
Impact category	**Reference unit**	**Result**
Acidification potential	kg SO2 eq/kWh el	1,15E-04
Climate change - GWP100	kg CO2 eq/kWh el	3,68E-02
Eutrophication	kg PO4 eq/kWh el	3,77E-05
Freshwater aquatic ecotoxicity	kg 1,4-DB eq/kWh el	1,74E-02
Human toxicity	kg 1,4-DB eq/kWh el	6,66E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq/kWh el	3,13E+01
Ozone layer depletion - ODP steady state	kg CFC-11 eq/kWh el	2,21E-09
Photochemical oxidation	kg ethylene eq/kWh el	8,49E-06
Terrestrial ecotoxicity	kg 1,4-DB eq/kWh el	2,07E-03

Table 4.24.: Life cycle impacts of 100 MW LFR reference plant per kWhe

100 MW		
Impact category	**Reference unit**	**Result**
Acidification potential	kg SO2 eq/kWh el	1,07E-04
Climate change - GWP100	kg CO2 eq/kWh el	3,47E-02
Eutrophication	kg PO4 eq/kWh el	3,44E-05
Freshwater aquatic ecotoxicity	kg 1,4-DB eq/kWh el	1,62E-02
Human toxicity	kg 1,4-DB eq/kWh el	6,38E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq/kWh el	2,87E+01
Ozone layer depletion - ODP steady state	kg CFC-11 eq/kWh el	1,90E-09
Photochemical oxidation	kg ethylene eq/kWh el	7,64E-06
Terrestrial ecotoxicity	kg 1,4-DB eq/kWh el	2,00E-03

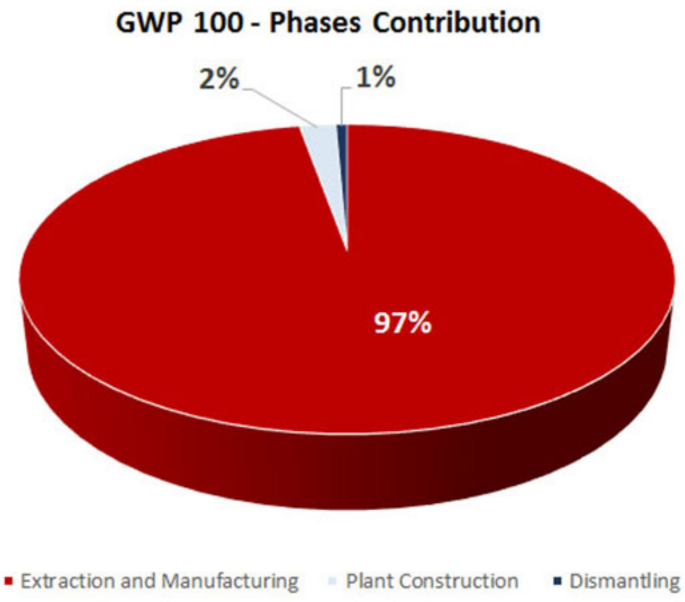

Figure 4.11.: GWP 100 phases contribution - PT plant with HTF heater

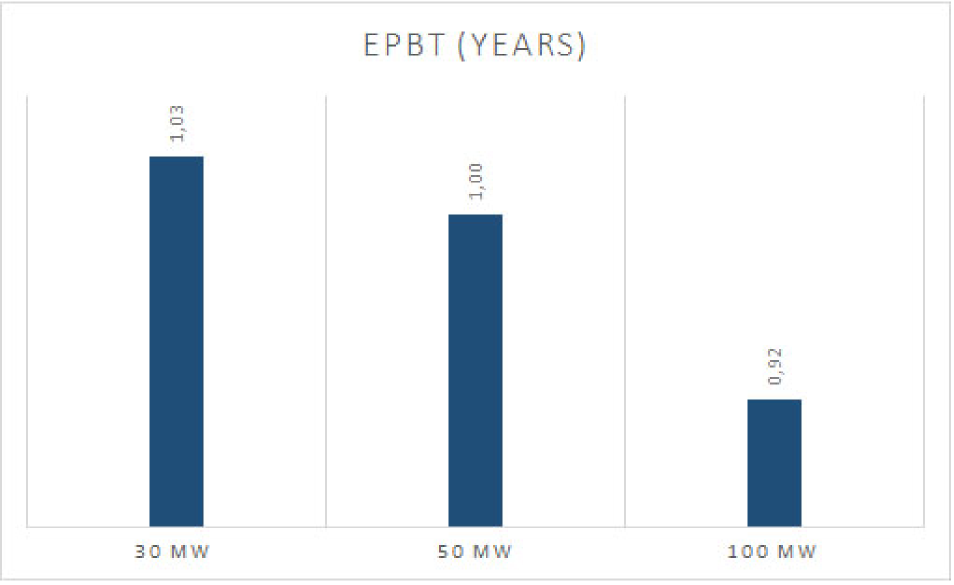

Figure 4.12.: Energy Payback Time of LFR reference plants

Chapter 5

Interpretation of Results

The Life Cycle Assessment presented in this study allowed for identifying the environmental critical issues of three different CSP technologies: parabolic trough, central tower and linear Fresnel. Furthermore, the ecological impact of using a natural gas backup system in PT plant, the effect of increasing the power scale and a sensitivity analysis of the DNI influence were detected.

From the obtained results seems that the technology with the best overall environmental profile cannot be identified. However, considering the GHG emissions for the scale with the lowest values (100 MW) and solar-only electricity generation case, central tower CSP has the lowest results ($22,7\ gCO2_{eq}/kWh_e$), followed by linear Fresnel ($34,7\ gCO2_{eq}/kWh_e$) and parabolic through ($46,9\ gCO2_{eq}/kWh_e$). Same considerations can be made from the evaluation of the three main pollutants considered in the LCI output values, as shown in figure 4.5.

Parabolic trough technology has the worst environmental performance probably due to the use of synthetic oil as heat transfer fluid. Not only the production of thermal oil increases the ecological impact of this technology, but even the necessary periodical replacement due to the aging processes and the possible leakages during the operation of the plant. Moreover, if natural gas HTF heater is employed for electricity generation, every impact category results higher and the GHG emission values triplicate (for example, from $46,9\ gCO2_{eq}/kWh_e$ to $152\ gCO2_{eq}/kWh_e$). Meanwhile, the results about LFR technology are highly influenced by the lower solar-to-electricity efficiency of this technology, which means higher solar field size for the same power rate and as a result higher impact of manufacturing and construction of collectors.

About the power rate influence, for all three technologies, the 100 MW scale results are the lowest. This power rate is the medium size for parabolic trough and central tower, but the large size for linear Fresnel. This outcome suggests that above a certain scale, the environmental impact of the plant increases more than its electricity production, at least for PT and CT, meanwhile, in LFR plant, biggest power rate could be an advantage. The reason for these different results could be related to the lack of heat transfer fluid and thermal energy storage system in LFR plant.

Phases contribution in GWP 100 graphs (see Figures 4.6, 4.7, 4.9 and 4.11) show that extraction of raw materials and manufacturing of components is the life cycle major contributor for every technology, except for the PT plant with HTF heater, where the O&M phase results prevalent due to the consumption of natural gas during the operation of the plant. For all the three technologies, dismantling and disposal phase have a small contribution to the impact categories.

In relation to the energy payback time, the LFR technology has the best result ($\sim$ 11 months), followed by CT ($\sim$ 19 months) and PT without HTF heater ($\sim$ 25 months). This highlight that LFR has the lowest consumption of primary energy, in addition, investment costs are lower than for parabolic trough projects and the land requirement is lower than for any other technology [30]. This evidence could be an incentive to further development of linear Fresnel plant, which is today the less commercially mature technology.

Compared to other LCA researches on CSP, reviewed in [22], the GHG emissions obtained in this study are lower than the mean value for PT and CT, but included in the statistical possible range. The GWP 100 result about Linear Fresnel plant is aligned with the only LCA available data from [18], bearing in mind that the comparison of different LCA studies could be misleading due to different considerations about the location of the plant, assessment methodology, and general assumptions. Discrepancies in the results could also be ascribed to the year of conduction of the study.

5.1. Comparison with fossil fuel competitors

For the comparison with other fossil fuel electricity production systems: nuclear, natural gas and hard coal power plants, Ecoinvent database was used for assessing the impacts. In particular, the production of high voltage electricity at a grid-connected nuclear boiling water reactor (BWR), in a conventional steam boiler natural gas power plant without CHP and in an average hard coal power plant in Spain were considered.

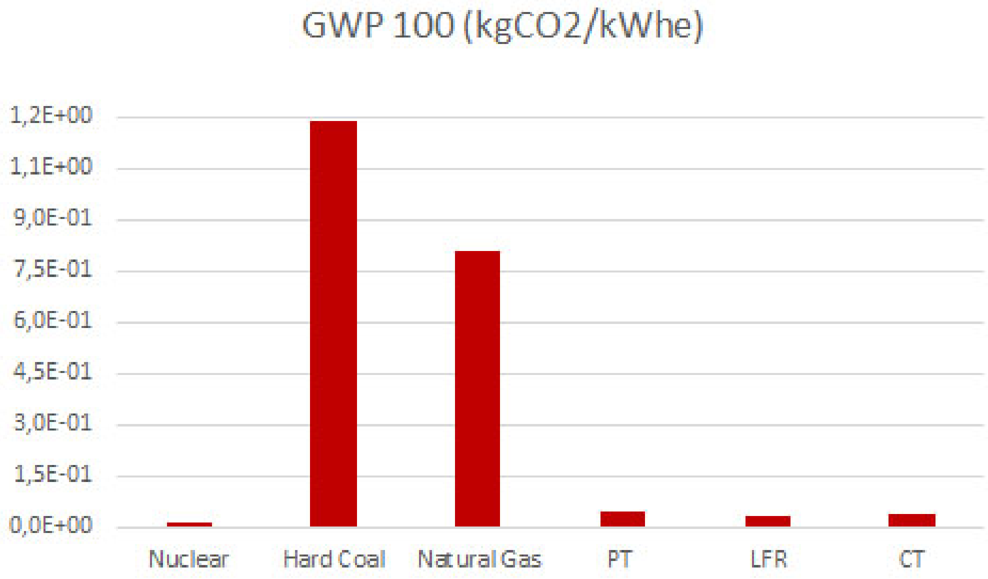

Figure 5.1.: GWP 100 comparison for other types of fossil fuel power plants

CSP electricity production has a clear advantage over hard coal and natural gas power plants for climate change, however the impact is higher than nuclear power. Indeed, these two technologies emit a small amount of greenhouse gasses during operation phase and the impact is mainly due to the construction, which is higher for CSP since it requires more material per kWh of electricity.

5.2. Sensitivity Analysis

The location of the plant has a significant influence on the LCA results. In order to detect the sensibility of the assessment to this parameter, a sensitivity analysis on the DNI was conducted. The irradiation has a direct effect on the power output of the plant and it was varied for each technology from 800 to 2400 $kWh/(m^2\ yr)$. The lower boundary corresponds to the irradiation in the northern Europe, above 50° N of latitude, whereas the upper boundary corresponds to the irradiation in the deserts of North Africa, below 30° N of latitude. Three main impact categories for every technology are involved in the sensitivity analysis: a global scale impact (GWP 100), a regional scale impact (Acidification Potential) and a local scale impact (Eutrophication).

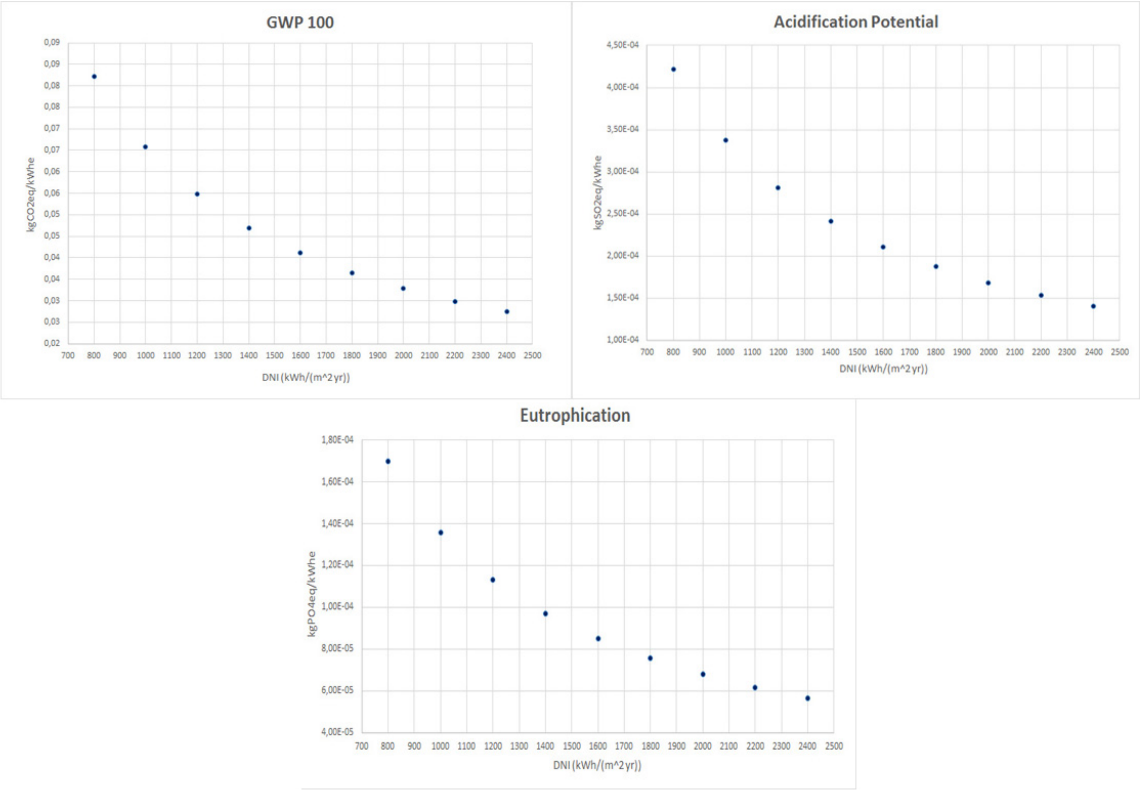

Figure 5.2.: DNI sensitivity analysis - PT plant

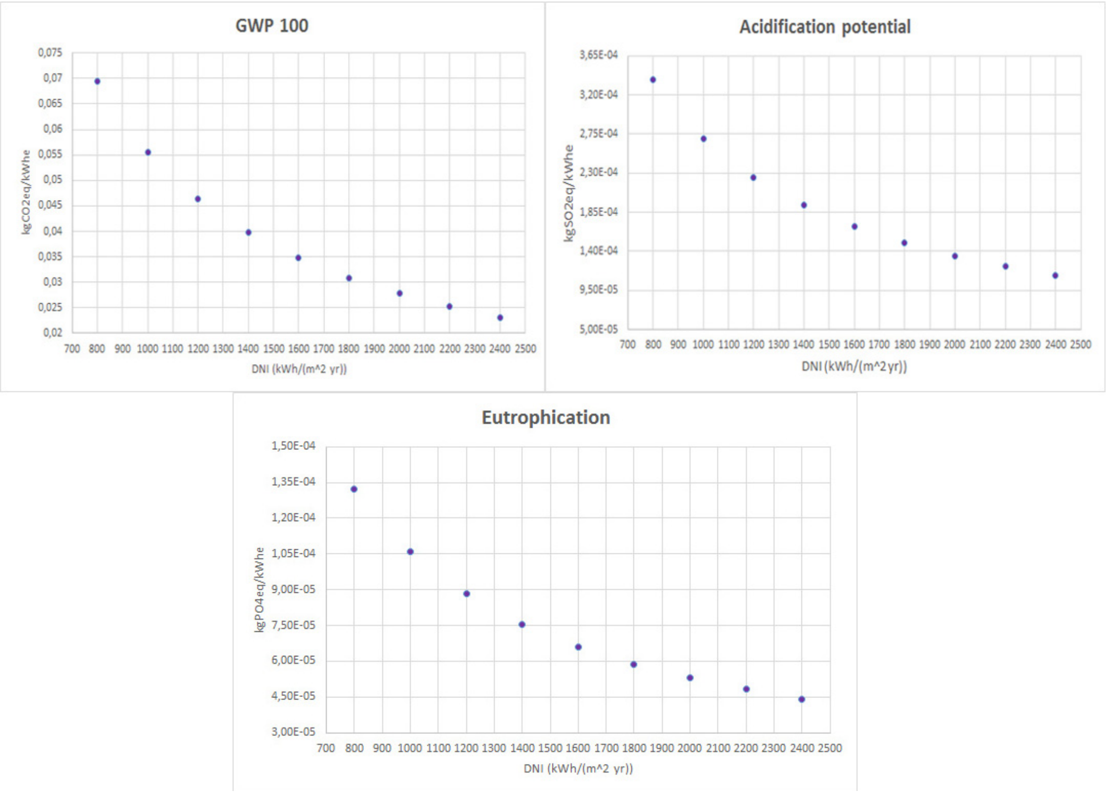

Figure 5.3.: DNI sensitivity analysis - CT plant

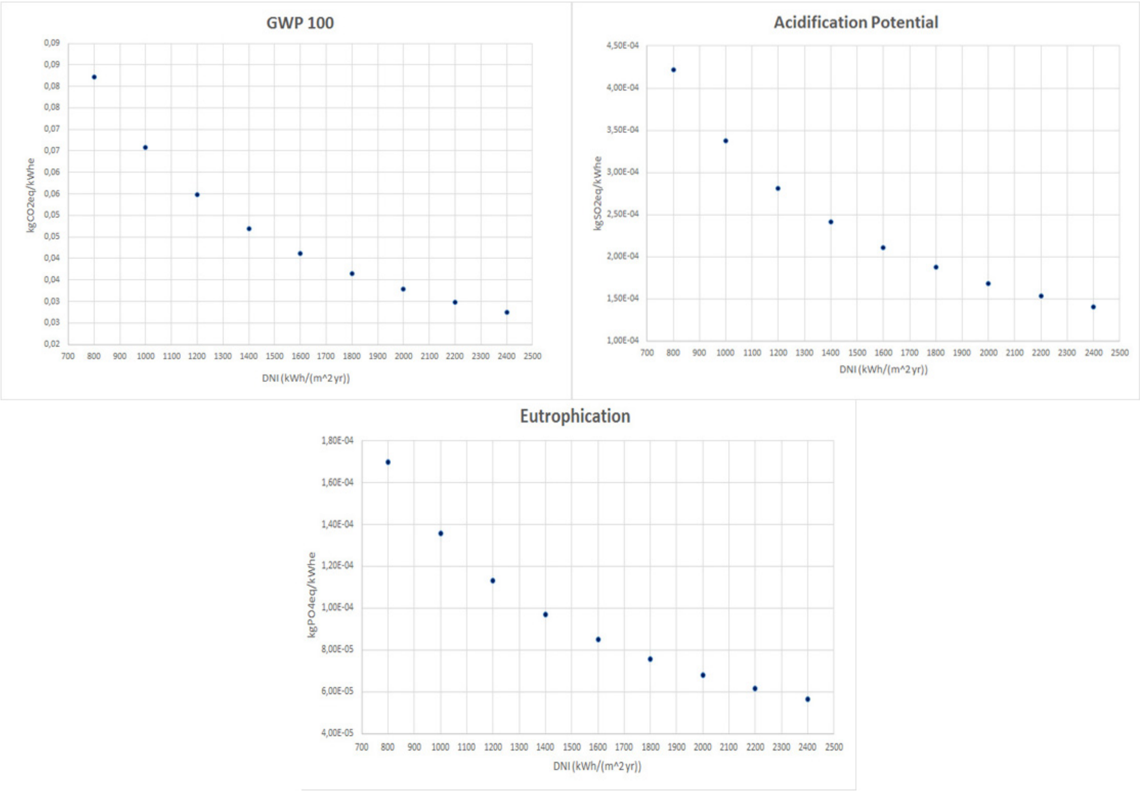

Figure 5.4.: DNI sensitivity analysis - LFR plant

The results of the sensitivity analysis are presented in Figures 5.2, 5.3 and 5.4. For all the three technologies the same trend can be identified: the impact results are three times higher in northern Europe than in North Africa, thanks to a greater electricity output. Moreover, the values are mainly influenced by the lowest DNI values, below 1600 $kWh/(m^2\ yr)$ the impact increase more rapidly, this suggests that the construction of CSP power plant above 44° N of latitude could be not only economically disadvantaged but even highly environmentally damaging. Even though they have different conversion efficiency values, a significant difference between the technologies cannot be evaluated from this sensitivity analysis.

Appendix A

Invetory Data

(a) Extraction and Manufacturing

Collectors		
Flat glass coated	2,81E+06	kg
Collector frame (reinforcing steel)	7,08E+06	kg
Foundation concrete	3,89E+03	m^3
Transport	5,63E+09	kg*km
Receiver		
Chromium steel	3,35E+05	kg
Anti-reflex coating	1,72E+04	m^2
Glass tube (borosilicate)	1,69E+05	kg
Transport	8,56E+08	kg*km
HTF system		
Syntethic oil	1,00E+06	kg
Diphenyl Ether (73,5%)	7,35E+05	kg
Biphenyl (26,5%)	2,65E+05	kg
Expansion vessel (reinforcing steel)	8,00E+04	kg
Cold Pipes (chromium steel)	1,89E+05	kg
Hot Pipes (chromium steel)	2,93E+05	kg
TES		
Oil-Salt heat exchanger (reinforcing steel)	4,80E+05	kg
Tanks		
Concrete	1,28E+04	m^3
Reinforcing steel	1,90E+06	kg
Rock wool	1,04E+04	kg
Salt	2,80E+04	t
Sodium nitrate	1,68E+04	t
Potassium nitrate	1,12E+04	t
Power Block (50MW)		
Chromium steel	1,62E+04	kg
Reinforcing steel	3,16E+06	kg
Concrete	5,13E+03	m^3
Aluminium	2,29E+05	kg
HTF heater		
Boiler (reinforcing steel)	7,66E+04	kg
Refractory	2,37E+05	kg

(b) Construction

Gravel	8,69E+06	kg
Pipe welding	9,57E+02	m
Tubes welding	4,04E+03	m
Excavation activities (digging)	5,05E+04	m^3
Filling activities	5,06E+04	m^3
Building machines consumes	8,80E+06	MJ

(c) Operation and Maintenance

Natural gas for HTF heater	6,76E+09	MJ
HTF replacement	1,00E+04	kg
Dyphenil Ether	7,35E+03	kg
Biphenil Ether	2,65E+03	kg
Natural gas anti-freezing	1,57E+08	MJ
Electricity from the Grid	5,00E+04	MWh
Mirror washing water	7,09E+08	lt
Steam cycle operation water	6,17E+08	lt

(d) Dismantling

Building machines consumes	8,80E+06	MJ

Table A.1.: 50 MW PT plant - Input Inventory

(a) Extraction and Manufacturing

Collectors		
Flat Glass Coated	5,63E+06	kg
Collector Frame (reinforcing steel)	1,42E+07	kg
Foundation Concrete	7,79E+03	m^3
Transport	1,13E+10	kg*km
Receiver		
Chromium steel	6,70E+05	kg
Anti-reflex coating	3,44E+04	m^2
Glass tube (borosilicate)	3,37E+05	kg
Transport	1,71E+09	kg*km
HTF System		
Syntethic oil	2,00E+06	kg
Diphenyl Ether (73,5%)	1,47E+06	kg
Biphenyl (26,5%)	5,30E+05	kg
Expansion vessel (reinforcing steel)	8,00E+04	kg
Cold pipes (chromium steel)	3,79E+05	kg
Hot pipes (chromium steel)	5,87E+05	kg
TES		
Oil-Salt heat exchanger (reinforcing steel)	4,80E+05	kg
Tanks		
Concrete	1,28E+04	m^3
Reinforcing steel	3,80E+06	kg
Rock wool	1,04E+04	kg
Salt	6,80E+04	t
Sodium nitrate	4,08E+04	t
Potassium nitrate	2,72E+04	t
Power Block (100MW)		
Chromium steel	2,59E+04	kg
Reinforcing steel	5,06E+06	kg
Concrete	8,21E+03	m^3
Aluminium	3,66E+05	kg
HTF heater		
Boiler (reinforcing steel)	1,33E+05	kg
Refractory	4,13E+05	kg

(b) Construction

Gravel	1,74E+07	kg
Pipe welding	1,56E+03	m
Tubes welding	8,08E+03	m
Excavation activities (digging)	1,01E+05	m^3
Filling activities	1,01E+05	m^3
Building machines consumes	1,76E+07	MJ

(c) Operation and Maintenance

Natural Gas for HTF heater	1,35E+10	MJ
HTF replacement	2,00E+04	kg
Dyphenil Ether	1,47E+04	kg
Biphenil Ether	5,30E+03	kg
Natural Gas Anti-Freezing	3,14E+08	MJ
Electricity from the Grid	1,00E+05	MWh
Mirror Washing Water	1,42E+09	lt
Steam Cycle Operation	1,23E+09	lt

(d) Dismantling

Building Machines Consumes	17600000	MJ

Table A.2.: 100 MW PT plant - Input Inventory

(a) Extraction and Manufacturing

Collectors		
Flat glass coated	1,13E+07	kg
Collector frame (reinforcing steel)	2,83E+07	kg
Foundation concrete	1,56E+04	m^3
Transport	2,25E+10	kg*km
Receiver		
Chromium Steel	1,34E+06	kg
Anti-reflex coating	6,87E+04	m^2
Glass tube (borosilicate)	6,74E+05	kg
Transport	3,43E+09	kg*km
HTF System		
Syntethic oil	4,00E+06	kg
Diphenyl Ether (73,5%)	2,94E+06	kg
Biphenyl (26,5%)	1,06E+06	kg
Expansion vessel (reinforcing steel)	2,40E+05	kg
Cold pipes (chromium steel)	7,58E+05	kg
Hot pipes (chromium steel)	1,17E+06	kg
TES		
Oil-Salt heat exchanger		
(reinforcing steel)	4,80E+05	kg
Tanks		
Concrete	3,08E+07	m^3
Reinforcing steel	7,60E+06	kg
Rock wool	1,04E+04	kg
Salt	1,65E+05	t
Sodium nitrate	9,90E+04	t
Potassium nitrate	6,60E+04	t
Power Block (200MW)		
Stainless steel (chromium steel)	5,18E+04	kg
Carbon steel (reinforcing steel)	1,01E+07	kg
Concrete	3,94E+07	m^3
Aluminium	7,32E+05	kg
HTF heater		
Boiler (reinforcing steel)	2,32E+05	kg
Refractory	7,19E+05	kg

(b) Construction

Gravel	3,48E+07	kg
Pipe welding	1,56E+03	m
Tubes welding	1,62E+04	m
Excavation activities (digging)	2,02E+05	m^3
Filling activities	2,02E+05	m^3
Building machines consumes	3,52E+07	MJ

(c) Operation and Maintenance

Natural gas for HTF heater	7,51E+10	MJ
HTF replacement	4,00E+04	kg
Dyphenil Ether	2,94E+04	kg
Biphenil Ether	1,06E+04	kg
Natural gas anti-freezing	6,28E+08	MJ
Electricity from the grid	2,00E+05	MWh
Mirror washing water	2,84E+09	lt
Steam cycle operation water	2,47E+09	lt

(d) Dismantling

Building machines consumes	3,5E+07	MJ

Table A.3.: 200 MW PT plant - Input Inventory

Table A.4.: Assumed densities of bulk materials

Stainless steel	8,03	g/cm^3
Borosilicate glass	2,23	g/cm^3
Therminol VP-1 (293°C)	828	kg/m^3
Therminol VP-1 (393°C)	709	kg/m^3
Concrete	2400	kg/m^3

(a) Extraction and Manufacturing

Collectors		
Solar Glass	5,86E+06	kg
Reinforcing Steel	1,31E+07	kg
Concrete	1,41E+04	m^3
Trasport	8,79E+09	kg*km
Tower		
Iron-nickel-chromium alloy	1,50E+04	kg
Coating Surface	3,38E+02	m^2
Concrete	5,15E+03	m^3
Reinforcing Steel	9,29E+05	kg
TES		
Molten Salt	2,15E+04	t
Sodium Nitrate	1,29E+04	t
Potassium Nitrate	8,61E+03	t
Chromium Steel	1,07E+07	kg
Concrete	1,15E+03	m^3
Hot pipes (Chromium Steel)	7,07E+03	kg
Cold Pipes (Chromium Steel)	6,89E+03	kg
Molten Salt HEX (Reinforcing Steel)	1,08E+06	kg
Power Block (50 MW)		
Aluminium	1,61E+05	kg
Concrete	3,18E+03	m^3
Reinforcing Steel	3,24E+06	kg
Chromium Steel	2,13E+04	kg

(b) Construction

Heliostat Foundation Excavation	1,41E+04	m^3
Tower Excavation	8,33E-02	m^3
Diesel for Construction	4,44E+07	MJ
Filling Activities	1,41E+04	m^3

(c) Operation and Maintenance

Mirror washing water	7,00E+05	m^3
Steam cycle operation water	8,99E+05	m^3
Molten Salt replacement	8,61E+02	t
Potassium Nitrate	3,44E+02	t
Sodium Nitrate	5,16E+02	t
Electricity from the Grid	3,07E+07	kWh

(d) Dismantling

Diesel for Construction	1,96E+07	MJ

Table A.5.: 50 MW CT plant - Input Inventory

(a) Extraction and Manufacturing

Collectors		
Solar Glass	1,17E+07	kg
Reinforcing Steel	2,62E+07	kg
Concrete	2,81E+04	m^3
Transport	1,76E+10	kg*km
Tower		
Iron-nickel-chromium alloy	3,01E+04	kg
Coating Surface	6,75E+02	m^2
Concrete	1,03E+04	m^3
Reinforcing Steel	1,31E+06	kg
TES		
Molten Salt	4,30E+04	t
Sodium Nitrate	2,58E+04	t
Potassium Nitrate	1,72E+04	t
Chromium Steel	1,90E+07	kg
Concrete	1,15E+03	m^3
Hot pipes (Chromium Steel)	1,00E+04	kg
Cold Pipes (Chromium Steel)	9,74E+03	kg
Molten Salt HEX (Reinforcing Steel)	2,16E+06	kg
Power Block (100 MW)		
Aluminium	2,57E+05	kg
Concrete	5,08E+03	m^3
Reinforcing Steel	5,18E+06	kg
Chromium Steel	3,41E+04	kg

(b) Construction

Heliostat Foundation Excavation	2,81E+04	m^3
Tower Excavation	2,16E-01	m^3
Diesel for Construction	8,87E+07	MJ
Filling Activities	2,81E+04	m^3

(c) Operation and Maintenance

Washing Water	1,40E+06	m^3
Steam Water	1,80E+06	m^3
Molten Salt Replacement	1,72E+03	t
Potassium Nitrate	6,89E+02	t
Sodium Nitrate	1,03E+03	t
Electricity from the Grid	6,13E+07	kWh

(d) Dismantling

Diesel for Contruction	3,91E+07	MJ

Table A.6.: 100 MW CT plant - Input Inventory

(a) Extraction and Manufacturing

Collectors		
Solar Glass	2,34E+07	kg
Reinforcing Steel	5,25E+07	kg
Concrete	5,63E+04	m^3
Transport	3,52E+10	km*kg
Tower		
Iron-nickel-chromium alloy	6,01E+04	kg
Coating Surface	1,35E+03	m^2
Concrete	2,06E+04	m^3
Reinforcing Steel	1,86E+06	kg
TES		
Molten Salt	8,61E+04	t
Sodium Nitrate	5,16E+04	t
Potassium Nitrate	3,44E+04	t
Chromium Steel	3,54E+07	kg
Concrete	1,15E+03	m^3
Hot pipes (Chromium Steel)	1,41E+04	kg
Cold Pipes (Chromium Steel)	1,38E+04	kg
Molten Salt HEX (Reinforcing Steel)	3,24E+06	kg
Power Block (200 MW)		
Aluminium	4,11E+05	kg
Concrete	8,13E+03	m^3
Reinforcing Steel	8,29E+06	kg
Chromium Steel	5,46E+04	kg

(b) Construction

Heliostat Foundation Excavation	5,63E+04	m^3
Tower Excavation	3,05E-01	m^3
Diesel for Construction	1,77E+08	MJ
Filling Activities	5,63E+04	m^3

(c) Operation and Maintenance

Washing Water	2,80E+06	m^3
Steam Water	3,60E+06	m^3
Molten Salt Replacement	3,44E+03	t
Potassium Nitrate	1,38E+03	t
Sodium Nitrate	2,07E+03	t
Electricity from the Grid	1,23E+08	kWh

(d) Dismantling

Diesel for Construction	7,82E+07	MJ

Table A.7.: 200 MW CT plant - Input Inventory

(a) Extraction and Manufacturing

Primary Reflectors		
Solar Glass	1,41E+06	kg
Steel Structure (reinforcing steel)	4,15E+06	kg
Concrete Foundation	1,88E+05	m^3
Transport	2,81E+09	kg*km
Receiver		
Stainless steel	1,86E+04	kg
Glass Tube (borosilicate)	6,07E+04	kg
Selective Coating	2,36E+03	m^2
Transport	1,75E+08	kg*km
Secondary Reflector		
Solar Glass	3,79E+04	kg
Transport	7,57E+07	kg*km
HTF System		
Cold pipes (reinforcing steel)	5,88E+04	kg
Hot pipes (chromium steel)	1,65E+05	kg
Steam Separator (cast Iron)	1,21E+06	kg
Steam Storage (chromium steel)	1,21E+06	kg
Power Block (30 MW)		
Stainless Steel (Chromium Steel)	1,08E+04	kg
Carbon Steel (Reinforcing Steel)	2,10E+06	kg
Concrete	3,41E+03	m^3
Aluminium	1,52E+05	kg

(b) Construction

Excavation	1,90E+05	m^3
Filling	1,88E+05	m^3
Diesel for construction	3,40E+06	MJ

(c) Operation and Maintenance

Mirror washing water	9,38E+06	lt
HTF (water)	4,77E+05	lt
Diesel for cleaner robot	1,50E+05	MJ

(d) Dismantling

Diesel for construction	3,40E+06	MJ

Table A.8.: 30 MW LFR plant - Input Inventory

(a) Extraction and Manufacturing

Primary Reflectors		
Solar Glass	2,34E+06	kg
Steel Structure (reinforcing steel)	6,91E+06	kg
Concrete Foundation	3,13E+05	m^3
Transport	4,69E+09	kg*km
Receiver		
Stainless steel	3,11E+04	kg
Glass Tube (borosilicate)	1,01E+05	kg
Coating Surface	3,93E+03	m^2
Transport	2,91E+08	kg*km
Secondary Reflector		
Solar Glass	6,31E+04	kg
Transport	1,26E+08	kg*km
HTF System		
Cold pipes (reinforcing steel)	9,80E+04	kg
Hot pipes (chromium steel)	2,75E+05	kg
Steam Separator (cast iron)	2,02E+06	kg
Steam Storage (chromium steel)	2,02E+06	kg
Power Block (50 MW)		
Stainless Steel (Chromium Steel)	1,62E+04	kg
Carbon Steel (Reinforcing Steel)	3,16E+06	kg
Concrete	5,13E+03	m^3
Aluminium	2,29E+05	kg

(b) Construction

Excavation Activities	3,16E+05	m^3
Filling Activities	3,13E+05	m^3
Diesel for construction	5,67E+06	MJ

(c) Operation and Maintenance

Mirror washing water	1,56E+07	lt
HTF (water)	7,95E+05	lt
Diesel for cleaner robot	2,49E+05	MJ

(d) Dismantling

Diesel for construction	5,67E+06	MJ

Table A.9.: 50 MW LFR plant - Input Inventory

(a) Extraction and Manufacturing

Primary Reflectors		
Solar Glass	4,69E+06	kg
Steel Structure (reinforcing steel)	1,38E+07	kg
Concrete Foundation	6,25E+05	m^3
Transport	9,38E+09	kg*km
Receiver		
Stainless steel	6,22E+04	kg
Glass Tube (borosilicate)	2,02E+05	kg
Coating Surface	7,85E+03	m^2
Transport	5,82E+08	kg*km
Secondary Reflector		
Solar Glass	1,26E+05	kg
Transport	2,52E+08	kg*km
HTF System		
Cold pipes (reinforcing steel)	1,96E+05	kg
Hot pipes (chromium steel)	5,50E+05	kg
Steam Separator (cast iron)	4,04E+06	kg
Steam Storage (chromium steel)	4,04E+06	kg
Power Block (100 MW)		
Stainless Steel (Chromium Steel)	1,08E+04	kg
Carbon Steel (Reinforcing Steel)	2,10E+06	kg
Concrete	3,41E+03	m^3
Aluminium	1,52E+05	kg

(b) Construction

Excavation	6,32E+05	m^3
Filling	6,25E+05	m^3
Diesel for construction	1,13E+07	MJ

(c) Operation and Maintenance

Mirror washing water	3,13E+07	lt
HTF (water)	1,59E+06	lt
Diesel for cleaner robot	4,99E+05	MJ

(d) Dismantling

Diesel for construction	1,13E+07	MJ

Table A.10.: 100 MW LFR plant - Input Inventory

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