



**Environmental and economic  
analysis of renewable energy  
producing systems with a focus  
on wooden towers as components  
of wind-solar systems  
-The Dali PowerTower case study-**

---

*Anca Stoica*  
2014

**Environmental Studies**  
Master thesis 30 ECTS  
Lund University



# Environmental and economic analysis of renewable energy producing systems with a focus on wooden towers as components of wind-solar systems

-The Dali PowerTower case study -

Anca Stoica

2014

**Master thesis 30 ECTS, Lund University**

Intern supervisor: Andrius Plepys, IIIIEE, Lund University

Extern supervisor: Sigvald Harryson, InnoVentum AB





# Abstract

This paper aims at assessing the economic features and the environmental impact of a wooden tower used in wind-solar renewable energy generating systems. The life cycle assessment method and return on investment method were used in order to achieve the objectives of the study.

Two types of towers were used in the analysis: an impregnated wooden tower and an untreated one. Besides wood, the tower is composed of steel parts. The life cycle assessment results show that the impregnated wooden tower has a lower potential environmental impact due to increased durability compared with the untreated one. Another important result is that steel manufacturing process and usage of German electricity grid mix represent the hot spots of both analysed systems. The results are sensitive regarding assumed transportation distances.

The economic assessment highlights the fact that a positive return on investment could be obtained in cases when the wind-solar system covers at least 62% of household's energy need. The return on investment results are also sensitive at input variables' values and a specific case calculation is recommended.

# Glossary of terms and abbreviations

GaBi	The applied Product System Modelling Software
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ReCiPe	The applied LCIA method
ALO	Agricultural land occupation [m <sup>2</sup> a]
CC	Climate change [kg CO <sub>2</sub> equivalents]
FD	Fossil depletion [kg oil equivalents]
FET	Freshwater ecotoxicity [kg 1.4 DB-equivalents]
FE	Freshwater eutrophication [kg P equivalents]
HT	Human toxicity [kg 1.4-DB equivalents]
IR	Ionising radiation [kg U235 equivalents]
MET	Marine ecotoxicity [kg 1.4-DB equivalents]
ME	Marine eutrophication [kg N equivalents]
MD	Metal depletion [kg Fe equivalents]
NLT	Natural land transformation [m <sup>2</sup> ]
OD	Ozone depletion [kg CFC-11 equivalents]
PMF	Particulate matter formation [kg PM <sub>10</sub> equivalents]
POF	Photochemical oxidant formation [kg NMVOC]
TA	Terrestrial acidification [kg SO <sub>2</sub> equivalents]
TET	Terrestrial ecotoxicity [kg 1.4-DB equivalents]
ULO	Urban land occupation [m <sup>2</sup> a]
WD	Water depletion [m <sup>3</sup> ]

# Table of Contents

1. Introduction .....	1
1.1. Introduction to InnoVentum .....	1
1.2 Objectives of the study .....	4
2. The analytical frame of the thesis and method .....	6
2.1. Life Cycle Assessment .....	6
2.2. Return on energy .....	13
2.3. Return on investment (ROI) .....	14
2.4 Method.....	14
3. Previous research .....	16
4. The Life Cycle of the wooden tower .....	19
4.1. The stakeholder network and the supply chain .....	19
4.2. Dali PowerTower System description .....	20
5. Results .....	25
5.1. Life cycle analysis .....	25
5.2. Return on energy .....	26
5.3. Return on investment (ROI) .....	27
6. Discussion.....	30
7. Conclusions .....	33
Appendix A. ....	39
Appendix B. ....	41
Appendix C. ....	44
Appendix D.....	58





# 1. Introduction

The issue of energy production and consumption affecting the environment is more acute due to higher targets in economic growth rates. On this background, an increased number of countries has already started climate mitigation programmes. As people understand the amplitude of their environmental impact, they are expected to reconsider their options for energy supply and to shift towards renewable energy. Taking the example of past catastrophes such as typhoon Hayan in 2013, which affected the Philippines to such an extent that even several months later the people did not have access to electricity, it can be argued that small-scale energy producing systems should gain more importance in a country's climate change strategy. For this reason, it is important that individuals are provided with information on the advantages offered by small-scale renewable electricity production. One way of producing small-scale clean energy is by using wind turbines that in some cases can form hybrid systems when solar panels are attached to the tower of the wind turbine.

Throughout the previous research it can be observed that all wind turbines had the tower made out of steel or concrete and all analysis had as case study this kind of systems. Sustainable manufactured wood-based products become more and more requested by consumers, retailers and even governments (Gonzales-Garcia, *et al.*, 2011). Developed countries adopt stricter regulations regarding the environmental impact of products during their life-time especially concerning the ways of producing the products (Gonzales-Garcia, *et al.*, 2011).

Nowadays there are few companies that produce the tower out of wood. One of them is InnoVentum AB, a Scandinavian small-scale wind turbine manufacturer, founded in May 2010 with headquarters located in Malmö. InnoVentum's products will be further analysed from an environmental and economic point of view.

## 1.1. Introduction to InnoVentum

### 1.1.1. History and vision

InnoVentum has as goal to provide environmental friendly solutions for renewable energy production at household level (InnoVentum AB, 2014a). The concept of small-scale and decentralized wind energy production started to gain shape for Sigvald Harryson, management consultant and university professor, 7 years ago. Being a passionate sailor, he began to combine his both interests and in year 2000 he installed solar panels on his sailboat. The energy produced was not enough to secure independence from the shore power and while on sea again he discovered that

the energy produced by a small 400-watt wind turbine was enough for a modern, well-equipped 14 m sailing yacht.

In 2008 Sigvald Harryson installed a small wind turbine on his new boat and furthermore this inspired him to establish InnoVenum. If the wind turbine was able to produce enough energy for his boat, small-scale wind turbines could be a solution even for households. After 2 years of market research and product performance he decided to build InnoVentum AB (InnoVentum AB, 2014b).

InnoVentum was established on the 5th of May 2010. Up till now InnoVentum has 10 installations in Sweden and 2 outside Sweden (InnoVentum AB, 2013a).

### 1.1.2 The InnoVentum concept

InnoVentum is a company within the renewable energy sector. It offers both small-scale wind turbines and hybrid solutions. The company builds the towers while the wind turbines and solar panels are supplied by external companies. When building the towers, Innoventum uses wood from managed forests (Daligault, 2014).

InnoVentum has 2 ranges of wind turbines and hybrid solutions: Dali range – smaller wind turbines with a rated power between 1,5 and 3,5 kW and larger wind turbines with a rated power between 11 and 50 kW (InnoVentum AB, 2014c). Innoventum's systems are modularized which makes it easier to transport and assembly them. Another environmental friendly characteristic would be the fact that some of the wooden towers are self-erecting which makes the use of trucks and cranes unnecessary (InnoVentum AB, 2014d).

There are some other companies manufacturing wooden wind turbine towers such as TimberTower in Germany (Timbertower, 2014) and Canadian Timber Structures (Canadian Timber Structures, 2014), but they offer big scale wind systems. Innoventum is the only small-scale wind turbine provider who uses wooden towers (Innoventum AB, 2014e).

By using wood from human-managed forests several advantages could potentially be attained:

- CO<sub>2</sub> could be captured and stored. Wood represents a “carbon sink” because during its lifetime a tree captures and stores CO<sub>2</sub> (CEI-BOIS, 2011).
- carbon sources could be reduced. Each cubic meter of wood saves a total of 2 tons of CO<sub>2</sub>. Every cubic meter of wood used instead of other building materials reduces CO<sub>2</sub> emissions by an average of 1.1 ton CO<sub>2</sub> (CEI-BOIS, 2011).
- managed forests are more efficient carbon sinks than forests which are left in a natural state. On the one hand younger trees absorb more CO<sub>2</sub> than mature trees and in the other hand mature trees

will eventually die and rot. When rotting the stored CO<sub>2</sub> will be returned to the atmosphere. By using wood from managed forests, the CO<sub>2</sub> could continue to be stored throughout the life of the resulting wood product (CEI-BOIS, 2011).

Most of the towers for wind systems are produced nowadays from steel. Steel production is energy intensive and associated with high levels of CO<sub>2</sub> emissions. The primary energy requirements to produce 1 metric ton of stainless steel from virgin materials are 79 GJ and the production releases 5.3 tons CO<sub>2</sub>. If recycled materials are used taking into consideration the global average operations of the stainless steel, 33% less energy is necessary and CO<sub>2</sub> emissions are 32% lower (3.6 tons). If only scrap would be used, currently not possible due to limited scrap availability energy use would be 67% less than virgin-based production and CO<sub>2</sub> emissions would reach 1.6 tons (Johnson, *et al.*, 2008). Thus high levels of CO<sub>2</sub> emissions are reached even when producing assemblies from recycled steel.

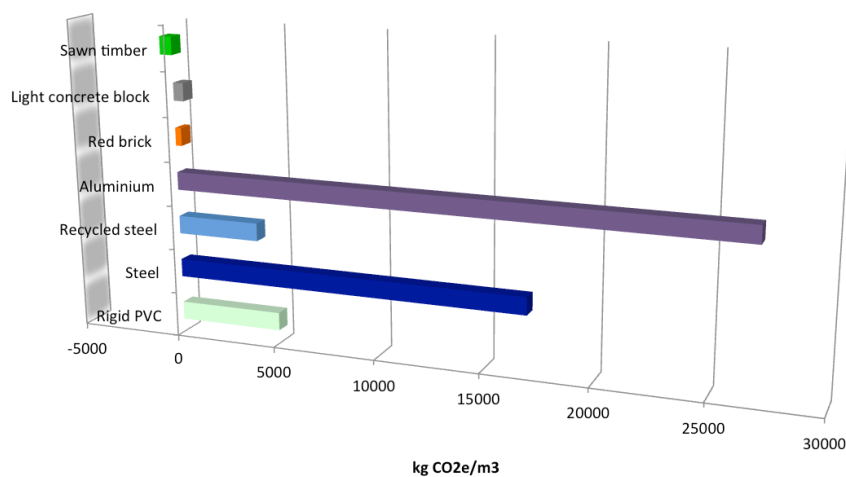


Figure 1. Net emissions of CO<sub>2</sub> (including carbon sink effect) from the production processes of different materials (CEI-BOIS, 2011)

### 1.1.3 Wooden towers offered by InnoVentum

In order to identify and map the life cycle of the wooden towers offered by Innoventum, a good understanding of its function and of the context the company activates in has to be reached. Innoventum's wooden towers have a double function: tower for the wind turbine and support for the solar panels (see Picture 1 in Appendix A). Both functions will be considered because even though the solar panels do not cover a big area the energy produced by them represents 15% out of the total energy produced by the system and cannot be excluded.

Innoventum has developed different designs for wooden towers used in systems for wind and sun energy. There are four types of towers: the Dali range with towers of 10, 12 and 16 m, the Dalifant

which has 20 m, the tower for the Endurance - Cash Cow which has a height of 24 or 36.5 m and the Giraffe with a height of 8 or 12 m. The hybrid solutions consist of the Dali PowerTower and the Giraffe. The focus of this thesis will be on the Dali PowerTower, which is a Dali tower with metal supports for the solar panels. This type of tower was chosen because it is targeting households.

All the solutions can be manufactured from two types of wood: impregnated Swedish pine or untreated Swedish pine. The difference between these two types of raw material lies in product durability and end of life stages. Impregnated timber pine has a higher level of durability, which determines a service life of 50 years (Daligault, 2014) while untreated timber pine has a service life of 20 years (Highley, 1995). The difference between end of life stages will be addressed later when the PowerTower system will be described.

The impregnated Dali Power Tower is composed of:

- Swedish pine
- bolts
- washers
- nuts
- wood screws
- welded metal plates (feet and top metal connection - pipe to generator not included)
- metal foundation screws
- glue
- wood preservatives (Daligault, 2014).

## 1.2 Objectives of the study

This thesis seeks to reveal a part of the information that both individuals and policy makers need to know when taking decisions related to small-scale energy production. According to Fleck and Huot (2009) the information on the environmental impact is relevant in the case of small-scale wind power because this technology aims at being an environmental friendly energy source. Besides finding out how much environmental friendly this technology is, it is also important to understand the return on energy and on investment associated with the implementation of this system. This economic assessment could play a significant role in determining the accessibility of this technology to potential users (Fleck and Huot, 2009). Therefore, this study will be based on a Life Cycle Analysis (LCA) and a return on investment calculation for InnoVentum's tower that is specifically designed for households.

The paper tries to answer the following research questions:

1. What is the potential environmental impact of the impregnated wooden tower and of the untreated wooden tower?
2. What is the return on energy for the impregnated wooden tower and for the untreated wooden tower?
3. What is the return of investment of the complete small-scale system?

## 2. The analytical frame of the thesis and method

### 2.1. Life Cycle Assessment

The interest in tackling climate change, the acknowledgement of existing environmental impacts and that natural resources are finite determined the development of several methodologies to assess and quantify the environmental impact of different processes and products (Wenzel, *et al.*, 1997). One of these methods is the Life Cycle Assessment (LCA) which is defined as: “An assessment method that quantifies all of the environmental consequences (i.e. on the natural environment, human health, and natural resources) of a product or service, considering its entire life cycle” (ISO 14040, 2006).

LCA was chosen as analytical framework of this thesis, as it provides a methodology to quantify the environmental performance of the wooden tower by having as raw material impregnated wood and untreated wood. The LCA methodology is used to answer the first two research questions of this thesis:

1. What is the potential<sup>1</sup> environmental impact of the impregnated wooden tower and of the untreated wooden tower?
2. What is the return on energy of the Dali PowerTower?

A life cycle is defined as a quantum of processes through which a product passes: extraction of raw materials, manufacturing, transportation, packaging, use and different end of life scenarios.

An example of a product's life cycle is illustrated in Figure 2.



Figure 2: Example of a product's life cycle

This thesis follows the life cycle assessment methodology as presented in ISO 14040 and ISO 14044 standards and the ILCD handbook which is in its turn based on the procedure described in the ISO 14040/14044 standards (ILCD, 2010).

---

<sup>1</sup> The term potential is used because an LCA doesn't contain precise time and location where the resources are extracted and emissions occur. The actual environmental impact cannot be obtained (Baumann and Tillman 2004 cited in Moberg, 2010).

By using the LCA perspective the environmental performance of new materials such as wood could be highlighted and furthermore the potential environmental impacts of wood prepared in different ways can be compared. The opportunities of product improvement are identified as analysing the product at different moments in its life cycle.

LCA is an appreciated research tool by many professionals in the industry field. Just as any other tool, LCA is not hidden of criticism. The critics have brought to attention several LCA limitations. The main limitation of any LCA is high subjectivity and uncertainty because of lack of access or data availability, data and result interpretation as well as choice of boundaries made while conducting an LCA. Time limitation together with other resources' constraints, are other factors that could influence the LCA results. This paper is characterized by all the mentioned factors since the current study is scheduled as a Master thesis research.

The LCA methodology framework is defined as an iterative process, which consists of four phases;

1. Goal and Scope definition
2. Life Cycle Inventory analysis (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Life Cycle Interpretation (ISO 14040 2006).

The four phases of the LCA methodology are summarized in Figure 3. The iterative process is represented by the double arrows, which express that the phases are constantly reviewed and updated during the study.



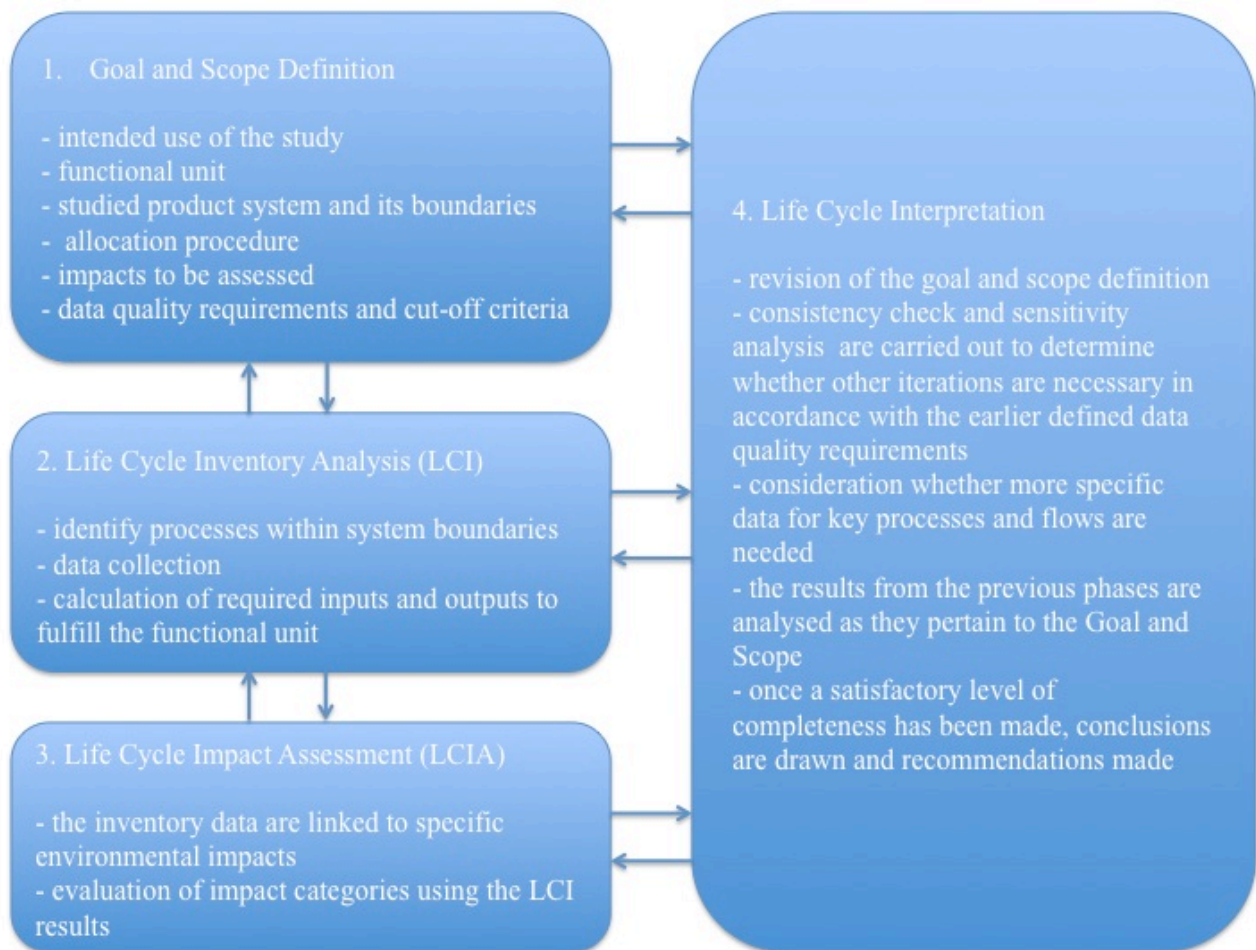


Figure 3. The four phases in an LCA study, based on the ISO 14040-14044 standards, as summarized by Hellmann (2013)

### 2.1.1. The Goal and Scope of the study

The thesis uses the LCA methodology in order to investigate the environmental profile of a product, InnoVentum’s wooden tower. The intended audience consists of university professors and students at master level since the study represents a master thesis.

“The functional unit is the quantified performance of a product system, used as a reference unit” (ILCD 2010 cited in Hellmann 2013:21).

The Swedish average household electricity consumption was obtained from Statistics Sweden and it equals 12400 kWh/year (12.4 MWh/year) (SCB, 2013). The properties of the various wind turbines and solar panels are presented in Table 2, B. The functional unit of this study is the delivery of 12400 kWh/year-produced electricity for a period of 50 years. The period of 50 years is chosen because the life-time of the impregnated tower is 50 years according to InnoVentum.

The reference flow is defined as the needed number of wooden towers, which can be combined with an appropriate wind turbine and solar panels giving the necessary electrical energy for a Swedish average household during a year. Considering the fact that the analysed products have different service lives, 50 years and 20 years, two reference flows are used. A Dali PowerTower can provide around 9000 kWh/ year and the average Swedish electricity consumption is 12400- kWh/year, then the functional flow for the system with a service life of 50 years will be 1.38 wooden towers. For the other system the reference flow is 3.44 wooden towers.

The analysed environmental impacts are climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), freshwater ecotoxicity (FET), human toxicity (HT), fossil depletion (FD), ionising radiation (IR), marine ecotoxicity (MET), marine eutrophication (ME), metal depletion (MD), particulate matter formation (PMF), photochemical oxidant formation (POF), terrestrial ecotoxicity (TET) and water depletion (WD).

There is one omitted impact category, natural land transformation due to data gaps and this represents an uncertainty of the study.

### 2.1.2. System Boundaries and cut off criteria

In the present study two types of models were constructed. In order to evaluate the environmental profile and to identify the influencing key parameters of the wooden tower, the entire life cycle of the tower is modelled. Figure 4 outlines the system boundaries of the LCA for the wooden tower.

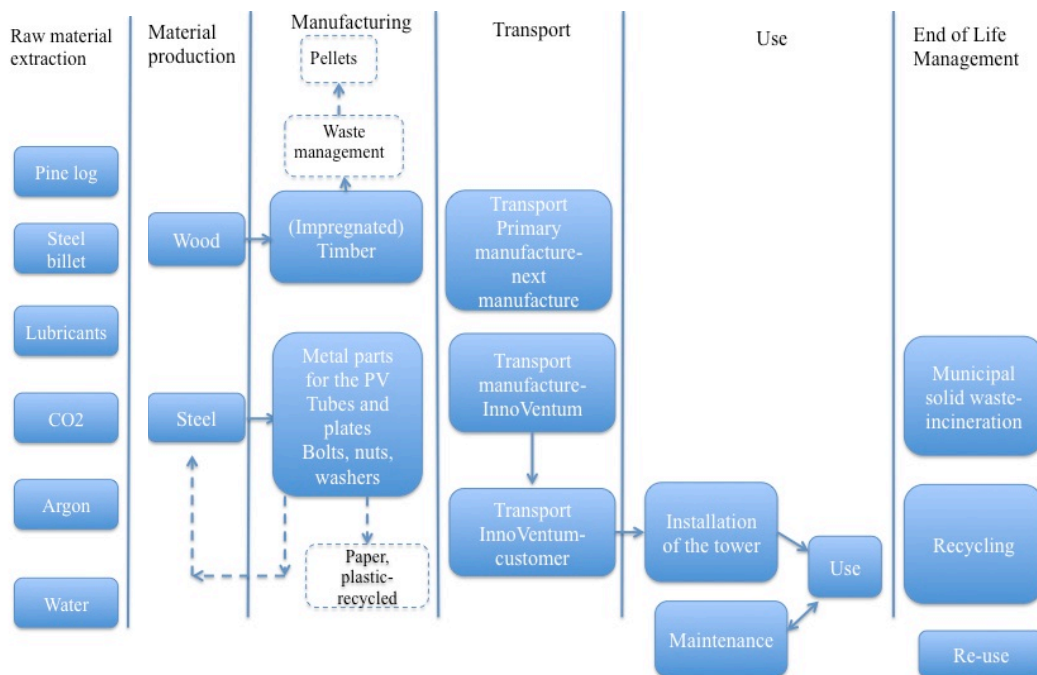


Figure 4. Outlining of the system boundaries of the LCA for the wooden tower (own source)

This LCA focuses on the wind-solar systems used in the Swedish market, thus the geographic boundary is Sweden. In terms of temporal boundaries this study covers a period of 7 years. It is believed that this time frame is enough to uncover the primary environmental effects associated with the wind-solar system and to realistically deal with the changing nature of tower technologies. Tower technologies do not have a rapid changing nature. The biosphere boundary is represented by initial system inputs CO<sub>2</sub>, water, argon, and outputs such as emissions to air, water or soil. The techno-sphere boundaries start with raw material acquisition and end with end of life management stages.

Several cut off criteria were used in the study:

- all the parts of the system that contribute with less than 5 % to the overall weight were excluded: packaging materials. Packaging material was not included in the model because according to the interview information only small amounts of plastic foil and wood is used and it was assumed that the package would weigh less than 5% of the total system mass (see Picture 2 in Appendix A).
- due to unavailable data two components of the impregnation solution, polyethyleneamine (<20% of the impregnation solution) and organic acid (<5% of the impregnation solution) were excluded. The liquid used for maintenance was excluded as well due to the same reason.
- due to data gaps the consumed electricity in manufacturing the nuts, bolts and screws was not included
- transportation to customer was not taken into account since the customer can be located at different distances from InnoVentum but sensitivity analysis was conducted related to different transportation distances.
- the electricity for putting in place the nuts and screws was not taken into account since it has a very low value of around 1.1 kWh.

### 2.1.3. Life-Cycle Inventory

Life-cycle inventory (LCI) represents the accounting of material and resource inputs and outputs for the life cycle of a system (Kozak, 2003). The environmental burdens measured in this case study include material input requirements, total energy consumed, air and water emissions, and total solid wastes associated with the product's life-cycle. The complete LCI list can be found in Table 1, Appendix B.

LCI data was collected for individual model elements of the system. Table 1 in Appendix B

describes the methods for collecting LCI data and presents LCI results for the product system.

The inventory data came from interviews and from the database of the used software. High quality data are essential to make a reliable evaluation. Data for the study were collected from different sources. The inventory data for the wooden and steel parts consist of on-site measurements. Other inventory data were obtained from GaBi databases. LCI data were updated with respect to the study's functional unit and 50-year time frame. No allocation procedure was used.

#### 2.1.4. The Life Cycle Impact Assessment (LCIA) method

The ReCiPe Life Cycle Impact Assessment (LCIA) was used during the study. ReCiPe represents an advanced LCIA methodology, which was engineered in order to help calculating life cycle impact category indicators (Blaser, *et al.*, 2012, ReCiPe 2013).

The main objective of the ReCiPe is to reduce the LCI results list in order to obtain more accurate impact category indicators. ReCiPe returns results at two levels: midpoint level and endpoint level (Goedkoop, *et al.*, 2012, ReCiPe, 2014).

ReCiPe comprises two sets of impact categories with associated sets of characterisation factors. Eighteen impact categories are addressed at the midpoint level. At the endpoint level, most of these mid-point impact categories are further converted and aggregated into three endpoint categories. Both mid-point and end-point categories are exemplified in Figure 5 (page 12).

Impact categories should highlight concerns of direct environmental relevance. For example, waste is not an impact category, but the generated effects of waste processing should be included in the used method regarding its effects on, for example, climate change, toxicity and land-use.

The midpoint can be defined as the place where mechanisms common to several substances are taken into account. For example, acidification comprises different steps, starting with the release of acidifying substances and ending with impacts on ecosystems. In a certain place along this pathway the acidifying substances have an effect on soil's properties. This place represents the midpoint. Other acidifying substances follow different pathways before the midpoint is reached, but after this point they follow the same pathway. Modelling the impacts beyond the midpoint is characterized of uncertainty (ReCiPe, 2014). Characterisation at the endpoint level models the impact on human health, on the natural environment and on natural resources (LC-Impact, 2014).

The Society of Environmental Toxicology and Chemistry (SETAC) (Fava, *et al.*, 1993) categorizes three major stages of LCIA:

- 1) Classification – the process of data correlation from inventory studies to various impact categories (e.g. ecosystem, human health, and natural resources).
- 2) Characterization – using specific impact assessment models in order to estimate the qualitative and/or quantitative impact potential for every category.
- 3) Valuation – assigning the relative values and/or weights to impacts.

The first two stages are viewed as mandatory stages of an LCIA while valuation stage is less developed (ISO 1996). Hence the first two stages are presented below and used in this study (Kozak, 2003:100).

Figure 5 contains 18 different midpoint impact categories. They form together the midpoint level. The figure summarizes the relation between the midpoint impact categories, endpoint damage categories and the single score.

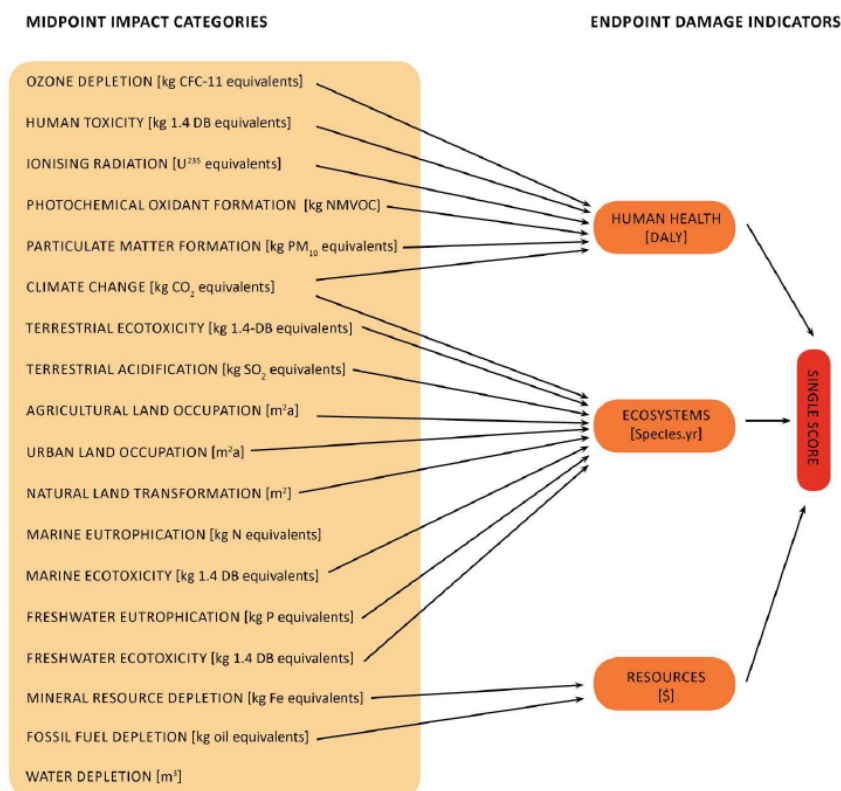


Figure 5. The relation between the midpoint impact categories, endpoint damage categories and single score in ReCiPe 2008 taken from Hellmann (2013)

The high number of applied assumptions leads to increased levels of uncertainty at the endpoint level. Another reason of uncertainty is that the environmental mechanisms are composed of a multitude of different effects, which further are grouped in only 3 types of impacts: ecosystem,

human health and resources (ReCiPe, 2014). The single score also known as weighted index (Bengtsson, *et al.*, 2012) is without dimension (Heijungs, *et al.*, 2002). In LCA the single score is not a mandatory element and is characterized as a process of translating the various impact categories by individual perception of importance (ISO 14044, 2006).

In order to obtain a single value for the total environmental impact, it is pursued to weigh the various environmental impacts relative to each other. Weighting is not mandatory and it is based on expert panels, monetisation or so-called distance to target methods (Baumann and Tillman, 2004). Because there is no consensus on how to perform the weighting (Finnveden, 1997) it is not favoured by ISO 14044 (2006) “weighting, shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public”. In many cases researchers choose to ignore this advice and offer comparisons characterized of high degree of subjectivity. This study stops therefore before valuation and the concept of weighting will not be further developed because it is not in the scope of this study.

## 2.2. Return on energy

Return on energy shows the relationship between the energy requirements over the whole life cycle of the tower (manufacturing, installation, use and dispose) versus the electrical energy output of the wind turbine and solar panels that can be attached to the tower.

The payback period is expressed in months and it measures the length of period in which wind-solar system could produce the energy used during the whole life cycle of the tower. The following equations adapted after Garrett and Rønde (2012) are used:

$$\text{Energy payback (months)} = \frac{\text{life cycle energy requirement for the tower (MJ)}}{\text{annual electrical energy output of the renewable energy producing system (MJ)}} \times 12 \text{ months}$$

$$\text{Return on energy} = \frac{\text{service life of the wind – solar system (months)}}{\text{energy payback (months)}}$$

The primary energy requirement for the whole life cycle of the tower is divided by the electrical energy output from the wind plant in order to obtain the energy payback. This approach accounts for the efficiency of the electricity power stations when determining the primary energy. The return on energy offers indications on how much time the tower should be used as a component of the whole system in order for the system to produce the energy requirements during the whole life cycle of the tower.

## 2.3. Return on investment (ROI)

Return on investment represents the economic and time measure of the payback of the wind system. Return on investment is a concept from the business world used for decision-making within industrial and corporate activities. In order to measure the ROI one has to compute the benefits of the investment and compare them with the costs generated by the investment. Both aspects are expressed in monetary terms. The ROI can be calculated via the expression (Moonen, 2003):

$$\text{Net benefits} = \text{Total benefits} - \text{Costs}$$

## 2.4 Method

The study was carried out with the help of the modelling software system GaBi 6.0. Education. GaBi is an intensively used LCA tool developed by PE international<sup>2</sup> (PE International, 2014). GaBi 6.0 Education includes fully functional GaBi software with an extensive database. GaBi Databases contain more than 70 000 life cycle inventory profiles and presents the largest internally consistent LCA databases. The metadata documentation of the data sets in GaBi Databases follows the recommendations of the "International Reference Life Cycle Data System" (ILCD) Entry Level Conformity Rules of the European Commission's European Platform on Life Cycle Assessment (PE International, 2014).

The potential impacts were computed by using the Life Cycle Impact Assessment (LCIA) method. ReCiPe 2008 was applied to calculate and analyse the investigated potential impacts.

The return on investment (ROI) calculation used in this thesis includes the following cost variables: the amortisation of the system, annual cost of consumed energy, interest rates if money is acquired through a bank loan, electricity prices and service costs during the lifetime of the system. The variables forming the total benefit are: annual produced energy, received incentives, yearly savings of electricity supply.

As an incentive for renewable energy production, Swedish Government funds up to 35% of the investment costs for solar panels. Moreover, renewable electricity producers can register for el-certificate (Energimyndigheten, 2014a). The el-certificate can be obtained by both private

---

<sup>2</sup> A working group in the field of Life Cycle Assessment and Life Cycle Engineering (PE International, 2014)

individuals and juridical entities that own a grid connected renewable energy producing system. The certificate is calculated based on the produced electricity. For 1 MWh the producer receives one el-certificate which can be sold (Energimyndigheten, 2014b).

Four ROI scenarios were modelled. An excel calculation was developed based on InnoVentum's return on investment mode. All the excel calculations can be accessed from a public folder and its location is presented in the reference list under the name ROI 2014.. All the assumptions will be presented in the results part of the thesis before each modelled scenario. The models are adapted to Swedish market conditions. No existing return on investment models for wind turbine systems was found and, therefore, no model comparison was possible.



### 3. Previous research

Analysis conducted on wind turbines have a long history, researchers primary focusing their studies on the return on energy, starting year 1977, (Kubiszewski, *et al.*, 2010) and continuing with LCAs of different wind systems or comparing wind systems with other energy sources (Price and Kendall, 2012).

Kubiszewski *et al.* (2010) review and synthesize 50 different analyses on net energy return<sup>3</sup> for electric power generation by wind turbines. In their research, they examine 119 wind turbines ranged from 0.0003 to 7.2 MW. They distinguish between assumptions, system boundaries and methodological approach. The average energy return on investment (EROI) for all studies is of 25.2. The result shows that in terms of return on energy wind turbines are better than fossil fuels (EROI=8), nuclear (EROI=15.8), and solar power generation technologies (EROI=6.5) (Kubiszewski, *et al.*, 2010).

As acknowledged by Price and Kendall (2012) LCAs for wind turbines have one of the following goals: comparing two sizes of wind turbine (e.g. Crawford 2009; Lee and Tzeng, 2008); comparing wind energy to other renewable energy sources (e.g. Varun, *et al.*, 2009); and sensitivity analysis of a parameter other than turbine size, such as transport distance (e.g. Tremeac and Meunier, 2009) on life cycle performance.

The energy used in order to manufacture and use a wind turbine system is considered to be recovered in only a number of months (Crawford, 2009). Thus the energy produced during a lifetime of 20 years can be many times greater than the one embodied in their production. If manufacturing the tower from alternative materials such as wood which is less energy intensive than steel and concrete (Johnson, *et al.*, 2008) would possibly reduce both the significance of the environmental impact from the manufacturing stage and faster recover the energy used in the manufacture stage.

Crawford (2009) analyses two wind turbine systems: an 850 kW wind turbine and a 3 MW wind turbine. The foundation for the turbines is made of 480 t concrete respectively 1140 t concrete, 15 t steel vs. 36 t steel and the tower is made of 69.07 t steel respectively 158.76 t steel. The results show that the tower makes up the next largest proportion of the embodied energy of the large

---

<sup>3</sup> Energy return on investment (EROI) is the ratio of energy delivered to energy costs (Kubiszewski, *et al.*, 2010).

turbine (25%). In the case of the smaller turbine, the tower reaches 18% of the embodied energy (Crawford, 2009).

Fleck and Huot (2009) conduct a life-cycle assessment in order to compare the environmental impacts and net-energy inputs an off-grid small wind turbine system (rated power of 400 W and a 1.17 m rotor diameter) and a single-home diesel generator system. The main analysed impacts were emission of greenhouse gases (GHG) including CO<sub>2</sub>, methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) over a twenty-year period. The small-scale wind power system was highlighted as giving a considerable environmental benefit. The wind generator system offered a 93% reduction of GHG emissions when compared to the diesel system (Fleck and Huot, 2009).

The main contributor to the environmental impacts appears to be the production phase of the turbine (Zhong, *et al.*, 2011). An important issue with previous studies is that they do not take into consideration all the life-cycle phases. According to Zhong *et al.* (2011) a study of 72 LCAs found that the manufacturing phase is analysed in all of them, only 70% take into consideration the installation phase, even a lower percentage respectively, 56% included maintenance and a very low percentage, 19%, took into consideration the decommissioning phase. The main reason of not including the decommissioning and disposal phase is lack of good data.

Garrett and Rønde (2012) studied a Vestas 2-MW GridStreamer and included in their assessment: raw materials, production of all parts, manufacturing (including over 100 global production factories for casting, machining, tower production, generator production, nacelle assembly and blades production, sales and servicing activities), transport stages, wind plant installation and erection, servicing, replacement parts and operations, use-phase electricity generation, and end-of-life treatment. For all life cycle stages excluding end-of-life the results show that the nacelle, tower and site parts (primarily site cables) have the most significant impact for all impact categories. Turbine foundation and blades have the most significant contribution. The primary contributor to the global warming potential indicator is the manufacturing stage with the production of the tower (25-30%), site cables (20%), nacelle (15%), blades (10-15%) and foundations (10%) (Garrett and Rønde, 2012).

No LCA studies could be found on wind systems with a wooden tower. Bolin and Smith (2011) conducted a cradle-to-grave LCA for a (penta)-treated wooden utility pole of 14 m length and a weight of 5956 kg. This type of pole is used for electricity distribution and transmission, and telecommunications. The authors have mainly used data from published sources. Indicators such as GHG, fossil fuel use, acidification, water use and ecological toxicity have lower values for penta-

treated poles than for concrete and steel poles. The eutrophication values are almost equal for the steel and wooden pole and higher for the concrete pole. The smog impact from penta-treated poles is greater than the smog impact from both concrete and steel poles (Bolin and Smith, 2011).

Regarding analysis on wood, different wooden products have been the focus in several LCAs. Some examples could be the production of wood-based products such as wood floor coverings (e.g. Nebel, *et al.*, 2006; Petersen and Solberg, 2003), particleboards (e.g. Rivela, *et al.*, 2006), hardboards (e.g. González- García *et al.*, 2009) and related wood items such as window frames (e.g. Asif, *et al.*, 2002; Richter and Gugerli, 1996), walls (e.g. Werner, 2001) and furniture (e.g. Taylor and van Langenberg, 2003) (González-García, *et al.*, 2011). In the early beginnings of environmental impacts assessments of wooden products the focus was on energy consumption in the production processes (Boyd, *et al.*, 1976; Ressel, 1986 cited in González-García, *et al.*, 2011).

The impact of different forestry systems and transport of wood could have an important environmental impact. Therefore, it should be included in the LCAs boundaries. However, some of the studies on production of wooden products have not analysed in detail the raw material production or they have turned to databases in their analysis. González-García *et al.* (2009) identified and compared the environmental burdens from forest operations in Sweden and Spain focused on pulpwood production and supply to pulp mills. The results of the study showed that logging operations and secondary hauling were the hot spots in both case studies. The Swedish case presented lower energy requirements and lower contributions to global warming potential, eutrophication potential and acidification impact categories.

Previous research is diverse when focusing on both wind systems and wooden products. From all the presented studies it can be concluded that wind power systems and wooden products have a better environmental profile than their alternatives. Moreover wind power systems present better energy return on investment than other energy producing systems (Kubiszewski, *et al.*, 2010). Conducting an environmental assessment on the wooden tower for the wind-solar system is of great relevance in this mentioned context. An important finding would be that all the studies are characterised by uncertainty due to not taking into account certain important operations mainly because of data gaps.

## 4. The Life Cycle of the wooden tower

### 4.1. The stakeholder network and the supply chain

Many different actors are involved in producing, distributing and selling the parts for the PowerTower. They all form the supply chain (Hellmann, 2013) of InnoVentum. In order to analyse and highlight where in the life cycle and supply chain hot spots exist, the relevant stakeholders are illustrated in Figure 6. This will allow to find out where environmental improvements could be implemented (McAloone and Bey, 2009, Wang, *et al.*, 2011).

Both the material and money flows are outlined in order to give a proper image on the relationship between the stakeholders and InnoVentum.

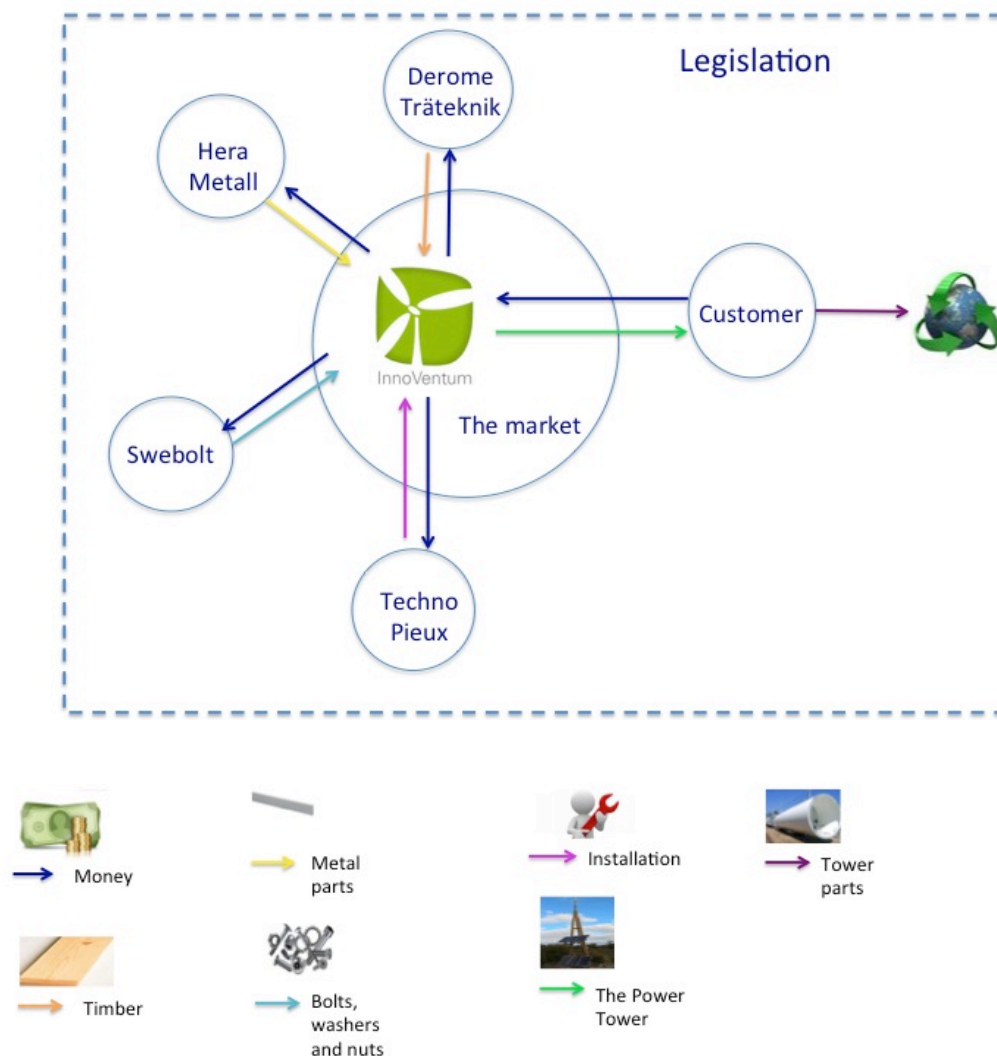


Figure 6. Main involved stakeholders in the network surrounding InnoVentum connected through the money and materials flows (own source).

## 4.2. Dali PowerTower System description

The Dali Power Tower system is a 12 m tall, 3-legged wooden tower with 8 photovoltaic panels (2 kWp mounted on the side and a 3.5 kW wind turbine mounted on top of the tower. The combined wind and solar annual energy production at wind speed of 12 m/s is around 9000 kWh out of which 1900 kWh are produced by the photovoltaic panels (InnoVentum AB, 2014f). The product systems being analysed in this study includes only the Dali PowerTower (see Picture 1, Appendix A).

As previously stated a typical LCA explores environmental impacts across several life cycle stages such as: raw material acquisition; material processing; product manufacture and assembly; use, maintenance; end of life management. In order to facilitate modelling, these boundaries can be modified (Kozak, 2003). Thus, the scheme used in this study investigates six separate life cycle stages: raw material acquisition, distribution of raw materials and products, parts manufacturing, assembly, use and end-of-life management. Maintenance is not included due to data gaps.

### Raw material acquisition

A PowerTower for a wind power system is composed of (impregnated) timber, metal parts used as support for the solar panels, nuts, screws and washers, and bolts used for foundation. The material acquisition and production stage include the following processes: forestry; steel manufacturing; CO<sub>2</sub>, argon, water and lubricants acquisition.

Most of the timber further used in the manufacturing process comes from managed forests in South of Sweden within a range of 250km (Lindqvist, 2014). Timber represents a renewable resource from the perspective that managed forests would be able to give wood in the future. Solid wood presents several physical and aesthetic properties that make it the most resourceful material in the construction and furniture industry (Gindl, *et al.*, 2003). A favourable mass/strength ratio, low thermal conductance, biodegradability and neutral carbon dioxide balance are just few of wood's positive characteristics. In order to diminish negative properties such as dimensional instability with changing moisture content, low natural durability of many species or unsatisfying mechanical properties, controlled chemical modification is used (Gindl, *et al.*, 2003). Moreover wood has as environmental advantage the fact that it is extracted with relatively little energy and in the same time it absorbs carbon dioxide through photosynthesis (PEFC, 2014).

Pine, also called redwood, is among the most common and cultivated coniferous tree in Europe and Russia. It is used for both indoor (furniture, door and window frames and doors) and outdoor constructions (roof constructions, fences, decks and towers). Outdoor uses are considered more

feasible if the pine is previously impregnated. The impregnation process can use different wood preservatives (Nordic Timber Export, 2014). In the case of Dali PowerTower, the used wood is pressure impregnated with Tanalith E. Tanalith E is water based wood preservative. When impregnated into the timber the preservative components bond with the wood structure and cannot easily be removed (Lonza, 2014). Tanalith is considered better than intensively used creosote based solutions from several health issues points of view: it doesn't affect the skin of workers nor leach during the service time of the wooden product (Arch Timber Protection, 2011). The timber for the tower contains wood preservatives in value of 8.0 kg/m<sup>3</sup> sapwood (Lindqvist, 2014).

The pine timber used by Derome Träteknik is PEFC (Programme for the Endorsement of Forest Certification) certified which is a proof that the wood comes from a sustainable managed forestry (Derome Träteknik AB, 2014a).

The definition of sustainable forestry used by PEFC is the one adopted in 1993 within Forest Europe 1993. The definition has been further developed with new criteria and indicators (Derome Träteknik AB, 2014b). The definition for sustainable forest management is:

*The sustainable forest management represents the management and use of forests and forest lands in such a way, and at such a pace that their biodiversity, productivity, regeneration capacity, vitality and ability, both now and in the future, relevant ecological, economic and social functions at local, national and global levels is preserved, without damaging other ecosystems.*<sup>4</sup>

The electricity required by the life cycle of the wooden tower is represented by the Swedish electricity grid mix. The steel used for all the parts of the system is assumed to be 85% virgin steel and it is produced partly in Canada and partly in Germany where is locally used in the manufacturing of nuts, screws, washers. Information on mass and transportation distances is presented in Table 1 in Appendix B.

#### Manufacturing Stage

The manufacturing phase for the PowerTower system involves several manufacturing processes: timber manufacturing, metal parts manufacturing and bolts manufacturing.

Tower's wooden pieces are manufactured by Derome Träteknik located in Scania region and the

---

<sup>4</sup> Original definition: Med uthålligt skogsbruk menas förvaltning och nyttjande av skog och skogsmark på ett sådant sätt, och i en sådan takt att dess biologiska mångfald, produktivitet, förnyingskapacitet, vitalitet och förmåga att både nu och i framtiden fylla viktiga ekologiska, ekonomiska och sociala funktioner på lokal, nationell och global nivå bevaras, utan att andra ekosystem skadas (Derome Träteknik AB, 2014b).

impregnation plant is Woodtech located in Varberg, 19 km away from Derome. It is a fully automatic pressure-impregnation plant. The energy used to produce one cubic meter of impregnated wood is 0.006 MWh/m<sup>3</sup> sawn timber and it is represented by electricity grid mix of Sweden (Lindqvist, 2014). Metal parts, bolts, washers, nuts and screws are the rest of the components of a wooden tower.

The metal parts for the photovoltaic panels are manufactured by Hera-Metall located in Prenzlau near Berlin, Germany. The primary materials for the manufacturing process are obtained from a local distributor/steel manufacturer called Thyssen Krupp, located in a range of 150 km (Michaelis, 2014). The energy used in order to manufacture the metal parts is assumed to be German electricity grid mix.

The bolts, washers, nuts and screws are provided by SWEbolt, a Swedish company located in Jönköping and Stockholm County. Due to data gaps the electricity used in their manufacturing is not taken into consideration in this study.

The metal foundation screws are provided by Techno Pieux, the company that also secures the installation of the tower. The primary material is Canadian steel, which is further transformed into steel tubes and plates. This material is made by the Canadian steel mill King, located in Hamilton, Ontario, Canada and delivered to:

- Acier Nova, located in LaSalle, Québec, Canada in order to manufacture the tubes
- Megantic Metal, located in Thetford Mines, Québec in order to manufacture the plates. Megantic Metal is the regional distributor and the steel supplier of Techno Pieux (Pelletier, 2014).

The energy used in manufacturing the screws is assumed to be New Zealand's electricity grid mix due to data unavailability on Canadian electricity grid mix. New Zealand appeared to be closest as electricity grid production type having around 52% of the electricity produced from hydroelectric sources while Canada has around 58% (The World Bank, 2014). Another reason is the existence of data on electricity grid mix for New Zealand in GaBi database.

#### Distribution Stage

After manufacturing, all the components are delivered to InnoVentum's warehouse and finally to the customer where the installation takes place.

Additional environmental burdens are associated with the production and disposal of components packaging. The packaging for the tower consists of a wooden and carton boxes and plastic folia are not taken into consideration because they represent less than 5% out of the total system and no data was available.

The components of the wooden tower are distributed from InnoVentum's warehouse in Malmö. The wood processed in Söderport goes directly to InnoVentum's warehouse in Malmö and it is transported by truck. The metal is coming from Prenzlau by road to Copenhagen and then to Malmö by boat. Due to missing data on the boat transportation all the transport is assumed to be made by truck. Metal screw for foundation is travelling from Canada to Techno Pieux's warehouse, and then goes directly to client's site (not passing through InnoVentum's warehouse). Boltings come from Sweden SWEbolt to Malmö by truck (Daligault, 2014).

### Assembly

The installation is secured by Techno Pieux. The electricity requested for welding during installation is produced by a generator on diesel (Pelletier, 2014).

As the tower can be erected without crane, InnoVentum uses only manpower to do assembly and erect the tower. Electricity is used to charge batteries of automatic bolt machine of 3.3 ampere hour and it is used for 1 hour and 30 minutes (Daligault, 2014).

### Use phase

During the use phase the necessary maintenance consists of applying a wood saturator every 5 years. InnoVentum recommends as saturator Textrol-Owatrol based on fish oil and it is not a mandatory process for the impregnated tower (Daligault, 2014). For the other type of the tower it is not known if any saturator is needed.

### End of Life Stage

The decommissioning is done by using only manpower. End-of-life burdens include the management of the wooden and metal parts composing the tower at the end of the service life.

As previously presented two models for the Dali PowerTower were developed. The first model covers the life cycle of an impregnated tower while the second model of an untreated wooden tower. Besides the fact that the model for the impregnated Dali Power Tower differs from the untreated tower from the points of view of included materials and energy, it also differs from the point of view of end-of-life management.

For both models the metal parts are managed by the municipality as waste for recovery. The wooden parts for the untreated Power Tower are recycled by the municipality. In the case of the impregnated Power Tower the wood is managed by the municipality. First the municipality or the waste management company has to make an analysis to check the type of solution the wood was impregnated with. In the case of the PowerTower because it is impregnated with a water-copper



based solution it is not classified as hazardous waste and it can be incinerated (IVL, 2013).

## 5. Results

### 5.1. Life cycle analysis

#### Impregnated Dali Power Tower

This study considers several environmental impacts to be investigated. This information is relevant since wind turbine systems are considered environmental friendly energy sources. Diagrams for all the impact categories can be found in Appendix C. All the results are presented at mid-point impact level as presented in the scope of the study. The results represent the impact of 1.38 wooden towers needed in a system able to generate the average Swedish electricity consumption at household level in one year for a period of 50 years.

The impregnated PowerTower presents burdens in all the impact categories except freshwater ecotoxicity where it has almost no impact. From the climate change point of view the tower has a total impact of 1297 kg CO<sub>2</sub> eq. The extraction and processing of steel both in Canada and in Germany are the hot spot of the entire life cycle. The electricity mix used in manufacturing the metal parts in Germany is highlighted as hot spot in the chain. Regarding terrestrial acidification, the manufacturing of the steel billet has highest impact, followed by the acquisition of pine log.

In categories targeting toxicity, steel again comes first followed by the German energy mix production and argon production. Argon appears as having the biggest impact also on ozone and water depletion and comes third in fossil depletion. The eutrophication potential of the tower is generated mainly by the production of the steel. Neither the impregnation material, the energy used in the impregnation process nor the waste management represents hot spots in the life cycle of the tower.

#### Untreated Dali PowerTower

The results represent the impact of 3.44 untreated wooden towers needed in a system able to generate the average Swedish electricity consumption at household level in one year for a period of 50 years. As previously stated the difference in the number of towers is due to the shorter service life of an untreated tower.

The impact on climate change from using 3.44 untreated wooden towers is in total 3223 kg CO<sub>2</sub> eq. where steel is the hot spot of the chain followed by the German electricity grid mix production. As well as for the impregnated PowerTower, the manufacturing of the steel billet has highest impact on terrestrial acidification, followed by the acquisition of pine log. For the rest of the impact

categories, the hot spots of the untreated wooden tower are the same as for the impregnated wooden tower.

### Comparison between the two types of tower

When it comes to comparing the total of each midpoint impact category of the two Power Towers it can be highlighted the model with untreated wood has higher possible impacts than the model with impregnated wood. Even though the wood is impregnated, by using a smaller number of impregnated Power Towers during a life cycle of 50 years leads to smaller impacts than the ones generated by the untreated towers. The durability gained through impregnation makes the tower more environmental friendly due to an increased service life. Even though the impregnation solution contains different chemicals it is classified as new generation solution and it does not make the wood environmentally dangerous. Therefore it is easier to be managed as waste and incinerated in normal conditions in order to produce energy.

## 5.2. Return on energy

The calculation of the return on energy is made in the following way:

$$\text{Energy payback (months)} = \frac{\text{life cycle energy requirement for the tower (in MJ)}}{\text{annual electrical energy output of the renewable energy producing system (in MJ)}} \times 12 \text{ months}$$

$$\text{Return on energy} = \frac{\text{service life of the wind – solar system (months)}}{\text{energy payback (months)}}$$

In the case of the impregnated Power Tower the energy payback equals:

$$\text{Energy payback (months)} = \frac{28\,503.41 \text{ MJ}}{32\,400 \text{ MJ}} \times 12 \text{ months} = 10.56 \text{ months}$$

An energy payback of 10.56 months may be interpreted that using the impregnated wooden tower as support for the wind turbine and solar panels will generate a payback period of minimum 10.56 months for the entire system. This is the minimum payback period because energy requirements for the wind turbine and solar panels will add to the energy requirements of the tower while the electrical output will remain the same.

In the case of the untreated Power Tower the energy payback equals:

$$\text{Energy payback (months)} = \frac{28\,341.36 \text{ MJ}}{32\,400 \text{ MJ}} \times 12 \text{ months} = 10.49 \text{ months}$$

The energy payback of the untreated tower is almost the same as the one of the impregnated Power Tower. This highlights the fact that wood impregnation does not have a big impact on the return on energy.

The interpretation of the return on energy of the system during its service life is not possible because the energy used in the life cycle of the other components is not known. It can be stated that the entire system can give maximum 57 times more energy than it consumed over its life cycle.

### 5.3. Return on investment (ROI)

Four scenarios of return on investment have been modeled: a scenario in which the wind-solar system receives subsidy from the Government in form of el-certificates/investment support and the power plant generates the maximum level of electricity according to its specifications, a scenario where no el-certificates/investment support are received and the maximum generated electricity level is used, a third model with el-certificates/investment support received and with a lower level of electricity generated by the plant and a final model with no el-certificates/investment support and lower produced electricity level.

All the input data for the ROI computation can be found in Appendix D. The price used in computations is the one for the impregnated tower system because the untreated wooden system was not produced until now and no price is known. The average electricity consumption at household level has the same value as the one used in the life cycle analysis, 12 400 kWh/year.

Table 1. Types of scenarios

<p><b>Scenario 1.</b> El-certificate/governmental support + maximum level of generated electricity (9000 kWh/year)</p>	<p><b>Scenario 2.</b> No el-certificate/governmental support + maximum level of generated electricity (9000 kWh/year)</p>
<p><b>Scenario 3.</b> El-certificate/governmental support + lower level of generated electricity (7000 kWh/year)</p>	<p><b>Scenario 4.</b> No el-certificate/governmental support + lower level of generated electricity (7000 kWh/year)</p>

Table 2. Summary electricity production vs. consumption at household level (%)

Scenario 1	73%
Scenario 2	73%
Scenario 3	56%
Scenario 4	56%

Table 3. Summary Accumulated net after 20 years (SEK)

Scenario 1	245 903
Scenario 2	65 956
Scenario 3	149 525
Scenario 4	-37 500

Table 4. Summary Average electricity price if electricity comes from the grid vs from private production

Electricity price, SEK	Average electricity price from the grid over 20 years	Average electricity price from wind-solar system over 20 years	Average electricity prices according to way of consumption
Scenario 1	1.99	1.39	1.56
Scenario 2	1.99	1.39	1.56
Scenario 3	1.99	1.79	1.88
Scenario 4	1.99	1.79	1.88

In both scenario 1 and 2 as presented in Table 1, the electricity generated by the system covers 73% of used electricity by a household (Table 2). The wind-solar system produces electricity at a price of 1.39 SEK/kWh (see table 4). Because the system covers only 73% of household's electricity consumption and the grid price has an average value of 1.99 SEK/kWh (see Table 4) the final price paid by the household is 1.56 SEK/kWh. Table 3 summarises the return on investment at the end of system's service life. As it can be seen the return on investment is 245 903 SEK in scenario 1, and 65 956 SEK in scenario 2.

In the other two scenarios (3 and 4 from Table 1) the electricity generated by the system covers 56% of household's consumption (Table 2). The wind-solar system produces electricity at a price of

1.79 SEK/kWh thus the final price paid by the household would be 1.88 SEK/kWh (Table 4). The return on investment at the end of system's service life is 149 525 SEK in scenario 3, respectively - 37 500 SEK in scenario 4 (Table 3).

The first 3 scenarios give positive net return on investment while scenario 4 gives a negative result. Several other scenarios with different electricity production levels were tested in order to see at which limit the results become positive. The scenario in which the system covers 62% of the consumed electricity gives a net result of 3.23 SEK. Therefore it can be argued that the system is profitable from an economic point of view if it covers at least 62% of the electricity need.

## 6. Discussion

The life cycle assessment on the two wooden towers highlights common hot spots of the models. The hot spots are represented by the steel billet production, German electricity grid mix and argon production. For some impact categories such as terrestrial acidification, pine log acquisition generates the second biggest potential impact after steel production. Impregnated wood appears to be a better option due to increased durability compared with the untreated wooden tower during a service life of 50 years.

Even though the life cycle assessment approach is widely used it is also characterized by criticism. When interpreting the value of different impact categories for the wooden tower the assumptions made during modelling the life cycle and the data quality of the model should be taken into consideration. When modelling, different cut-off criteria were taken into account in order to simplify the model and being able to represent it. For example the transportation to the customer was not included in the model therefore sensitivity analysis was conducted on possible transportation distances.

Assuming that a customer lives 600 km away from InnoVentum's warehouse the system's total impact on climate change would increase with 79 kg CO<sub>2</sub> eq. Another changed impact category would be particulate matter formation and photochemical oxidant formation where the impact of transportation appears as hot spot in the life cycle.

Steel production appeared as having the biggest impact in almost all impact categories. Approximate 50% of the steel used for manufacturing the components of the PowerTower is produced in Canada and it is associated with long distances and big transportation truck. If the distance would be decreased to only 500 km within Canada the climate change impact would decrease with 19 kg CO<sub>2</sub> eq. It can be argued that transportation is an important part of the model and if not taken into consideration in a correct way then the obtained impact could vary.

The fact that different parts that contribute with less than 5% at the overall weight were excluded can also make the result vary. Data gaps on the two components of the impregnation solution, especially polyethyleneamine, which represents around 20% of the impregnation solution, could have a big impact on the model results. Model assumptions on used electricity for steel production and manufacturing in Canada take into account the electricity grid mix from New Zealand as it is similar to the Canadian one. A reliability issue of the LCA results could come from the use of substitutes because even though they resemble they do not have the same value as the one needed in

the model and thus the results could be impacted. Another uncertainty could arise from not including the maintenance process due to data gaps regarding the maintenance solution. This uncertainty does not have a big impact on the total results especially because it is not a mandatory process. By substituting the Swedish forestry with the German one as it was obtained from the database, the results could be impacted. The impact of different forestry system and transport of wood could have an important environmental impact (González-García *et al.*, 2009).

The LCA results refer to a reference flow of more than one wooden tower. The fact that the system targets households led to a functional unit correlated with 12 400 kWh/year and therefore to a reference flow higher than 1 wooden tower because the system can produce only around 9000 kWh/year. Assuming that more than 1 wooden tower is necessary for a system producing 12 400 kWh can also impact the results. If a tower can in fact hold a bigger wind turbine, which produces enough energy to sustain a household than the impact would have a lower value.

This study could have several expected values for Innoventum. It can enable consumers to make an informed decision on which energy producing system to choose. When somebody wants an environmental friendly product can become sceptical towards impregnated materials. This study highlights the fact that if the impregnation solution has a specific composition could make the product more environmental friendly than an untreated one especially because of increased durability.

The study provides industry with an analysis that evaluates the life-cycle impacts of a wooden tower. Manufacturers and distributors of wind turbines could complement their products with InnoVentum's wooden towers. The analysis could assist manufacturers in evaluating alternative products and processes that reduce the risk to human health and the environment. In the same time the study provides guidance for improving the design of the tower by highlighting the hot spots and provides specific data for communicating the environmental benefits of wooden towers to clients and consumers.

The study provides an academic reference for evaluating the wooden tower and perhaps helps InnoVentum in obtaining the necessary approvals for future installations. It also represents a basis for developing regulatory and economic instruments that encourage wind and solar electricity production.

When compared with previous studies, the results show similar finding as the one of González-García *et al.* (2009). Pine log acquisition is a possible hot spot in the life cycle of the wooden products. Comparison with other studies is hard to be undertaken due to differences in analysed



products and system boundaries. In order to compare the results the models should be developed under similar assumptions and conditions.

The return on energy calculation is characterized by subjectivity and uncertainty as it uses LCA's results. Crawford (2009) too finds that the energy used in order to manufacture and use a wind turbine system is considered to be recovered in only a number of months. The comparison is not totally valid since it is not recommended to compare the results with those from other studies, which used different assumptions and boundaries.

The return on investment calculation is based on different assumptions such as maximum generated electricity at a wind speed of 12 m/s or lower level of generated electricity, average electricity consumption at household level and loaned amount. For a more accurate calculation all the input variables should be specific for the household that wants to install such a system. For example variables such as household positioning, wind speed in the region, if the money invested are from personal savings or loaned, if the system is grid connected or not, consumed electricity level by the household should be household characteristic. Nevertheless the result obtained in scenario 5 can be used as threshold. If the potential user of the system does not rely on governmental subventions then the system should cover at least 62% of the needed electricity in order to reach a positive return on investment in a 20 years period.

Regarding the estimated electricity price, the results highlight the fact that the average electricity price from the wind-solar system becomes lower than the average electricity price from the grid.

What it is important to consider when thinking about procuring such a system is not only the expected return on investment but also the environmental profile of the product and the energy security that it offers. For instance when the system is off-grid it offers energy independence in case of grid collapse. From the point of view of the solar panels, the tower offers increased security in cases of fire because they are easier to be accessed than when installed on the roof.

## 7. Conclusions

As resulted from this study the impregnated wooden tower is a better solution than the untreated one. Because of the type of impregnation solution the end of life management does not imply careful handling of the wood. The wood is not managed as dangerous material in Sweden and therefore it can be used in incineration with other materials or products. It could be of interest to assess the end of life management in other countries as well, in case the procedure of dealing with this type of wood is different.

Relevant and important future research would be on comparing the potential environmental impact, return on energy and on investment of the impregnated wooden tower with its alternatives: steel and concrete tower. As concluded by Bolin and Smith (2011), wood appears as having a more environmental friendly profile than its alternatives so it would be of importance to see if in this case the result is the same. The environmental analysis comparison should be complemented by an economic comparison as well. More accurate data on what type of steel is used in the manufacturing process, if virgin or recycled steel should be obtained if engaging in this type of exercise especially if comparing the results with the ones of a steel tower.

The minimum energy payback is around 10 months for both types of wooden towers while the maximum return on energy is around 57 times the energy invested in manufacturing the tower/system. An actual figure on the return on energy cannot be obtained because other components of the system were not taken into account.

The return on investment calculations show how important the input data is. Variation in used variables could lead to very different return on investment results. Even though the return on investment is not really an economic gain in certain scenarios other aspects such as environmental profile and security should be taken into account. Many times these cannot be quantified as having an objective economic value but in many cases people and other stakeholders could see them as being more important than the generated economic value.

Considering the fact that no other studies were conducted on wooden towers for renewable energy systems this study could be regarded as a first step in environmental and economic assessments. Models with different boundaries should be further analysed in order to possibly reveal other results or in case of similar results to reinforce the findings of the present study.

## **Acknowledgements**

This study represents a master thesis within the program Applied Climate Change Strategies of the Environmental Studies Department of Lund University and it is conducted from February 2014 to August 2014.

The thesis corresponds to 30 ECTS credits and represents my research, i.e. investigations, modelling, analyses and results, carried out in that period of time.

I would like to express my gratitude to Sigvald Harryson, Morgan Widung and Julien Degault from InnoVentum AB for allowing me the opportunity to conduct a Master thesis within a realistic framework and taking their time to answer my questions.

A special thank you to Andrius Plepys, IIIIEE for supervision, good collaboration and constructive feedback.

I would also like to thank all who have been helpful throughout this project. Thank you Benoit Pelletier from Techno Pieux, Johan Lindqvist from Derome Träteknik and Raimo Michaelis from Hera-Metall for answering all my questions regarding data.

Anca Stoica, Lund 11<sup>th</sup> of August 2014

## Bibliography

- Arch Timber Protection. (2011). *10 good reasons to choose Tanapole*. Retrieved 8/4, 2014 from FED: [http://12.41.255.90/Fed/WOOD/Common/Tanapole\\_folder\\_June\\_2011.pdf](http://12.41.255.90/Fed/WOOD/Common/Tanapole_folder_June_2011.pdf)
- Baumann, H., & Tillman, A. (2004). *The Hitch Hiker's Guide to LCA*. Lund, Sweden: Studentlitteratur.
- Bengtsson, J., Emhart, C., Florenzano, A., Guccione, L., & Jaramillo, C. (2012). LCA-based hotspot analysis of food products to inform a major Chilean retailer's sustainability strategy. *PARALLEL SESSION 5A: FOOD LABELLING*. 8th Int. Conference on LCA in the Agri-Food Sector, 1-4 Oct 2012.
- Blaser, F., Wager, P., & Böni, H. (2012). *Measuring the use of natural resources and its impacts, Indicators and their application* (1 ed.). Swiss Academies of Arts and Sciences.
- Bolin, C., & Smith, S. (2011). Life cycle assessment of pentachlorophenol-treated wooden utility poles with comparisons to steel and concrete utility poles. *Renewable and Sustainable Energy Reviews*, 15, 2475–2486.
- Canadian Timber Structures. (2014). *Making wind even greener*. Retrieved 4/24, 2014 from Canadian Timber Structures: [canadiantimberstructures.com](http://canadiantimberstructures.com)
- CEI-BOIS. (2011). *Tackle climate change: use wood, Wood in sustainable development*. London, United Kingdom: Ideas London.
- Crawford, R. (2009). Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. *Renewable and Sustainable Energy Reviews*, 13, 2653–2660.
- Daligault, J. (2014, 3 11). Life cycle assessment interview. (A. Stoica, Interviewer) Malmö, Sweden.
- Derome Träteknik AB. (2014b). *Deromegruppens miljöpolicy*. Retrieved 5/1, 2014 from Derome Träteknik: <http://www.derome.se/om-derome/kvalitet-och-miljo/miljopolicy>
- Derome Träteknik AB. (2014a). *Ledande på takstolar i trä*. Retrieved 5/1, 2014 from Derome Träteknik: <http://www.derometrateknik.se/takstolar>
- Energimyndigheten. (2014b). *Mikroproducent*. Retrieved 8/5, 2014 from Energimyndigheten: <http://www.energimyndigheten.se/Foretag/Elcertifikat/Elproducent/mikroproducent/>
- Energimyndigheten. (2014a). *Stöd till solceller*. Retrieved 8/5, 2014 from Energimyndigheten: <http://www.energimyndigheten.se/Hushall/Aktuella-bidrag-och-stod-du-kan-soka/Stod-till-solceller/>
- Fava, J., Consoli, F., Denison, R., Mohin, T., & Vigon, B. (1993). *A Conceptual Framework for Life-Cycle Impact Assessment*. Society of Environmental 111 Toxicology and Chemistry (SETAC) and SETAC Foundation for Environmental Education. Pensacola, FL.
- Finnveden, G. (1997). Valuation Methods within LCA- Where are the Values? *Int. J. LCA*, 2, 163-169.
- Fleck, B., & Huot, M. (2009). Comparative life-cycle assessment of a small wind turbine for residential off-grid use. *Renewable Energy* (34), 2688–2696.
- Garrett, P., & Rønde, K. (2012). Life cycle assessment of wind power: comprehensive results from a state-of-the-art approach. *Int J Life Cycle Assess*, 18, 37–48.
- Gindl, W., Zargar-Yaghubi, F., & Wimmer, R. (2003). Impregnation of softwood cell walls with melamine-formaldehyde resin. *Bioresource Technology*, 87, 325–330.
- Goedkoop, M., Heijungs, R., De Schryver, A., Struijs, J., & Van Zelm, R. (2012, 7). ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the

midpoint and the endpoint level. *Report I: Characterisation* (1 (revised)). VROM - Ruimte en Milieu, Ministerie van Volkshuistvesting , Ruimtelijke Ordening en Milieubeheer.

González-García, S., Berg, S., Feijoo, G., & Moreira, M. (2009). Environmental impacts of forest production and supply of pulpwood: Spanish and Swedish case studies. *Int J Life Cycle Assess*, 14, 340–353.

González-García, S., Silva, F., Moreira, M., Pascual, R., Lozano, R., Gabarrell, X., et al. (2011). Combined application of LCA and eco-design for the sustainable production of wood boxes for wine bottles storage. (J. Schweinle, Ed.) *International Journal Life cycle assesment*, 224-237.

Harryson, S. (2012). *InnoVentum AB – Part I, Open Invention for New Business Creation, but where is the Commercialization?* Malmö: Copenhagen Business School.

Heijungs, R., Goedkoop, M., Struijs, J., Effting, S., Sevenster, M., & Huppes, G. (2002). *Towards a life cycle impact assessment method which comprises category indicators at the midpoint and endpoint level, Report of the first project phase: Design of the new method.* (N. Universiteit Leiden, Ed.) Retrieved 7/1, 2014 from Leidenuniv:  
[http://www.leidenuniv.nl/cml/ssp/publications/recipe\\_phase1.pdf](http://www.leidenuniv.nl/cml/ssp/publications/recipe_phase1.pdf)

Hellmann, M. (2013). *Sustainable Packaging Optimisation- Investigation and Analysis of a Packaging solution for Fresh Fish in a Life Cycle Perspective.* Technical University of Denmark, Management Engineering. Technical University of Denmark.

Highley, T. (1995). Comparative Durability of Untreated Wood in Use Above Ground. *International Biodeterioration & Biodegradation*, 409-419.

IVL. (2013). *Allt impregnerat trä är inte längre farligt avfall.* Retrieved 7/28, 2014 from IVL-Svenska Miljöinstitutet:  
<http://www.ivl.se/press/nyheter/nyheter/alltimpregnerattraarintelangrefarligtavfall.5.7df4c4e812d2da6a416800072928.html>

ILCD: European Commission. (2010). *ILCD handbook- International Reference Life Cycle Data System- General Guide for Life Cycle Assessment- Detailed Guidance.* Luxembourg, Luxembourg: European Commission JRC.

InnoVentum AB. (2013a). *InnoVentum Power to the People.* Retrieved 11/15, 2013 from Management team: <http://www.innoventum.se/management-team/>

InnoVentum AB. (2013b). *Dali PowerTower by InnoVentum.* Retrieved 7/31, 2014 from Flickr: <https://www.flickr.com/photos/65985813@N07/10114009566/in/set-72157636241590185>

InnoVentum AB. (2014a). *InnoVentums Affärsplan.* Malmö, Sweden: InnoVentum AB.

Innoventum AB. (2014b). *Our Milestones.* Retrieved 3/22, 2014 from Innoventum power to the people: <http://www.innoventum.se/company>

Innoventum AB. (2014c). *Products.* Retrieved 4/24, 2014 from Innoventum power to the people: <http://www.innoventum.se/products/>

Innoventum AB. (2014d, 3 22). *Innoventum for the planet.* Retrieved 3 22, 2014 from Innoventum power to the people: <http://www.innoventum.se/innoventum-for-the-planet/>

Innoventum AB. (2014e). *Why Innoventum?* Retrieved 3/23, 2014 from Innoventum Power to the people: <http://www.innoventum.se/buy-now/why-innoventum/>

InnoVentum AB. (2014f). *Dali PowerTower.* Retrieved 8/1, 2014 from InnoVentum Power to the People: <http://www.innoventum.se/power-tower/>

ISO 14040 . (2006). *Environmental Management- Life Cycle Assessment- Principles and Framework* (4 ed.). Brussels, Belgium: International Standard, European Committee for Standardization.

- ISO 14044. (2006). *Environmental management - Life Cycle Assessment - Requirements and Guidelines*. International Standard, European Committee for Standardization, Brussels.
- Johnson, J., Reck, B., Wang, T., & Graedel, T. (2008). The energy benefit of stainless steel recycling. *Energy Policy* (36), 181–192.
- Kubiszewski, I., Cleveland, C., & Endres, P. (2010). Meta-analysis of net energy return for wind power systems. *Renewable Energy* (35), 218–225.
- Kozak, G. (2003). *Printed Scholarly Books and E-book Reading Devices: A Comparative Life Cycle Assessment of Two Book Options*. University of Michigan, Center for Sustainable Systems. Michigan: University of Michigan.
- LC-Impact. (2014). *Life Cycle Impact Assessment (LCIA)*. Retrieved 8/3, 2014 from LC-Impact: <http://www.lc-impact.eu/life-cycle-impact-assessment-lcia>
- Lindqvist, J. (2014). Derome Träteknik interview. (A. Stoica, Interviewer)
- Lonza. (2014). *TANALITH E*. Retrieved 5/10, 2014 from Lonza Wood Protection: <http://lonzawood.com/tanalith/tanalith-e/>
- McAloone, T., & Bey, N. (2009). *Environmental improvement through product development - a guide*. Retrieved 7/6, 2014 from Danmarks Tekniske Universitet: <http://www.mek.dtu.dk/sektioner/kp/Forskning/omraader/ecodesign/guide.aspx>
- Michaelis, R. (2014). Hera-Metall Interview. (A. Stoica, Interviewer)
- Moberg, Å. (2010). *Assessment of media and communication from a sustainability perspective*. Royal Institute of Technology, Department of Urban Planning and Environment. Stockholm: US AB, Sweden.
- Moonen, J. (2003). Simplified Return on Investment. *Interactive Learning Environments*, 11 (2), 147-165.
- Nordic Timber Export. (2014). *About Spruce and Pine*. Retrieved 5/1, 2014 from Nordic Timber Export: <http://www.nordictimber.nl/en-GB/Products/About-spruce-and-pine.aspx>
- PE International. (2014). *LCA Databases*. Retrieved 7/5, 2014 from GaBi Software: <http://www.gabi-software.com/sweden/databases/>
- PEFC. (2014b). *Hållbart skogsbruk*. Retrieved 5/1, 2014 from Svenska PEFC: <http://pefc.se/hallbart-skogsbruk-2/>
- PEFC. (2014a). *Konsumera hållbart*. Retrieved 5/1, 2014 from Svenska PEFC: <http://pefc.se/konsumera-hallbart/>
- Pelletier, B. (2014). Techno Pieux Interview. (A. Stoica, Interviewer)
- Price, L., & Kendall, A. (2012). Wind Power as a Case Study Improving Life Cycle Assessment Reporting to Better Enable Meta-Analyses. *Journal of Industrial Ecology*, 16, 22-27.
- ReCiPe. (2014). *ReCiPe 2008 official homepage*. Retrieved 3/7, 2014 from ReCiPe: [www.lcia-recipe.net](http://www.lcia-recipe.net)
- ROI. (2014). Accessed from <https://www.dropbox.com/sh/jt13kpkb8pq6wtc/AAC5Gs7nLweJ-7miXO3oRKhza?dl=0>
- SCB. (2013). *Elanvändningen i Sverige efter användningsområde (SNI 2007). År 2008 - 2012*. Retrieved 20/12, 2013 from Statistiska centralbyrån: [http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START\\_\\_EN\\_\\_EN0105/EIAnvSNI2007Ar/?rxid=1081efa6-e033-4157-88fe-ac6cac2fa75e](http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__EN__EN0105/EIAnvSNI2007Ar/?rxid=1081efa6-e033-4157-88fe-ac6cac2fa75e)
- SCB. (2014). *Priser på elenergi och på överföring av el (nättariffer)*. Retrieved 3/7, 2014 from Statistiska centralbyrån: [http://www.scb.se/sv/\\_Hitta-statistik/Statistik-efter-](http://www.scb.se/sv/_Hitta-statistik/Statistik-efter-)

amne/Energi/Prisutvecklingen-inom-energiomradet/Priser-pa-elenergi-och-pa-overforing-av-el-nattariffer/Aktuell-Pong/6429/

The World Bank. (2014). *Electricity production from hydroelectric sources (% of total)*. Retrieved 8/1, 2014 from The World Bank <http://data.worldbank.org/indicator/EG.ELC.HYRO.ZS>

Timbertower. (2014). *TimberTower*. Retrieved 4/24, 2014 from TimberTower: <http://www.timbertower.de/en/>

Zhong, Z., Song, B., & Loh, P. (2011). LCAs of a polycrystalline photovoltaic module and a wind turbine. *Renewable Energy*, 36, 2227-2237.

Wang, Y., Akkerman, R., & Grunow, M. (2011). *Supply Chain Planning for Super Chilled Food Products*. Retrieved 7/6, 2014 from Social Science Research Network: [http://papers.ssrn.com/sol3/papers.cfm?abstract\\_id=1923948](http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1923948)

Wenzel, H., Hauschild, M., & Alting, L. (1997). *Environmental Assessment of Products, Methodology, Tools and Case Studies in Product Development*. London, United Kingdom: Chapman&Hall.

Appendix A.



Picture 1. The Dali PowerTower (source: InnoVentum AB, 2013b)





Picture 2. Packaging for an off-grid Dali Power Tower (source: Daligault, 2014)

## Appendix B.

Table 1. Inventory for the Dali PowerTower (registered in GaBi)

<b>Inventory Dali PowerTower</b>				
<b>Input</b>	<b>Source/Country of process</b>	<b>Quantity</b>	<b>Assumption</b>	<b>Quantity data source</b>
Pine log	Raw material extraction from managed forests- Germany instead of Sweden	1590 kg	Due to unavailable data for wood extraction in Sweden, the process from Germany was used	Case specific- Derome Träteknik interview
Steel billet for photovoltaics support	Raw material extraction and manufacturing of steel from 15% steel scrap, rest is virgin steel- Germany	100 kg		Case specific- Herra Metall interview
Steel billet for foundation	Raw material extraction and manufacturing of steel from 15% steel scrap, rest is virgin steel - Germany instead of Canada	242 kg	A mix of 15% steel scrap with 85% virgin steel was assumed in the model	Case specific- Techno Pieux interview
Gasoline for installation machinery	Gasoline mix (regular) -EU-27	3.29 kg		Case specific- Techno Pieux interview
Cutting and drilling lubricant for foundation pieces	Lubricants at refinery- (US)	4.62 kg	US data was used as a substitute for Canadian data	Case specific- Techno Pieux interview
Process water for steel manufacturing	Europe	0.115 kg		Case specific- Techno Pieux interview
Argon liquid	Raw material extraction -Germany	72.7 kg		Case specific- Techno Pieux interview
Carbon dioxide	US	2.99 kg		Case specific- Techno Pieux interview
O2 (3%) = 1,68 l (not requested for extension R3)				Case specific- Techno Pieux interview
Boric acid		1.2 kg		Literature

Diethanolamine		4.8 kg		Literature
Propiconazole		0.12 kg		Literature
Copper carbonate		4.92 kg		Literature
Surfactants		1.2 kg		Literature
Tebuconazole		0.12 kg		Literature
Water		5.64 kg		Literature
Polyethyleneamine	N/A	4.8 kg		Literature
Organic acid	N/A	1.2 kg		Literature
Steel billet for Bolts/washers/nuts/wood screws	Raw material extraction and manufacturing of steel from 15% steel scrap, rest is virgin steel-Germany	80 kg		Case specific-InnoVentum interview
Electricity for manufacturing bolts/washers etc	N/A	N/A		N/A
Electricity for manufacturing foundation	Electricity grid mix-New Zealand	17.04 MJ	Because no data was available for electricity grid mix in Canada, it was substituted with the most similar grid mix in the world, the one of New Zealand	Case specific-Techno Pieux interview
Electricity for manufacturing wooden parts	Electricity grid mix-Sweden	36 MJ		Case specific-Derome TrätekNIK interview
Electricity for manufacturing metal support for PV	Electricity grid mix-Germany	450 MJ		Case specific-Herra Metall interview
Electricity for impregnation	Electricity grid mix-Sweden	64.8 MJ		Case specific-Derome TrätekNIK interview
Electricity for installation		5 amper hour		Case specific-InnoVentum interview
Transportation of foundation parts by truck Euro, 3 34-40 tons	US diesel mix	1699 km		Case specific-Techno Pieux interview

Transportation of metal and wooden parts by truck Euro 3, 20-26 tons	EU-27 diesel mix	1000 km		Case specific-Herra Metall and InnoVentum interview
Transportation of wooden parts after impregnation by truck Euro 3, 20-26 tons	EU-27 diesel mix	19 km		Case specific-Derome Träteknik interview
Transportation to customer	N/A	N/A		N/A
A very small amount of packaging material (paper, plastic foil)/ few steel remains of the manufacturing				Case specific-Herra Metall interview and InnoVentum interview
Maintenance solution	N/A	N/A		N/A

Table 2. Technical Specifications Dali PowerTower

Technical Specifications Dali PowerTower



	URBAN	LIFESTYLE	LITE	PERFORMANCE
Rated output, wind turbine	1,75 kW at 13,5 m/s	1,5 kW at 10 m/s	3,0 kW at 12 m/s	3,5 kW at 12 m/s
Rotor diameter, wind turbine	1,5 m	3,0 m	3,0 m	4,05 m
Märkeffekt, 8 solpaneler	2,0 kWp	2,0 kWp	2,0 kWp	2,0 kWp
Annual energy prod. at 6 m/s (wind and solar)	3 190 kWh	6 040 kWh	5 400 kWh	9 190 kWh
Grid connection	220 V – 50 Hz	220 V – 50 Hz	48 V DC off-grid	220 V – 50 Hz
Available off-grid	No	Yes	Yes	Yes
Tower footprint	Triangular, 2,83 m <sup>2</sup>	Triangular, 2,83 m <sup>2</sup>	Triangular, 2,83 m <sup>2</sup>	Triangular, 2,83 m <sup>2</sup>
Building permission (Sweden)	Not required	Not required	Not required	Required

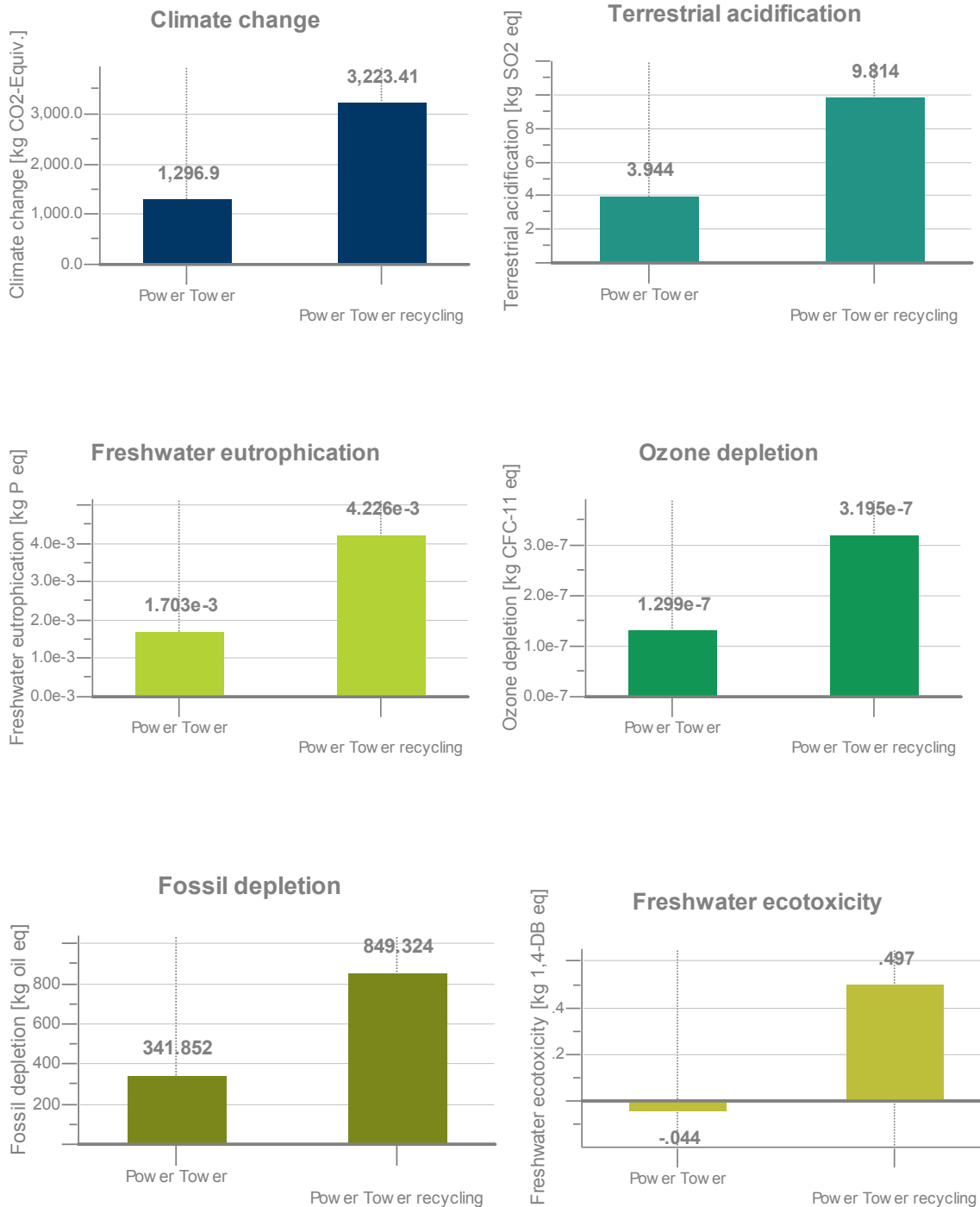
(Source: InnoVentum AB, 2014f)

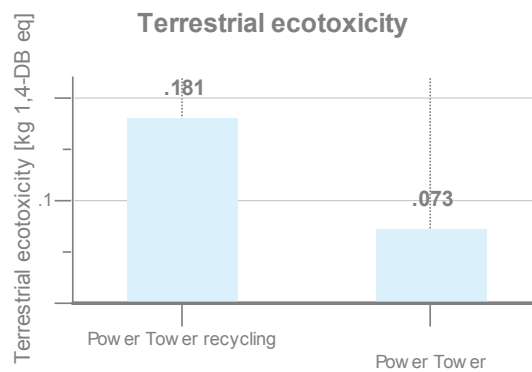
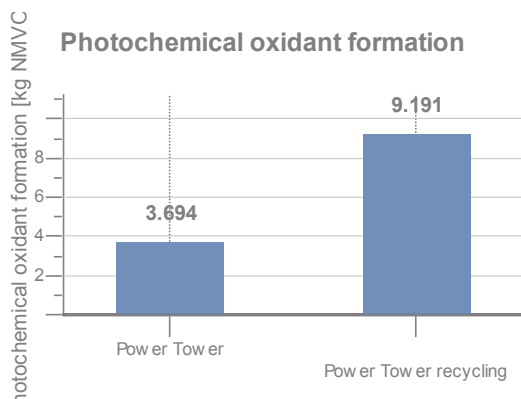
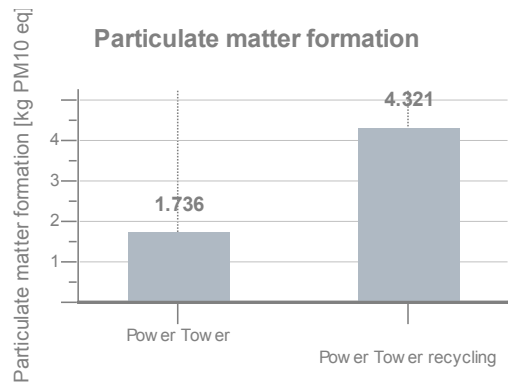
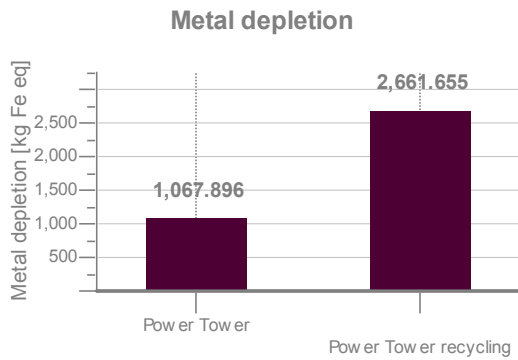
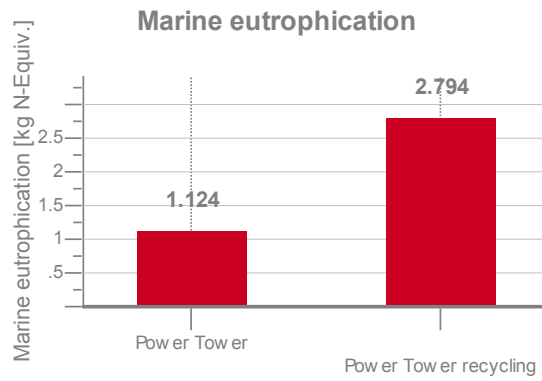
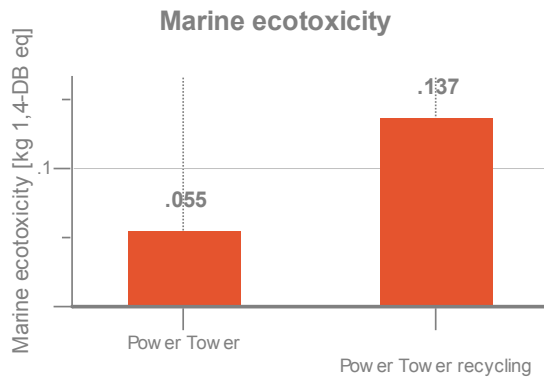
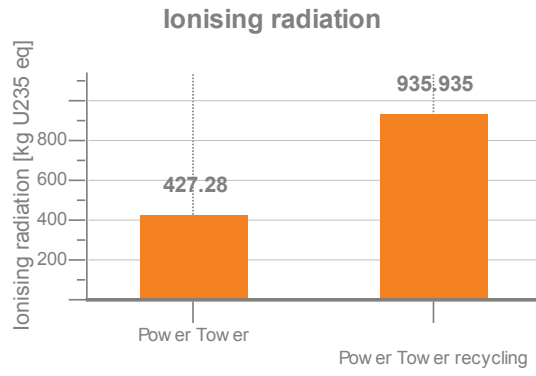
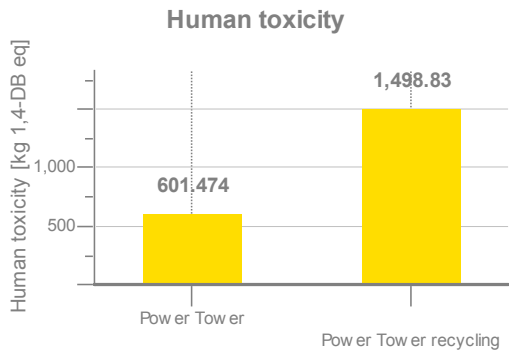
# Appendix C.

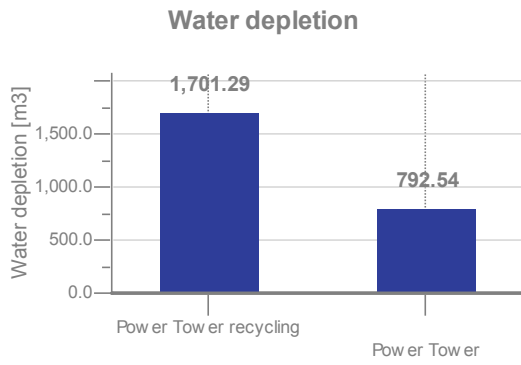
Diagrams level 1. Comparison impregnated PowerTower and untreated PowerTower

Legend: Power Tower= impregnated Power Tower

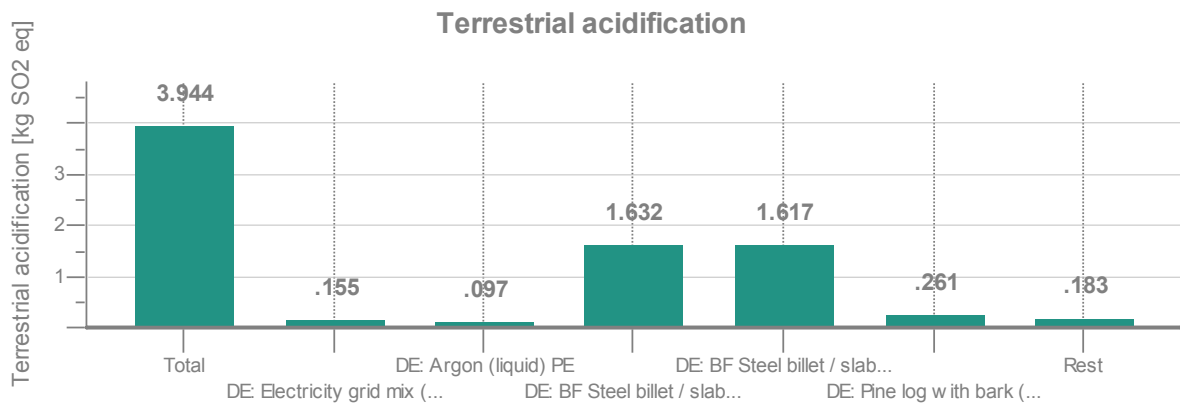
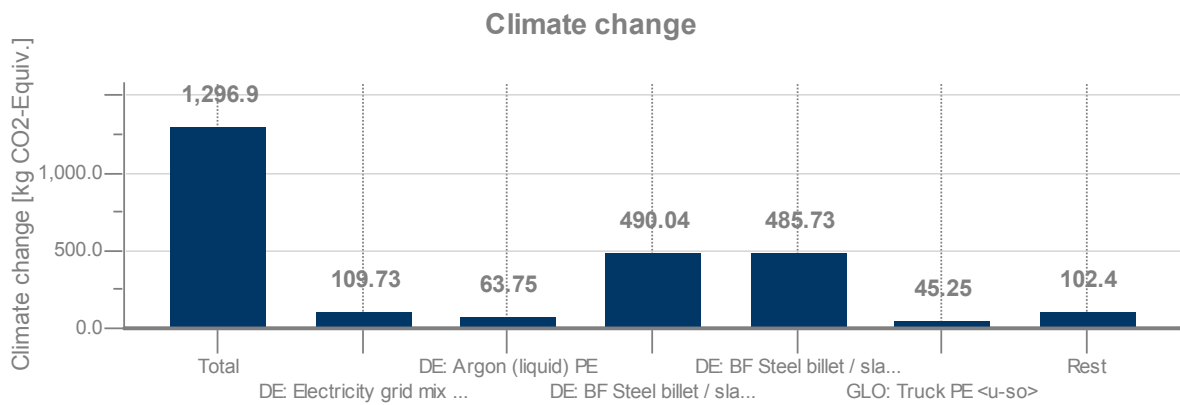
Power Tower recycling=untreated Power Tower

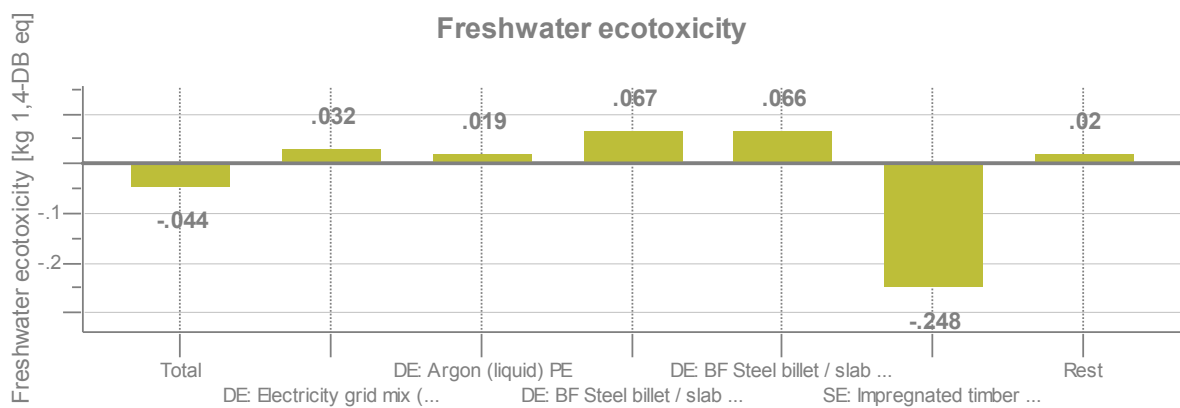
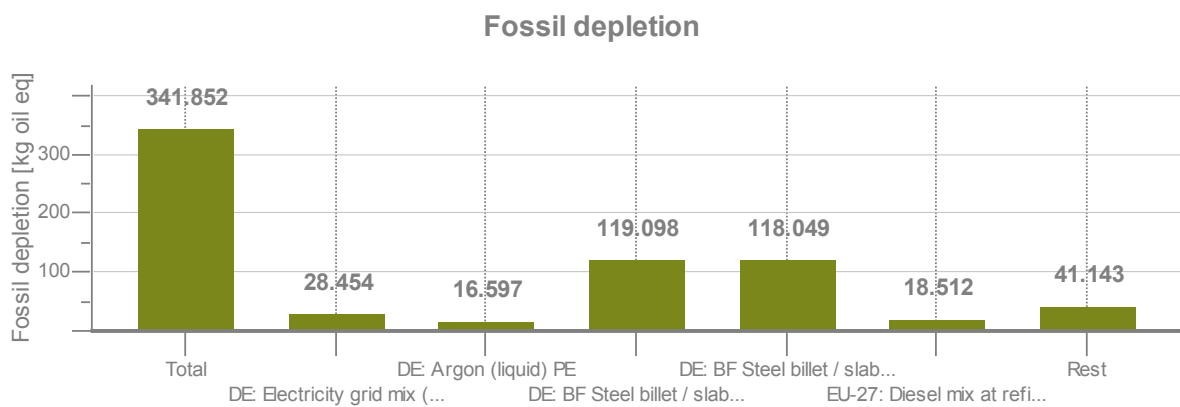
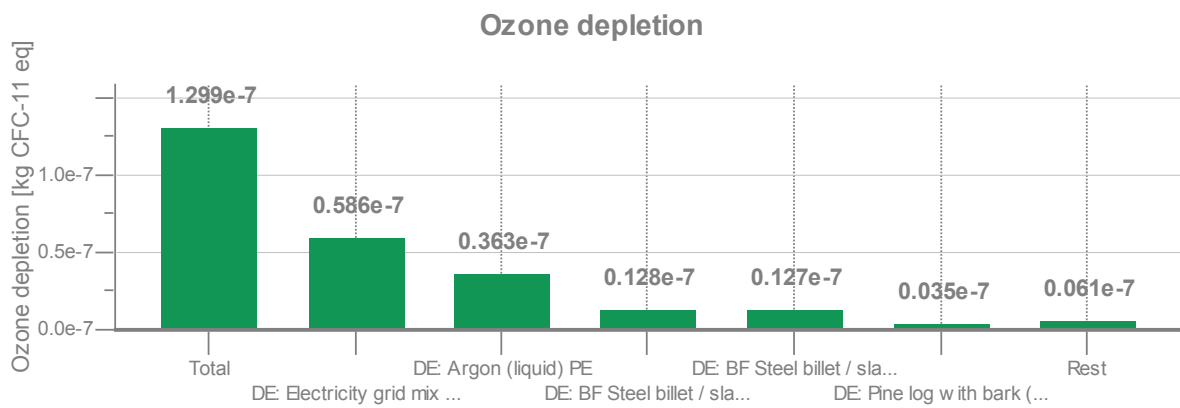
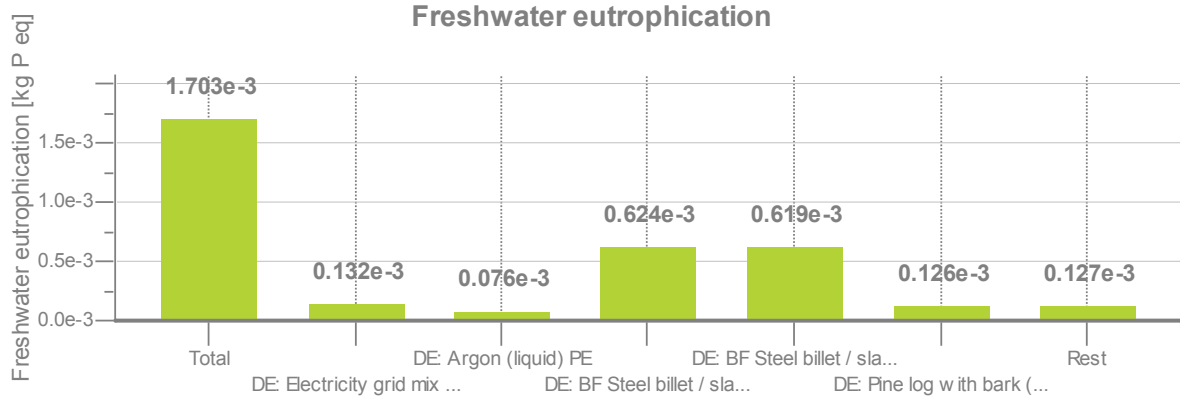






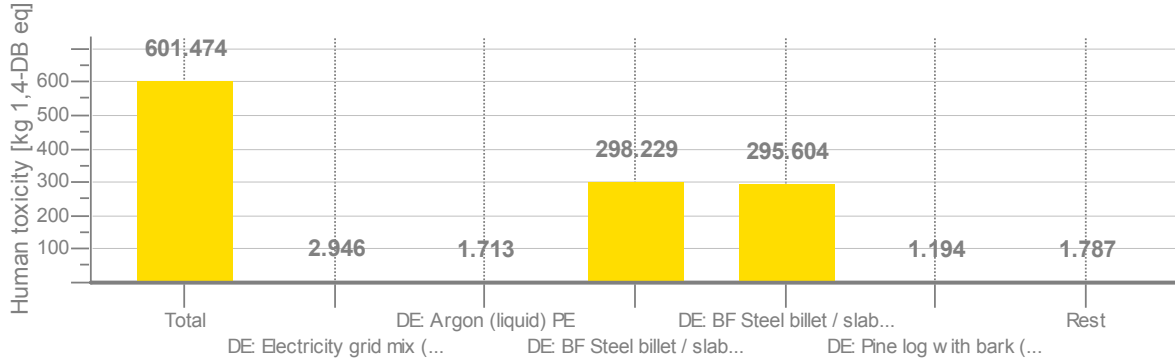
## Diagrams level 2. Potential environmental impacts of the impregnated PowerTower



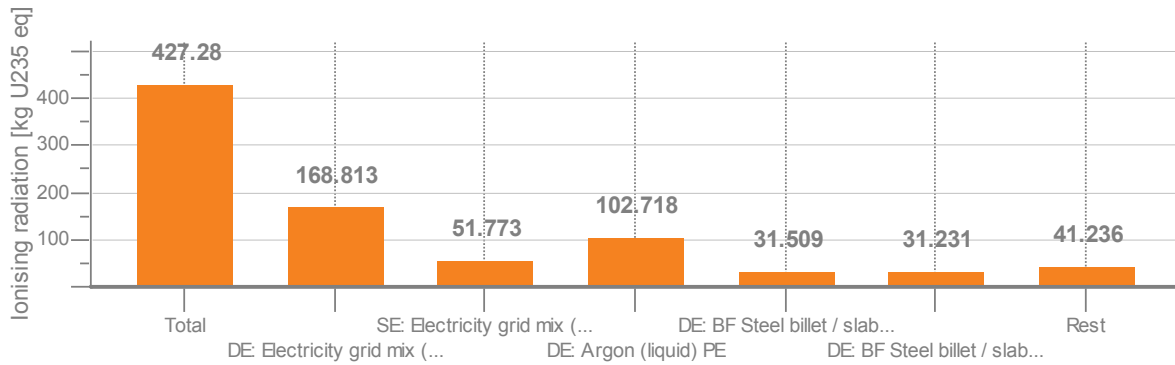




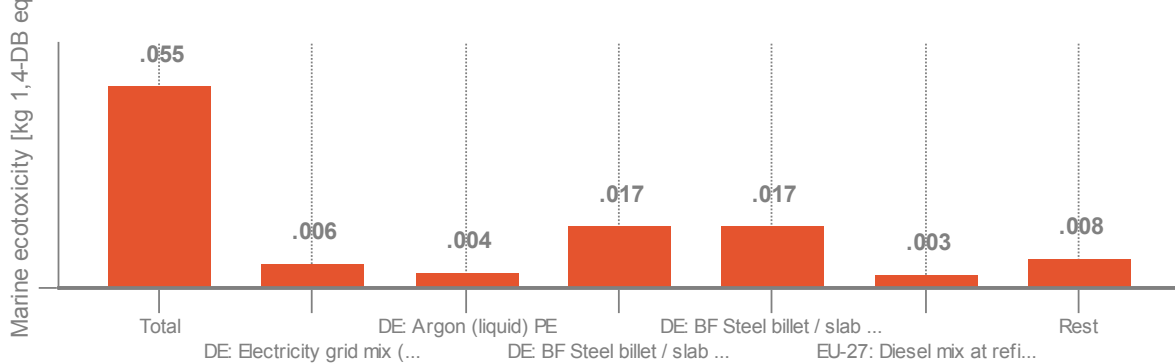
### Human toxicity



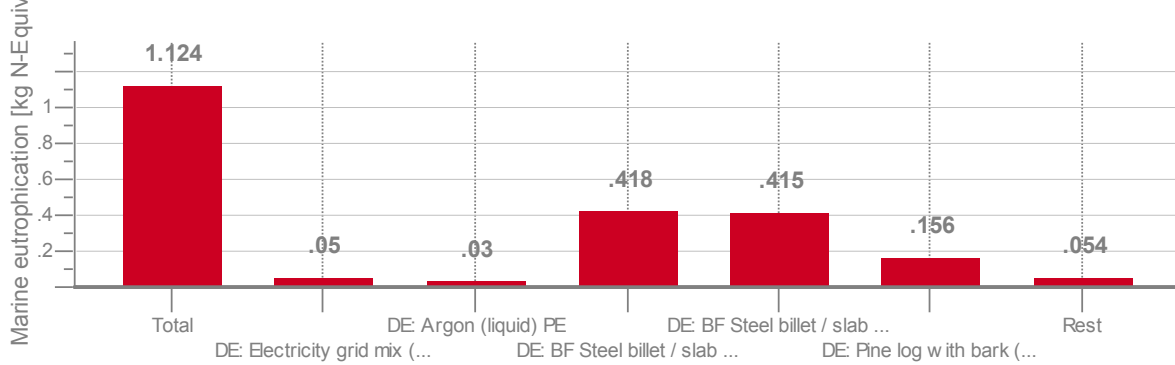
### Ionising radiation



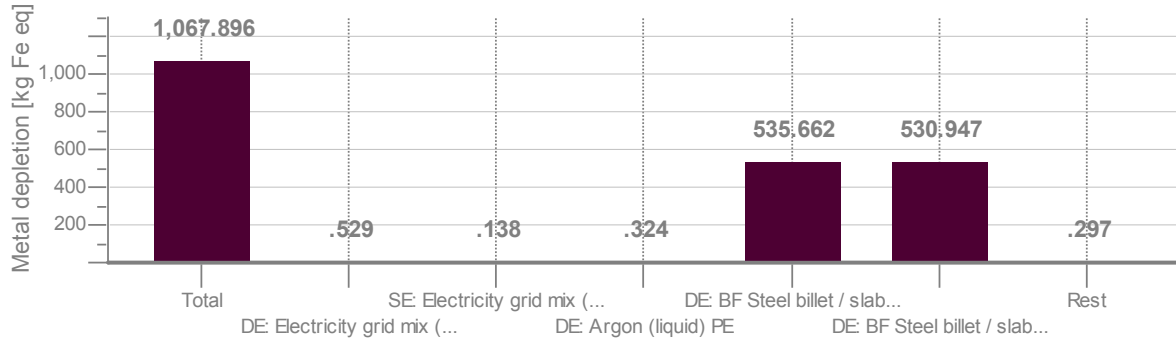
### Marine ecotoxicity



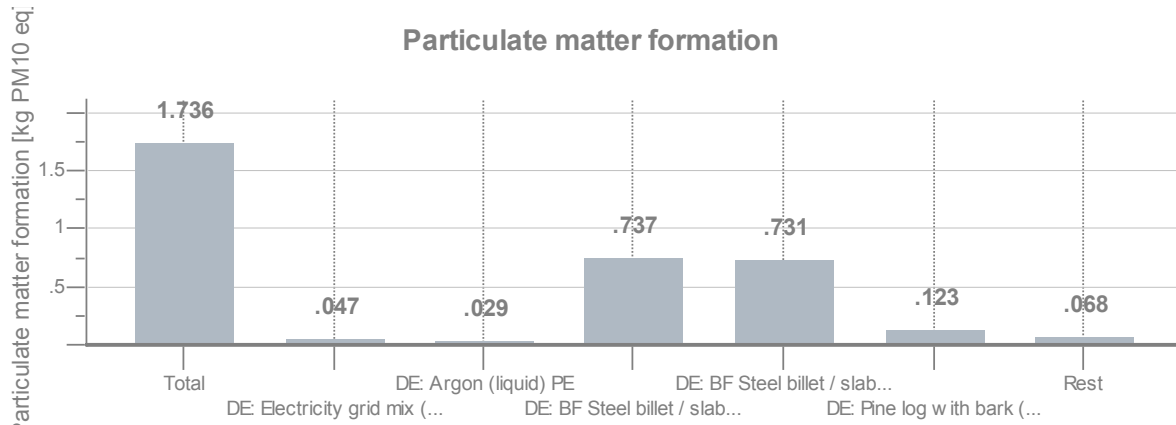
### Marine eutrophication



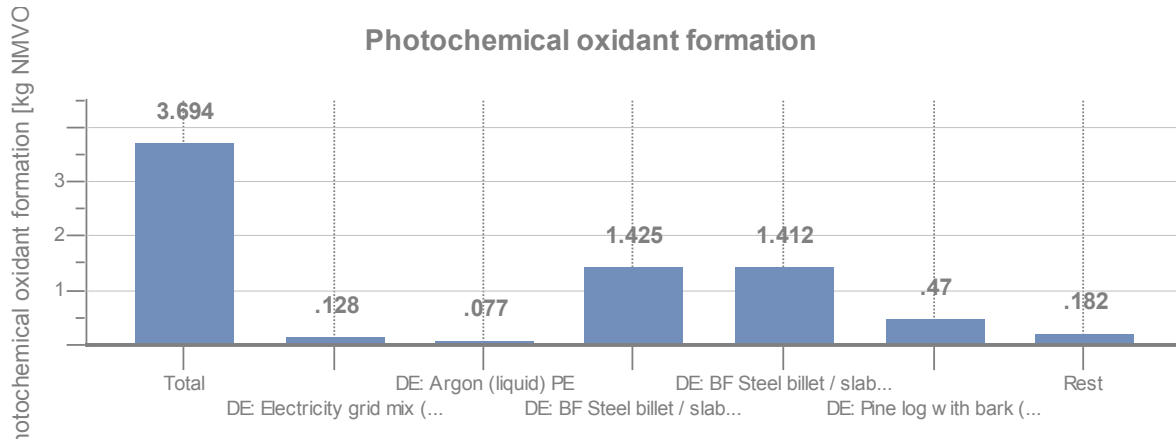
### Metal depletion



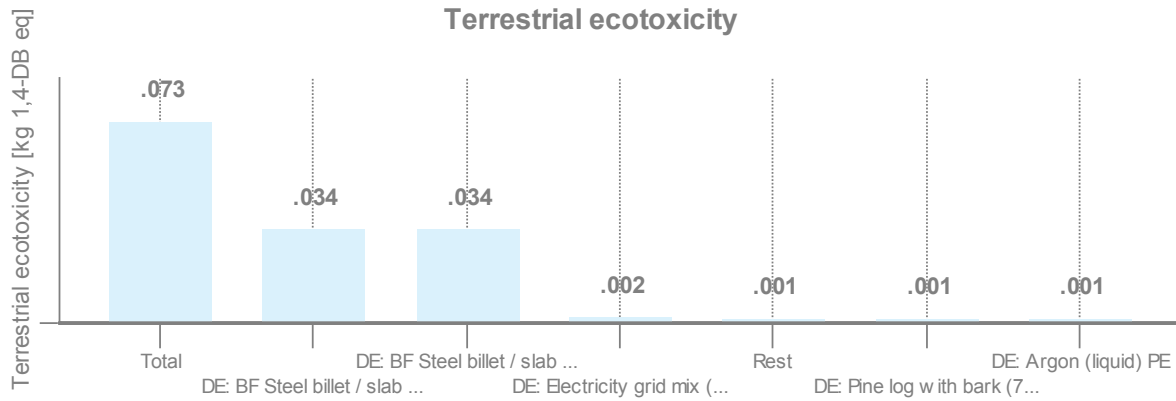
### Particulate matter formation



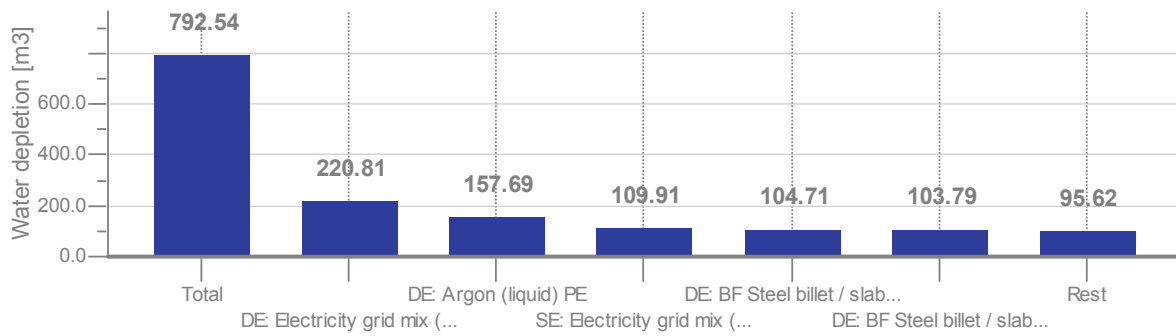
### Photochemical oxidant formation



### Terrestrial ecotoxicity

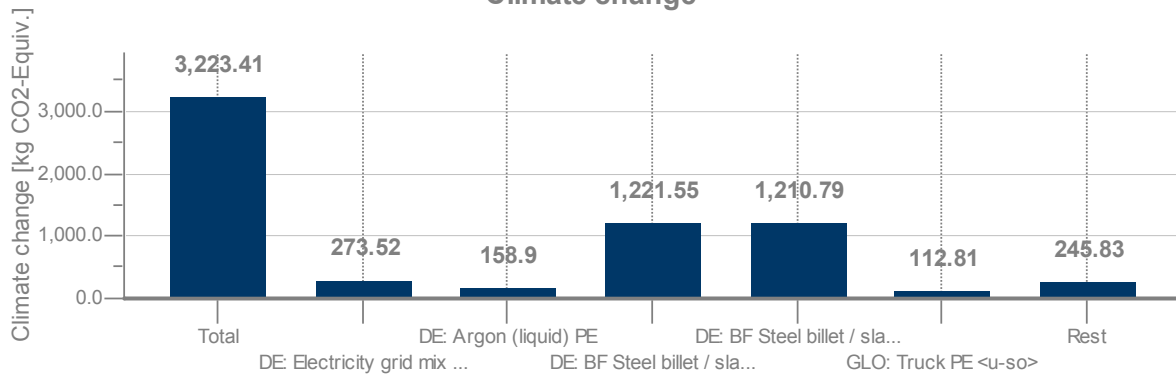


### Water depletion

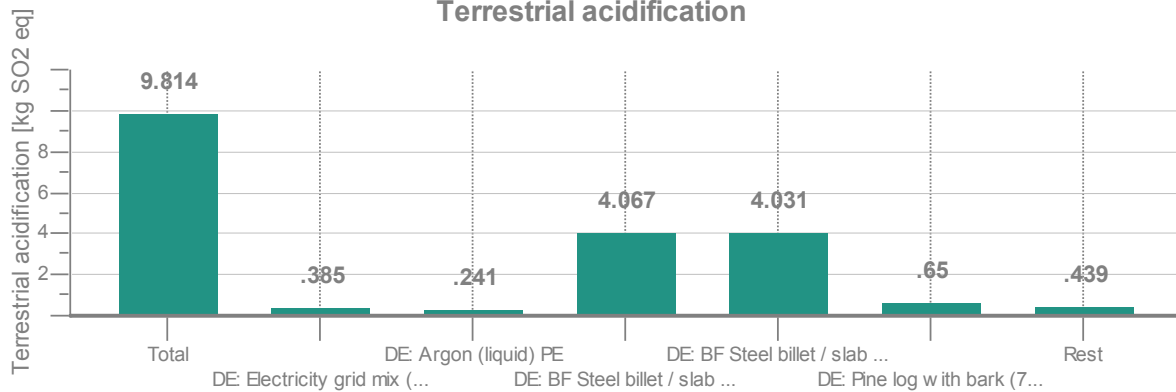


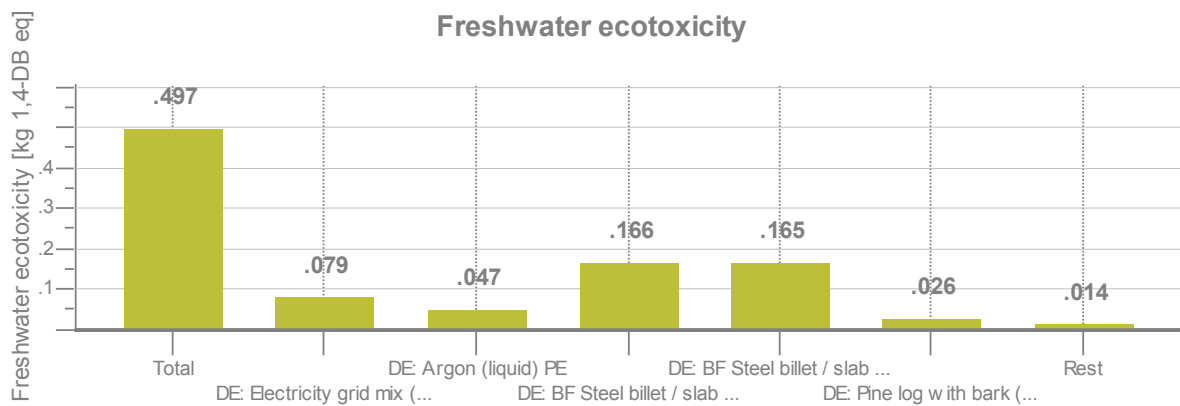
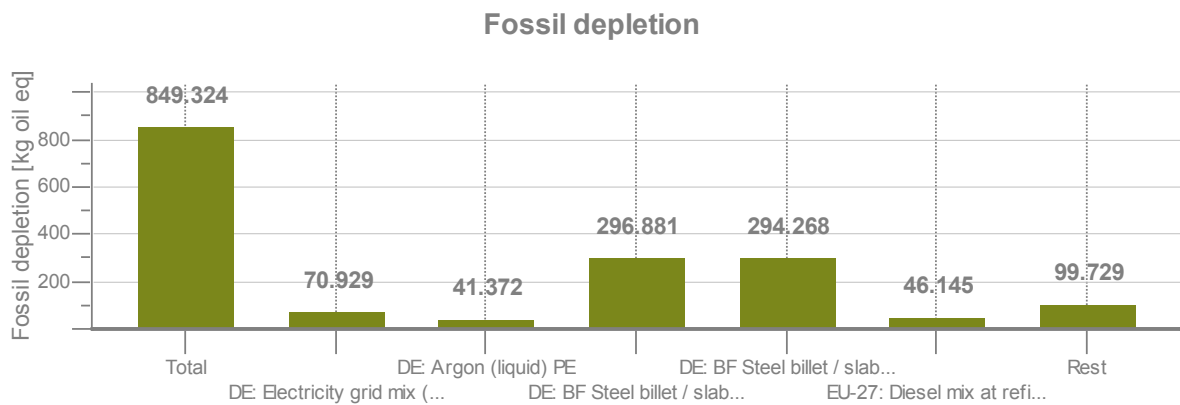
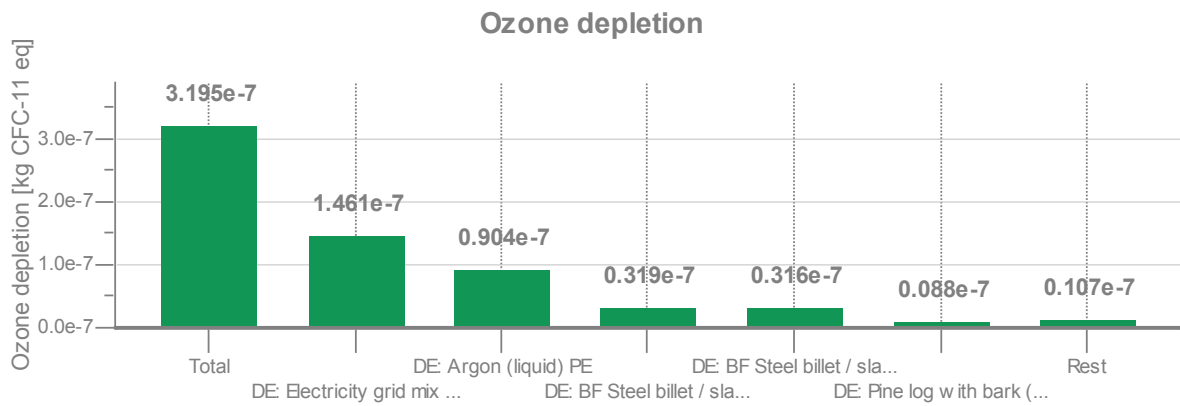
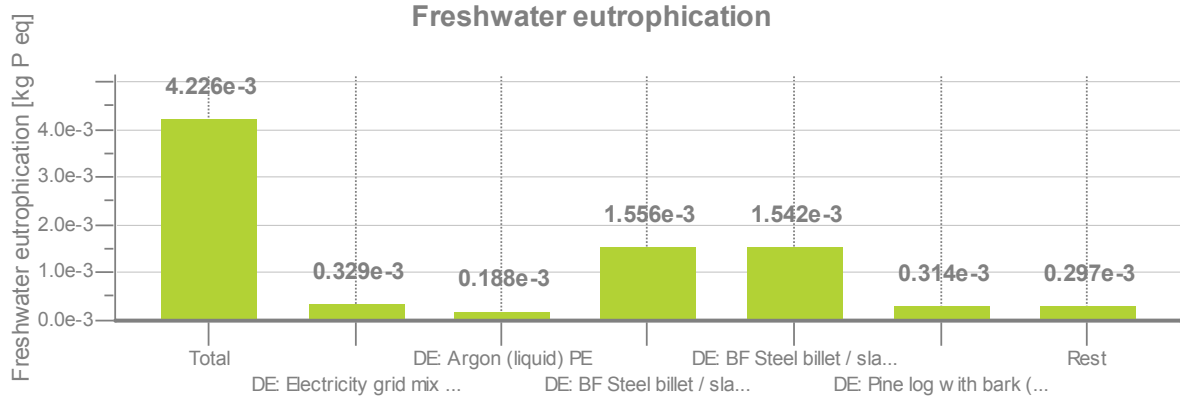
### Diagrams level 3. Potential environmental impacts of the untreated PowerTower

### Climate change

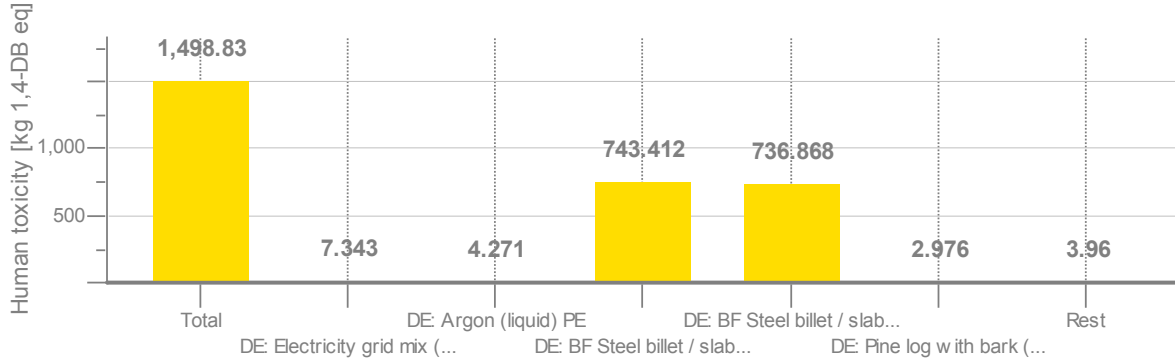


### Terrestrial acidification

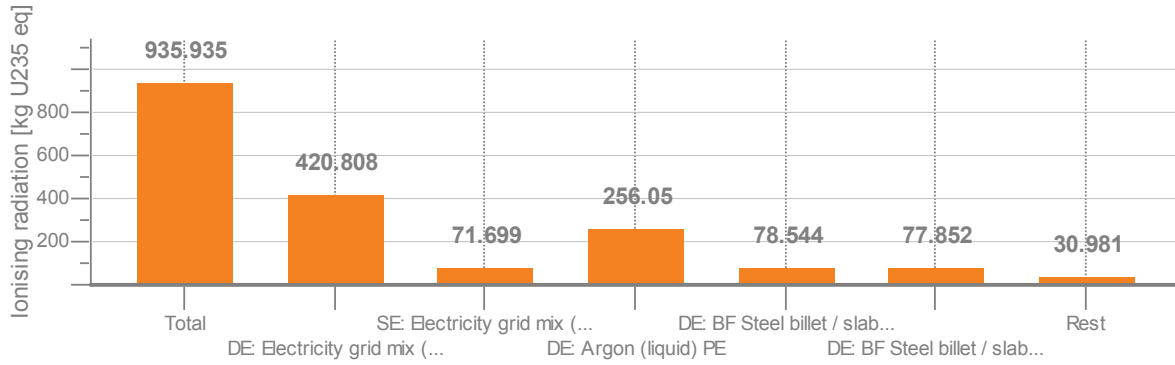




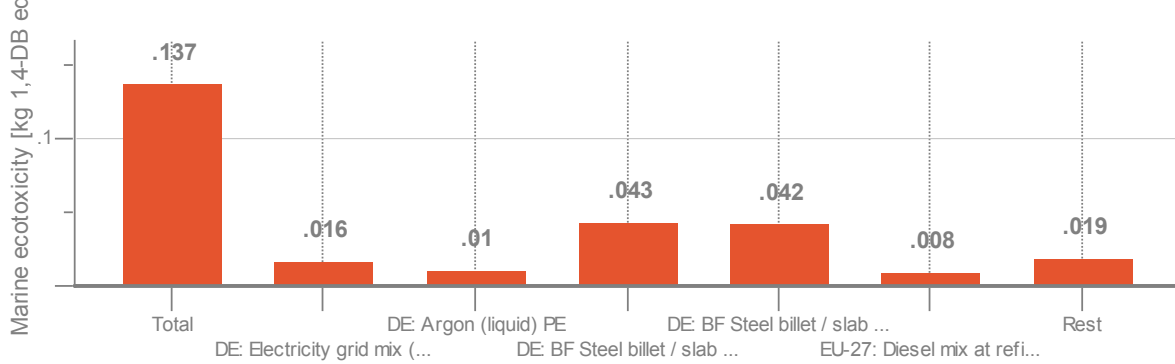
### Human toxicity



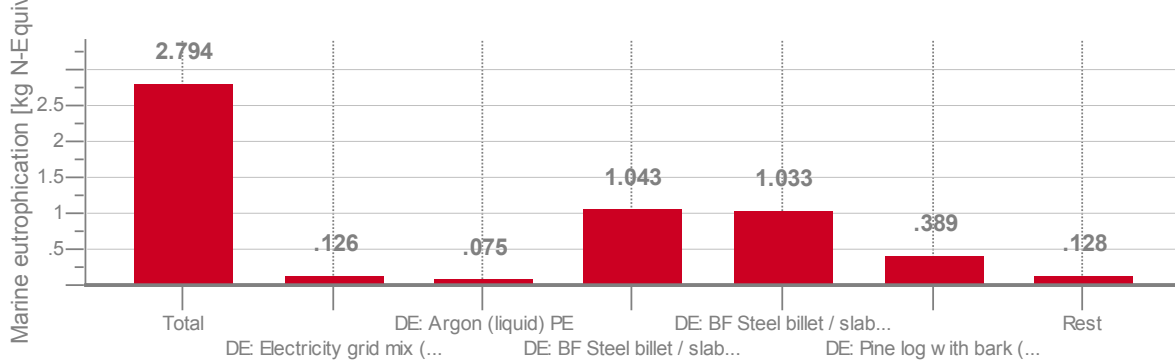
### Ionising radiation



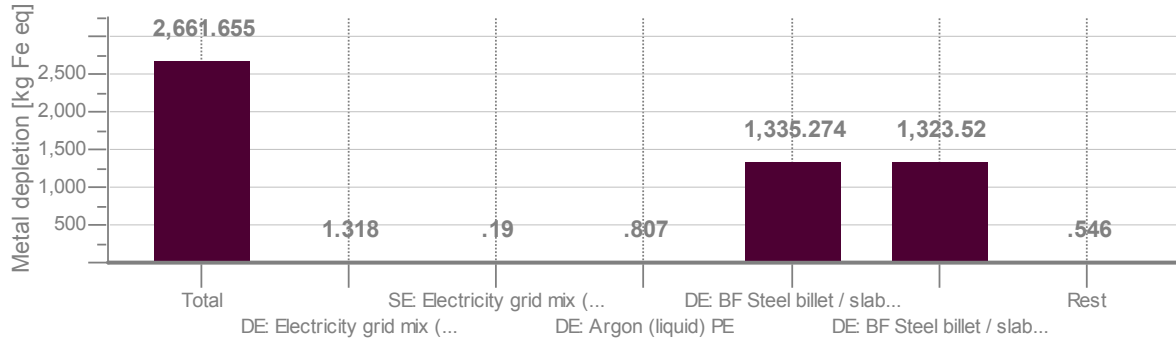
### Marine ecotoxicity



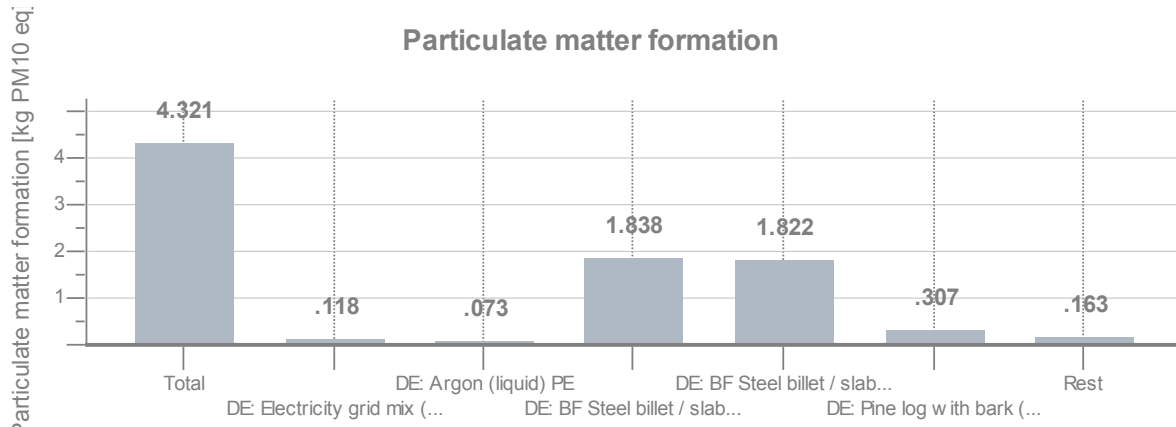
### Marine eutrophication



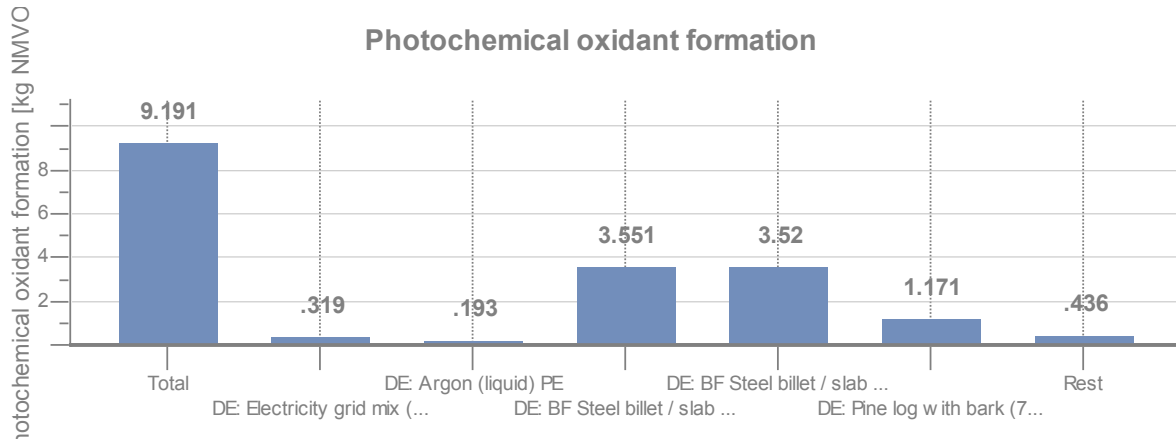
### Metal depletion



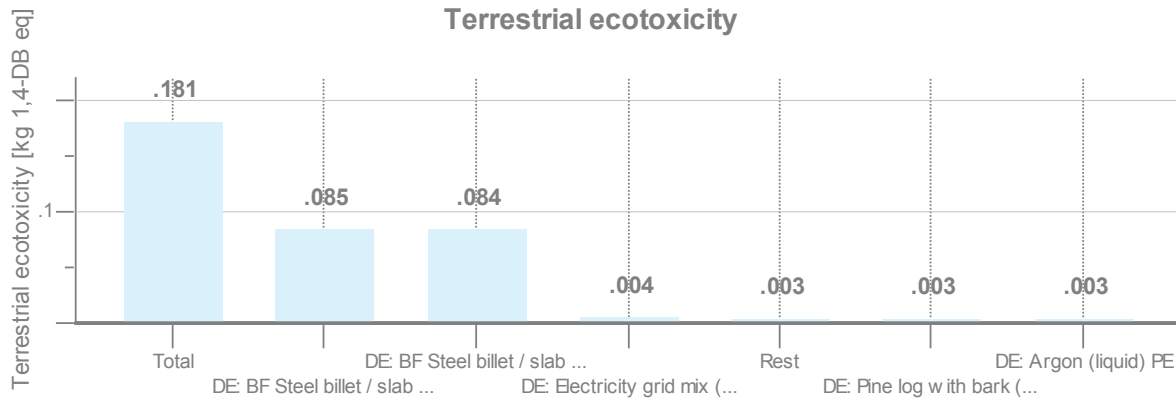
### Particulate matter formation



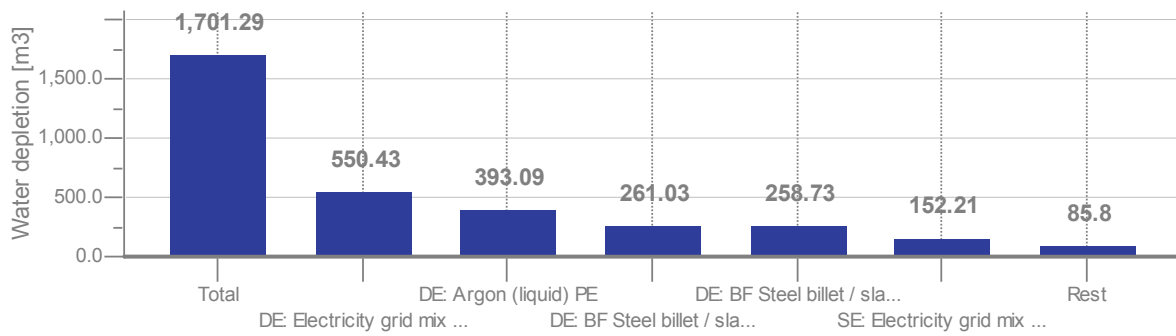
### Photochemical oxidant formation



### Terrestrial ecotoxicity



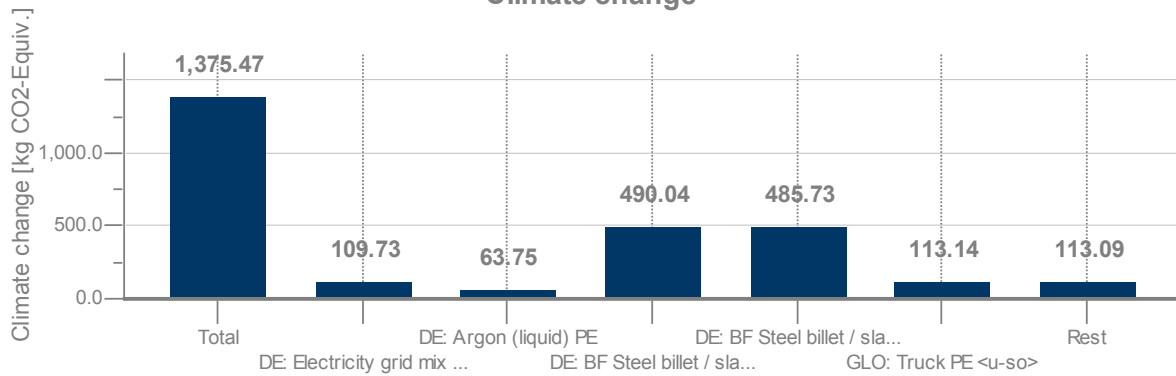
### Water depletion



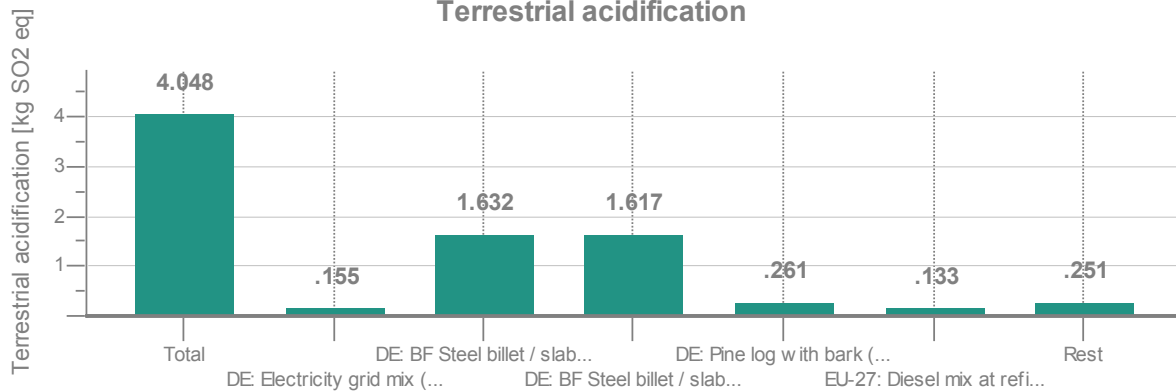
### Diagrams level 4. Sensitivity analysis –Transportation

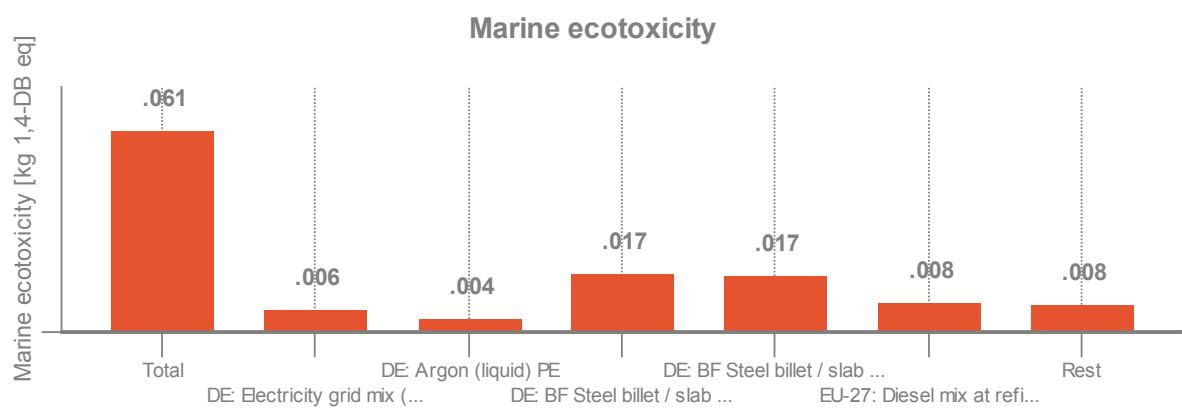
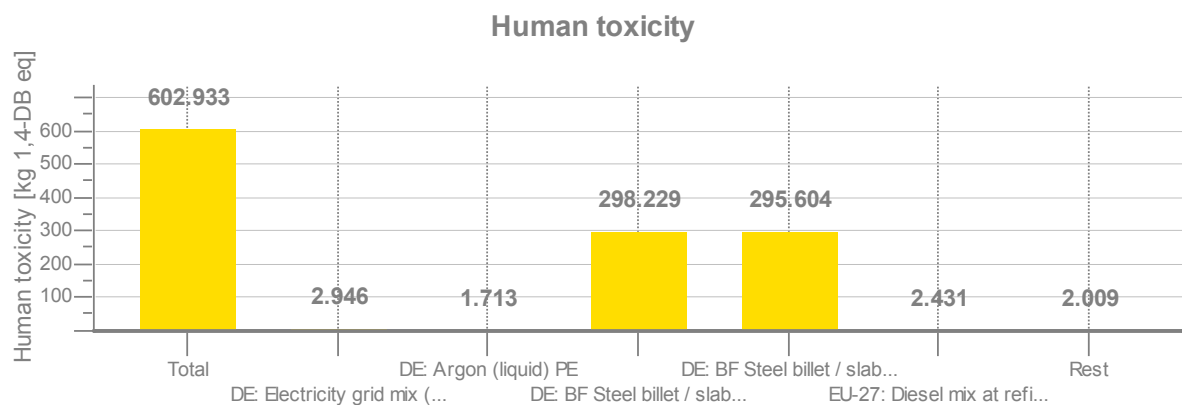
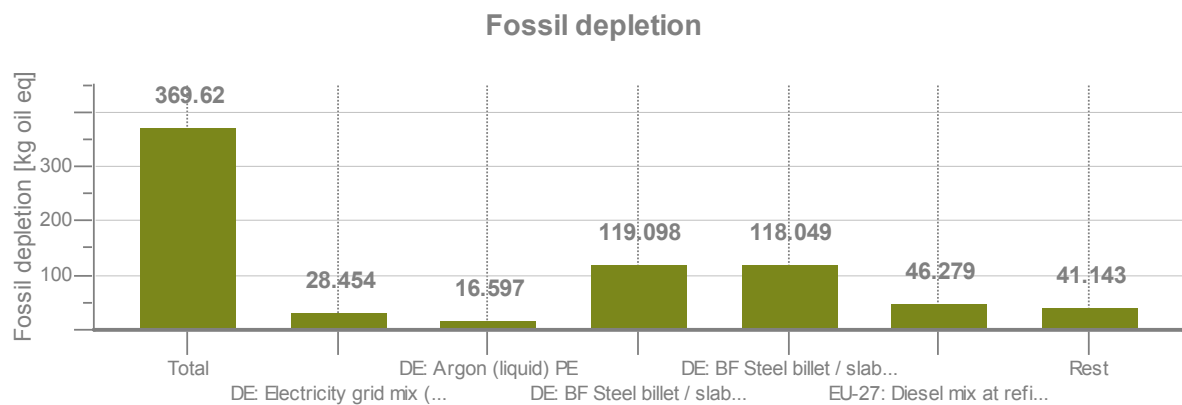
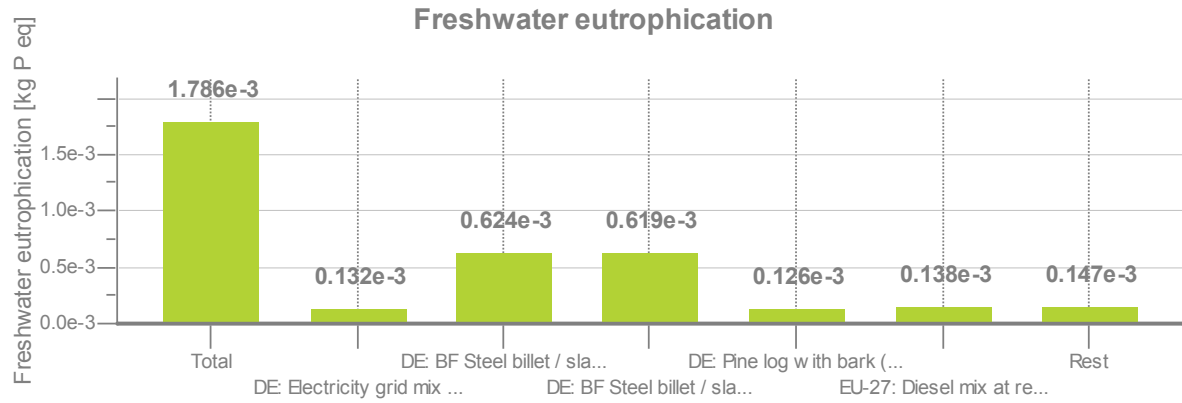
Diagrams for impact categories due to increased transportation with 600 km within Sweden

### Climate change

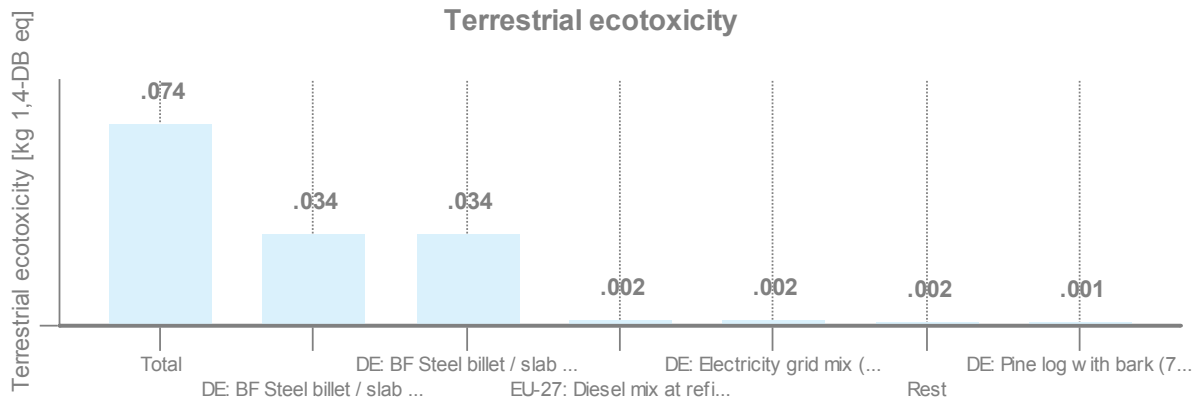
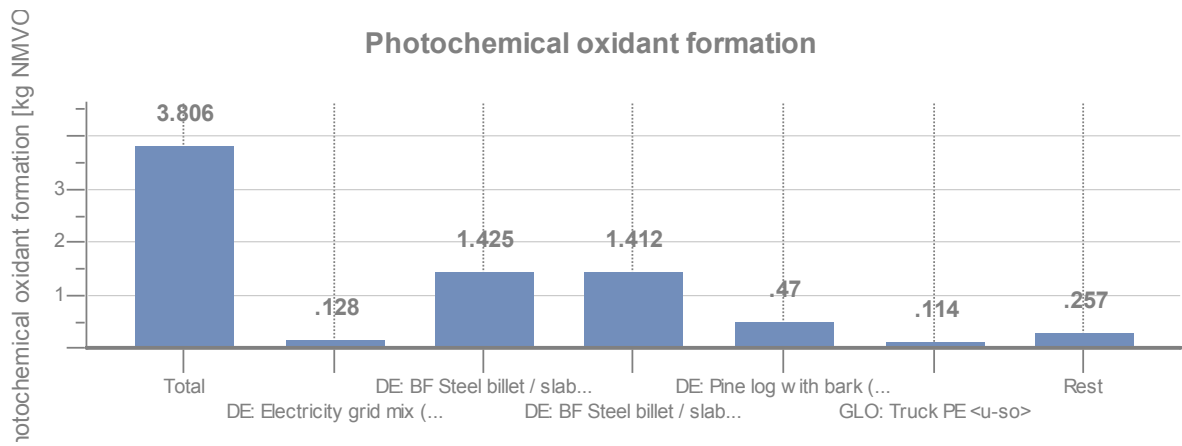
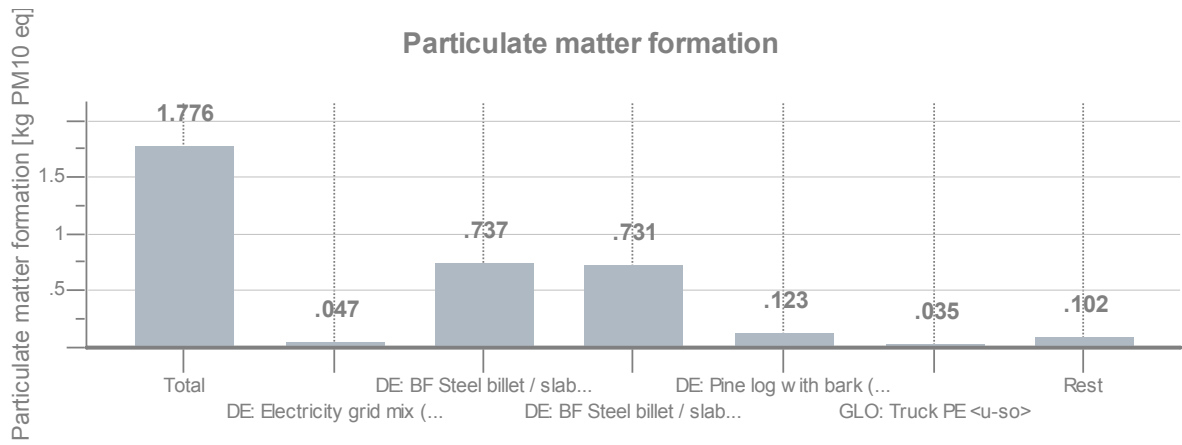


### Terrestrial acidification

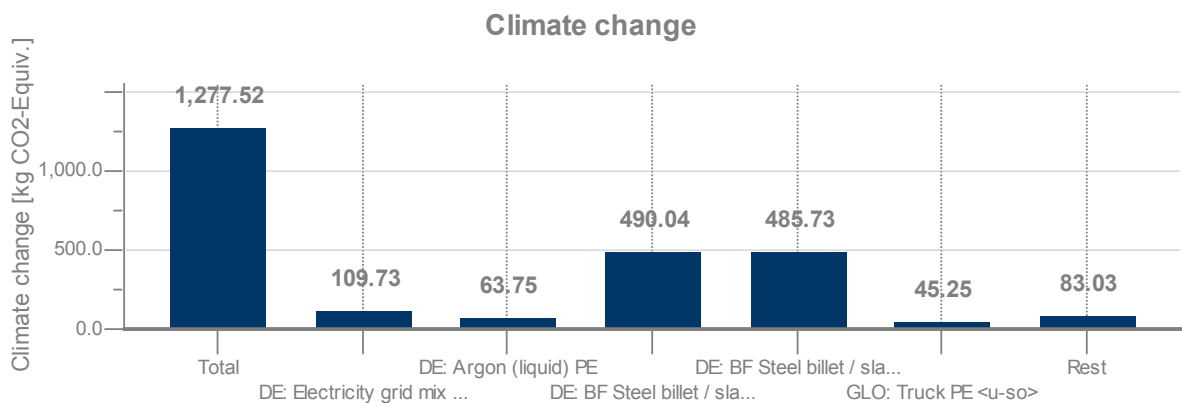




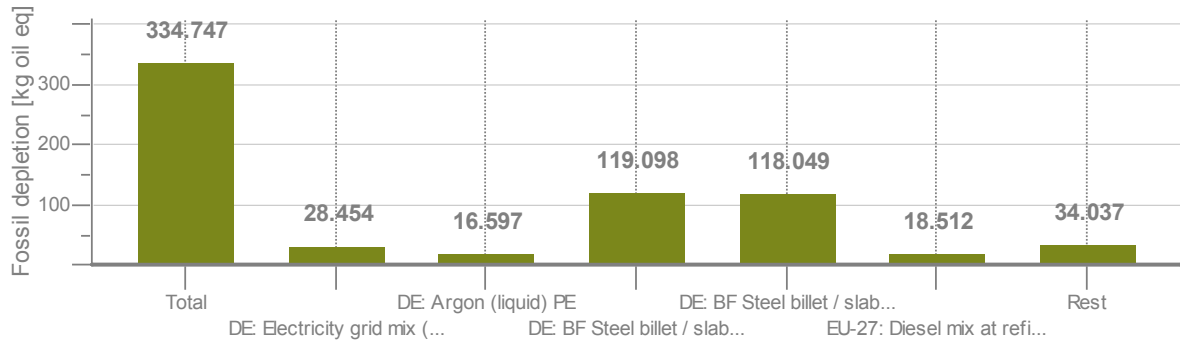




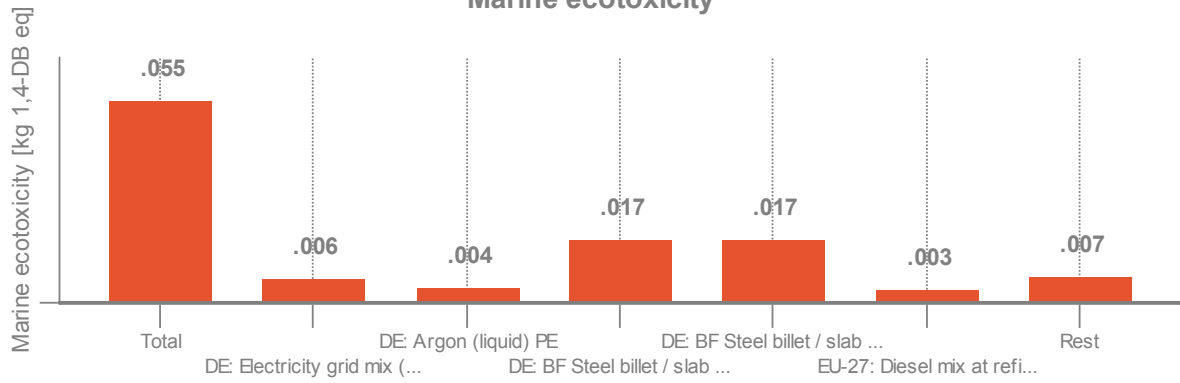
Diagrams for impact categories due to decreased transportation distance to 500 km within Canada



### Fossil depletion



### Marine ecotoxicity



## Appendix D.

Table 1. Electricity prices for different types of customers, average value

Öre/kWh excluding taxes

Client type	1 Jan 1996	1 Jan 1997	1 Jan 1998	1 Jan 1999	1 Jan 2000	1 Jan 2001	1 Jan 2002	1 Jan 2003	Av. 2004	Av. 2005	Av. 2006	Av. 2007	Av. 2008	Av. 2009	Av. 2010	Av. 2011	Av. 2012
Apartment	28,2	29,2	29,0	27,1	25,8	27,0	35,6	51,9	48,8	48,5	65,3	64,0	79,1	79,1	84,9	93,3	83,7
Villa without el-heat	26,7	27,6	26,8	26,3	23,4	24,2	31,6	47,1	43,5	42,1	58,9	57,5	72,4	72,3	77,7	85,3	75,6
Villa with el-heat	24,7	25,9	25,1	24,4	21,8	22,5	29,6	44,7	40,8	39,1	55,7	54,3	69,2	69,1	74,2	81,5	71,7

Table 2. Annual price increase rate

Client type	16 year trend	10 year trend	8 year trend	5 year trend
Apartment	8%	10%	8%	6%
Villa without el-heat	8%	11%	8%	6%
Villa with el-heat	8%	11%	9%	6%

Source: SCB (2014)

### Scenario 1

#### Return on investment

Performance Dali Power Tower : +8 solar panels (2 kW or 1900 kWh) - 12 m/s - governmental support for investment in solar panels 35% and el-certificate

	INPUT DATA
Investment cost (SEK)	180.000
Own investment (%)	20%
Invested amount from own saving (SEK)	36.000
Invested amount from bank loan (SEK)	144.000
Average loan interest fee (%)	4,1%
Funding period (year)	15
Annual amortisement	9.600
Governmental support for solar panels	63.000
Support for investment (year)	2

Annual electricity consumption (kWh)	12.400
Annual electricity production (kWh)	9.000

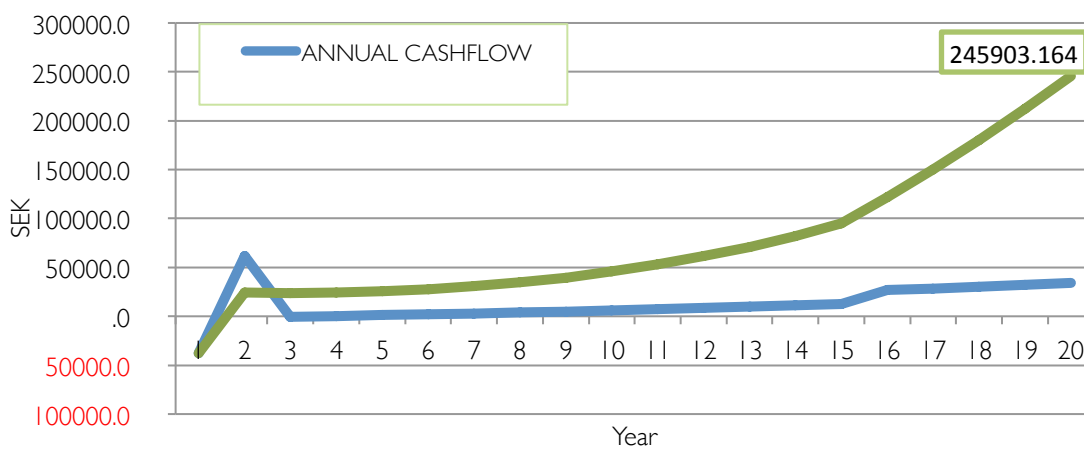
Electricity price/kWh (SEK)	1,08
Estimated electricity price increase (%)	6%
Elcertificate (SEK/ kWh)	0,23
Total electricity price year 1	1,31

Service	1.000
Estimated annual service increase (%)	3%

SUMMARY	
Electricity production vs consumption %	73%
Accumulated netto after 20 years, SEK	245.903

ELECTRICITY PRICE (SEK)	
Average electricity price from the grid over 20 years	1,99
Average electricity price from wind-solar system over 20 years	1,39
Average electricity prices according to way of consumption	1,56

### Return on investment graph Scenario 1



### Scenario 2

#### Return on investment

Performance Dali Power Tower : +8 solar panels (2kW or 1900kwh) - 12 m/s - without governmental support for investment in solar panels and el-certificate

	INPUT DATA
Investment cost (SEK)	180.000
Own investment (%)	20%
Invested amount from own saving (SEK)	36.000
Invested amount from bank loan (SEK)	144.000
Average loan interest fee (%)	4,1%
Funding period (year)	15
Annual amortisement	9.600
Governmental support for solar panels	0
Support for investment (year)	2
Annual electricity consumption (kWh)	12.400
Annual electricity production (kWh)	9.000

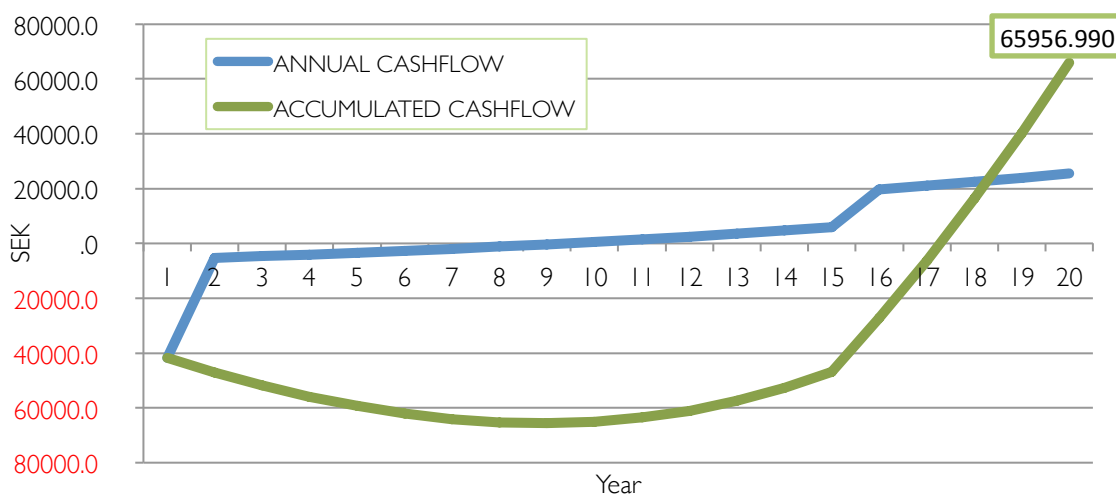
Electricity price/kWh (SEK)	1,08
Estimated electricity price increase (%)	6%
Elcertificate (SEK/ kWh)	0,00
Total electricity price year 1	1,08

Service	1.000
Estimated annual service increase (%)	3%

SUMMARY	
Electricity production vs consumption %	73%
Accumulated netto after 20 years, SEK	65.957

ELECTRICITY PRICE (SEK)	
Average electricity price from the grid over 20 years	1,99
Average electricity price from wind-solar system over 20 years	1,39
Average electricity prices according to way of consumption	1,56

### Return on investment graph Scenario 2



### Scenario 3

#### Return on investment

Performance Dali Power Tower : +8 solar panels (2kW or 1900kwh) - less generated electricity - governmental support for investment in solar panels 35% and el-certificate

INPUT DATA	
Investment cost (SEK)	180.000
Own investment (%)	20%
Invested amount from own saving (SEK)	36.000
Invested amount from bank loan (SEK)	144.000
Average loan interest fee (%)	4,1%

Funding period (year)	15
Annual amortisement	9.600
Governmental support for solar panels	63.000
Support for investment (year)	2

Annual electricity consumption (kWh)	12.400
Annual electricity production (kWh)	7.000

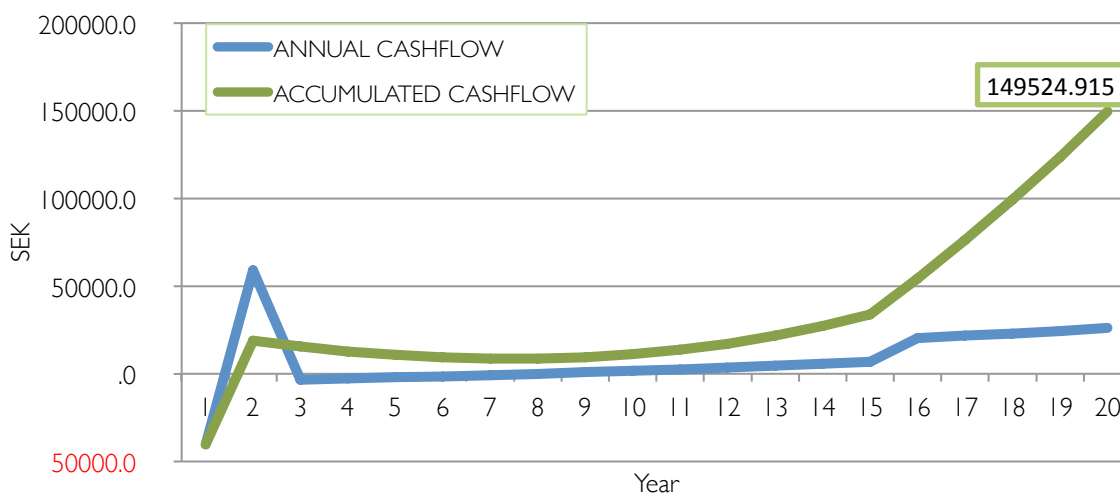
Electricity price/kWh (SEK)	1,08
Estimated electricity price increase (%)	6%
Elcertificate (SEK/ kWh)	0,23
Total electricity price year 1	1,31

Service	1.000
Estimated annual service increase (%)	3%

SUMMARY	
Electricity production vs consumption %	56%
Accumulated netto after 20 years, SEK	149.525

ELECTRICITY PRICE (SEK)	
Average electricity price from the grid over 20 years	<b>1,99</b>
Average electricity price from wind-solar system over 20 years	<b>1,79</b>
Average electricity prices according to way of consumption	<b>1,88</b>

Return on investment graph Scenario 3



## Scenario 4

### Return on investment

Performance Dali Power Tower : +8 solar panels (2kW or 1900kwh) - less generated energy- without governmental support for investment in solar panels and el-certificate

	INPUT DATA
Investment cost (SEK)	180.000
Own investment (%)	20%
Invested amount from own saving (SEK)	36.000
Invested amount from bank loan (SEK)	144.000
Average loan interest fee (%)	4,1%
Funding period (year)	15
Annual amortisement	9.600
Governmental support for solar panels	0
Support for investment (year)	2

Annual electricity consumption (kWh)	12.400
Annual electricity production (kWh)	7.000

Electricity price/kWh (SEK)	1,08
Estimated electricity price increase (%)	6%
El-certificate (SEK/ kWh)	0,00
Total electricity price year 1	1,08

Service	1.000
Estimated annual service increase (%)	3%

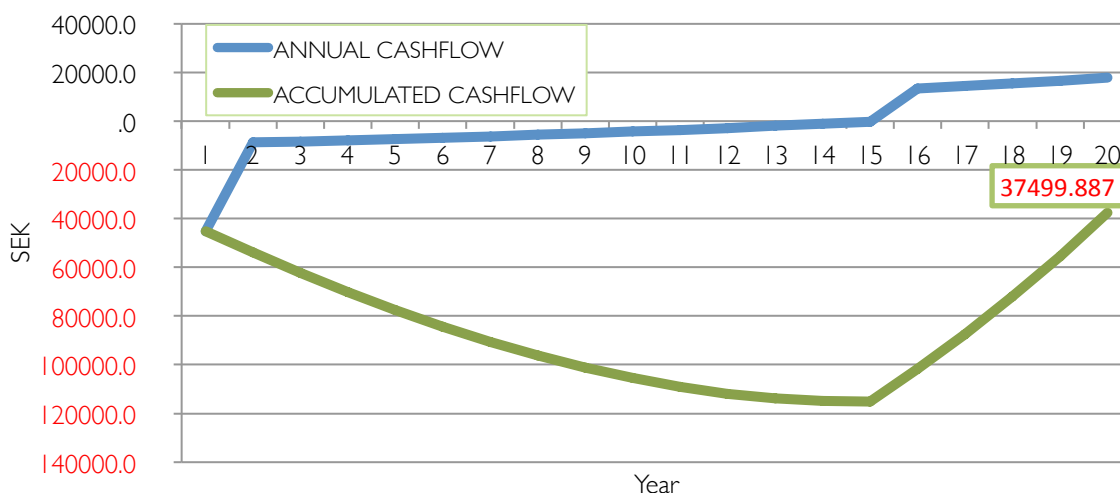
### SUMMARY

Electricity production vs. consumption %	56%
Accumulated net after 20 years, SEK	-37.500

### ELECTRICITY PRICE (SEK)

Average electricity price from the grid over 20 years	<b>1,99</b>
Average electricity price from wind-solar system over 20 years	<b>1,79</b>
Average electricity prices according to way of consumption	<b>1,88</b>

### Return on investment graph Scenario 4



### Scenario 5

#### Return on investment

Performance Dali Power Tower : +8 solar panels (2kW or 1900kwh) -7 725 kWh/year generated electricity - without governmental support for investment in solar panels and el-certificate

	INPUT DATA
Investment cost (SEK)	180.000
Own investment (%)	20%
Invested amount from own saving (SEK)	36.000
Invested amount from bank loan (SEK)	144.000
Average loan interest fee (%)	4,1%
Funding period (year)	15
Annual amortisement	9.600
Governmental support for solar panels	0
Support for investment (year)	2
Annual electricity consumption (kWh)	12.400
Annual electricity production (kWh)	7.725
Electricity price/kWh (SEK)	1,08
Estimated electricity price increase (%)	6%
Elcertificate (SEK/ kWh)	0,00
Total electricity price year 1	1,08
Service	1.000
Estimated annual service increase (%)	3%



### SUMMARY

Electricity production vs consumption %	62%
Accumulated netto after 20 years, SEK	3

### ELECTRICITY PRICE (SEK)

Average electricity price from the grid over 20 years	<b>1,99</b>
Average electricity price from wind-solar system over 20 years	<b>1,62</b>
Average electricity prices according to way of consumption	<b>1,76</b>

Return on investment graph Scenario 5.

